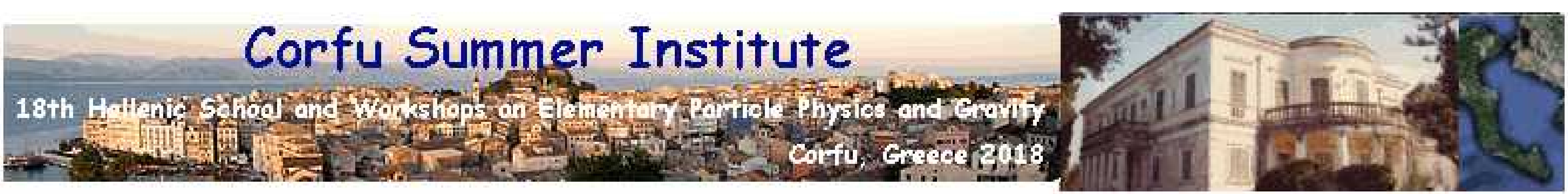
Decoding the nature of Dark Matter

Alexander Belyaev

Southampton University & Rutherford Appleton Laboratory



Corfu Summer Institute: Workshop on the Standard Model and Beyond
31 August 2018 to 9 September 2018

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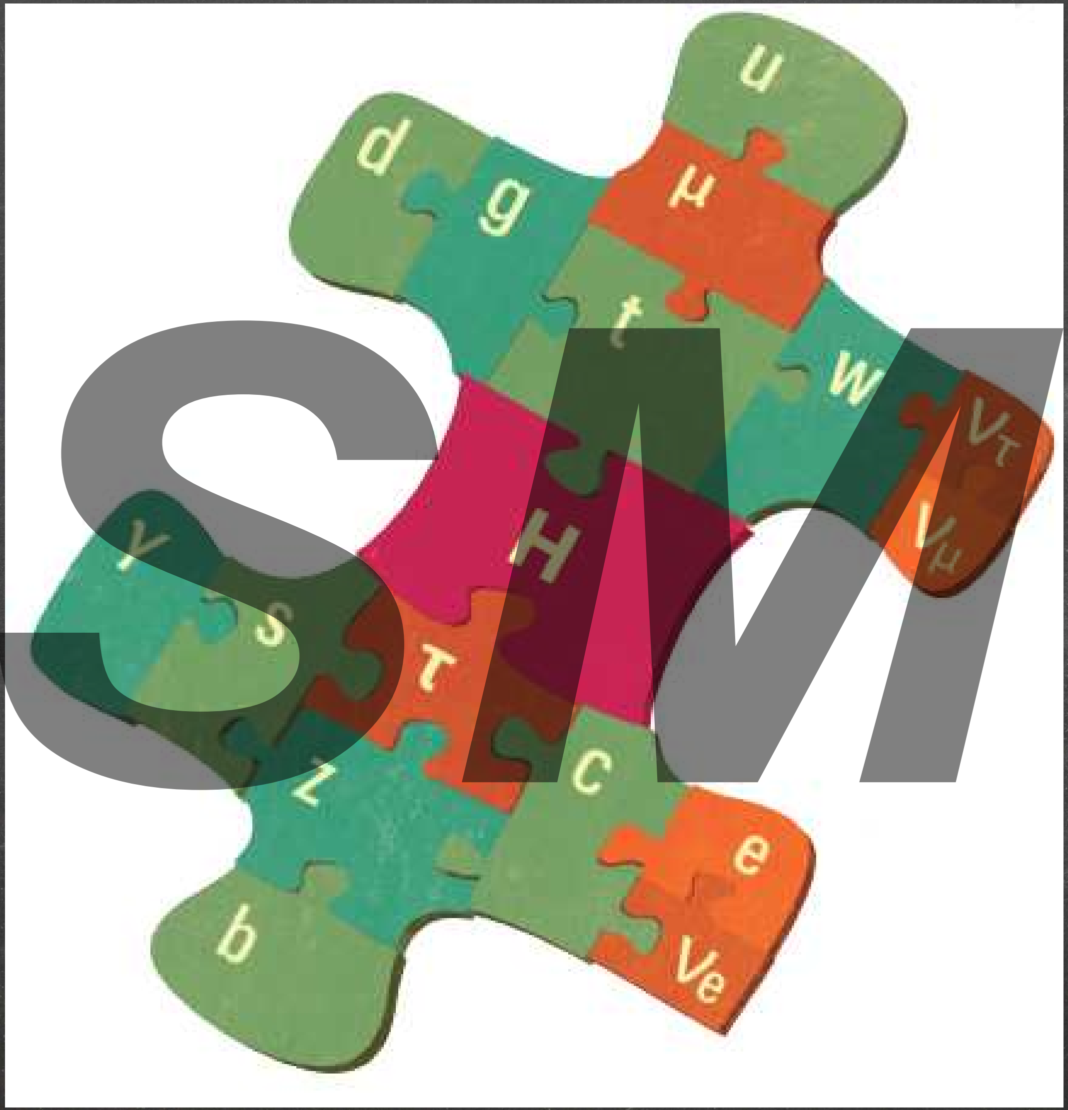
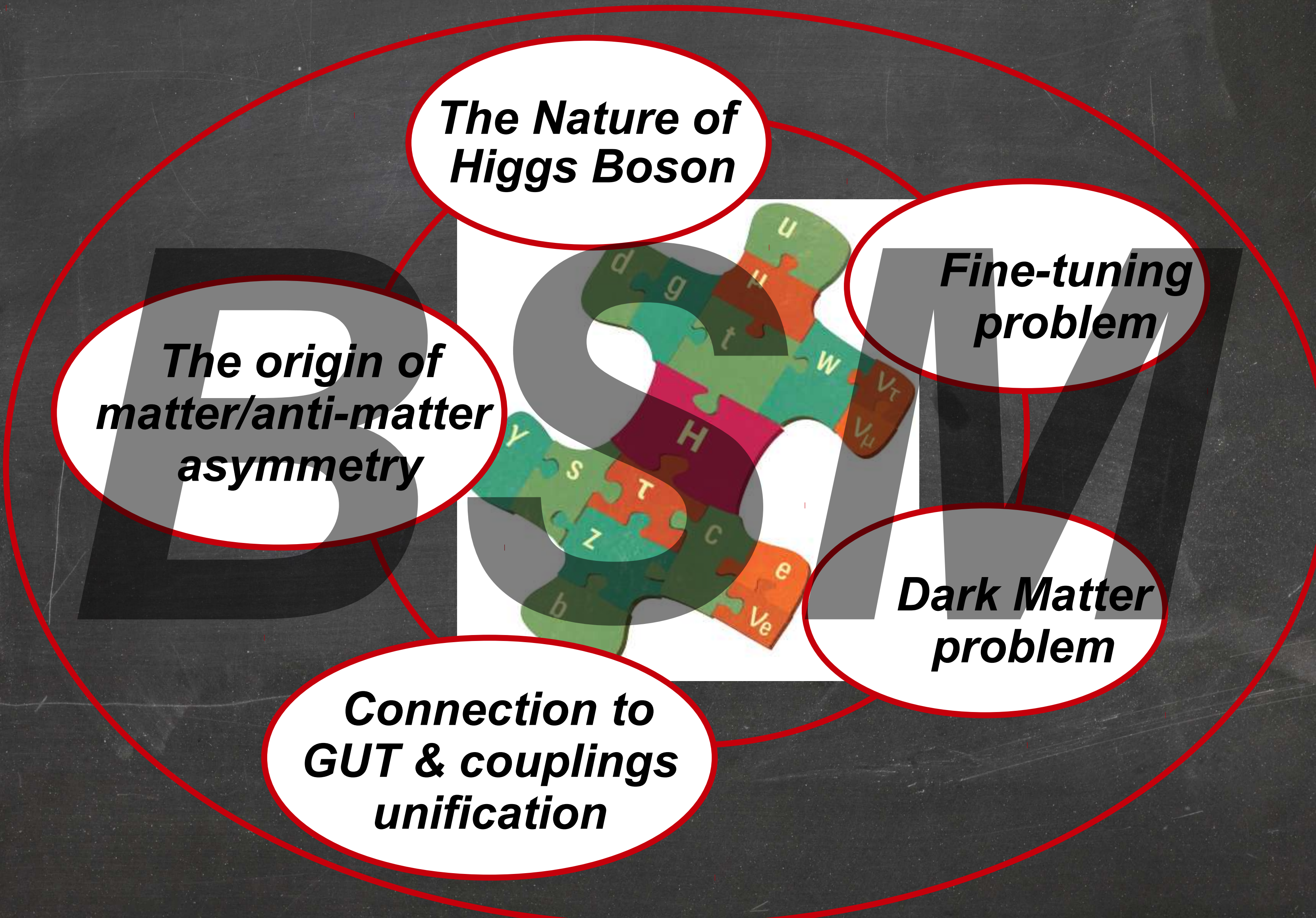
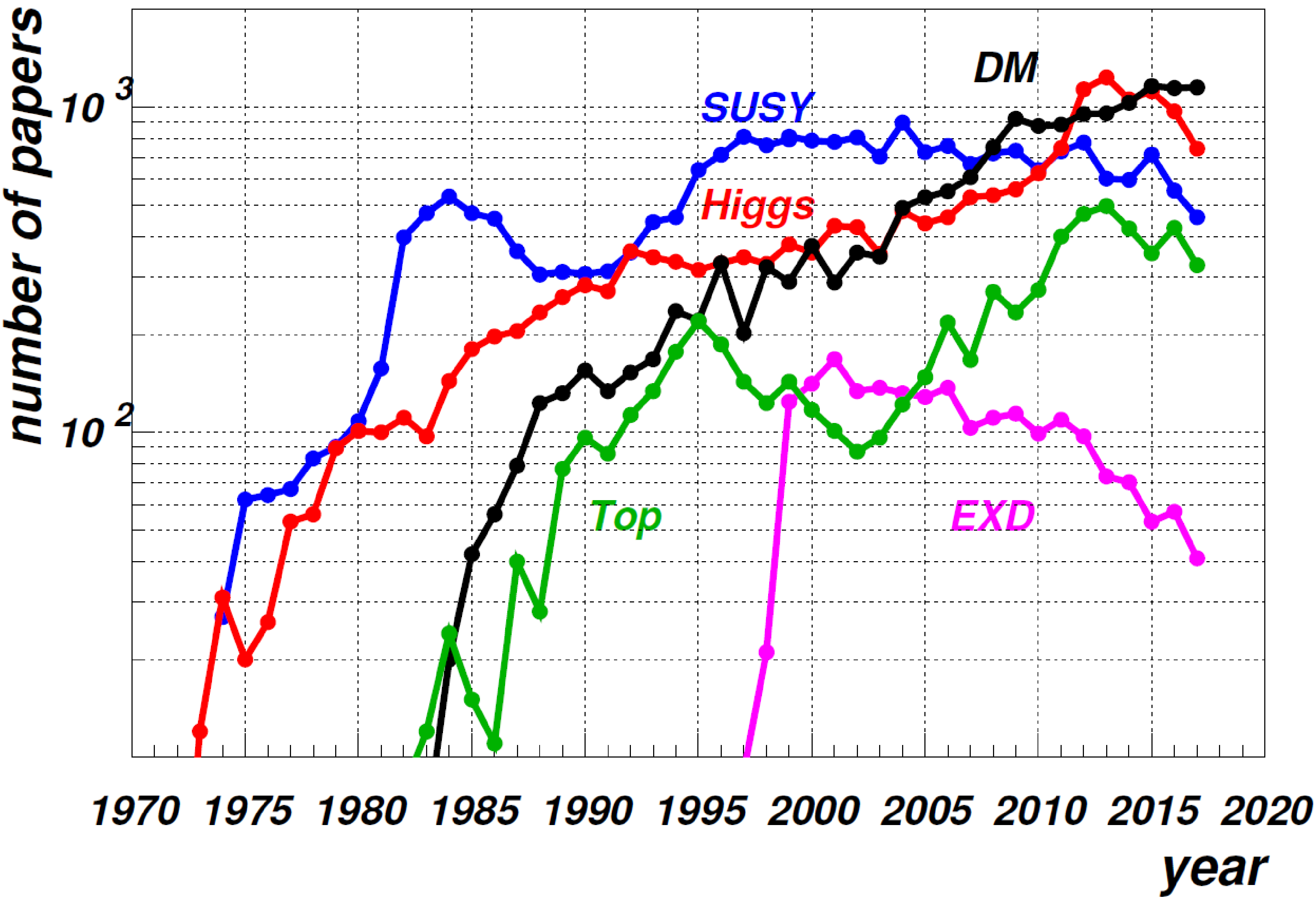
Higgs Boson Discovery has finished the SM puzzle



Higgs Boson Discovery has finished the SM puzzle, but it is just a piece of some (more) complete and consistent one!



Why we are so keen to study DM?



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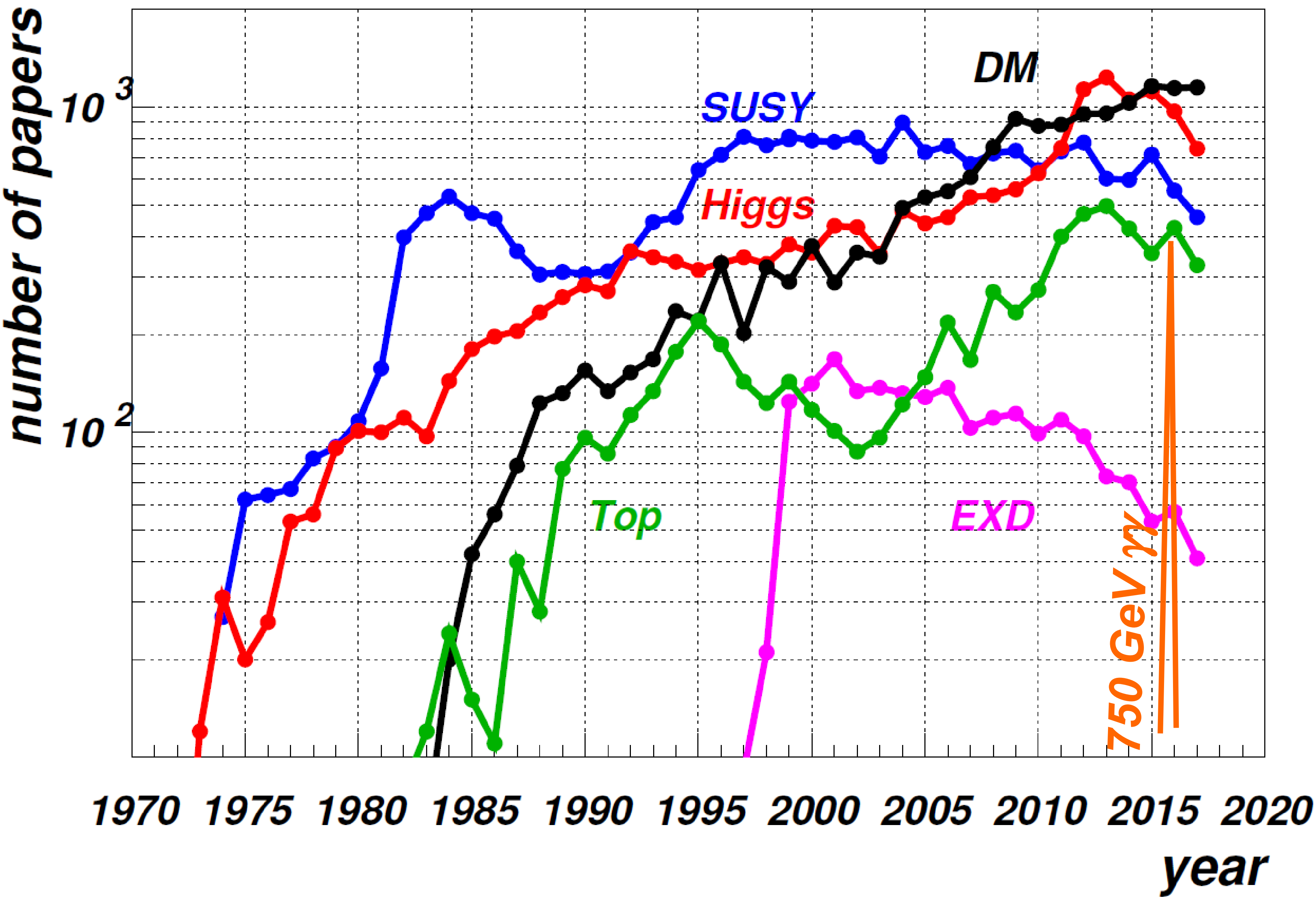

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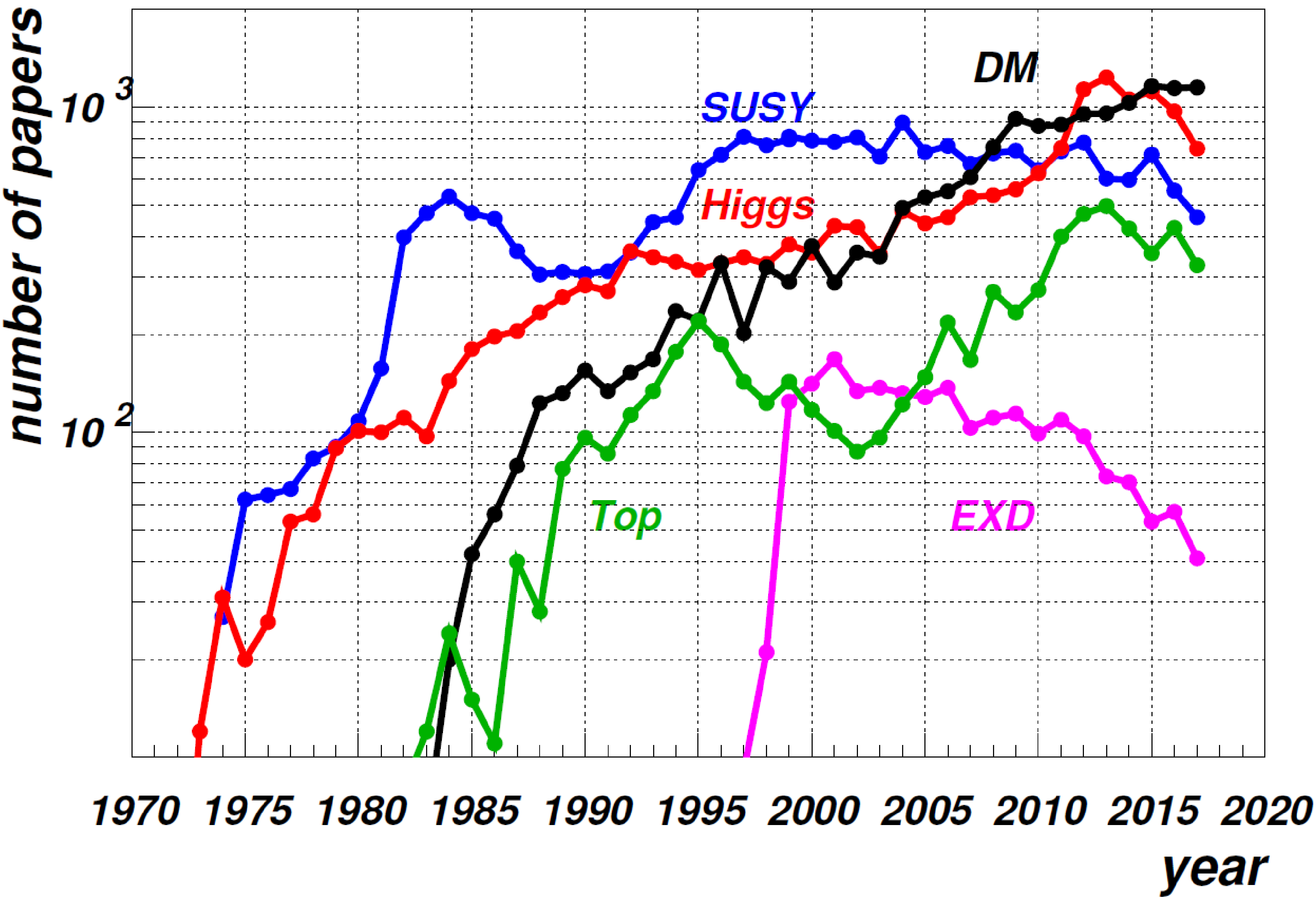
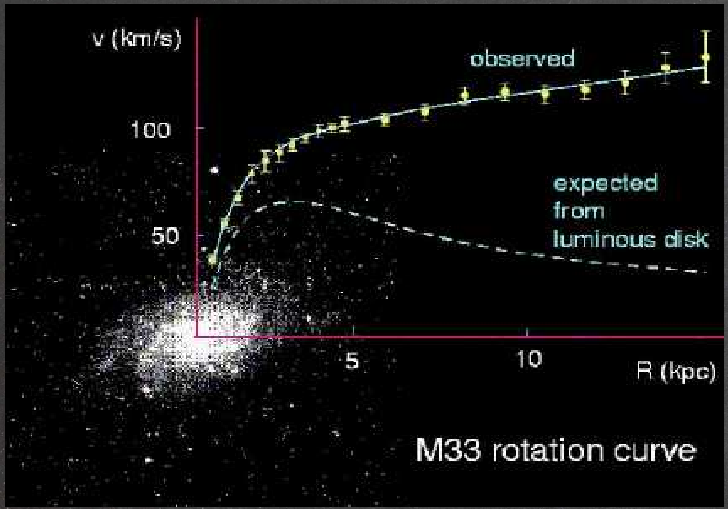
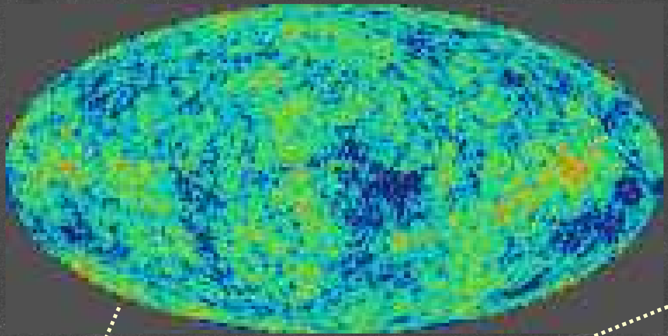


Because the existence of DM is the strongest evidence for BSM!

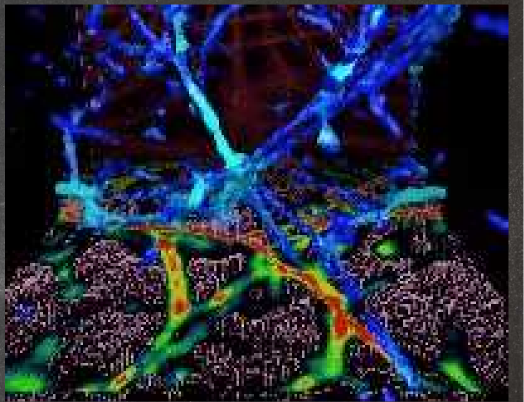
Galactic rotation curves

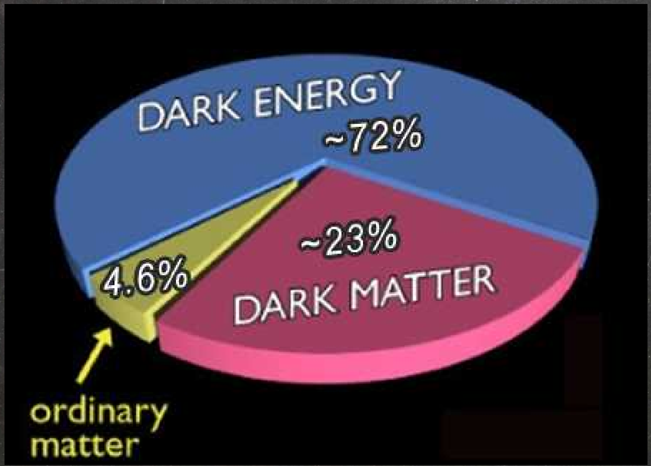


CMB: WMAP and PLANCK



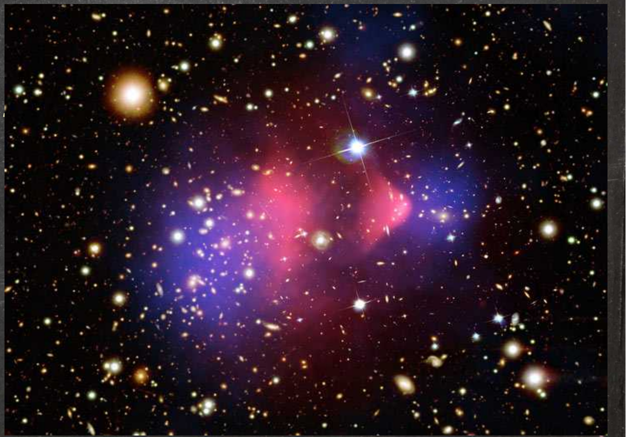
Large Scale Structures





Gravitational lensing

Bullet cluster



Even though we know almost nothing about it!

Spin ?

Mass ?

Stable
- Yes ? No ?
- symmetry behind stability ?

Couplings
- gravity V
- Weak ?
- Higgs ?
- Quarks/gluons ?
- Leptons ?
- New mediators ?

Thermal relic
- Yes ? No ?

How we can decode the fundamental nature of Dark Matter?

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We need a DM signal first!

How we can decode the fundamental nature of Dark Matter?

We need a DM signal first!

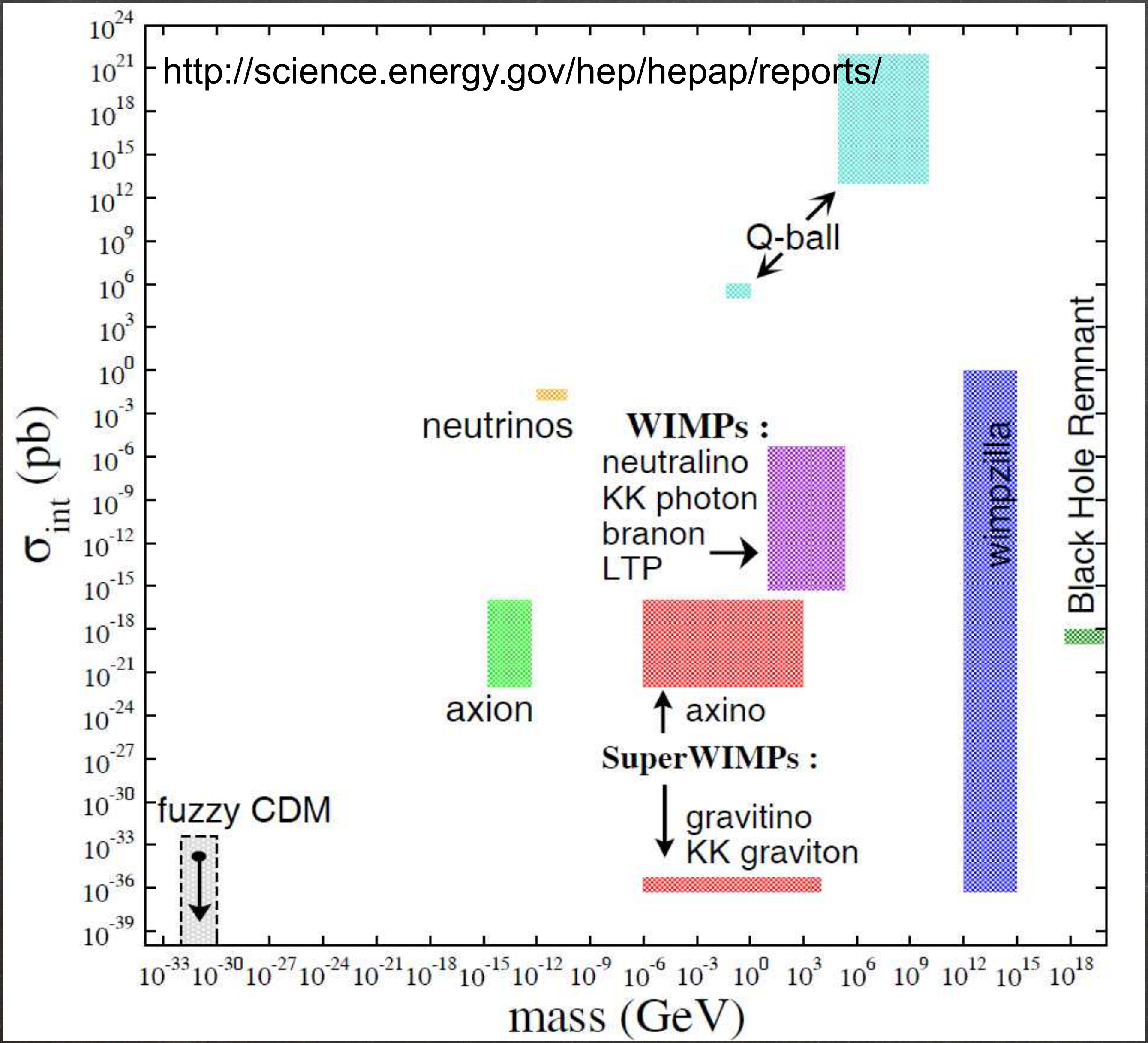
But at the moment we can:

- ⇨ understand what kind of DM is already excluded
- ⇨ explore theory space and prepare ourselves to discovery and decoding of DM

Collaborators & Projects

• I.Ginzburg, D.Locke, A. Freegard, T. Hosken, AB	to appear
• S.Novaes, P.Mercadante, C.S. Moon,T.Tomei, S. Moretti, M.Tomas, L. Panizzi, AB	arXiv:**1809.00933**
• G.Cacciapaglia, J.McKay, D. Marin, A.Zerwekh, AB	arXiv:**1808.10464**
• E.Bertuzzo, C.Caniu, G. di Cortona, O.Eboli, F. Iocco, A.Pukhov, AB	arXiv:**1807.03817**
• T. Flacke, B. Jain, P. Schaefers, AB	arXiv:**1707.07000**
• G. Cacciapaglia, I. Ivanov, F. Rojas, M. Thomas, AB	arXiv:**1612.00511**
• I. Shapiro, M. Thomas, AB	arXiv:**1611.03651**
• L. Panizzi, A. Pukhov, M.Thomas, AB	arXiv:**1610.07545**
• D. Barducci, A.Bharucha, W. Porod, V. Sanz, AB	arXiv:**1504.02472**

DM candidates: interaction vs mass



- Planck mass BH remnants: tiny black holes protected by gravity effects [Chen '04] from decay via Hawking radiation
- Wimpzillas: very massive non-thermal WIMPs [Kolb,Chung,Riotto'98]
- Q-balls: topological solitons that occur in QFT [Coleman '86]
- EW scale WIMPs, protected by parity – LSP, LKP, LTP particles
- SuperWIMPs: electrically and color neutral DM interacting with much smaller strength (perhaps only gravitationally)
- Neutrinos: usual neutrinos are too light- HDM, subdominant component only (to be consistent with large scale structures); but heavier gauge singlet neutrinos can be CDM
- Axions: $$\frac{\theta_{QCD}}{32pi^2} F^{\mu\nu}\tilde{F}^{\mu\nu}$$

  θ_{QCD} is replaced by a quantum field, the potential energy allows the field to relax to near zero strength, axion as a consequence

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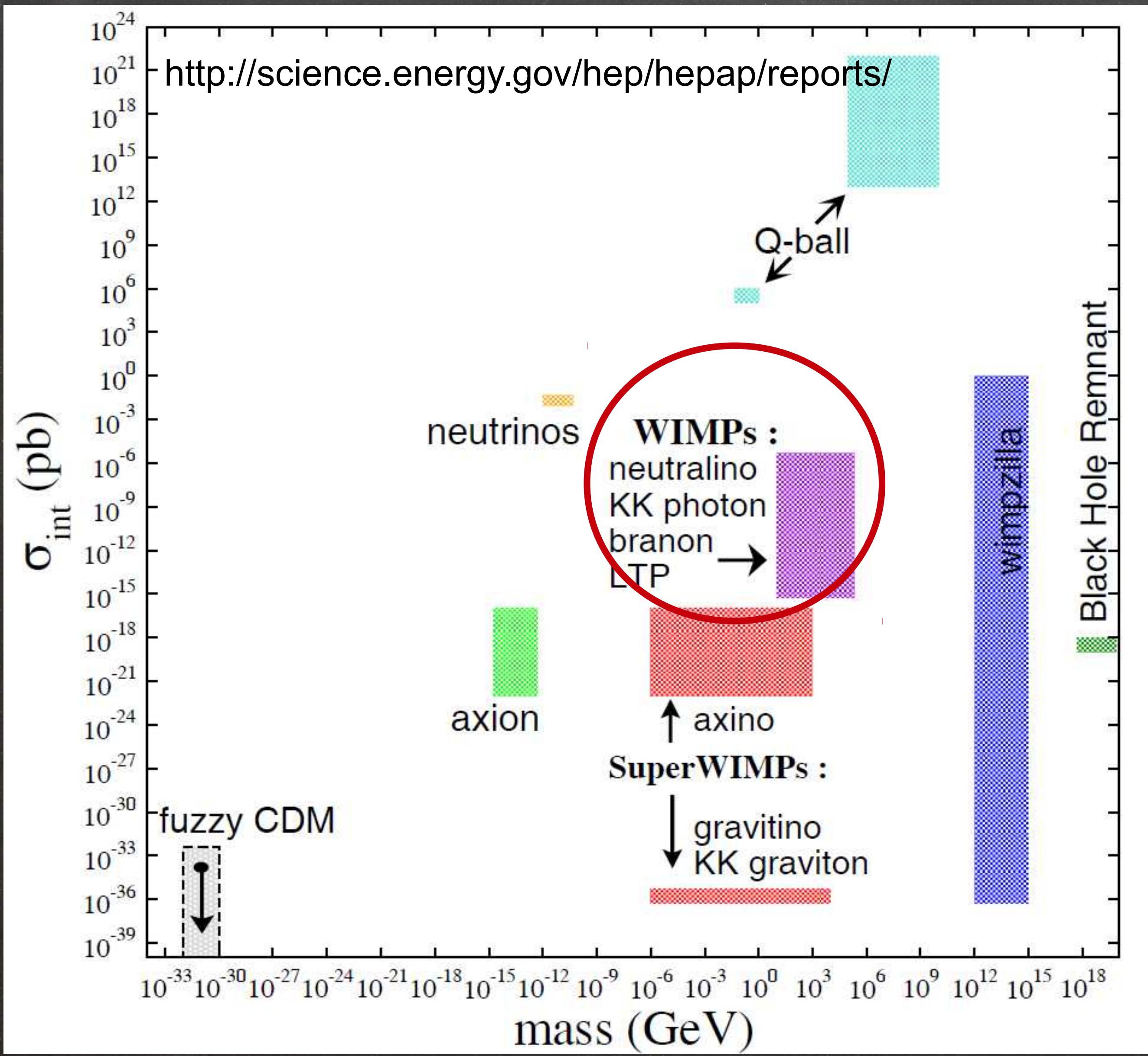

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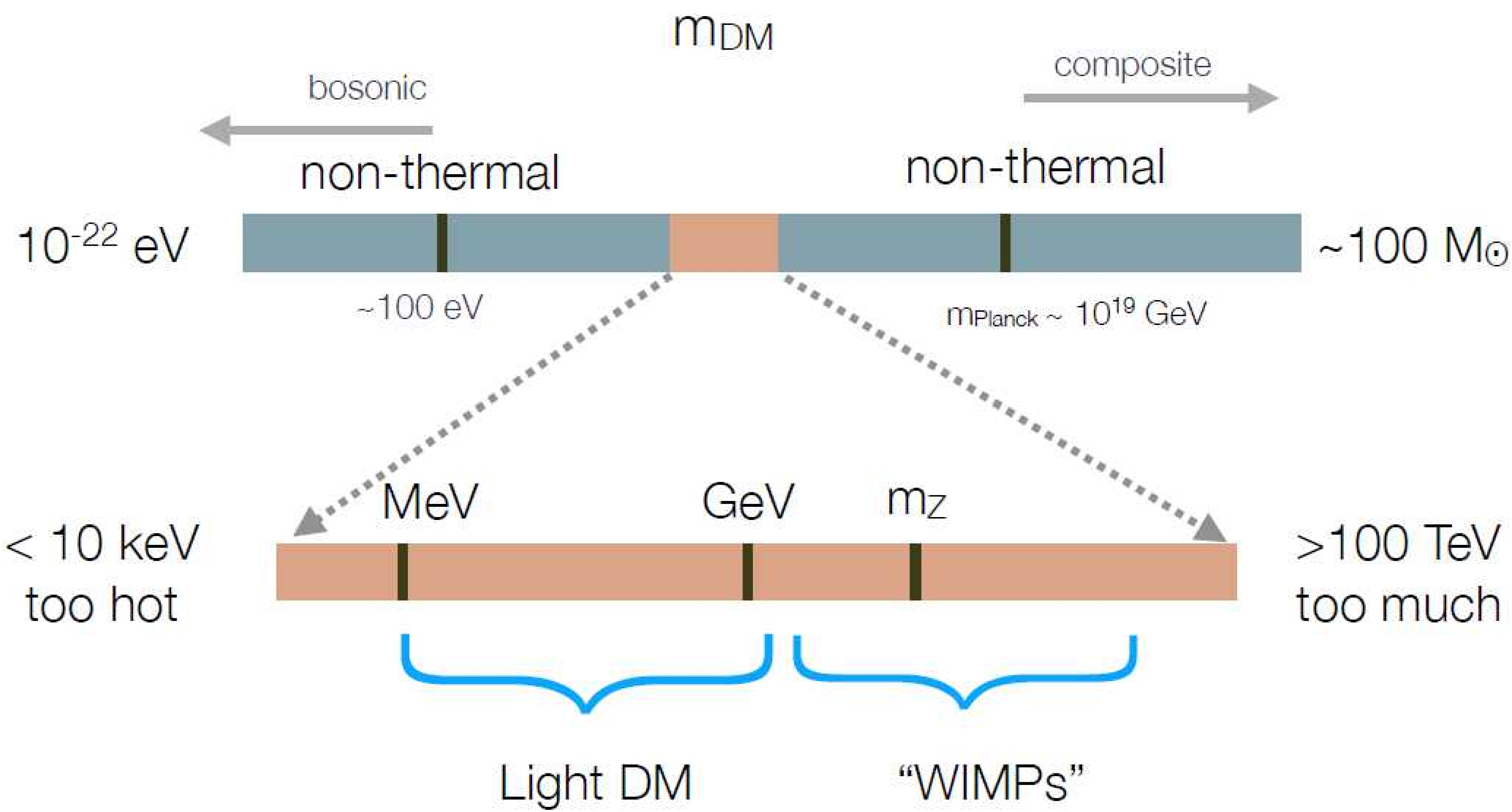
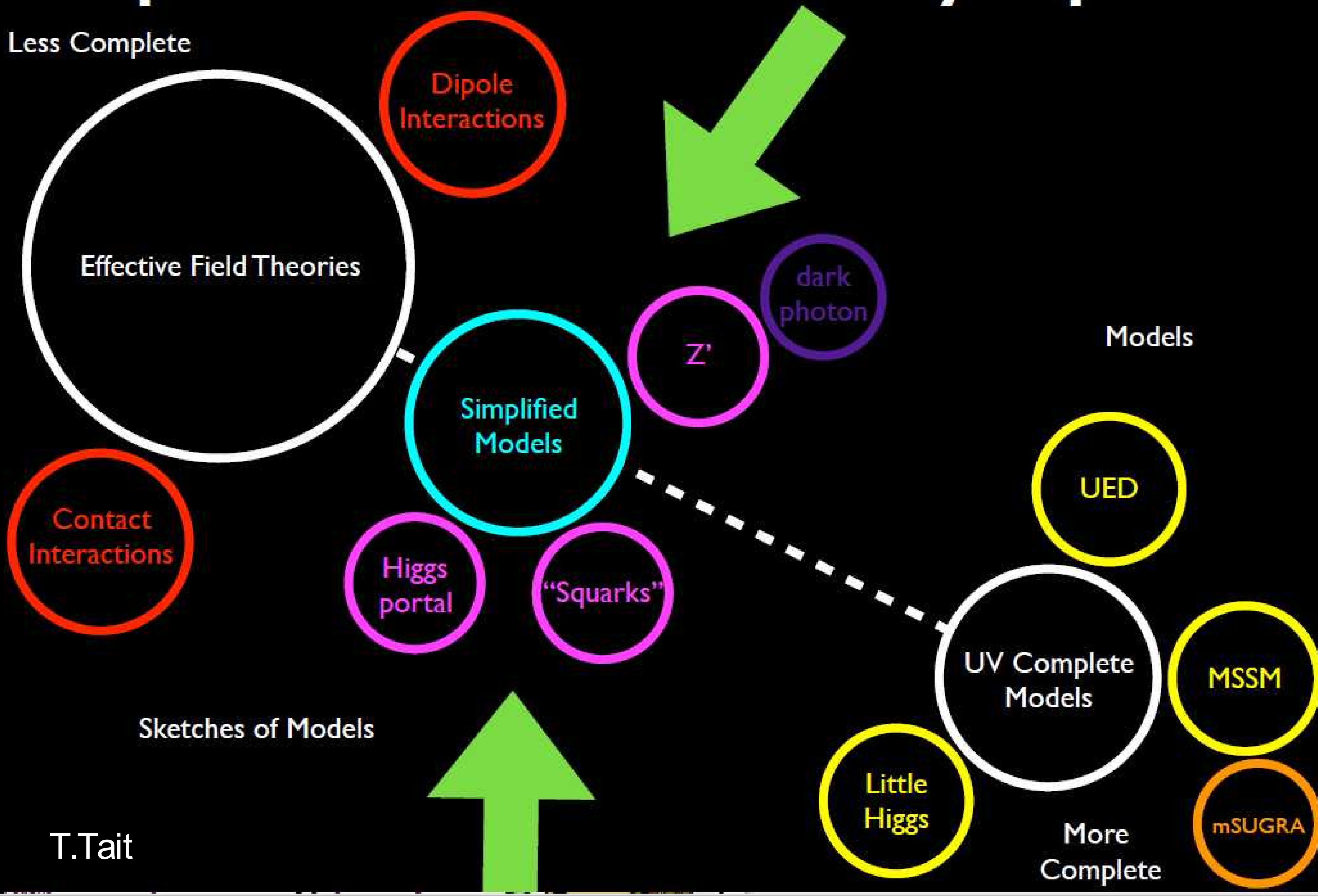
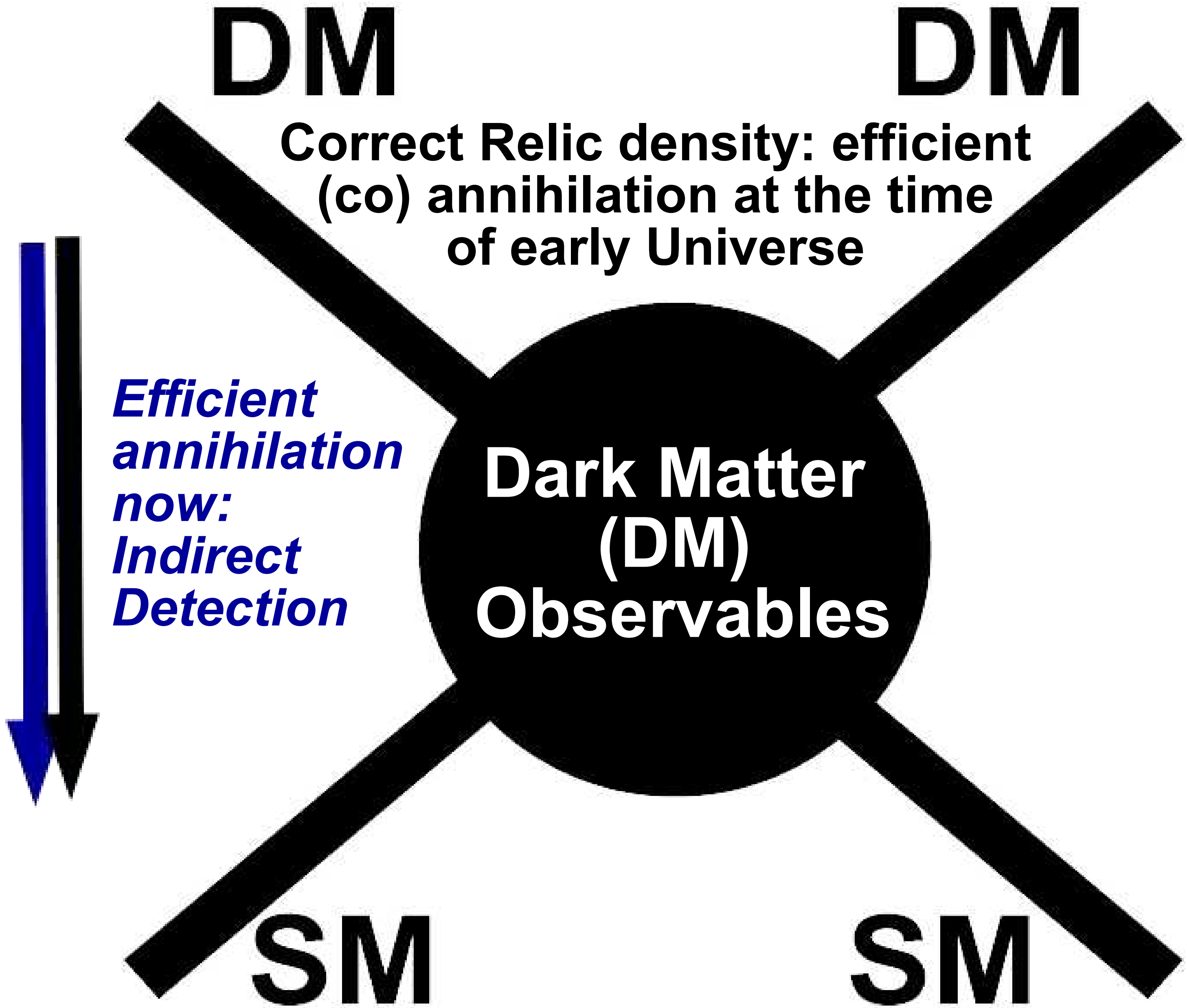
Mass range for thermal DM



Spectrum of Theory Space

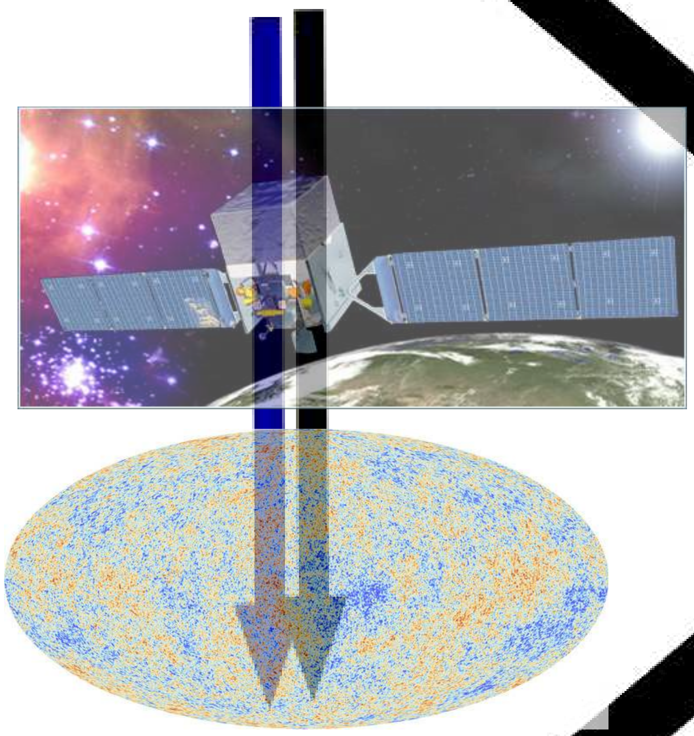


T.Tait


DM
DM
Correct Relic density: efficient (co) annihilation at the time of early Universe
Efficient annihilation now: Indirect Detection
Dark Matter (DM) Observables
SM
SM

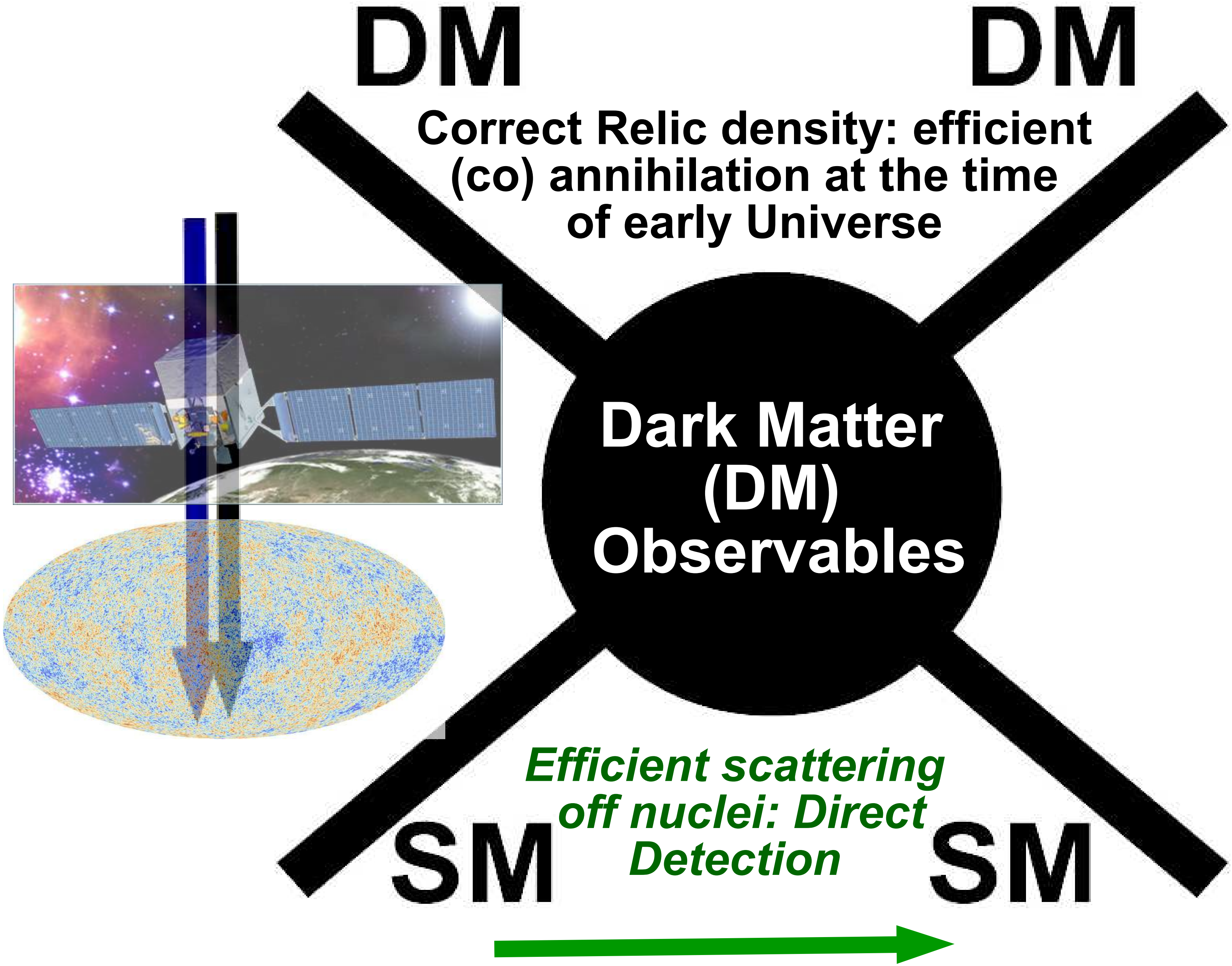
DM DM

Correct Relic density: efficient (co) annihilation at the time of early Universe



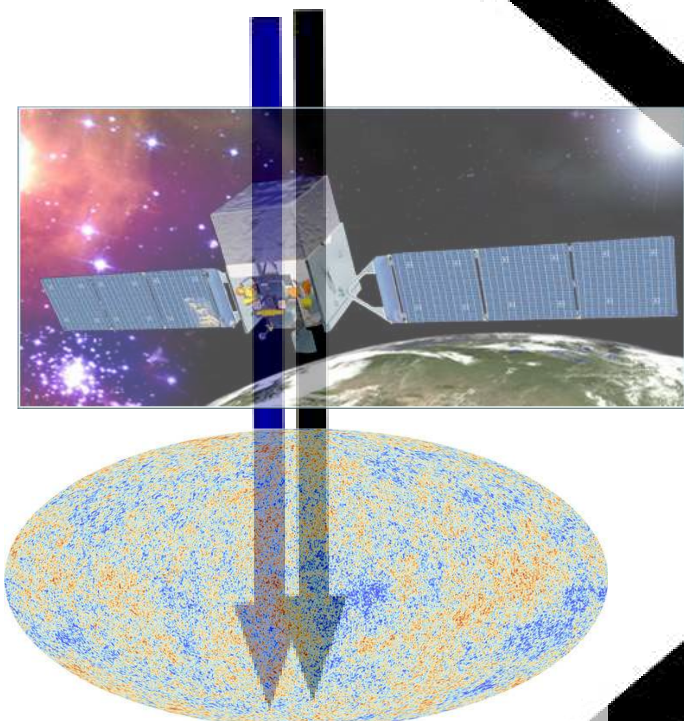
Dark Matter (DM) Observables

SM SM


DM
DM
Correct Relic density: efficient (co) annihilation at the time of early Universe
Dark Matter (DM) Observables
Efficient scattering off nuclei: Direct Detection
SM
SM

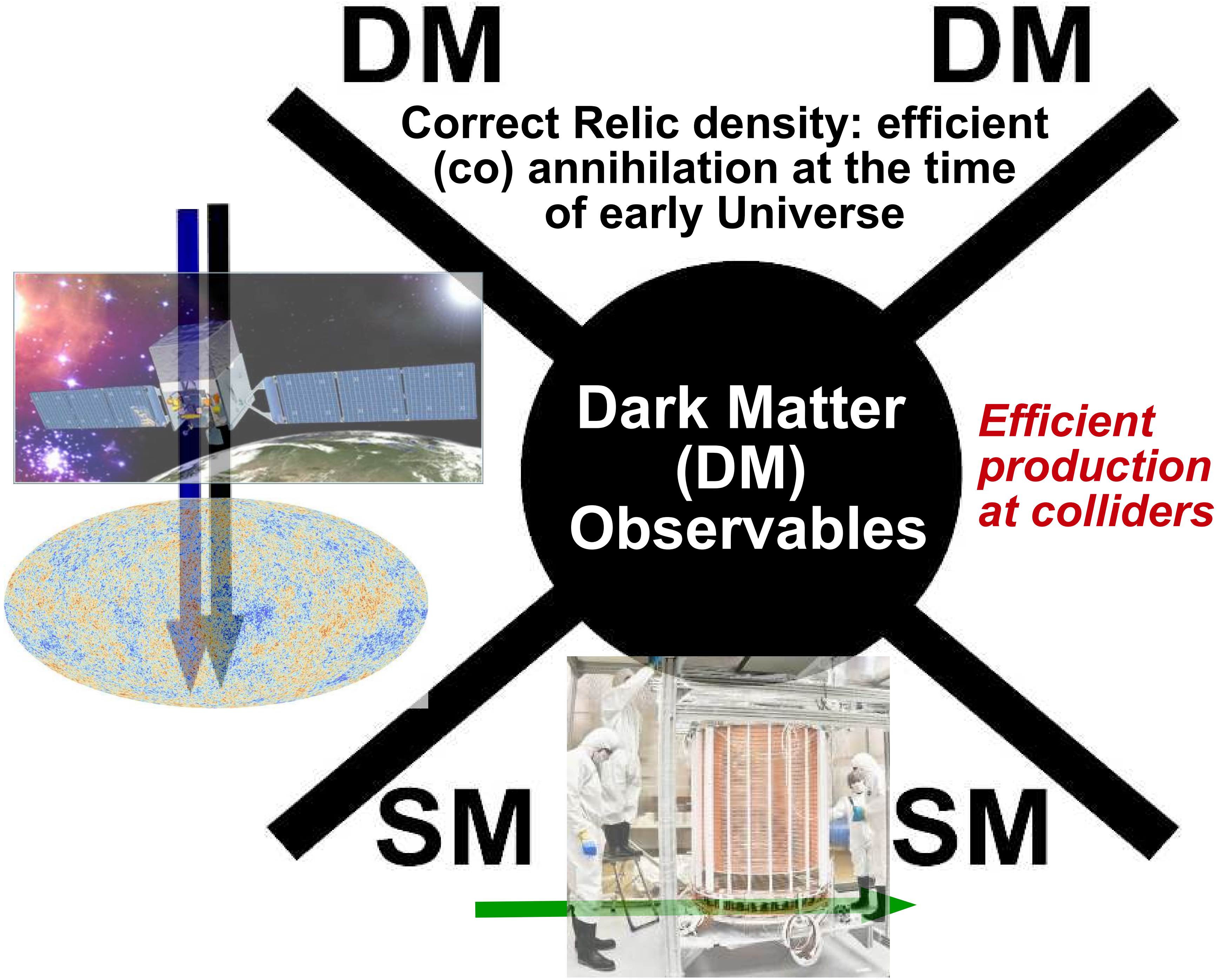
DM DM

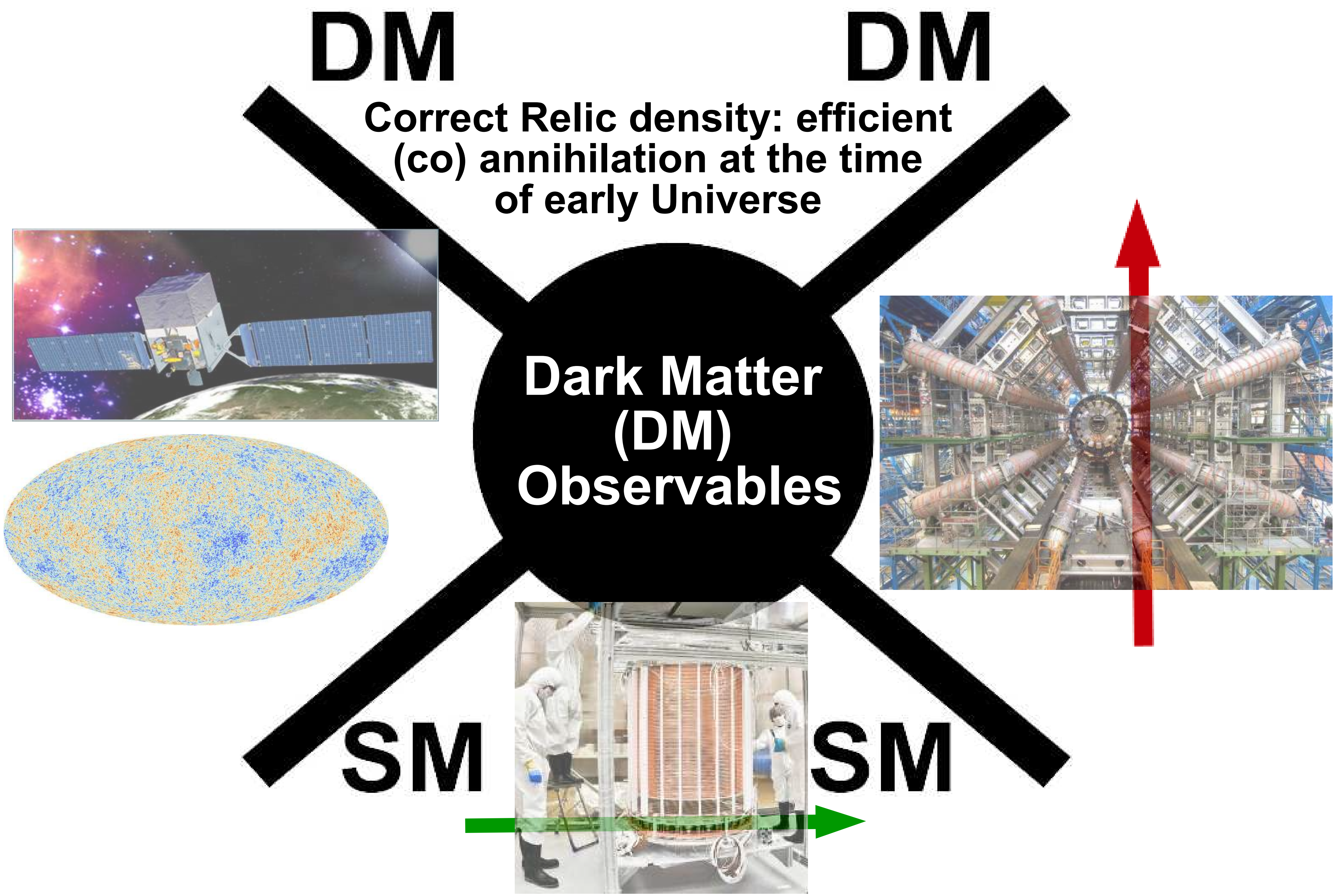
Correct Relic density: efficient (co) annihilation at the time of early Universe



Dark Matter (DM) Observables

SM SM


DM
DM
Correct Relic density: efficient (co) annihilation at the time of early Universe
Dark Matter (DM) Observables
Efficient production at colliders
SM
SM


DM
DM
Correct Relic density: efficient
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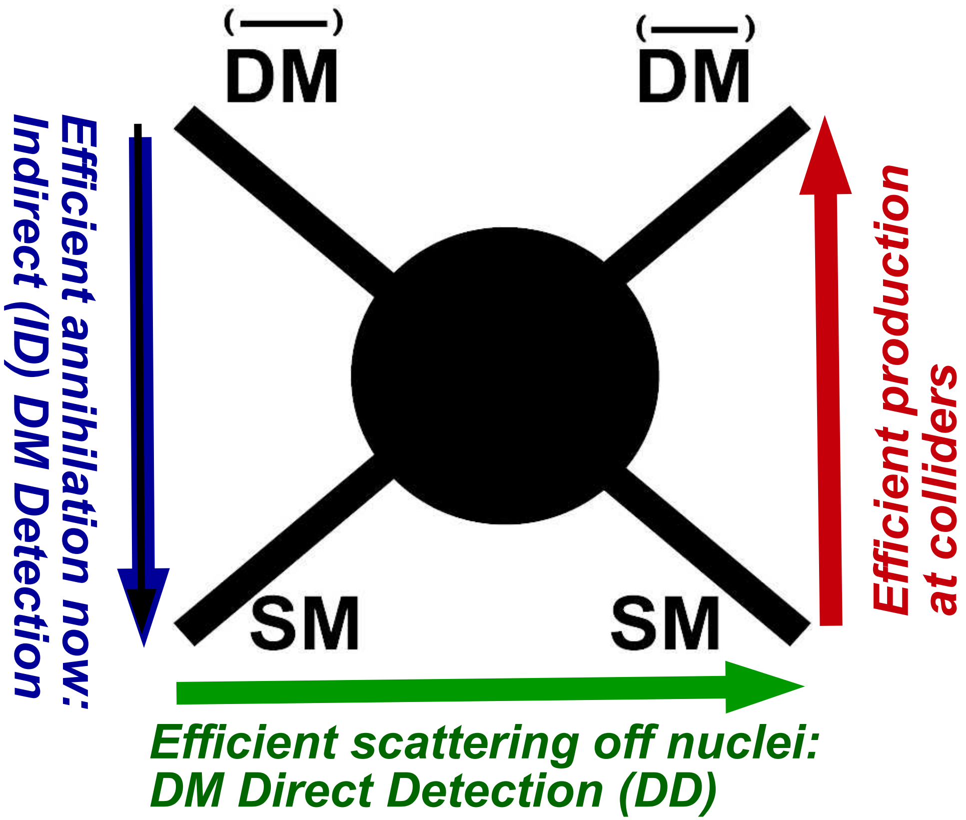
of early Universe
Dark Matter
(DM)
Observables
SM
SM

Complementarity of DM searches

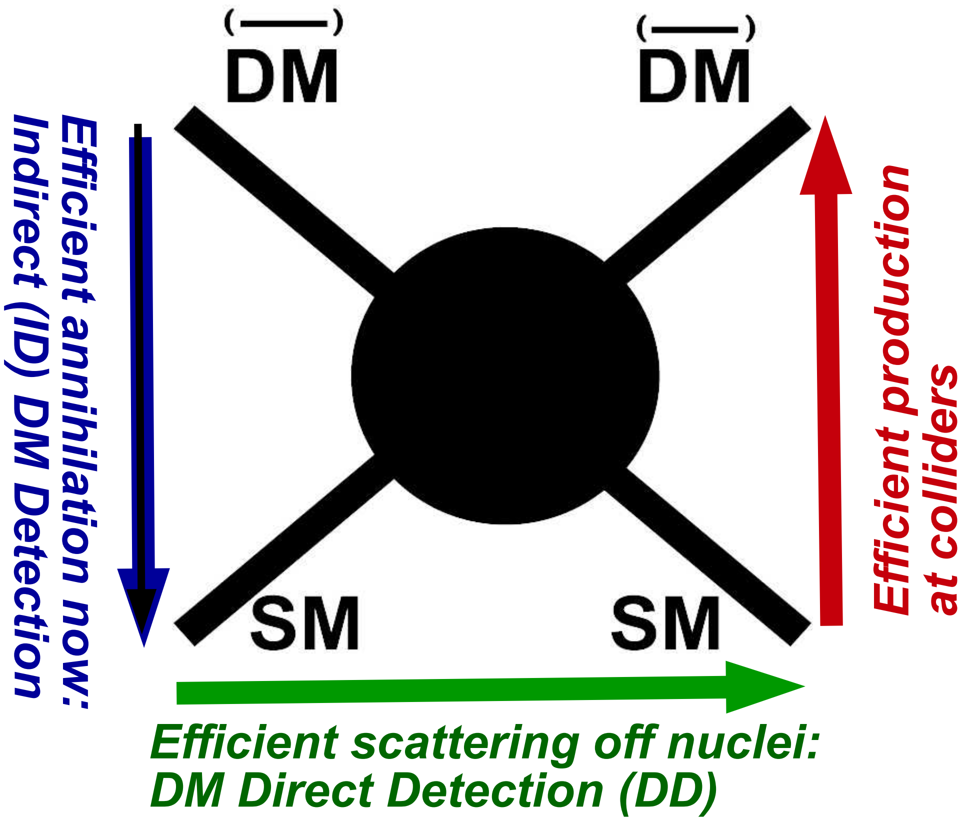


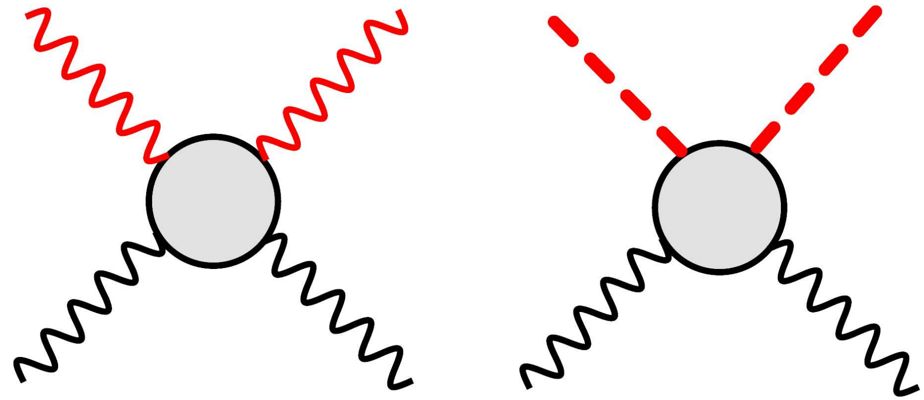
Important: there is no 100%correlation between signatures above. E.g. the high rate of annihilation does not always guarantee high rate for DD!

Actually there is a great complementarity in this:

- In case of NO DM Signal – we can efficiently exclude DM models
- In case of DM signal – we can efficiently determine the nature of DM

Complementarity of DM searches





Example of DM interactions with negligible/suppressed DD rates

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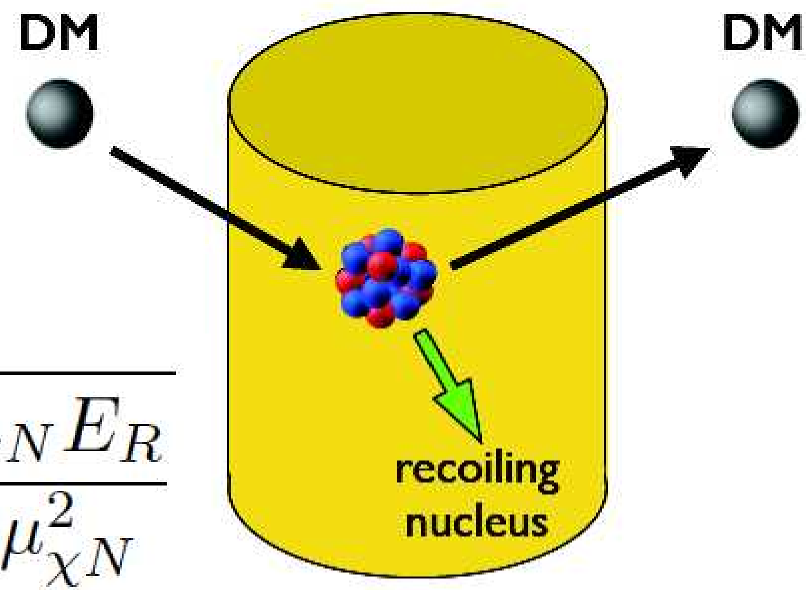
Direct Dark Matter Detection

See also Maria Martinez' talk

- Search for the recoil energy of a nucleus in an underground detector after collision with a WIMP

  Elastic recoil energy

$$E_R = \frac{2\mu_{\chi N}^2 v^2}{m_N} \cos^2\theta$$



- Minimum WIMP speed required to produce a recoil energy

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_{\chi N}^2}}$$

- The differential event rate (per unit detector mass):

astrophysics

$$\frac{dR}{dE_R} = \frac{\rho_\chi}{m_\chi m_N} \int_{v>v_{\min}} d^3v \, \frac{d\sigma_{\chi N}}{dE_R} \, v \, f_{\mathrm{det}}(\mathbf{v}, t)$$

Direct Dark Matter Detection

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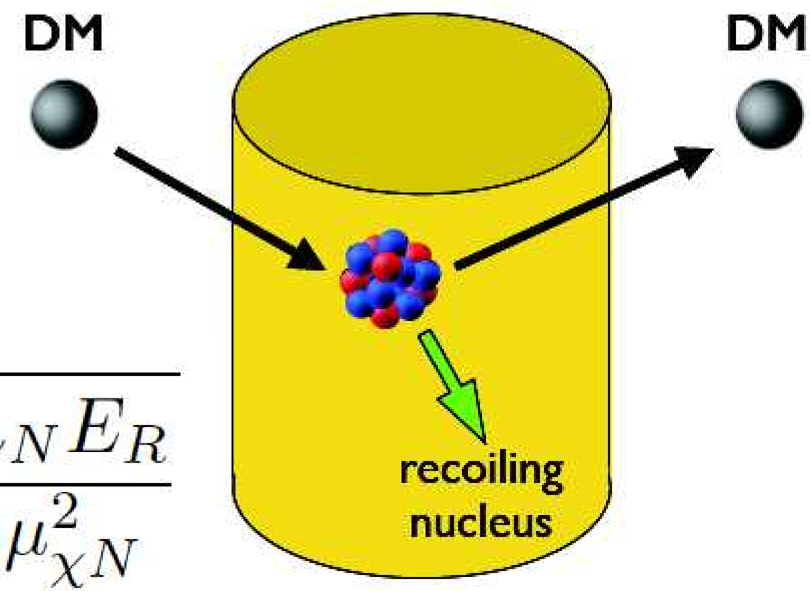

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particle physics — astrophysics — halo integral

Direct Dark Matter Detection

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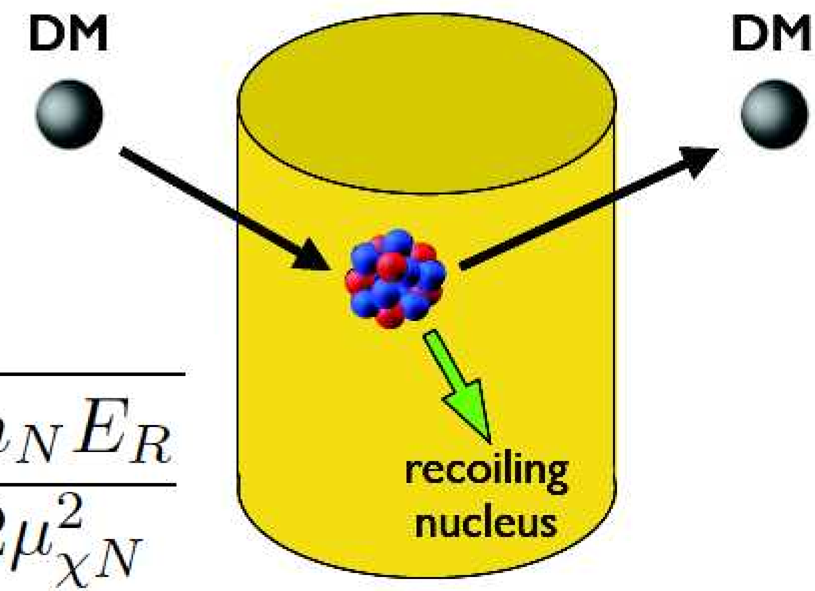

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astrophysics

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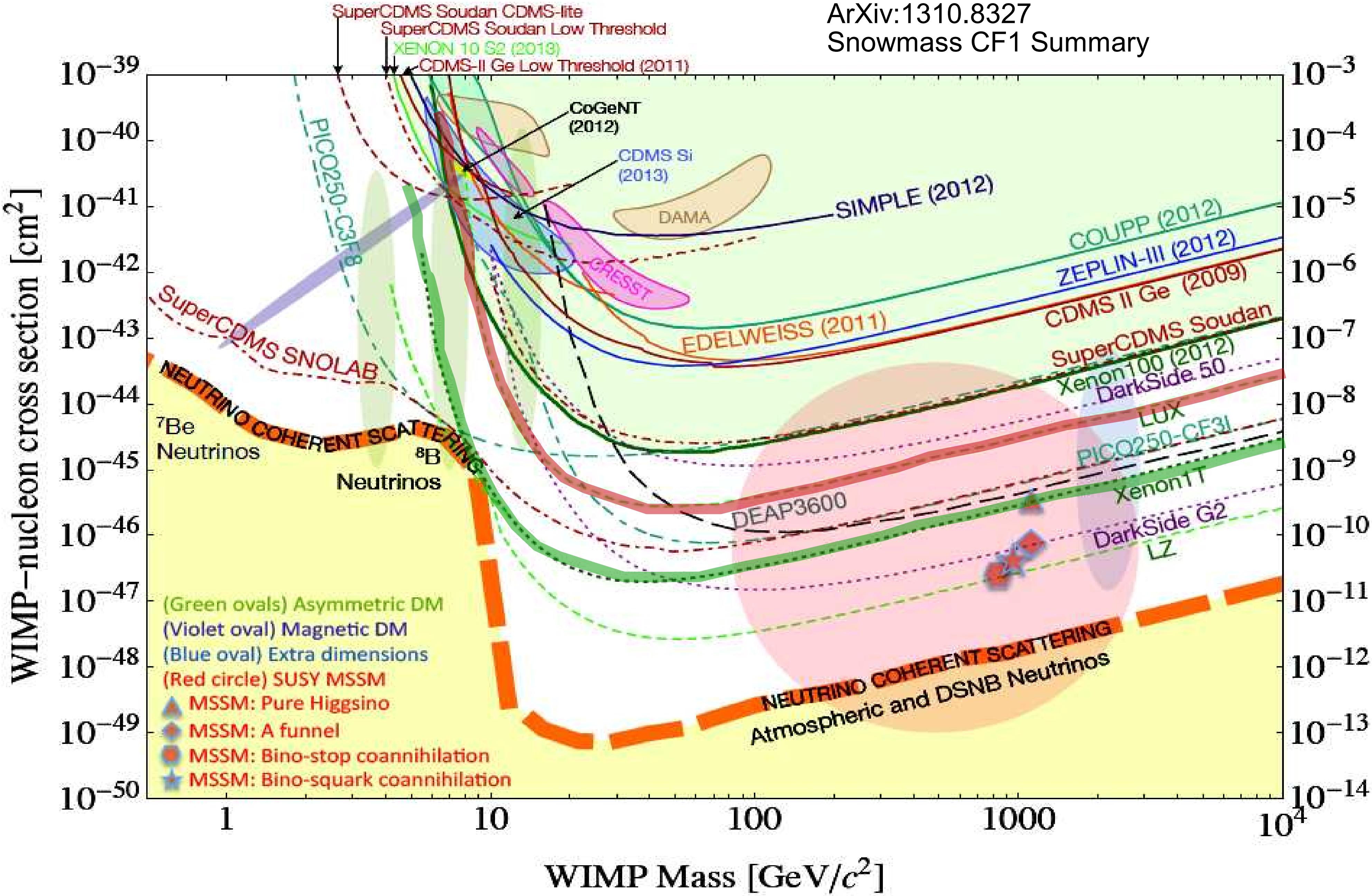
particle physics

halo integral

the source of uncertainty!

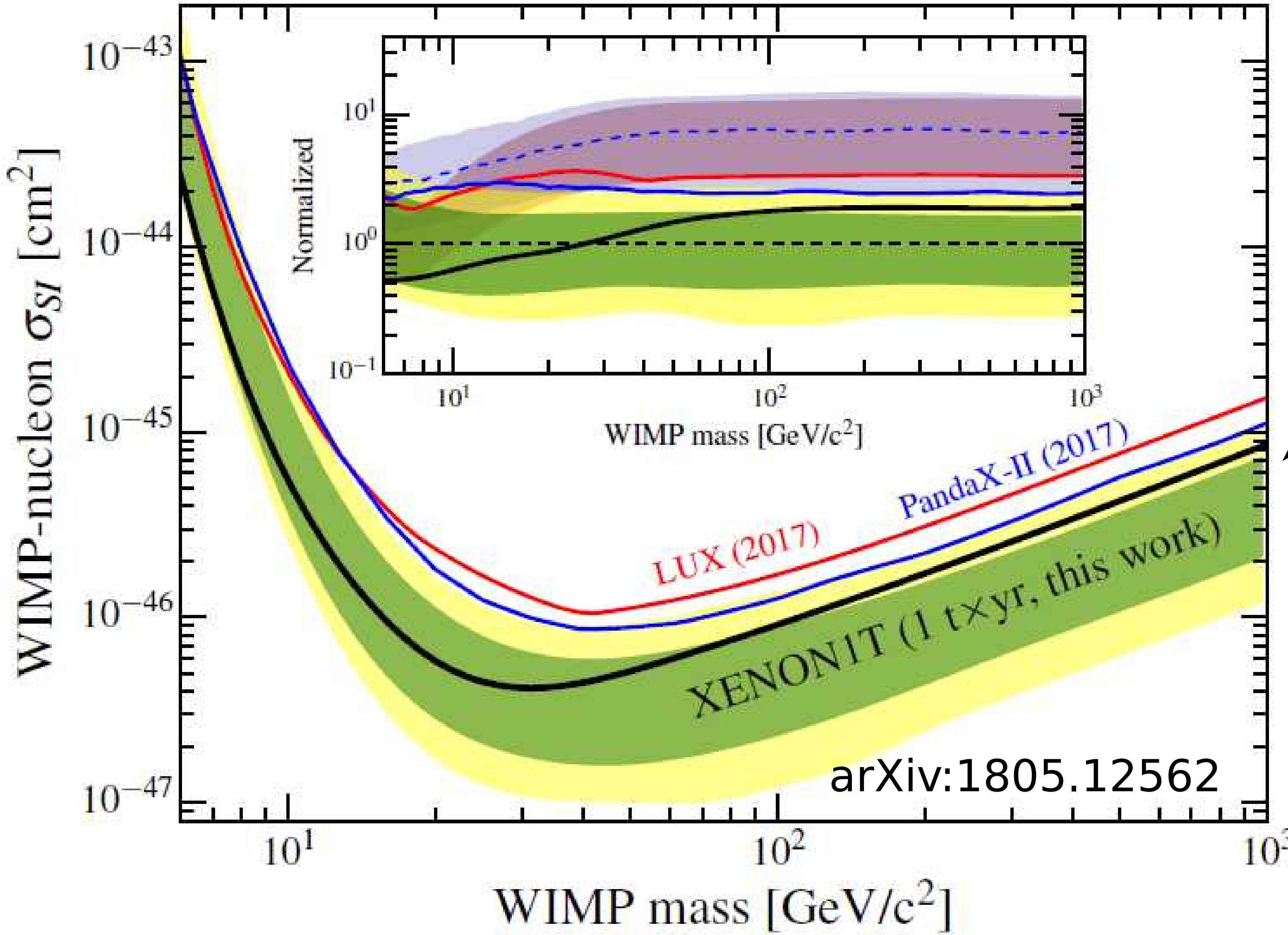
Power of DM DD to rule out theory space

ArXiv:1310.8327
Snowmass CF1 Summary



Latest XENON 1T results

10^{-46} cm^2 = 10^{-10} pb



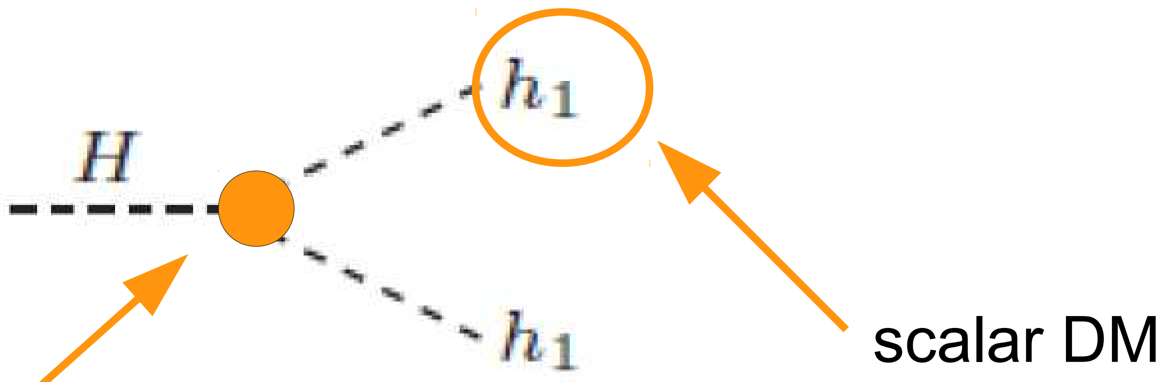
The limit scales linearly with M_{DM}

Power of DM DD to rule out theory space

Inert 2 Higgs Doublet Model

$$\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \qquad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} h^+ \\ h_1 + i h_2 \end{pmatrix}$$

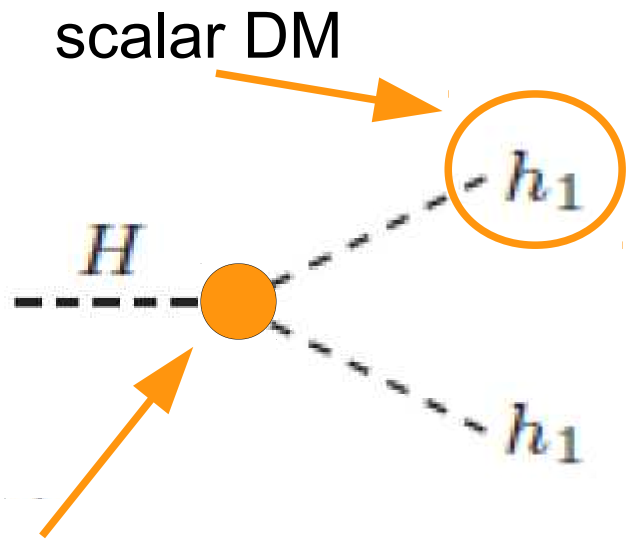
$$\begin{aligned} V &= -m_1^2(\phi_1^\dagger \phi_1) - m_2^2(\phi_2^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_1)^2 + \lambda_2(\phi_2^\dagger \phi_2)^2 \\ &+ \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_2^\dagger \phi_1)(\phi_1^\dagger \phi_2) + \frac{\lambda_5}{2}\left[(\phi_1^\dagger \phi_2)^2 + (\phi_2^\dagger \phi_1)^2\right] \end{aligned}$$



$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

Power of DM DD to rule out theory space

Inert 2 Higgs Doublet Model



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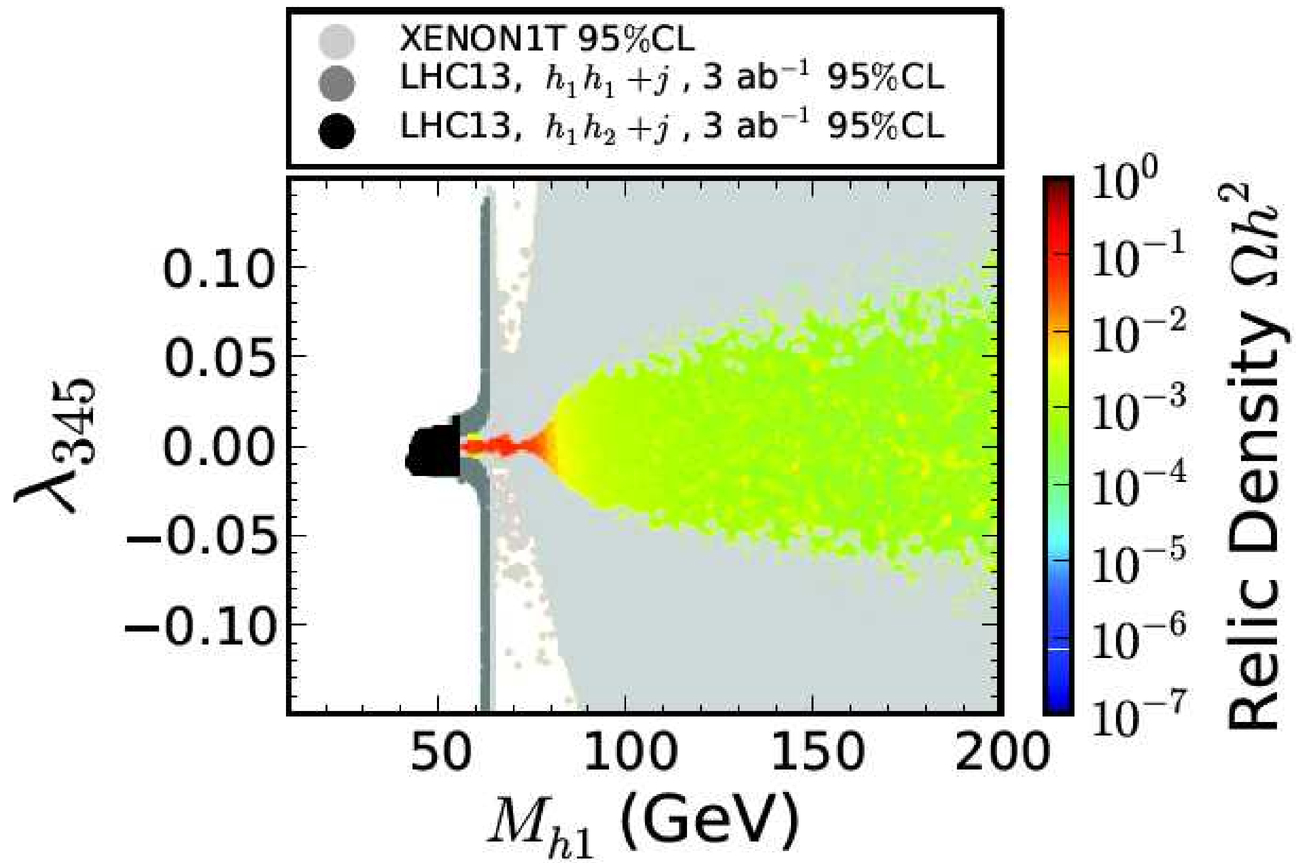


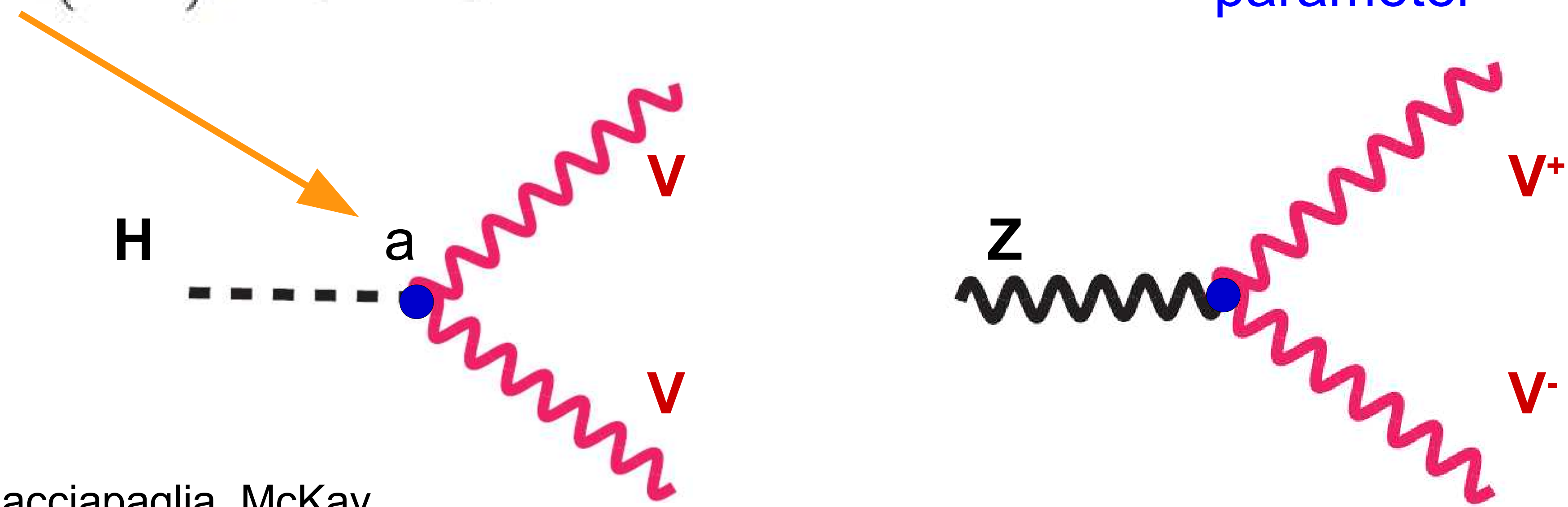
Cacciapaglia, Ivanov, Rojas, Thomas, AB arXiv:**1610.07545**
Novaes, Mercadante, Moon, Tomei, Moretti, Tomas, Panizzi, AB arXiv:**1809.00933**

Power of DM DD to rule out theory space

Vector DM Model

$$\mathcal{L} = \mathcal{L}_{SM} - Tr\{D_\mu V_\nu D^\mu V^\nu\} + Tr\{D_\mu V_\nu D^\nu V^\mu\}$$
$$-\frac{g^2}{2} Tr\{[V_\mu, V_\nu][V^\mu, V^\nu]\}$$
$$-igTr\{W_{\mu\nu}[V^\mu, V^\nu]\} + \tilde{M}^2 Tr\{V_\nu V^\nu\}$$
$$+a\left(\Phi^\dagger\Phi\right) Tr\{V_\nu V^\nu\}$$

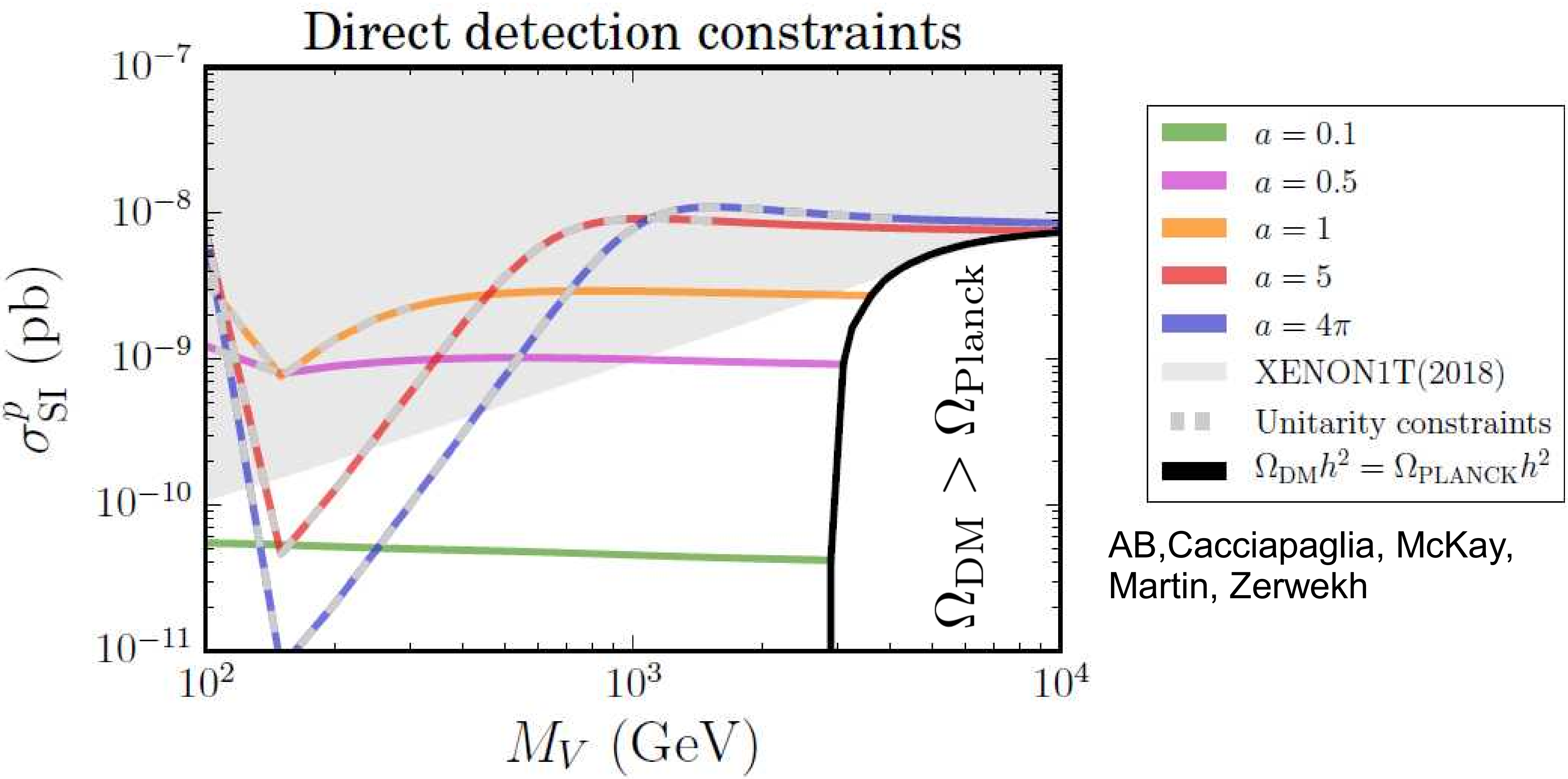
- DM from vector triplet
- SM gauge coupling
- $V_{DM}V_{DM}H$ coupling is the only free parameter



AB,Cacciapaglia, McKay, Martin, Zerwekh

Power of DM DD to rule out theory space

Vector DM Model



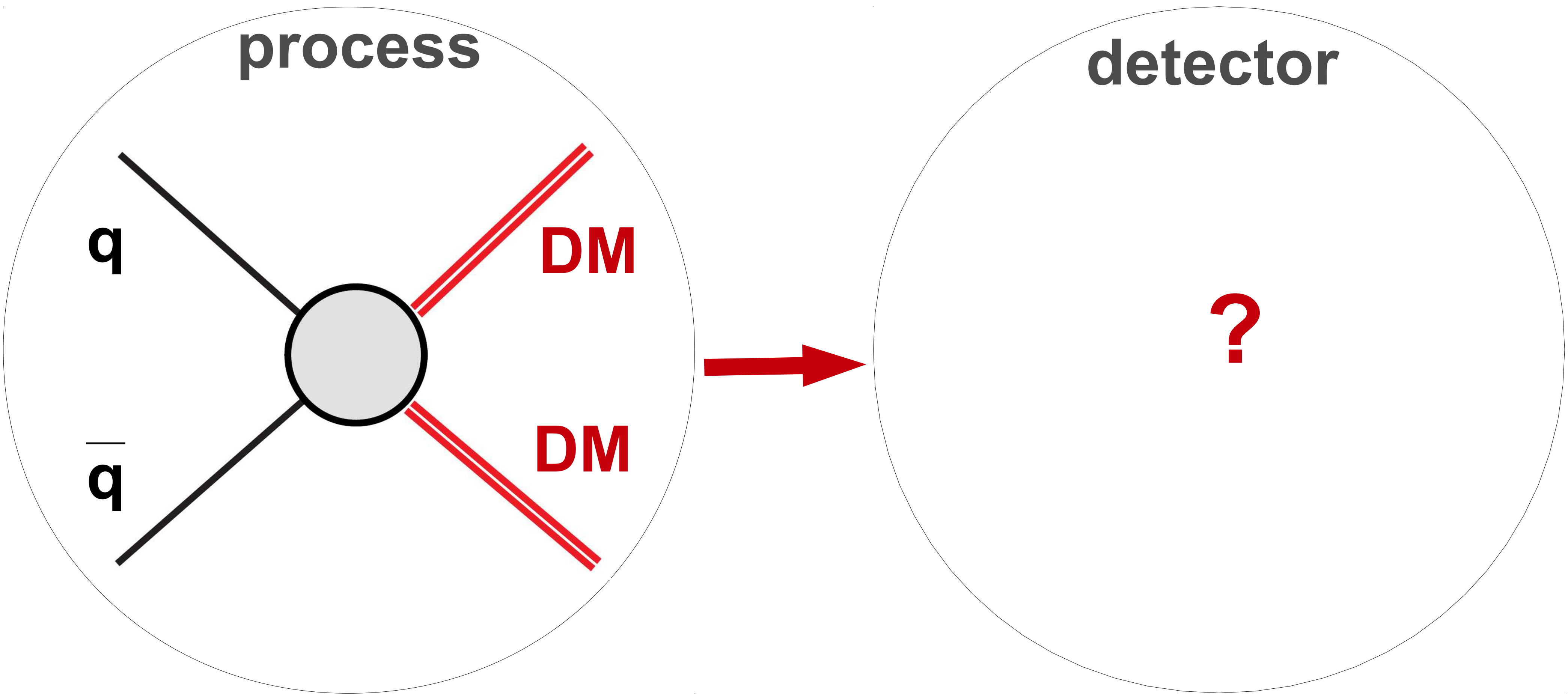
AB,Cacciapaglia, McKay, Martin, Zerwekh

- ZENON 1T excludes **both** large $HV_{DM}V_{DM}$ couplings and large M_{DM}
- The **lower masses** (rest of space) can be covered at future colliders

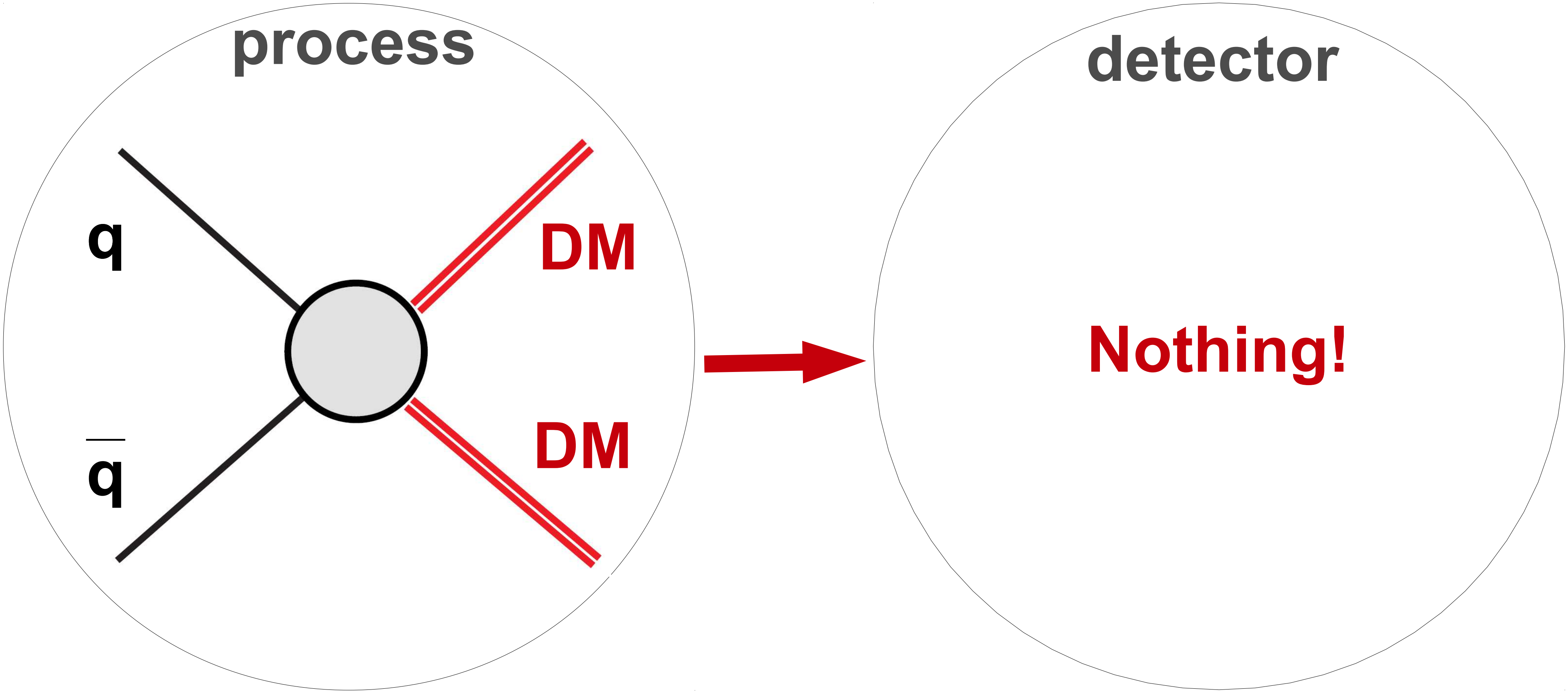
Power of DM DD to rule out theory space

- DM Interaction with SM particles is very limited, mainly from DM DD experiments
- E.g. coupling of Dirac Fermion DM interaction with Z-boson is excluded above **10^{-3}** level with DM DD searches
- Majorana Fermion DM does not have this problem, the limit comes from Higgs interactions, the coupling above **0.1** is excluded

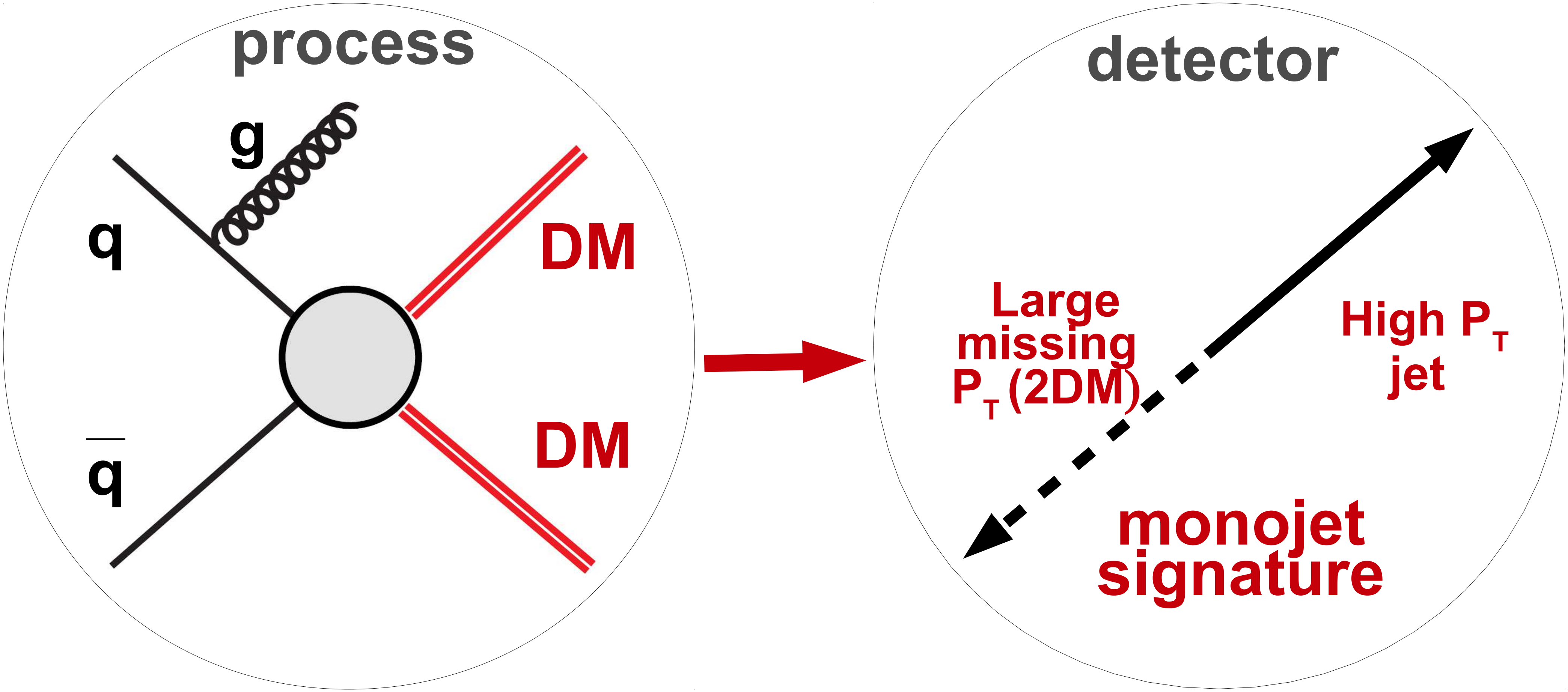
DM DD interplay with Collider Searches



Hunting for DM at Colliders



Hunting for DM at Colliders

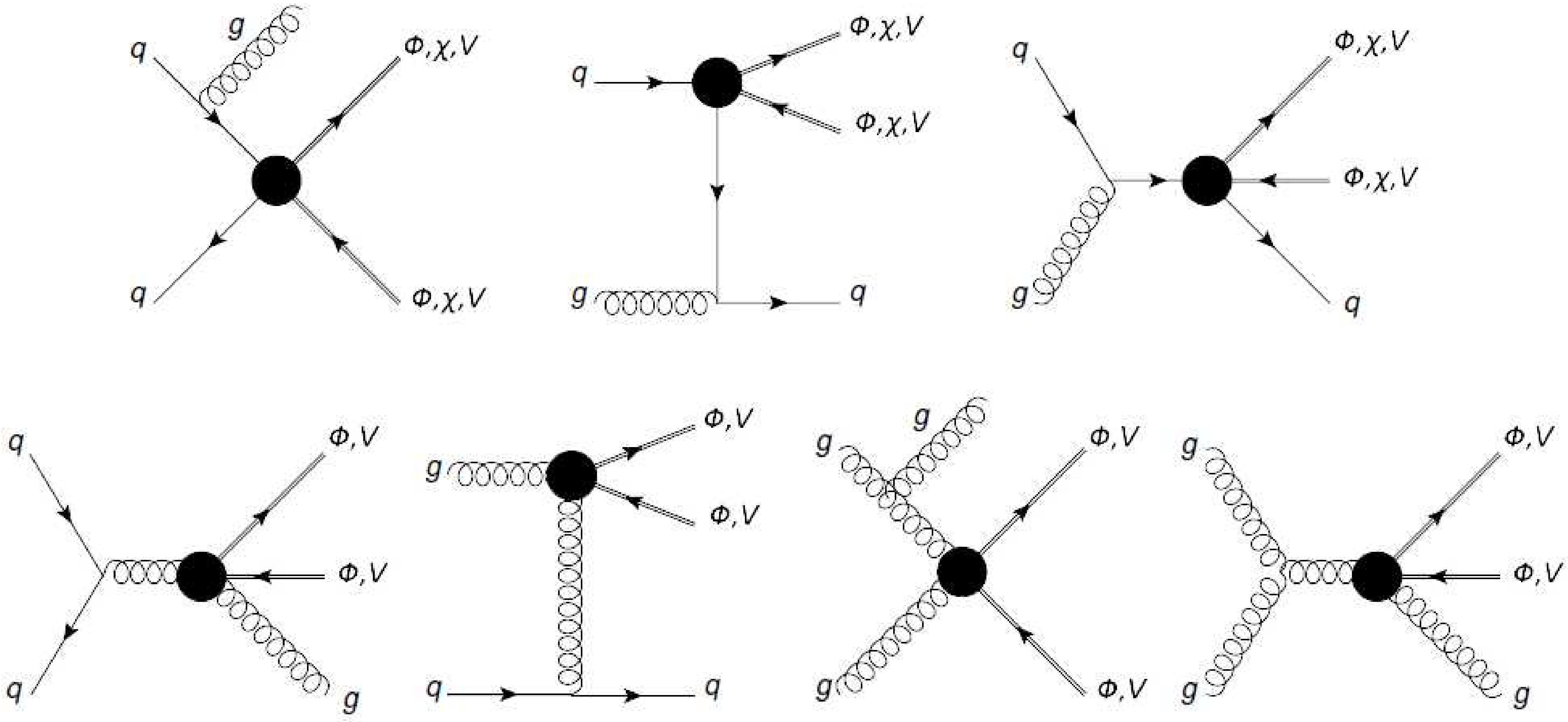


Can we test DM properties at the LHC?

We explore the LHC potential to probe DM operators with different DM spin using the shape missing transverse momentum **(MET)**

- we use the EFT approach: simplicity and model independence
- explore the complete set of DIM5/DIM6 operators involving two SM quarks (gluons) and two DM particles
- consider DM with spin=0, 1/2, 1
- use mono-jet signature at the LHC

Mono-jet diagrams from EFT operators



DIM5/6 operators (spin 0,1/2,1)

Complex scalar DM†	
$\frac{\bar{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	$[C1]^*$
$\frac{\bar{m}}{\Lambda^2}\phi^\dagger\phi\bar{q}i\gamma^5 q$	$[C2]^*$
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q$	$[C3]$
$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu\gamma^5 q$	$[C4]$
$\frac{1}{\Lambda^2}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	$[C5]^*$
$\frac{1}{\Lambda^2}\phi^\dagger\phi\tilde{G}^{\mu\nu}G_{\mu\nu}$	$[C6]^*$

Dirac fermion DM†	
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$	$[D1]^*$
$\frac{1}{\Lambda^2}\bar{\chi}i\gamma^5\chi\bar{q}q$	$[D2]^*$
$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}i\gamma^5 q$	$[D3]^*$
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	$[D4]^*$
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$[D5]$
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$[D6]$
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$[D7]$
$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$[D8]$
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$[D9]^*$
$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}i\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	$[D10]^*$

Complex vector DM‡	
$\frac{\bar{m}}{\Lambda^2}V^\dagger_\mu V^\mu\bar{q}q$	$[V1]^*$
$\frac{\bar{m}}{\Lambda^2}V^\dagger_\mu V^\mu\bar{q}i\gamma^5 q$	$[V2]^*$
$\frac{1}{2\Lambda^2}(V^\dagger_\nu\partial_\mu V^\nu - V^\nu\partial_\mu V^\dagger_\nu)\bar{q}\gamma^\mu q$	$[V3]$
$\frac{1}{2\Lambda^2}(V^\dagger_\nu\partial_\mu V^\nu - V^\nu\partial_\mu V^\dagger_\nu)\bar{q}i\gamma^\mu\gamma^5 q$	$[V4]$
$\frac{\bar{m}}{\Lambda^2}V^\dagger_\mu V_\nu\bar{q}i\sigma^{\mu\nu}q$	$[V5]$
$\frac{\bar{m}}{\Lambda^2}V^\dagger_\mu V_\nu\bar{q}\sigma^{\mu\nu}\gamma^5 q$	$[V6]$
$\frac{1}{2\Lambda^2}(V^\dagger_\nu\partial^\nu V_\mu + V^\nu\partial^\nu V^\dagger_\mu)\bar{q}\gamma^\mu q$	$[V7P]$
$\frac{1}{2\Lambda^2}(V^\dagger_\nu\partial^\nu V_\mu - V^\nu\partial^\nu V^\dagger_\mu)\bar{q}i\gamma^\mu q$	$[V7M]$
$\frac{1}{2\Lambda^2}(V^\dagger_\nu\partial^\nu V_\mu + V^\nu\partial^\nu V^\dagger_\mu)\bar{q}\gamma^\mu\gamma^5 q$	$[V8P]$
$\frac{1}{2\Lambda^2}(V^\dagger_\nu\partial^\nu V_\mu - V^\nu\partial^\nu V^\dagger_\mu)\bar{q}i\gamma^\mu\gamma^5 q$	$[V8M]$
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V^\dagger_\nu\partial_\rho V_\sigma + V_\nu\partial_\rho V^\dagger_\sigma)\bar{q}\gamma_\mu q$	$[V9P]$
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V^\dagger_\nu\partial^\nu V_\mu - V^\nu\partial^\nu V^\dagger_\mu)\bar{q}i\gamma_\mu q$	$[V9M]$
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V^\dagger_\nu\partial_\rho V_\sigma + V_\nu\partial_\rho V^\dagger_\sigma)\bar{q}\gamma_\mu\gamma^5 q$	$[V10P]$
$\frac{1}{2\Lambda^2}\epsilon^{\mu\nu\rho\sigma}(V^\dagger_\nu\partial^\nu V_\mu - V^\nu\partial^\nu V^\dagger_\mu)\bar{q}i\gamma_\mu\gamma^5 q$	$[V10M]$
$\frac{1}{\Lambda^2}V^\dagger_\mu V^\mu G^{\rho\sigma}G_{\rho\sigma}$	$[V11]^*$
$\frac{1}{\Lambda^2}V^\dagger_\mu V^\mu\tilde{G}^{\rho\sigma}G_{\rho\sigma}$	$[V12]^*$

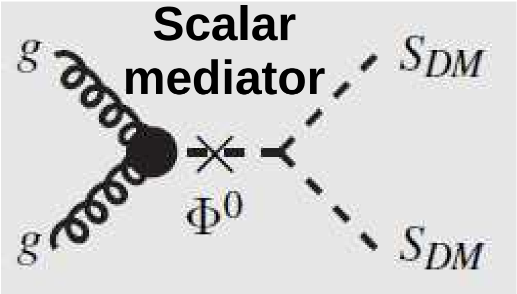
* operators applicable to real DM fields, modulo a factor 1/2

† Listed in J. Goodman *et al.*, *Constraints on Dark Matter from Colliders*, Phys.Rev. **D82** (2010) 116010, [arXiv:1008.1783]

‡ All but V11 and V12 listed in Kumar *et al.*, *Vector dark matter at the LHC*, Phys. Rev. **D92** (2015) 095027, [arXiv:1508.04466]

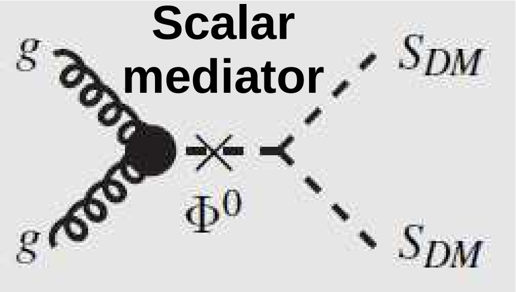
Mapping EFT operators to simplified models

C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$, $\frac{1}{\Lambda^2}\phi^*\phi \tilde{G}^{\mu\nu}G^{\mu\nu}$ →

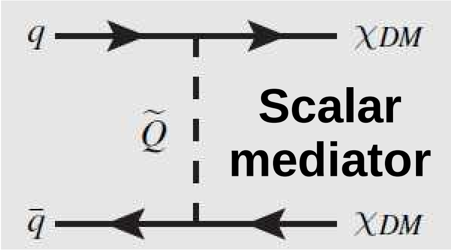


Mapping EFT operators to simplified models

C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$, $\frac{1}{\Lambda^2}\phi^*\phi \tilde{G}^{\mu\nu}G^{\mu\nu}$ →

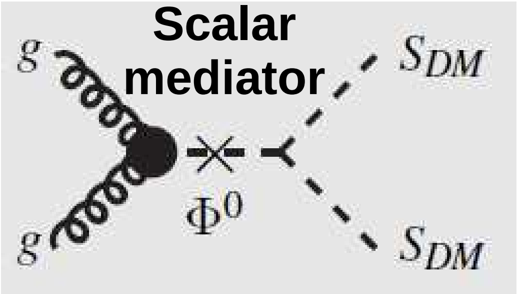


D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ →

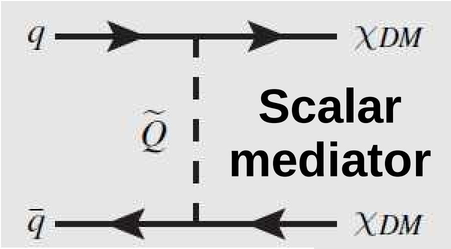


Mapping EFT operators to simplified models

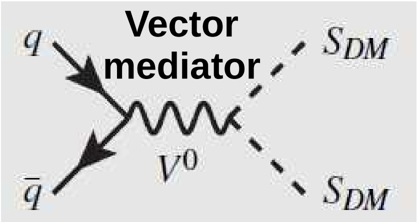
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$, $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$ →



D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ →

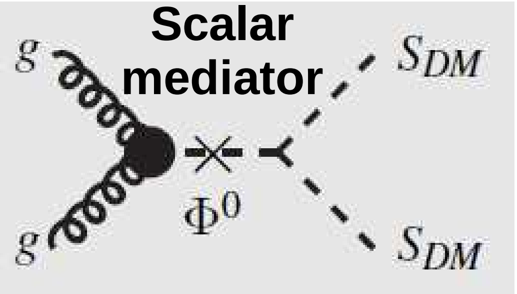


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ →

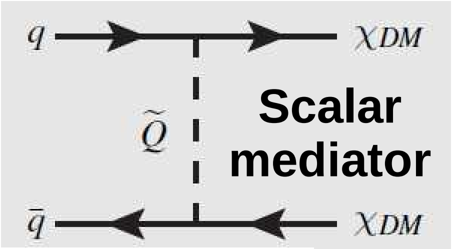


Mapping EFT operators to simplified models

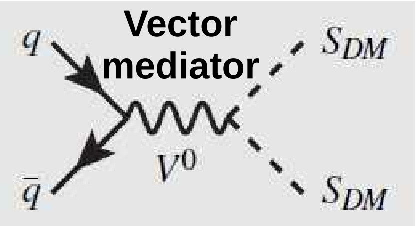
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$, $\frac{1}{\Lambda^2}\phi^*\phi \tilde{G}^{\mu\nu}G^{\mu\nu}$ →



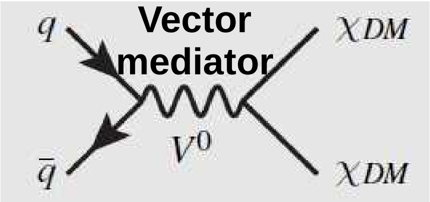
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ →

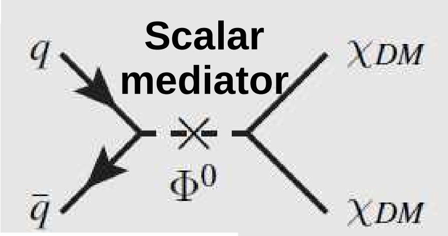


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ →



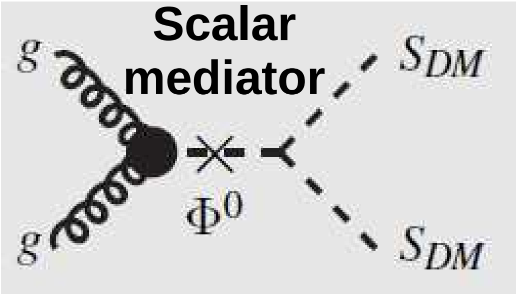
D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ →



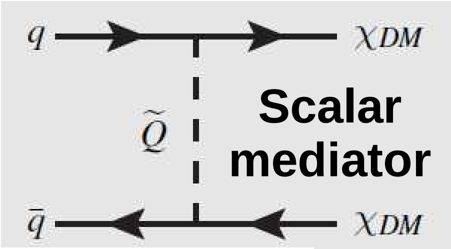


Mapping EFT operators to simplified models

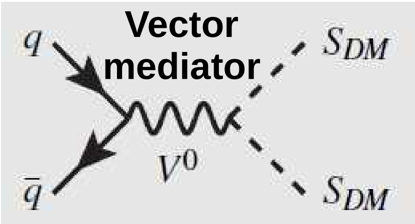
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$ $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$ →



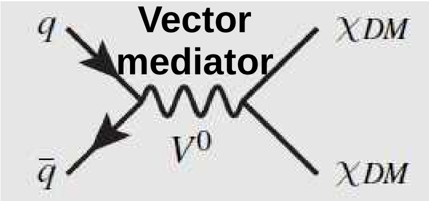
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ →

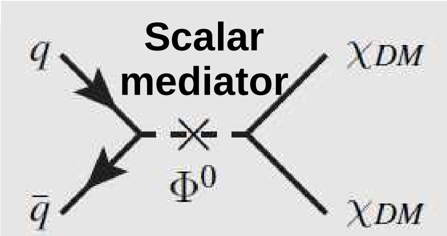


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ →

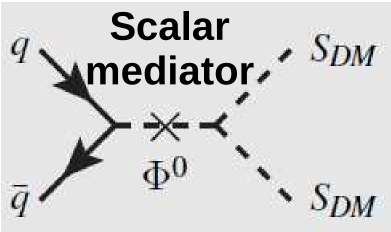


D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ →



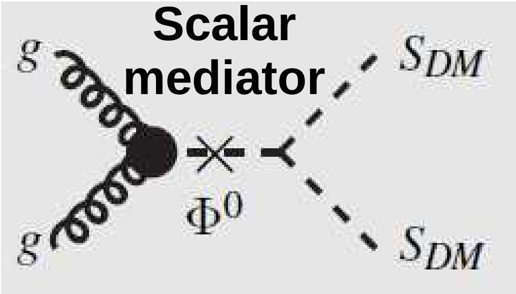


C1 $\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q$ →

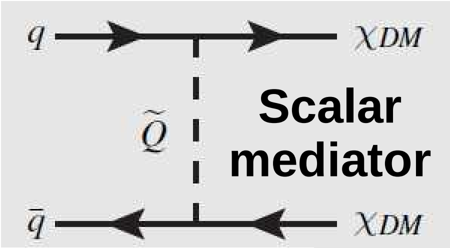


Mapping EFT operators to simplified models

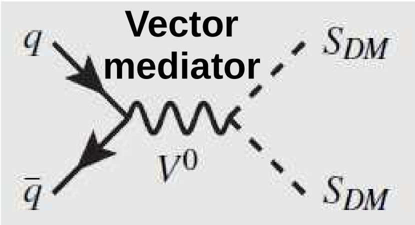
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$ $\frac{1}{\Lambda^2}\phi^*\phi \tilde{G}^{\mu\nu}G^{\mu\nu}$ $\longrightarrow$



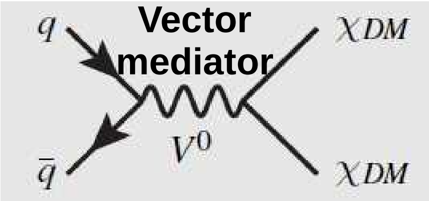
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ $\longrightarrow$

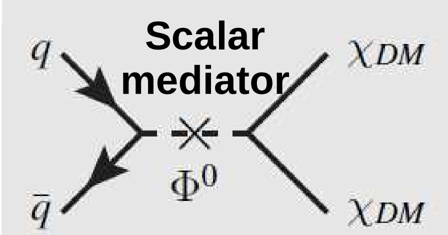


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ $\longrightarrow$

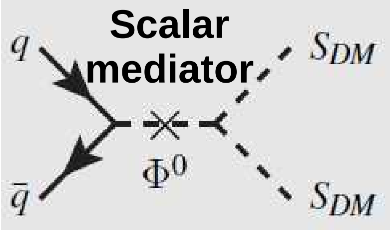


D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ $\longrightarrow$





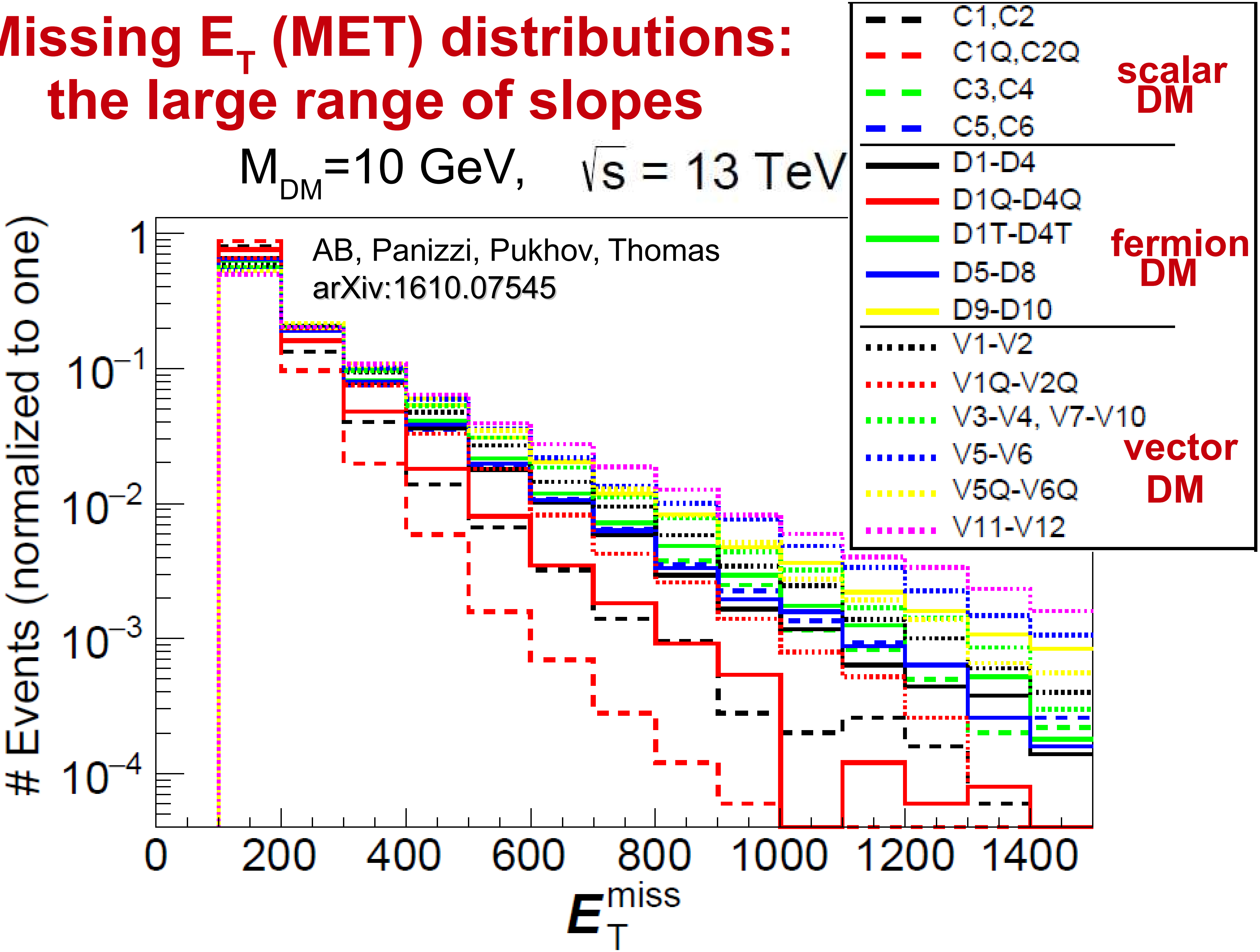
C1 $\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q$ $\longrightarrow$



D9,D10 $\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q \longrightarrow \frac{8}{\Lambda^2}\Big[\, \bar{\chi}q\bar{q}\chi - \frac{1}{4}\left(\bar{\chi}\chi\bar{q}q + \bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q + \bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q - \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q\,\right)\Big]$

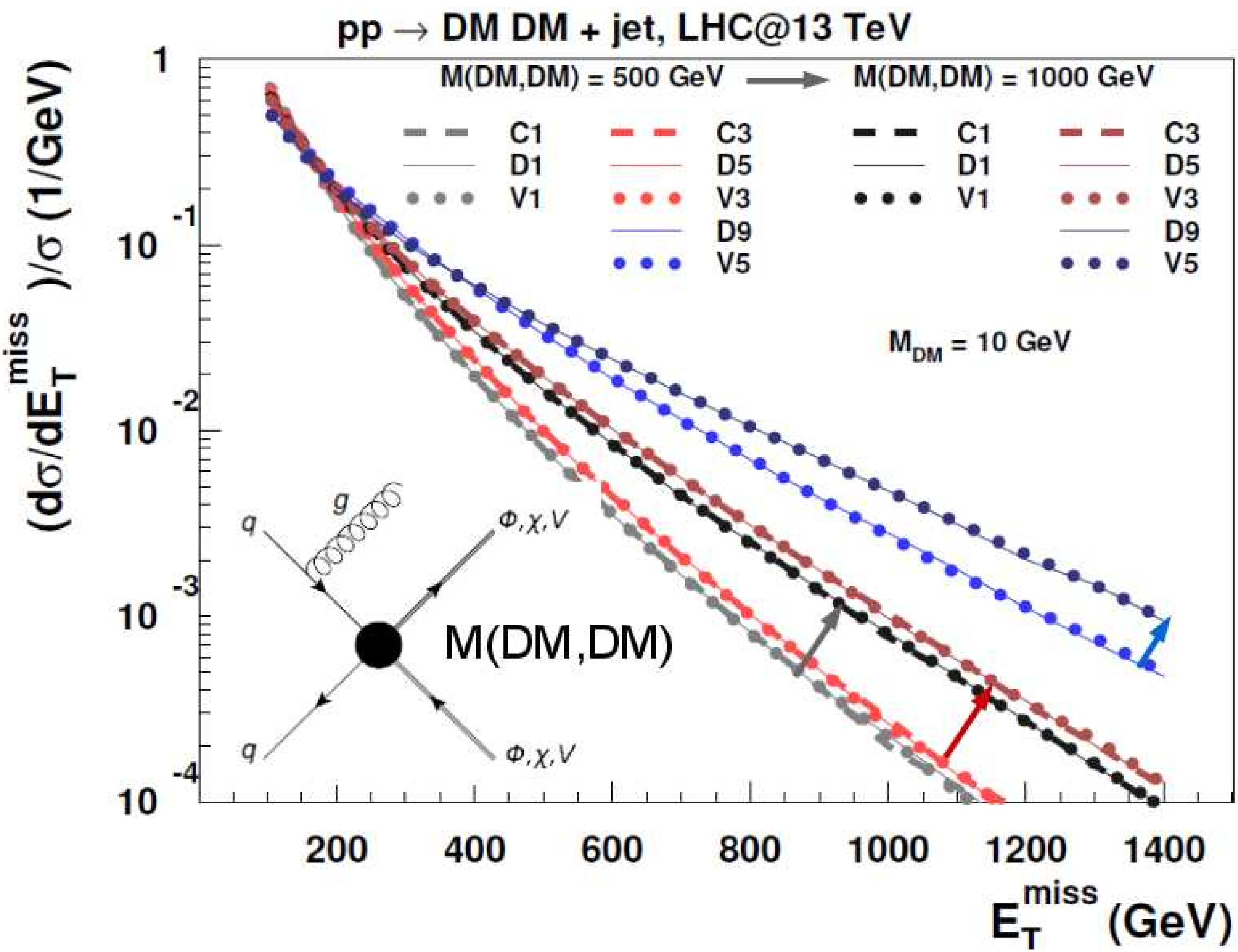
Missing E_T (MET) distributions: the large range of slopes

M_{DM}=10 GeV, $\sqrt{s}$ = 13 TeV



Properties of MET distributions:

- MET distributions are the same for the fixed mass of DM pair [M(DM,DM)] & fixed SM operator
- With the increase of M(DM,DM), MET slope decreases (PDF effect)



$$\frac{\tilde{m}}{\Lambda^2}\phi^*\phi\bar{q}q \quad [C1]$$

$$\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q \quad [D1]$$

$$\frac{\tilde{m}}{\Lambda^2}V^{\dagger\mu}V_\mu\bar{q}q \quad [V1]$$

$$\frac{1}{\Lambda^2}\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi\bar{q}\gamma^\mu q \quad [C3]$$

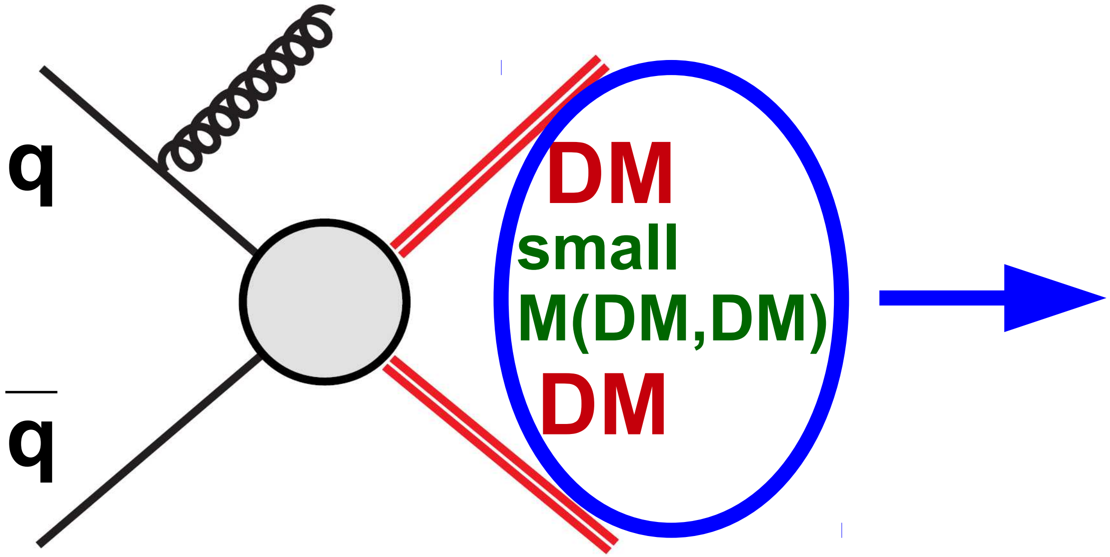
$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q \quad [D5]$$

$$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q \quad [D9]$$

$$\frac{\tilde{m}}{\Lambda^2}V_\mu^\dagger V_\nu\bar{q}i\sigma^{\mu\nu}q \quad [V5]$$

Properties of MET distributions for small and large M(DM,DM)

- MET distributions are the same for the fixed mass of DM pair [M(DM,DM)] & fixed SM operator
- With the increase of M(DM,DM), MET slope decreases (PDF effect)



for $p_T(g)$ increase

Δ (x1 x2)/(x1 x2) is large

and MET slope is steep

Properties of MET distributions for small and large M(DM,DM)

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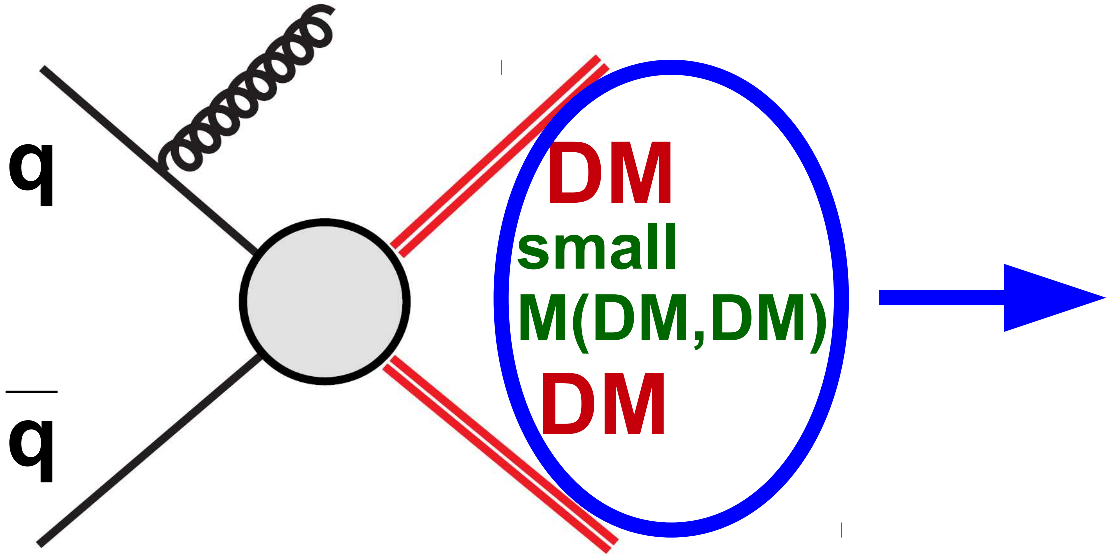
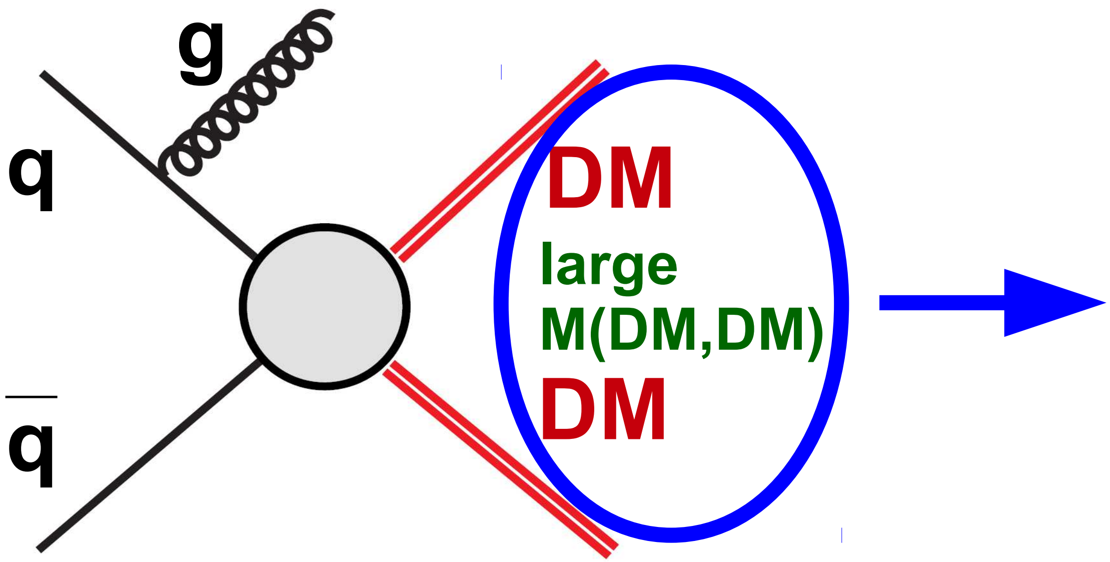
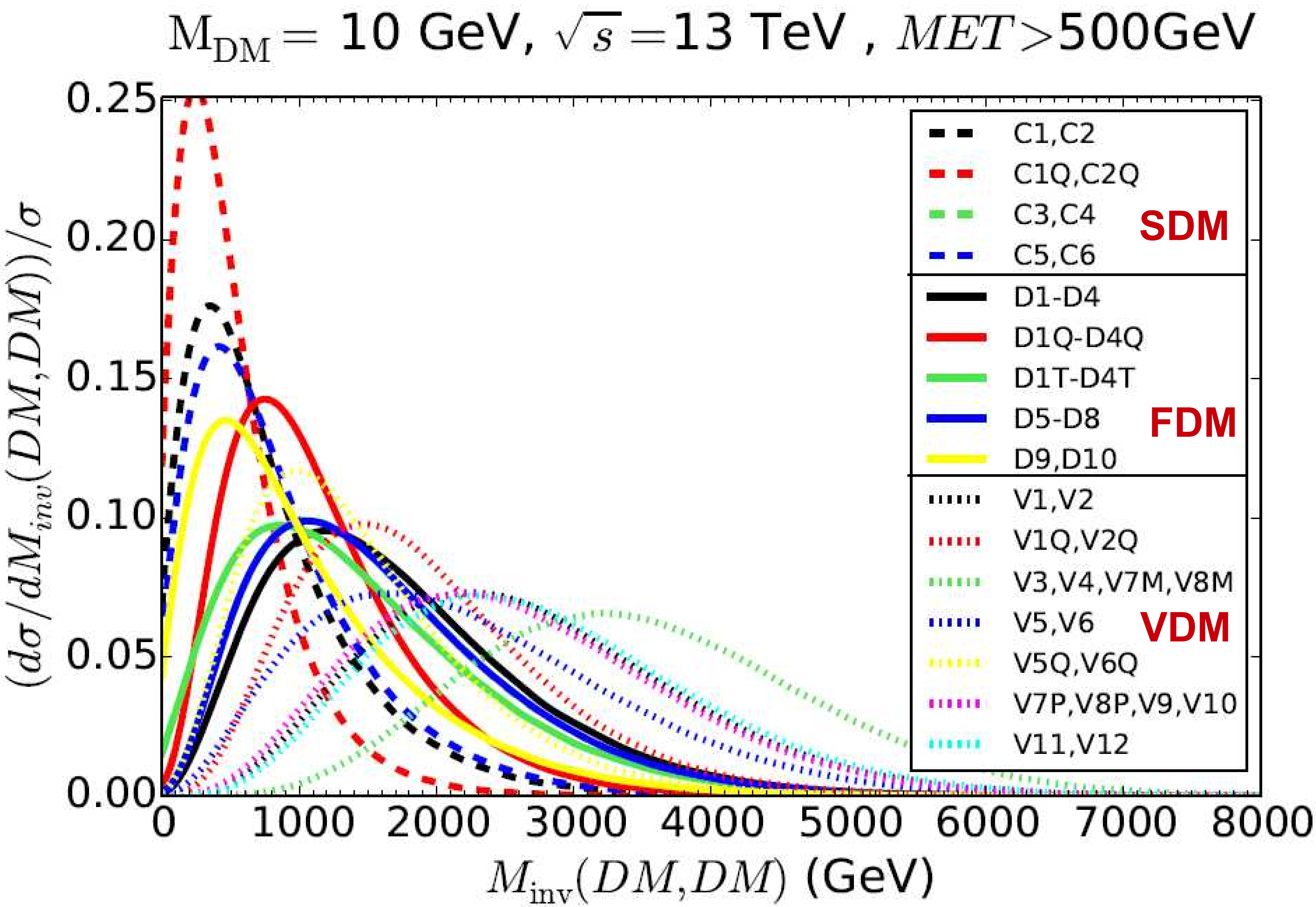


for $p_T(g)$ increase
Δ (x1 x2)/(x1 x2) is large
and MET slope is steep



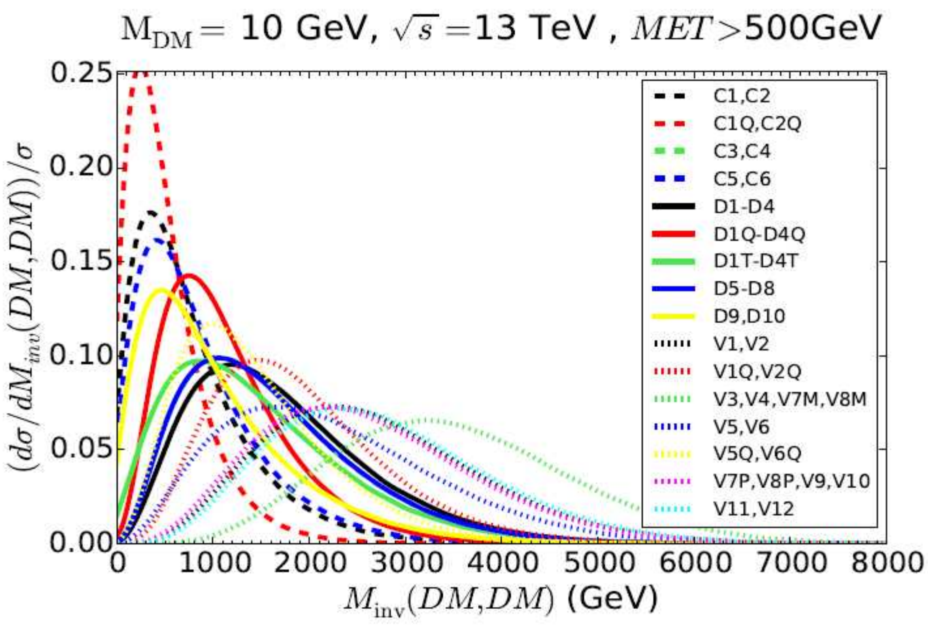
for $p_T(g)$ increase
Δ (x1 x2)/(x1 x2) is small
and MET slope is gradual

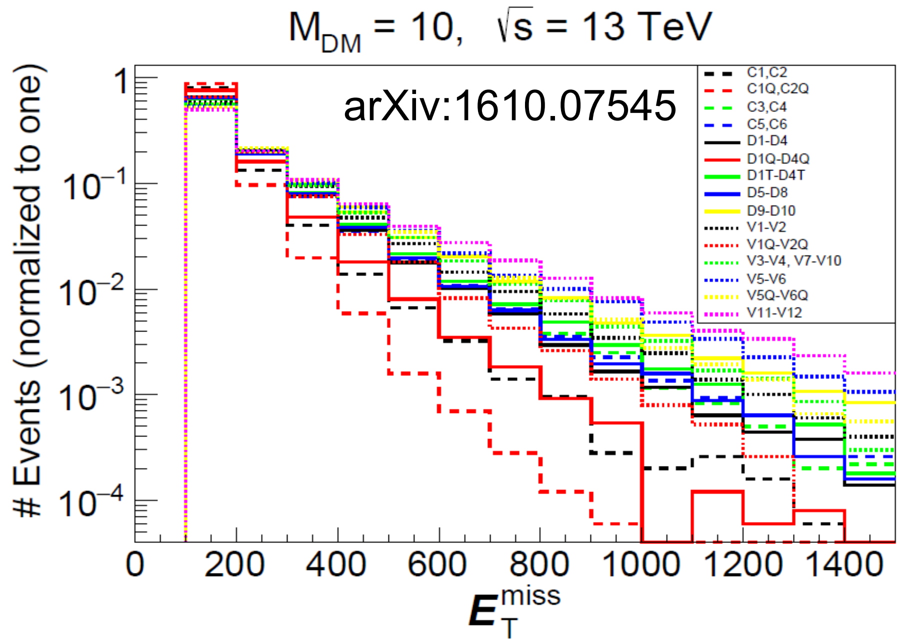
On the other hand, M(DM,DM) distributions, defined by the EFT operators are different!



Distinguishing DM operators/theories

The harder M(DM,DM) distributions ⟷ **The flatter MET shapes**





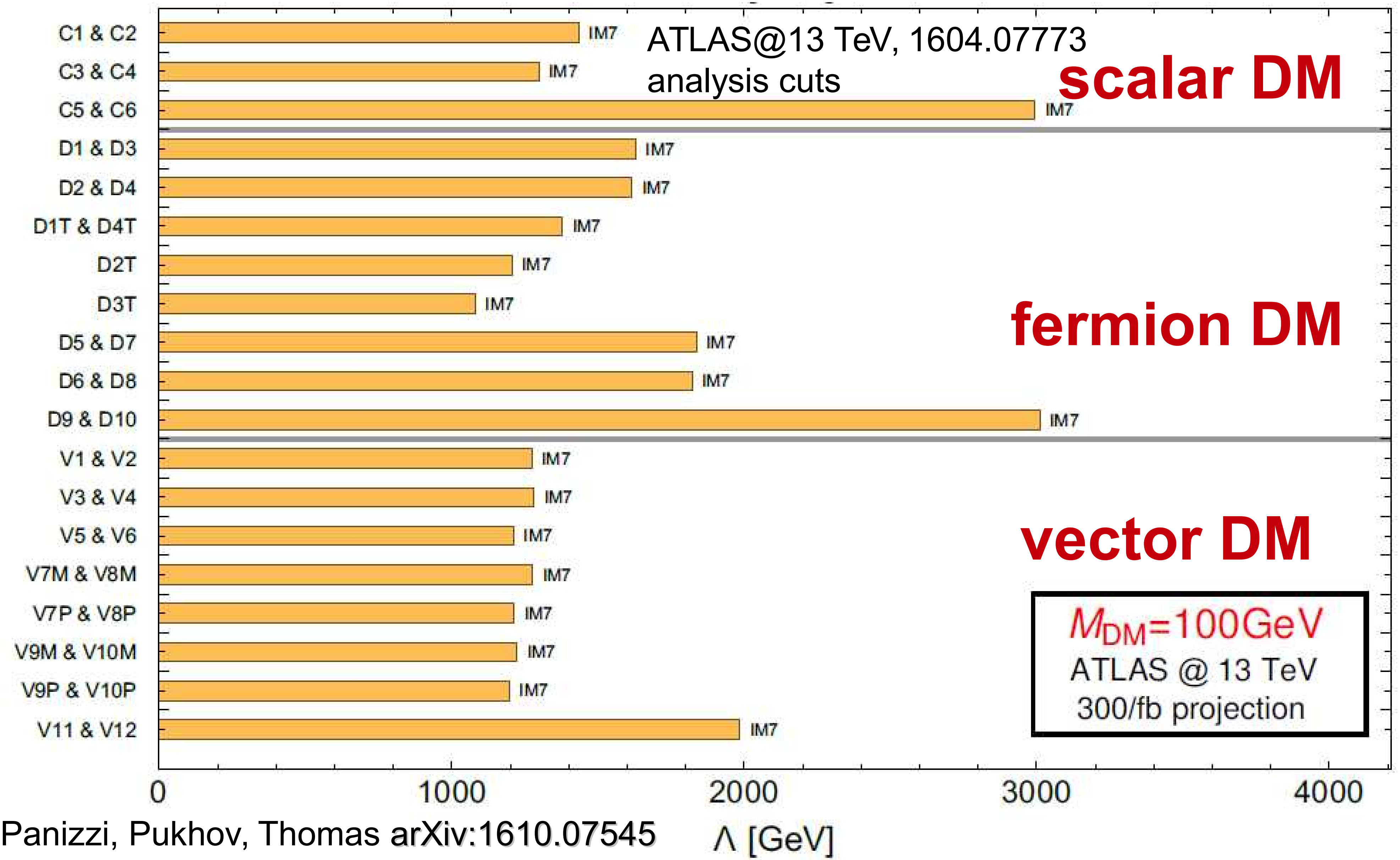
operator energy dependence → M_{DMDM} shape → MET shape

➪ projection for 300 fb^{-1}: some operators C1-C2,C5-C6,D9-D10,V1-V2,V3-V4,V5-V6 and V11-12 can be distinguished from each other

➪ Application beyond EFT: when the DM mediator is not produced on-the-mass-shell and M_{DMDM} is not fixed: t-channel mediator or mediators with mass below $2M_{DM}$

LHC@13TeV reach projected 100 fb^{-1}

LanHEP→ CalcHEP→ LHE→ CheckMATE



AB, Panizzi, Pukhov, Thomas arXiv:1610.07545

Distinguishing the DM operators: χ^2 for pairs of DM operators

$$\chi^2_{k,l} = \min_{\kappa} \sum_{i=3}^{7} [(\frac{1}{2} N_i^k - \kappa \cdot N_i^l)/(10^{-2} BG_i)]^2$$

: if χ^2>9.48 (95%CL for 4 DOF) – operators can be distinguished!

			Complex Scalar DM				Dirac Fermion DM			
			100 GeV		1000 GeV		100 GeV		1000 GeV	
			C1	C5	C1	C5	D1	D9	D1	D9
Complex Scalar DM	100 GeV	C1	0.0	**19.7**	**25.54**	**74.63**	**11.73**	**41.79**	**25.78**	**52.58**
		C5	**15.74**	0.0	0.37	**16.25**	1.11	3.93	0.74	7.35
	1000 GeV	C1	**19.89**	0.36	0.0	**11.82**	2.33	2.09	0.27	4.58
		C5	**50.86**	**13.86**	**10.34**	0.0	**21.03**	3.7	**11.18**	1.53
Dirac Fermion DM	100 GeV	D1	**9.88**	1.17	2.52	**25.99**	0.0	9.23	2.4	**14.17**
		D9	**30.49**	3.59	1.96	3.96	7.99	0.0	2.71	0.52
	1000 GeV	D1	**20.31**	0.73	0.27	**12.92**	2.25	2.93	0.0	5.42
		D9	**37.38**	6.54	4.18	1.6	**11.96**	0.5	4.89	0.0

Distinguishing the DM operators: χ^2 for pairs of DM operators

$$\chi^2_{k,l} = \min_{\kappa} \sum_{i=3}^{7} [(\frac{1}{2}N_i^k - \kappa \cdot N_i^l)/(10^{-2}BG_i)]^2$$

: if χ^2>9.48 (95%CL for 4 DOF) – operators can be distinguished!

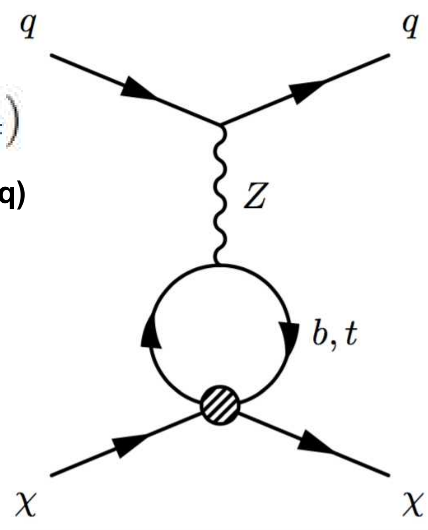
			Complex Scalar DM				Dirac Fermion DM				Complex Vector DM							
			100 GeV		1000 GeV		100 GeV		1000 GeV		100 GeV				1000 GeV			
			C1	C5	C1	C5	D1	D9	D1	D9	V1	V3	V5	V11	V1	V3	V5	V11
Complex Scalar DM	100 GeV	C1	0.0	19.7	25.54	74.63	11.73	41.79	25.78	52.58	22.97	32.89	54.35	73.34	25.18	34.61	52.34	80.85
		C5	15.74	0.0	0.37	16.25	1.11	3.93	0.74	7.35	0.18	1.53	8.2	15.73	0.44	1.9	7.24	19.13
	1000 GeV	C1	19.89	0.36	0.0	11.82	2.33	2.09	0.27	4.58	0.06	0.45	5.29	11.41	0.06	0.68	4.42	14.36
		C5	50.86	13.86	10.34	0.0	21.03	3.7	11.18	1.53	11.57	6.82	1.26	0.01	10.84	6.1	1.61	0.14
Dirac Fermion DM	100 GeV	D1	9.88	1.17	2.52	25.99	0.0	9.23	2.4	14.17	1.85	5.09	15.34	25.37	2.29	5.85	13.85	29.81
		D9	30.49	3.59	1.96	3.96	7.99	0.0	2.71	0.52	2.49	0.62	0.73	3.69	2.31	0.39	0.56	5.36
	1000 GeV	D1	20.31	0.73	0.27	12.92	2.25	2.93	0.0	5.42	0.32	0.82	6.33	12.58	0.08	1.18	5.08	15.7
		D9	37.38	6.54	4.18	1.6	11.96	0.5	4.89	0.0	4.98	2.02	0.06	1.44	4.56	1.61	0.04	2.55
Complex Vector DM	100 GeV	V1	18.06	0.17	0.06	13.34	1.72	2.68	0.32	5.5	0.0	0.77	6.25	12.9	0.1	1.06	5.34	16.03
		V3	24.86	1.45	0.44	7.57	4.57	0.65	0.79	2.14	0.74	0.0	2.68	7.25	0.57	0.03	2.04	9.59
		V5	38.36	7.24	4.79	1.3	12.86	0.7	5.67	0.06	5.61	2.5	0.0	1.14	5.24	2.04	0.13	2.13
		V11	50.03	13.43	10.0	0.01	20.55	3.45	10.89	1.39	11.2	6.54	1.11	0.0	10.52	5.83	1.49	0.16
	1000 GeV	V1	19.73	0.43	0.06	12.46	2.13	2.48	0.08	5.02	0.1	0.59	5.83	12.09	0.0	0.89	4.78	15.14
		V3	25.96	1.78	0.65	6.72	5.21	0.4	1.12	1.7	1.01	0.03	2.17	6.41	0.85	0.0	1.65	8.6
		V5	37.33	6.47	4.04	1.68	11.72	0.55	4.59	0.04	4.84	1.93	0.14	1.55	4.34	1.57	0.0	2.72
		V11	54.48	16.14	12.42	0.13	23.85	4.95	13.43	2.41	13.74	8.55	2.03	0.16	13.01	7.73	2.57	0.0

Importance of the operator running in the DM DD ↔ Collider interplay

- In case of axial operators, e.g

$c_A^{(q)} c_\chi \overline{\chi} \gamma^\mu \chi \overline{q} \gamma_\mu \gamma_5 q \qquad (D7)$ or $c_A^{(q)} c_\phi \phi^\dagger \overleftrightarrow{\partial}_\mu \phi \overline{q} \gamma^\mu \gamma_5 q \qquad (C4)$

couplings $\mathbf{c}_V^{(q)}$ arise due to the running of the wilson coeffcient $\mathbf{c}_A^{(q)}$ leading to sizable constraints on the DM DD constraints



Importance of the operator running in the DM DD ↔ Collider interplay

- In case of axial operators, e.g

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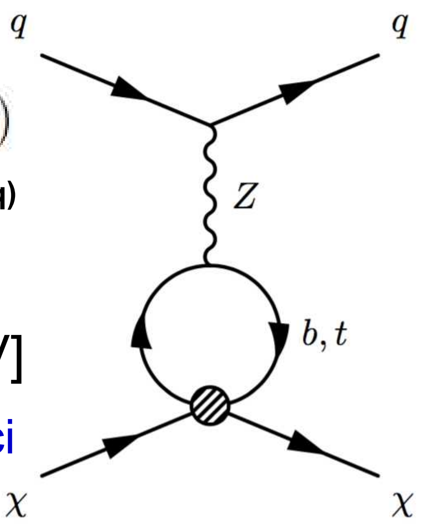
$\mathbf{c_A^{(u)}, c_A^{(d)}, c_V^{(u)}, c_V^{(d)}=(1,1,0,0)}$[1TeV] → (1.1, 1.1, 0.04, -0.07)[1GeV]

runDM program (**github.com/bradkav/runDM**) by D’Eramo, Kavanagh Panci



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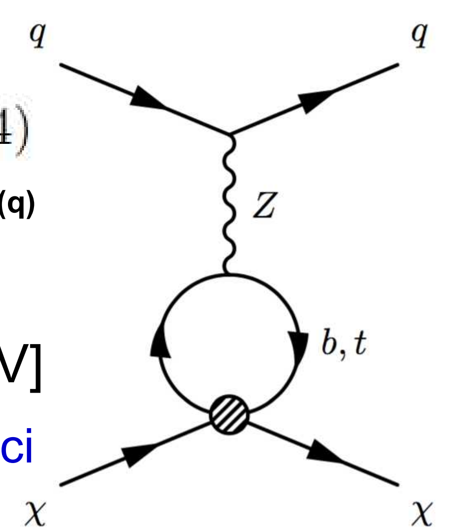

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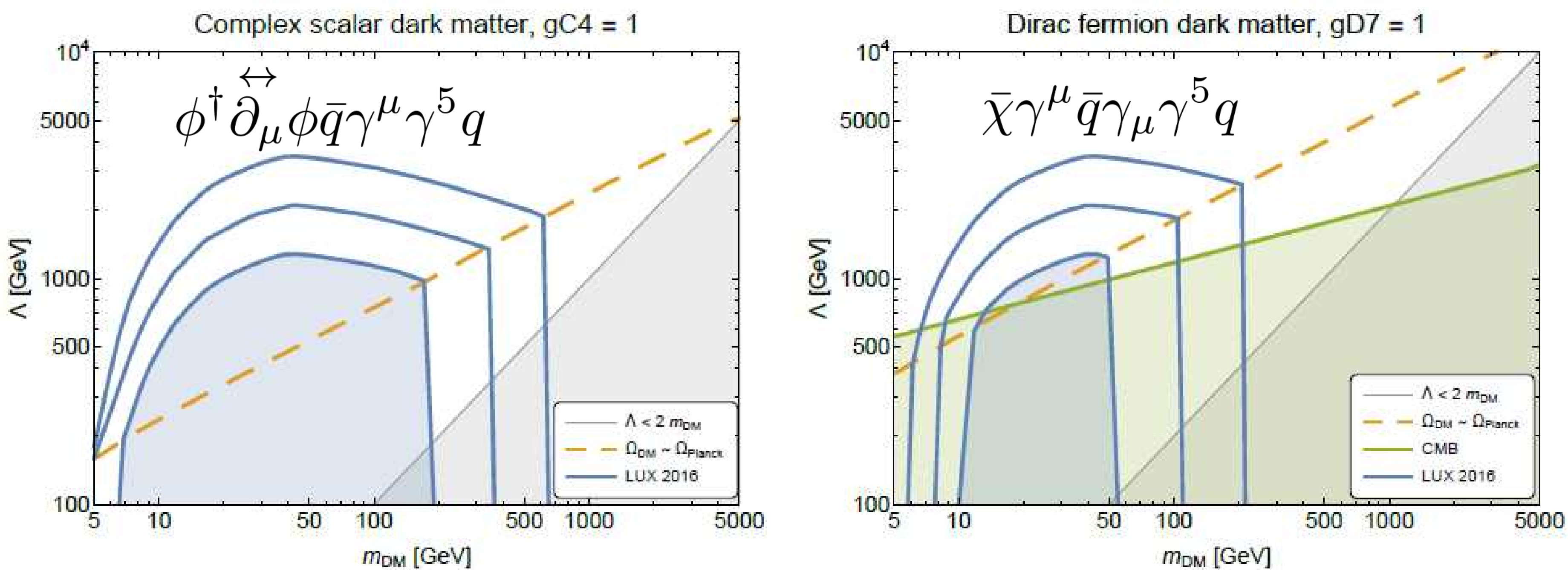
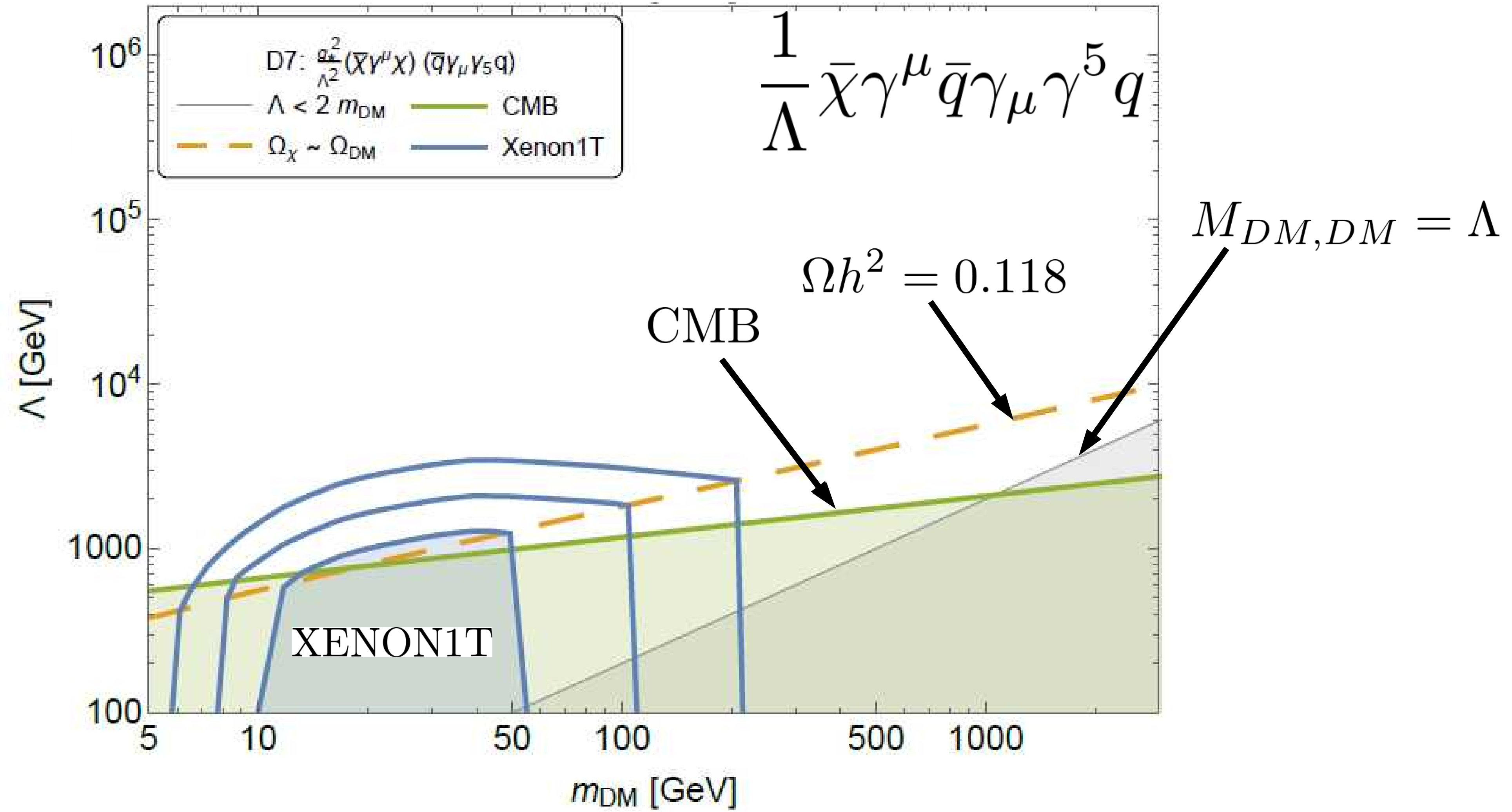


AB, Bertuzzo, Caniu, di Cortona, Eboli, Iocco, Pukhov 2018

DM DD ↔ Collider interplay

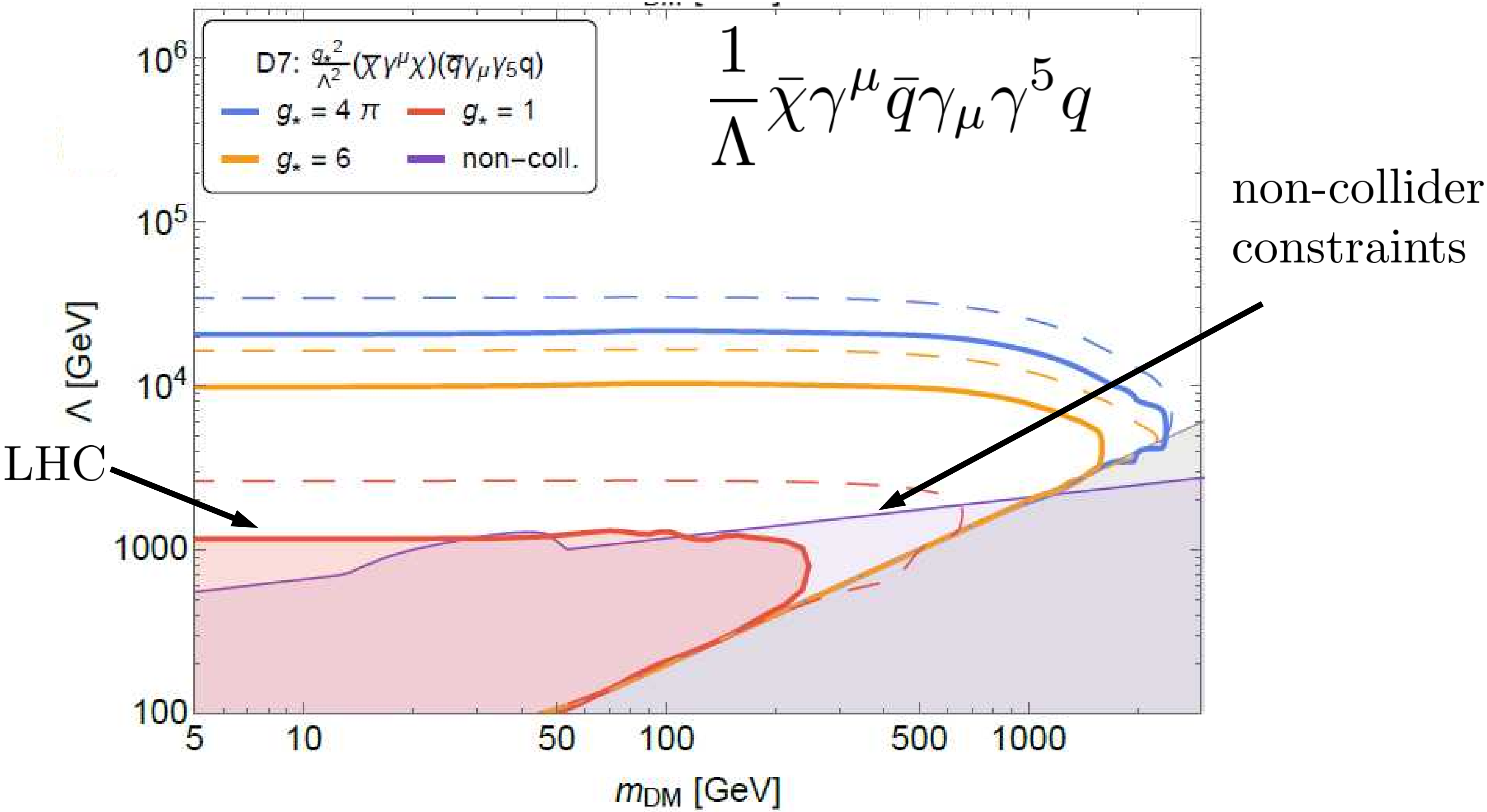
AB, Bertuzzo, Caniu, di Cortona, Eboli, Iocco, Pukhov 2018



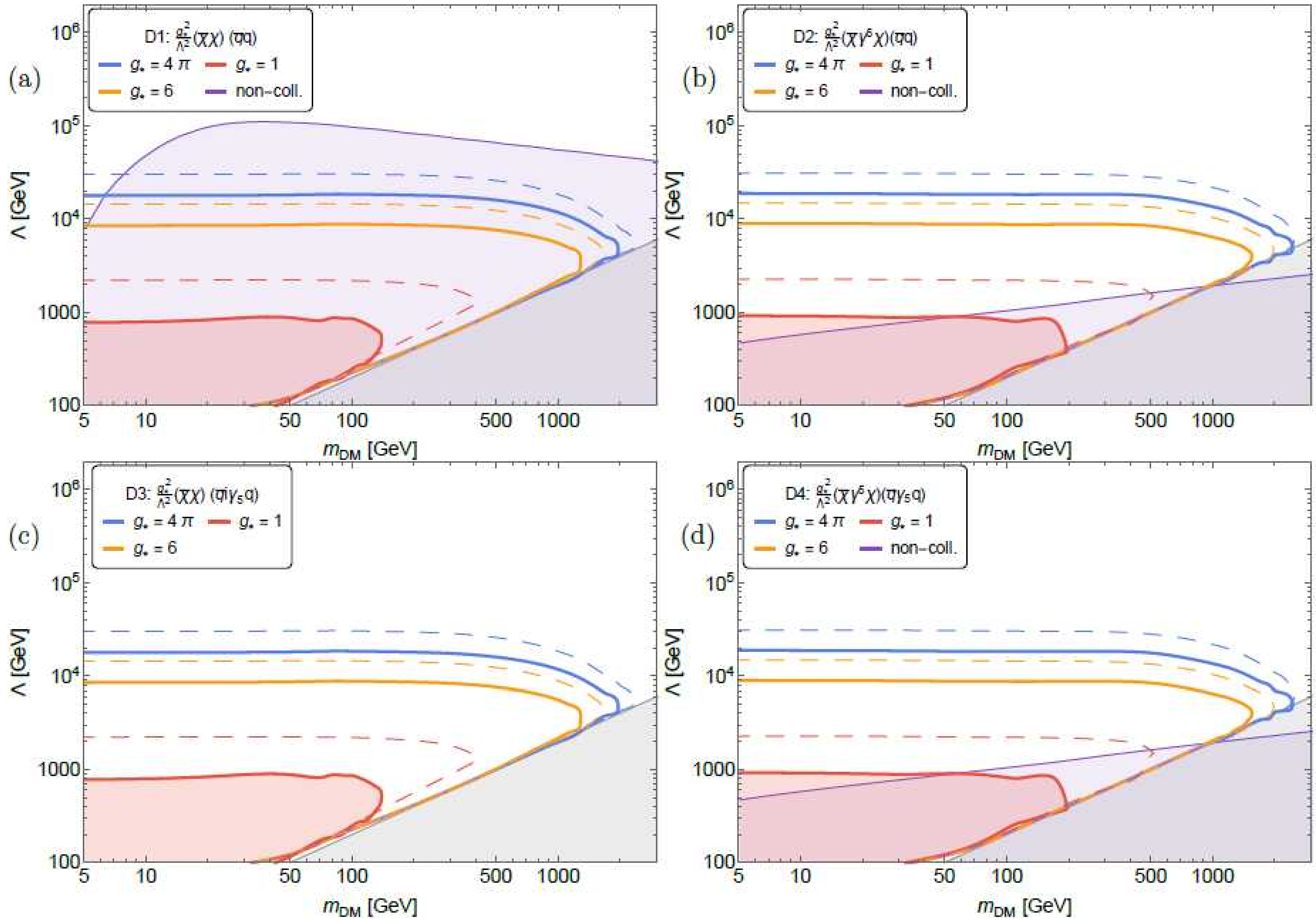
$$\text{CMB:} \quad p_{\text{ann}} < 4.1 \times 10^{-28} \, \frac{\text{cm}^3}{\text{s GeV}} \ \text{at} \ 95\% \ \text{C.L.} \ , \ \text{where} \quad p_{\text{ann}} = \sum_j f_j(600, m_{\text{DM}}) \frac{\langle \sigma v \rangle_j (600)}{m_{\text{DM}}}$$

DM DD ↔ Collider interplay

AB, Bertuzzo, Caniu, di Cortona, Eboli, Iocco, Pukhov 2018

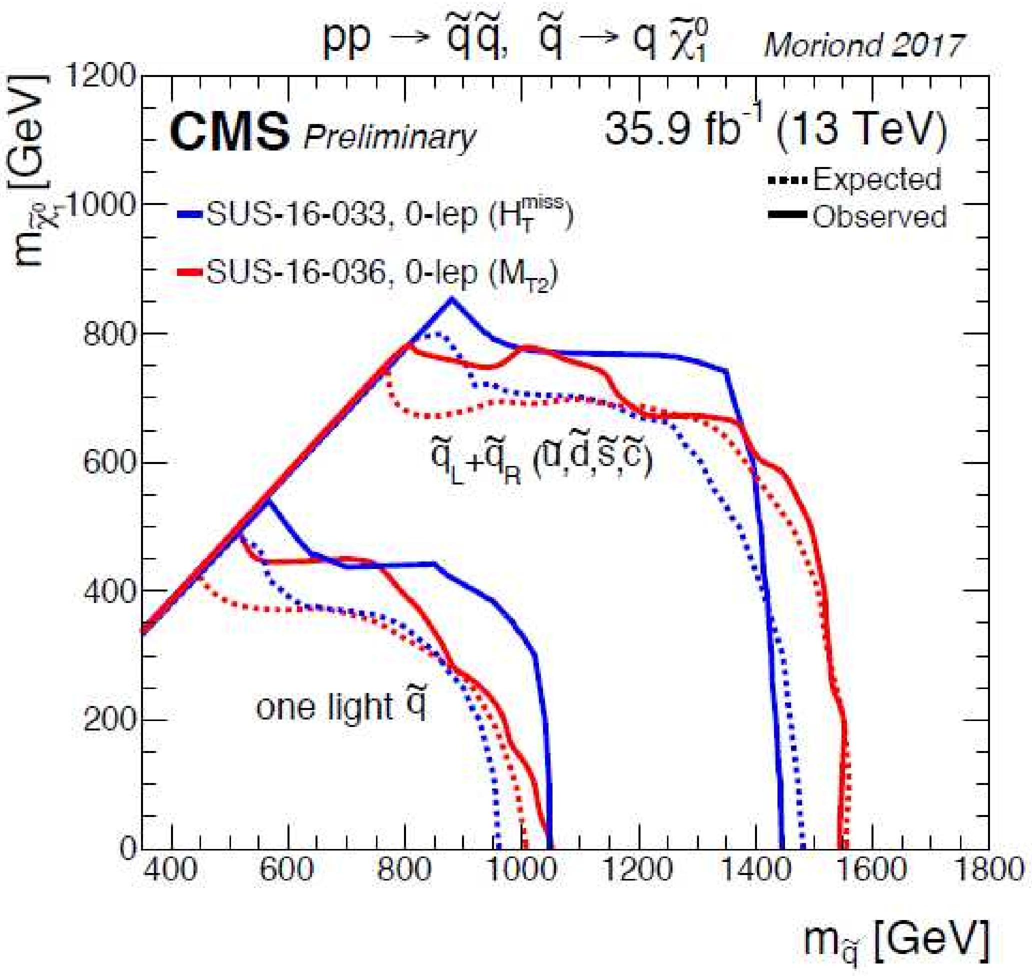


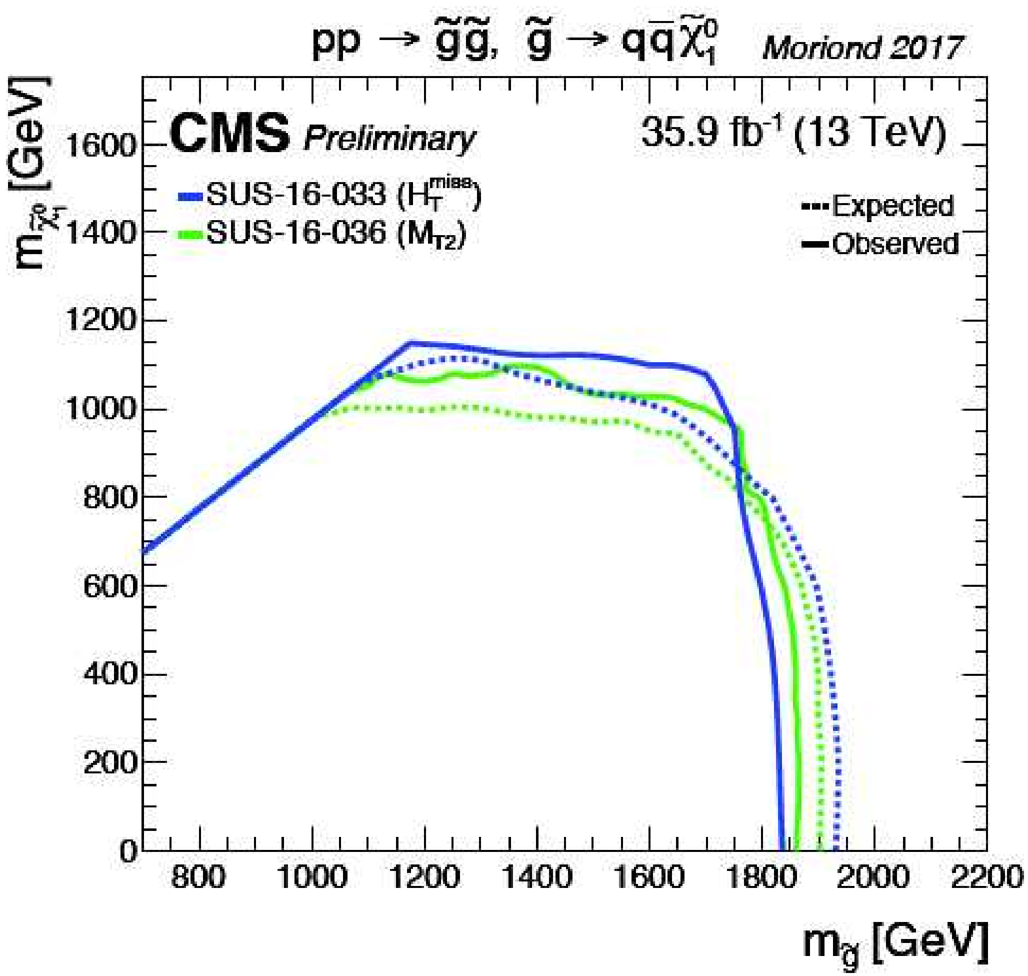
DM DD ↔ Collider interplay



Beyond the EFT: SUSY

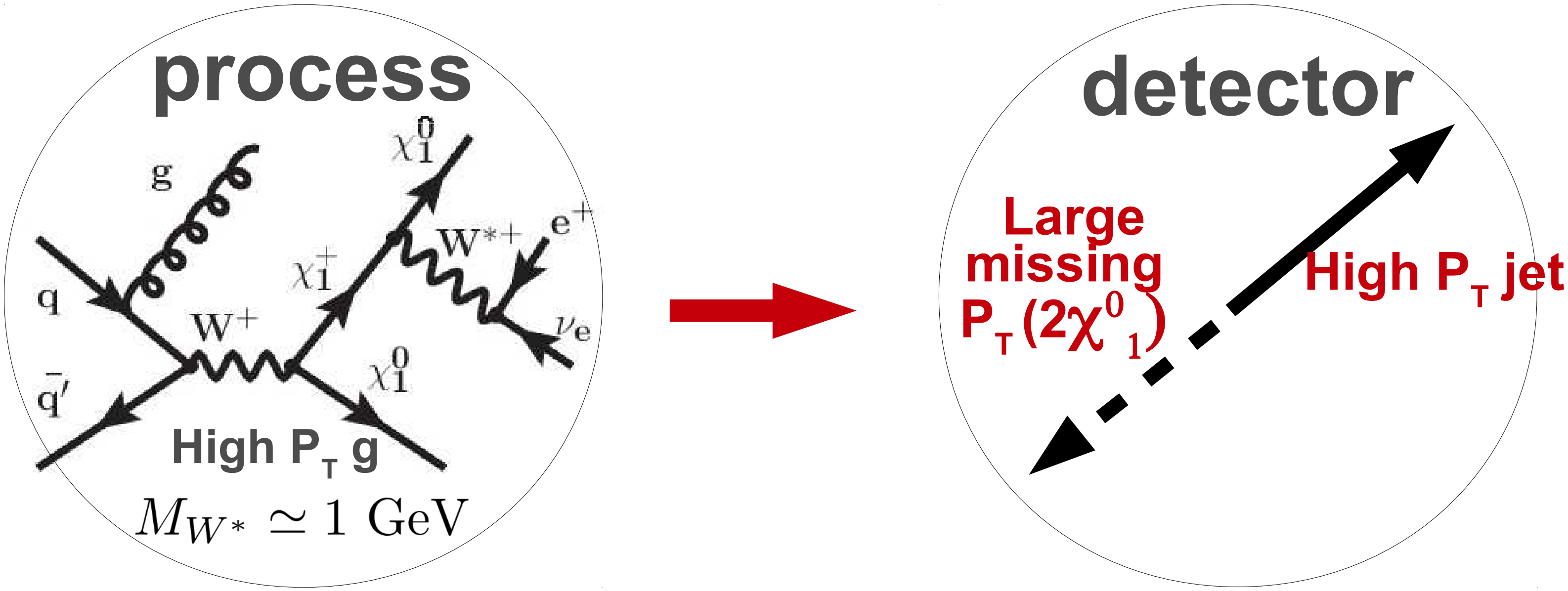
There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 1.9 TeV





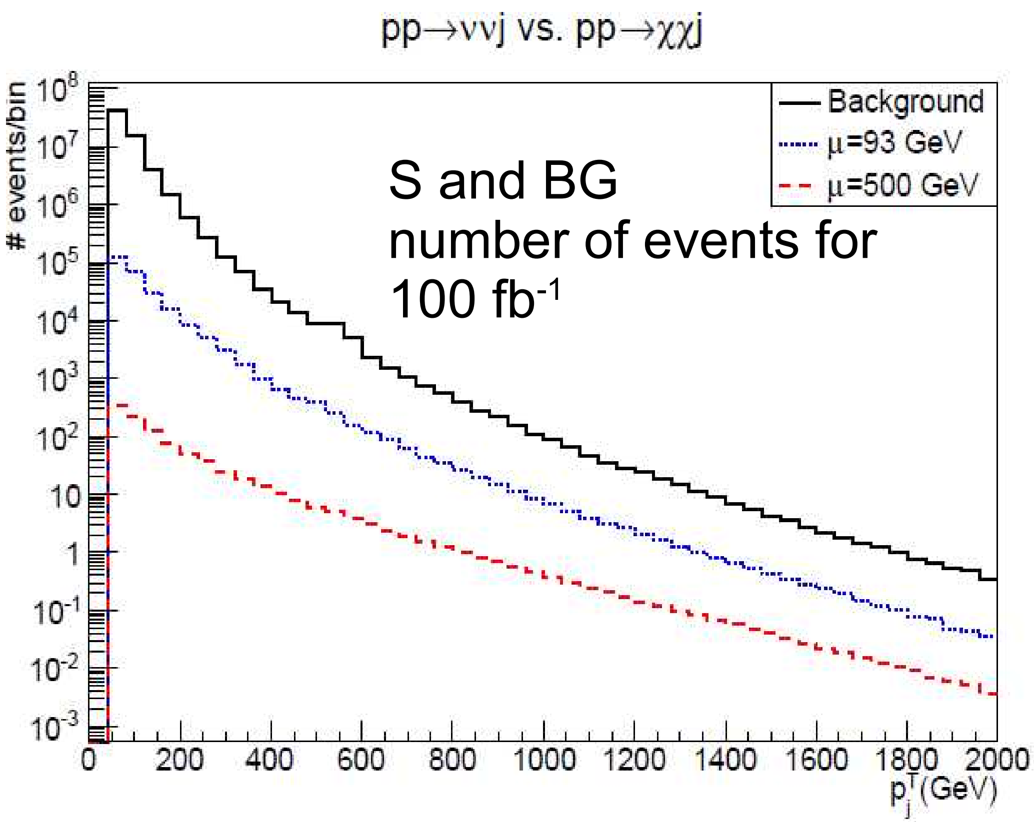
SUSY Compressed Mass Spectrum scenario

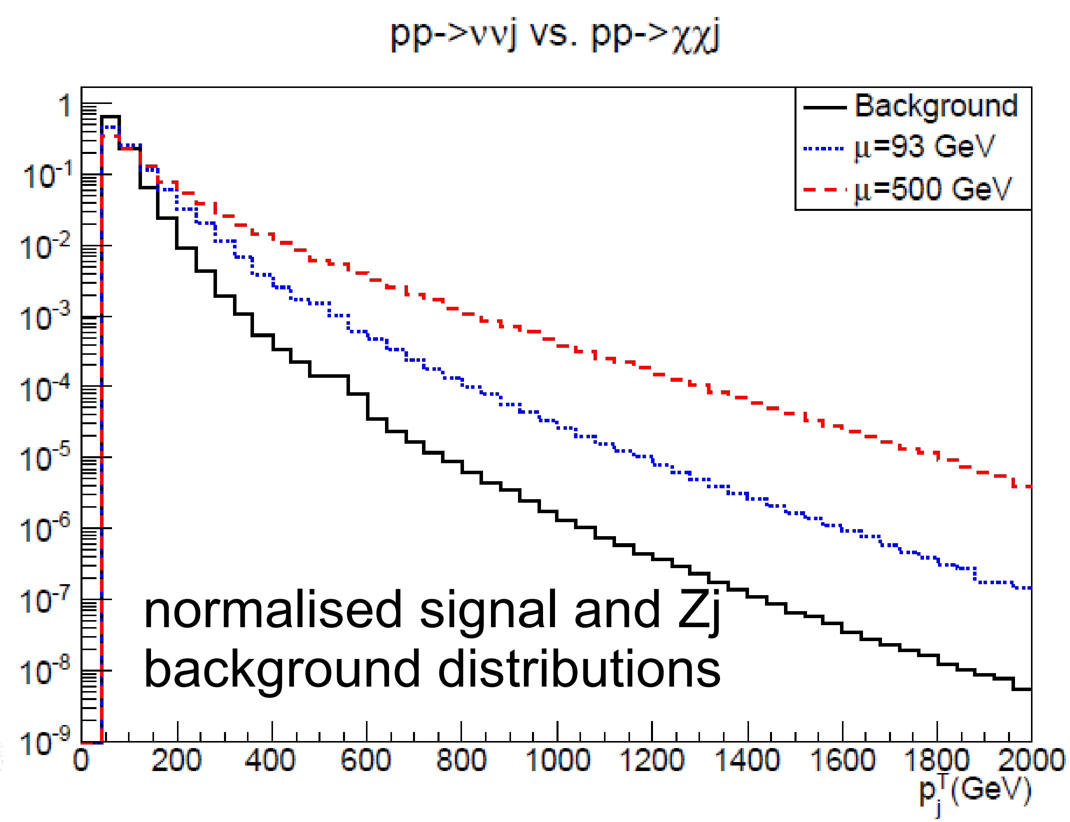
- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for leptonic signatures
- The only way to probe CHS is a mono-jet signature
  ["Where the Sidewalk Ends? ..." Alves, Izaguirre,Wacker '11] ,
  which has been used in studies on compressed SUSY spectra, e.g.
  Dreiner,Kramer,Tattersall '12; Han,Kobakhidze,Liu,Saavedra,Wu'13;
  Han,Kribs,Martin,Menon '14



Signal vs Background

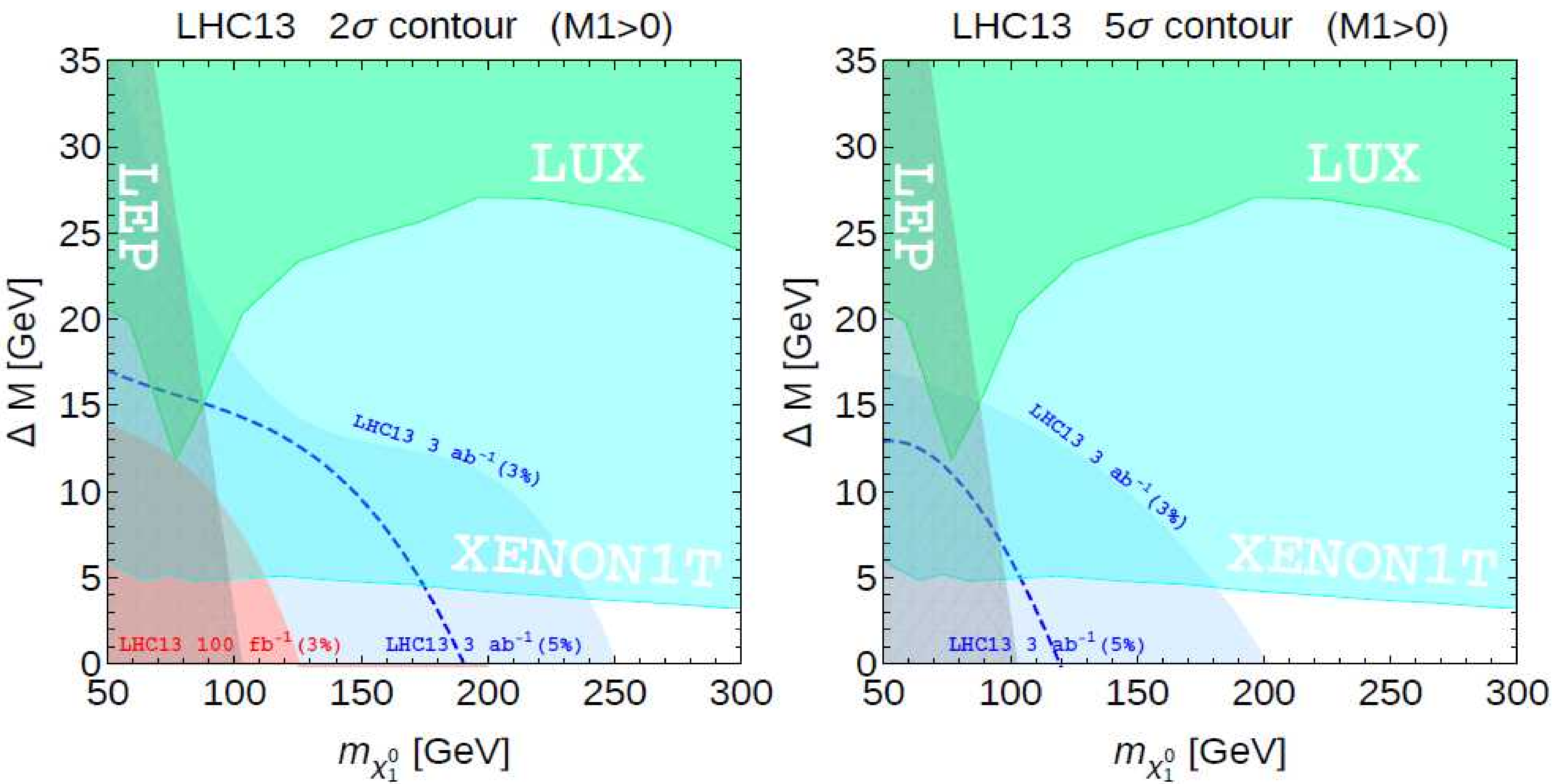
- difference in rates is pessimistic ...
- but the difference in shapes is encouraging: large DM mass → biger M(DM,DM) → flatter MET





Signal and Zj background p_T^j distributions for the 13 TeV LHC

LHC/DM direct detection sensitivity

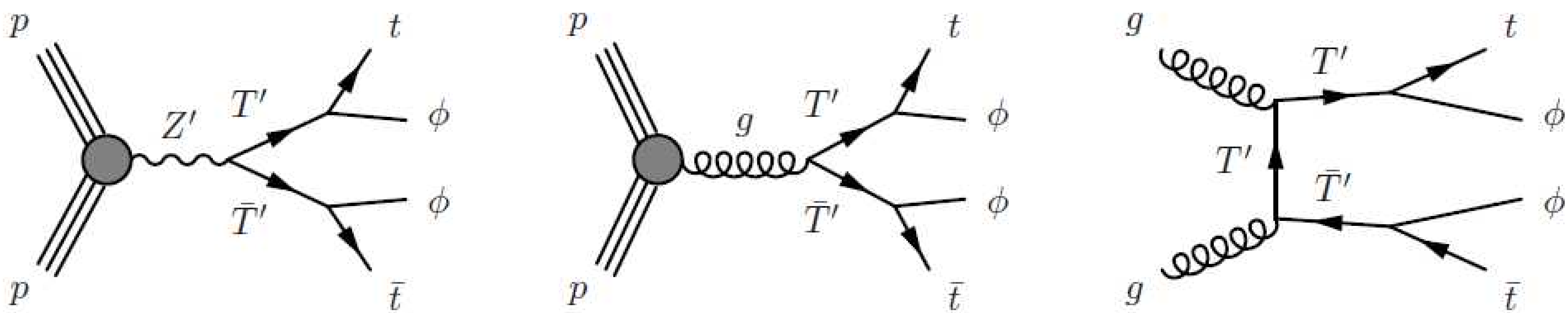


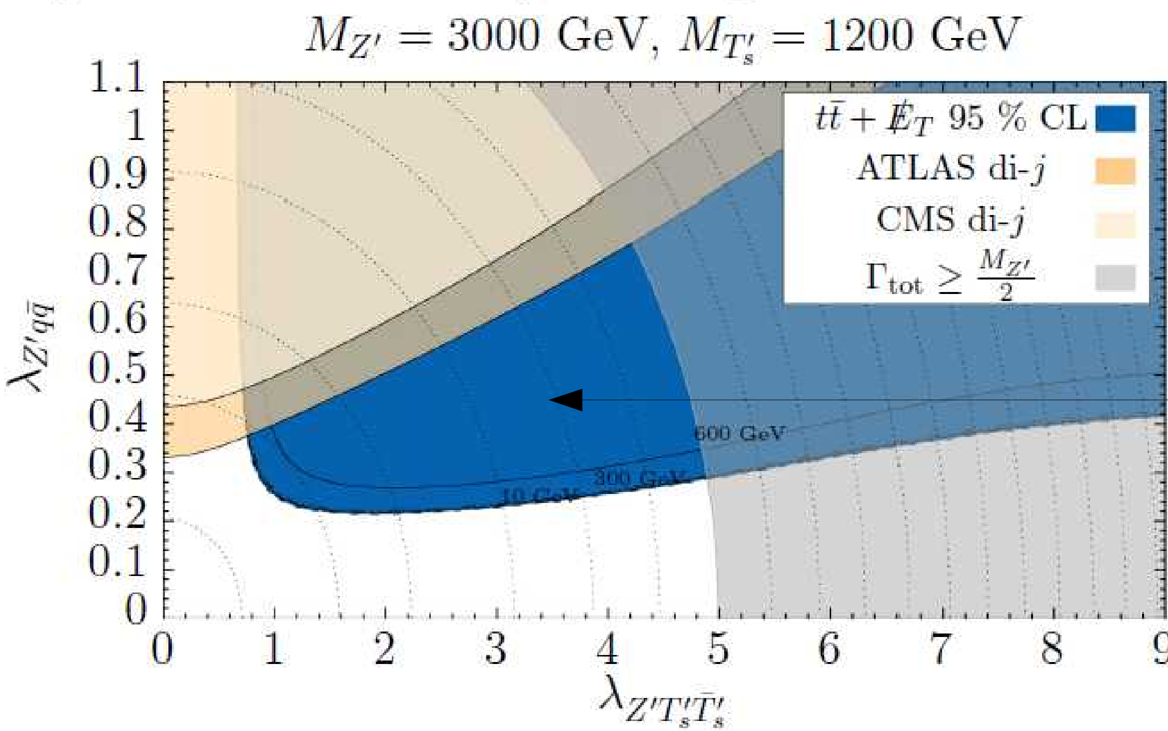
AB, Barducci,Bharucha,Porod,Sanz JHEP, 1504.02472

- SUSY DM, can be around the corner (~100 GeV), but it is hard to detect it!
- Great complementarity of DD and LHC for small DM (NSUSY) region

Beyond the mono-jet signature

Example of the vector resonance in the Composite Higgs model:
Z'→ TT→ t t DM DM signature

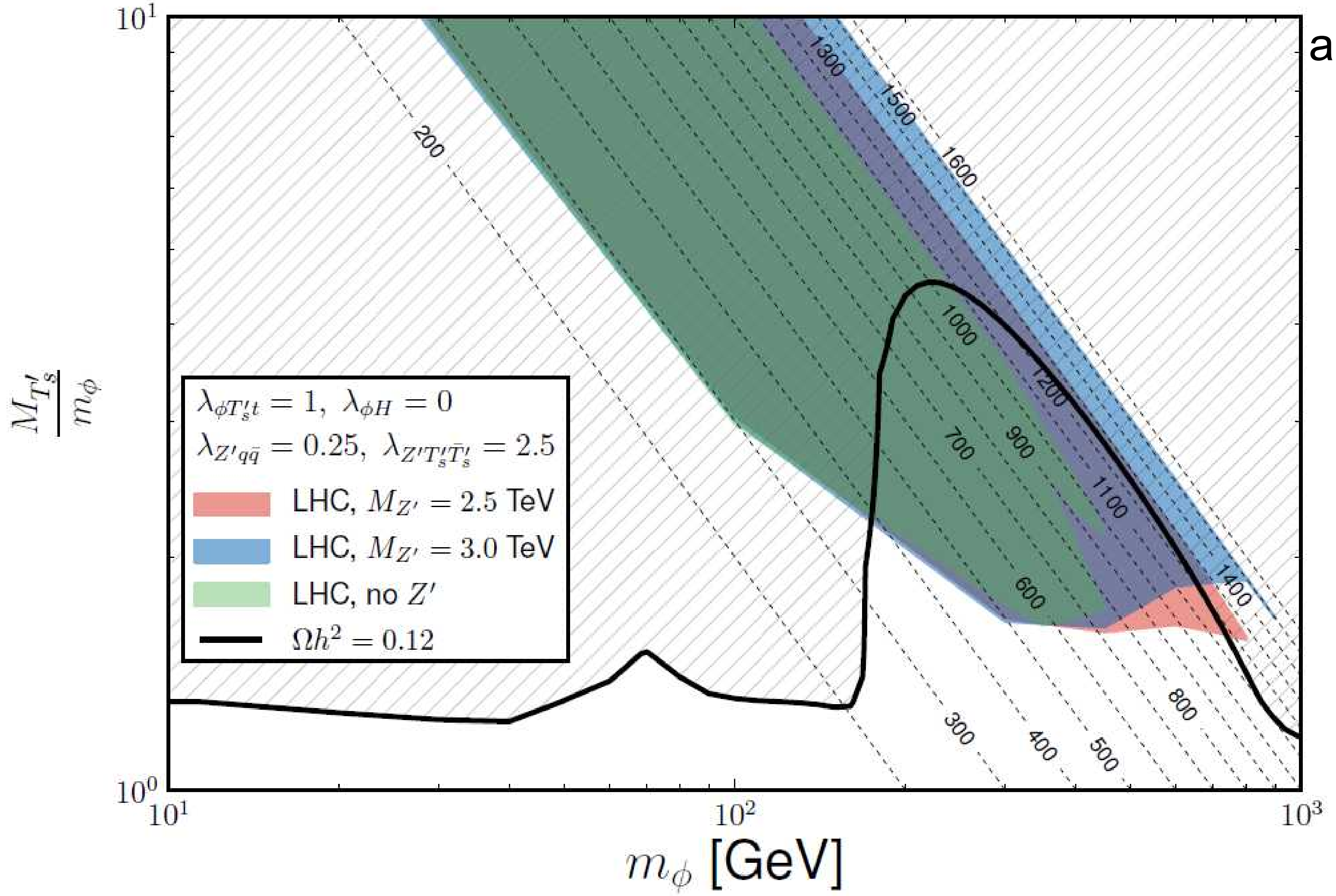




Current LHC reach
with tt+ MET signature
based on
ATLAS_CONF_2016_050
results

Flacke, Jaine, Schaefers, AB, 2017

The role of Z' vs QCD for pp→ TT→ t t DM DM



arXiv: 1707.07000

Z' + QCD TT production

➪LHC is probing now DM and top partner masses up to about 0.9 and 1.5 TeV respectively: above bounds from QCD production alone by ~ factor of two

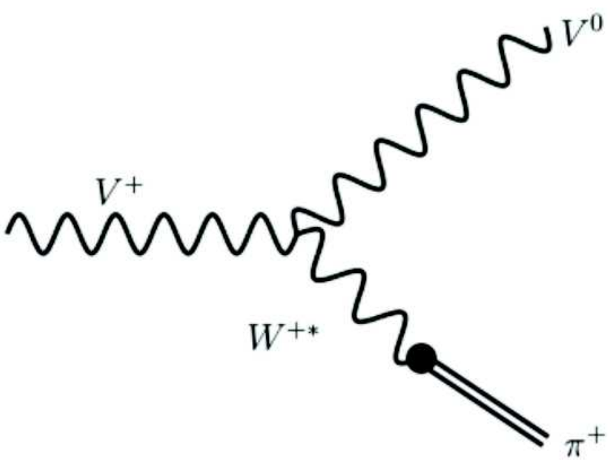
➪DM DD rates are loop-suppressed

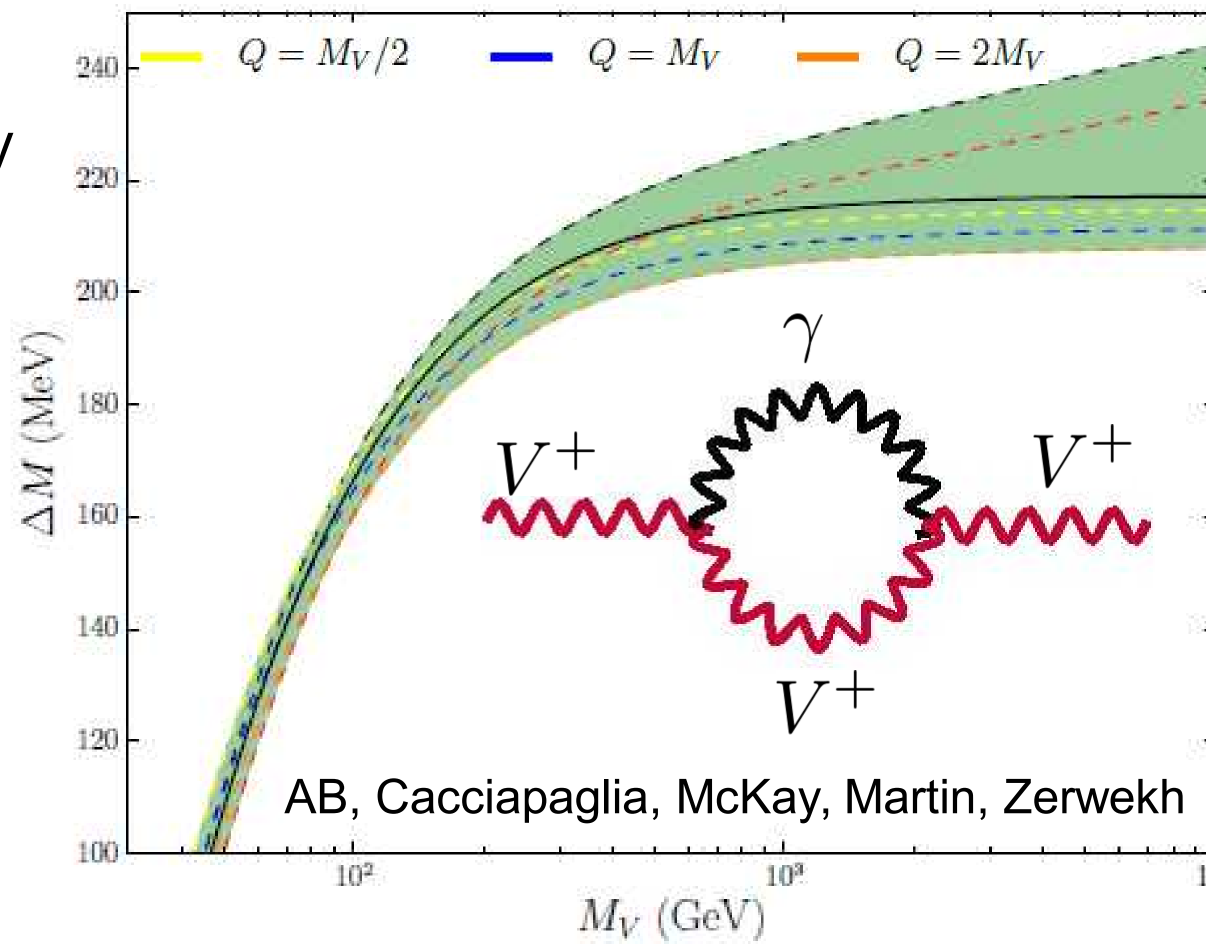
Disappearing Charged Tracks from: VDM as an example

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{SM} &- Tr\{D_\mu V_\nu D^\mu V^\nu\} + Tr\{D_\mu V_\nu D^\nu V^\mu\} \\ &- \frac{g^2}{2} Tr\{[V_\mu, V_\nu][V^\mu, V^\nu]\} \\ &- igTr\{W_{\mu\nu}[V^\mu, V^\nu]\} + \tilde{M}^2 Tr\{V_\nu V^\nu\} \\ &+ a\left(\Phi^\dagger \Phi\right) Tr\{V_\nu V^\nu\}\end{aligned}$$

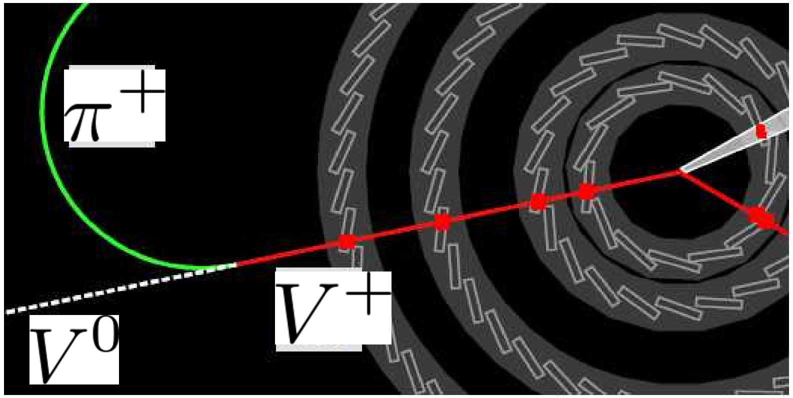
The small mass gap (~ pion mass) between DM and its charged partner will lead to the disappearing charge tracks signatures

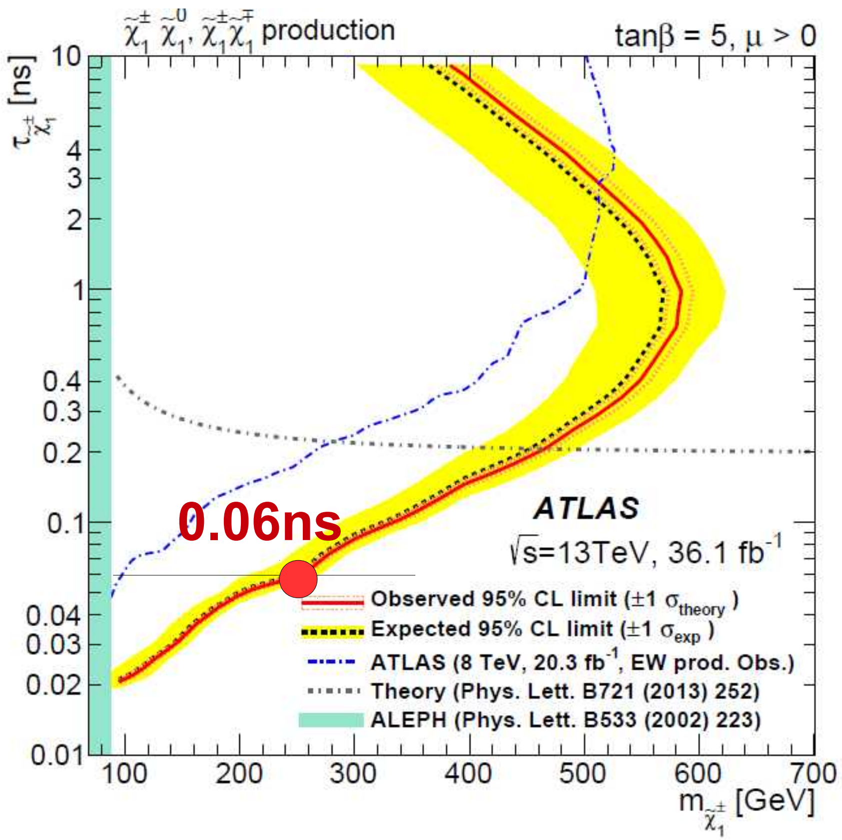
The life-time should be properly evaluated using W-pion mixing (otherwise overestimated by factor of 10)

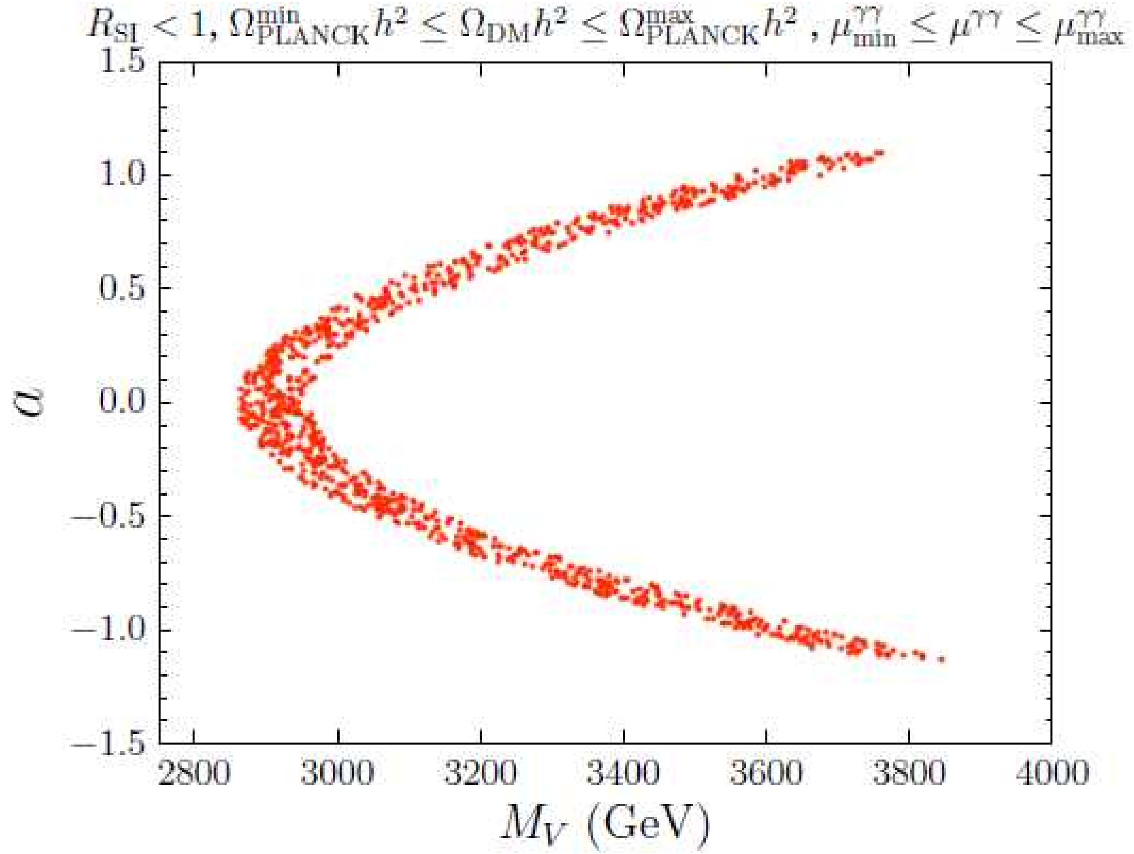




Collider sensitivity to VDM mass

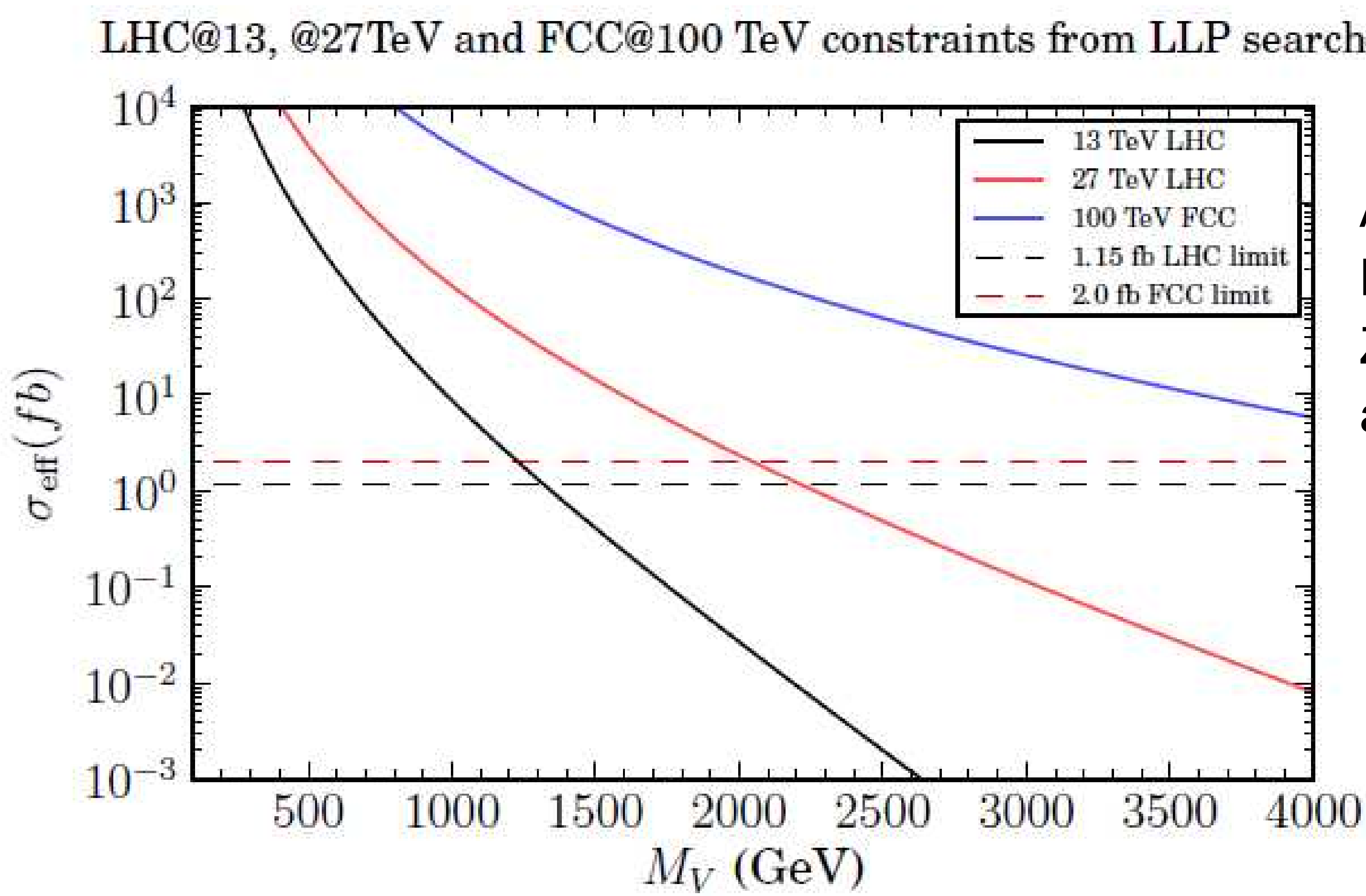






Using ATLAS arXiv:1712.02118 for LHC interpretation
and
Mahbubani,Schwaller, Zurita
ArXiv:1703.05327
For 100 TeV FCC projections

Collider sensitivity to VDM mass



AB, Cacciapaglia, McKay, Martin, Zerwekh arXiv:**1808.10464**

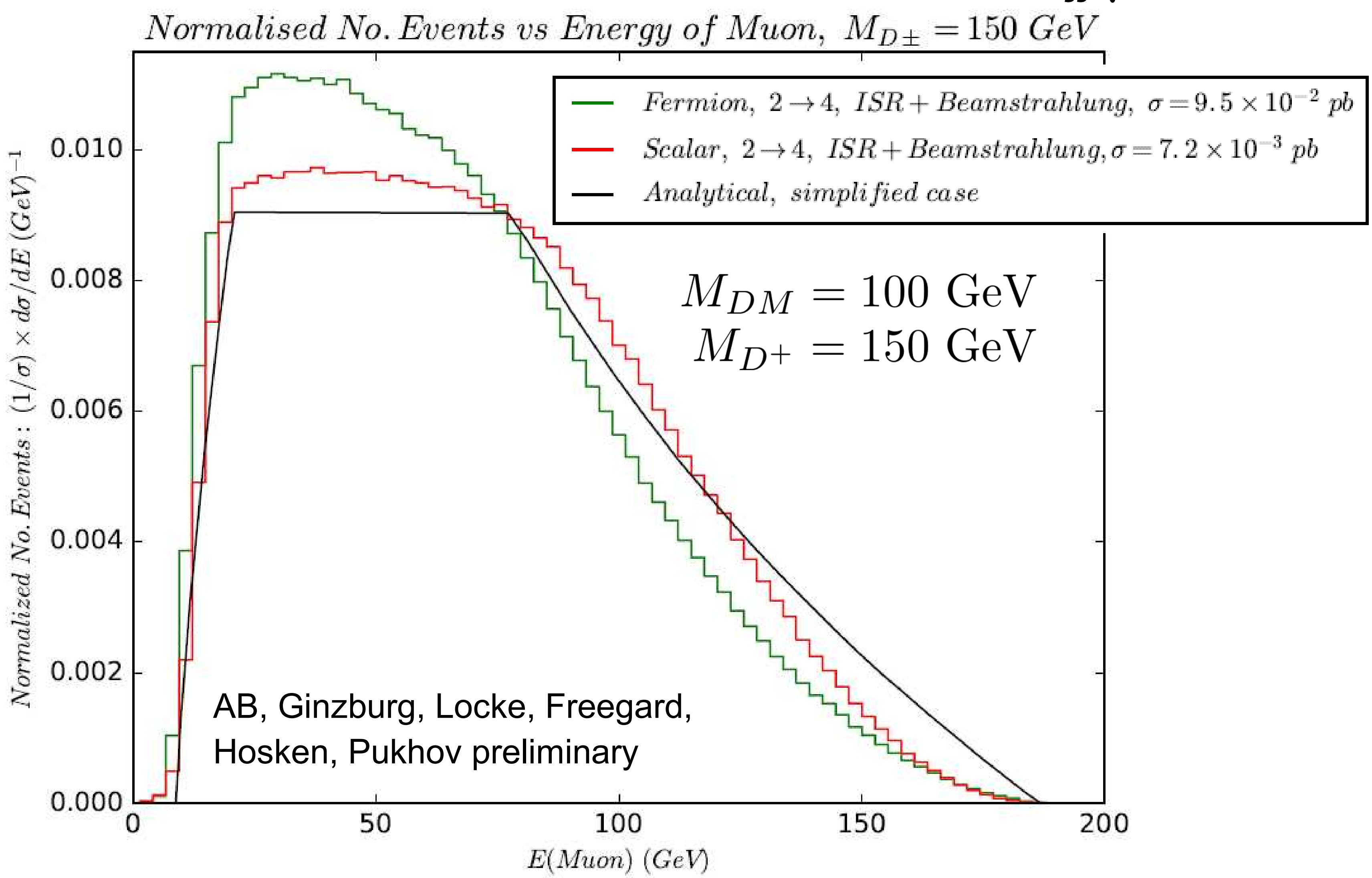
Current bound from LHC on DM mass from the minimal vector triplet model: **1.3 TeV** !

100 TeV FCC will cover DM mass **beyond 4TeV:** will discover or close the model

Decoding the nature of DM at the ILC

muon spectrum from the models with scalar and fermion DM

e+e- → D+ D- → DM DM W+ W- → DM DM jj μ ν



Decoding Problem: Data → Theory link

- probably the most challenging problem to solve – **the inverse problem of decoding of the underlying theory from signal**
  - requires database of models, database of signatures
  - requires smart procedure based on machine learning of matching signal from data with the pattern of the signal from data

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- **HEPMDB (High Energy Physics Model Database)** was created in 2011 **hepmdb.soton.ac.uk**
  - convenient centralized storage environment for HEP models
  - it allows to evaluate the LHC predictions and perform event generation using CalcHEP, Madgraph for any model stored in the database
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- As a HEPMDB spin-off the **PhenoData** project was created **hepmdb.soton.ac.uk/phenodata**
  - stores data (digitized curves from figures, tables etc) from those HEP papers which did not provide data in arXiv or HEPData
  - has an easy search interface and paper identification via arXiv, DOI or preprint numbers

Summary

➪DM DD detection provides a very powerful probe of DM theory space – in general provides DM mass probe beyond the collider reach

➪Colliders – provide DM detection power in the region “blind” for DM DD, typically below 1 TeV

➪Several ways to decode DM nature from the signal which we hope to observe soon (slopes of MET, cross sections, signatures, …)

➪New prospects: new DD experiments, new ideas, prospects for directional DM detection, new signatures at colliders (VFB, LL, …), future colliders (great potential of ILC and FCC – see Albert's talk)

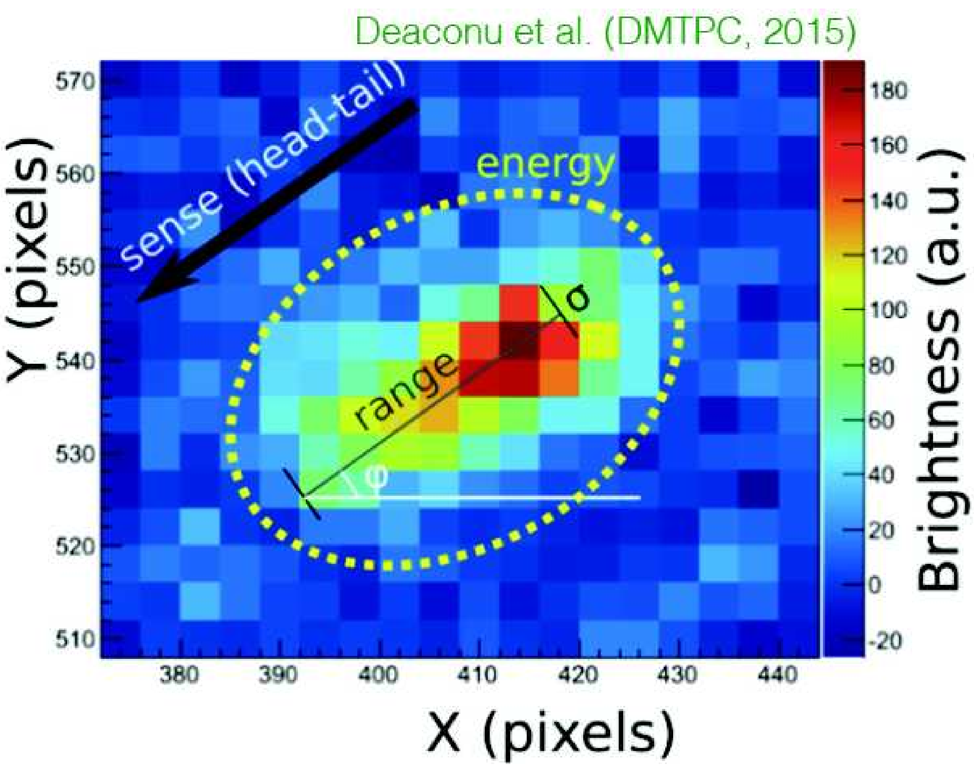
➪Great synergy of collider and non-collider experiments (DD, CMB, relic density)

Thank you!

Backup Slides

DM DD: directional detection – going beyond the neutrino floor

- The idea is to measure both the energy and the direction of the recoil
- Most mature technology is the gaseous Time Projection Chamber (TPC) : DRIFT, MIMAC, DMTPC, NEWAGE, D3



- Detecting recoil tracks in nuclear emulsion (e.g. NEWS experiment)
  Aleksandrov et al. [1604.04199]
- Directional detection is HARD,
  But it is also very POWERFUL.

Relation of the actual dimension (D) and the naive one (d) for VDM operators

V_{DM} Operator	Λ_d	d	Λ_D	D	$\Delta_\sigma(\sigma_{2\to 2}\propto E^{\Delta_\sigma})$	Amplitude Enhancement
V1,V2,V5,V6	$\frac{1}{\Lambda}$	5	$\frac{M_{DM}^2}{\Lambda^3}$	7	4	$(E/M_{DM})^2$
V3,V4,V7M,V8M,V11,V12	$\frac{1}{\Lambda^2}$	6	$\frac{M_{DM}^2}{\Lambda^4}$	8	6	$(E/M_{DM})^2$
V7P,V8P,V9,V10	$\frac{1}{\Lambda^2}$	6	$\frac{M_{DM}}{\Lambda^3}$	7	4	E/M_{DM}

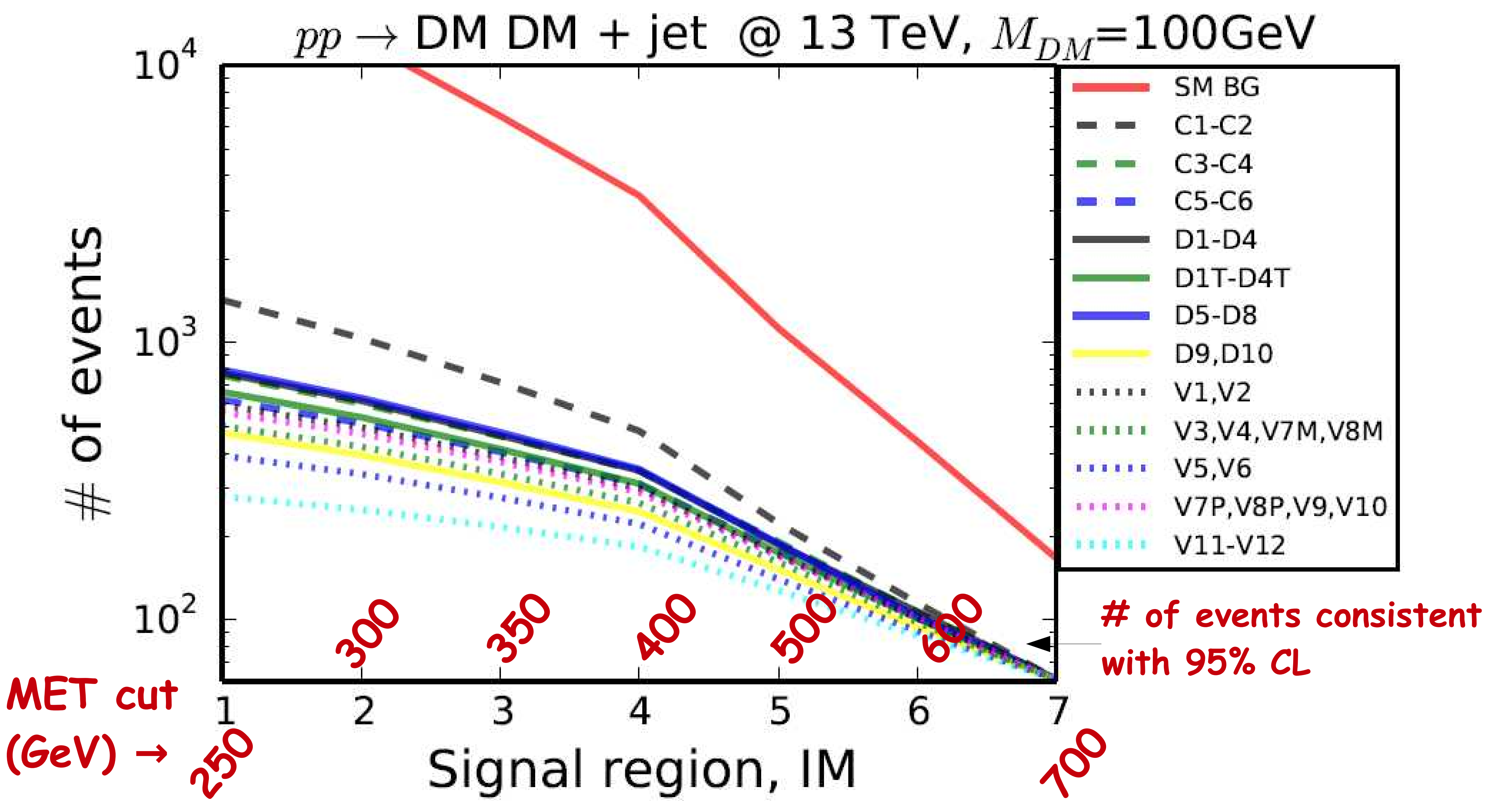
- we suggest a **new parametrisation** of VDM operators: since the energy E and the collider limit on L are of the same order, it is natural to use an additional $\mathbf{M_{DM}/\Lambda}$ factor for each power of $\mathbf{E/M_{DM}}$ enhancement, so collider limits are **not artificially enhanced**
[~100 TeV !!! for MDM =1 GeV, see Kumar, Marfatia, Yaylali 1508.04466]
and will be of the same order as limits for other operators

- Dictionary between limits on Λ in different parametrisations:

$$\Lambda_D = (\Lambda_d^{d-4} M_{DM}^{D-d})^{\frac{1}{D-4}} \quad \text{and} \quad \Lambda_d = (\Lambda^{D-4} M_{DM}^{d-D})^{\frac{1}{d-4}}$$

Distinguishing DM operators

operator energy dependence → M_{DMDM} shape → MET shape



On the BG uncertainty

- **The BG is statistically driven, e.g. pp-> Zj → nnj BG is defined from the pp → Zj → l^+l^-j one**

CMS-PAS-EXO-16-013

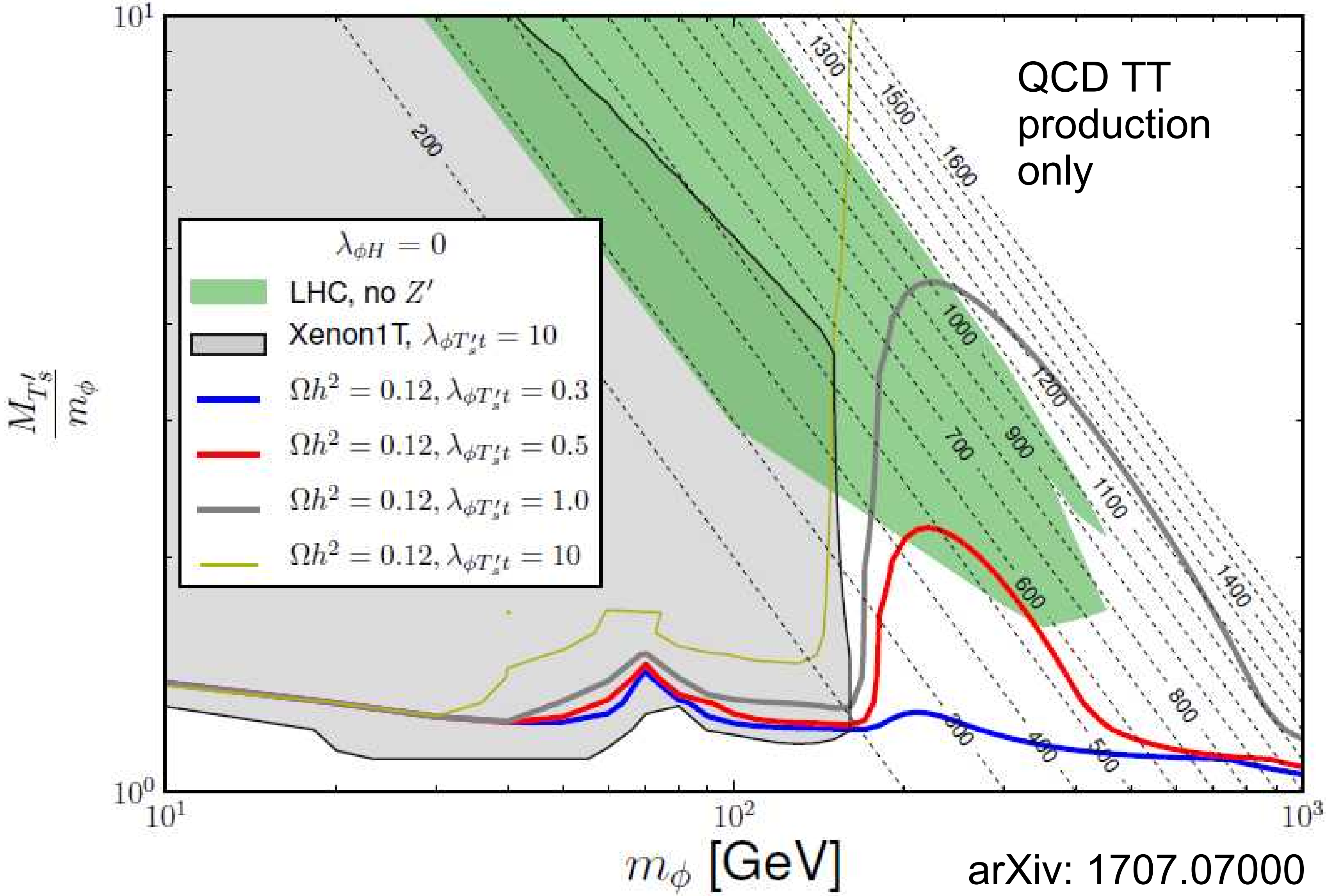
E_T^{miss} Range (GeV)	$Z(\nu\nu)$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	γ+jets	Top	Diboson	QCD	Total (Pre-fit)	Total (Post-fit)	Data
200 – 230	14919 ± 221	11976 ± 196	207 ± 13	230 ± 14	564 ± 55	251 ± 41	508 ± 171	27761 ± 1464	28654 ± 171	28601
230 – 260	7974 ± 116	5776 ± 101	92.9 ± 5.7	101 ± 6	267 ± 26	157 ± 26	308 ± 104	14114 ± 757	14675 ± 97	14756
260 – 290	4467 ± 70	2867 ± 50	37.9 ± 2.3	63.7 ± 3.9	116 ± 11	77.3 ± 12.7	38.3 ± 21.0	7193 ± 351	7666 ± 68	7770
290 – 320	2518 ± 46	1520 ± 34	18.4 ± 1.1	29.6 ± 1.8	56.7 ± 5.6	42.9 ± 7.1	29.8 ± 10.5	4083 ± 204	4215 ± 48	4195
320 – 350	1496 ± 35	818 ± 20	10.0 ± 0.6	19.7 ± 1.2	33.6 ± 3.3	25.4 ± 4.2	9.0 ± 5.4	2385 ± 118	2407 ± 37	2364
350 – 390	1204 ± 31	555 ± 15	3.9 ± 0.2	12.7 ± 0.8	24.5 ± 2.4	22.1 ± 3.6	6.0 ± 3.5	1817 ± 87	1826 ± 32	1875
390 – 430	684 ± 20	275 ± 9	2.1 ± 0.1	8.3 ± 0.5	9.8 ± 1.0	13.9 ± 2.3	3.0 ± 1.6	978 ± 45	998 ± 23	1006
430 – 470	382 ± 14	155 ± 6	0.96 ± 0.06	4.9 ± 0.3	9.4 ± 0.9	6.6 ± 1.1	1.0 ± 0.8	589 ± 30	574 ± 17	543
470 – 510	248 ± 11	87.3 ± 3.8	0.47 ± 0.03	3.7 ± 0.2	0.22 ± 0.02	5.1 ± 0.8	0.65 ± 0.44	337 ± 15	344 ± 12	349
510 – 550	160 ± 8	52.2 ± 2.7	0.23 ± 0.01	2.0 ± 0.1	2.7 ± 0.3	2.2 ± 0.4	0.28 ± 0.19	211 ± 9	219 ± 9	216
550 – 590	99.5 ± 6.0	29.2 ± 1.9	0.12 ± 0.01	1.8 ± 0.1	0.94 ± 0.09	2.0 ± 0.3	0.19 ± 0.14	134 ± 6	134 ± 7	142
590 – 640	77.3 ± 4.9	18.9 ± 1.4	0.09 ± 0.01	0.46 ± 0.03	< 0.13	1.7 ± 0.3	0.11 ± 0.08	100 ± 4	98.5 ± 5.8	111
640 – 690	44.8 ± 3.5	11.2 ± 0.9	0.017 ± 0.001	0.19 ± 0.01	< 0.13	1.5 ± 0.2	0.06 ± 0.05	59.6 ± 2.6	58.0 ± 4.1	61
690 – 740	27.8 ± 2.5	6.1 ± 0.6	0.013 ± 0.0008	0.57 ± 0.04	< 0.13	0.69 ± 0.11	0.02 ± 0.02	36.6 ± 1.5	35.2 ± 2.9	32
740 – 790	21.8 ± 2.3	5.3 ± 0.6	< 0.005	0.28 ± 0.02	0.23 ± 0.02	0.11 ± 0.02	0.02 ± 0.02	23.8 ± 1.0	27.7 ± 2.7	28
790 – 840	13.5 ± 1.9	2.8 ± 0.4	< 0.005	0.18 ± 0.01	0.27 ± 0.03	0.010 ± 0.001	0.008 ± 0.007	15.3 ± 0.7	16.8 ± 2.2	14
840 – 900	9.5 ± 1.4	2.0 ± 0.3	< 0.005	0.28 ± 0.02	< 0.13	0.25 ± 0.04	< 0.008	12.2 ± 0.6	12.0 ± 1.6	13
900 – 960	5.4 ± 1.0	1.1 ± 0.2	< 0.005	< 0.08	< 0.13	0.37 ± 0.06	< 0.008	7.6 ± 0.3	6.9 ± 1.2	7
960 – 1020	3.3 ± 0.8	0.77 ± 0.21	< 0.005	0.12 ± 0.01	< 0.13	0.23 ± 0.04	< 0.008	5.2 ± 0.3	4.5 ± 1.0	3
1020 – 1160	2.5 ± 0.8	0.52 ± 0.16	< 0.005	< 0.08	< 0.13	0.16 ± 0.03	< 0.008	3.6 ± 0.2	3.2 ± 0.9	1
1160 – 1250	1.7 ± 0.6	0.3 ± 0.11	< 0.005	< 0.08	< 0.13	0.16 ± 0.03	< 0.008	2.3 ± 0.1	2.2 ± 0.7	2
> 1250	1.4 ± 0.5	0.19 ± 0.08	< 0.005	< 0.08	< 0.13	0.06 ± 0.01	< 0.008	1.6 ± 0.1	1.6 ± 0.6	3

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/EXO-16-013/#AddFig

Complementarity of LHC and non-LHC DM searches

for the model with Vector Resonances, Top Partners and Scalar DM

TT→ t t DM DM



arXiv: 1707.07000

LHC@13TeV Reach for spin 0 and ½ DM

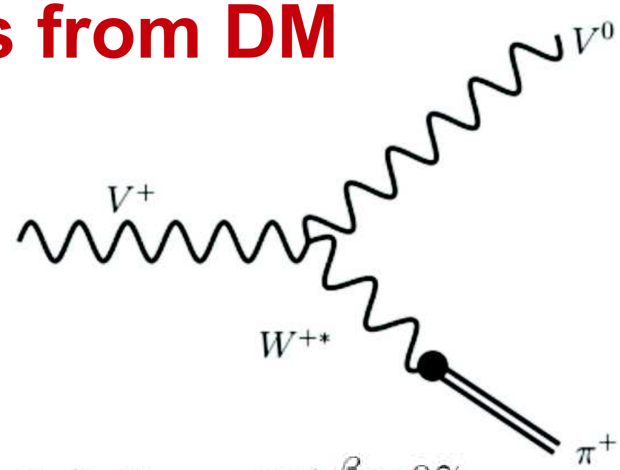
	Operators	Coefficient	Excluded Λ (GeV) at 3.2 fb^{-1}			Excluded Λ (GeV) at 100 fb^{-1}		
			DM Mass			DM Mass		
			10 GeV	100 GeV	1000 GeV	10 GeV	100 GeV	1000 GeV
Complex Scalar DM	C1 & C2	$1/\Lambda$	456	424	98	1168	1115	267
	C3 & C4	$1/\Lambda^2$	750	746	400	1134	1131	662
	C5 & C6	$1/\Lambda^2$	1621	1576	850	2656	2611	1398
Dirac Fermion DM	D1 & D3	$1/\Lambda^2$	931	940	522	1386	1405	861
	D2 & D4	$1/\Lambda^2$	952	936	620	1426	1399	1022
	D1T & D4T	$1/\Lambda^2$	735	729	476	1217	1199	780
	D2T	$1/\Lambda^2$	637	638	407	1053	1052	670
	D3T	$1/\Lambda^2$	586	625	391	969	938	644
	D5 & D7	$1/\Lambda^2$	1058	967	721	1580	1591	1190
	D6 & D8	$1/\Lambda^2$	978	1050	579	1608	1585	955
	D9 & D10	$1/\Lambda^2$	1587	1592	958	2613	2619	1580

LHC@13TeV Reach for spin 1 DM

	Operators	Coefficient	Excluded Λ (GeV) at 3.2 fb^{-1}			Excluded Λ (GeV) at 100 fb^{-1}		
			DM Mass			DM Mass		
			10 GeV	100 GeV	1000 GeV	10 GeV	100 GeV	1000 GeV
Complex Vector DM	V1 & V2	M_{DM}^2/Λ_D^3	831	833	714	1162	1161	997
	V3 & V4	M_{DM}^2/Λ_D^4	930	931	833	1196	1193	1070
	V5 & V6	M_{DM}^2/Λ_D^3	784	791	711	1095	1104	993
	V7M & V8M	M_{DM}^2/Λ_D^4	930	926	882	1195	1193	1130
	V7P & V8P	M_{DM}/Λ_D^3	796	791	652	1112	1102	911
	V9M & V10M	M_{DM}/Λ_D^3	796	799	737	1109	1114	1027
	V9P & V10P	M_{DM}/Λ_D^3	794	782	609	1110	1089	850
	V11 & V11A	M_{DM}^2/Λ_D^4	1435	1442	1309	1844	1850	1683

Disappearing Charged Tracks from DM

The small mass gap between (~ pion mass) DM and its charged partner will lead to the disappearing charge tracks



The life-time should be properly evaluated using W-pion mixing

$$\mathcal{L}_{\pi^- V^+ V^0} = \frac{g^2 f_\pi}{2\sqrt{2} M_W^2}[g_{\beta\gamma}(p_{V^+} - p_{V^0})_\alpha + g_{\alpha\gamma}(p_{V^+} - p_{V^0})_\beta] p^\alpha_{\pi^-} \pi^- V^{+\beta} V^{0\gamma}$$