Direct detection and collider interplay in decoding the nature of Dark Matter

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2nd World Summit on Exploring the Dark Side of the Universe
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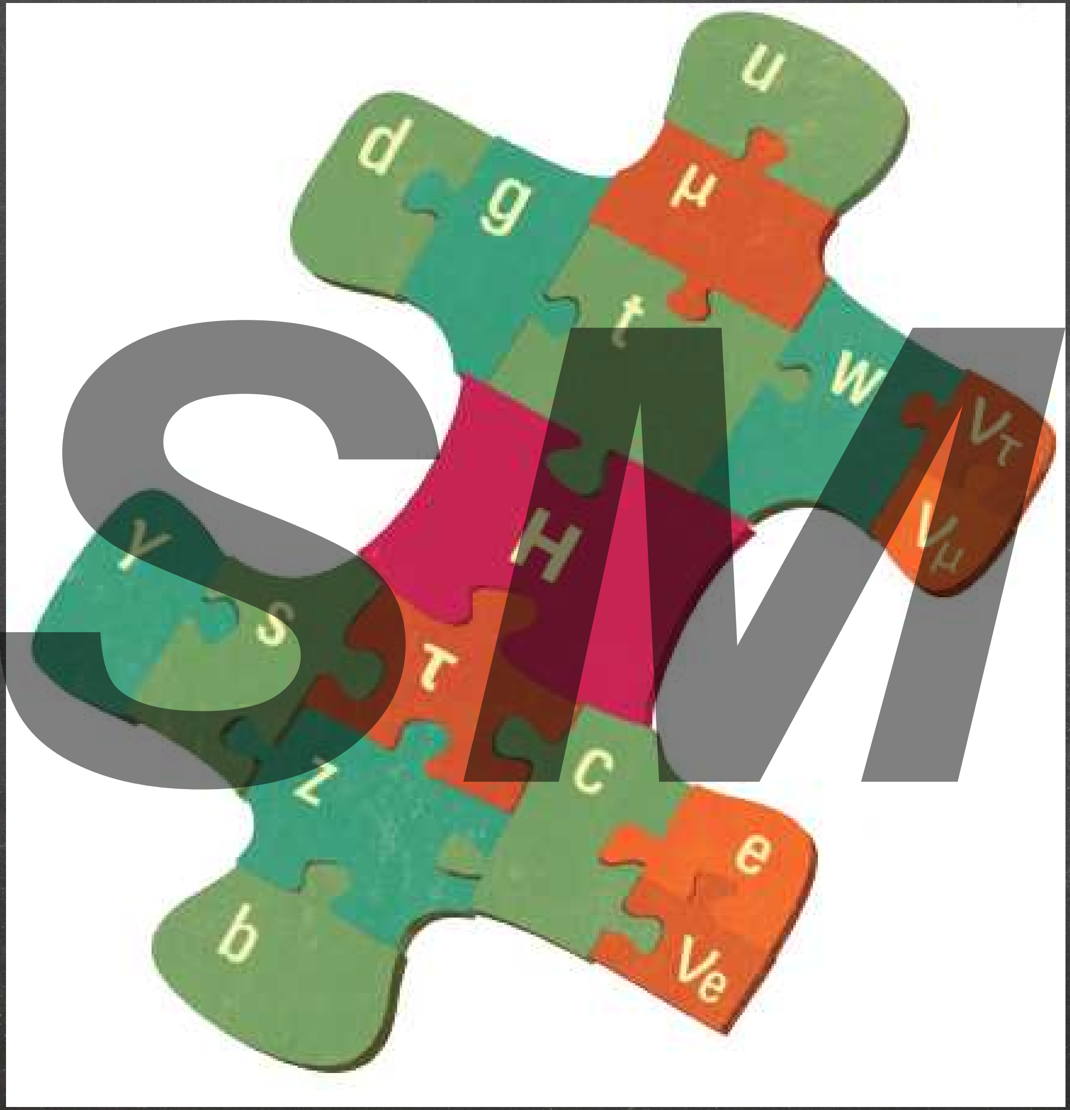
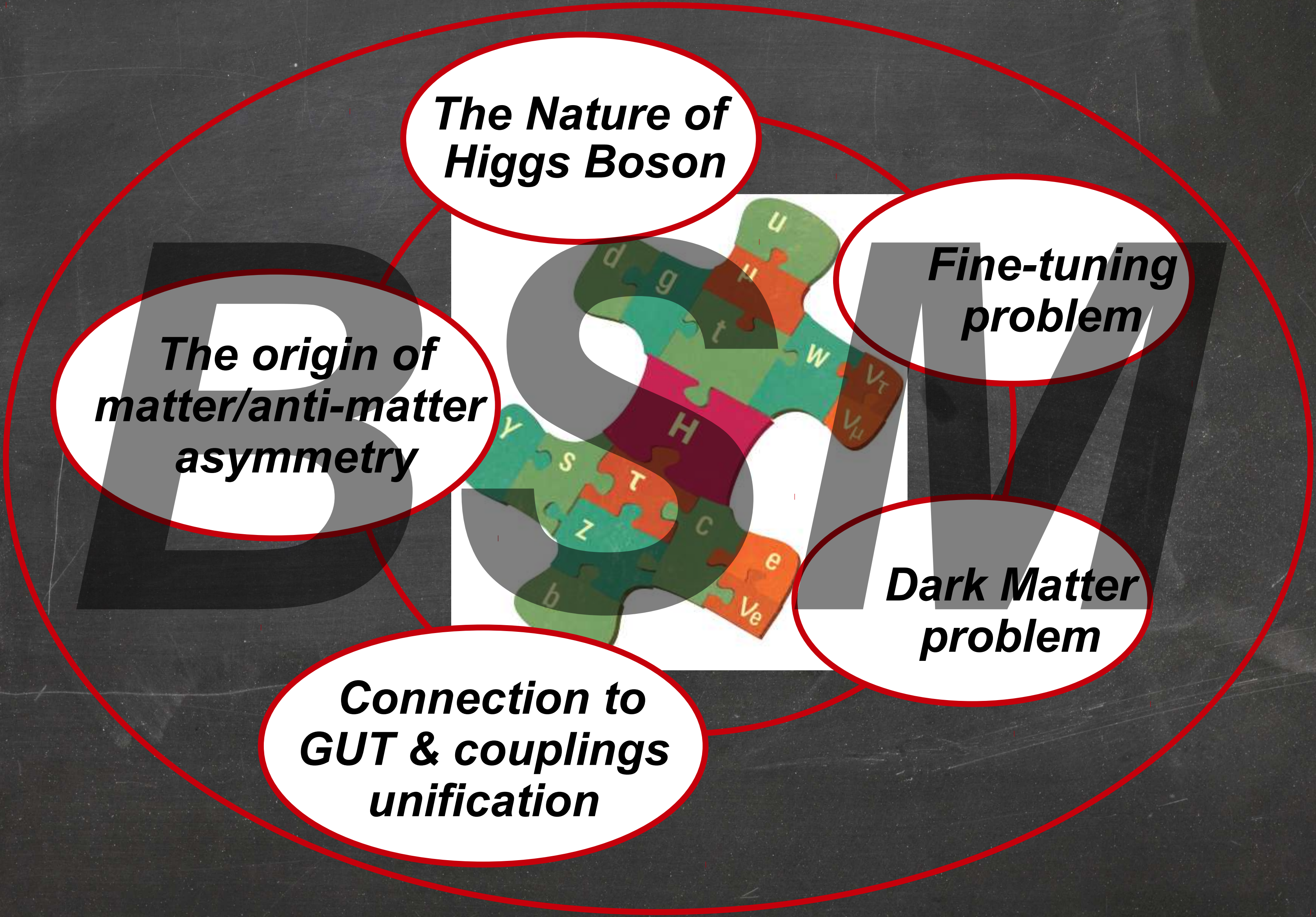
Higgs Boson Discovery has finished the SM puzzle



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



The Nature of Higgs Boson

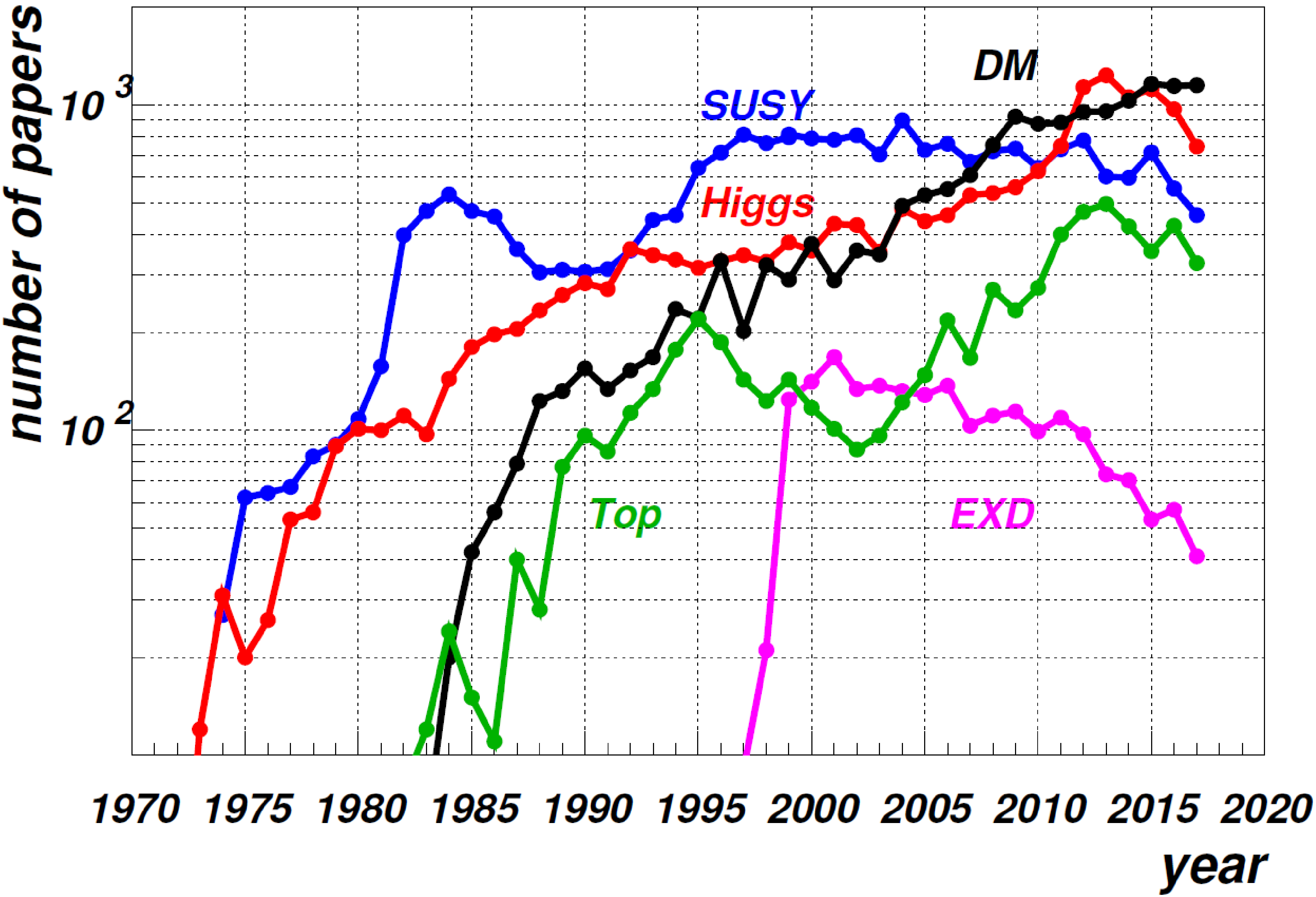
Fine-tuning problem

The origin of matter/anti-matter asymmetry

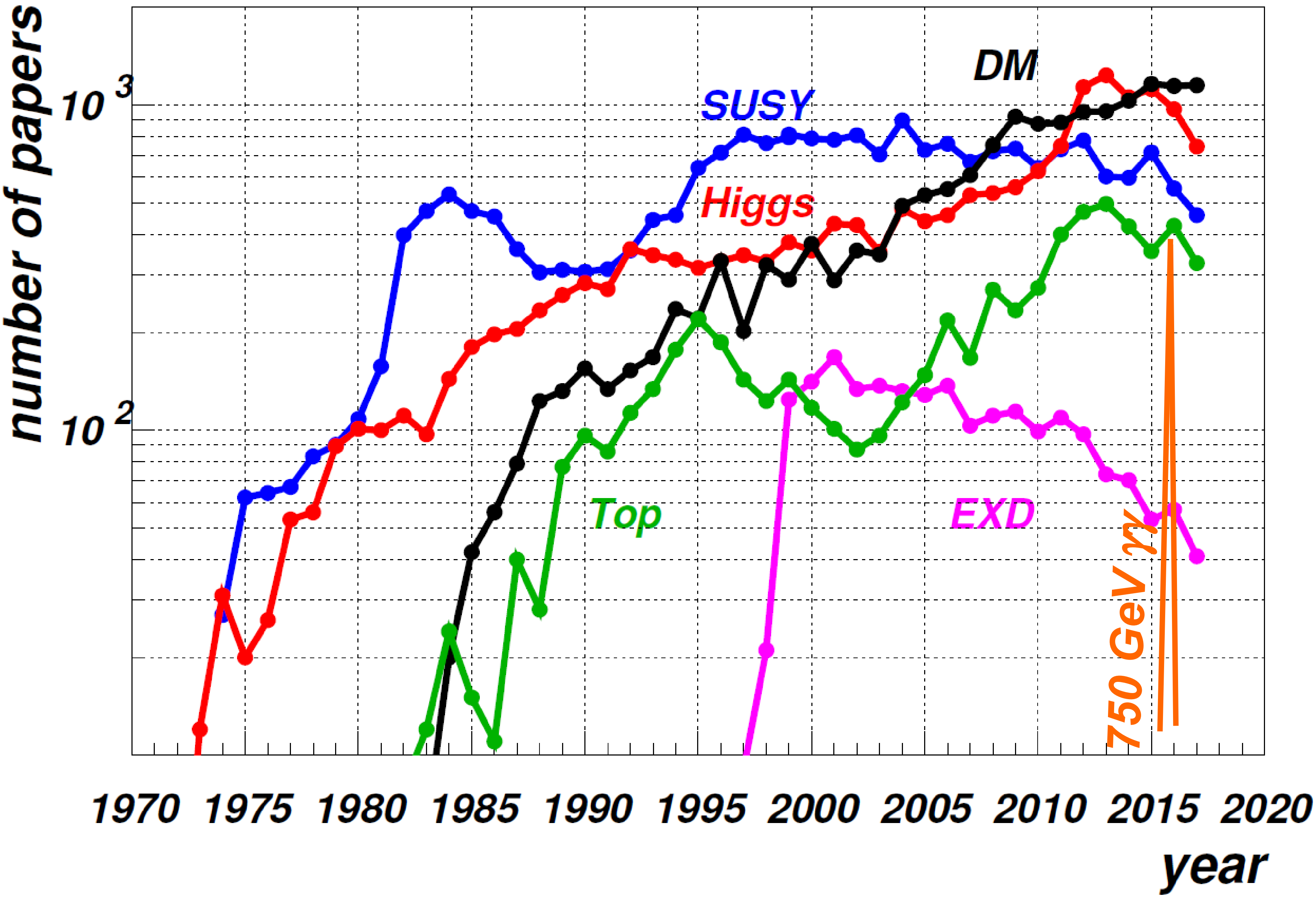
Dark Matter problem

Connection to GUT & couplings unification

Why we are so keen to study DM?



Why we are so keen to study DM?



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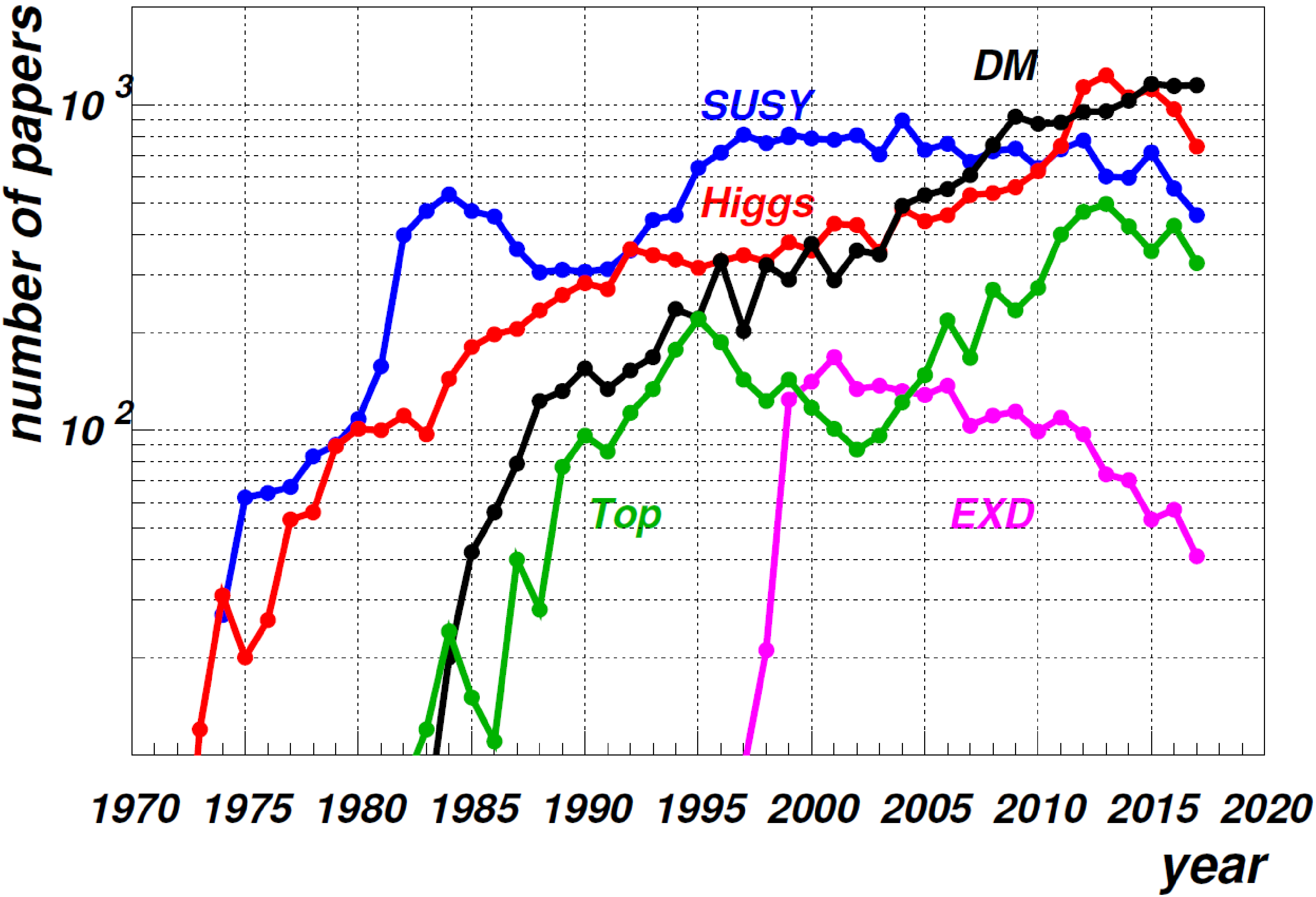
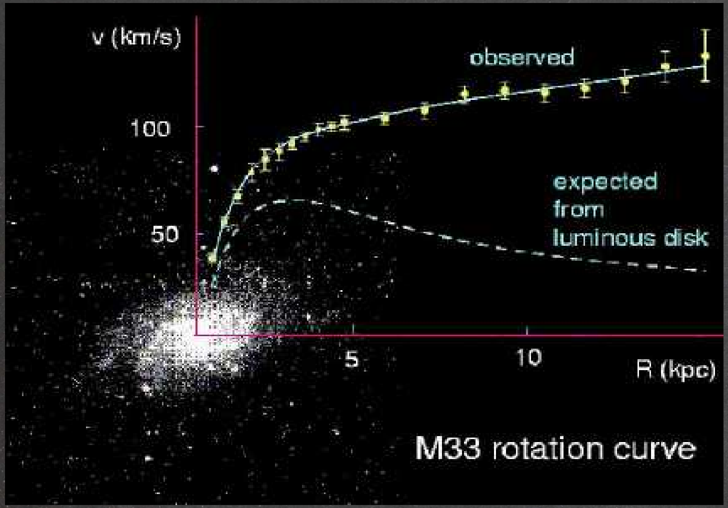
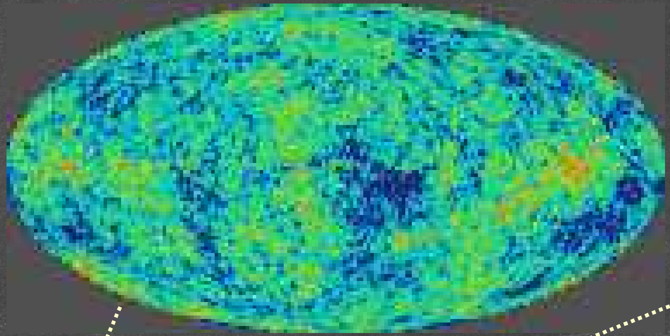


Because the existence of DM is the strongest evidence for BSM!

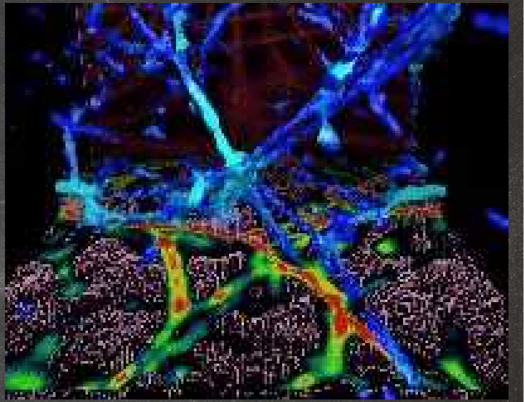
Galactic rotation curves

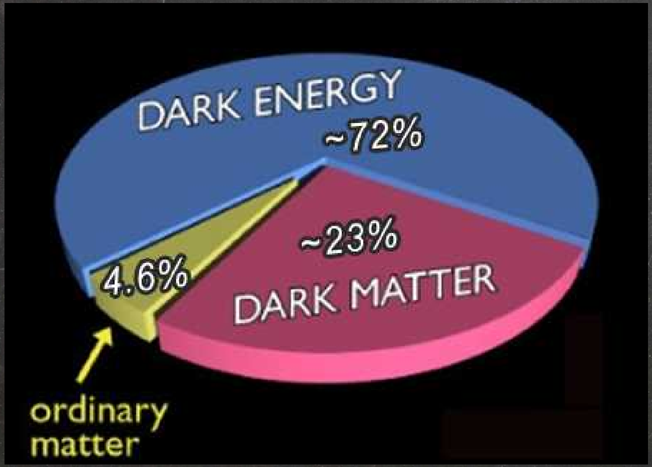


CMB: WMAP and PLANCK

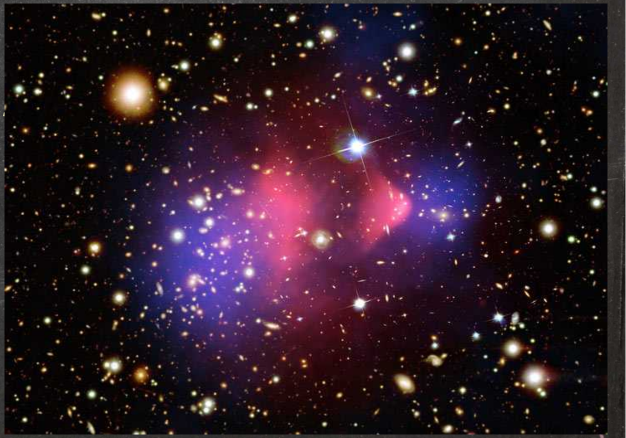


Large Scale Structures





Bullet cluster



Gravitational lensing

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 ?

What we can do to decode the fundamental nature of Dark Matter?

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We need a DM signal first!

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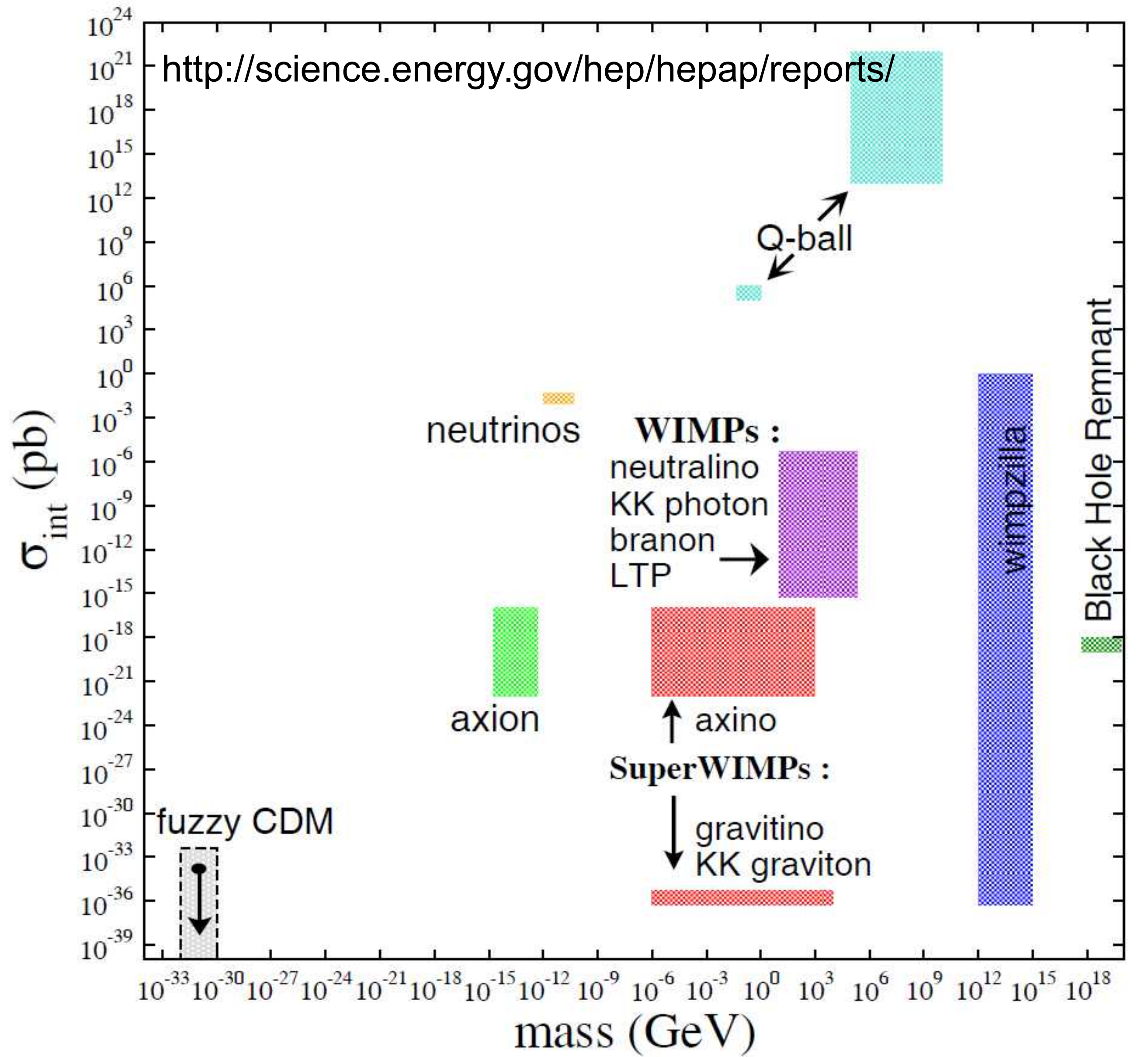
We need a DM signal first!

But In the absence of signal we can :

1) already conclude what kind of DM Is already excluded
2) explore theory space and prepare ourselves to DM discovery and DM decoding

DM candidates: interaction vs mass


http://science.energy.gov/hep/hepap/reports/

- 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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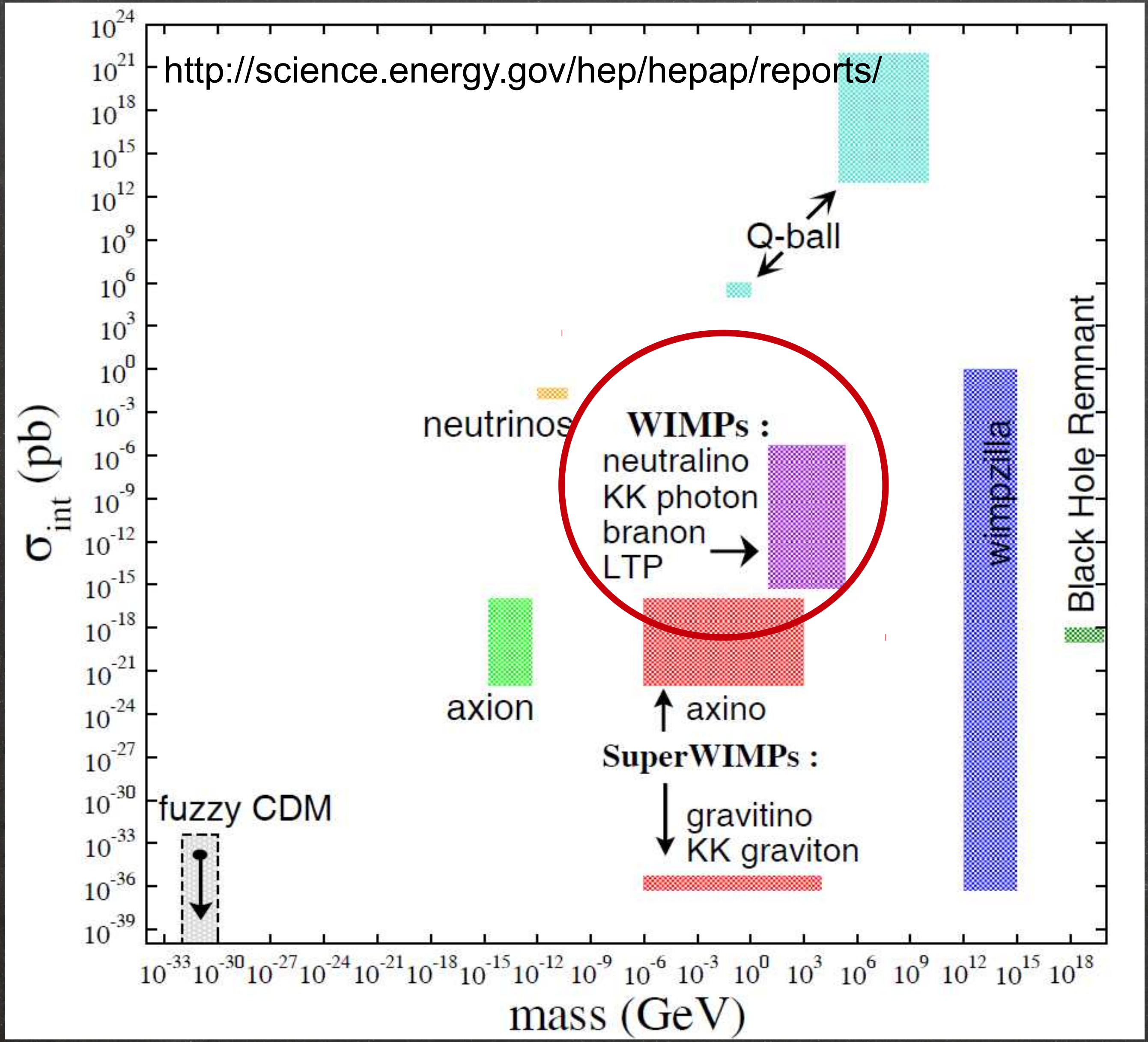
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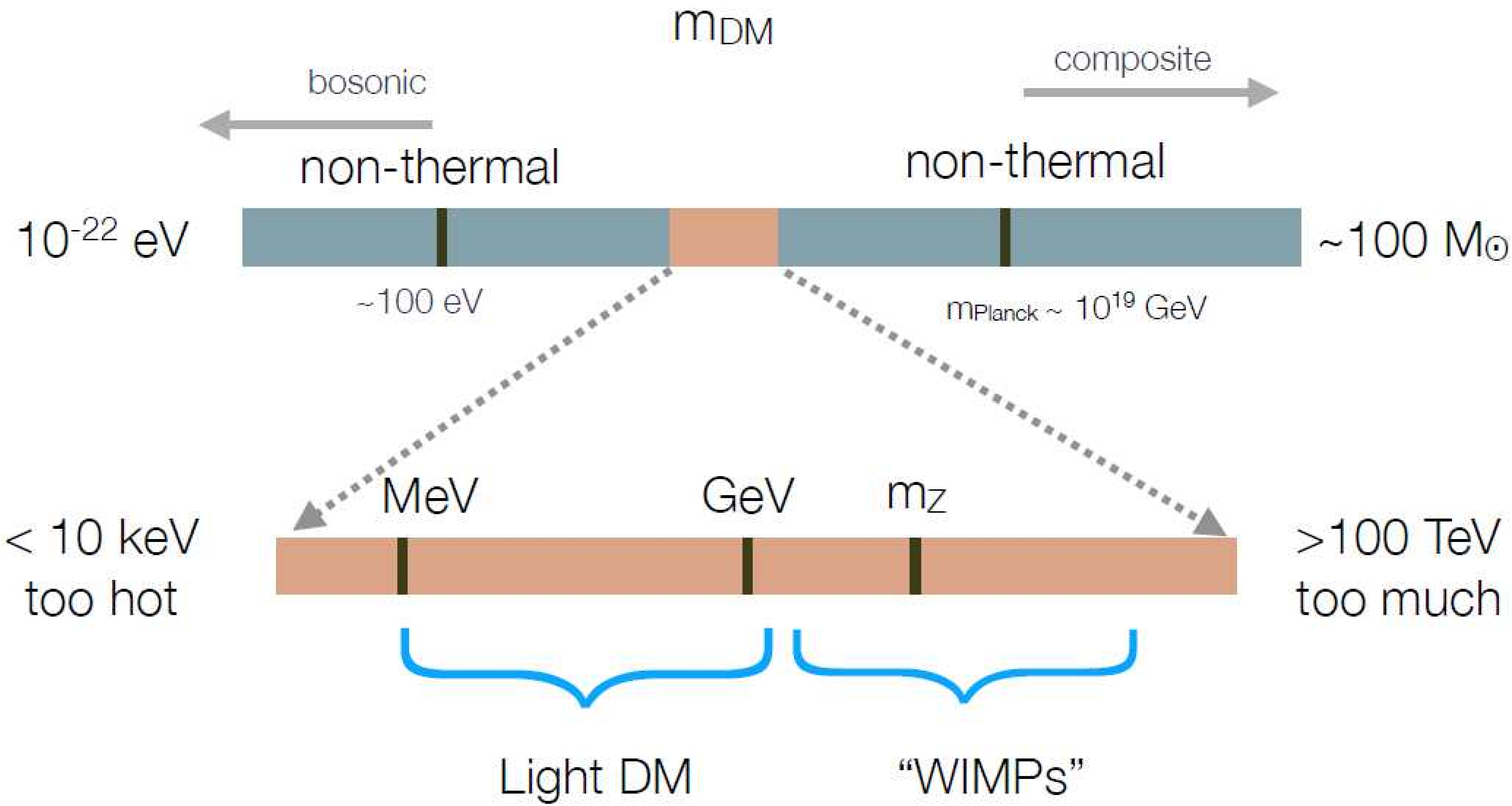
Mass range for thermal DM



m_{DM}

bosonic

composite

non-thermal

non-thermal

10^{-22} eV

~100 $M_\odot$

~100 eV

m_{Planck} ~ 10^{19} GeV

MeV

GeV

m_Z

< 10 keV

too hot

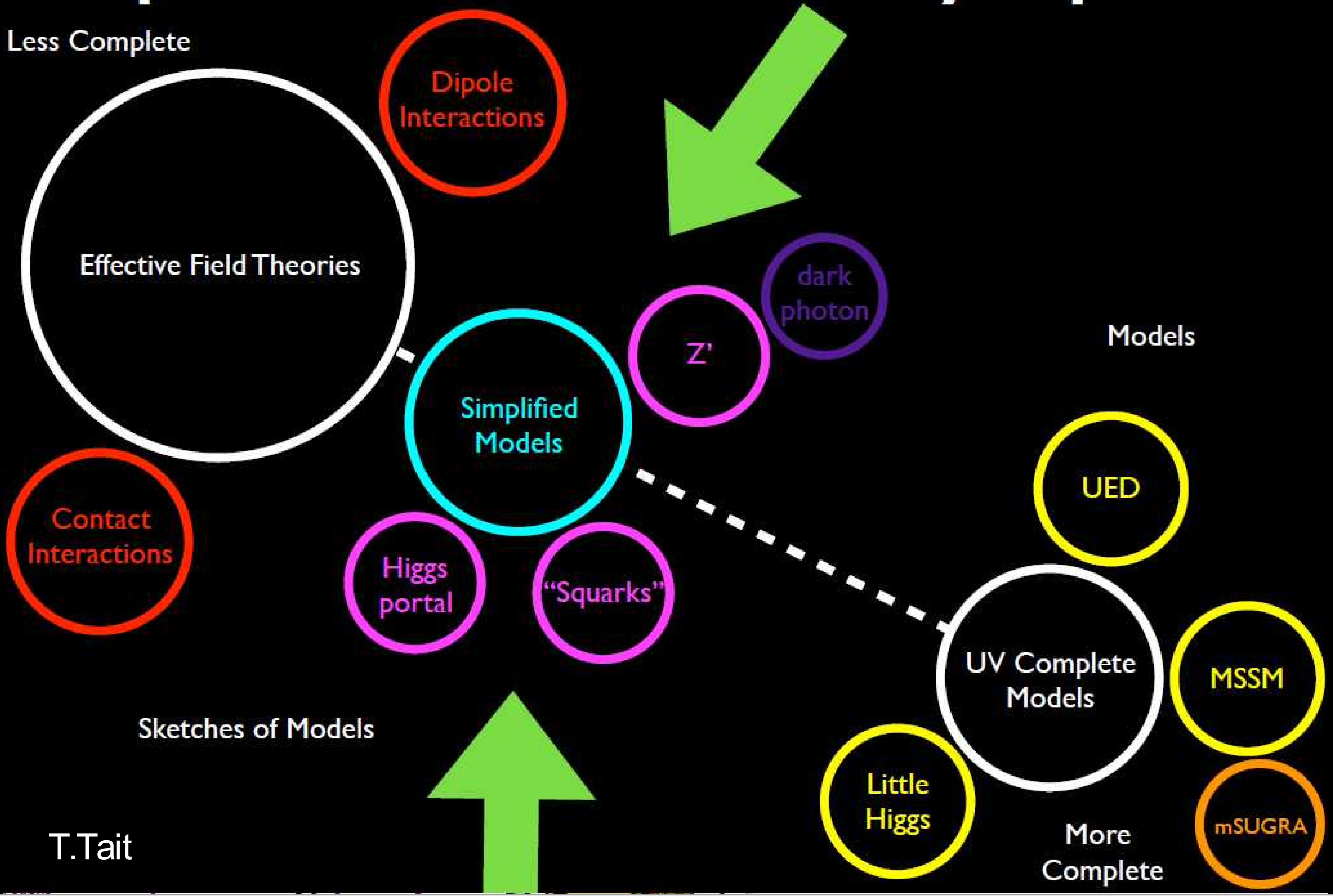
>100 TeV

too much

Light DM

"WIMPs"

Spectrum of Theory Space



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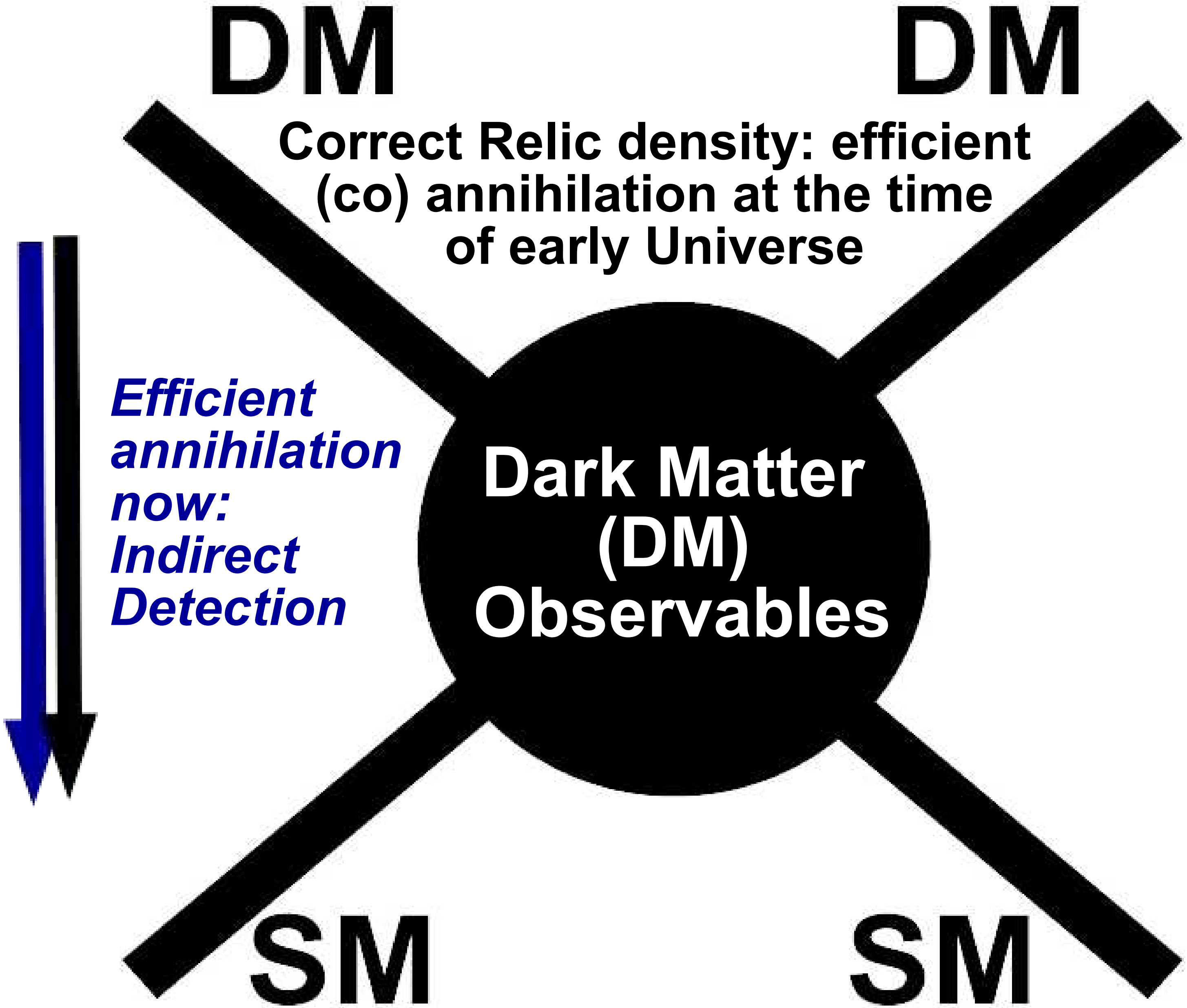


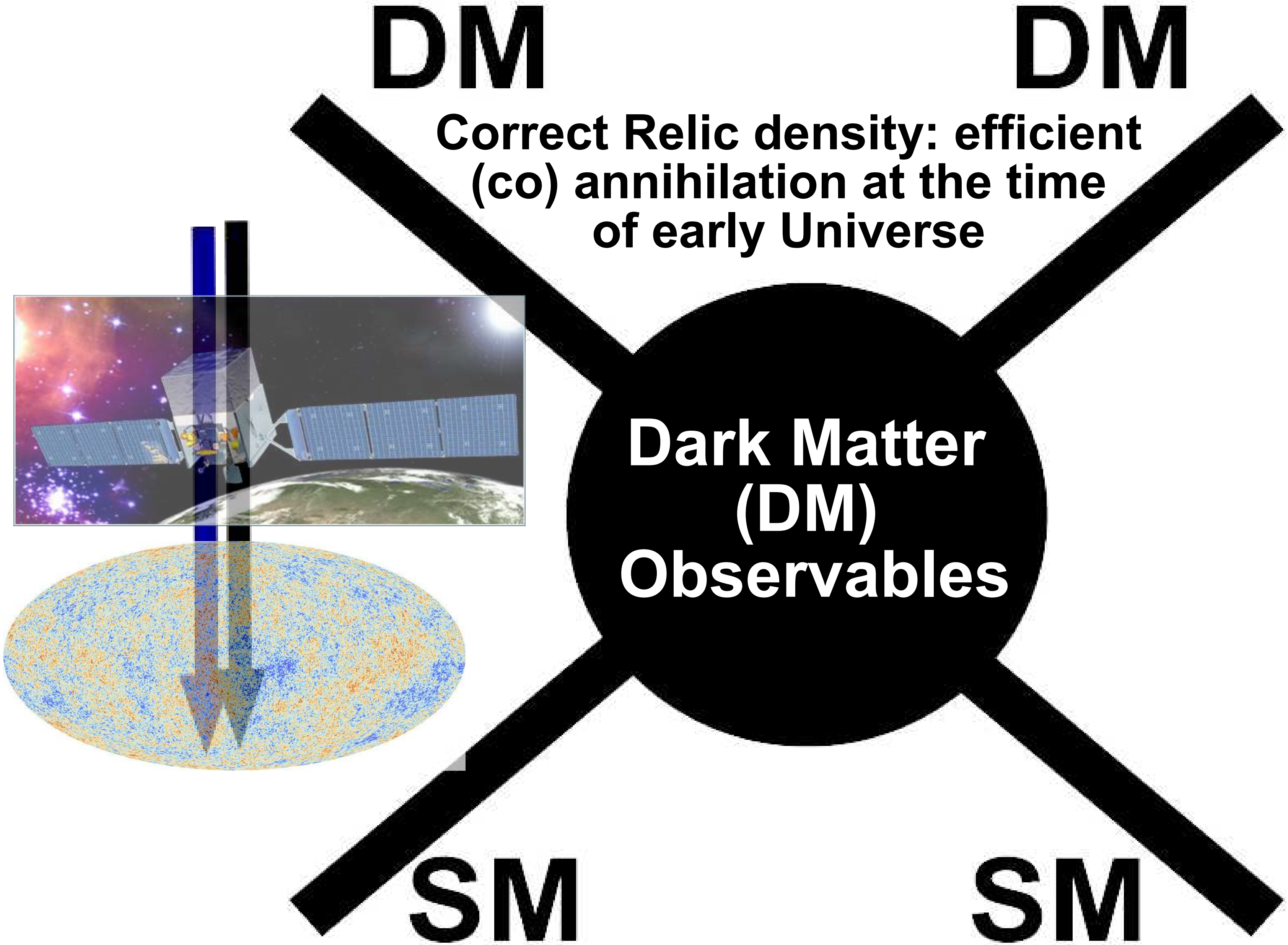
DM **DM**

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

Efficient annihilation now: Indirect Detection

Dark Matter (DM) Observables

SM **SM**



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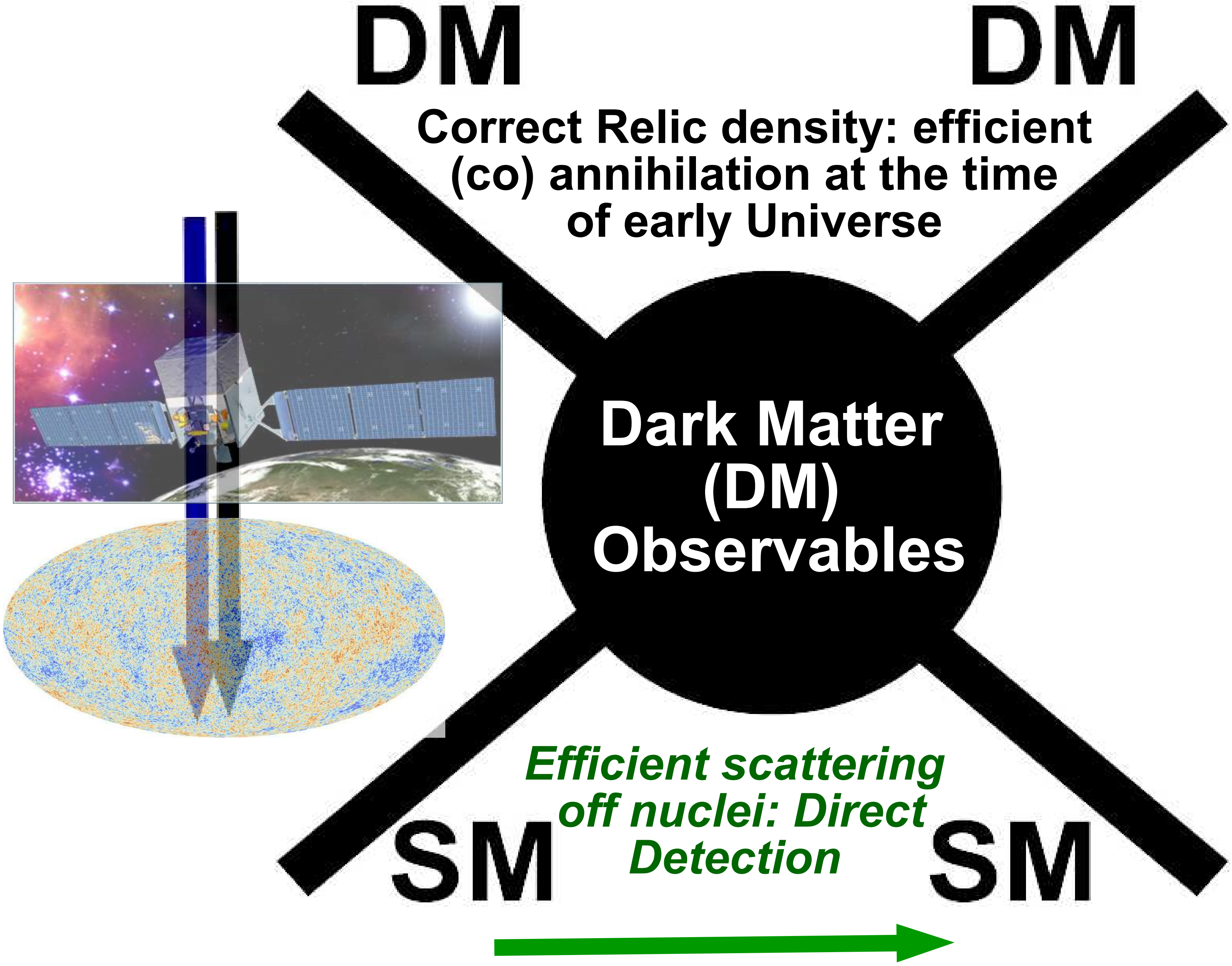

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Dark Matter (DM) Observables

Efficient scattering off nuclei: Direct Detection

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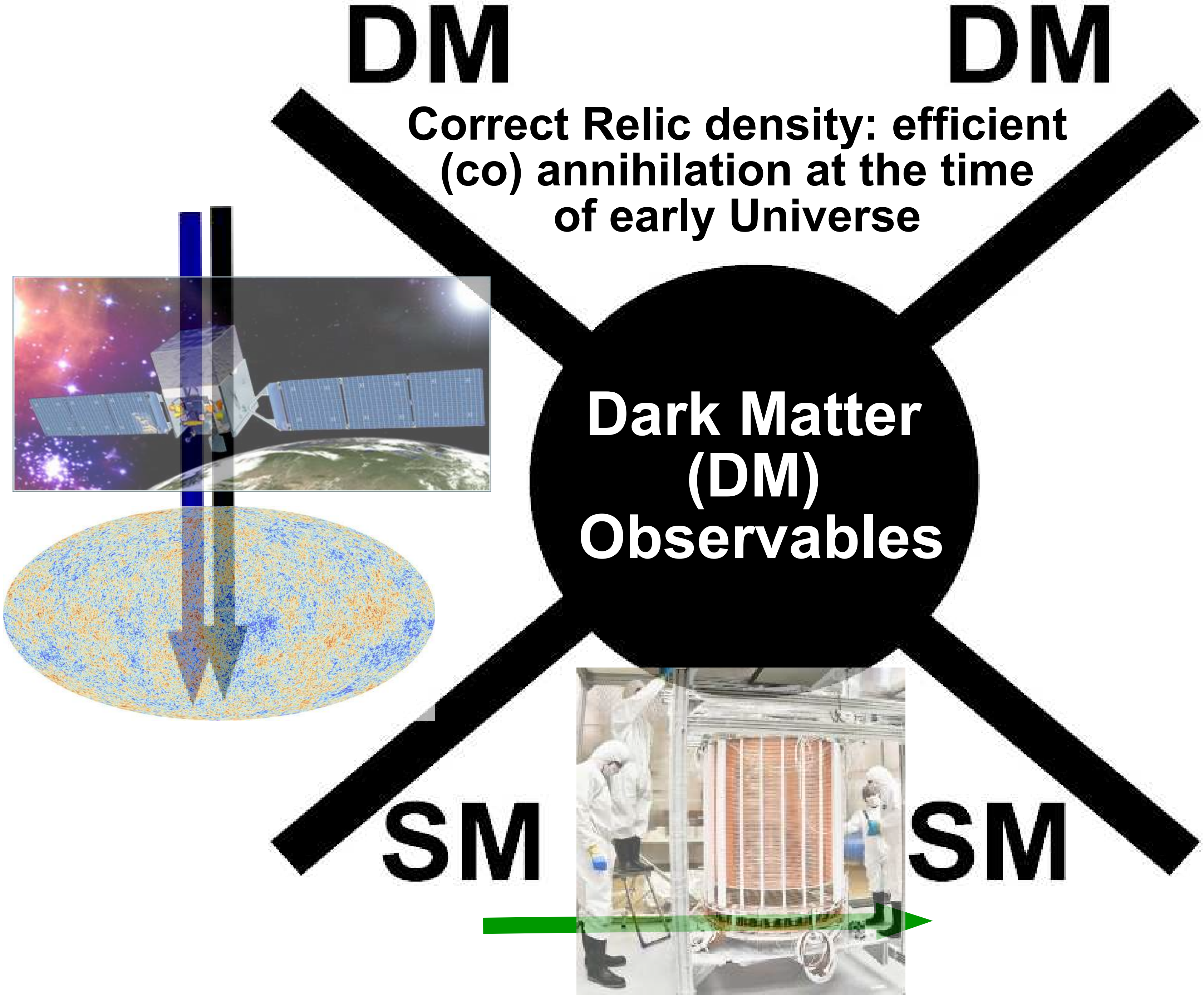

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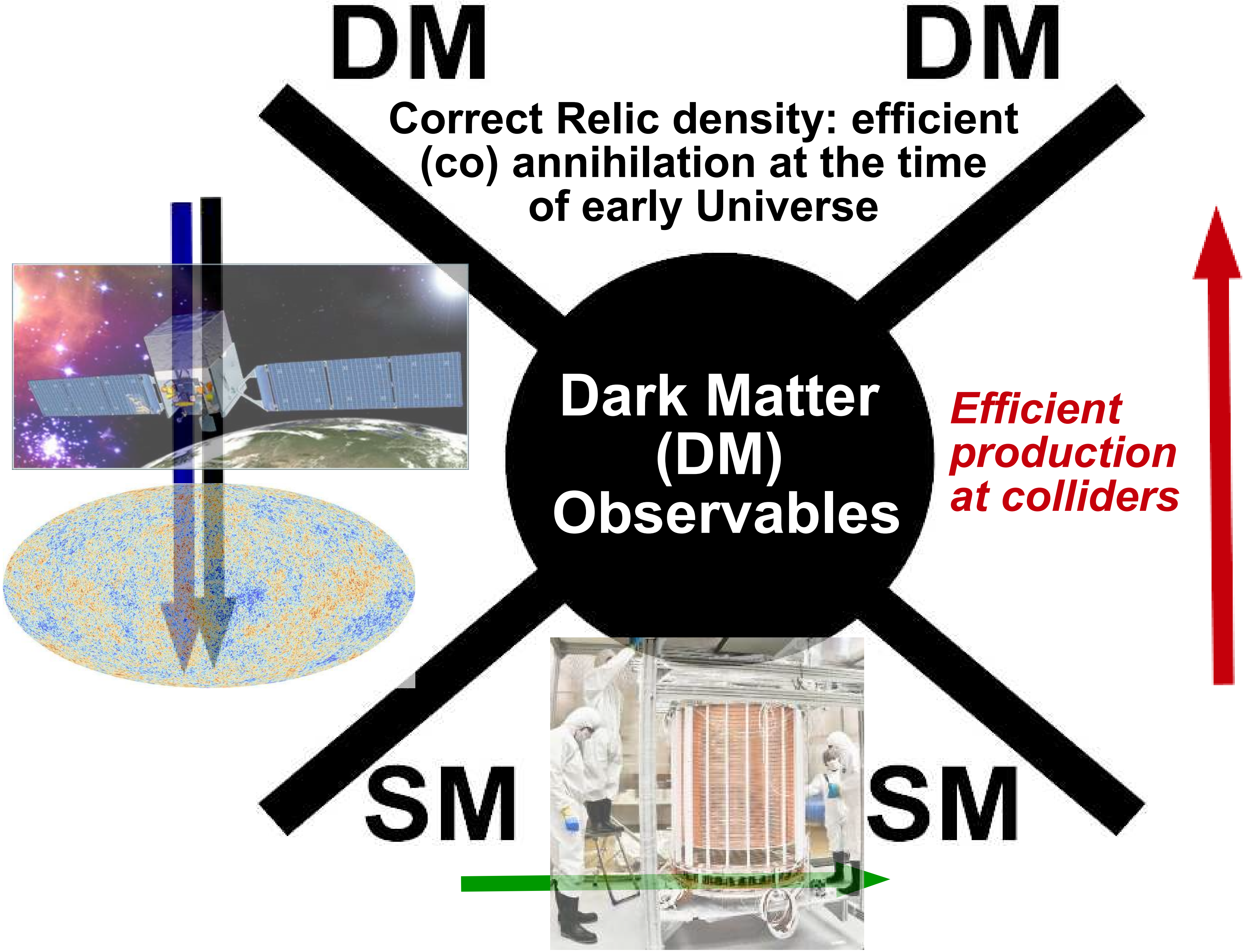

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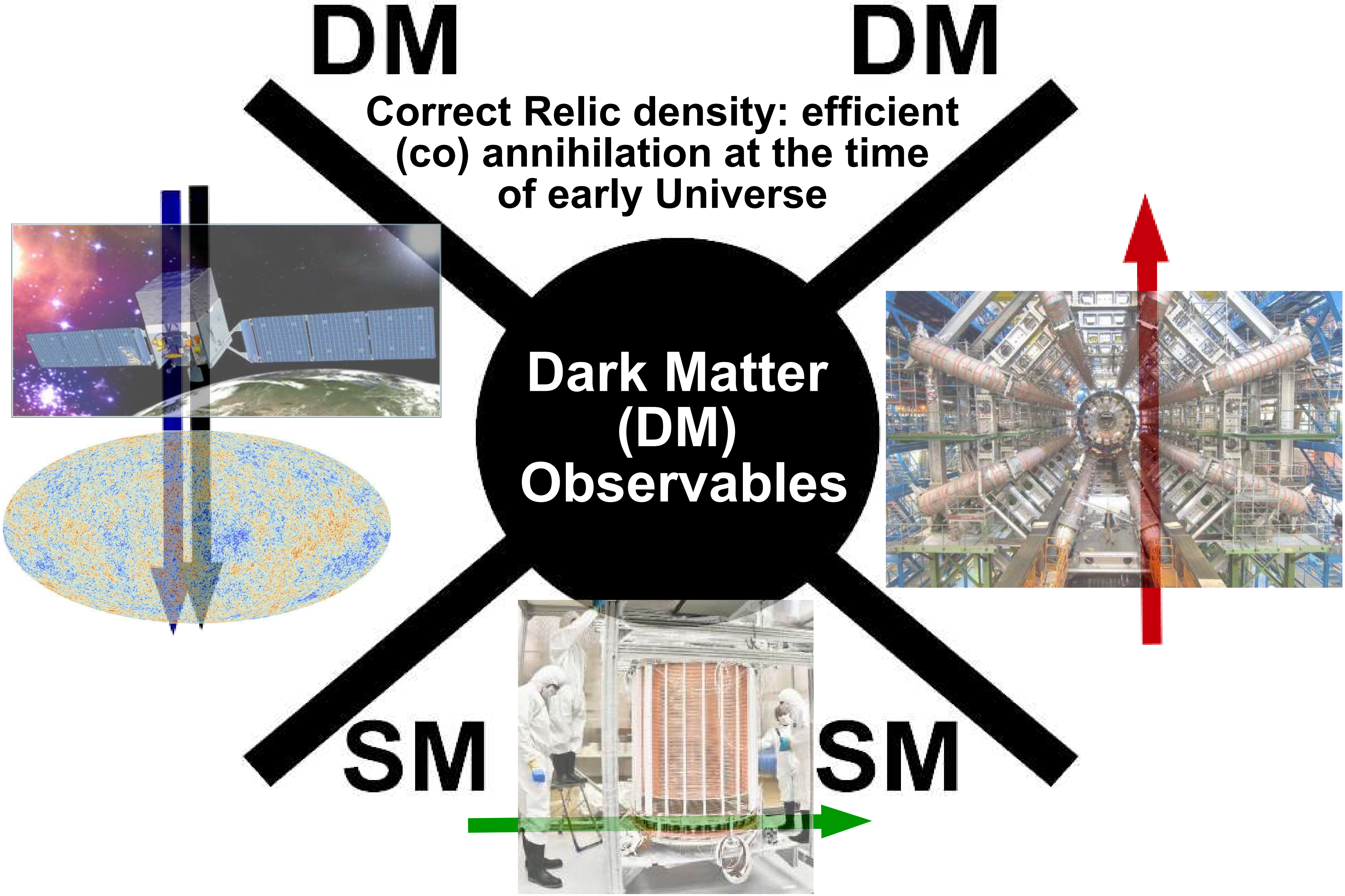
Dark Matter (DM) Observables

Efficient production at colliders



DM DM

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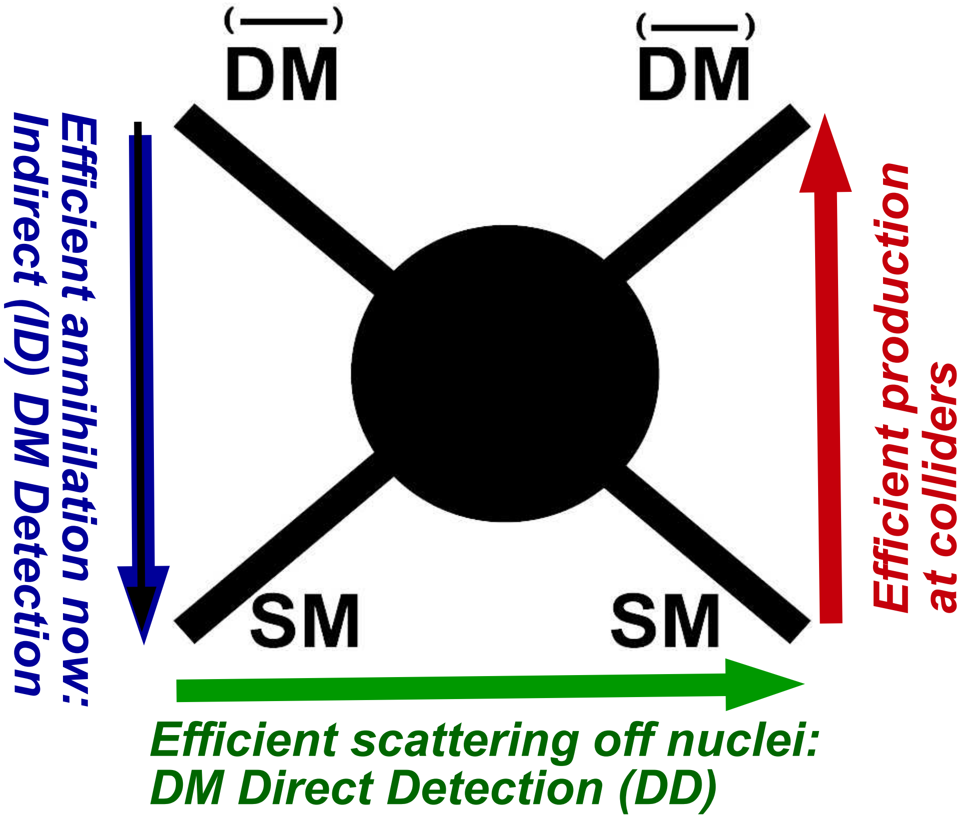
Dark Matter (DM) Observables

SM SM

Complementarity of DM searches



Efficient annihilation now:
Indirect (ID) DM Detection

Efficient production
at colliders

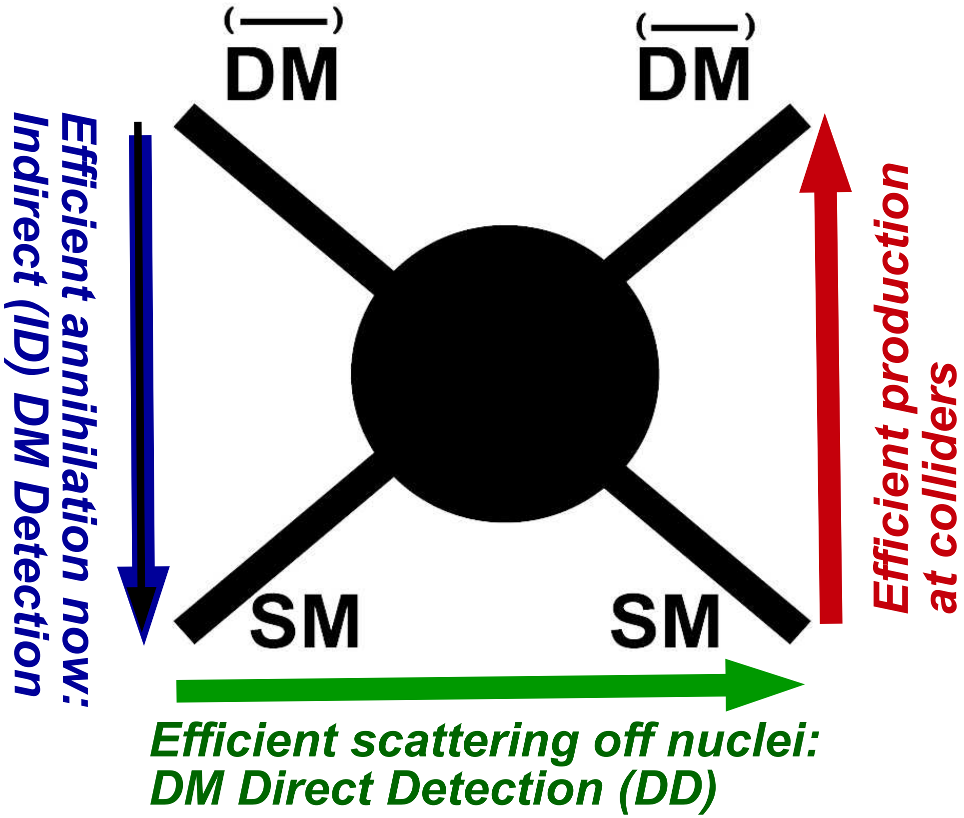
Efficient scattering off nuclei:
DM Direct Detection (DD)

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



(—) DM

(—) DM

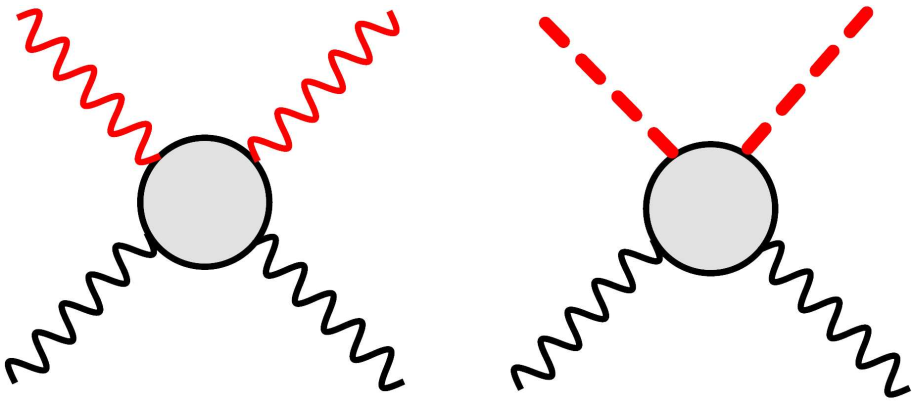
SM

SM

Efficient annihilation now: Indirect (ID) DM Detection

Efficient production at colliders

Efficient scattering off nuclei: DM Direct Detection (DD)



Example of DM interactions with

negligible/suppressed DD rates

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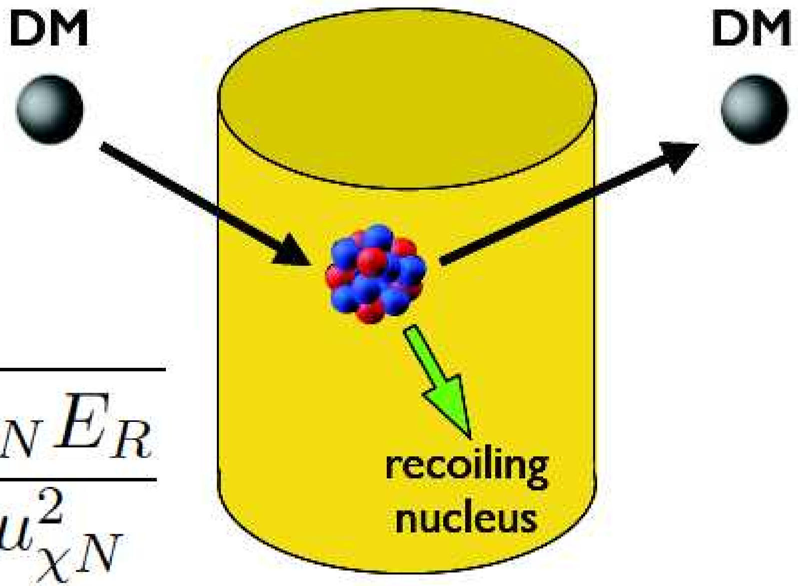
Direct Dark Matter Detection

- 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

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

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

astrophysics

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

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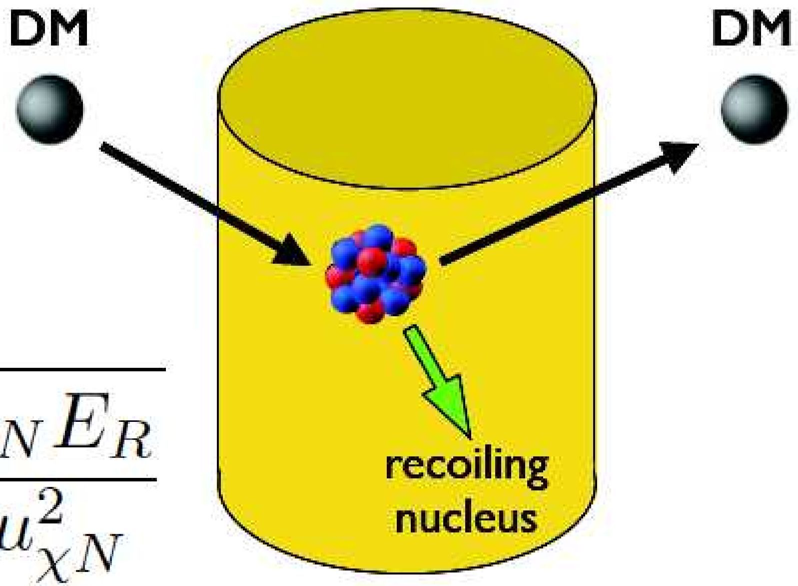

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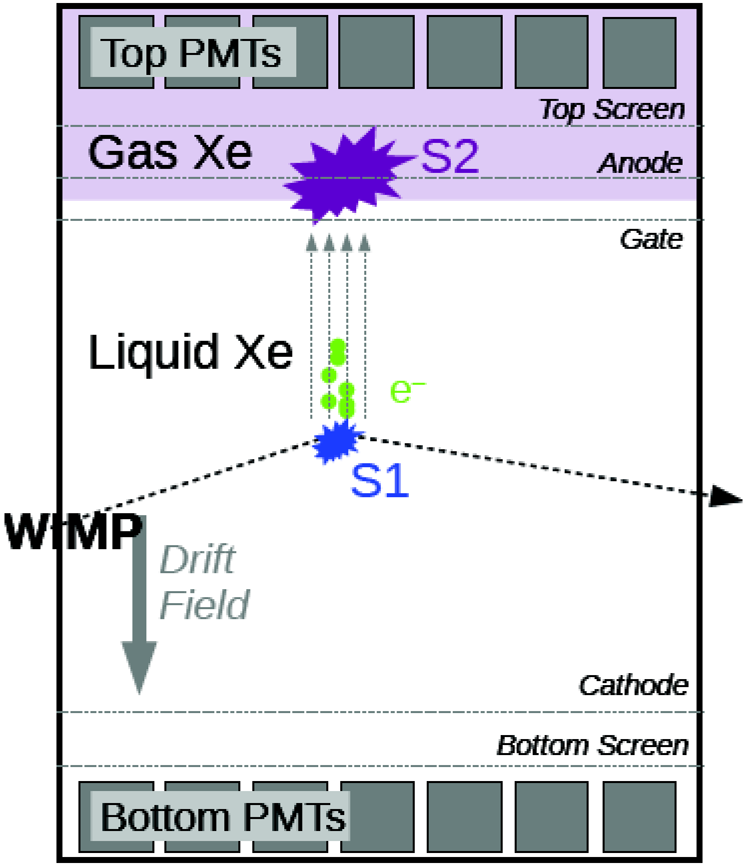
halo integral

particle physics

DM DD experiments

XENON 1T detector as an example

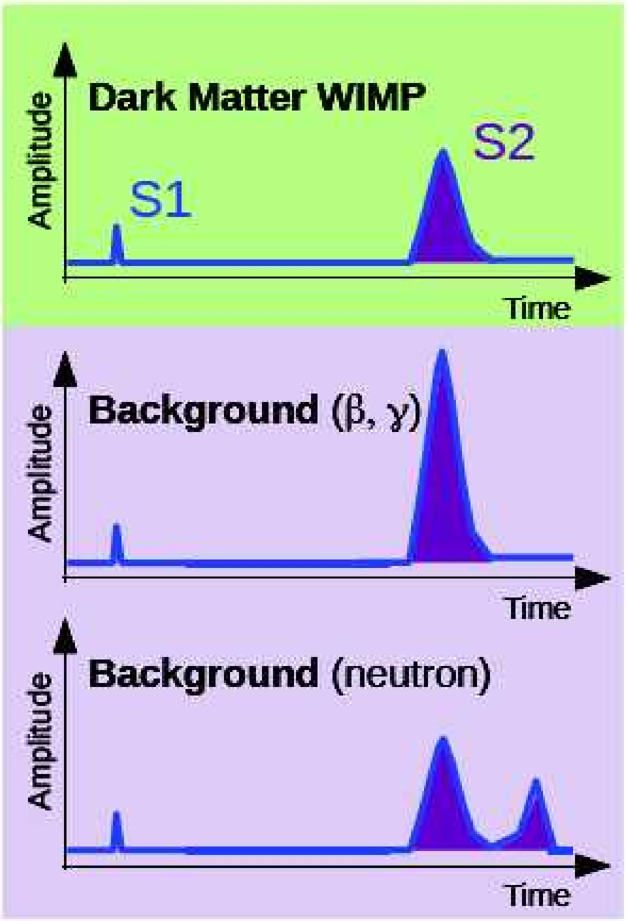


- using a target of 2 tonnes of liquid Xenon
- shielded by rock equivalent to 3.6 km water at the LNGS

Two-phase time-projection chamber

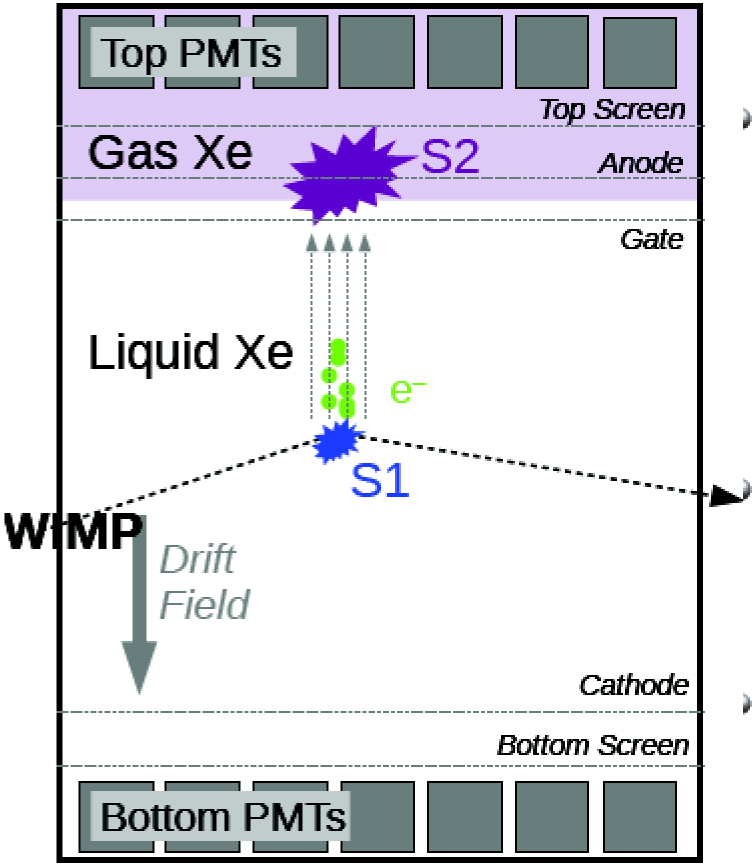
- Xenon atoms will emit scintillation light (S1), as well as free electrons
- Electrons drift at a known speed in an electric field, until they are accelerated at the top of the detector in the gas phase, producing an amplified scintillation (S2)
- Photomultipliers at the top and bottom of the time projection chamber (TPC) detect both the first (S1) and second (S2) flashes

XENON 1T detector as an example



- The S2/S1 size ratio allows for discrimination between nuclear recoils from WIMPs or neutrons and electronic recoils from β or γ

XENON 1T detector as an example



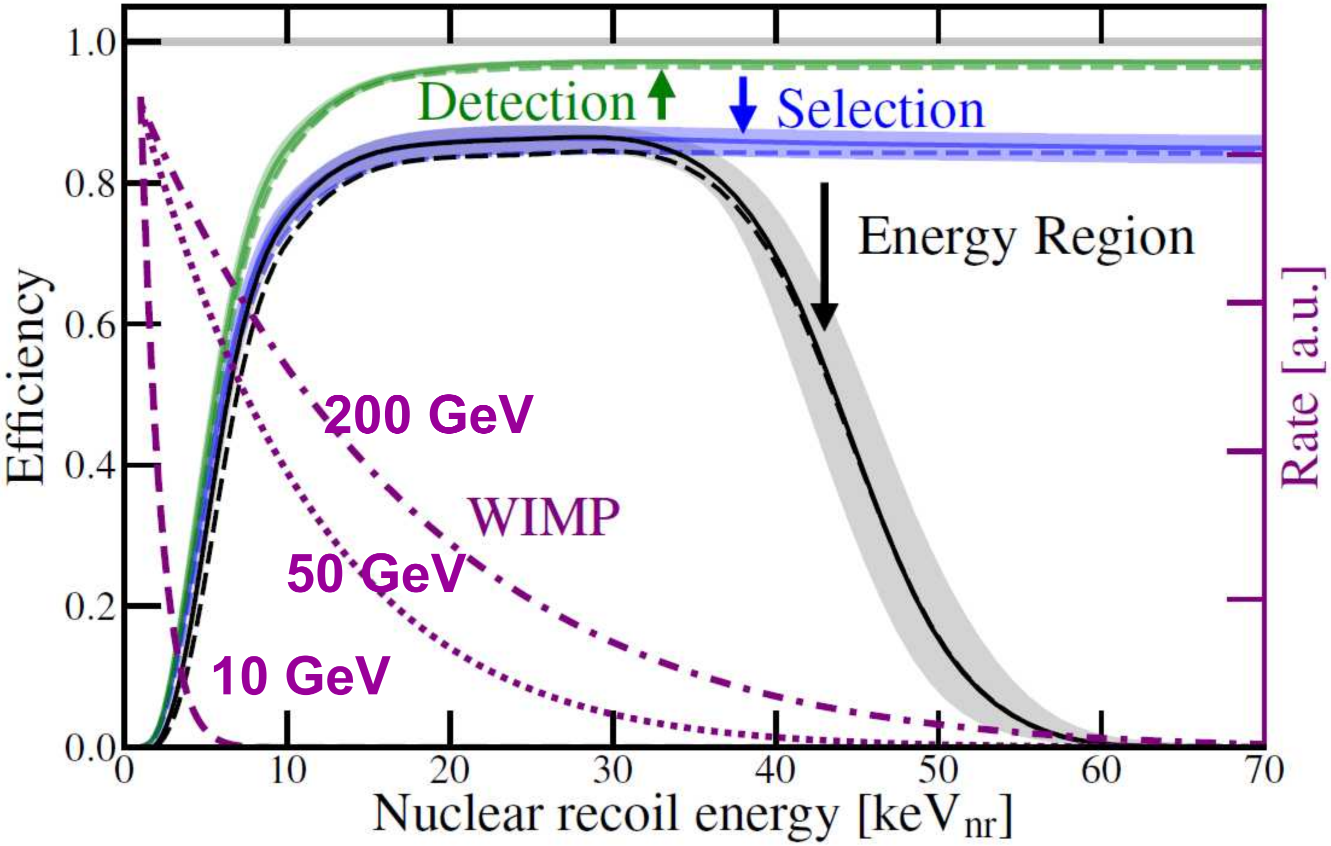
- The S2/S1 size ratio allows for discrimination between nuclear recoils from WIMPs or neutrons and electronic recoils from β or γ

- The time delay between S1 and S2 → the vertical position of the interaction

- The localization of the S2 pattern in the top PMT array → horizontal position of the interaction

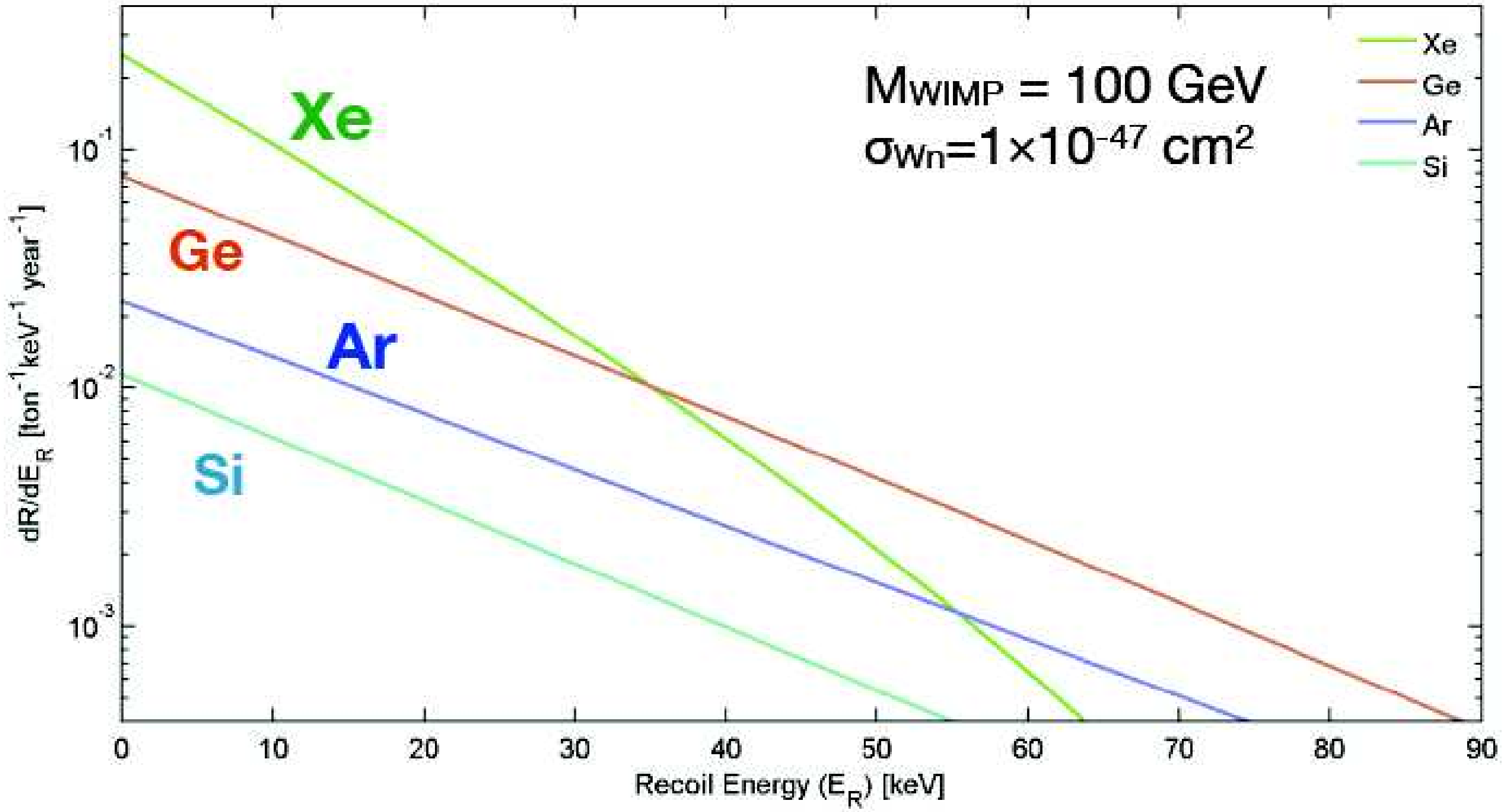
XENON 1T results

arXiv:1805.12562



- The efficiency of S1 detection - green
- S1 detection and selection - blue

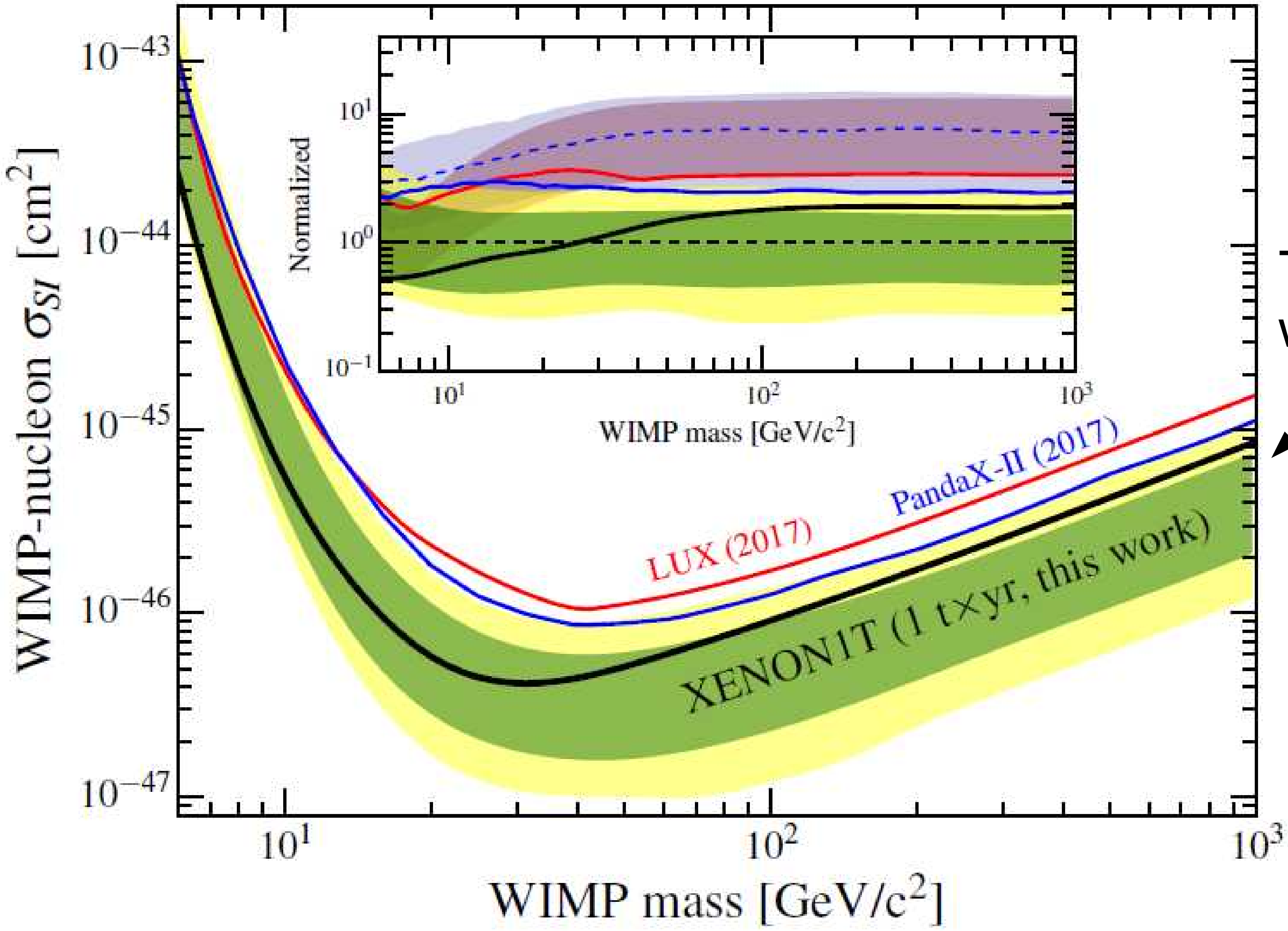
Expected nuclear recoil spectrum



- Spin Independent (SI) and Spin Dependent (SD) [PandaX-II] rates come from coherent scattering
- SI : protons and neutrons contribute to amplitude with the same sing
- SD : the is a compensation of contributions of coupled nucleons (nucleons with opposite spin which occupy the same energy level)
- **SI amplitude is proportional to A^2, SD one – to nuclei spin J**

XENON 1T results

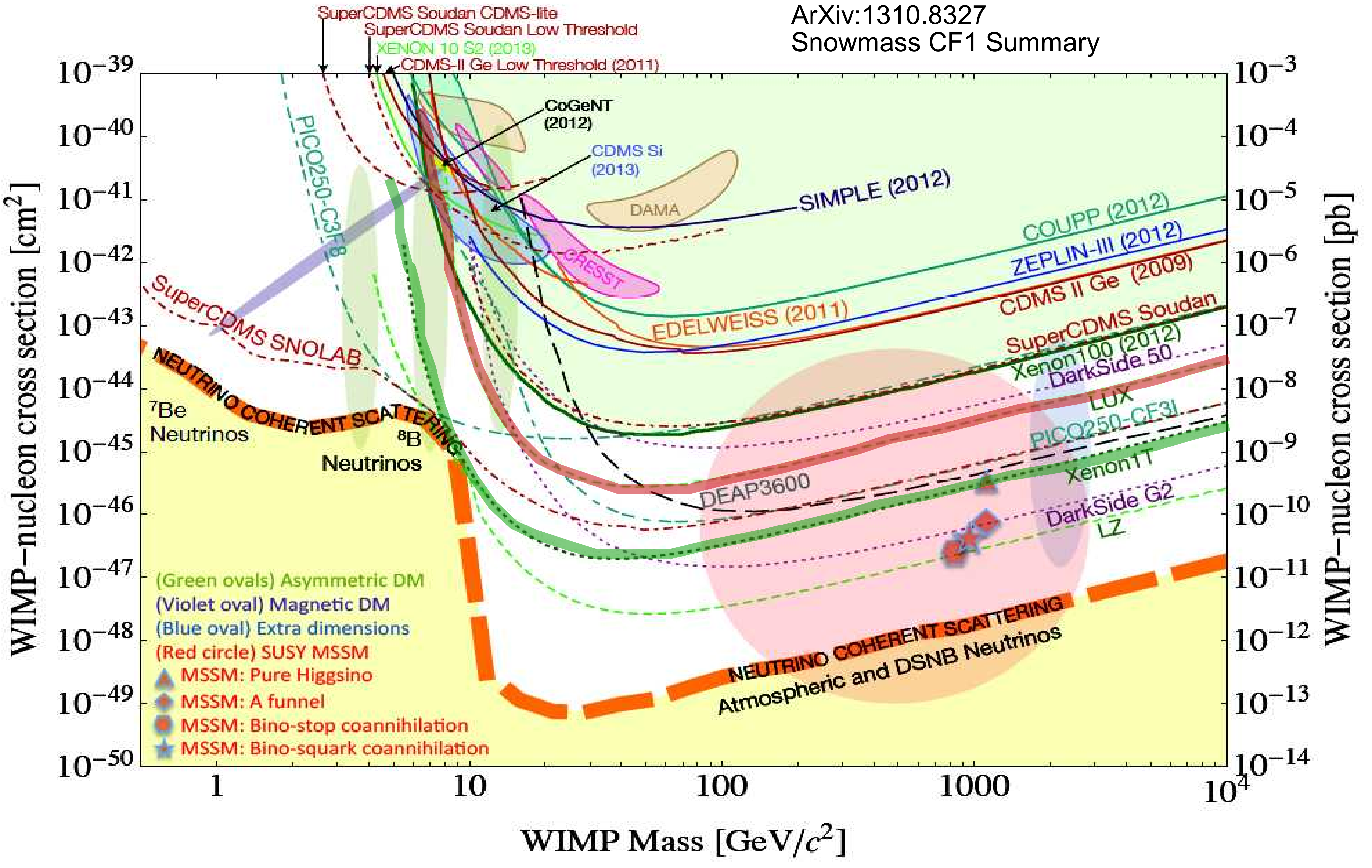
arXiv:1805.12562



The limit scales with M_{DM}

Power of DM DD to rule out theory space

ArXiv:1310.8327
Snowmass CF1 Summary

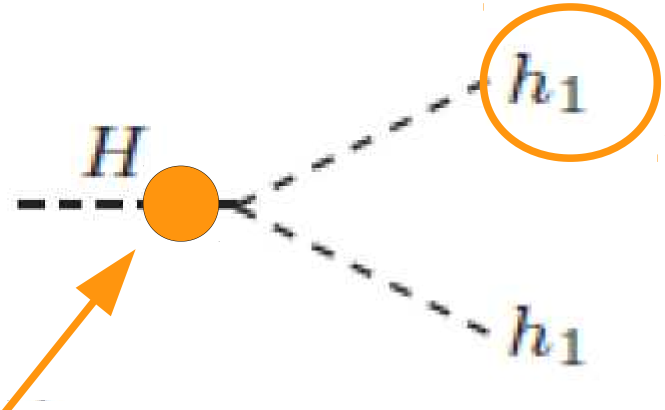


Power of DM DD to rule out theory space

Inert 2 Higgs Doublet Model

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

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



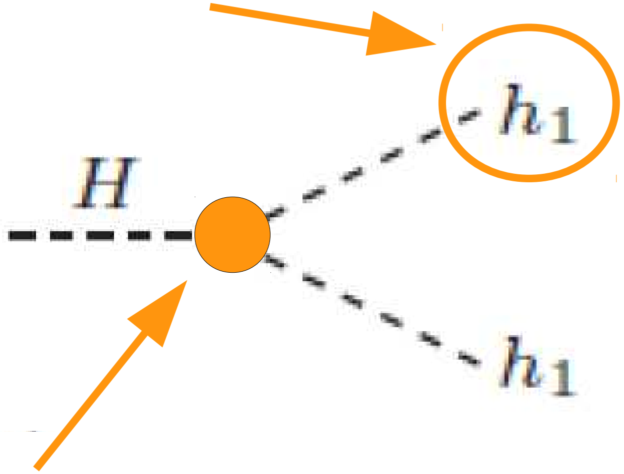
scalar DM

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

Power of DM DD to rule out theory space

Inert 2 Higgs Doublet Model

scalar DM



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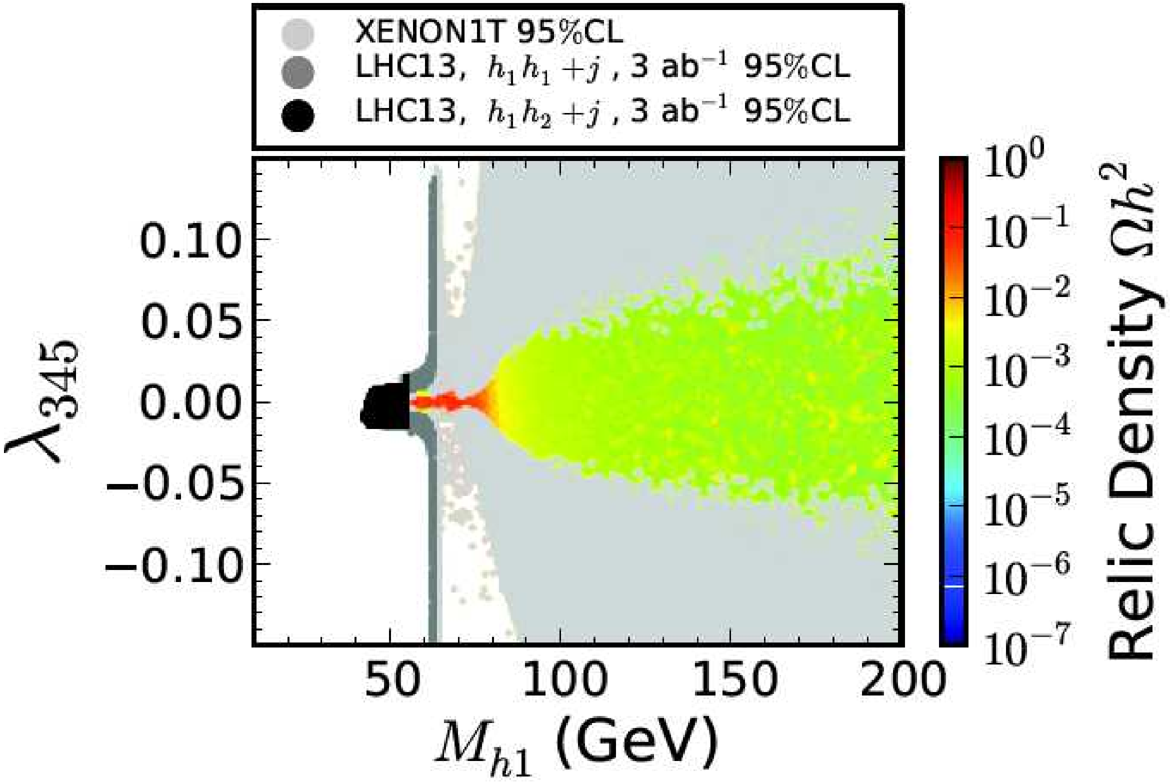


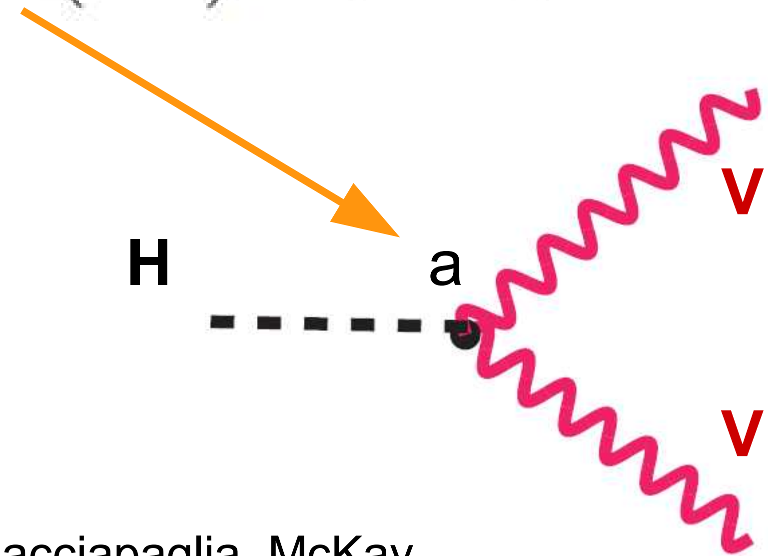
AB, G. Cacciapaglia, I. Ivanov, F. Rojas, M. Thomas, PRD 2017

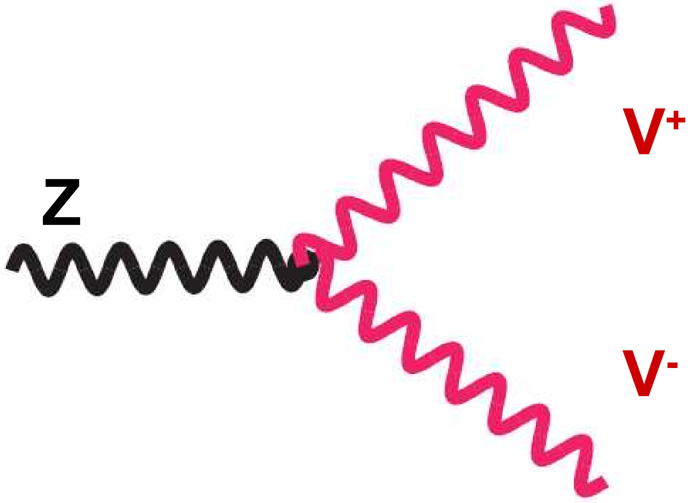
Power of DM DD to rule out theory space

Vector DM Model

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

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

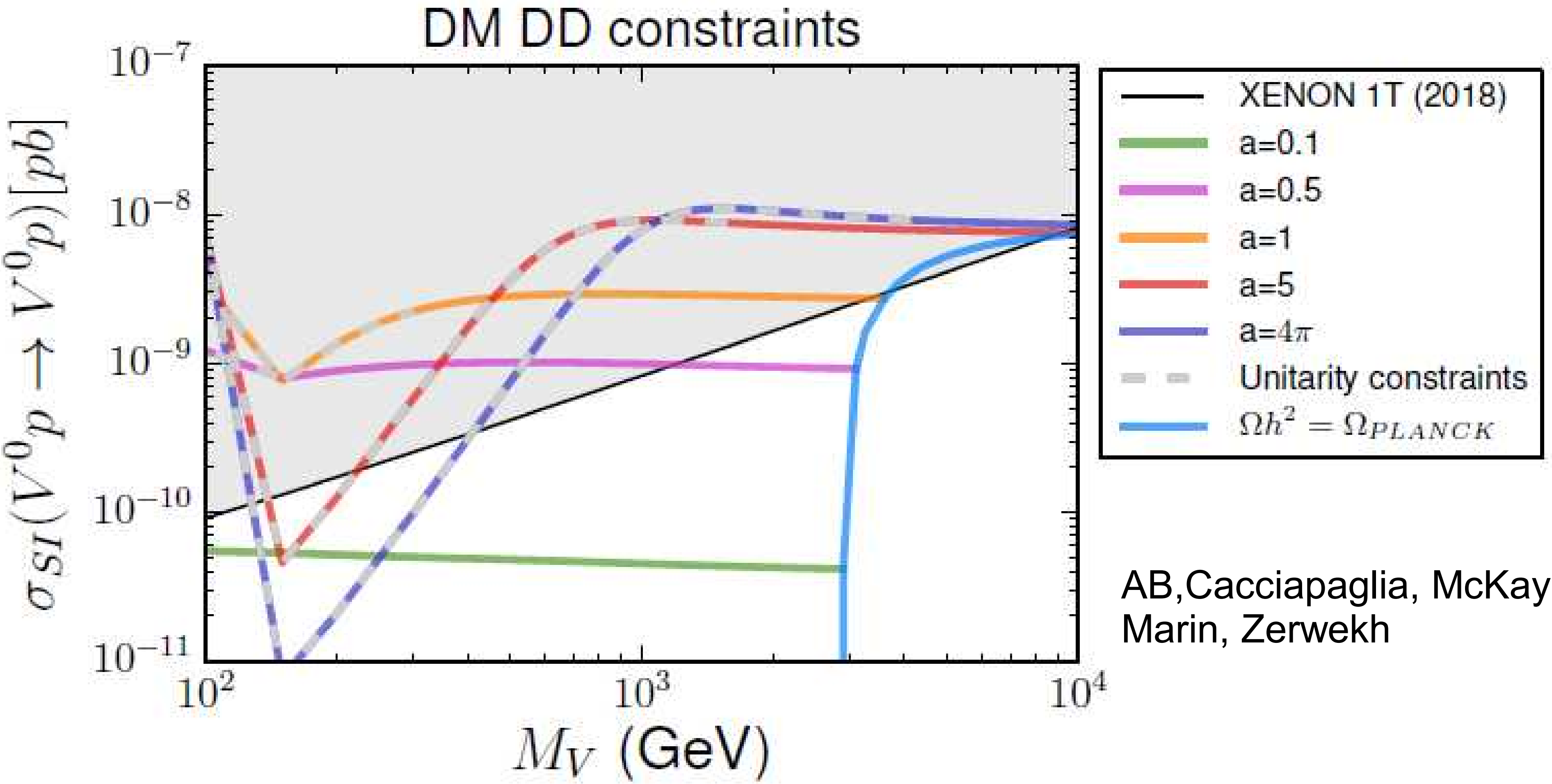




AB,Cacciapaglia, McKay,
Marin, Zerwekh

Power of DM DD to rule out theory space

Vector DM Model



AB,Cacciapaglia, McKay, Marin, Zerwekh

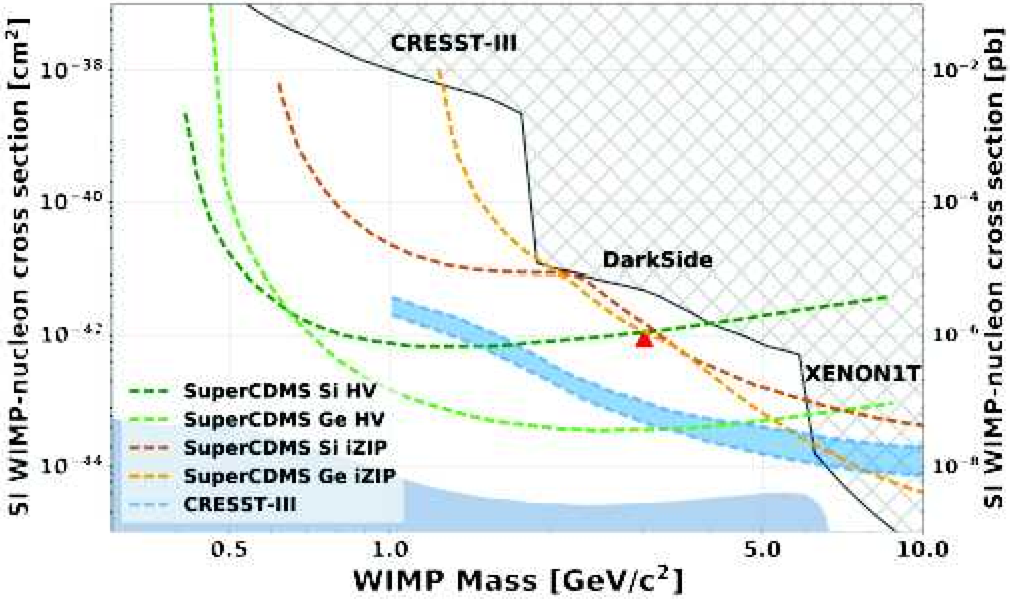
- ZENON 1T excludes **both** large $HV_{DM}V_{DM}$ couplings and large M_{DM}
- The **rest** of the parameter space can be covered at future colliders

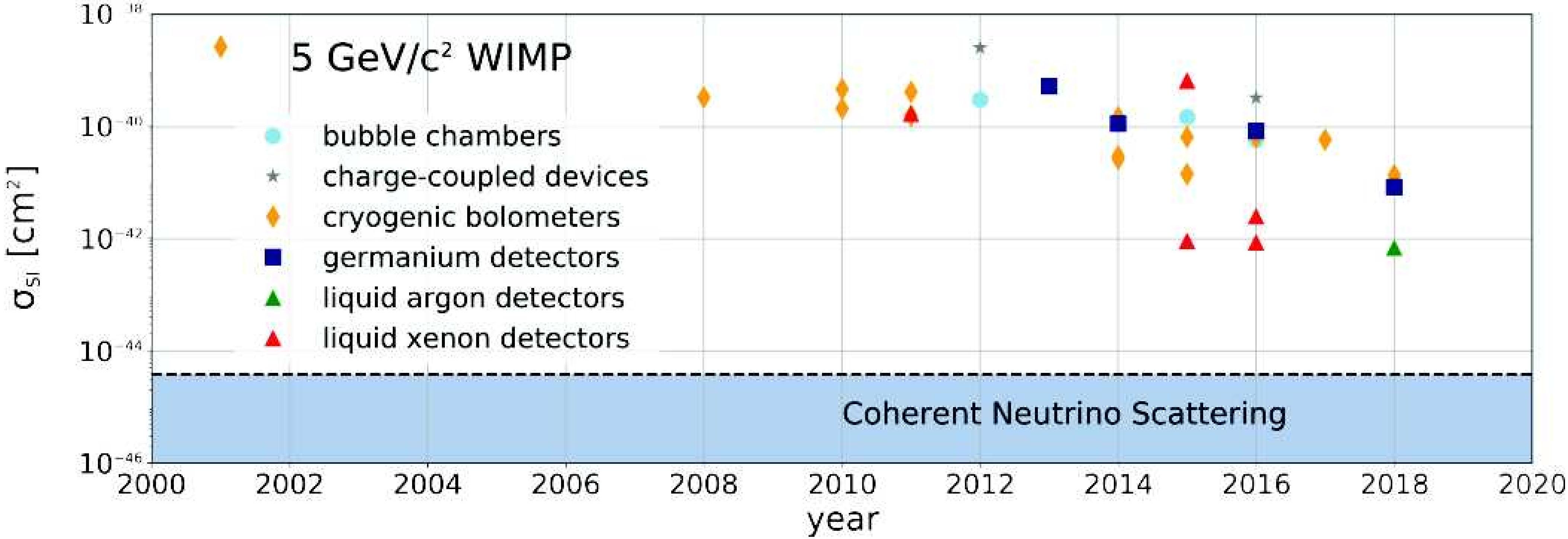
Power of DM DD to rule out theory space

- DM Interaction with SM particles is very limited
- 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

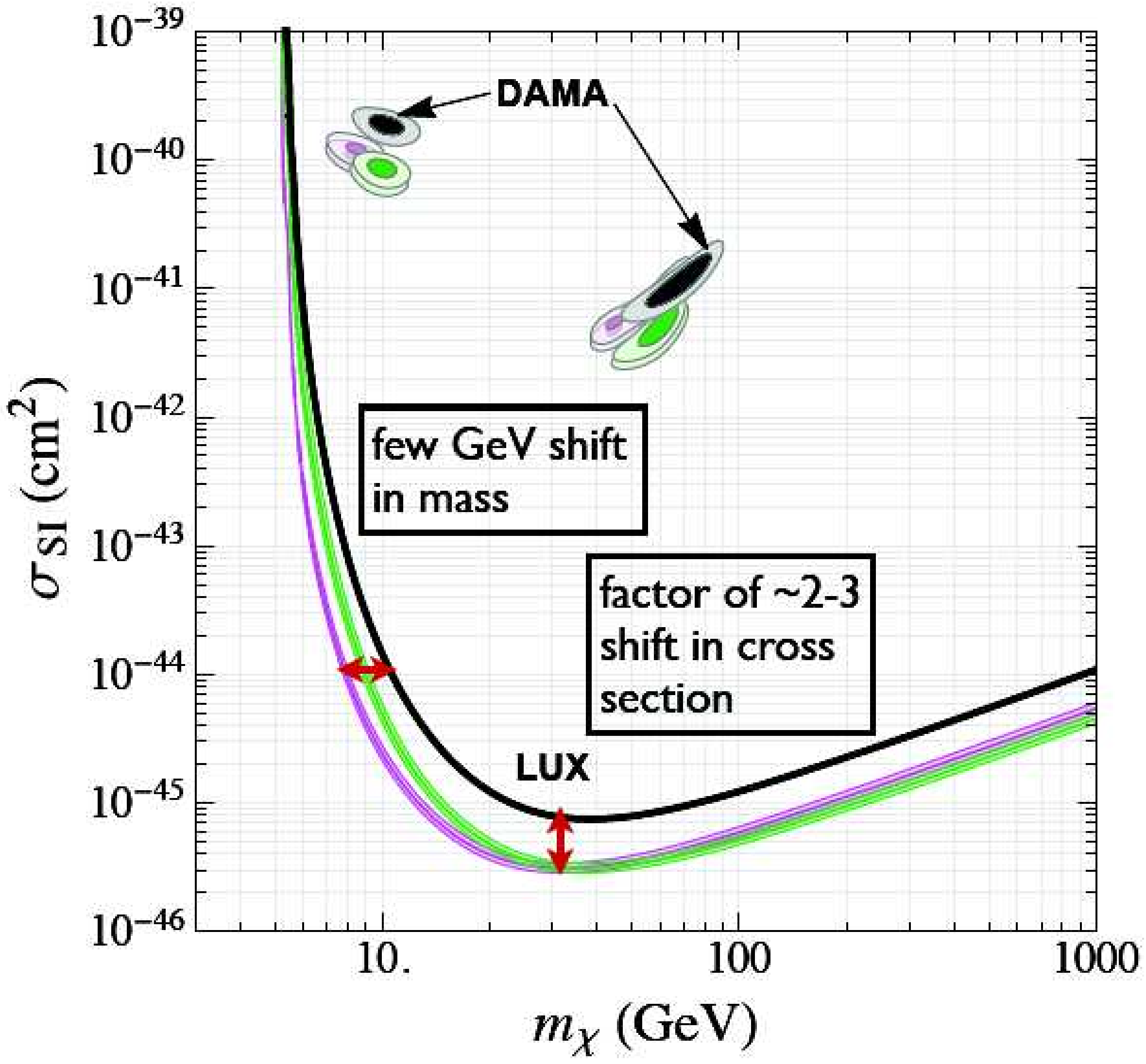
Extending DM Masses into lower range

- 2~3 orders of magnitude above the “neutrino floor”
- challenges: background reduction/discrimination at the lowest threshold



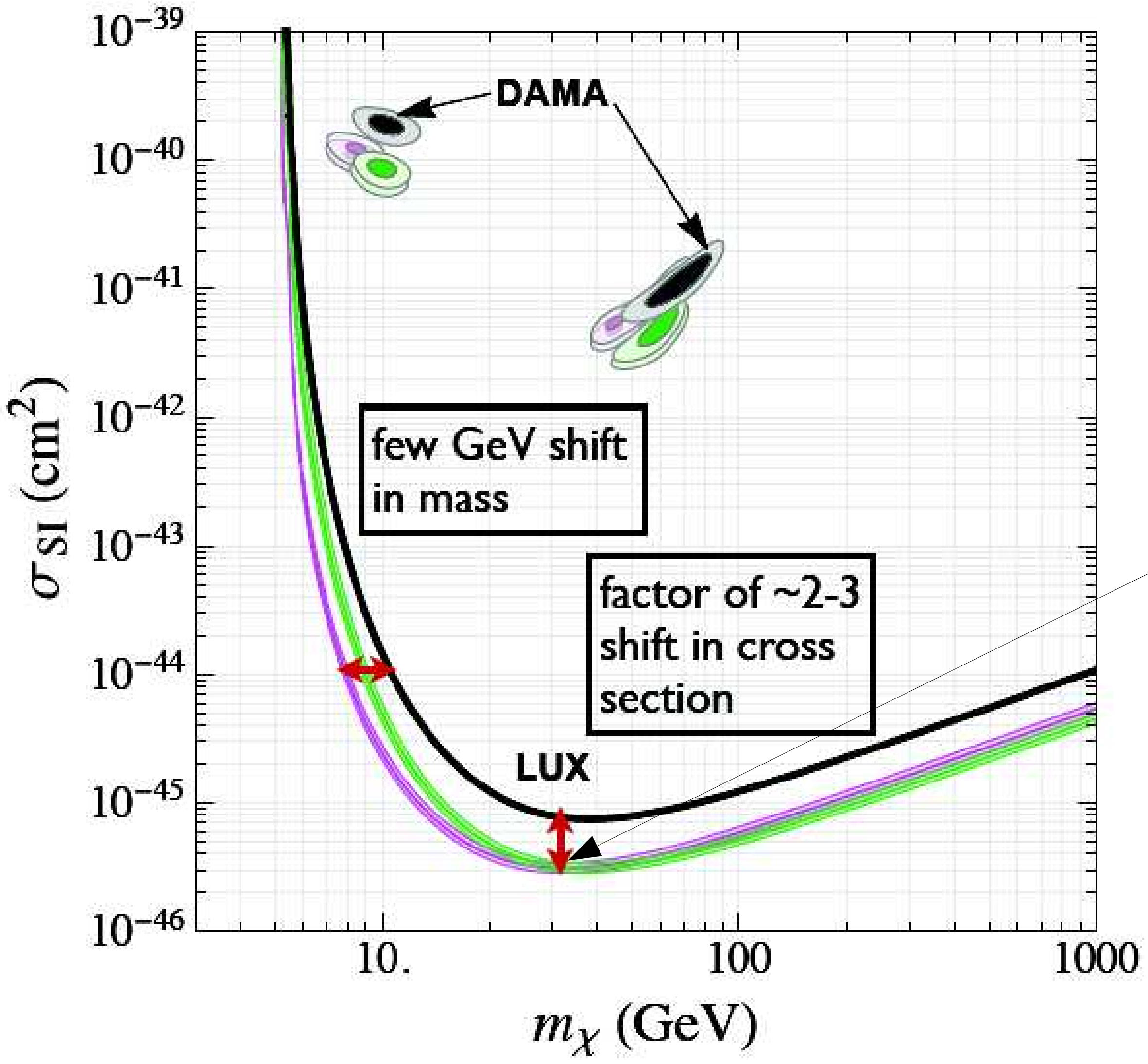


DM DD: uncertainties



Ioco et al, 2011
Bozorgnia et al., 2016
Kelso et al., 2016
Sloane et al., 2016

DM DD: uncertainties



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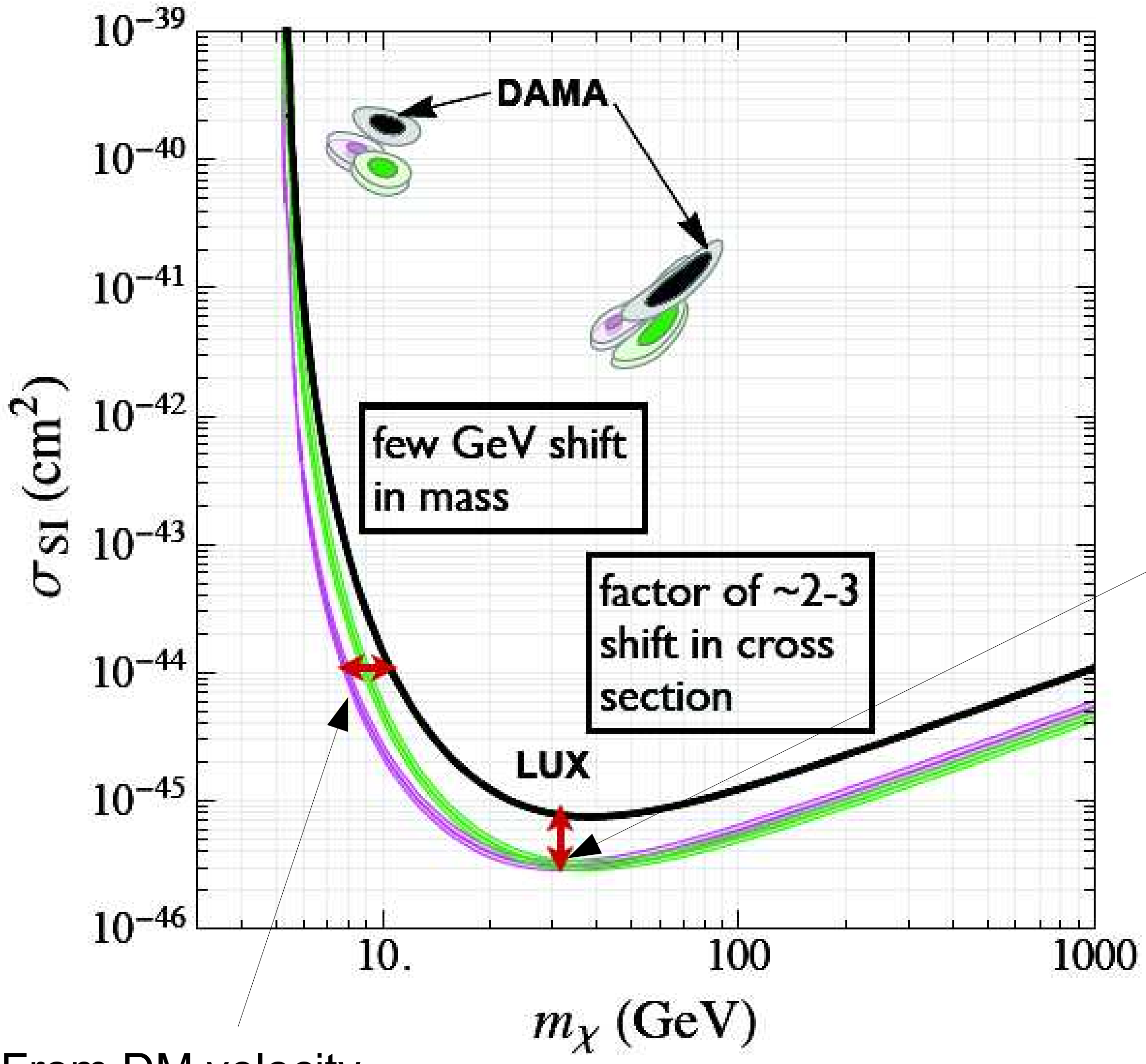
From local relic density uncertainty, based on data analysis

DM DD: uncertainties



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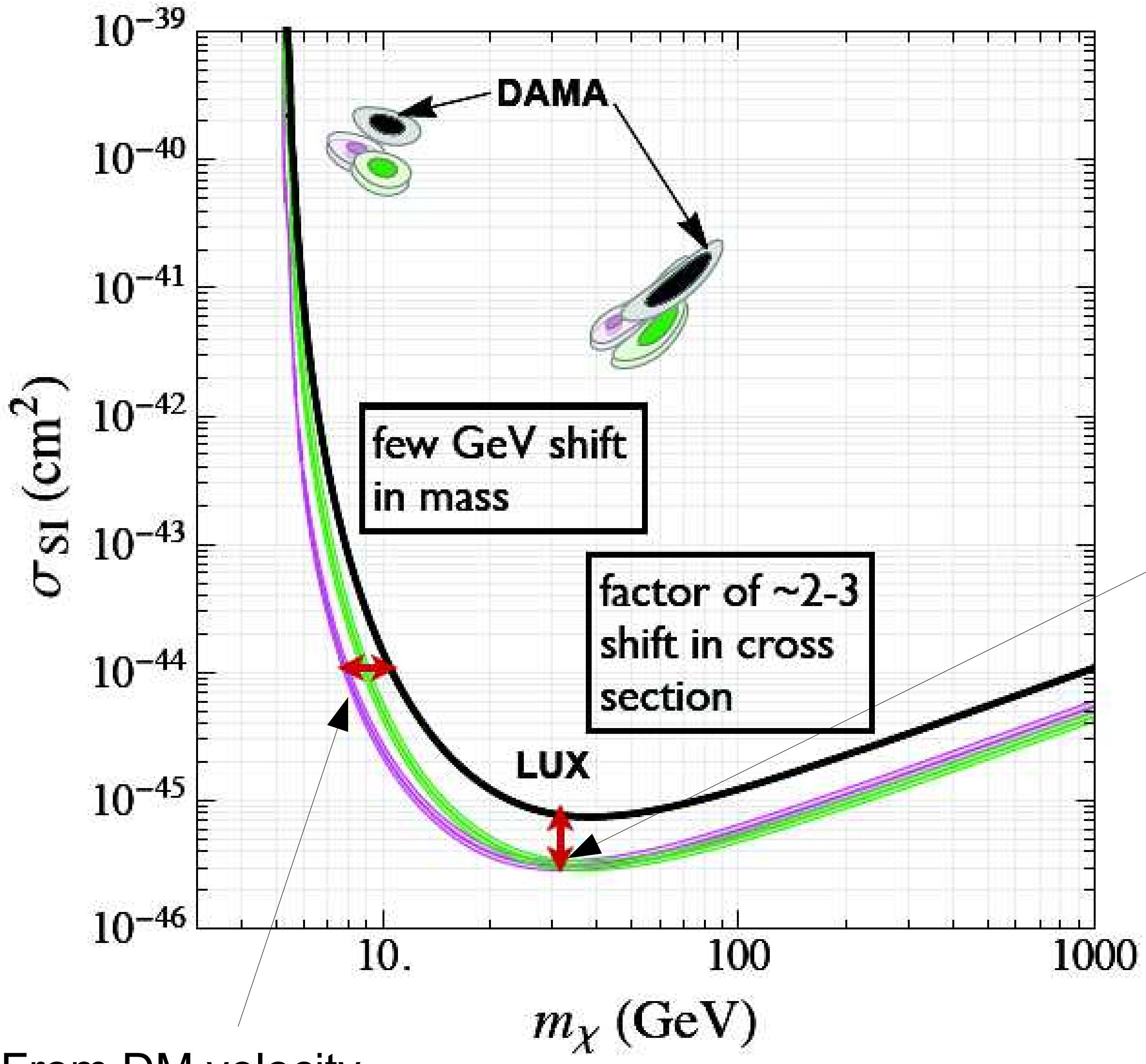
From local relic density uncertainty, based on data analysis

From DM velocity uncertainty, based on analysis of the simulations

DM DD: uncertainties



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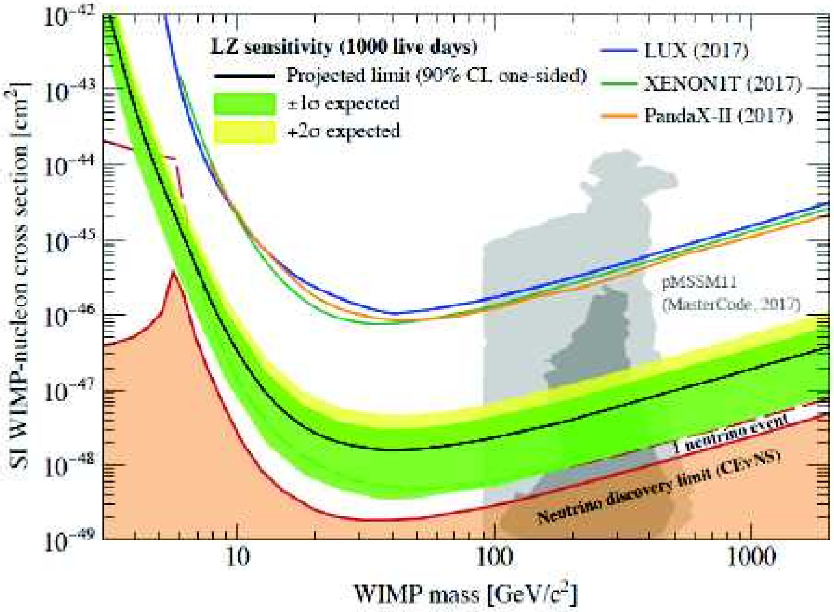
From local relic density uncertainty, based on data analysis

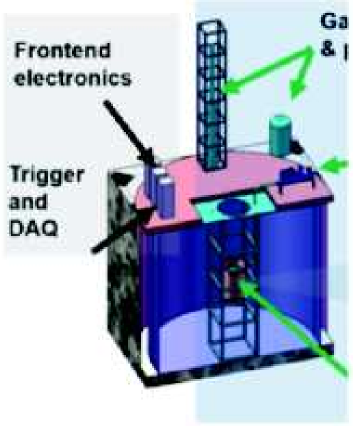
From DM velocity uncertainty, based on analysis of the simulations

DAMA results, even being controversial played a very positive role:
boosted exploration uncertainties in all details,
boosted low DM mass exploration
motivated robust cross check with SABRE in opposite hemisphere

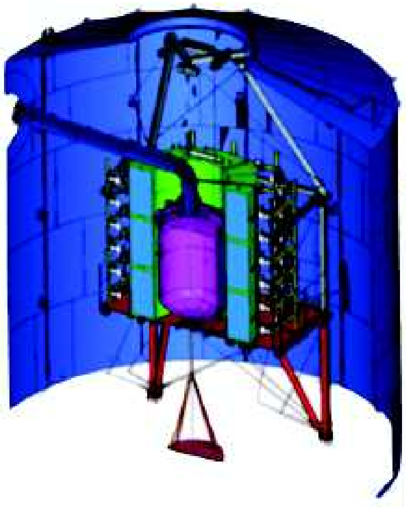
DM DD: prospects



- Results from running experiments and secondary results from completed ones
- XENONnT: 2019 8t, 4t fiducial
- PandaX-4T: 2020 4t
- LZ:2020 10t, 5.6t fiducial
- DARWIN:2024 50t

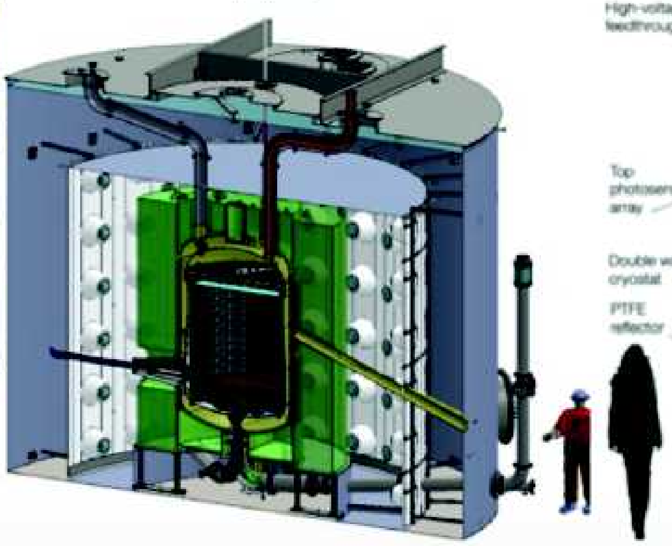


PandaX-4T

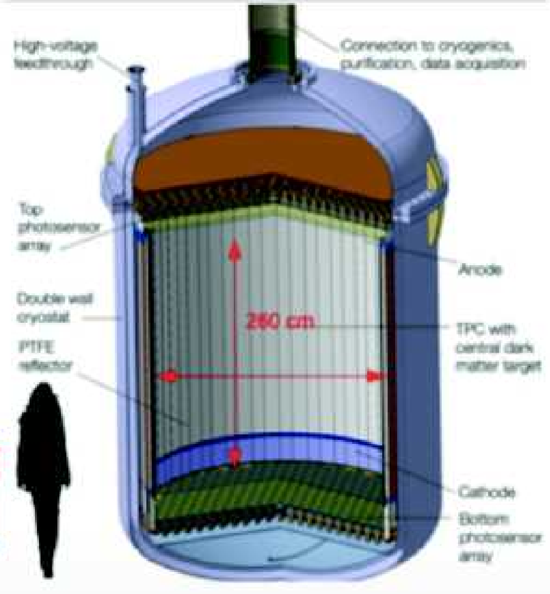


XENONnT

LZ



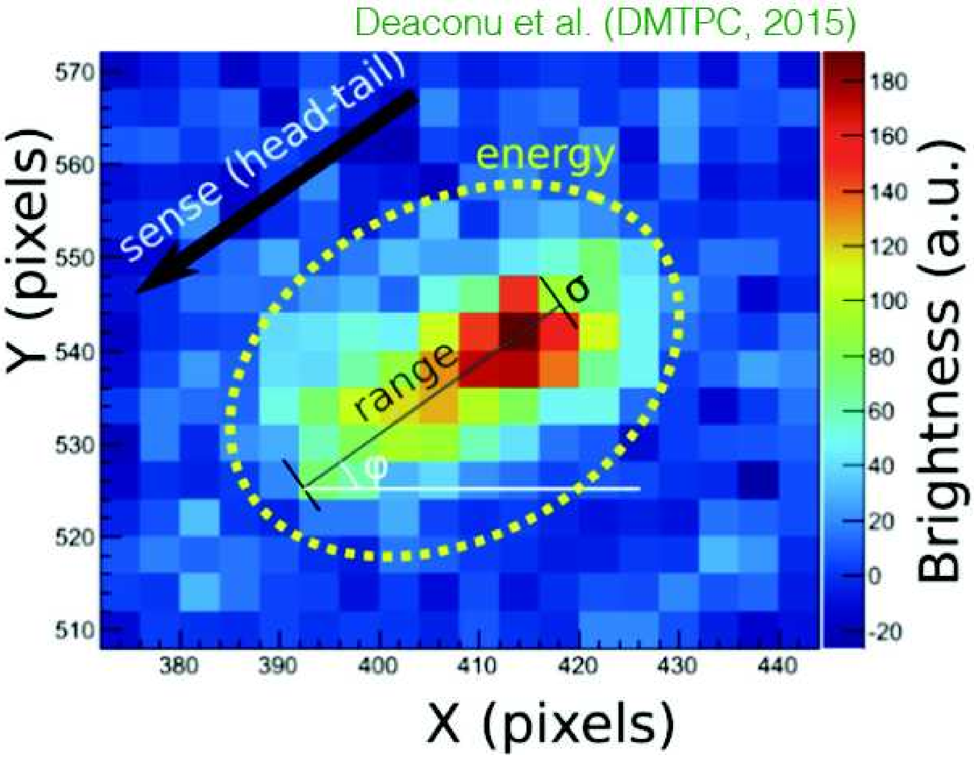
DARWIN



DM DD: directional detection – going beyond the neutrino floor

- The idea is to measure both the energy and the direction of the recoil

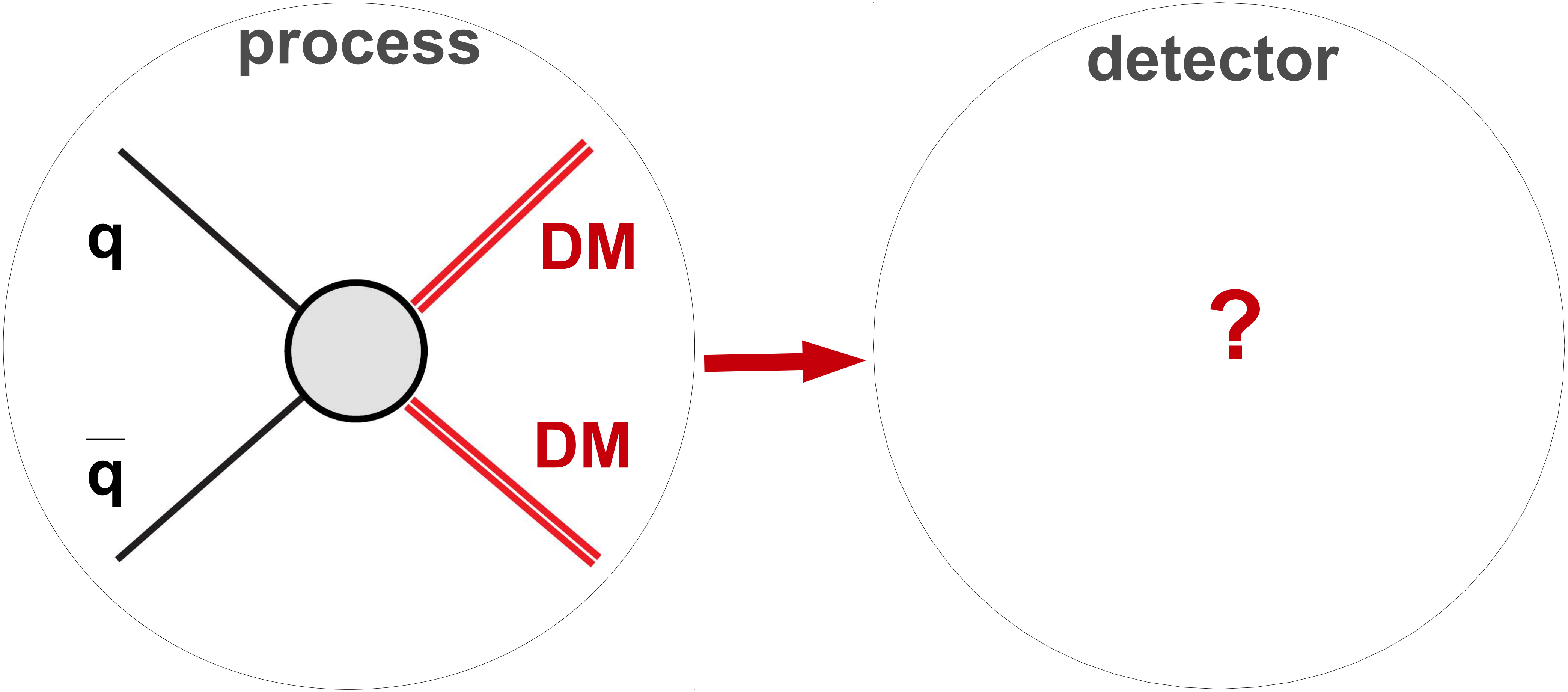
- Most mature technology is the gaseous Time Projection Chamber (TPC) : DRIFT, MIMAC, DMTPC, NEWAGE, D3



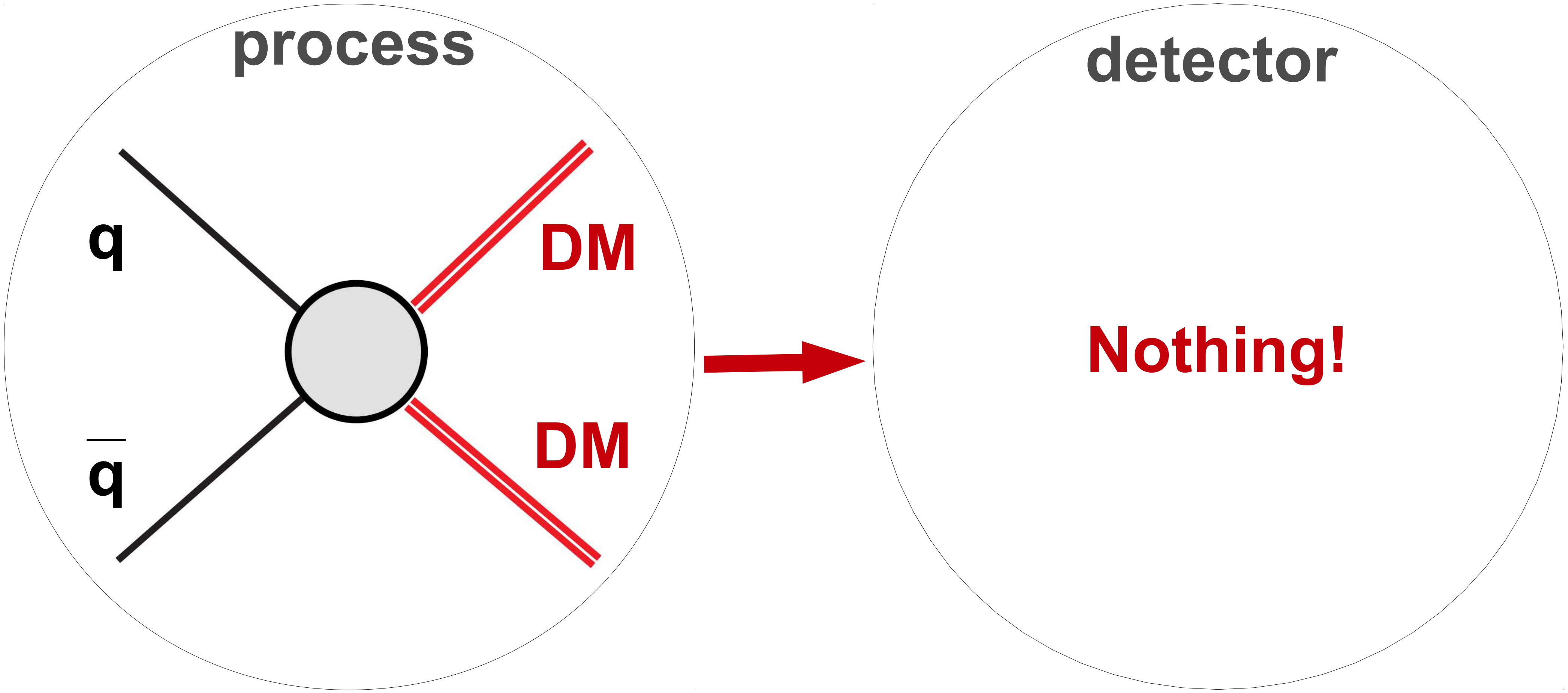
- Detecting recoil tracks in nuclear emulsion (e.g. NEWS experiment)
  Aleksandrov et al. [1604.04199]

- Directional detection is HARD,
  But it is also very POWERFUL.

DM DD interplay with Collider Searches



Hunting for DM at Colliders



process

q

$\bar{q}$

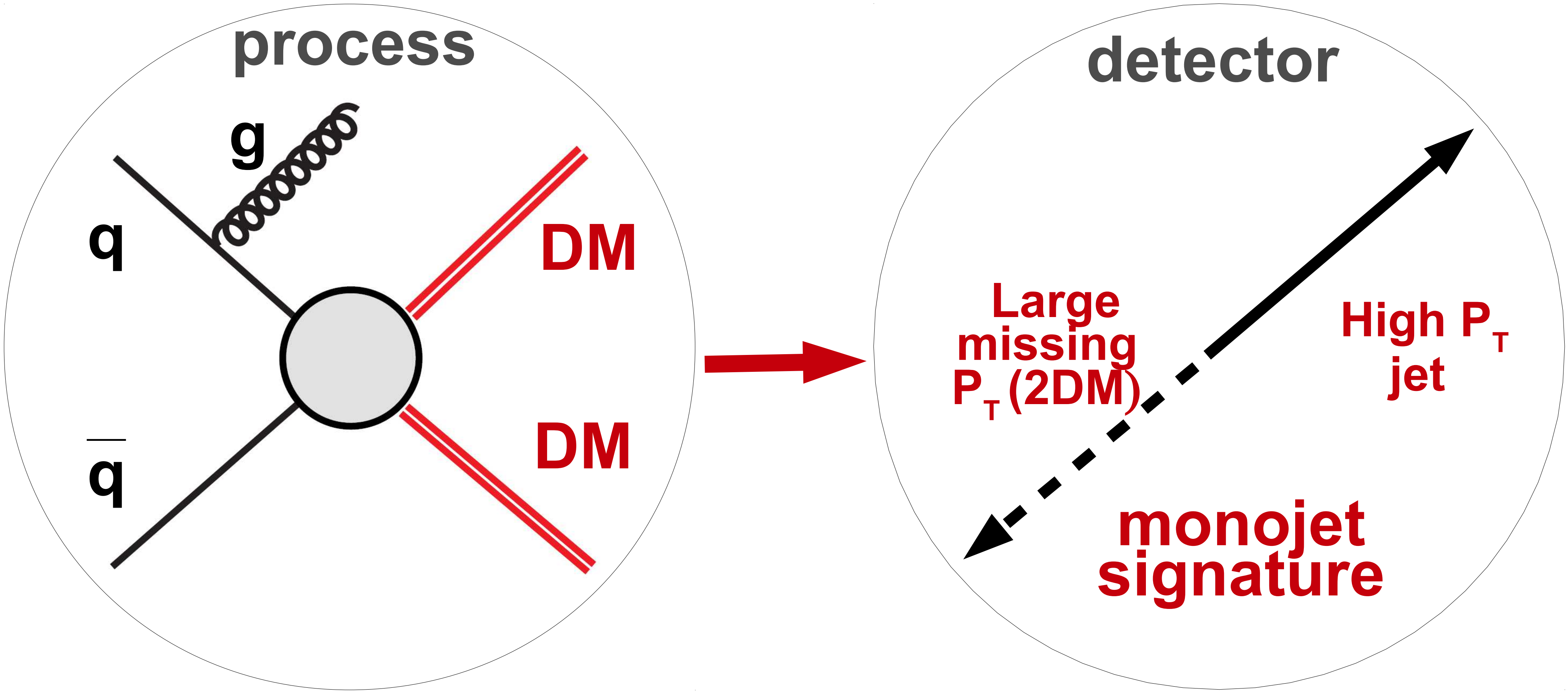
DM

DM

detector

Nothing!

Hunting for DM at Colliders

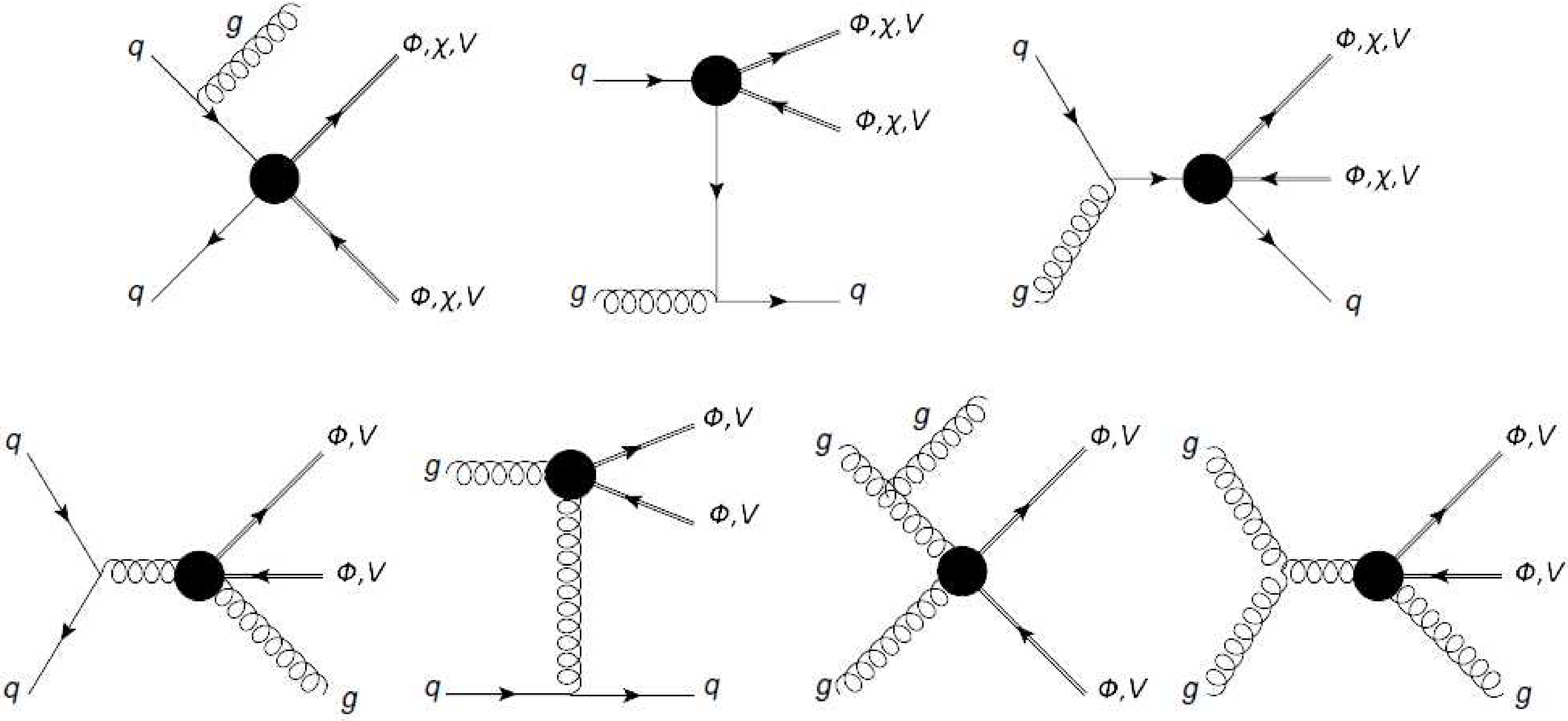


Can we test DM properties at the LHC?

Let us check the effects of DM spin on Missing transverse momentum **(MET)** distributions at the LHC:

- let us start with EFT approach first – the simplest model-independent approach:
- Complete set of DIM5/DIM6 operators involving two SM quarks (gluons) and two DM particles
- consider spin=0, 1/2, 1 DM
- mono-jet signature
- explore LHC discovery potential for scenarios with different DM spins and potential to distinguish these scenarios

Mono-jet diagrams from EFT operators



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

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

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

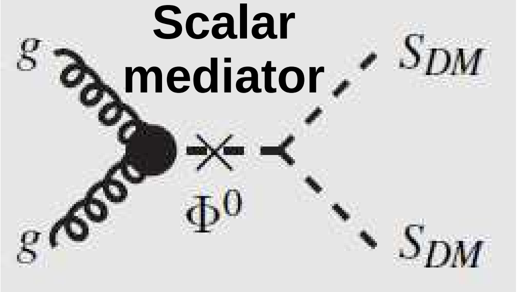
* operators applicable to real DM fields, modulo a factor 1 / 2

† 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]

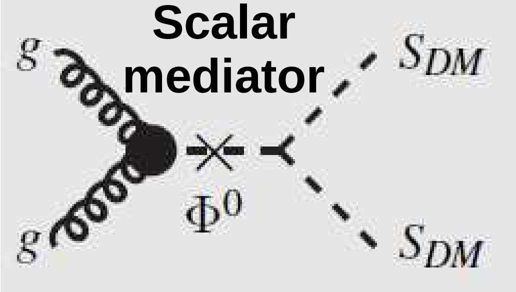
Mapping EFT operators to simplified models

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

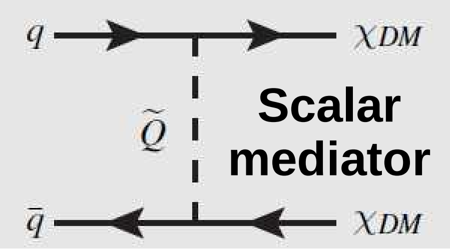

Scalar mediator

Mapping EFT operators to simplified models

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


Scalar mediator

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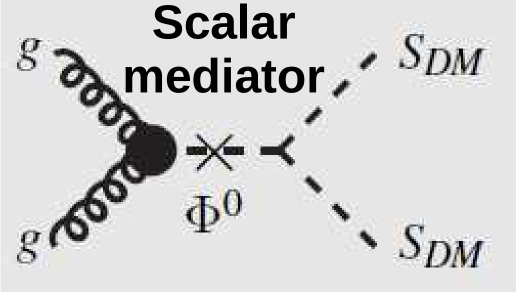
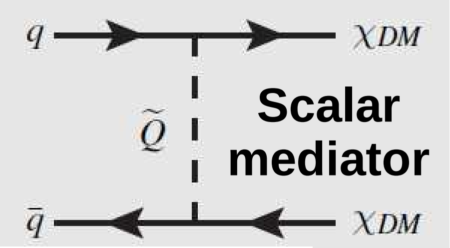


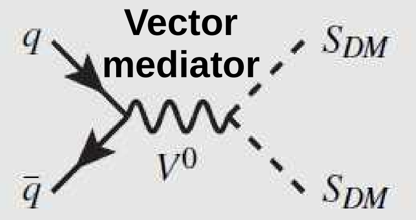
Scalar mediator

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



Scalar mediator

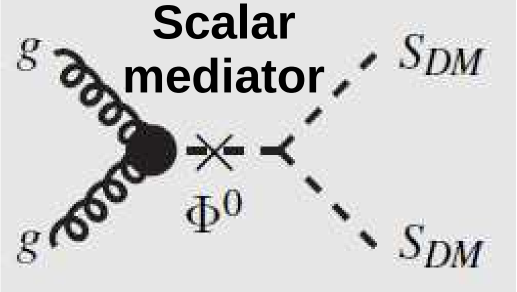
C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q \longrightarrow$



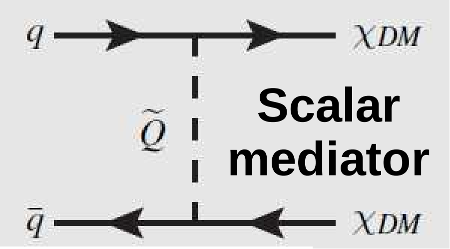
Vector mediator

Mapping EFT operators to simplified models

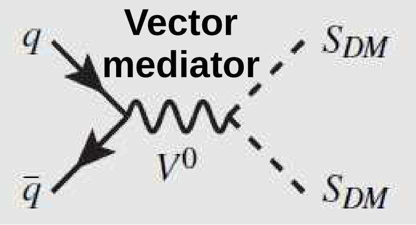
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$, $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$ →



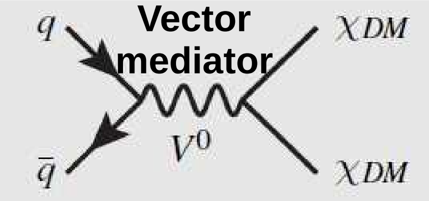
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$ →

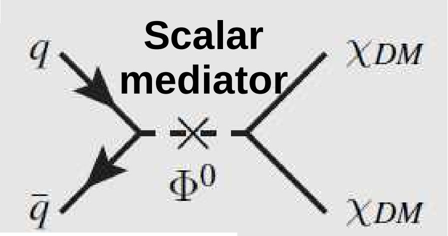


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi-(\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$ →



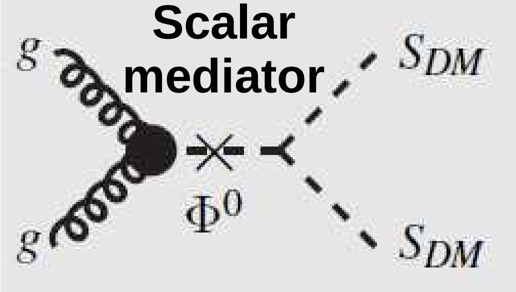
D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$ →



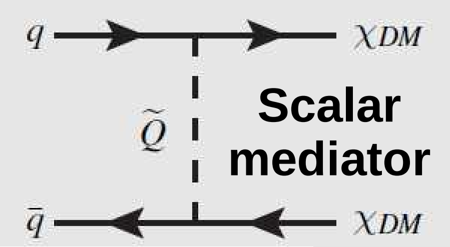


Mapping EFT operators to simplified models

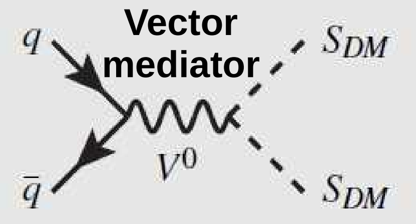
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$ $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu}$



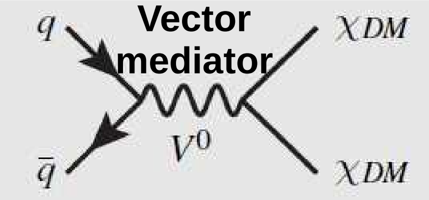
D1T-D4T $\frac{1}{\Lambda^2}\bar{\chi}q\bar{q}\chi$

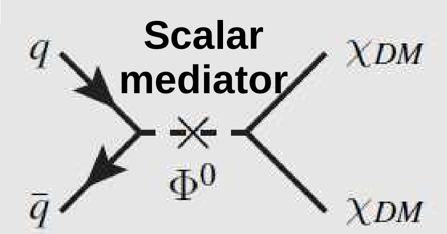


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi-(\partial_\mu\phi^*)\phi]\bar{q}\gamma^\mu q$

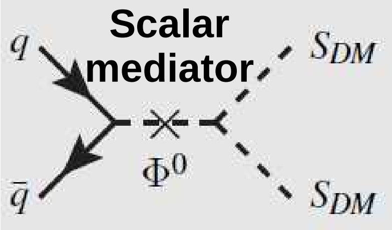


D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar{\chi}\chi\bar{q}q$



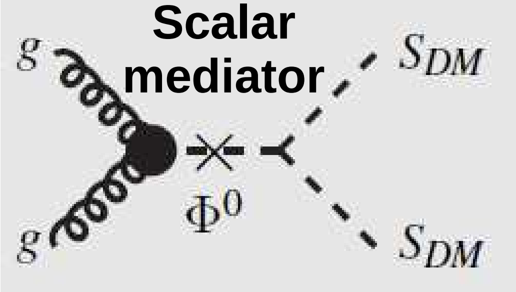


C1 $\frac{1}{\Lambda^2}\phi^*\phi\bar{q}q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar{q}q$

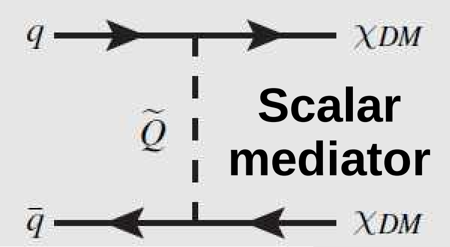


Mapping EFT operators to simplified models

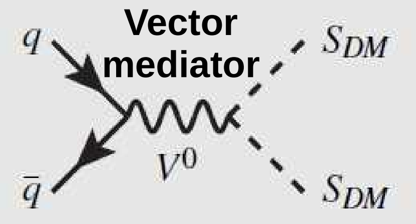
C5,C5A $\frac{1}{\Lambda^2}\phi^*\phi G^{\mu\nu}G^{\mu\nu}$ $\frac{1}{\Lambda^2}\phi^*\phi\tilde{G}^{\mu\nu}G^{\mu\nu} \longrightarrow$



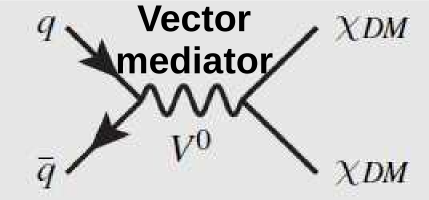
D1T-D4T $\frac{1}{\Lambda^2}\bar\chi q\bar q\chi \longrightarrow$

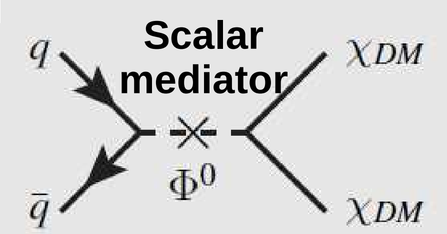


C3 $\frac{i}{\Lambda^2}[\phi^*(\partial_\mu\phi - (\partial_\mu\phi^*)\phi]\bar q\gamma^\mu q \longrightarrow$

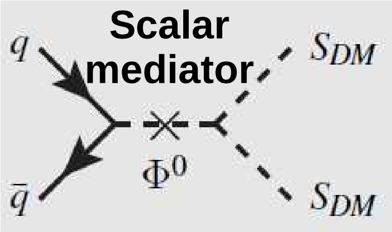


D1-D4, D5-D8 $\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$ $\frac{1}{\Lambda^2}\bar\chi\chi\bar q q \longrightarrow$





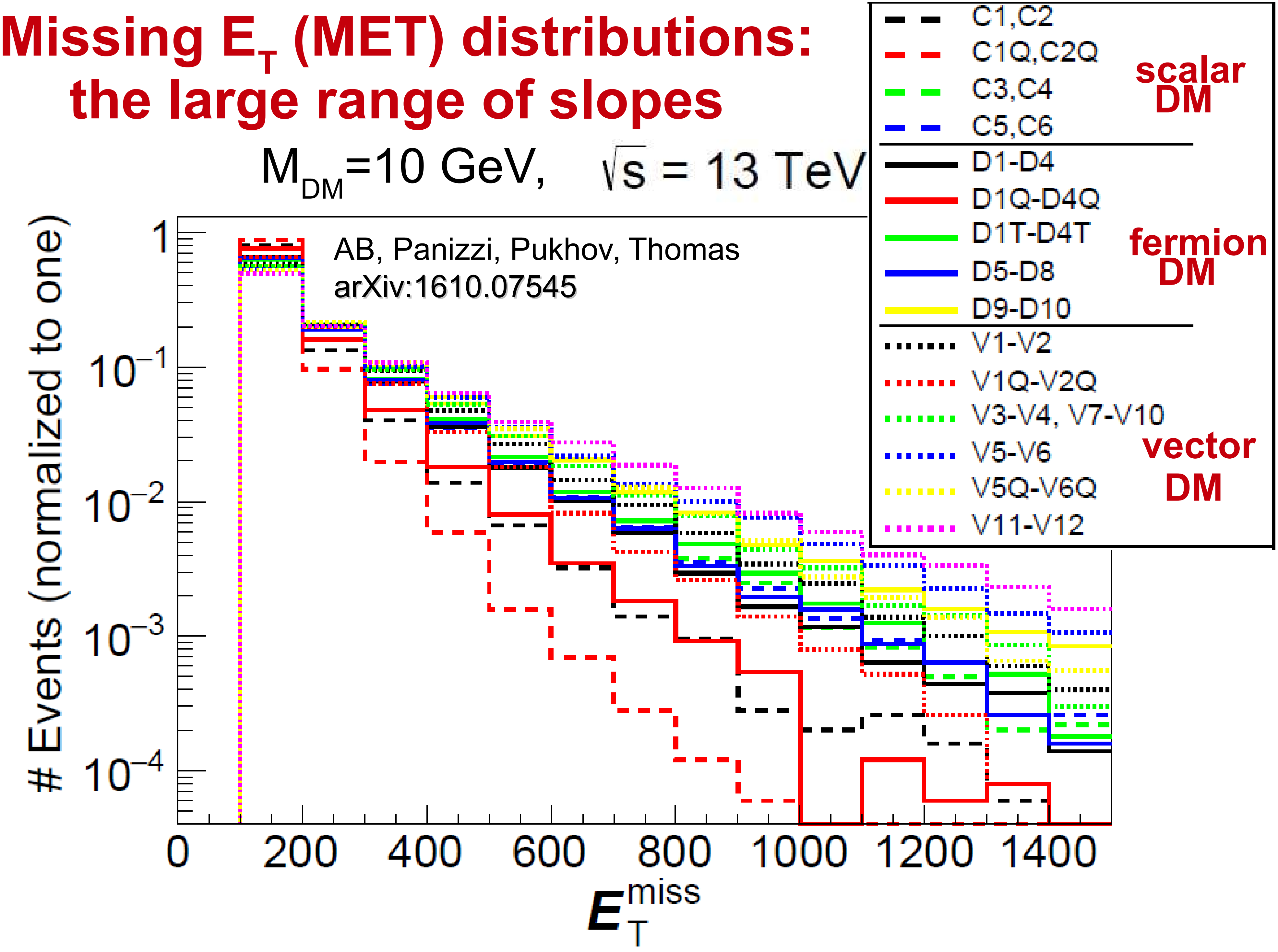
C1 $\frac{1}{\Lambda^2}\phi^*\phi\bar q q\Phi \Longrightarrow \frac{v}{\Lambda^2}\phi^*\phi\bar q q \longrightarrow$



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

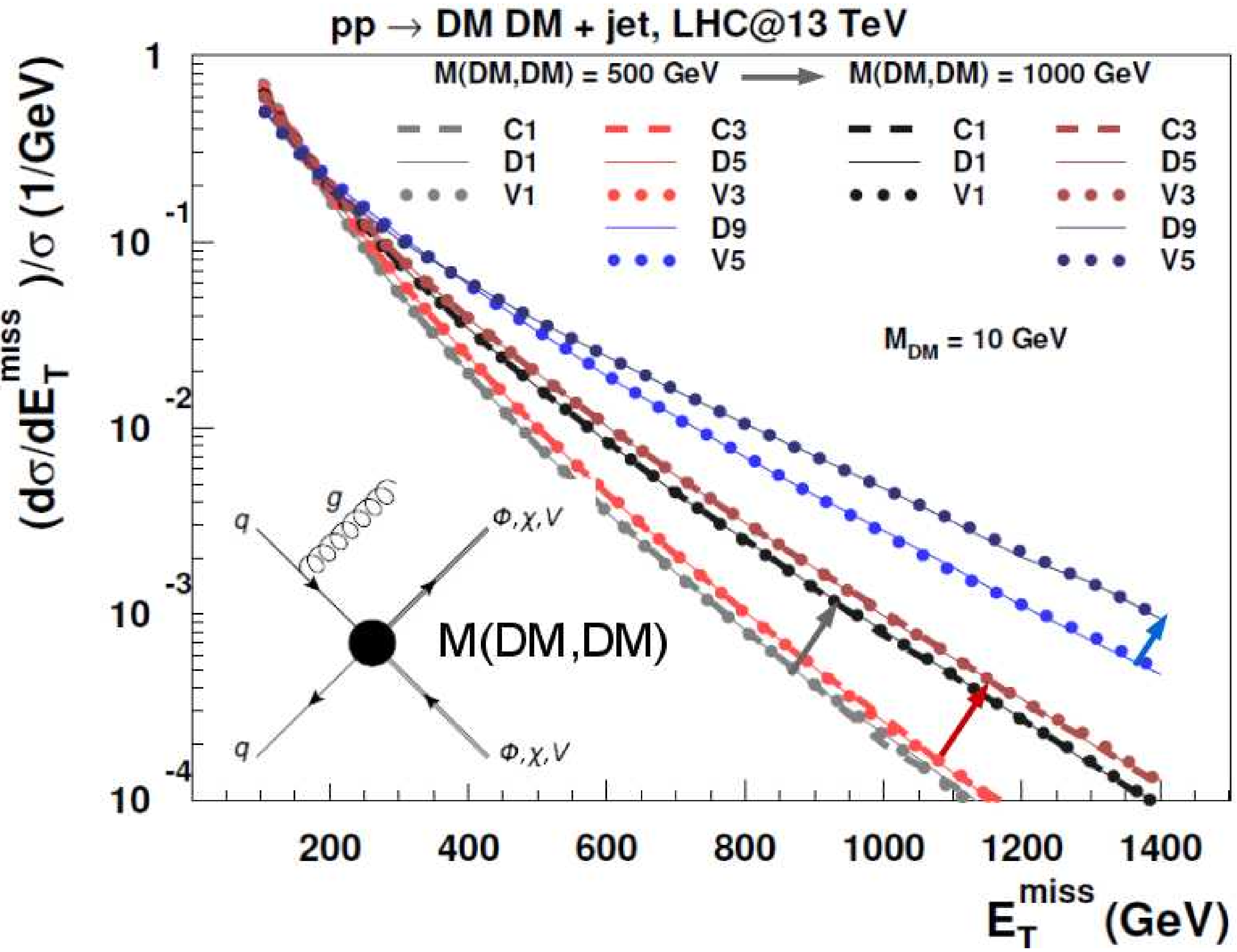
Missing E_T (MET) distributions: the large range of slopes

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)



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

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

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

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

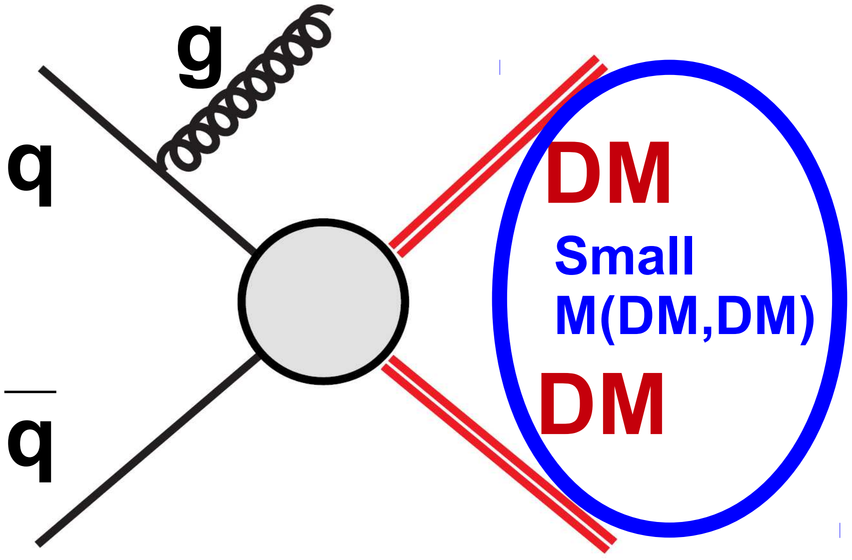
$$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$ [D5]

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

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

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)

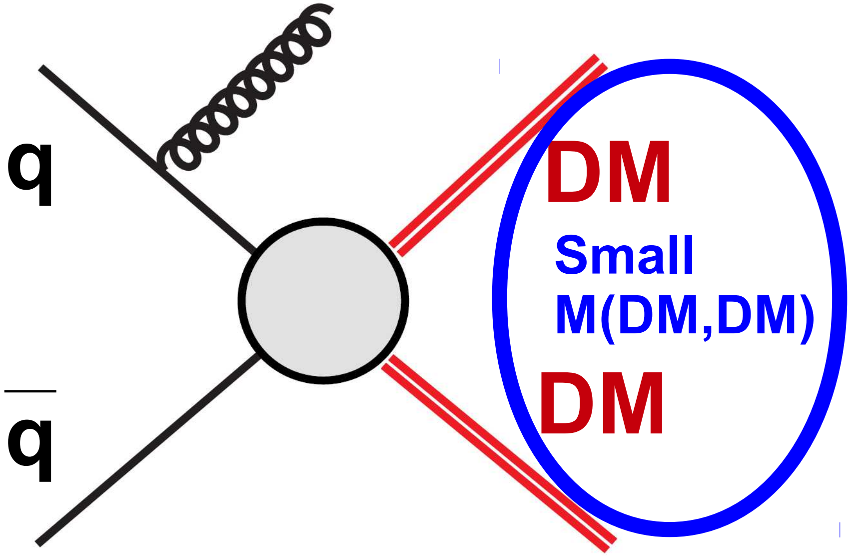


$P_T(g)$ small → $P_T(g)$large

Δ (x1 x2)/(x1 x2) is large and MET slope is steep

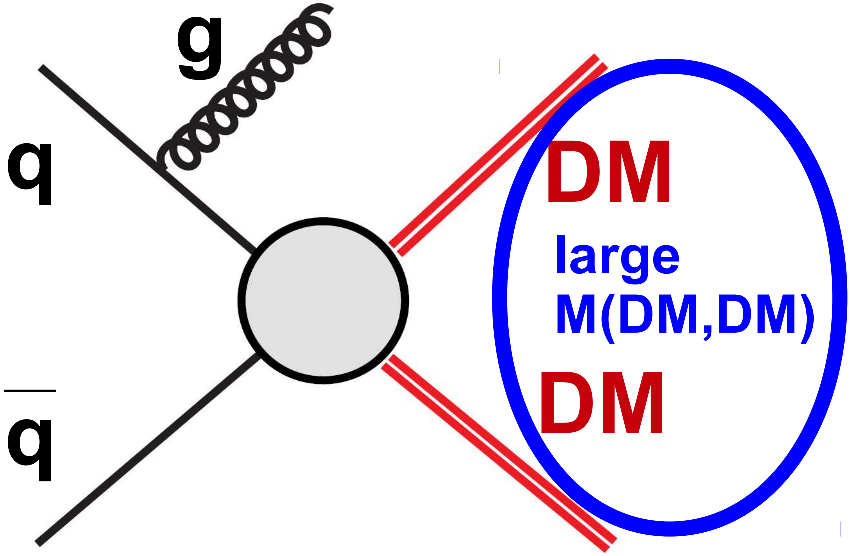
Properties of MET distributions:

- 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)



$P_T(g)$ small → $P_T(g)$large

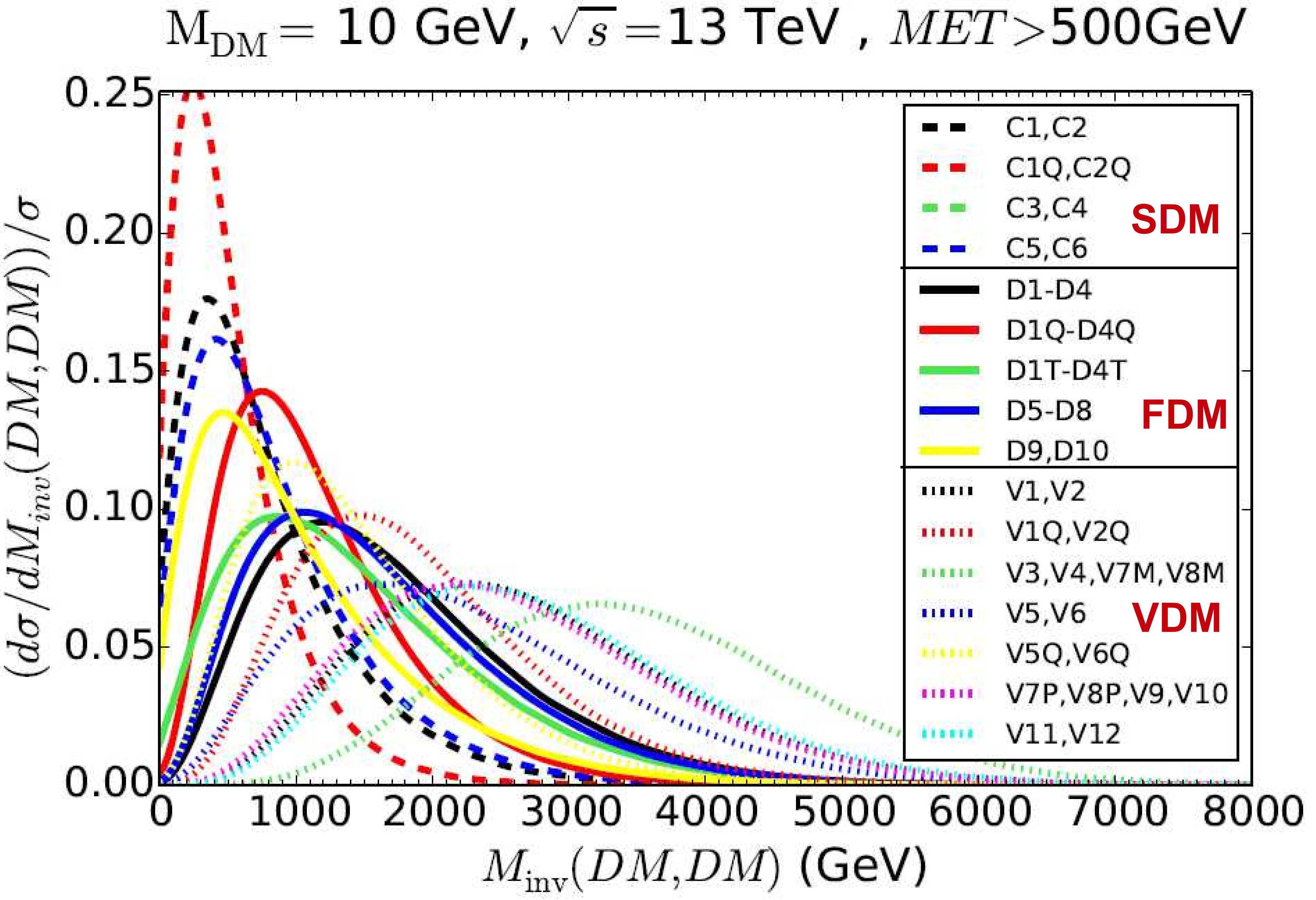
Δ (x1 x2)/(x1 x2) is large and MET slope is steep



$P_T(g)$ small → $P_T(g)$large

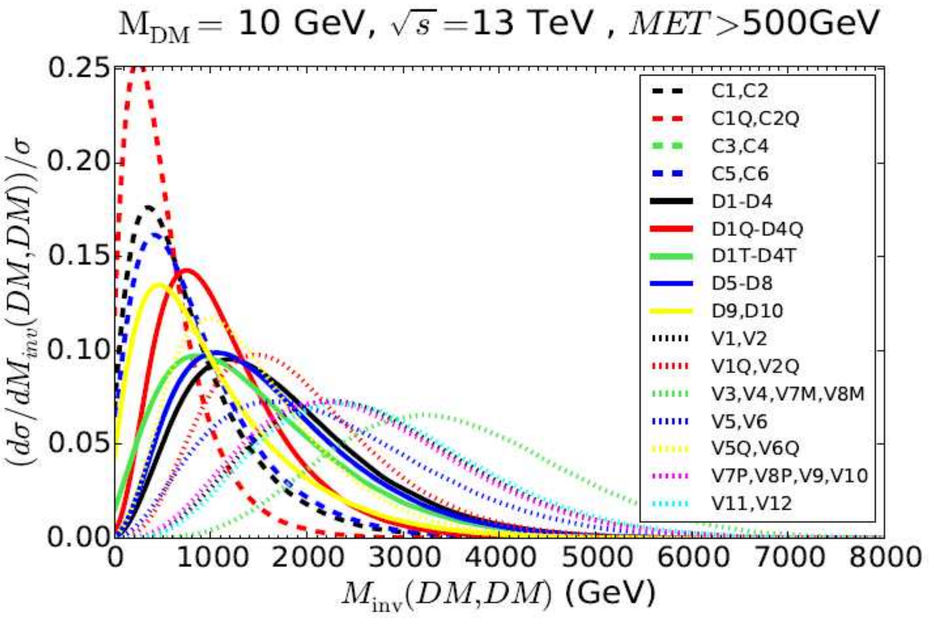
Δ (x1 x2)/(x1 x2) is small and MET slope is gradual

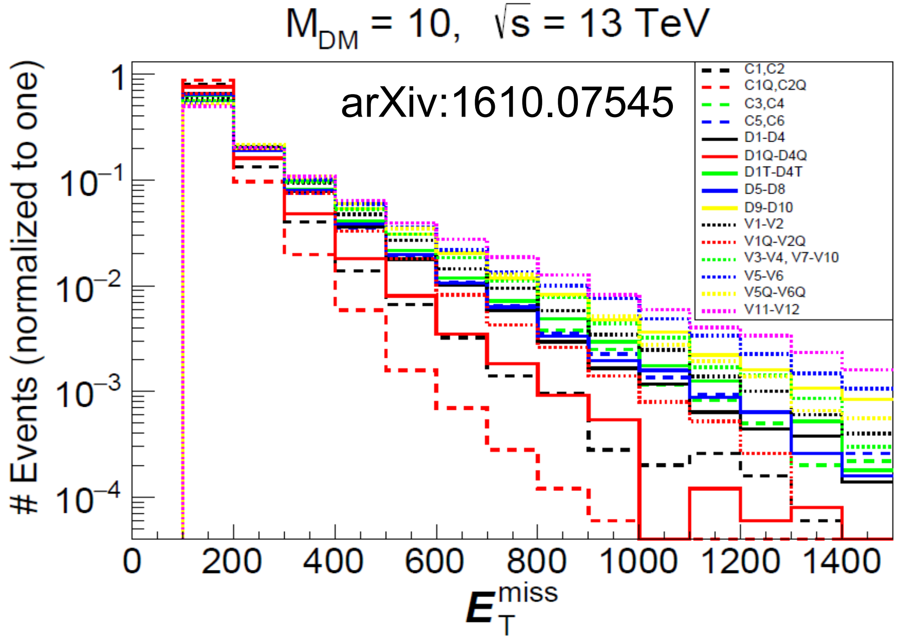
On the other hand, M(DM,DM) distributions, defined by the EFT operators are different!



Distinguishing DM operators/theories

M(DM,DM) distributions ⟷ are correlated with Different MET shapes

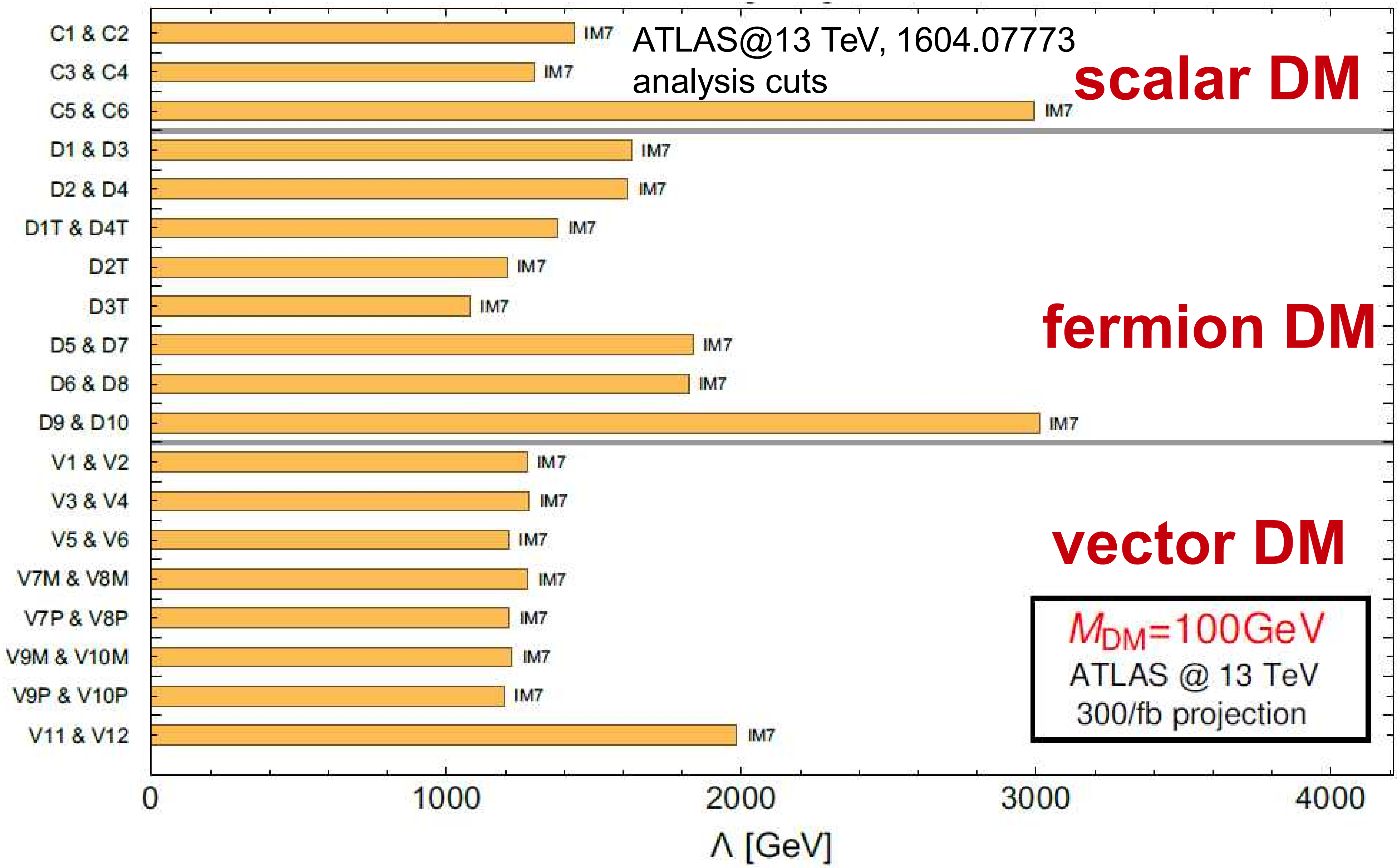




- energy dependence of the DM operator → M_{DMDM} distributions → slopes of MET
- projection for 300 fb^{-1}: some operators C1-C2,C5-C6,D9-D10,V1-V2,V3-V4,V5-V6 and V11-12 can be distinguished from each other
- Application beyond EFT: when the DM mediator is not produced on-the-mass-shell and M_{DMDM} is not fixed: t-channel mediator or mediators with mass below $2M_{DM}$

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

LanHEP→ CalcHEP/ Madgraph → LHE→ CheckMATE 2 chain



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

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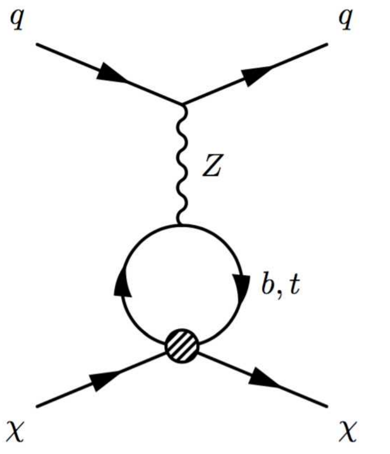

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$\mathbf{c_A^{(u)}, c_A^{(d)}, c_V^{(u)}, c_V^{(d)}=(1,1,0,0)}$[5TeV] → (**1.1, 1.1, 0.04, -0.07**)[1GeV]

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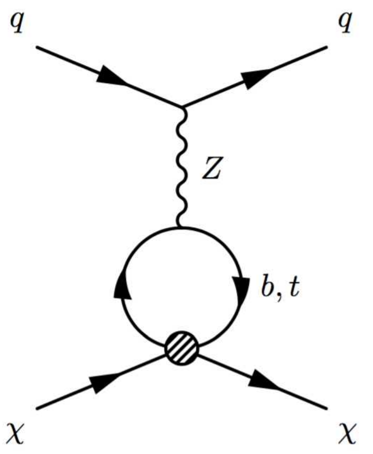

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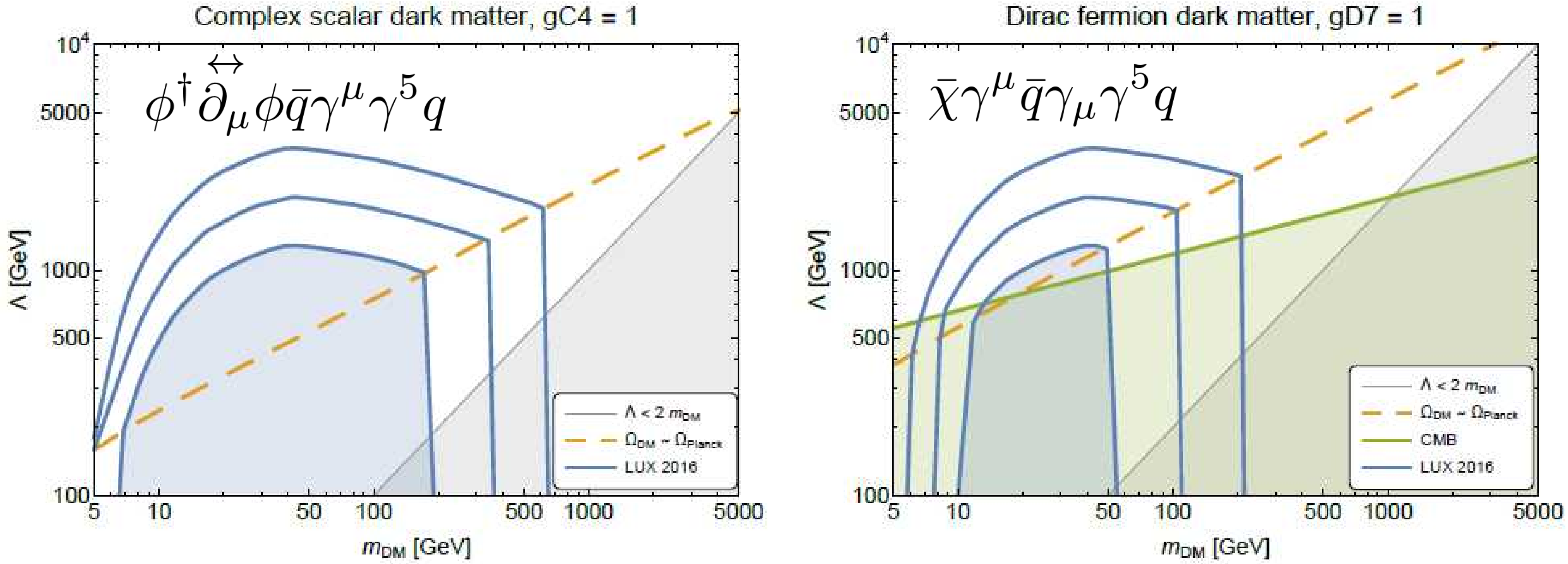
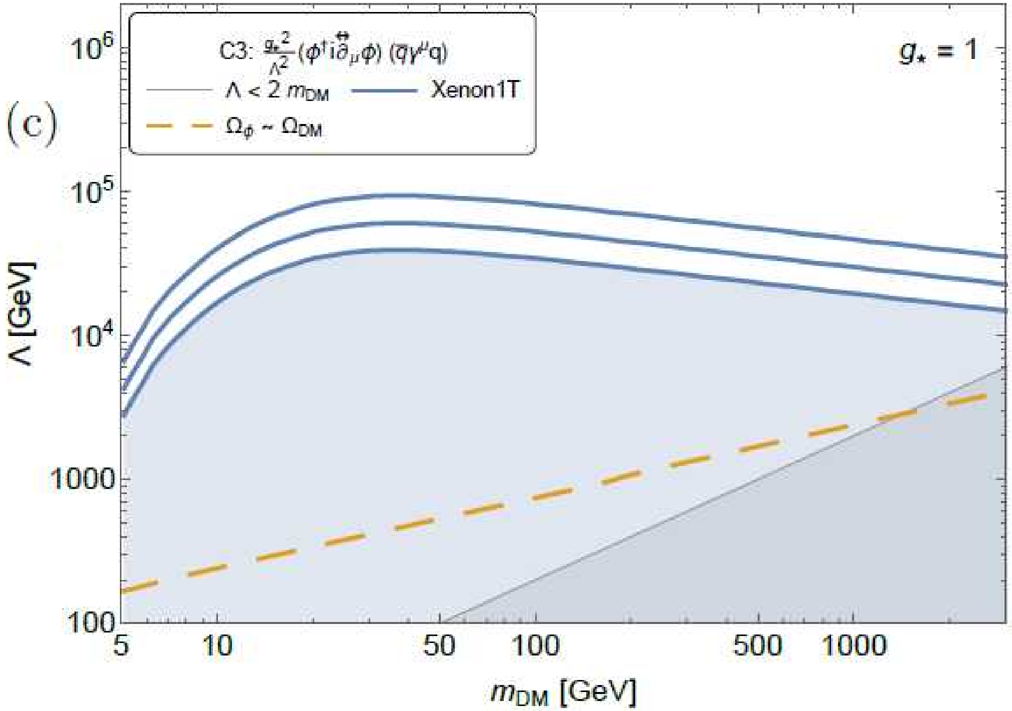
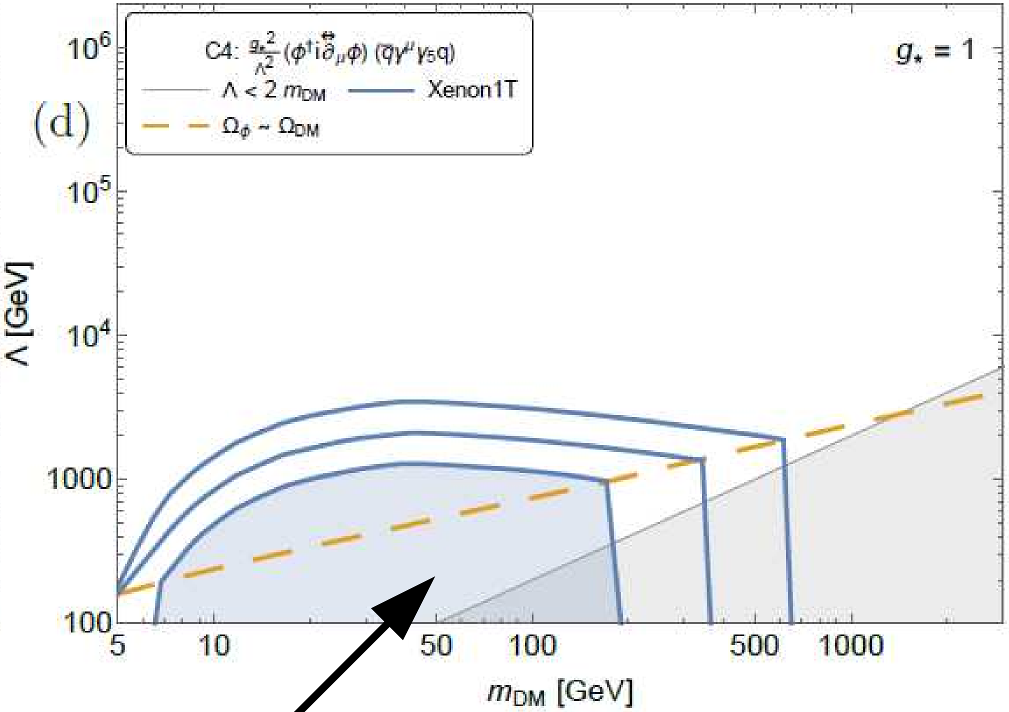


AB, Bertuzzo, Caniu, di Cortona, Eboli, Pukhov

DM DD ↔ Collider interplay

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

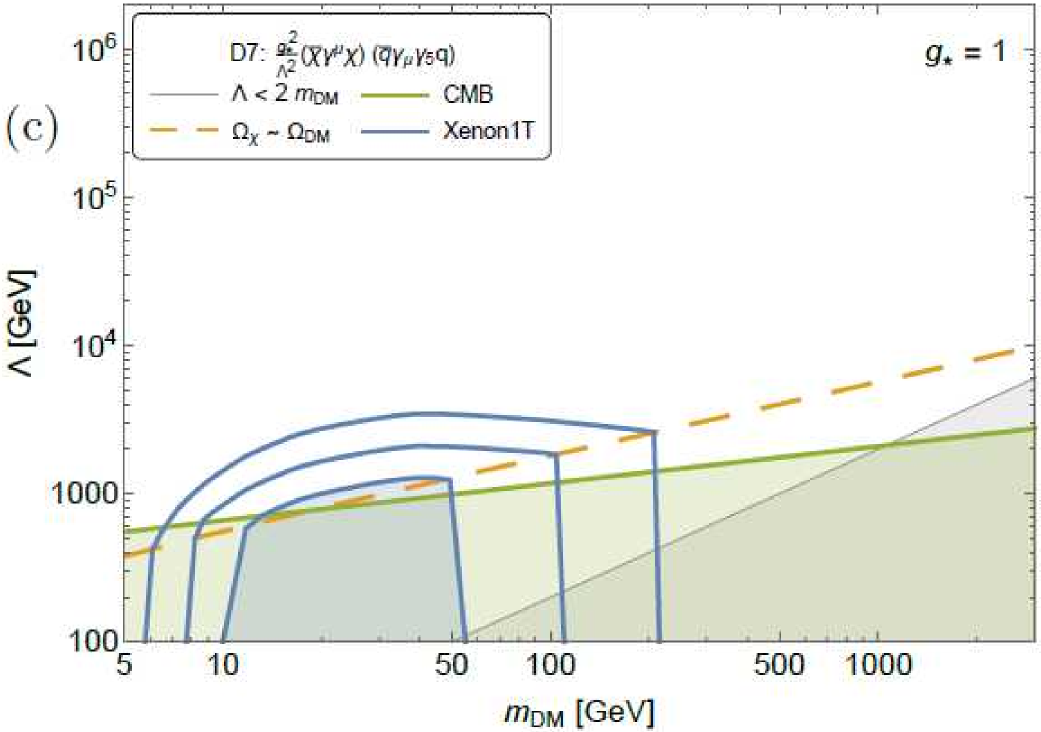


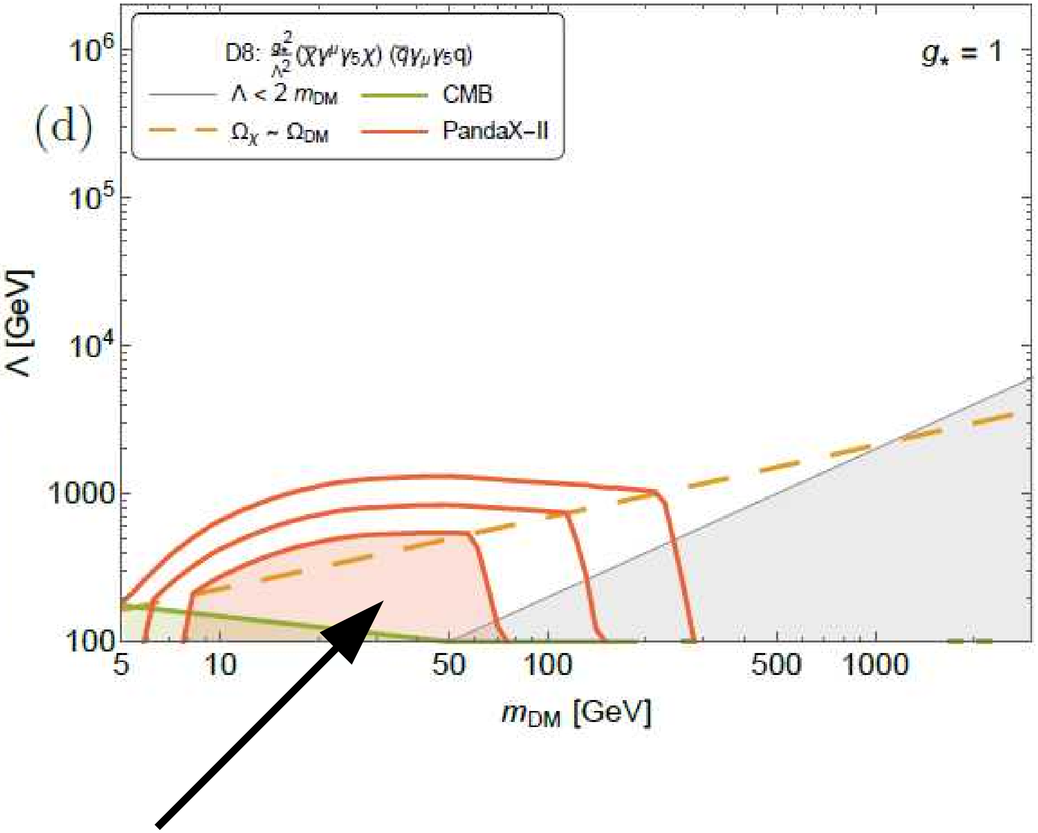


- The effect of RGE running between LHC and DM DD scales

DM DD ↔ Collider interplay

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

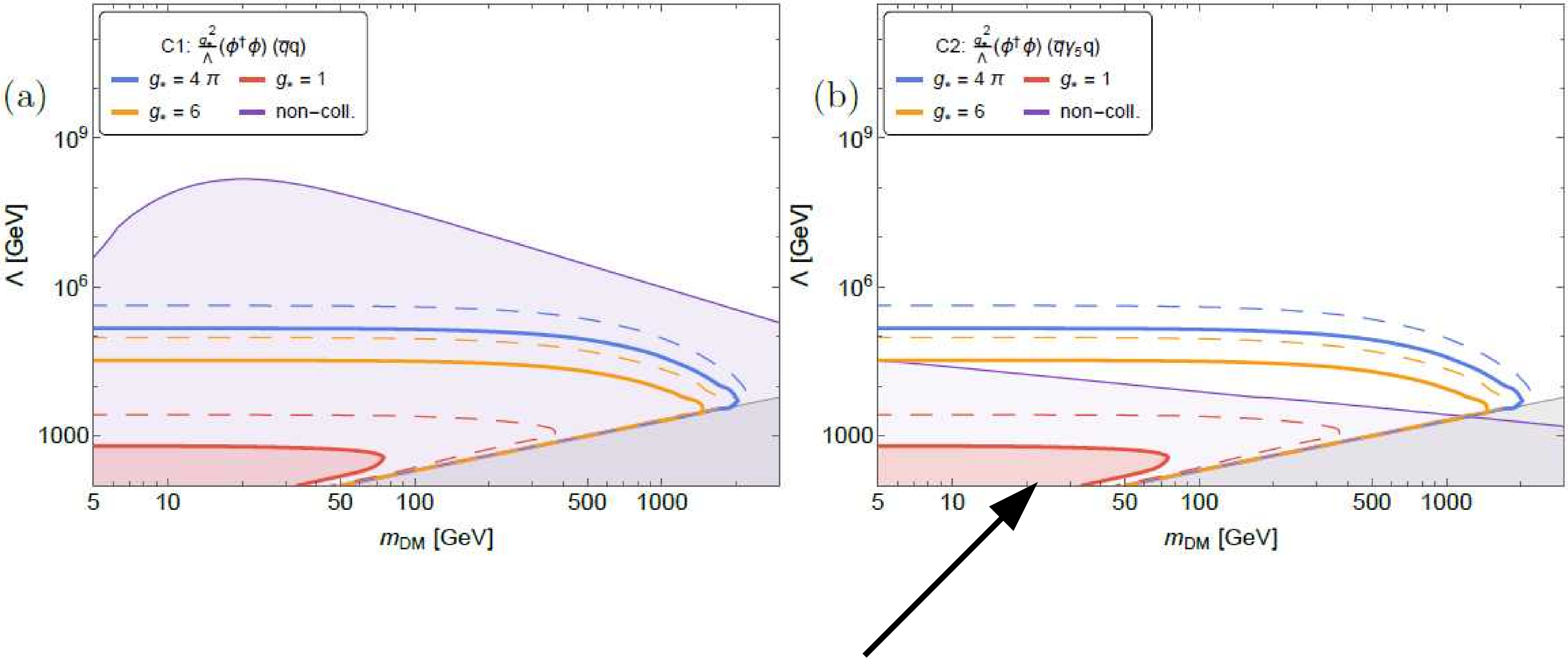




- SD exclusion from PANDAX

DM DD ↔ Collider interplay

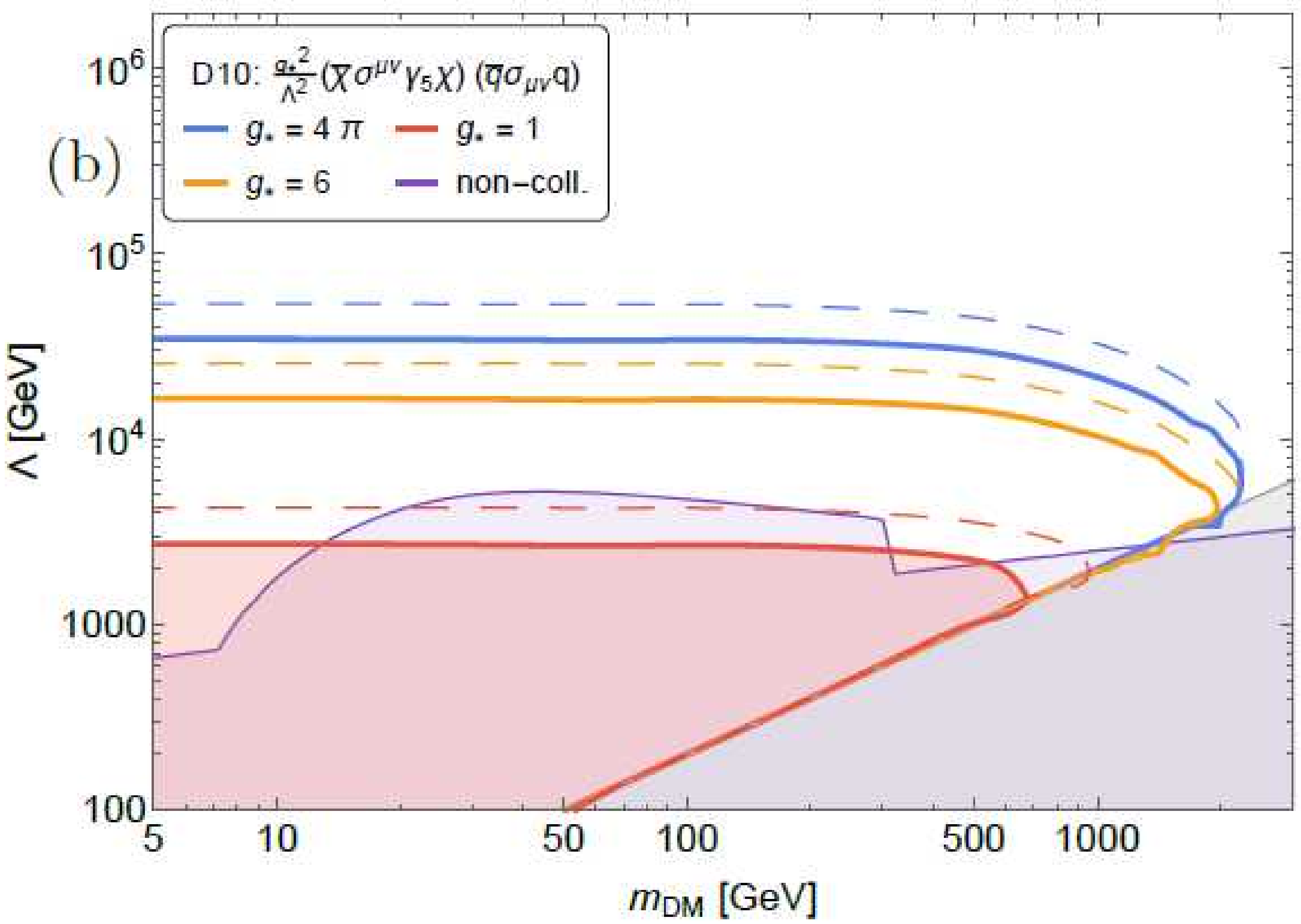
AB, Bertuzzo, Caniu, di Cortona, Eboli, Pukhov



- NO DD exclusion

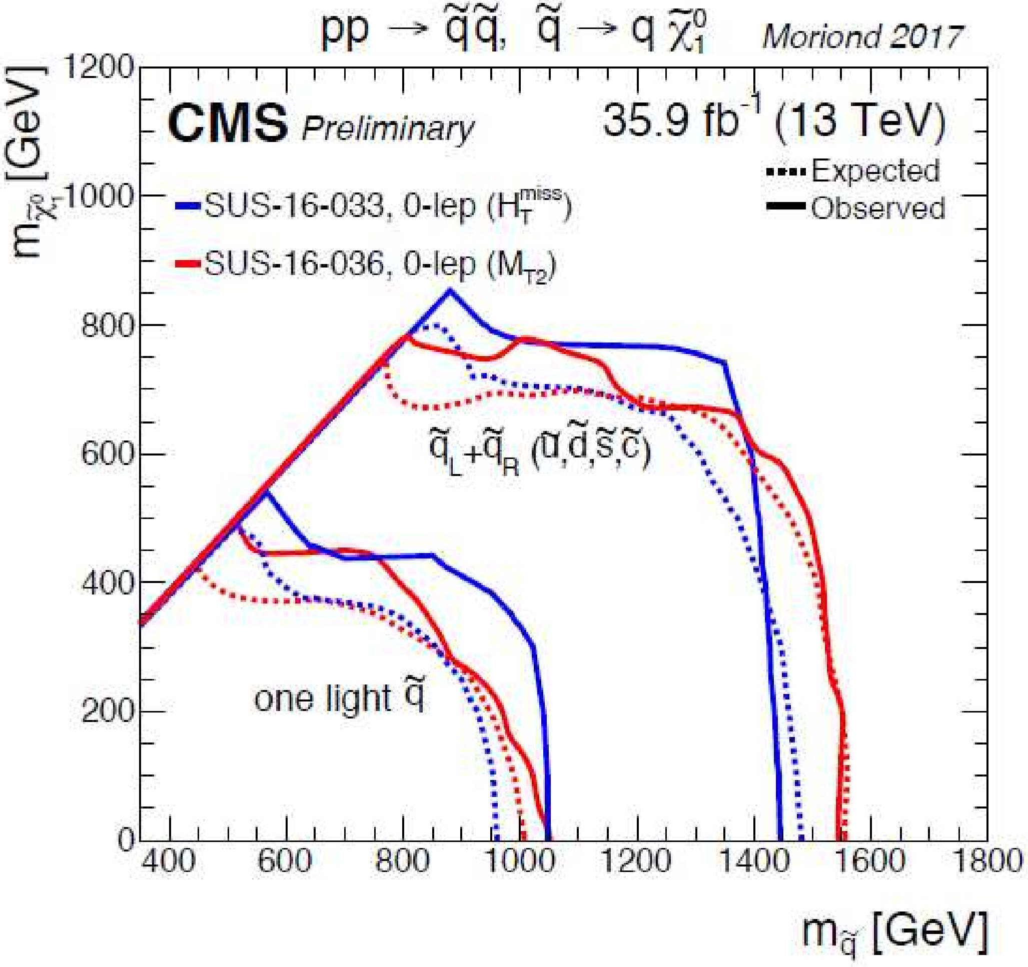
DM DD ↔ Collider interplay

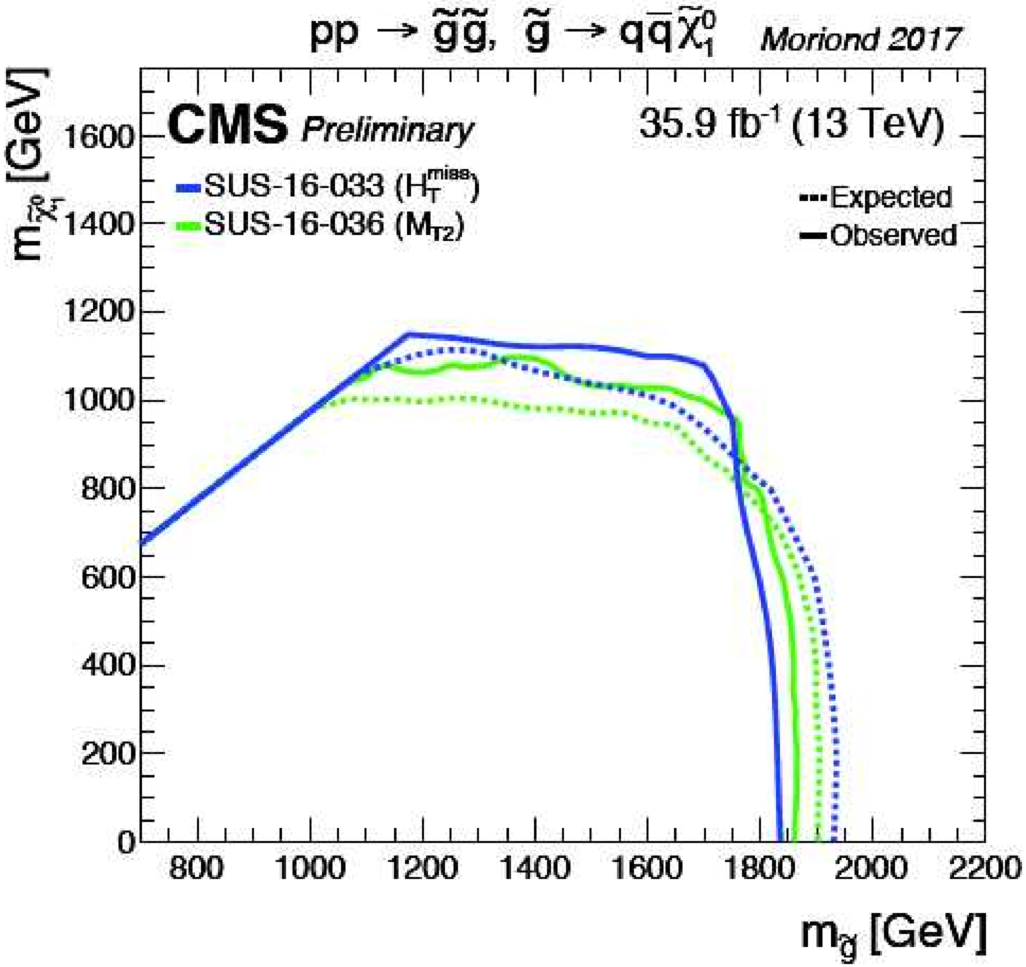
AB, Bertuzzo, Caniu, di Cortona, Eboli, Pukhov



Application for the case beyond EFT: SUSY

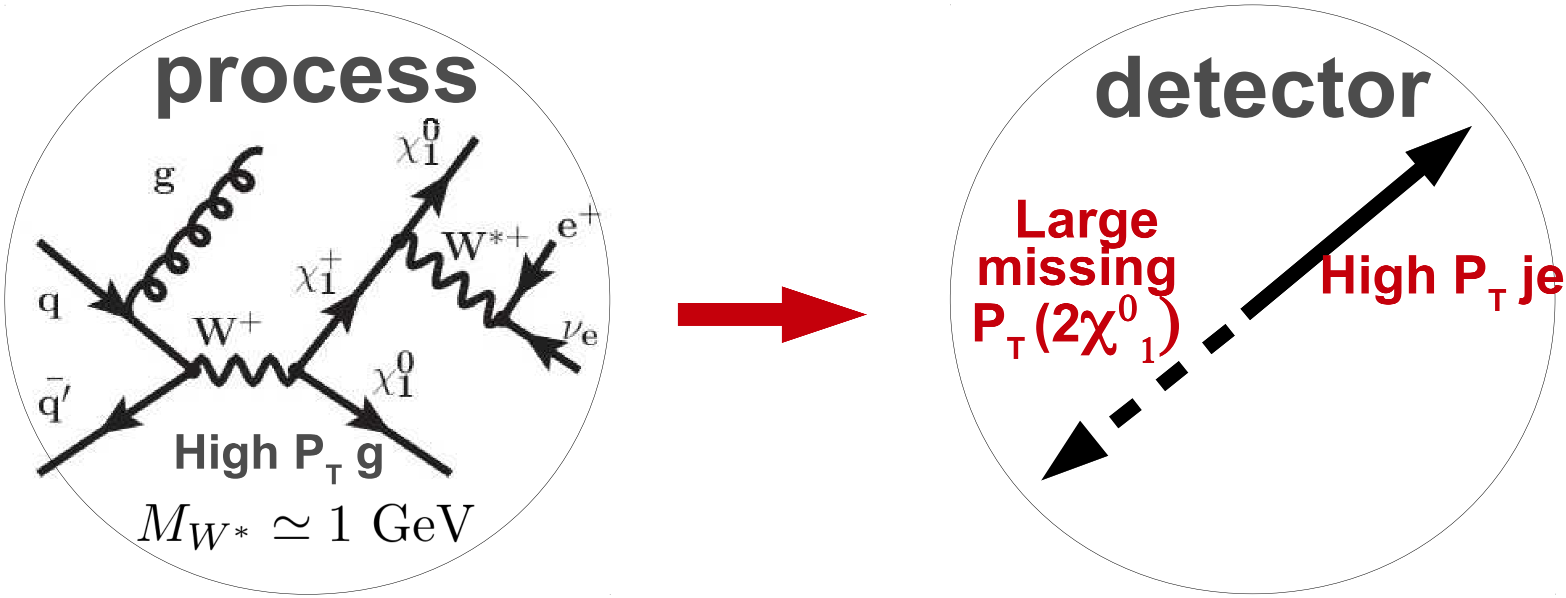
There is no limit on the LSP mass if the mass of strongly interacting SUSY particles above ~ 1.9 TeV





SUSY Compressed Mass Spectrum scenario

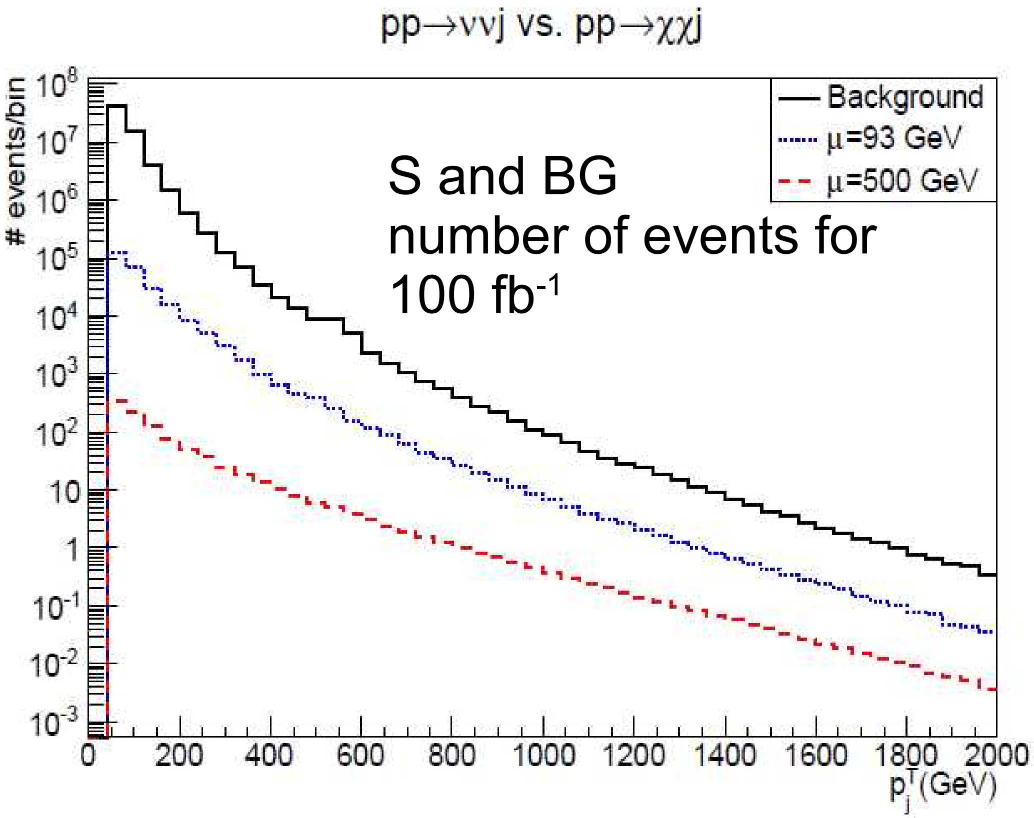
- The most challenging case takes place when only $\chi^0_{1,2}$ and $\chi^\pm$ are accessible at the LHC, and the mass gap between them is not enough for any leptonic signature
- The only way to probe CHS is a mono-jet signature
  [“Where the Sidewalk Ends? ...” Alves, Izaguirre,Wacker '11] ,
  which 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



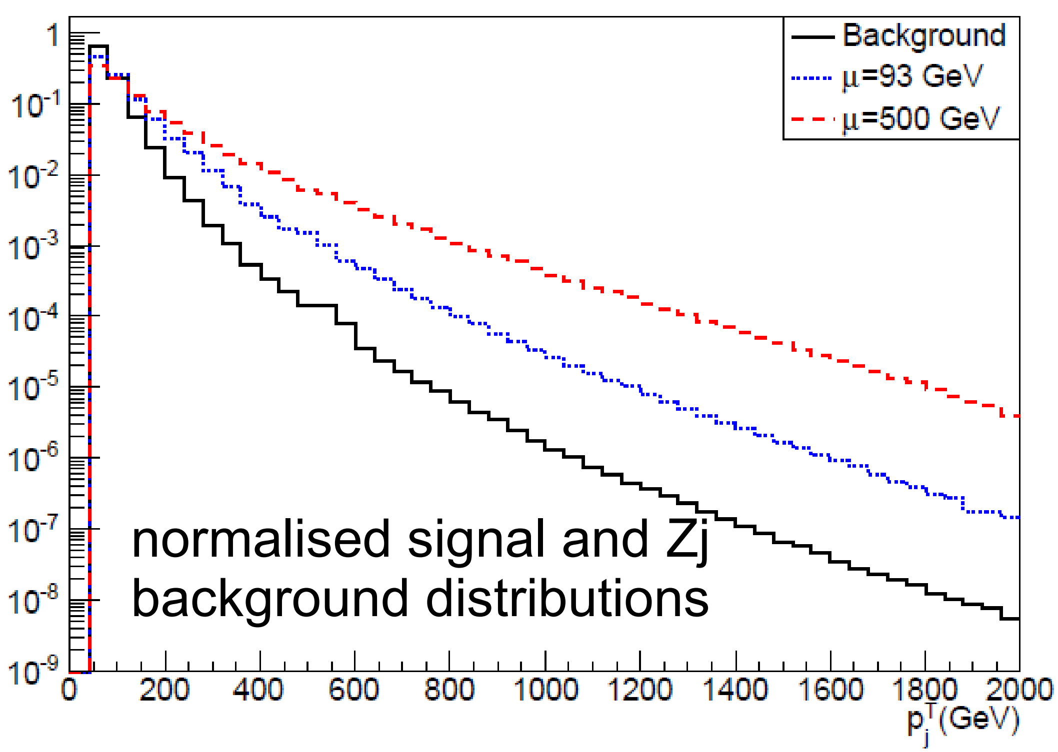
Signal vs Background

- *difference in rates is pessimistic ...*

- *but the difference in shapes is encouraging, especially for large DM mass → biger M(DM,DM) → flatter MET*



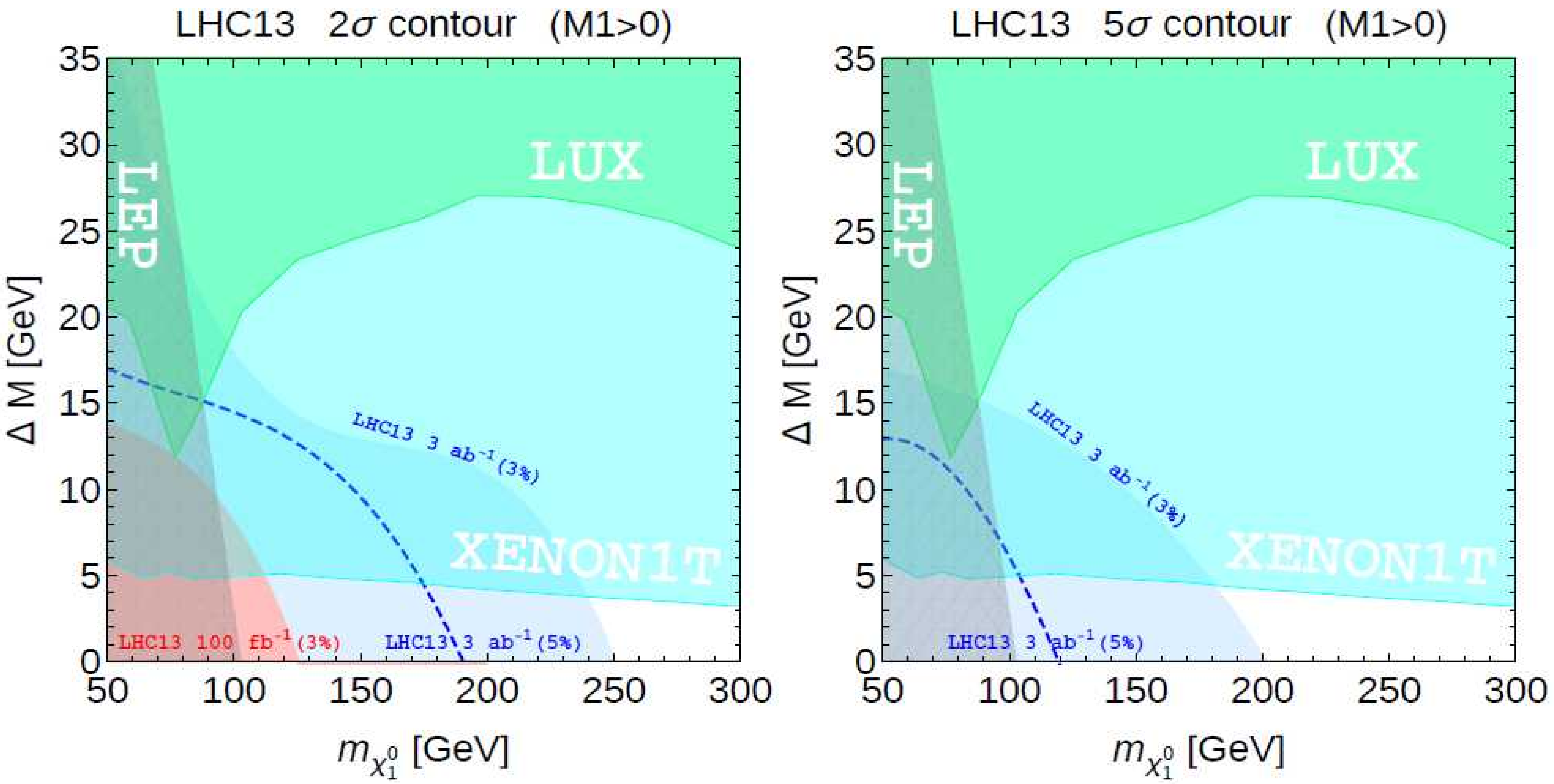
S and BG number of events for 100 fb^{-1}



normalised signal and Zj background distributions

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

LHC/DM direct detection sensitivity

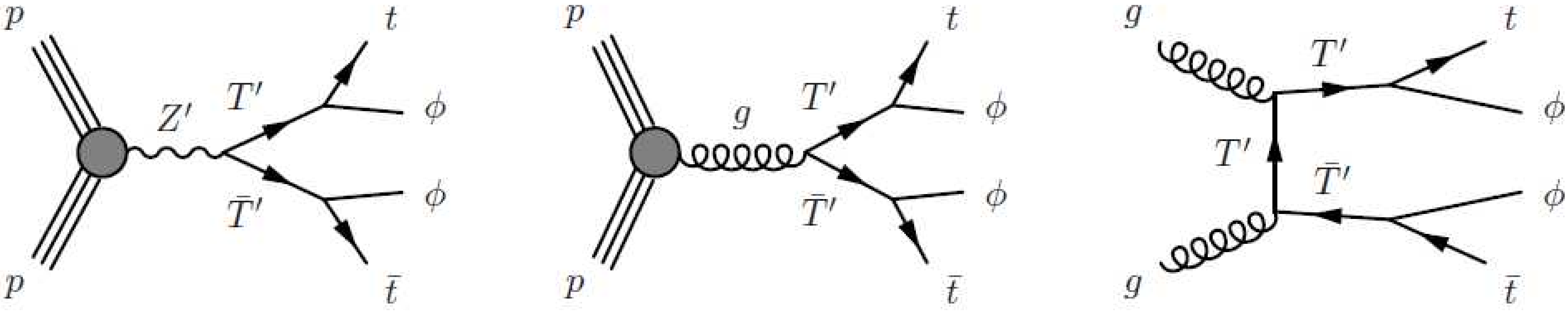


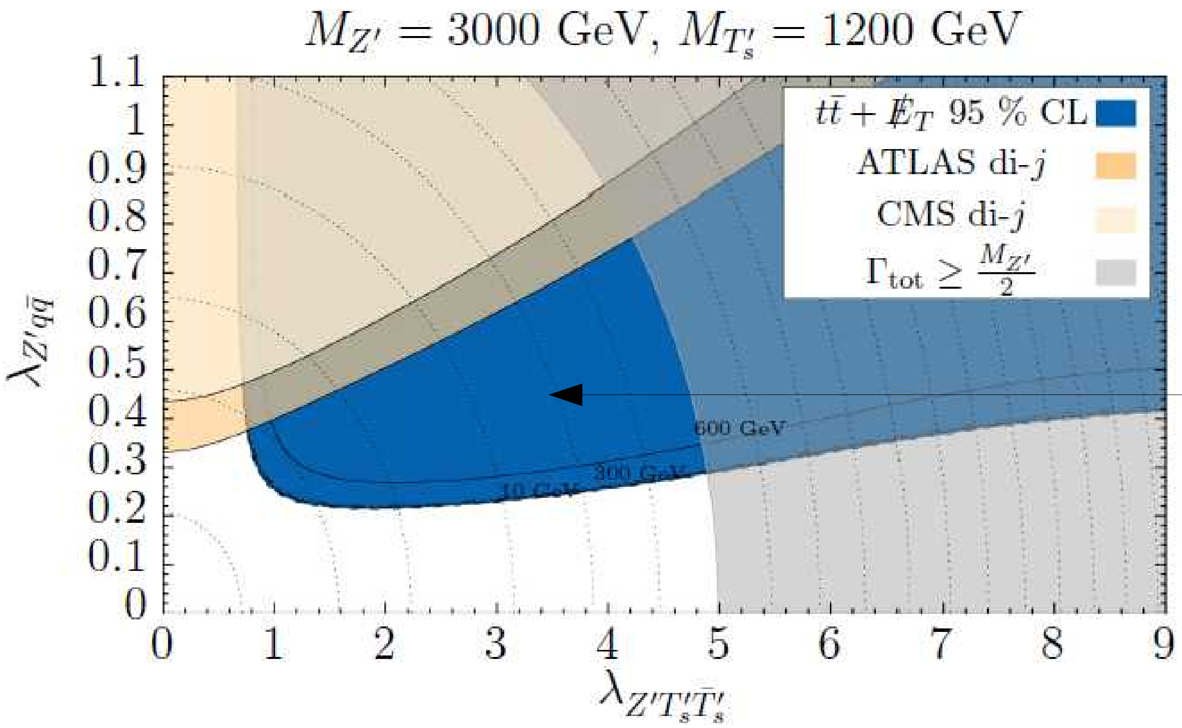
AB, Barducci,Bharucha,Porod,Sanz JHEP, 1504.02472

- 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

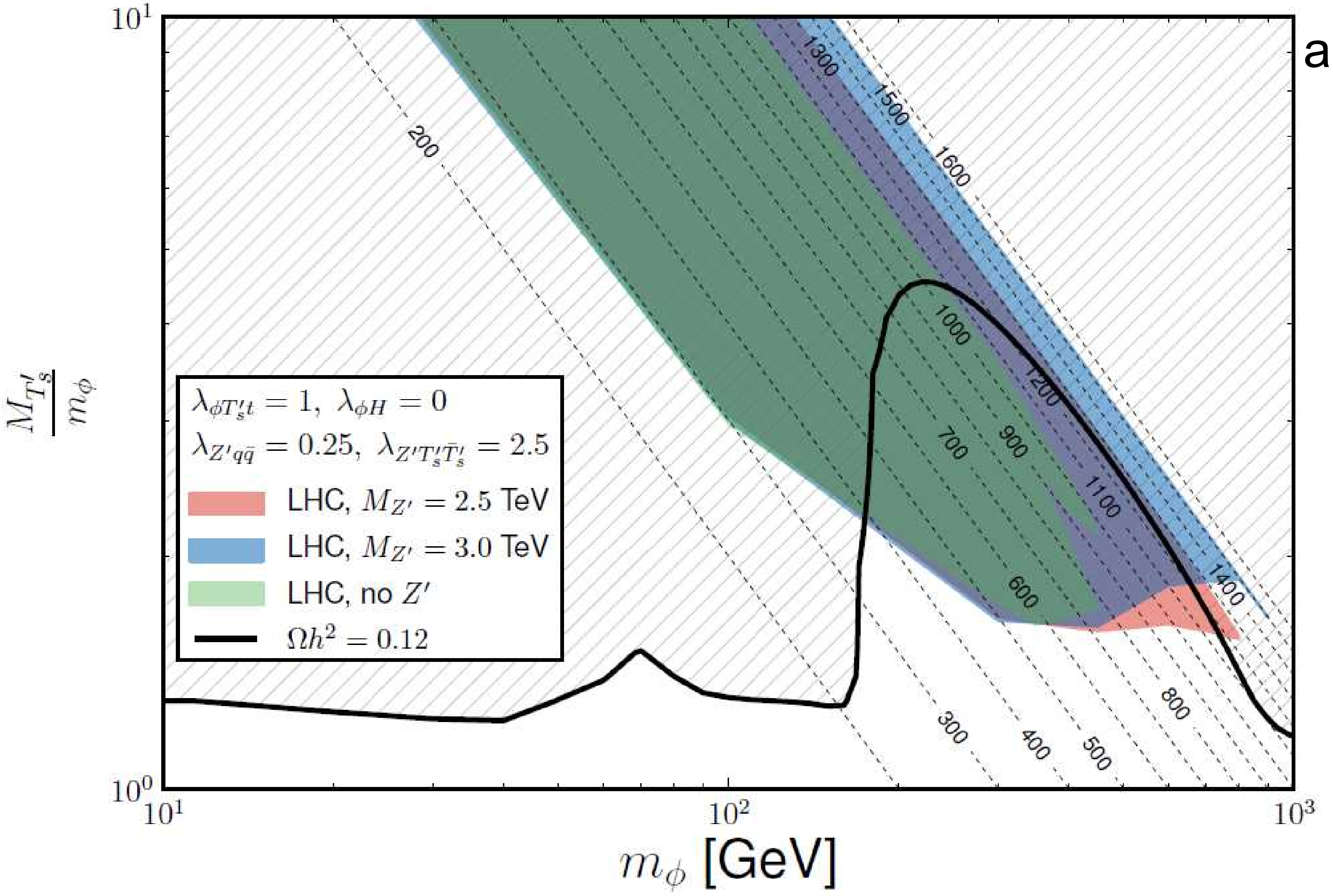




Current LHC reach with tt+ MET signature based on ATLAS_CONF_2016_050 results

Flacke, Jaine, Schaefers, AB
arXiv: 1707.07000

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



arXiv: 1707.07000

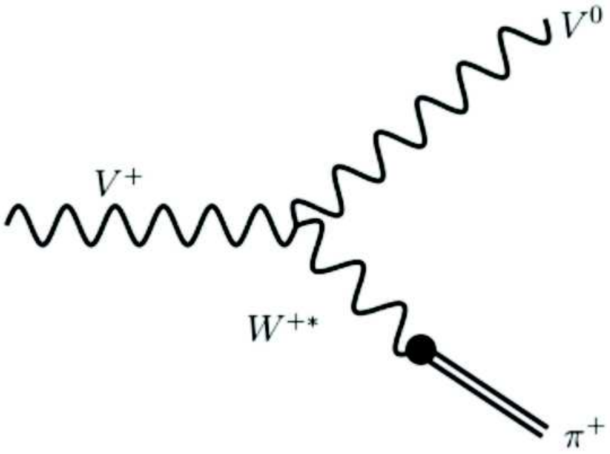
Z' + QCD TT production

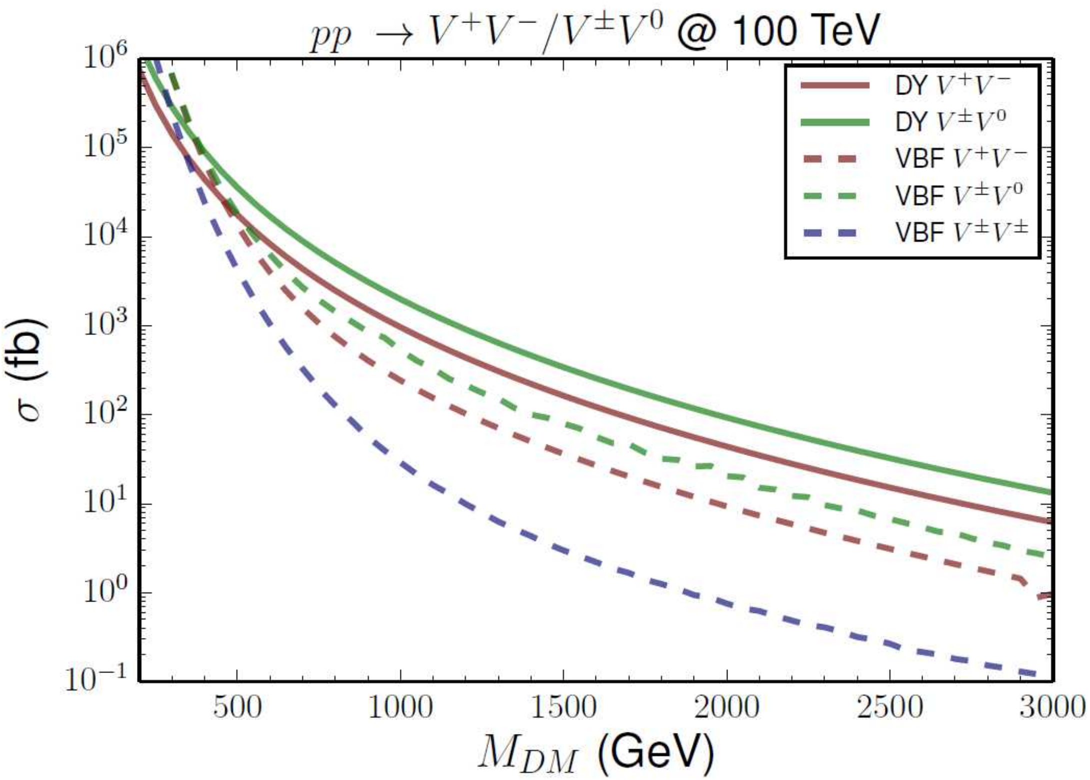
- LHC is probing now DM and top partner masses up to about 0.9 and 1.5 TeV respectively: above bounds from QCD production alone by ~ factor of two
- DM DD rates are loop-suppressed

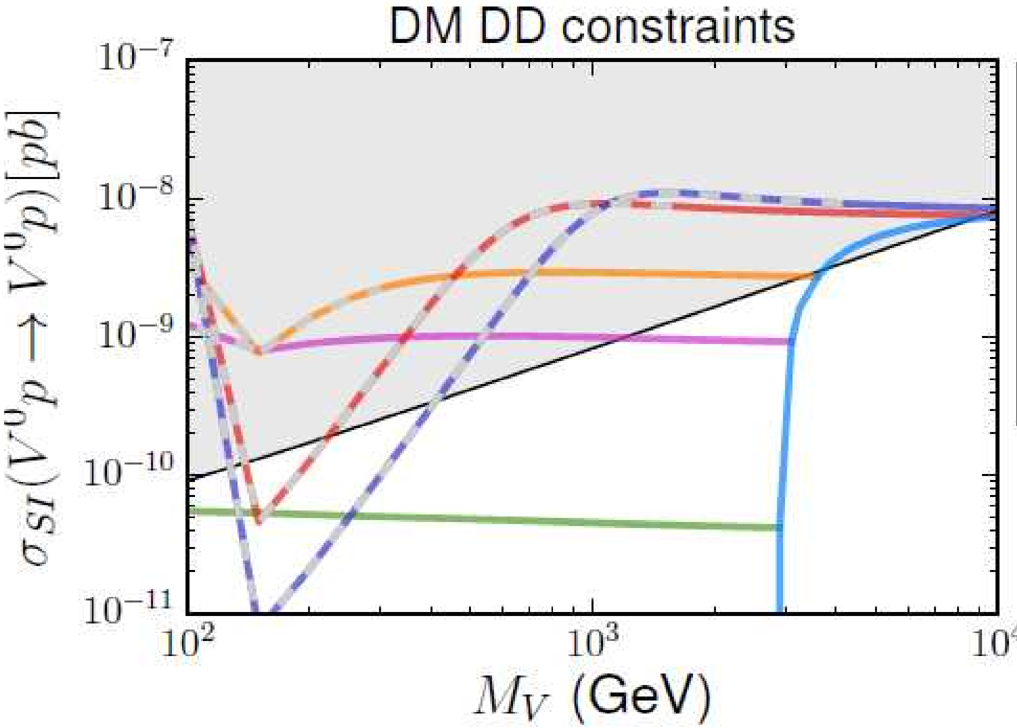
Disappearing Charged Tracks from DM

The small mass gap between (~ pion mass) 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)





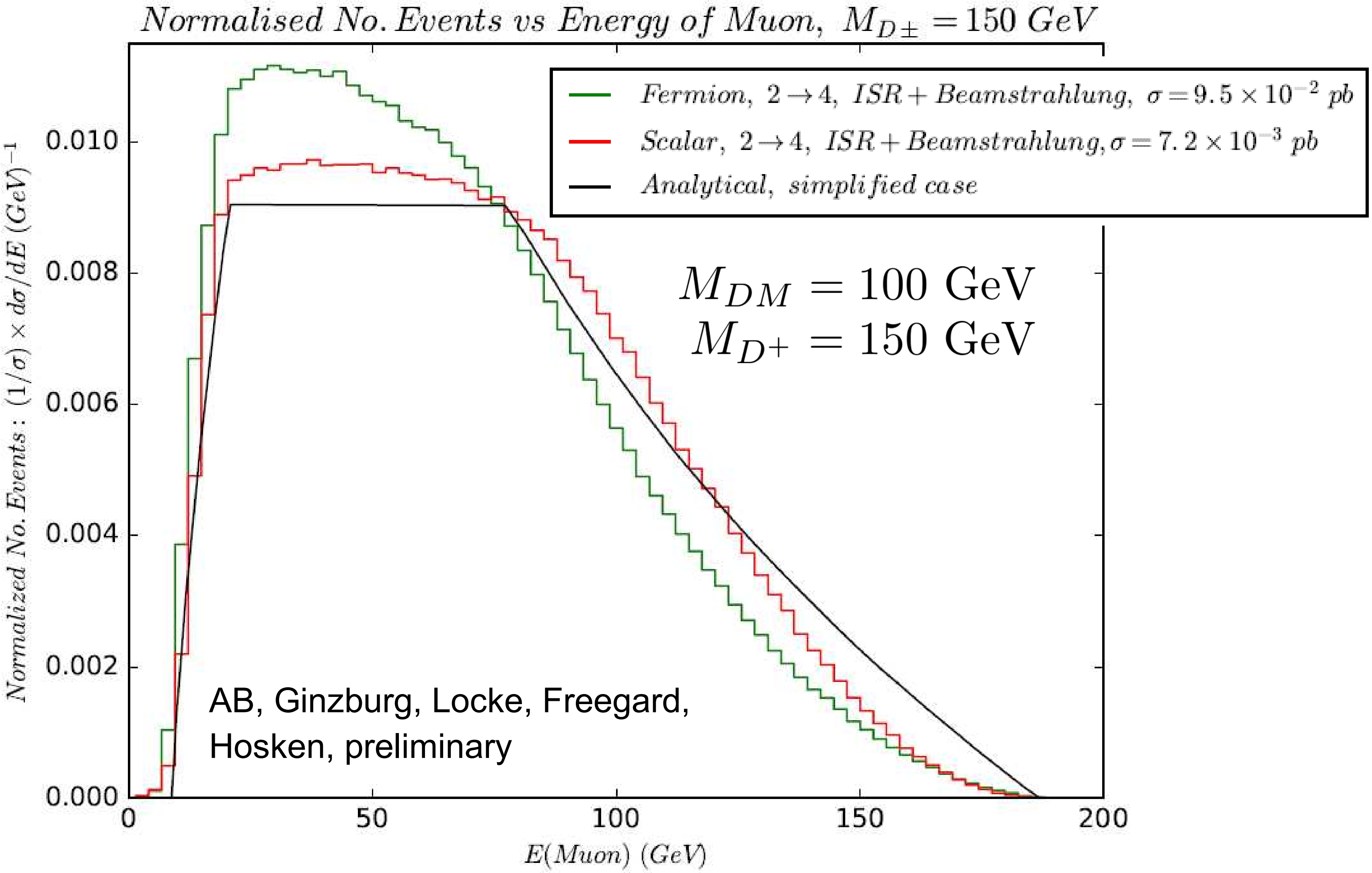


AB, Cacciapaglia, McKay, Marin, Zerwekh

Decoding the nature of DM at the ILC

muon spectrum from the models with scalar and fermion DM

$$e^+e^- \to D^+ D^- \to DM\ DM\ W^+ W^- \to DM\ DM\ jj\ \mu\ \nu$$



$$M_{DM} = 100 \text{ GeV}$$
$$M_{D^+} = 150 \text{ GeV}$$

AB, Ginzburg, Locke, Freegard, Hosken, preliminary

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

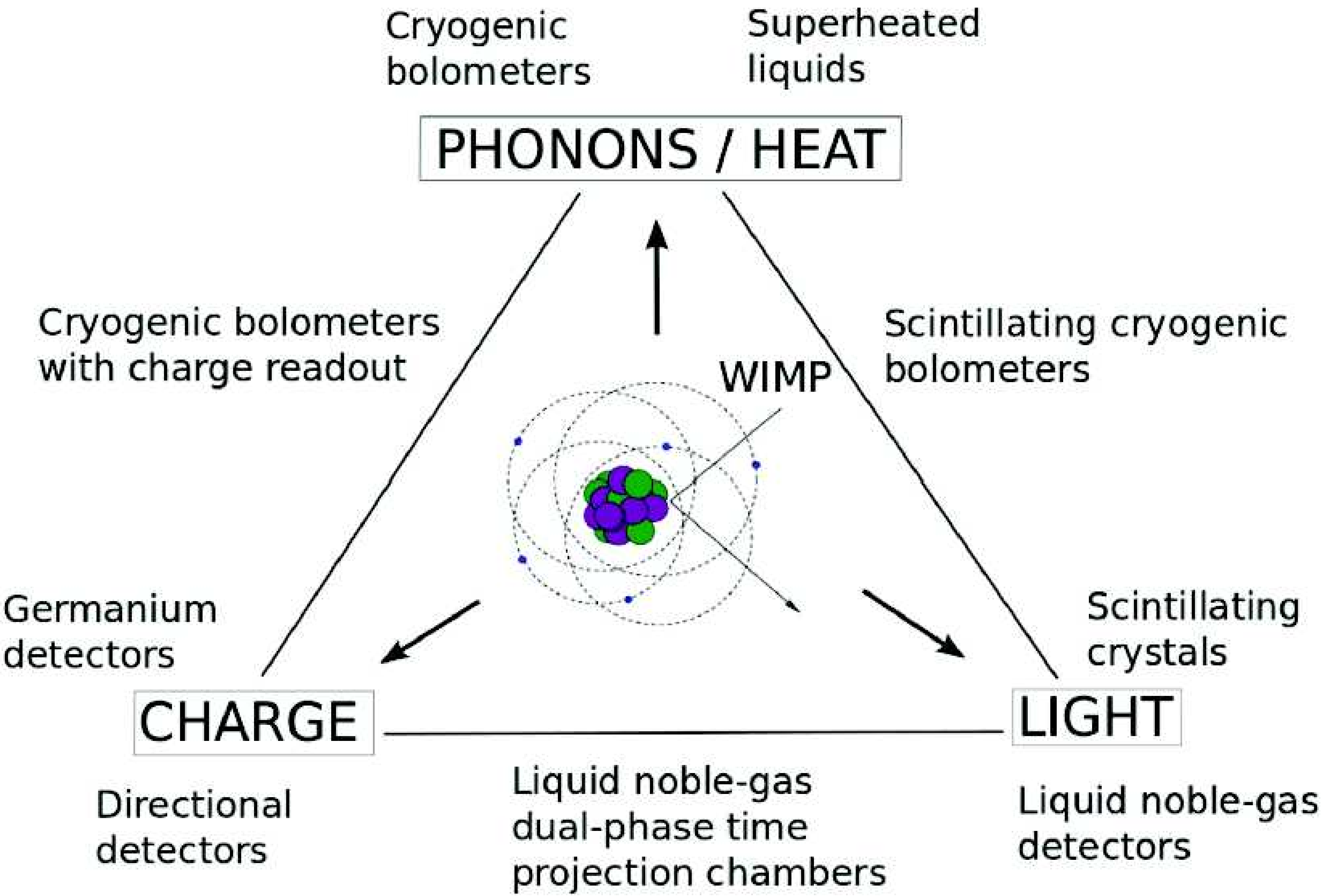
Summary

- 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 we hope to observe soon
- New prospects: new DD experiments, new ideas, prospects for directional DM detection, new signatures at colliders (VFB, long lived …), new colliders (hopefully!)

Thank you!

Backup Slides

Direct detection Techniques



Cryogenic bolometers

Superheated liquids

PHONONS / HEAT

Cryogenic bolometers with charge readout

Scintillating cryogenic bolometers

WIMP

Germanium detectors

Scintillating crystals

CHARGE

LIGHT

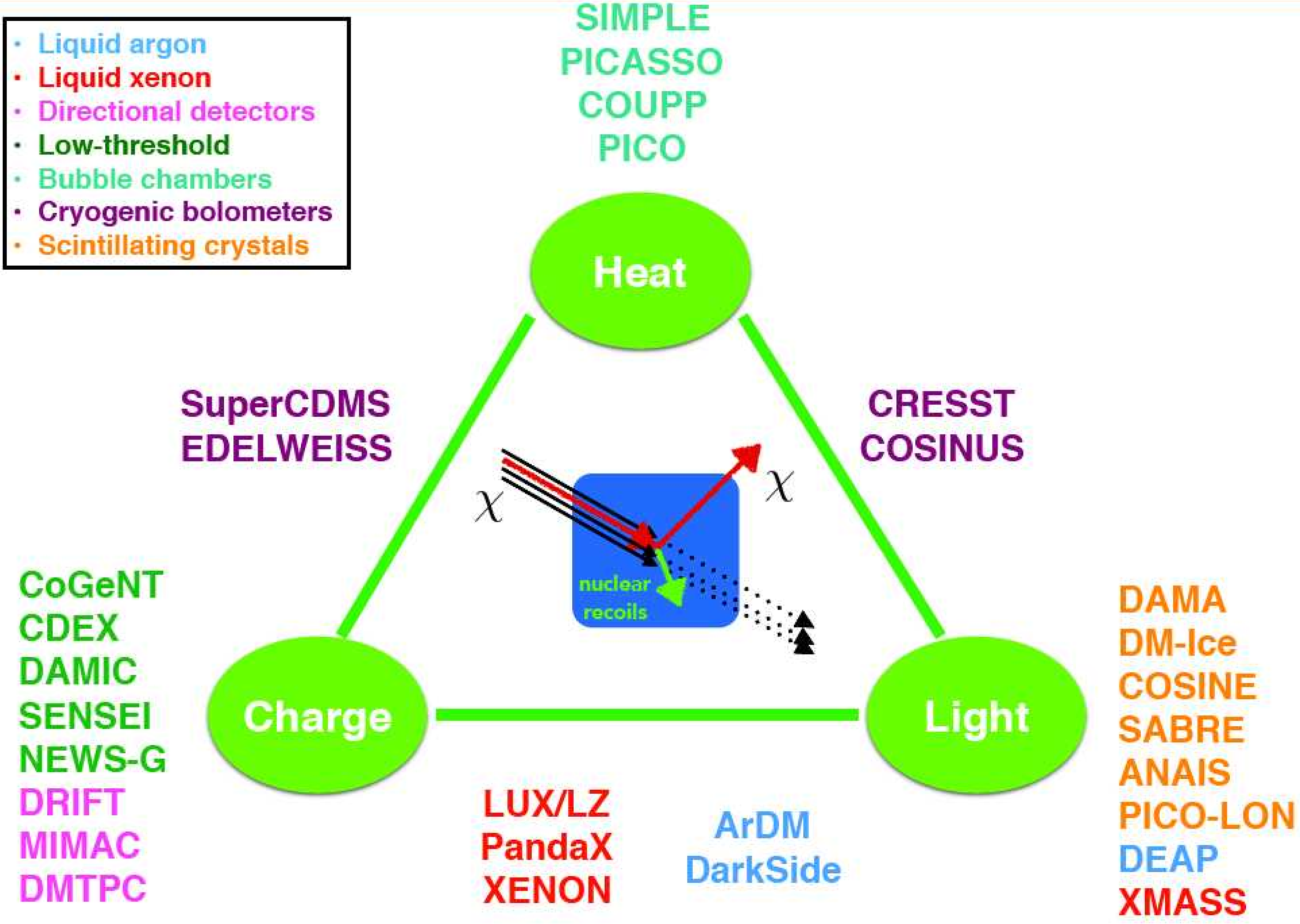
Directional detectors

Liquid noble-gas dual-phase time projection chambers

Liquid noble-gas detectors

J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

Direct Detection Techniques



- Liquid argon
- Liquid xenon
- Directional detectors
- Low-threshold
- Bubble chambers
- Cryogenic bolometers
- Scintillating crystals

SIMPLE
PICASSO
COUPP
PICO

SuperCDMS
EDELWEISS

CRESST
COSINUS

CoGeNT
CDEX
DAMIC
SENSEI
NEWS-G
DRIFT
MIMAC
DMTPC

LUX/LZ
PandaX
XENON

ArDM
DarkSide

DAMA
DM-Ice
COSINE
SABRE
ANAIS
PICO-LON
DEAP
XMASS

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

- the connection between physics at high and low energy is crucial to properly explore complementarity collider and non-collider DM experiments
- RGEs for the EFT introduce the mixing between different operators

Kopp,Niro,Schwetz,Zupan(2009); Hill, Solon(2012); Frandsen, Haisch, Kahlhoefer, Mertsch, Schmidt-Hoberg (2012); Kopp,Michaels, Smirnov(2014); Crivellin,D'Eramo,Procura(2014);Crivellin, Haisch(2014); Berlin, Robertson,Solon,Zurek(2016); D'Eramo, de Vries, Panci(2016); D'Eramo,Kavanagh, Panci(2016)

$$\mathcal{L} \supset -\frac{J^{\mu}_{DM} J_{SM,\mu}}{\Lambda^2}, \qquad J^{SM}_{\mu} = \sum_{i=1}^{3} \left[c^{(i)}_{Vq}(\Lambda)\, \overline{q^{(i)}} \gamma_\mu q^{(i)} + c^{(i)}_{Aq}(\Lambda)\, \overline{u^{(i)}} \gamma_\mu \gamma_5 u^{(i)} + \ldots \right]$$

let us take, for example, $J^{\mu}_{DM} = c_{V\chi}\, \overline{\chi} \gamma^\mu \chi + c_{A\chi}\, \overline{\chi} \gamma^\mu \gamma_5 \chi$

Once the wilson coefficient are evolved at the low scale, we need to match the low energy parton-level lagrangian with the low energy nucleon one

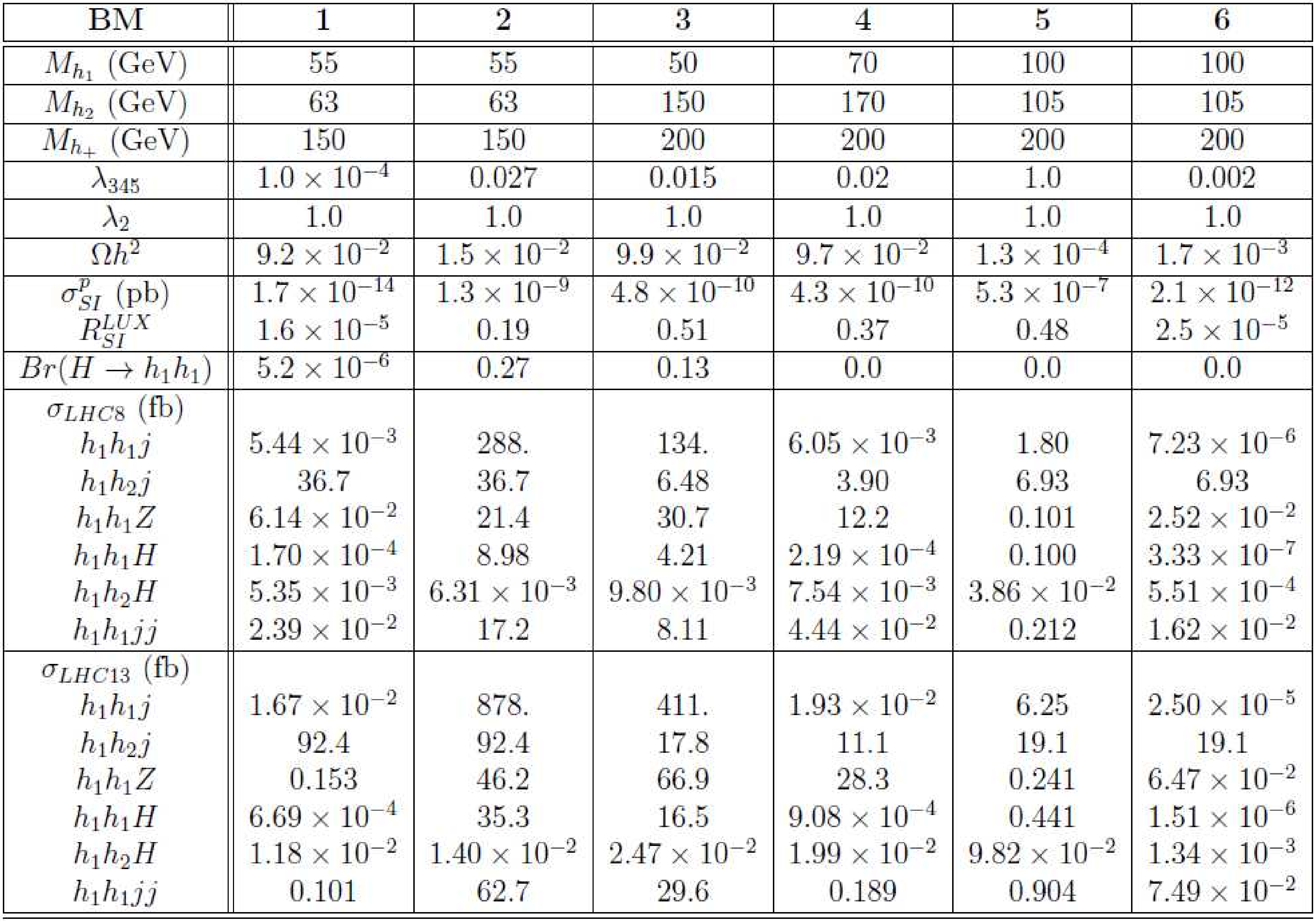
$$\mathcal{L} \supset -\frac{J^{\mu}_{DM}}{\Lambda^2} \left(c^{(N)}_{V} \overline{N} \gamma_\mu N + c^{(N)}_{A} \overline{N} \gamma_\mu \gamma_5 N \right)$$

and

$$\sigma^{N}_{SI} = \frac{\mu^2_N}{\pi} \frac{(c_{V\chi} c^{(N)}_{V})^2}{\Lambda^4}$$

where $\mu_N = m_\chi m_N / (m_\chi + m_N)$

i2HDM benchmarks



BM	1	2	3	4	5	6
M_{h_1} (GeV)	55	55	50	70	100	100
M_{h_2} (GeV)	63	63	150	170	105	105
M_{h_+} (GeV)	150	150	200	200	200	200
λ_{345}	1.0×10^{-4}	0.027	0.015	0.02	1.0	0.002
λ_2	1.0	1.0	1.0	1.0	1.0	1.0
Ωh^2	9.2×10^{-2}	1.5×10^{-2}	9.9×10^{-2}	9.7×10^{-2}	1.3×10^{-4}	1.7×10^{-3}
σ^p_{SI} (pb)	1.7×10^{-14}	1.3×10^{-9}	4.8×10^{-10}	4.3×10^{-10}	5.3×10^{-7}	2.1×10^{-12}
R^{LUX}_{SI}	1.6×10^{-5}	0.19	0.51	0.37	0.48	2.5×10^{-5}
$Br(H \to h_1 h_1)$	5.2×10^{-6}	0.27	0.13	0.0	0.0	0.0
σ_{LHC8} (fb)						
$h_1 h_1 j$	5.44×10^{-3}	288.	134.	6.05×10^{-3}	1.80	7.23×10^{-6}
$h_1 h_2 j$	36.7	36.7	6.48	3.90	6.93	6.93
$h_1 h_1 Z$	6.14×10^{-2}	21.4	30.7	12.2	0.101	2.52×10^{-2}
$h_1 h_1 H$	1.70×10^{-4}	8.98	4.21	2.19×10^{-4}	0.100	3.33×10^{-7}
$h_1 h_2 H$	5.35×10^{-3}	6.31×10^{-3}	9.80×10^{-3}	7.54×10^{-3}	3.86×10^{-2}	5.51×10^{-4}
$h_1 h_1 jj$	2.39×10^{-2}	17.2	8.11	4.44×10^{-2}	0.212	1.62×10^{-2}
σ_{LHC13} (fb)						
$h_1 h_1 j$	1.67×10^{-2}	878.	411.	1.93×10^{-2}	6.25	2.50×10^{-5}
$h_1 h_2 j$	92.4	92.4	17.8	11.1	19.1	19.1
$h_1 h_1 Z$	0.153	46.2	66.9	28.3	0.241	6.47×10^{-2}
$h_1 h_1 H$	6.69×10^{-4}	35.3	16.5	9.08×10^{-4}	0.441	1.51×10^{-6}
$h_1 h_2 H$	1.18×10^{-2}	1.40×10^{-2}	2.47×10^{-2}	1.99×10^{-2}	9.82×10^{-2}	1.34×10^{-3}
$h_1 h_1 jj$	0.101	62.7	29.6	0.189	0.904	7.49×10^{-2}

A Simplified Model with Vector Resonances, Top Partners and Scalar DM

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{SM} + \mathcal{L}_{kin} + \mathcal{L}_{Z'q} + \mathcal{L}_{Z'\ell} + \mathcal{L}_{Z'Q'} + \mathcal{L}_{\phi Q'} - V_\phi \\
\mathcal{L}_{kin} &= -\frac{1}{4}\left(\partial_\mu Z'_\nu - \partial_\nu Z'_\mu\right)\left(\partial^\mu Z'^\nu - \partial_\nu Z'^\mu\right) + \frac{M_{Z'}^2}{2} Z'_\mu Z'^\mu \\
&\quad + \frac{1}{2}\partial_\mu \phi \, \partial^\mu \phi - \frac{m_\phi^2}{2}\phi^2 \\
&\quad + \overline{T'_s}\left(i\not{D} - M_{T'_s}\right) T'_s + \overline{Q'_d}\left(i\not{D} - M_{T'_d}\right) Q'_d \,, \\
\mathcal{L}_{Z'q} &= \lambda_{Z'q\bar{q},L/R} \, Z'_\mu \left(\bar{q}_{L/R} \, \gamma^\mu \, q_{L/R}\right) \,, \\
\mathcal{L}_{Z'\ell} &= \lambda_{Z'\ell^+\ell^-,L/R} \, Z'_\mu \left(\bar{\ell}_{L/R} \, \gamma^\mu \, \ell_{L/R}\right) \,, \\
\mathcal{L}_{Z'Q'} &= \lambda_{Z'T'_s\overline{T'_s},L/R} \, Z'_\mu \left(\overline{T'}_{s,L/R} \, \gamma^\mu \, q_{L/R}\right) \\
&\quad + \lambda_{Z'T'_d\overline{T'_d},L/R} \, Z'_\mu \left(\overline{T'}_{d,L/R} \, \gamma^\mu \, T'_{d,L/R}\right) \\
&\quad + \lambda_{Z'T'_d\overline{T'_d},L/R} \, Z'_\mu \left(\overline{B'}_{d,L/R} \, \gamma^\mu \, B'_{d,L/R}\right) \,, \\
\mathcal{L}_{\phi Q'} &= \left(\lambda_{\phi T'_s t} \, \phi \, \bar{t}_R \, T'_{s,R} + \lambda_{\phi T'_d t} \, \phi \, \bar{t}_L \, T'_{d,L} + \lambda_{\phi T'_d t} \, \phi \, \bar{b}_L \, B'_{d,L}\right) + \text{h.c.} \,, \\
V_\phi &= \frac{\lambda_\phi}{4!}\phi^4 + \frac{\lambda_{\phi H}}{2}\phi^2\left(|H|^2 - \frac{v^2}{2}\right) .
\end{aligned}
$$

Parameterisation of the Vector DM operators

- The cross section for qq(gg) → DM DM process with

  a power of the energy asymptotic, Δ_s takes a form: $\sigma_{2\to 2} \propto \frac{1}{\Lambda^2} \times \left(\frac{E}{\Lambda}\right)^{\Delta_\sigma}$

- On the other hand, from EFT operator we have: $\sigma_{2\to 2} \propto \frac{1}{E^2} \times \left(\frac{E^{D-4}}{\Lambda^{D-4}}\right)^2$

  where ***D*** **is the actual energy** dimension of the EFT operator

- So, one finds: $\Delta_\sigma = 2(D-5) \implies D = \Delta_\sigma/2 + 5$
  - ***Note: D*** can be different from naive dimension ***d = 5 or 6***
  - consider V7P as an example: $\frac{1}{2\Lambda^2}(V_\nu^\dagger \partial^\nu V_\mu + V^\nu \partial^\nu V_\mu^\dagger)\bar{q}\gamma^\mu q$
  - with *d*=*6*, however for each (allowed) VDM longitudinal polarisation there is an additional **(E/M_{DM})** factor, so the actual energy scaling of VDM EFT operator, ***D*** is different!

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 **M_{DM}/Λ** factor for each power of **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

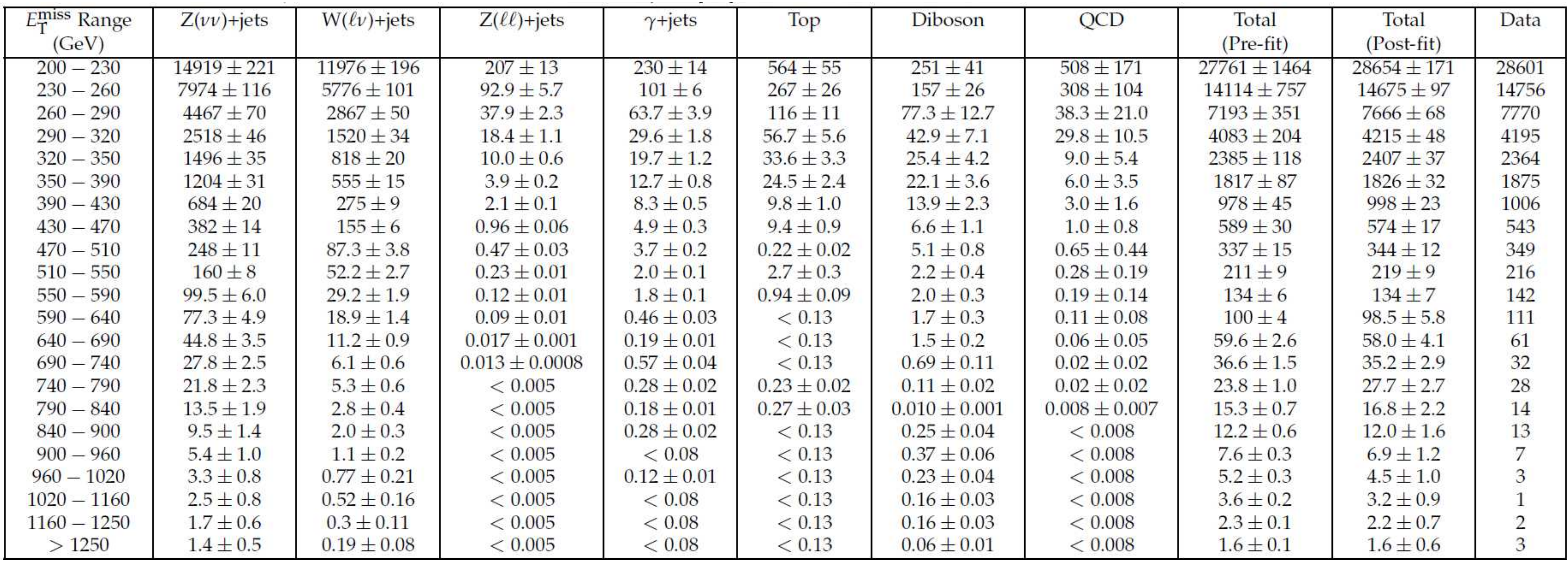
- Dictionary between limits on Λ in different parametrisations:

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

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



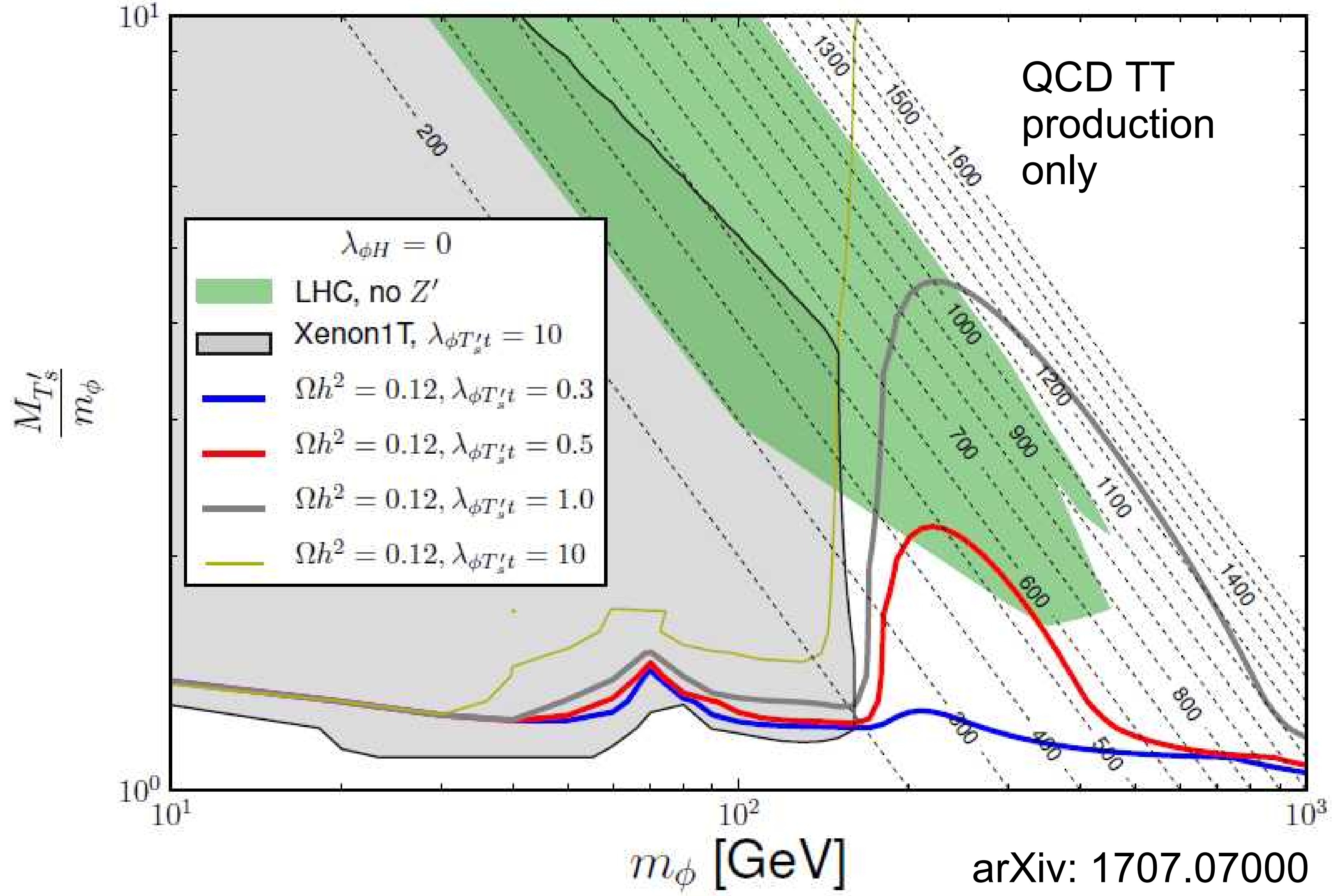
E_T^{miss} Range (GeV)	Z(νν)+jets	W(ℓν)+jets	Z(ℓℓ)+jets	γ+jets	Top	Diboson	QCD	Total (Pre-fit)	Total (Post-fit)	Data
$200-230$	14919 ± 221	11976 ± 196	207 ± 13	230 ± 14	564 ± 55	251 ± 41	508 ± 171	27761 ± 1464	28654 ± 171	28601
$230-260$	7974 ± 116	5776 ± 101	92.9 ± 5.7	101 ± 6	267 ± 26	157 ± 26	308 ± 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

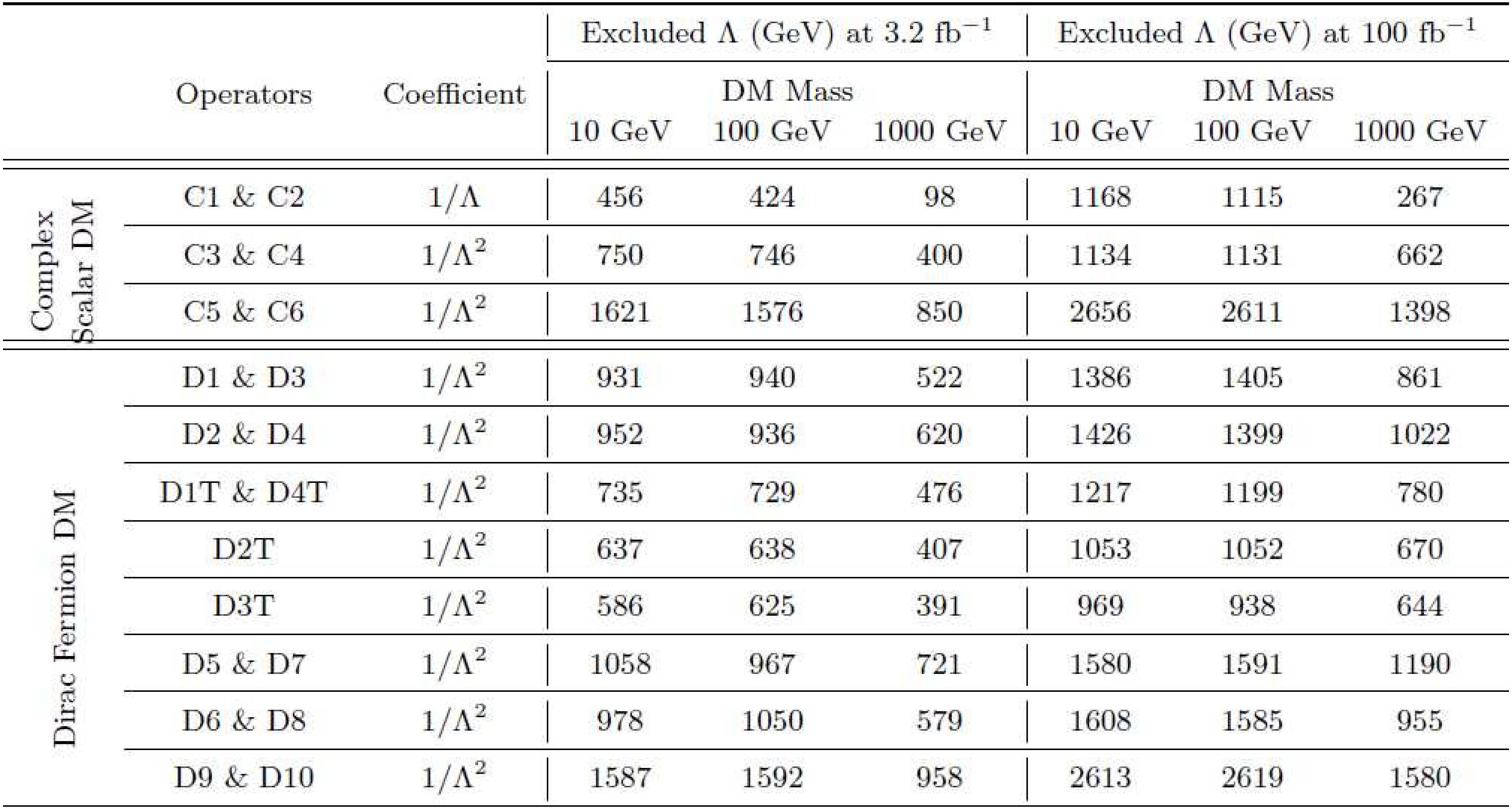
TT→ t t DM DM



QCD TT production only

arXiv: 1707.07000

LHC@13TeV Reach for spin 0 and ½ DM

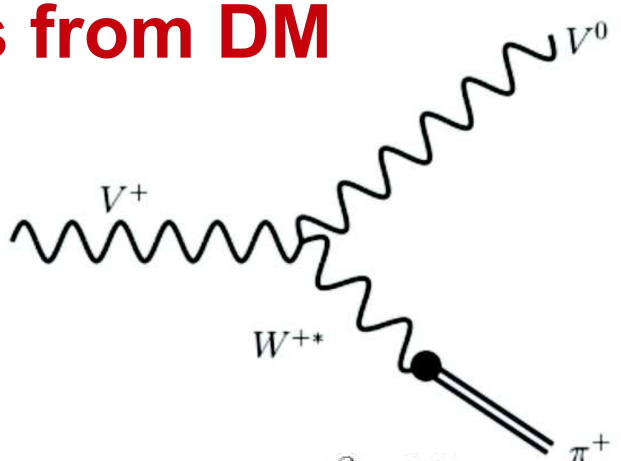


	Operators	Coefficient	Excluded Λ (GeV) at 3.2 fb^{-1}			Excluded Λ (GeV) at 100 fb^{-1}		
			DM Mass			DM Mass		
			10 GeV	100 GeV	1000 GeV	10 GeV	100 GeV	1000 GeV
Complex Scalar DM	C1 & C2	$1/\Lambda$	456	424	98	1168	1115	267
	C3 & C4	$1/\Lambda^2$	750	746	400	1134	1131	662
	C5 & C6	$1/\Lambda^2$	1621	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

			Excluded Λ (GeV) at 3.2 fb^{-1}			Excluded Λ (GeV) at 100 fb^{-1}		
	Operators	Coefficient	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

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