The Interplay between Direct Detection and Collider searches

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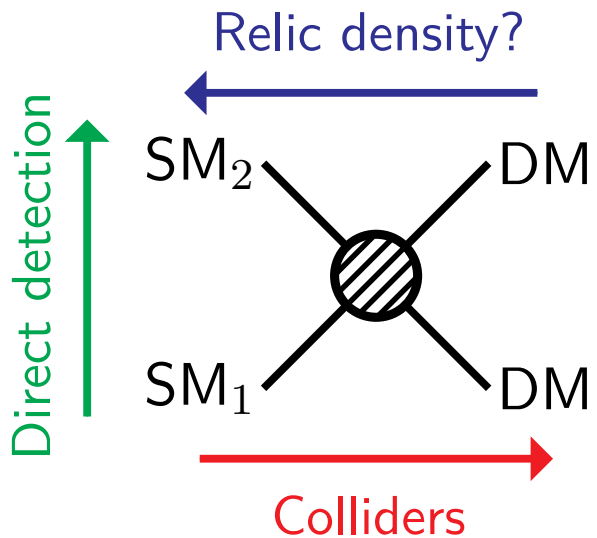
Dark Matter: the first steps

- **Hypothesis**: non-gravitational DM-SM interactions
  DM mass in 1 GeV – 10 TeV
  - $\Rightarrow$ DM-nucleus interactions: Direct Detection (DD)
  - $\Rightarrow$ DM production at colliders
- Starting point: focus on a single DM-SM interaction process



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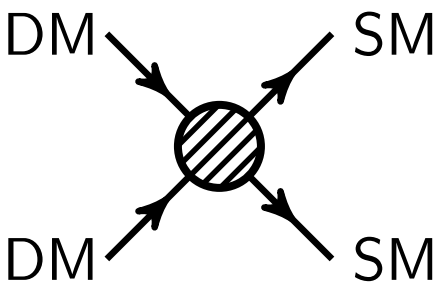
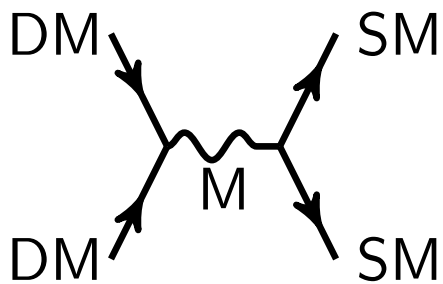
Effective Operators

Direct detection



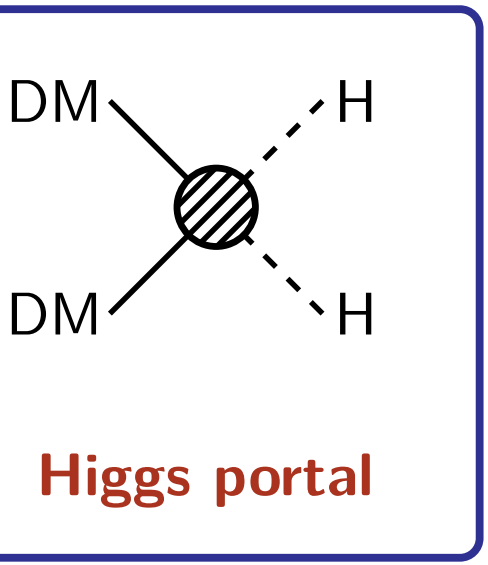
Simplified Models

Colliders

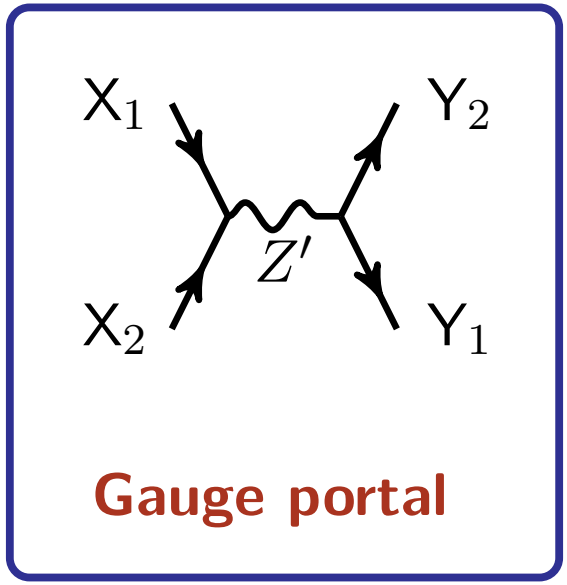


- NOT consistent theories! $\Rightarrow$ Very limited range of validity
- Limited number of parameters – Simple and generic conclusions

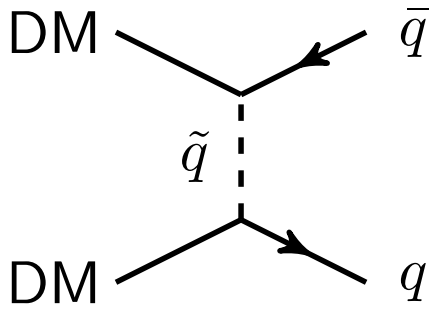
Simplified models: the portals



Higgs portal



Gauge portal



"Squark" portal

- Manageable number of parameters: from 2 to 8
- Categorizing: DM spin + type of interactions

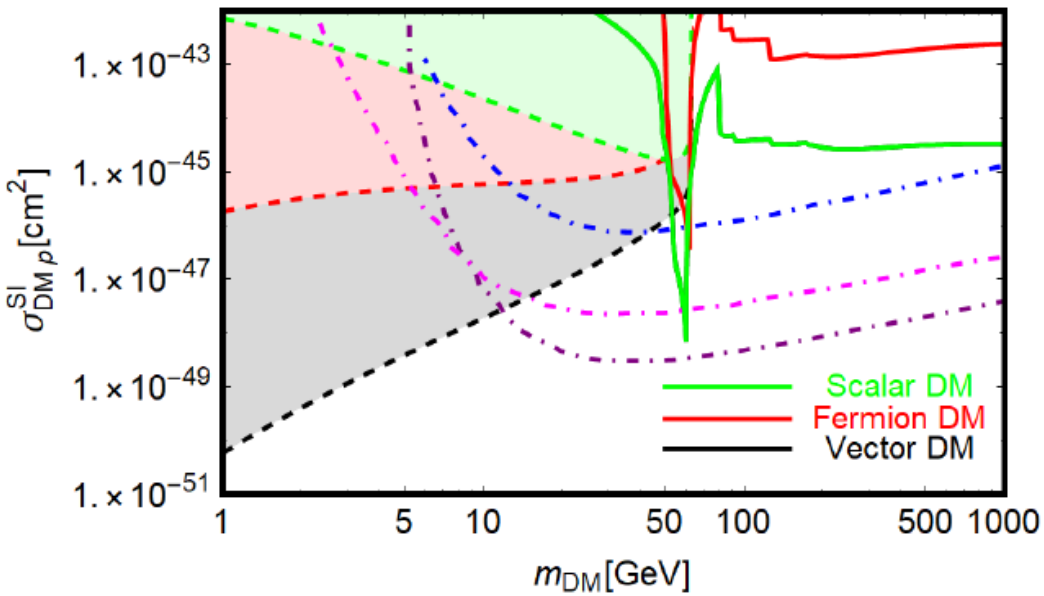
Example: $\overline{\chi} h \chi$ $i$vs $\overline{\chi} \gamma_5 h \chi$

- Limited number of LHC searches:
  - Higgs invisible width
  - (mono)jet + $\not{E}_T$
  - dijet/dilepton resonances

Portals: main conclusions

Complementarity

- Colliders: $m_{\rm DM} \lesssim 10$ GeV
- Direct detection
  10 GeV $\rightarrow$ multi-TeV



[Arcadi et al, arXiv:1903:03616]

- **Direct detection "on/off switch"**
  - **Spin-Independent (SI)** cross-section: tight constraints
  - **Spin-dependent (SD)/velocity-suppressed SI**: very weak constraints
- **"Blind spots"**:
  - Pseudoscalar Higgs portal: $\overline{\chi}\gamma_5 h\chi$
  - Leptophobic axial-vector Z': $\overline{\chi}\gamma_\mu\gamma_5\chi Z'^\mu$
  - Squark portal with Majorana DM

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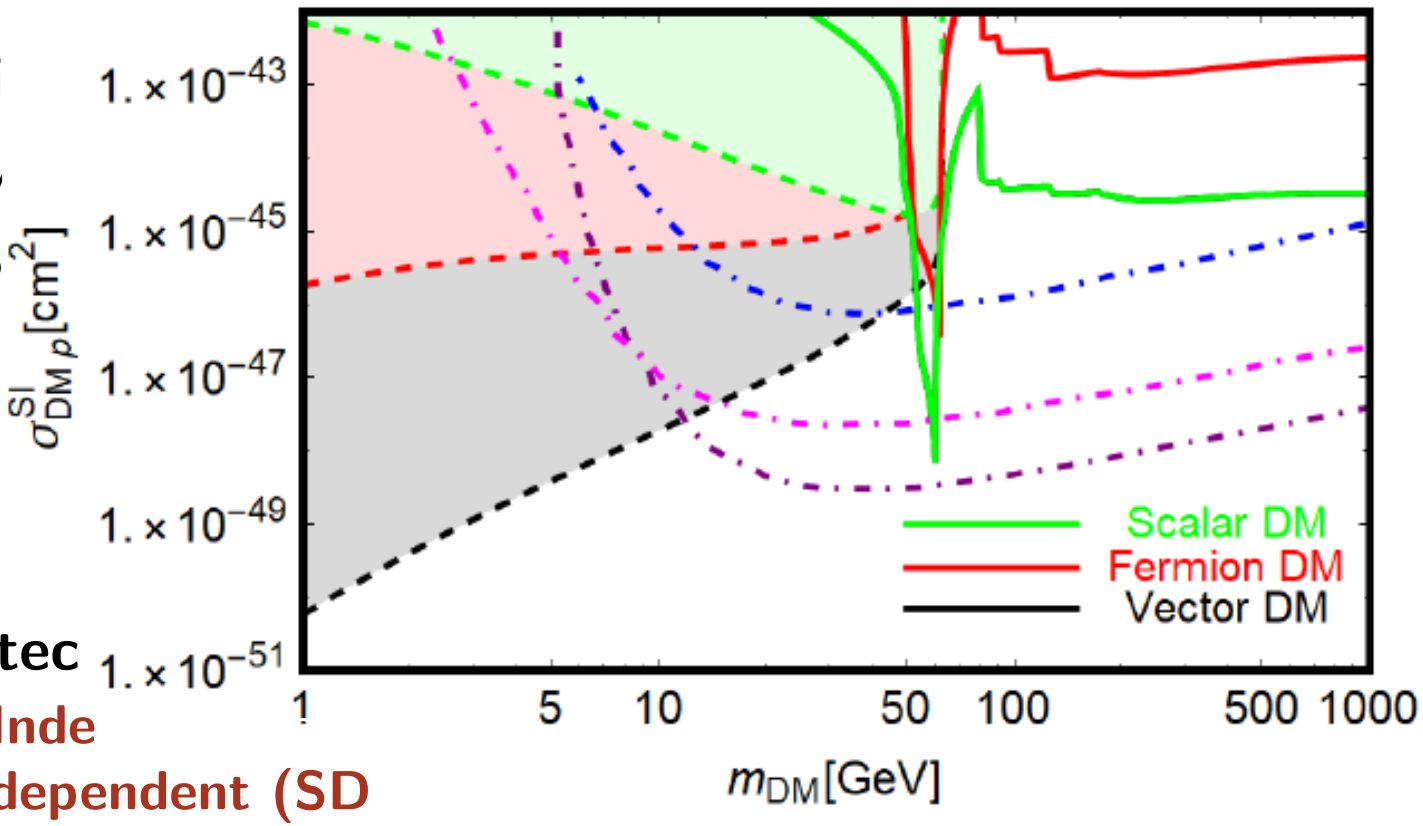

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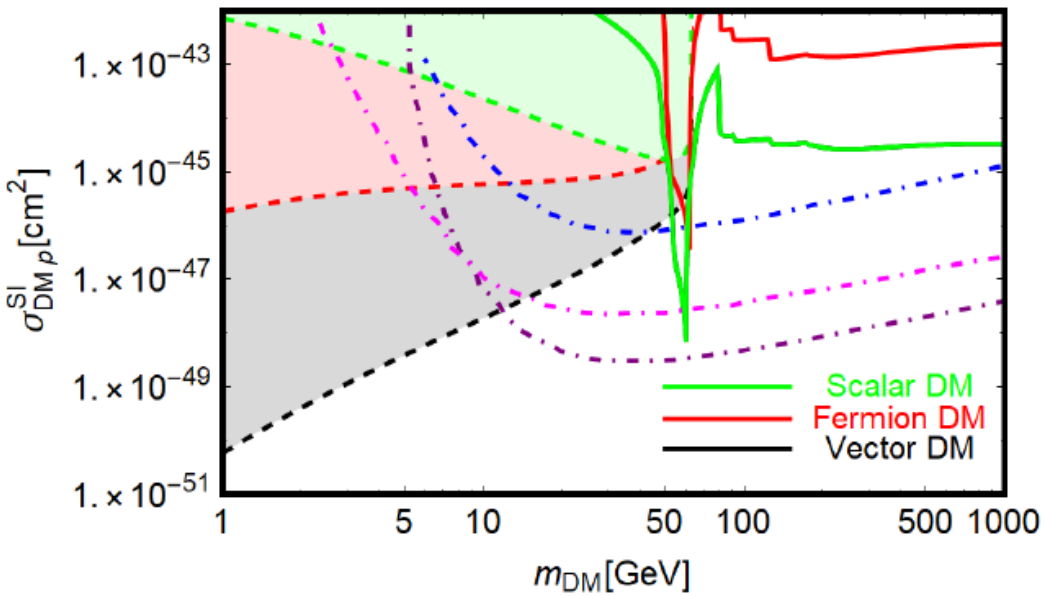

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Dark matter viewed from portals

Direct Detection

$m_{\text{DM}} \gtrsim 10$ GeV

SI unsuppressed

Strong constraints up to $\mathcal{O}(10)$ TeV

SI suppressed

Very weak or no constraints

Colliders

$1\,\text{GeV} \longrightarrow 1\,\text{TeV}$

Monojet + $\not{E}_T$

jets + $\not{E}_T$

Di-jet resonances

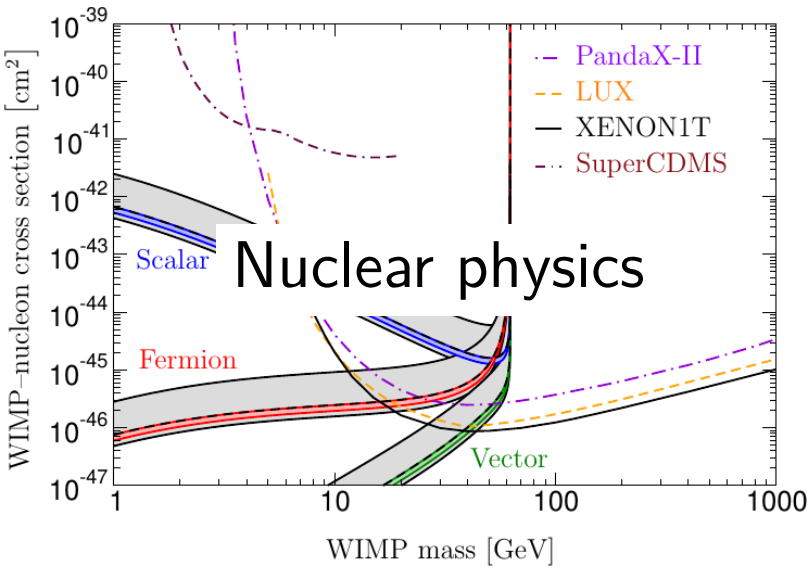
Higgs invisible decay

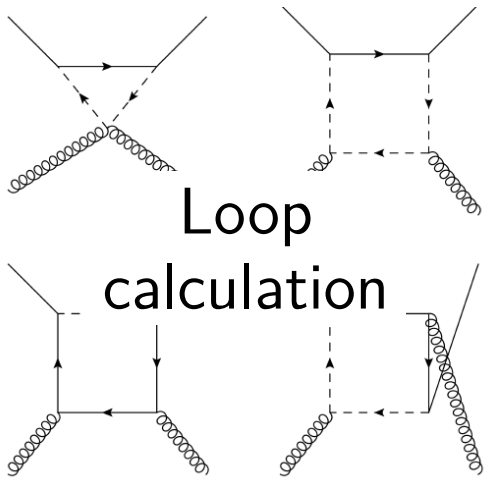
Di-lepton resonances

The portals: deeper and beyond

- Uncertainty evaluation/precision studies
- The curse of complexity: making models consistent
- Complex dark sectors and compressed signatures
- Summary and perspectives

Dealing with uncertainties

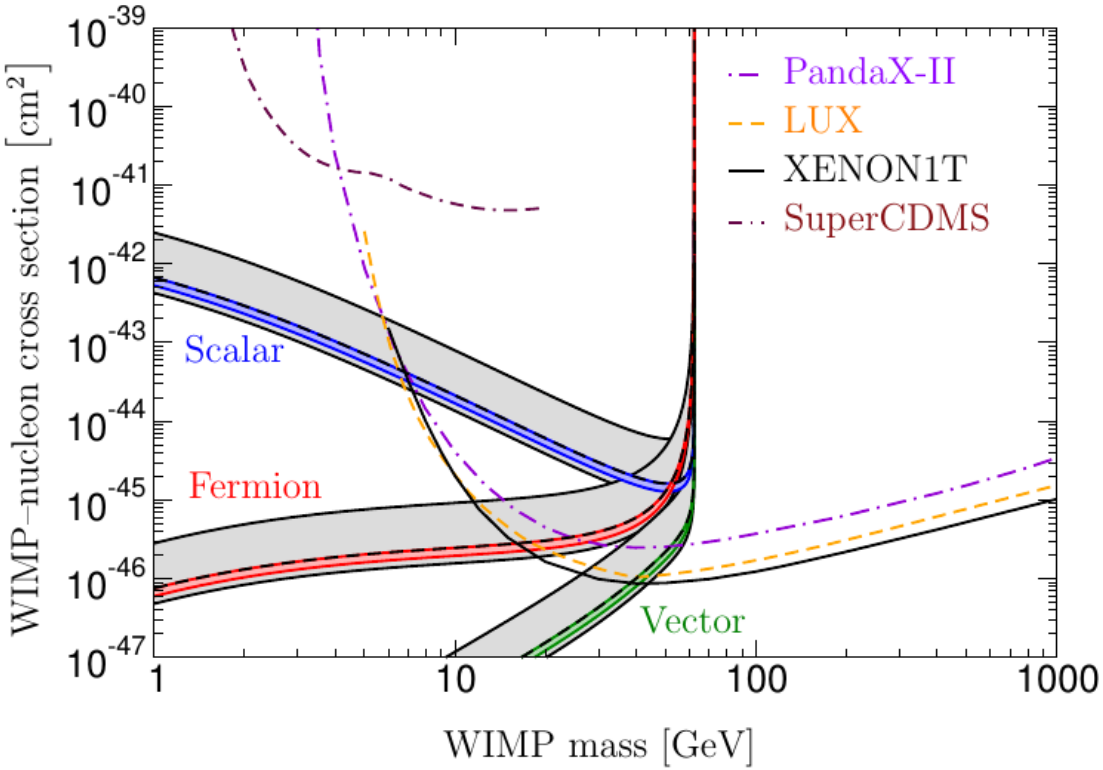




Nuclear physics and loop corrections

Nuclear Physics:

- From DM coupling to quarks to couplings to nucleons
- Chiral EFT allows to considerably reduce uncertainties on effective couplings

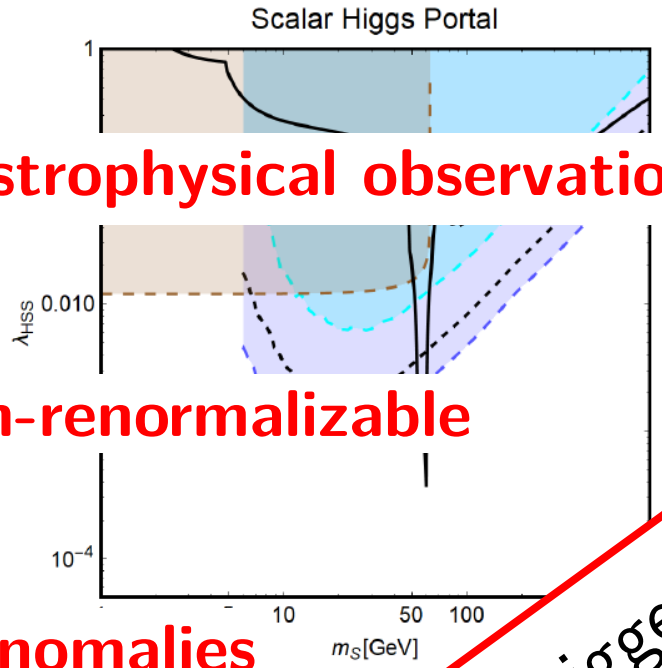


[Hoferichter et al, [arXiv:1903.11075]]

Loop calculation:

- See previous talks by K. Mohan and R. Santos
- Crucial in the "blind spots" of the portal models
- Loop-level SI interactions give the strongest bounds!
- Need to compute RGE running effects and k-factors for the LHC

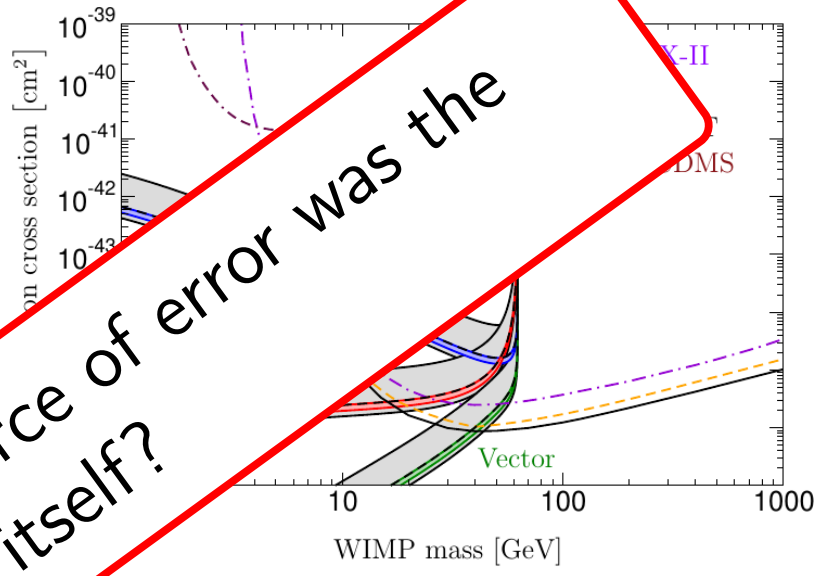
Uncertainties: Yes but...



Astrophysical observations

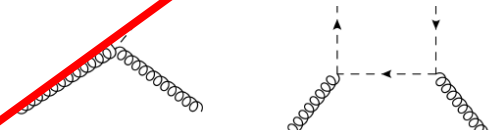
Non-renormalizable

Anomalies

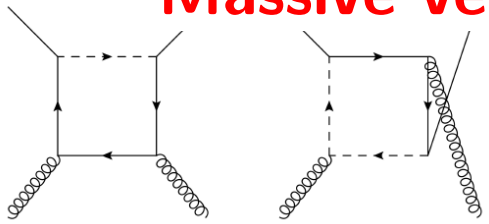


What if our biggest source of error was the model itself?

Extended dark sectors?



Massive vector bosons



The problem with consistency: the Z' portal

$$\mathcal{L}_{\text{dark}} \supset Z'_\mu \bar{\chi}\gamma^\mu(g^V_\chi - ig^A_\chi\gamma_5)\chi + Z'_\mu \sum_q \bar{q}\gamma^\mu(g^V_q - ig^A_q)q$$

$$+ Z'_\mu \sum_\ell \bar{\ell}\gamma^\mu(g^V_\ell - ig^A_\ell)\ell + \frac{1}{2}M^2_{Z'}\, Z'_\mu Z'^\mu$$

- Unitarity: dark $U(1)'$ symmetry with a Higgs singlet S
- Anomalies: SM and dark charges must obey sum rules...
  [Ellis et al, JHEP 08 (2017) 053]
- Surprisingly hard to achieve for a leptophobic axial-vector Z'
  [SEH, K. Nordström, Scipost Phys. 6 (2019) no.2, 020]
- "Minimal model": 6 new Weyl fermions, 13 new parameters!
  - New SU(2) doublets – Doublet-singlet mixing
  - SI interactions are back $\Rightarrow$ constraints from XENON1T
  - Heavy fermions $\Rightarrow$ LHC EWinos searches & final state leptons

Just making gauge portal models consistent leads to a completely unexpected phenomenology

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Extended sectors: The Higgs portal

With fermionic dark matter

$$\mathcal{L} \supset \begin{cases} \frac{c}{\Lambda}\chi^\dagger\chi H^\dagger H & \text{Non-renormalizable} \\ \lambda_\chi\, \chi^\dagger H \chi & \text{Impossible!} \end{cases}$$

Completions:

[LHC DM working group, Phys.Dark Univ. 100351], [Arcadi et al, arXiv:1903:03616]

- **Additional fermions**: Vector-like/chiral fermions, 4-rth generation
- **Additional scalars**: (pseudo)scalar singlet
- **Combined models**: 2HDM + fermions
  singlet coupling to DM *and* SM-charged fermions

Phenomenology:

- From 4 to 14 parameters! Most models explored by ATLAS [ATLAS, JHEP 05 (2019) 142]
- **Direct detection**: robust conclusions,scalar/pseudoscalar dichotomy
- **Colliders**: monojets + $\not{E}_T$, scalar resonances, SUSY searches, new fermions, Higgs coupling measurements, collimated diphoton pairs...

Beyond the portals: updated picture

Direct Detection

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SI unsuppressed

Strong constraints up to $\mathcal{O}(10)$ TeV

SI suppressed

Are you sure?
Loop effects
Extended dark sectors

Monojet + $\not{E}_T$
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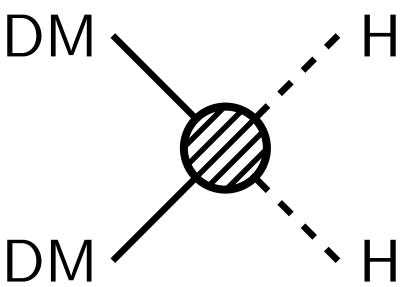
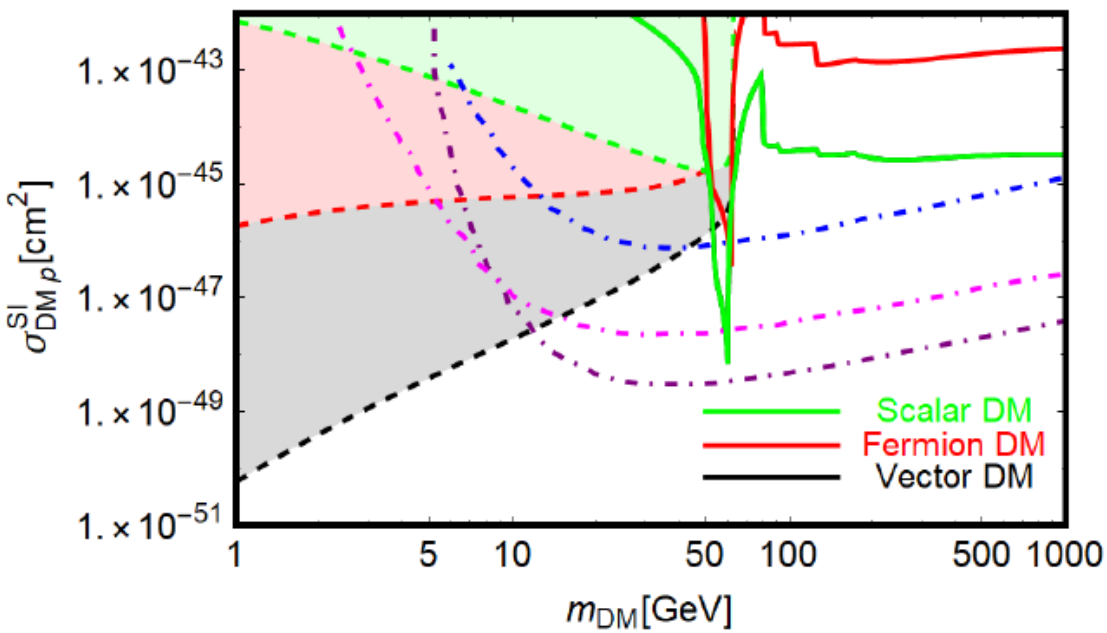
EWPT
Heavy fermions

Reviving thermal dark matter

- Direct detection + LHC bounds can push us into regions where DM annihilation is extremely inefficient
- These regions are often overlooked in thermal DM scenarios
- How could this change with extended dark sectors?





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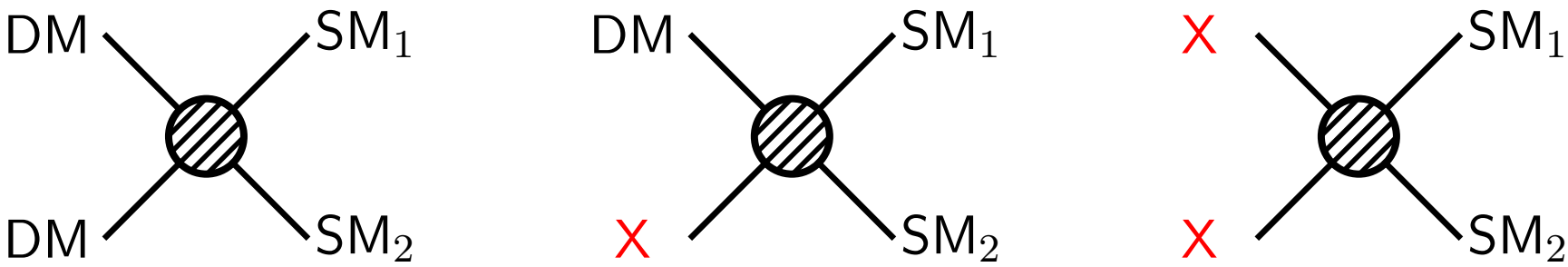


- **Coannihilation**: DM in equilibrium with another particle X
  $\Rightarrow$ new ways of depleting the dark sector
- X can be anything: strongly interacting, charged, etc...
- Colliders push us into very compressed topologies: down to $\mathcal{O}(10)\%$ at the LHC and $\mathcal{O}(1)\%$ at FCC-hh
  [Baker et al, JHEP 1512 (2015) 120], [SEH et al, JHEP 1704 (2017) 118]
- DM-SM couplings can now be tiny!

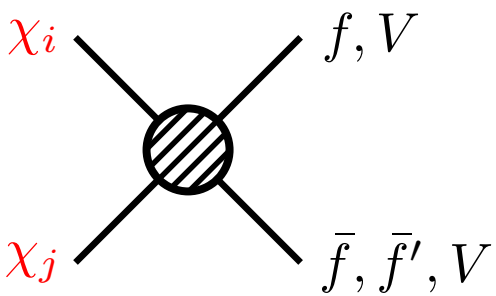
Direct detection and long-lived searches

Example: a singlet-triplet Higgs portal

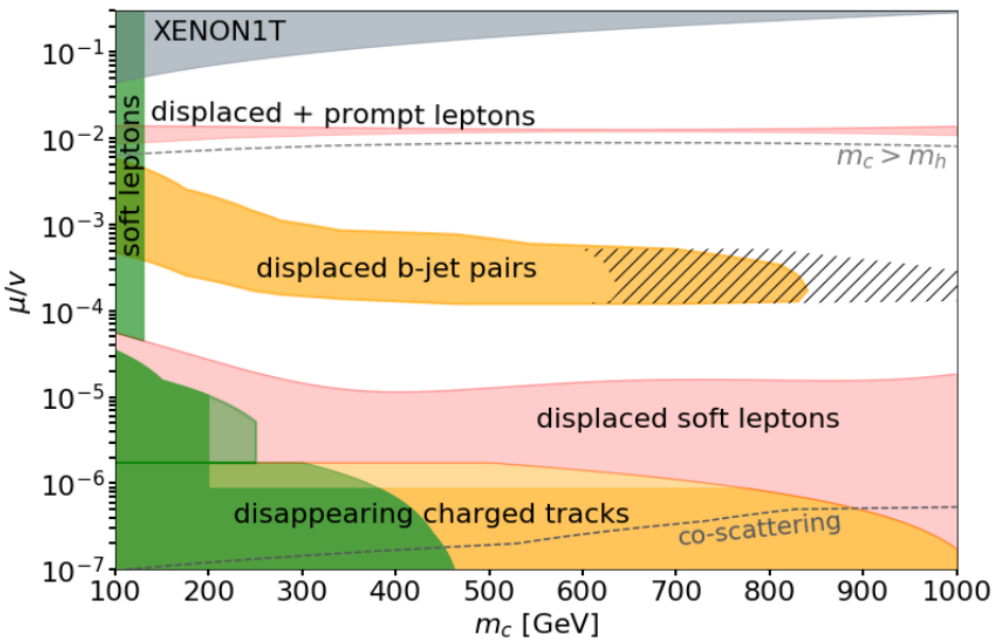
[A. Filimonova, S. Westhoff, JHEP 1902 (2019) 140]

$$\mathcal{L} \supset \frac{\kappa_S}{\Lambda}\overline{\chi_S}\chi_S H^\dagger H + \frac{\kappa_T}{\Lambda}\mathrm{Tr}[\overline{\chi_T}\chi_T]H^\dagger H + \frac{\mu}{v^2}(H^\dagger\overline{\chi_T}H)\chi_S + ...$$

- Unsuppressed annihilation of heavy dark fermions
- DM-SM interactions can be suppressed $\Rightarrow$ displaced vertices



$\sigma \propto \mathcal{O}(g^2)$



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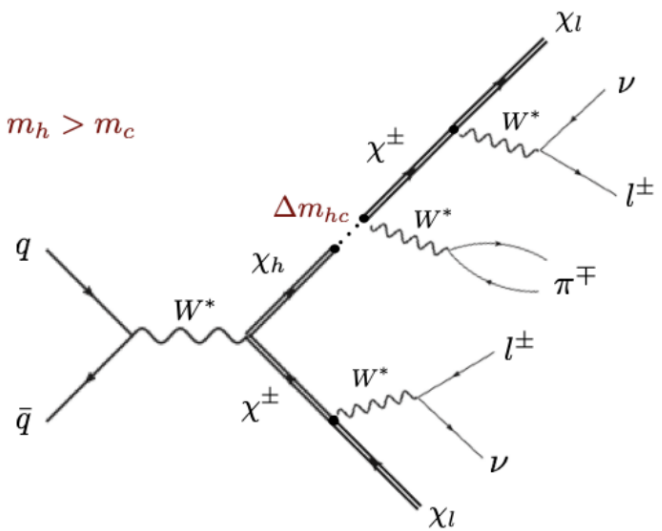

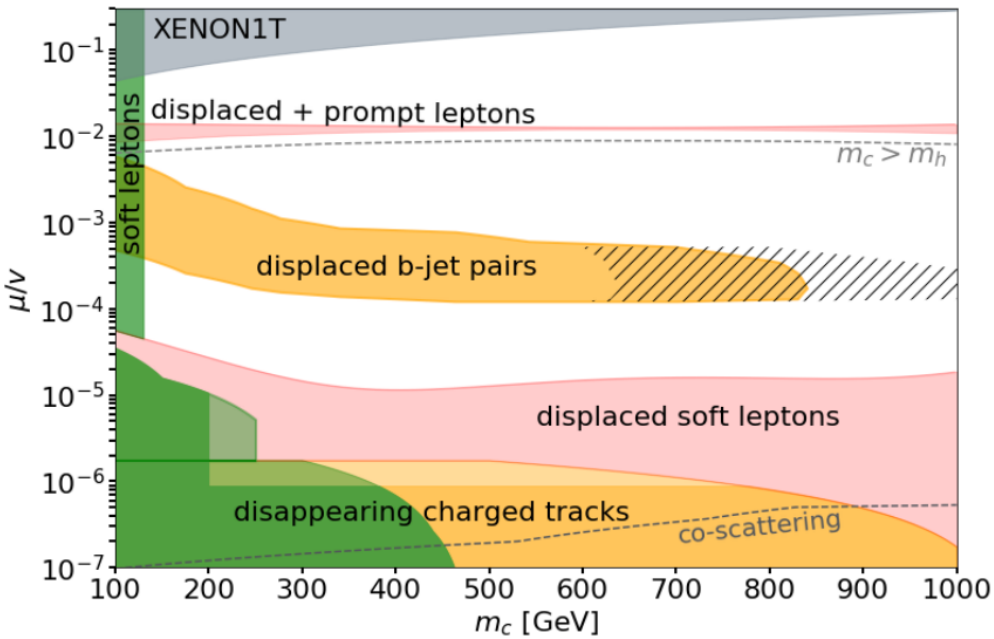

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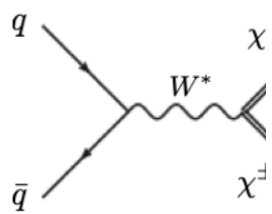
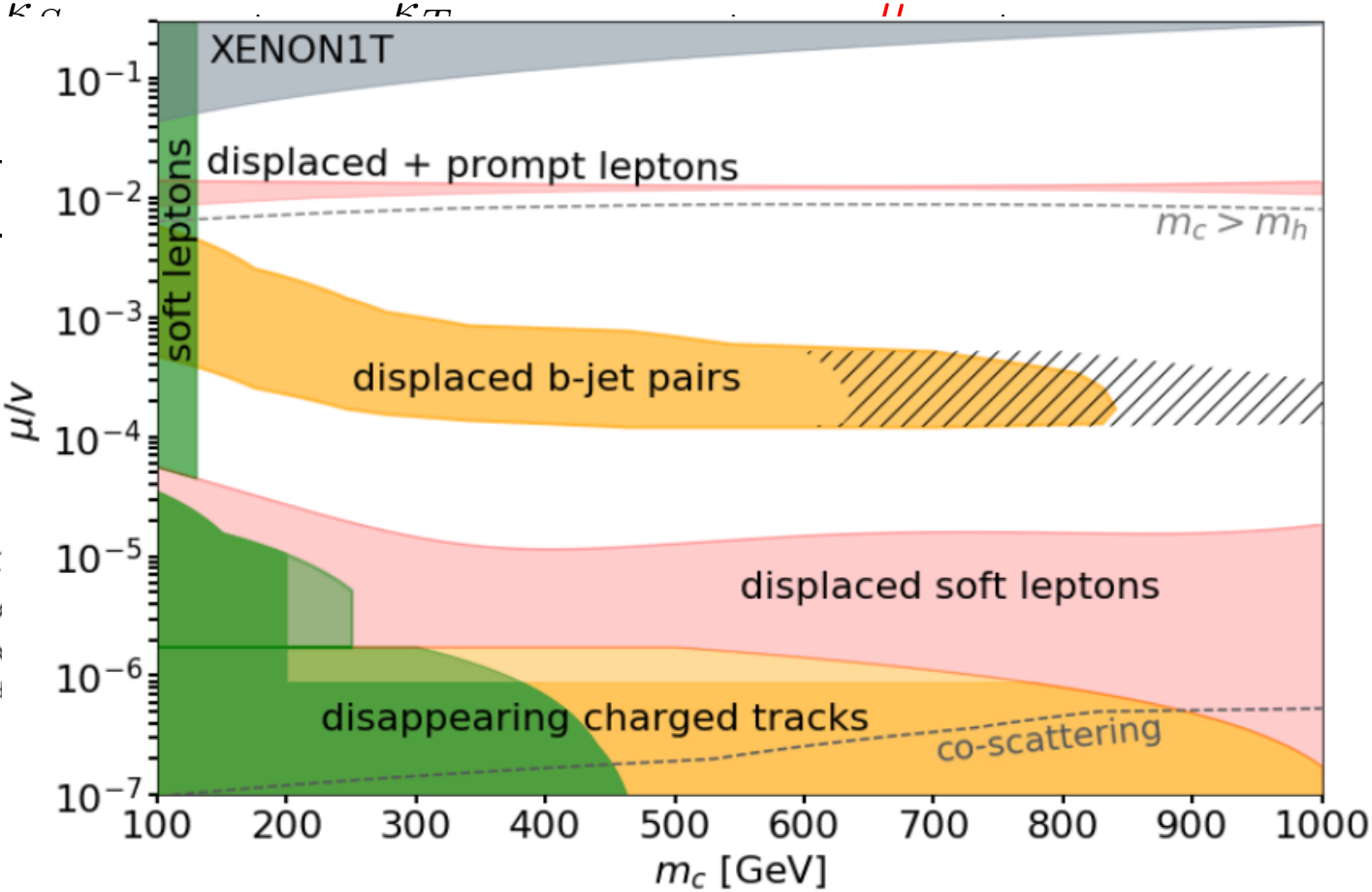
$\mathcal{L} \supset$

- Unsu
- DM-

$m_h > m_c$





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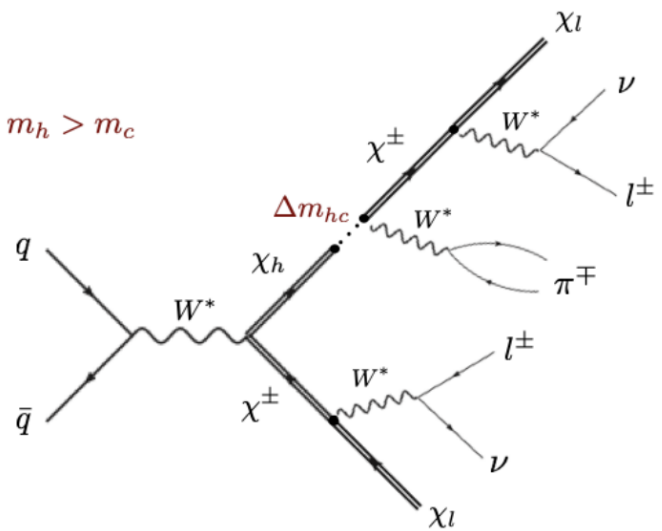
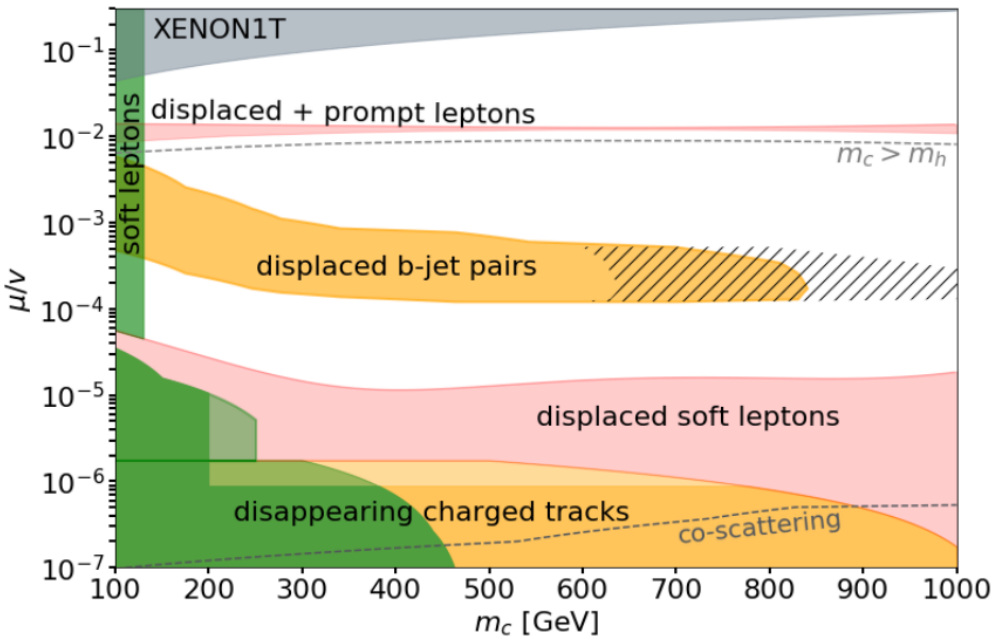




Interplay between direct detection and long-lived searches!

Strongly interacting dark sectors and exotic searches

Astrophysics favors DM self-interactions...
[Bernreuther et al, arXiv:1907.04346]

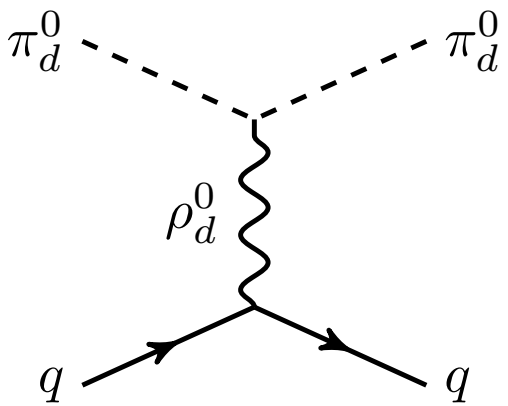
$SU(3)' - \Lambda_{\text{dark}}$ $\qquad$ $SU(3) - \Lambda_{QCD}$

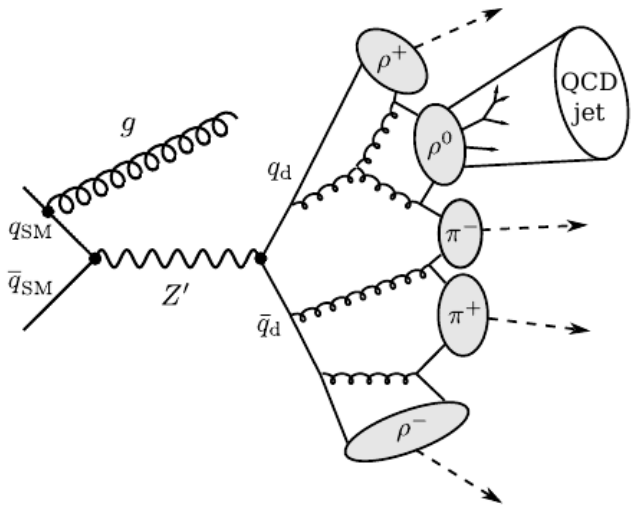
Dark quarks q_d
$\pi_d^0, \pi_d^\pm, \rho_d$

Z' (TeV)

SM quarks q_{SM}
$\pi^0, \pi^\pm, \rho, \ldots$

Below Λ_{dark} $\qquad$ **Above Λ_{dark}**





Direct detection $\qquad$ **Dark showers at colliders**

Strong dark sector interactions can link direct detection to exotic searches

So finally...

Direct Detection

$m_{\text{DM}} \gtrsim 10$ GeV

SI unsuppressed

Strong constraints up to $\mathcal{O}(10)$ TeV

SI suppressed

Are you sure?

Loop effects

Extended dark sectors

Monojet + $\not{E}_T$

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EWPT

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R-hadrons

Displaced vertices

Compressed spectra

Dark showers

Conclusion

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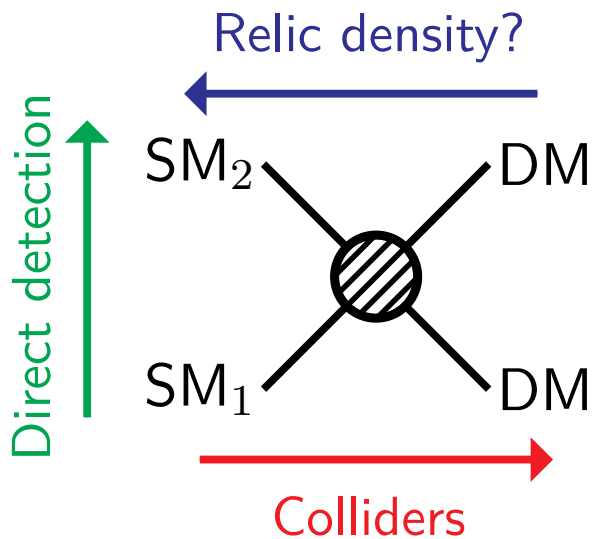
- Or should we just move beyond this picture?



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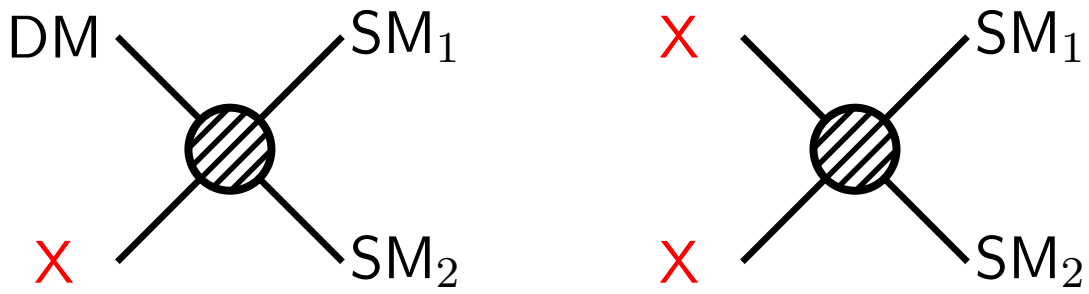

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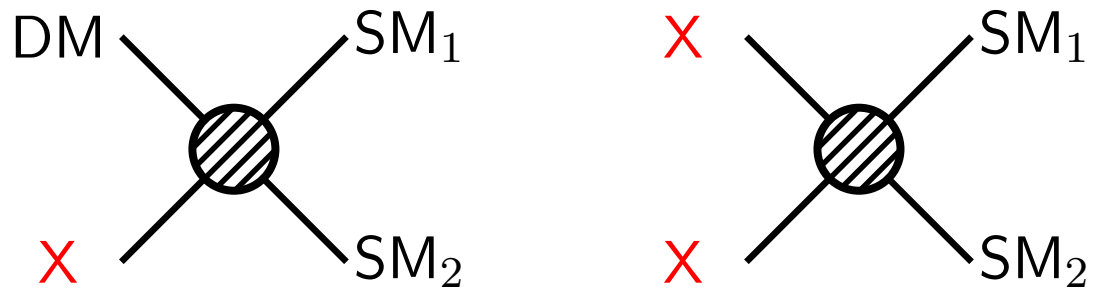

- Need to apply our simplified model tools to more diverse mechanisms involving additional dark sector particles
- The thermal freeze-out hypothesis should not overly restrict us. We should consider all possible evolution scenarios beyond DM self-annihilation

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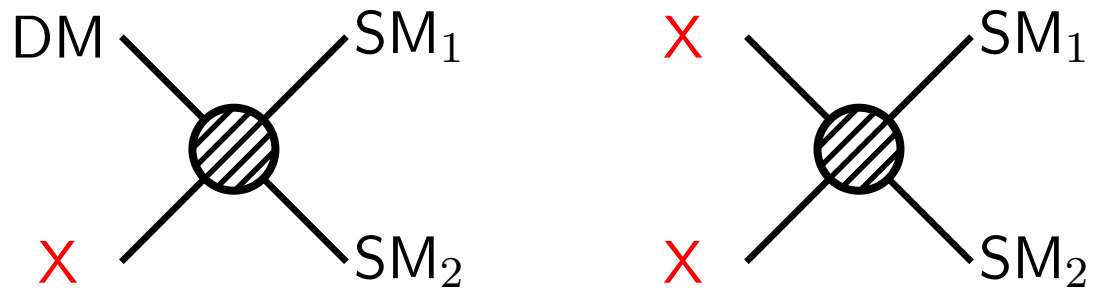

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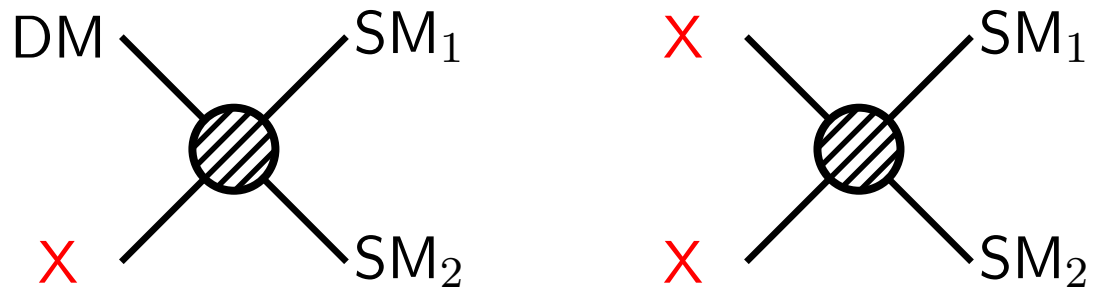

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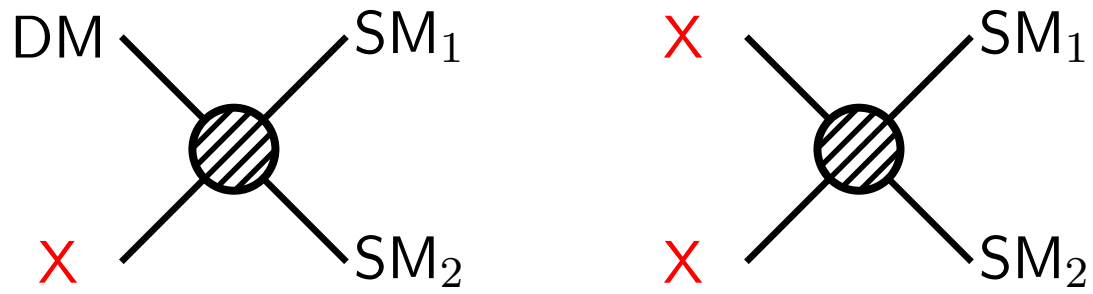

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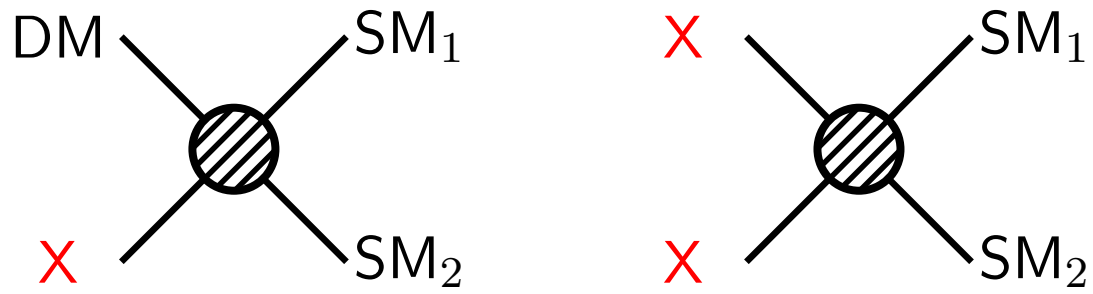

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  - New (machine learning assisted?) scanning techniques