# Anomaly-free dark matter evading direct detection

Workshop on the Standard Model and Beyond,
Corfu Summer Institute 2018

Collab. with

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arXiv:1807.07921

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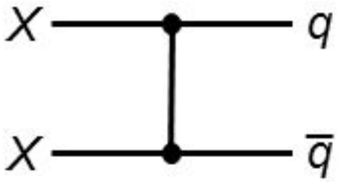
In the last years we have moved from

“WIMP miracle”

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

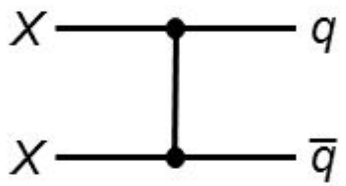



$m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

In the last years we have moved from

“WIMP miracle” → “Trouble with WIMPs”

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

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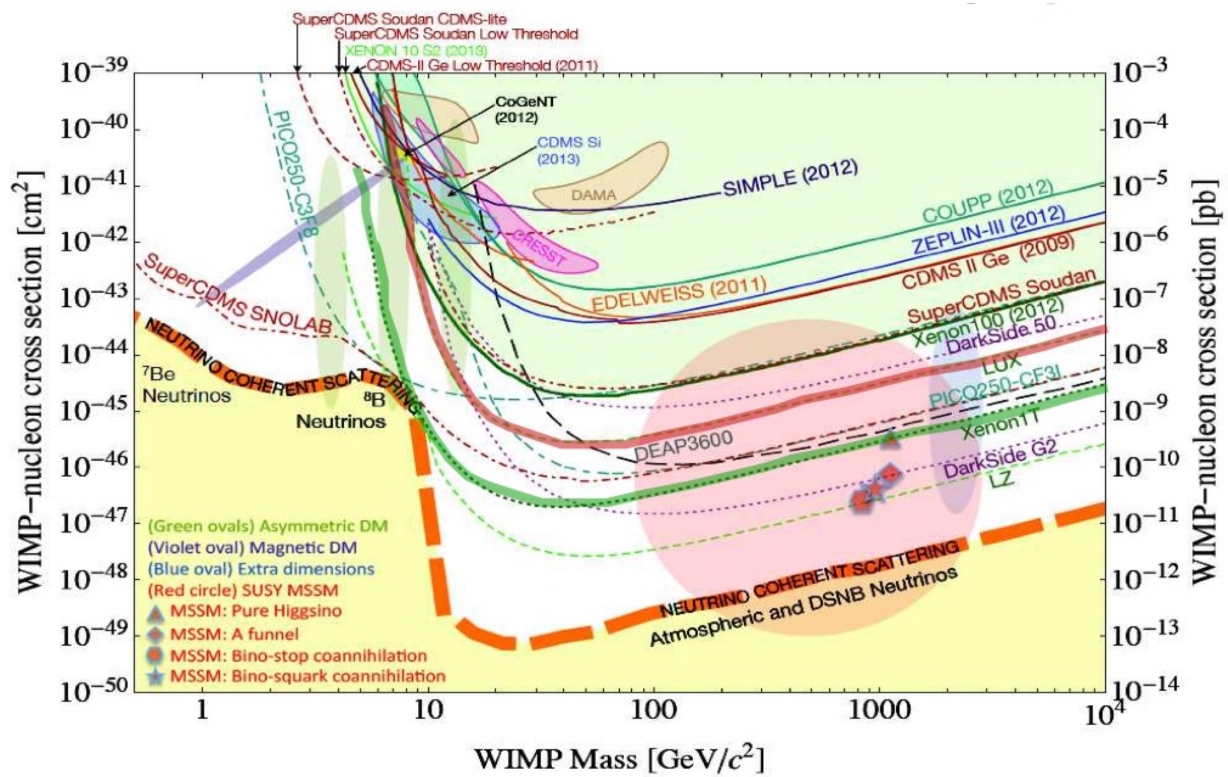
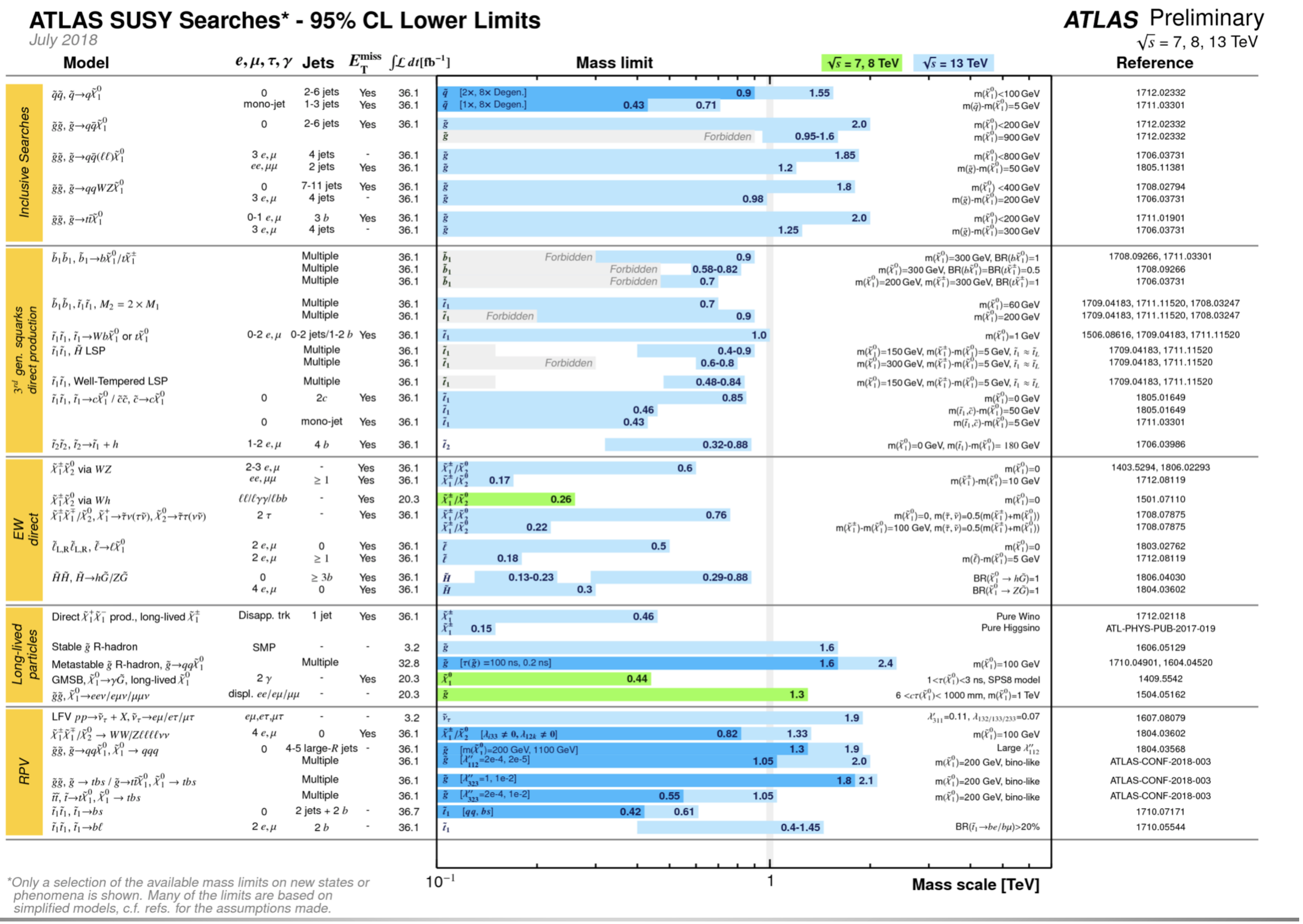
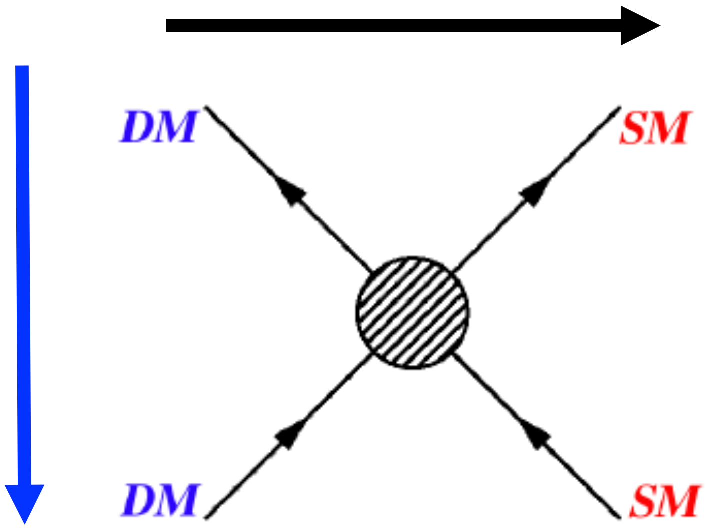


# Somehow resembles the “LHC tsunami” for BSM physics:




(From Albert De Roeck talk)

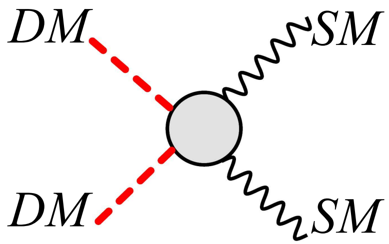
However, although a substantial annihilation rate in the early universe is necessary to get the correct relic abundance




This does not necessarily mean that the DD cross section is large

There are mechanisms that suppress DD cross section

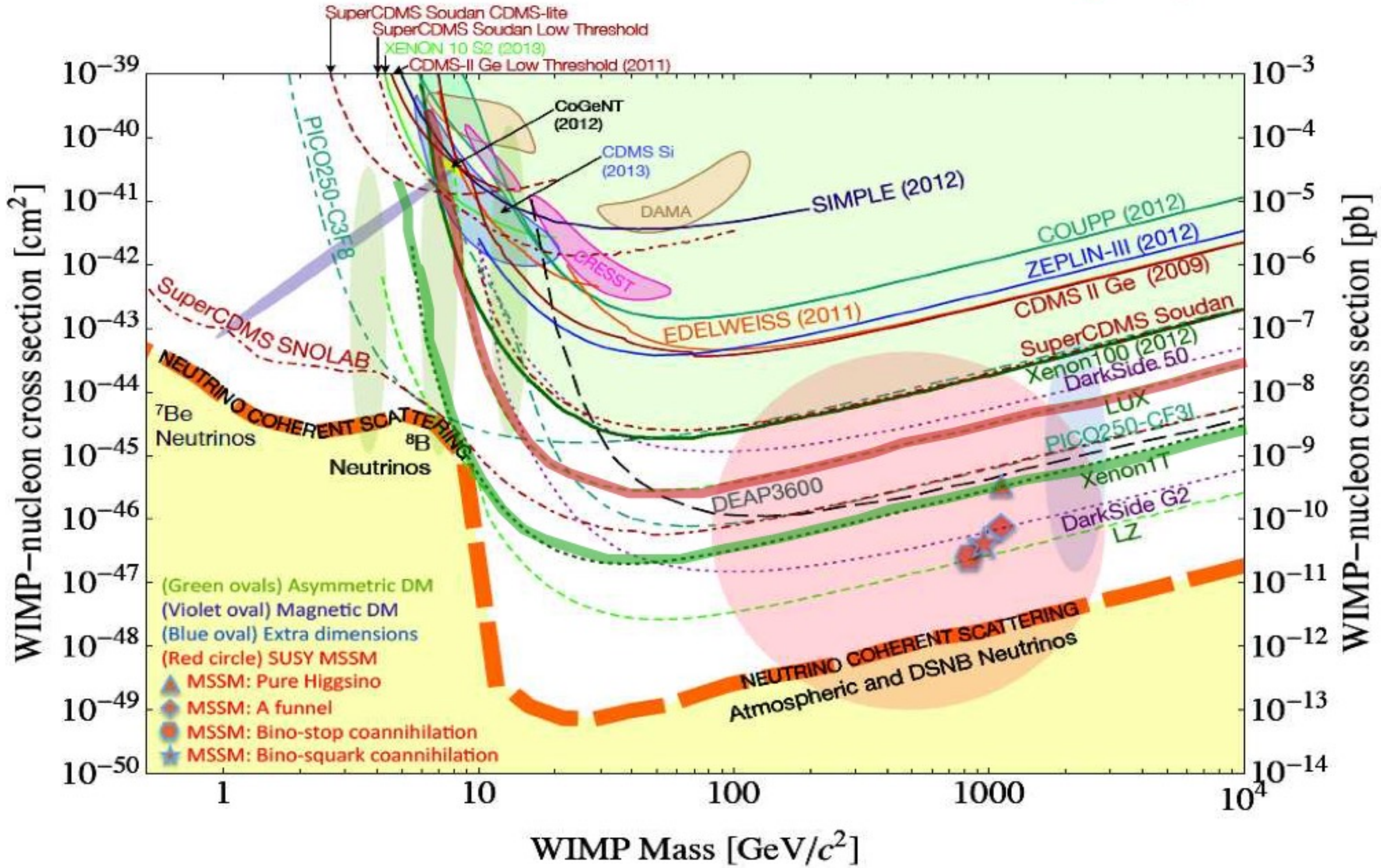
## There are mechanisms that suppress DD cross section

- 

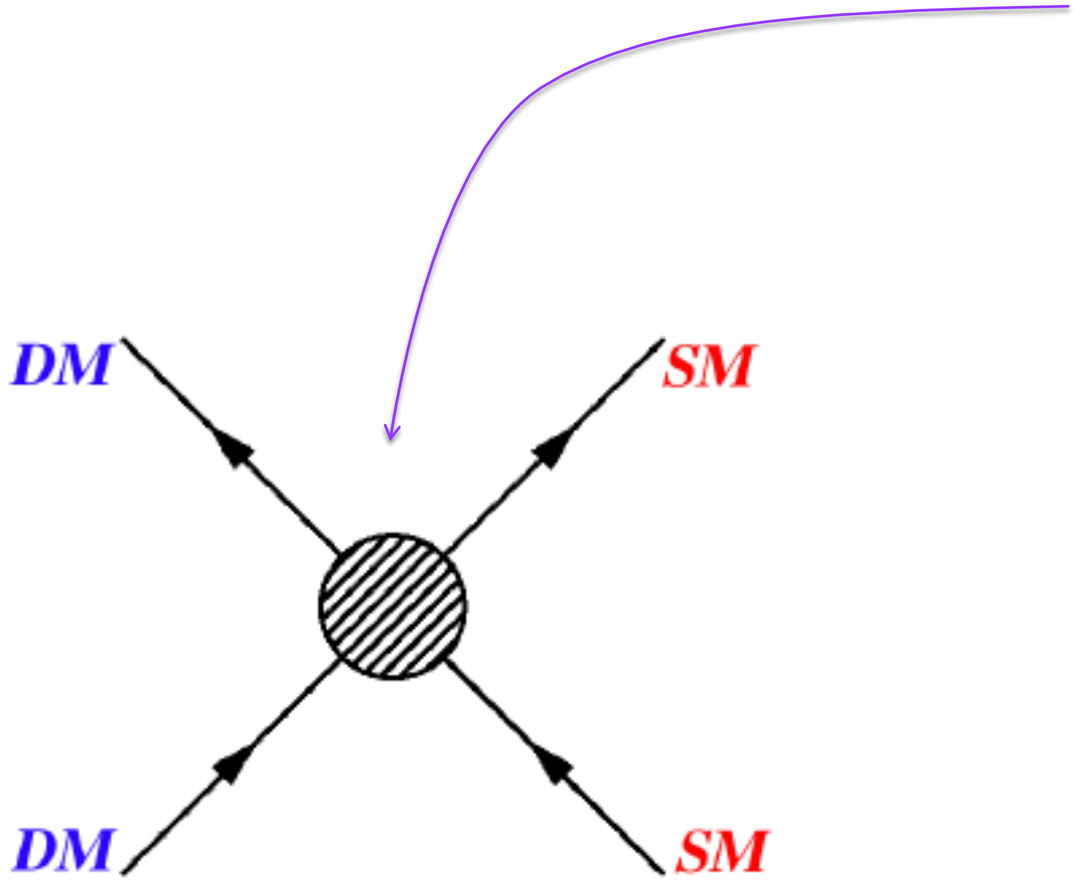
(see A. Belyaev's talk)

- Spin-dependent DD cross section
- Velocity-suppressed DD
- Annihilation through funnels
- Co-annihilation

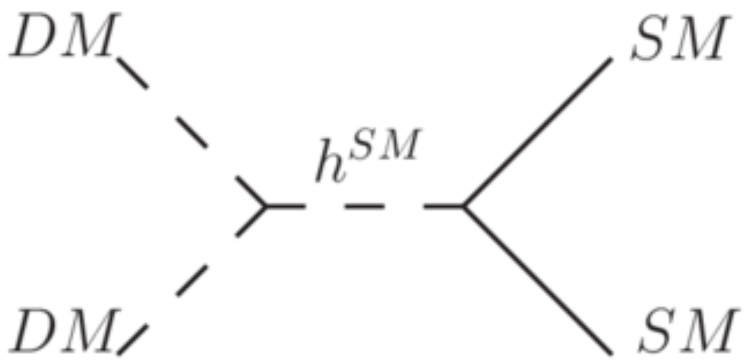
# So, perhaps the DD tsunami is not that scary



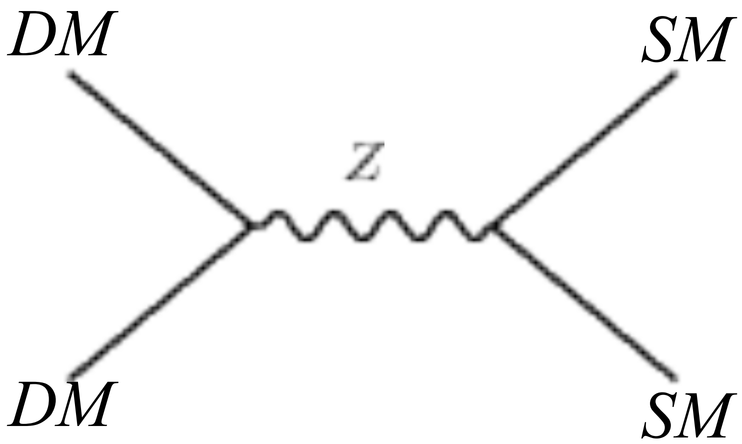
Essentially, everything depends on the content of the blob



# Obvious possibilities



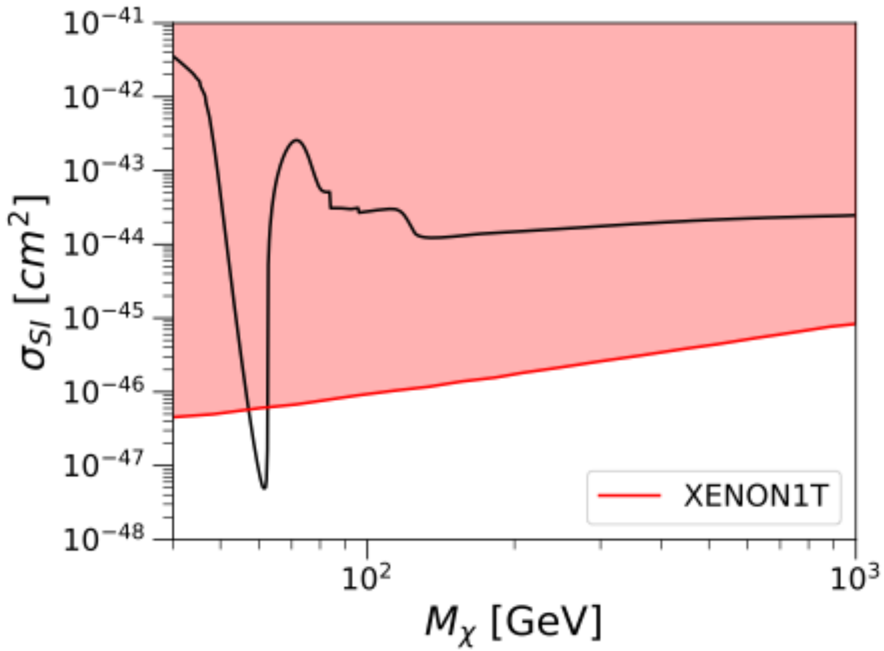

Higgs-portal




Z-portal

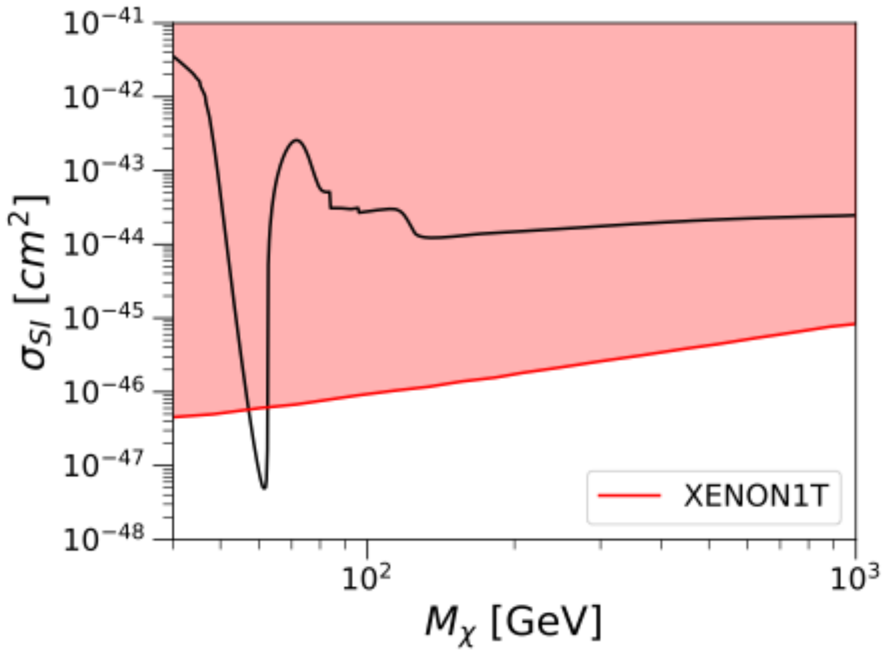
# Both are in trouble with DD

Higgs-portal

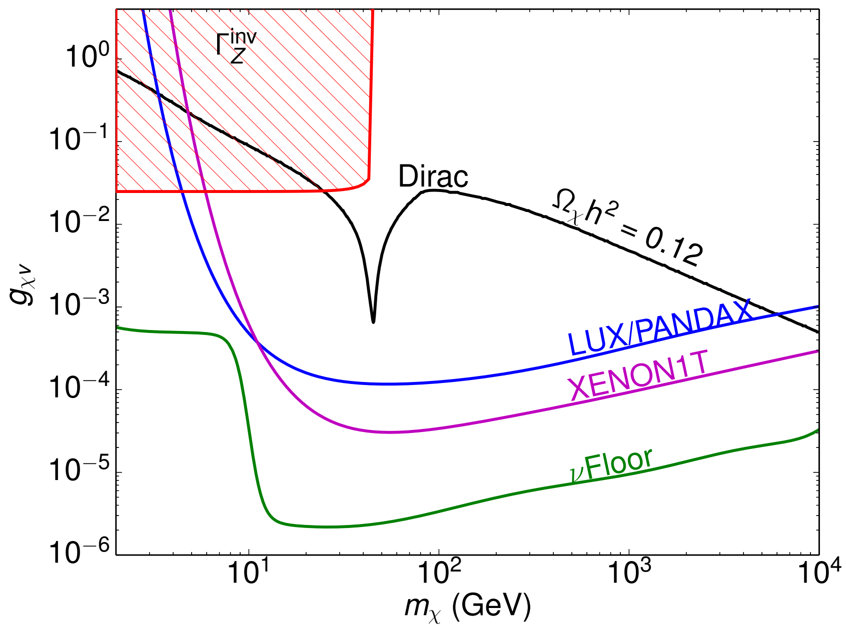


# Both are in trouble with DD

Higgs-portal



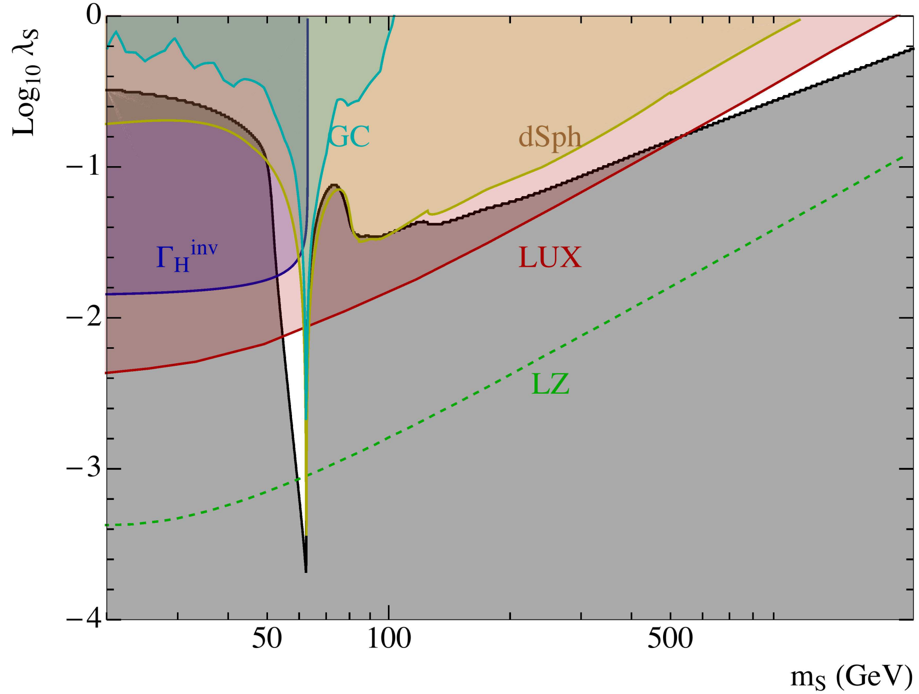

Z-portal (vect. coupling)



## However, this scheme is probably oversimplified

- ★ Dark sector may contain extra stuff
- ★ There may be other mediators

E.g. for singlet-scalar Higgs-portal



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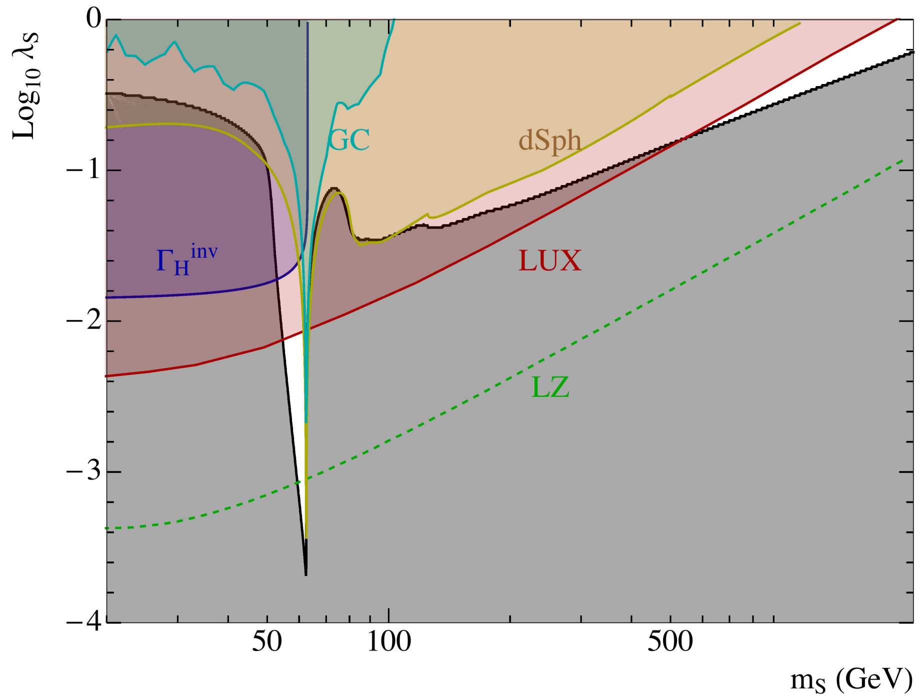
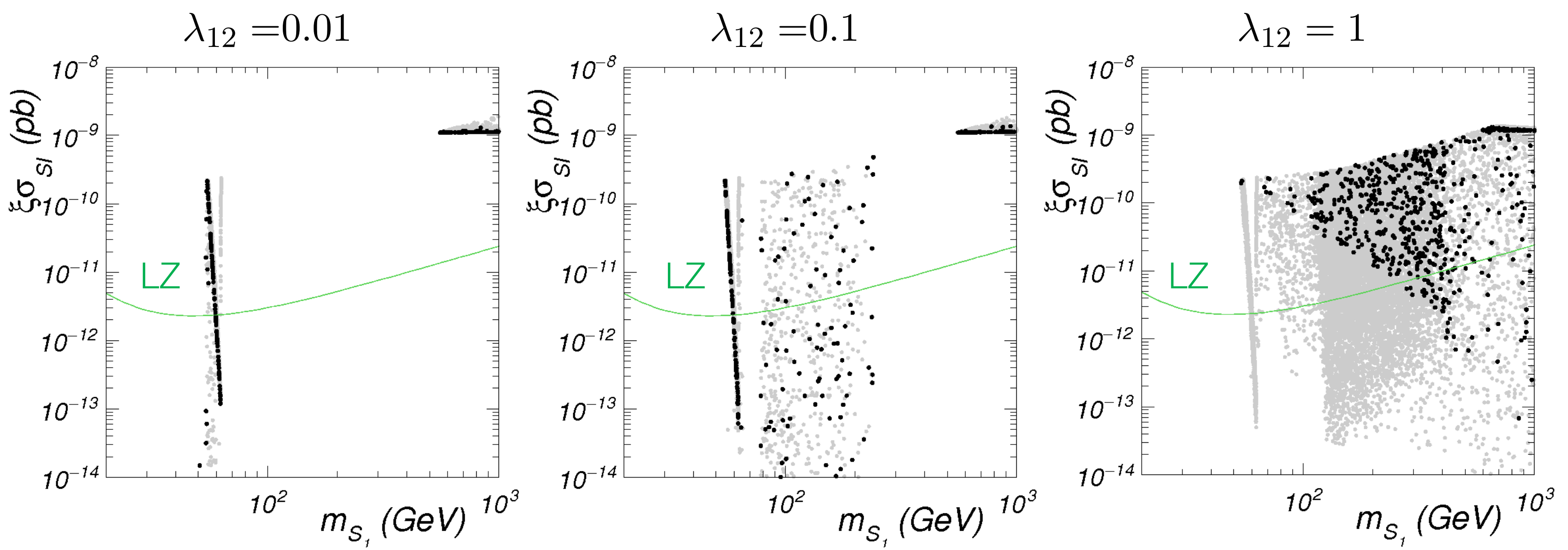



With extended dark sector $S \rightarrow \{S_1,\ S_2\}$



Let us focus now on new mediators, in particular on new gauge bosons ( Z´ ), arising from extra U(1) factors in the symmetry group.

This case has been often considered, typically in the context of Simplified DM models (SDMM):

$$SM \text{ sector} \quad + \quad \{\chi \ , \ Z'\}$$

DM mediator

However, SDMM are usually inconsistent, as they do not fulfill:

- Gauge invariance (which e.g. requires an extra scalar field, *S*)

  Kahlhoefer et al. 2016

- Anomaly cancellation (which requires to extend the dark fermionic sector)

  Ellis et al. 2017

  Fileviez et al.

Two of the strongest constraints on these models come from:

- DD limits
- Di-lepton production at LHC

Two of the strongest constraints on these models come from:

- DD limits (greatly alleviated if the coupling of Z' to DM is axial)

- Di-lepton production at LHC (greatly alleviated if Z' is leptophobic)

See e.g. Ellis et al. 2017

Let us start by considering Leptophobia:

$$Y'_{L_i} = Y'_{e_i} = 0$$

- From the lepton Yukawas $y_i^e \bar{L}_i H e_i$ : $\quad Y'_H = 0$
- From the quark Yukawas $y_i^u \bar{Q}_i \bar{H} u_i \quad y_i^d \bar{Q}_i H d_i$ :

  $$Y'_{Q_i} = Y'_{u_i} = Y'_{d_i}$$

- Same $Y'$ for the three generations: $U(1)' \equiv U(1)_B$

  $$Y'_{Q_i} = Y'_{u_i} = Y'_{d_i} = 1/3$$

Note: vectorial Z' couplings to quarks

New symmetry group $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)'$

$$U(1)' \equiv U(1)_B$$

Anomaly equations

$SU(3)_C^2 \times U(1)'$ anomaly $\longrightarrow \mathrm{Tr}[\{\mathcal{T}_i, \mathcal{T}_j\} Y'] = 0$

$SU(3)_C^2 \times U(1)_Y$ anomaly $\longrightarrow \mathrm{Tr}[\{T_i, T_j\} Y] = 0$

$SU(2)_W^2 \times U(1)'$ anomaly $\longrightarrow \mathrm{Tr}[\{T_i, T_j\} Y'] = 0$

$SU(2)_W^2 \times U(1)_Y$ anomaly $\longrightarrow \mathrm{Tr}[\{T_i, T_j\} Y] = 0$

$U(1)_Y^2 \times U(1)'$ anomaly $\longrightarrow \mathrm{Tr}[Y^2 Y'] = 0$

$U(1)_Y \times U(1)'^2$ anomaly $\longrightarrow \mathrm{Tr}[Y Y'^2] = 0$

$U(1)'^3$ anomaly $\longrightarrow \mathrm{Tr}[Y'^3] = 0$

$U(1)_Y^3$ anomaly $\longrightarrow \mathrm{Tr}[Y^3] = 0$

Gauge gravity $\longrightarrow \mathrm{Tr}[Y] = \mathrm{Tr}[Y'] = 0$

(Previous analyses by
Ellis et al. and Fileviez et al.)

Initially, dark sector contains a singlet fermion $\chi \equiv (\chi_L,\ \chi_R)$
with vanishing Y' . $\chi \ \equiv \ DM$

However

$SU(2)^2 \times U(1)_{Y'}$

requires extra particles transforming non-trivially under SU(2).

Simplest choice: extra doublet

$$\psi \equiv (\psi_L,\ \psi_R)$$

$U(1)^2_Y \times U(1)_{Y'}$

requires extra particles transforming non-trivially under $U(1)_{Y'}$

Simplest choice: extra singlet

$$\eta \equiv (\eta_L,\ \eta_R)$$

Minimal dark sector: $\{\chi_{L,R},\ \psi_{L,R},\ \eta_{L,R}\}$

In addition, one extra scalar, $S$ , is required to break U(1)$_{Y'}$ and give mass to the dark fermions

We have completely classified the anomaly-free leptophobic solutions ($\equiv$ U(1)$_B$ extensions) with minimal dark sector.

For any choice of $Y_\psi, Y_\eta$ there is a continuum of possible choices of the other $Y$' charges

See details at arXiv:1807.07921

Requiring, in addition, that the coupling of $Z'$ to DM is Axial, i.e.

$$Y'_{\chi_L} = -Y'_{\chi_R}$$

There are still infinite solutions. However, only in two of them the Y' charges are rational:

$$\{Y_\psi, Y_\eta\} = \left\{\pm\frac{1}{2}, \pm 1\right\},\ \left\{\pm\frac{7}{2}, \pm 5\right\},$$

$$\{Y'_{\psi_L}, Y'_{\psi_R}, Y'_{\eta_L}, Y'_{\eta_R}, Y'_{\chi_L}, Y'_{\chi_R}\} = \left\{-\frac{3}{2}, \frac{3}{2}, \frac{3}{2}, -\frac{3}{2}, \frac{3}{2}, -\frac{3}{2}\right\}.$$

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Minimal dark scalar-sector

Note: vectorial Z' couplings to quarks & axial coupling to DM ⇒ DD effective operator is spin-dependent and velocity-suppressed

# Minimal (leptophobic & axial) model

Fermionic content

SU(2) ↓ Y ↓ Y' ↓

$$\psi_L\,(\,2,\ -\tfrac{1}{2},\ -\tfrac{3}{2}\,) \qquad \eta_L\,(\,1,\ -1,\ -\tfrac{3}{2}\,) \qquad \chi_L\,(\,1,\ 0,\ \tfrac{3}{2}\,)$$

$$\psi_R\,(\,2,\ -\tfrac{1}{2},\ \tfrac{3}{2}\,) \qquad \eta_R\,(\,1,\ -1,\ \tfrac{3}{2}\,) \qquad \chi_R\,(\,1,\ 0,\ -\tfrac{3}{2}\,)$$

+ 1 complex scalar

$$S\,(\,1,\ 0,\ -3\,)$$

which takes a VEV , giving mass to the new boson $Z'$ and the dark fermions

The model was already written down explicitly by Fileviez et al. 2014

# Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm kin} + \mathcal{L}_{\rm fer} + \mathcal{L}_{\rm scal}$$

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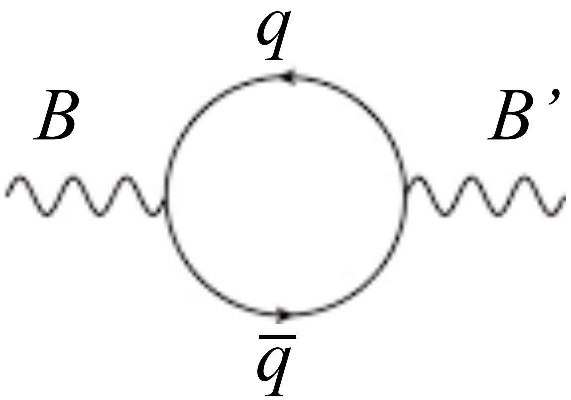
$$\mathcal{L}_{\rm kin} \supset -\frac{1}{2}\, \epsilon\, F^{Y}_{\mu\nu}\, F^{Y'\mu\nu}$$

Even if initially $\epsilon = 0$ (at some scale $\Lambda'$), it is radiatively generated:

$$\epsilon = \frac{e g_q}{2\pi^2 \cos\theta_W} \log\frac{\Lambda'}{\mu} \simeq 0.02\; g_q\; \log\frac{\Lambda'}{\mu}$$



$\epsilon \neq 0$ has important phenomenological implications:

- $Z$ and $Z$' mix with $\theta' \simeq \epsilon \sin\theta_w \frac{m_Z^2}{m_{Z'}^2 - m_Z^2}$

- This induces corrections to $S$ and $T$ parameters (EWPO)

- And di-lepton production at LHC
(since it enables $Z' \to \ell\ell$ )

$$
\begin{aligned}
\mathcal{L}_{\rm fer} \supset \quad & -y_1\bar{\psi}_L H\eta_R - y_2\bar{\psi}_L\bar{H}\chi_R - y_3\bar{\psi}_R H\eta_L - y_4\bar{\psi}_R\bar{H}\chi_L \\
& - \lambda_\psi\bar{\psi}_L\psi_R S - \lambda_\eta\bar{\eta}_R\eta_L S - \lambda_\chi\bar{\chi}_R\chi_L S - \lambda_L\chi_L\chi_L S - \lambda_R\chi_R\chi_R S^\dagger \\
& + (\text{h.c.}).
\end{aligned}
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$$+ \, ({\rm h.c.}).$$

$\lambda_L$, $\lambda_R$ lead to the split of the two degrees of freedom of $\chi$ , thus spoiling the axial coupling of DM

Fortunately $\lambda_L = \lambda_R = 0$ is protected by a global U(1) symmetry (~ ‘dark leptonic number’)

$$
\begin{aligned}
\mathcal{L}_{\rm fer} \supset \quad & - y_1 \bar{\psi}_L H \eta_R - y_2 \bar{\psi}_L \bar{H} \chi_R - y_3 \bar{\psi}_R H \eta_L - y_4 \bar{\psi}_R \bar{H} \chi_L \\
& - \lambda_\psi \bar{\psi}_L \psi_R S - \lambda_\eta \bar{\eta}_R \eta_L S - \lambda_\chi \bar{\chi}_R \chi_L S \\
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The extra fermionic fields, $\psi, \eta$, can have an interesting phenomenology in colliders and a relevant role in the thermal production of DM (e.g. through co-annihilation effects)

For the moment we are interested in the simplest scenario, so we will assume their masses are large enough to integrate them out.

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$$\Rightarrow \quad \mathcal{L}_{\rm eff}^{\rm DM} = \mathcal{L}_{\rm kin} - \lambda_\chi \bar{\chi}_R \chi_L S + \frac{1}{\Lambda} \bar{\chi}_R \chi_L |H|^2 + \cdots + (\text{h.c.})$$

with $\quad \dfrac{1}{\Lambda} = \dfrac{y_2 y_4}{m_\psi}$

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3 annihilation channels: *Z'*-portal, *s*-portal and *H*-portal

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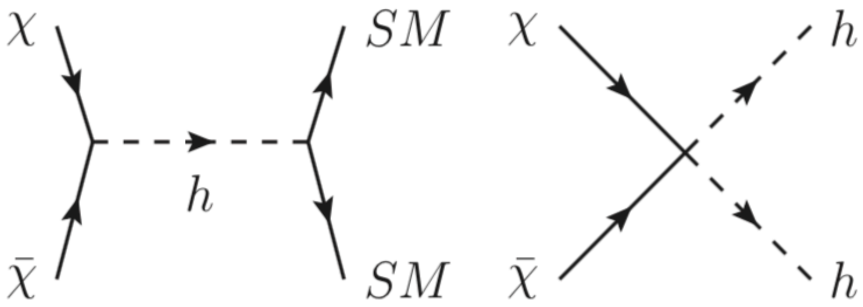

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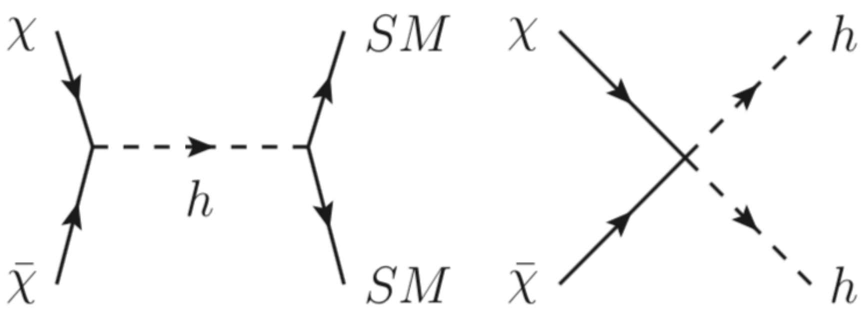
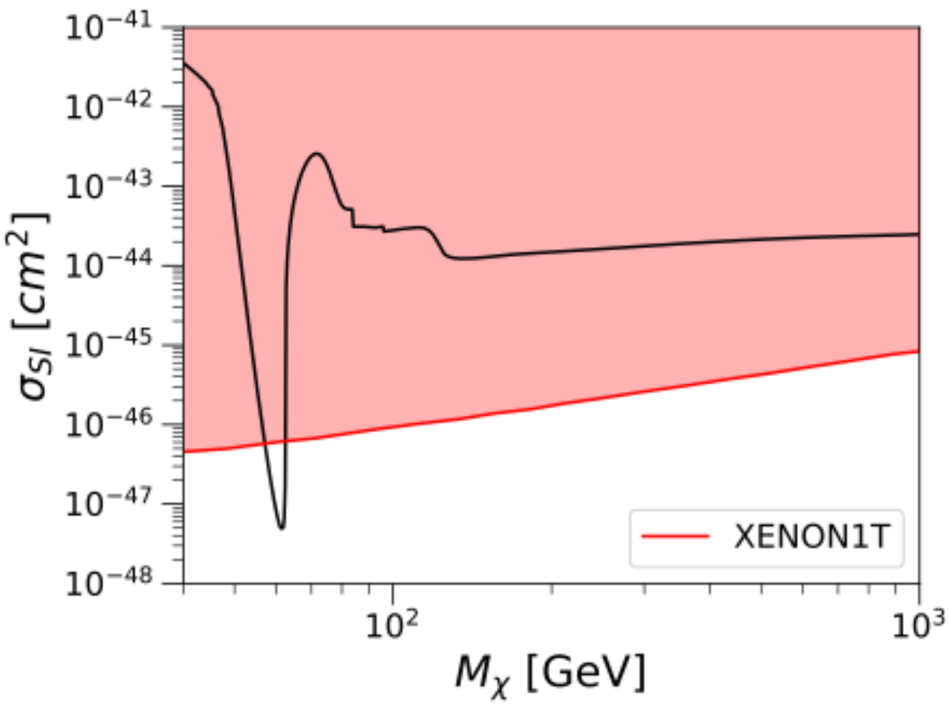



Excluded except at the resonance

We will assume it is negligible

# Finally

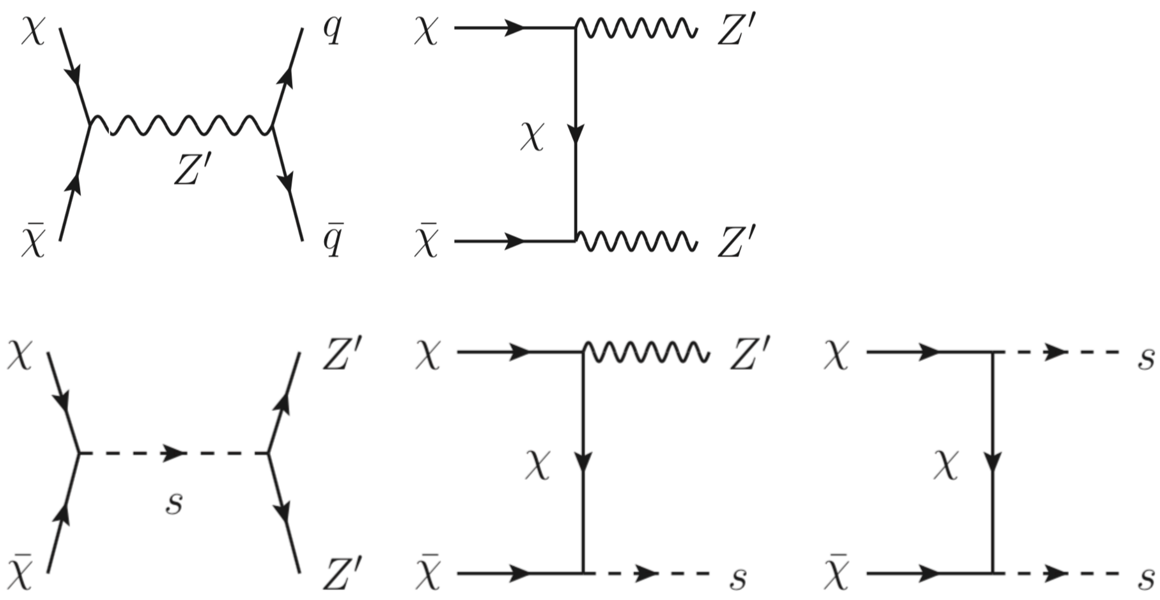
$$\mathcal{L}_{\rm scal} \supset \quad - m_S^2 |S|^2 - \lambda_S^2 |S|^4 - \lambda_{HS}^2 |H|^2 |S|^2$$

We will take $\lambda_{\rm HS} \sim 0$ to avoid constraints from $H$-$s$ mixing

# Relic density

Annihilation through *Z'* and *s* :

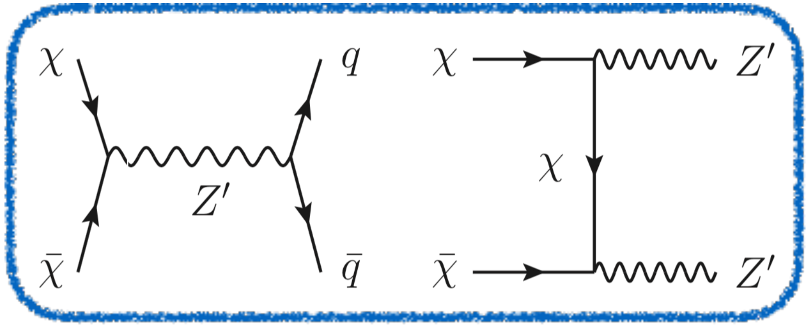
$$\mathcal{L}_{\text{eff}}^{\text{DM}} = \mathcal{L}_{\text{kin}} - \lambda_\chi \bar{\chi}_R \chi_L S + \frac{1}{\Lambda} \bar{\chi}_R \chi_L |H|^2 + \cdots + (\text{h.c.})$$



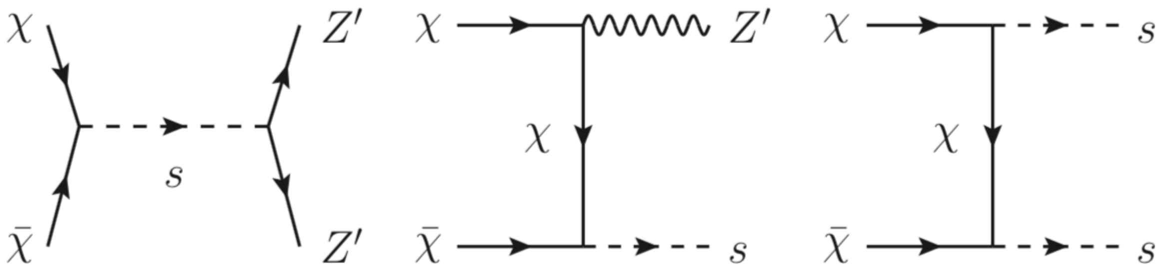
# Relic density

Annihilation through $Z'$ and $s$ :

$$\mathcal{L}_{\rm eff}^{\rm DM} = \mathcal{L}_{\rm kin} - \lambda_\chi \bar{\chi}_R \chi_L S + \frac{1}{\Lambda} \bar{\chi}_R \chi_L |H|^2 + \cdots + ({\rm h.c.})$$




$m_s \gg m_{Z'}, m_\chi$



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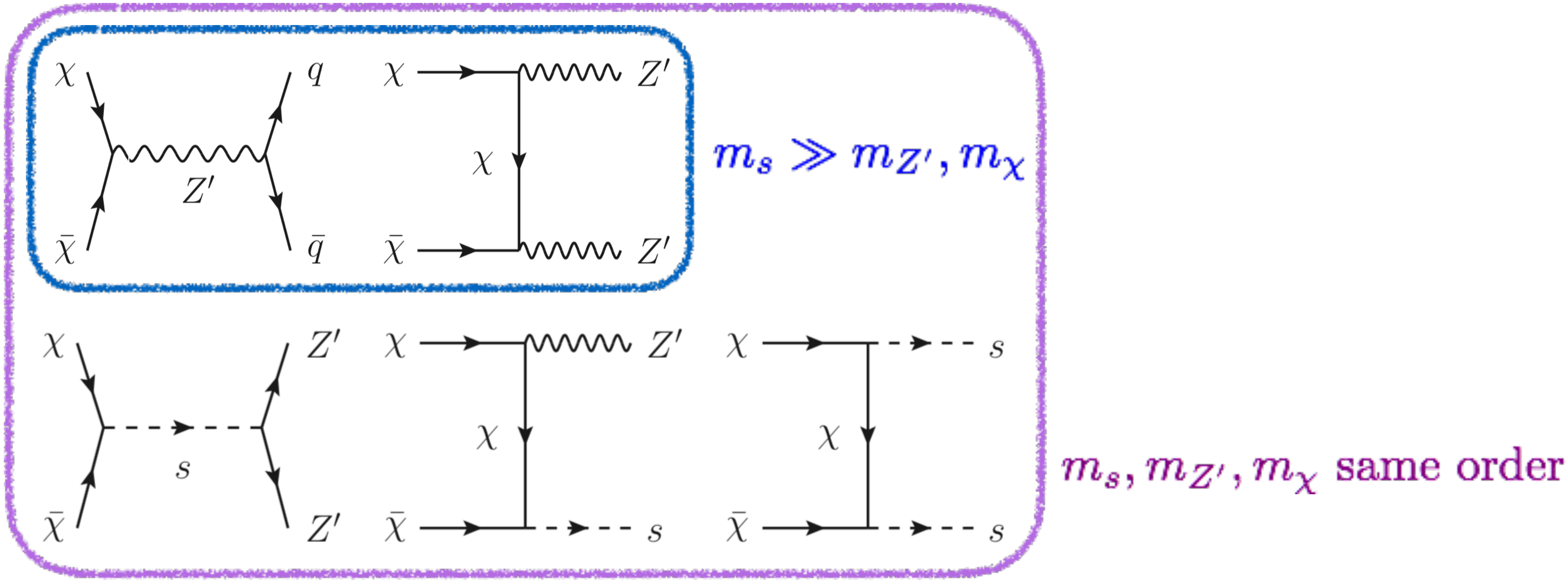



Two regimes: $m_s \gg m_{Z'}, m_\chi$ and $m_s = 2$ TeV

Note that the DM annihilation rate (and thus $\Omega^{\mathrm{DM}}$) depends on three parameters:

$$\{g_B, m_{Z'}, m_\chi\}$$

(plus $m_s$ if the $s$-field is relevant)

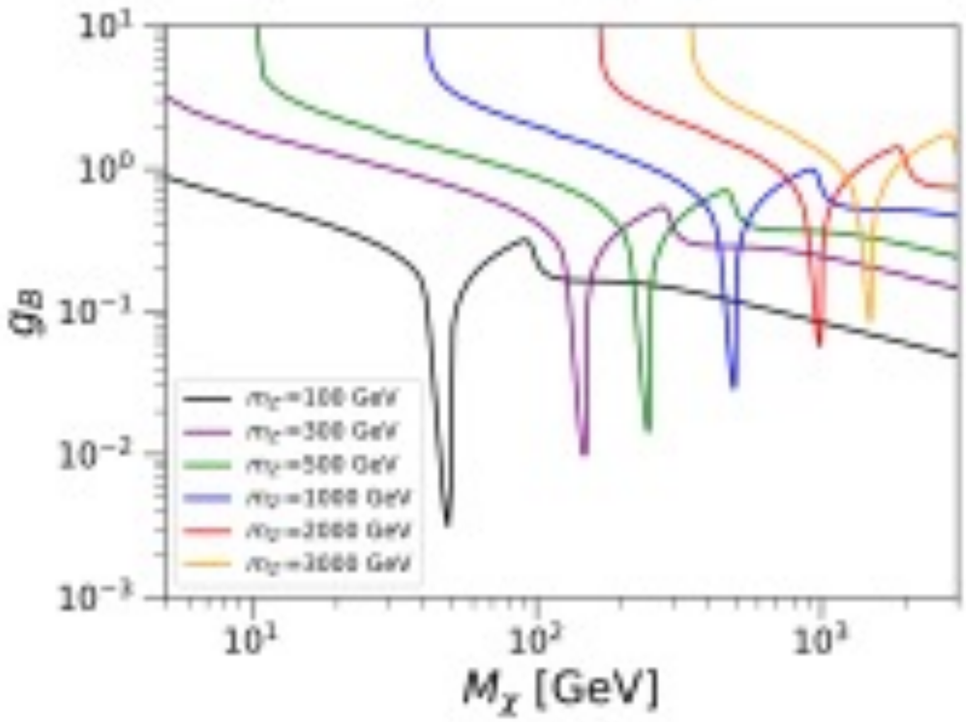
Thus the model is more predictive than a SDMM

$$g_q = \tfrac{1}{3} g_B,\ g_{\mathrm{DM}} = \tfrac{3}{2} g_B$$

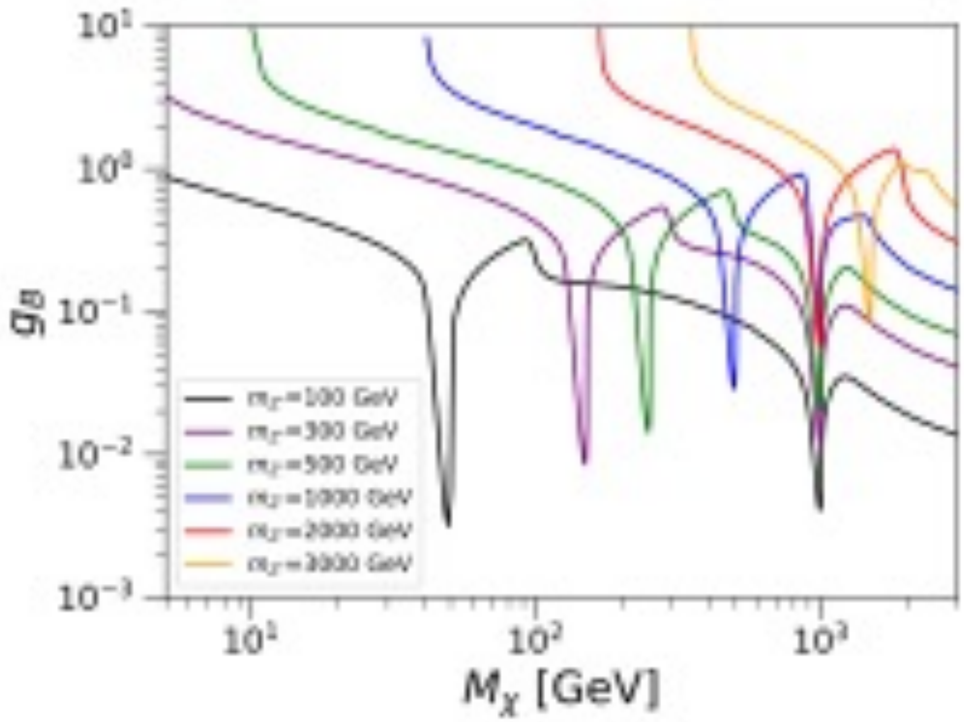
Notice that $g_q^2 \simeq \frac{1}{20} g_{\mathrm{DM}}^2$ , which is good for the phen. consistency

For each value of $\{m_{Z'}, m_\chi, m_s\}$ there is a (unique) value of $g_B$ that reproduces $\Omega_{\rm DM}^{\rm obs}$

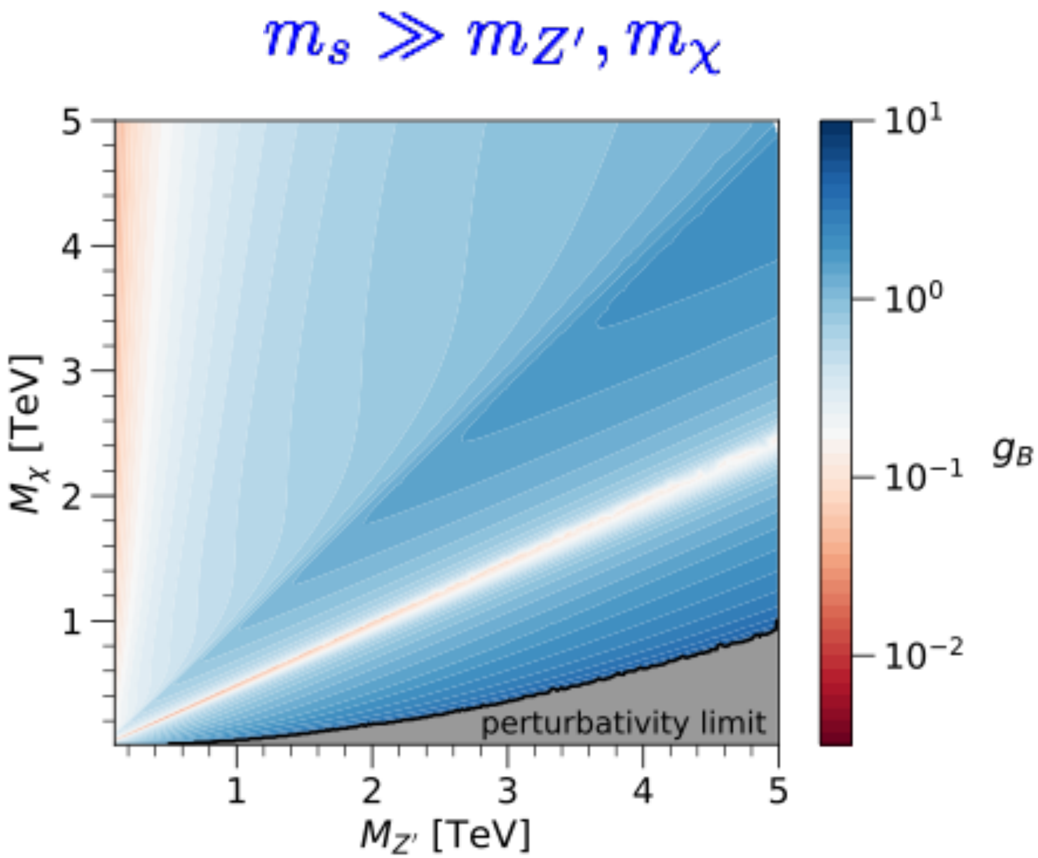
$m_s \gg m_{Z'}, m_\chi$

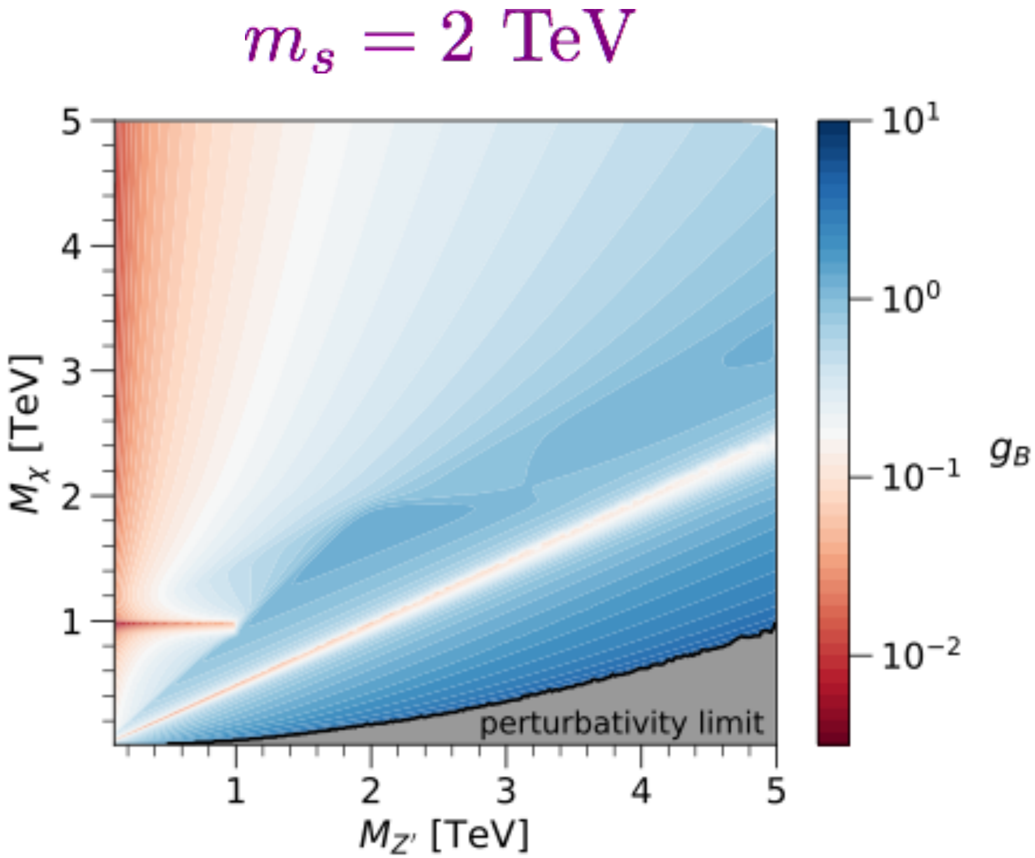



$m_s = 2$ TeV



$$\Omega_{\rm DM} = \Omega_{\rm DM}^{\rm obs}$$




$g_B$ is in the perturbative regime in most of the parameter space

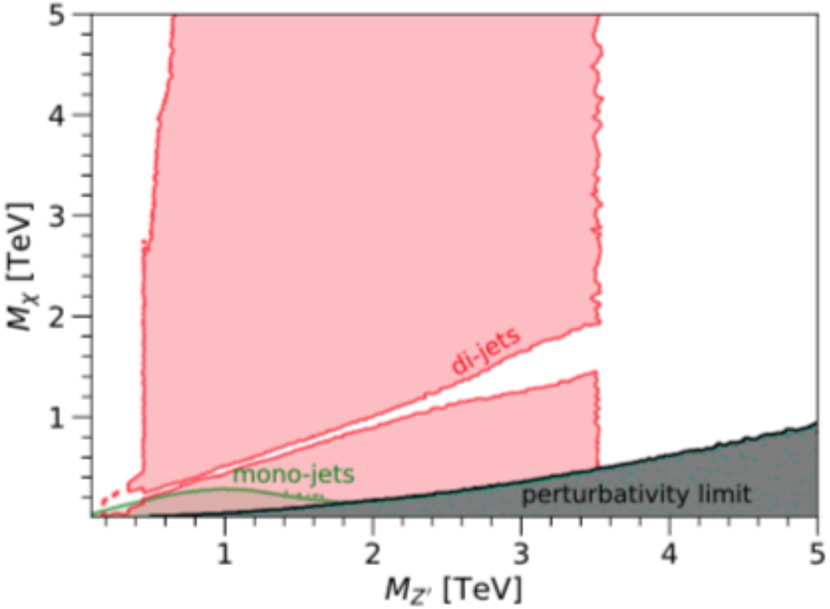
# Constraints

- DD (spin-dependent & velocity-suppressed) cross section is very small
- ID is velocity-suppressed as well
- Main constraints come from colliders and EWPO

- ★ $S$ and $T$ parameters
- ★ Di-lepton production at the LHC
- ★ Di-jet production
- ★ Mono-jets

$$\log(\Lambda'/m_{Z'}) = 1$$

$m_s = 15$ TeV

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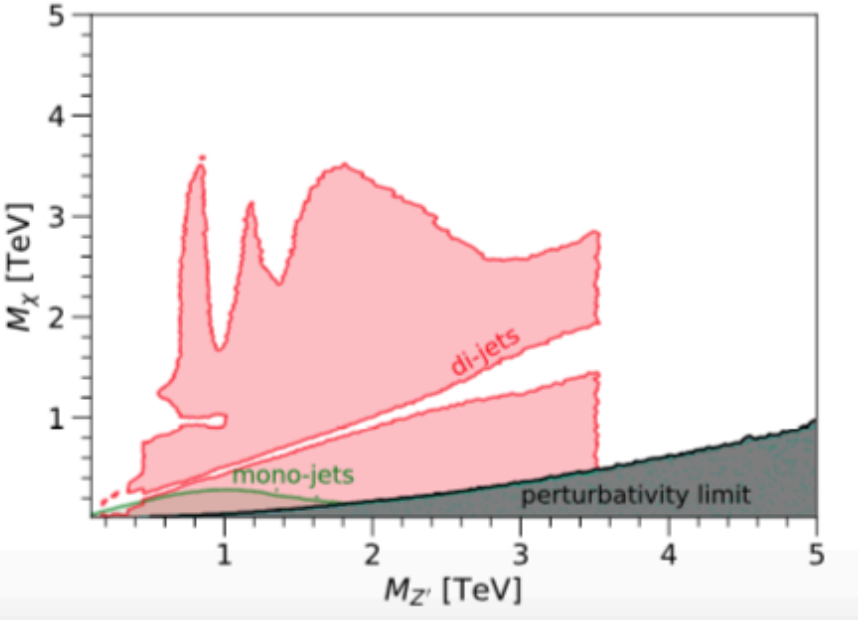
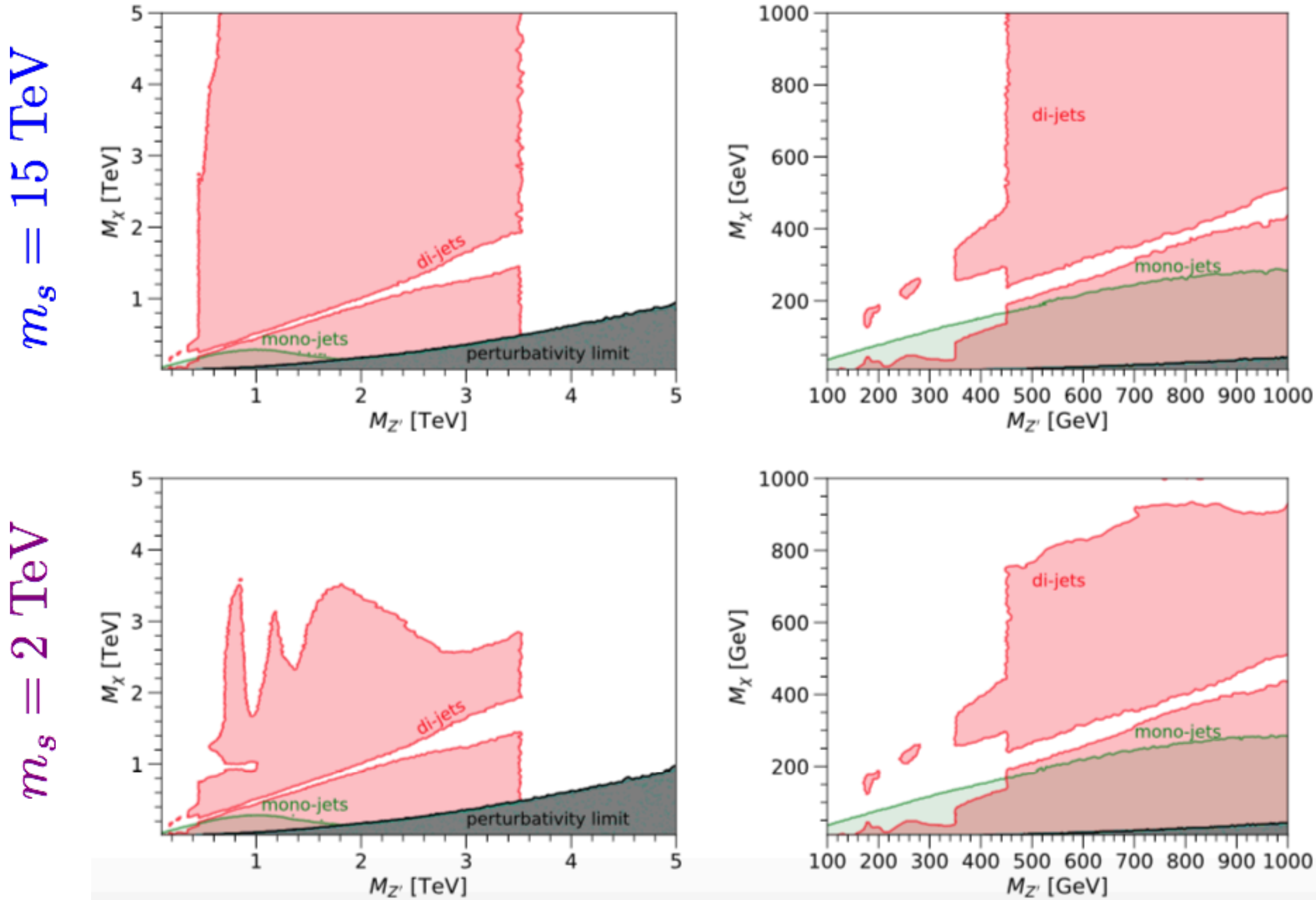
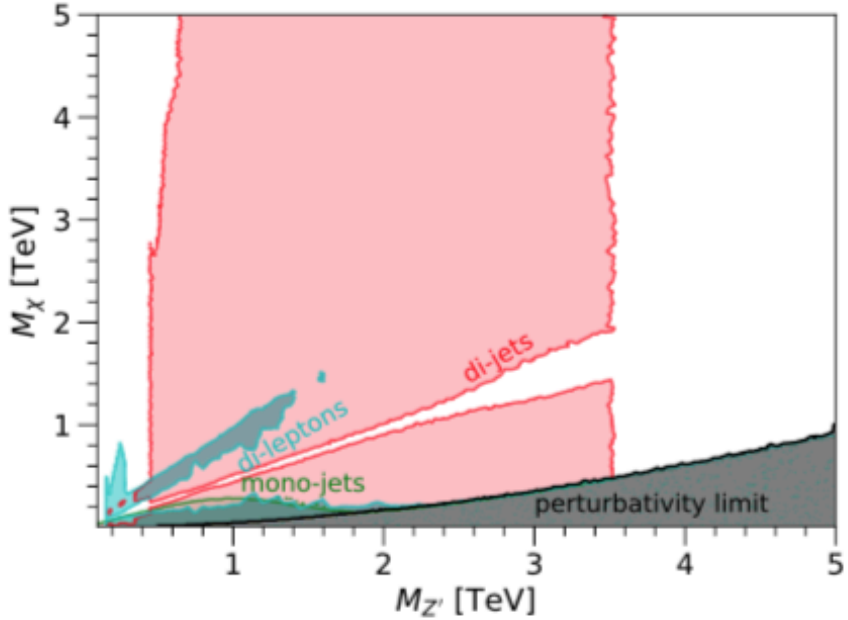


$$\log(\Lambda'/m_{Z'}) = 1$$

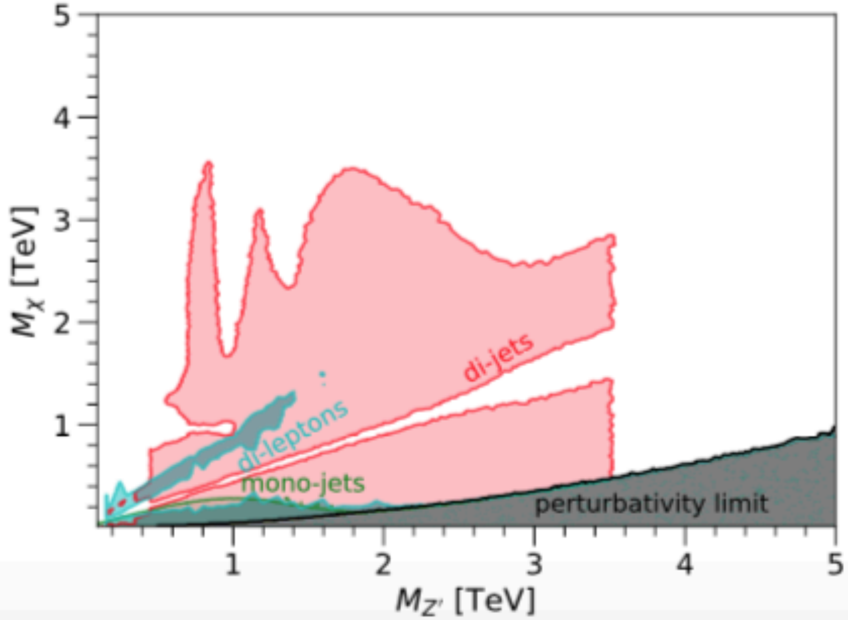


$$\log(\Lambda'/m_{Z'}) = \log(100 m_{Z'}/m_{Z'}) = 4.6$$

$m_s = 15$ TeV



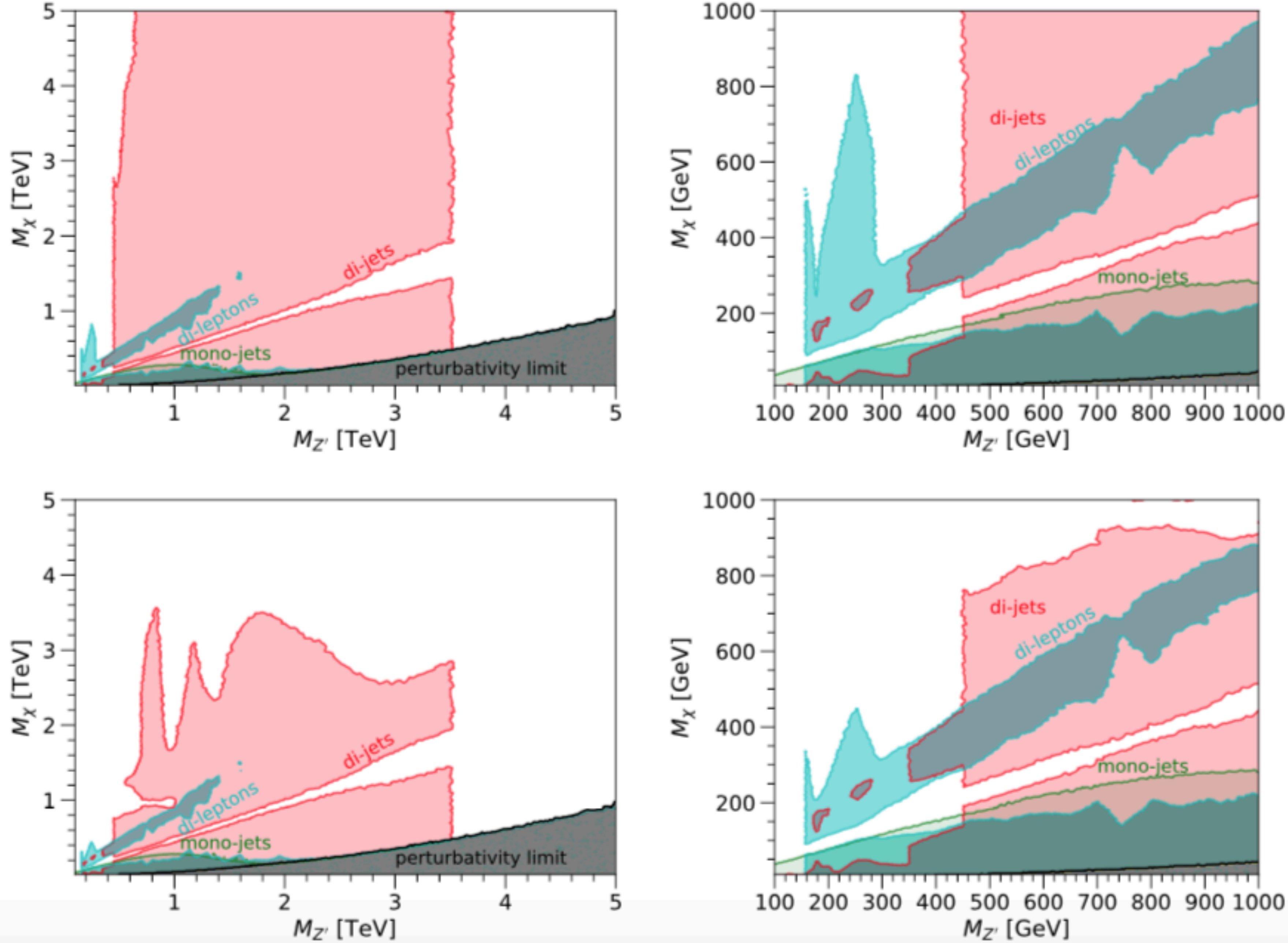

$m_s = 2$ TeV



$$\log(\Lambda'/m_{Z'}) = \log(100 m_{Z'}/m_{Z'}) = 4.6$$

$m_s = 15$ TeV

$m_s = 2$ TeV



# Conclusions

- WIMP models are still an attractive scenario for DM, with much space and possibilities to explore

- Simplified DM models may be too simple. Typically, the dark sector can (must) be extended. There can be additional mediators.

# Conclusions

- Z′-portal models are in good shape if the Z′ is leptophobic, with axial DM couplings (evading DD).

- Anomaly-cancellation requires to extend the dark sector, almost in a unique way (with minimal content). The Z′ couplings to quarks and DM become fixed.

- Interesting prospects for detection at LHC