Anomaly-free dark matter evading direct detection

Workshop on the Standard Model and Beyond Corfu Summer Institute 2018

Collab. with

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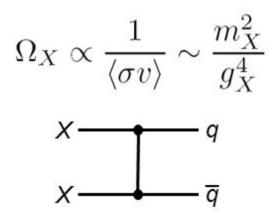
arXiv:1807.07921

Alberto Casas



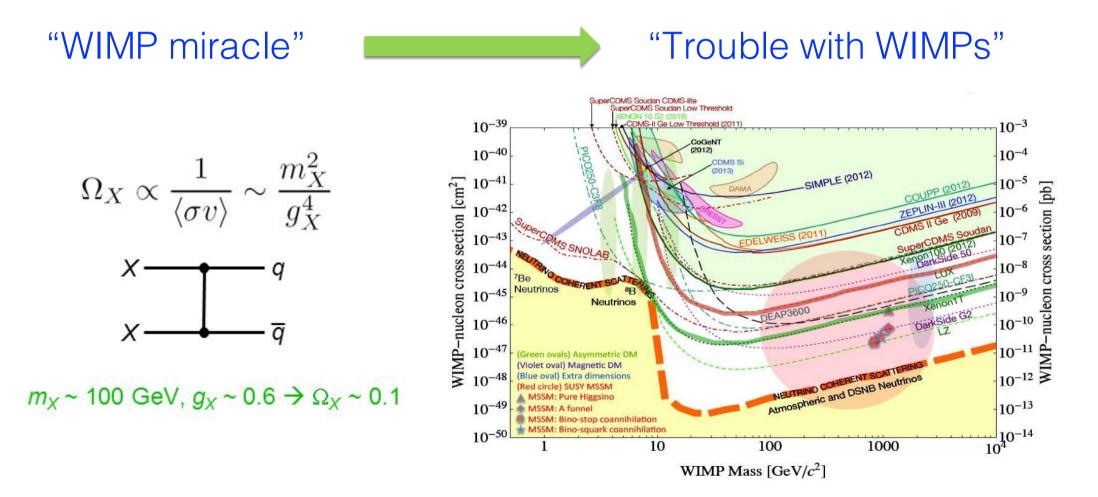
In the last years we have moved from

"WIMP miracle"



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

In the last years we have moved from



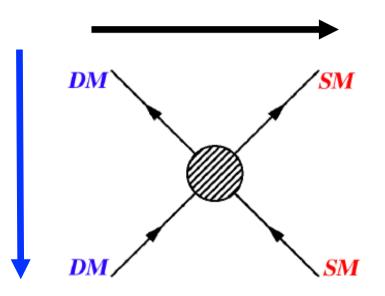
Somehow resembles the "LHC tsunami" for BSM physics:

ATLAS Preliminary ATLAS SUSY Searches* - 95% CL Lower Limits $\sqrt{s} = 7, 8, 13 \text{ TeV}$ July 2018 Model e, μ, τ, γ Jets $E_{T}^{\text{miss}} \int \mathcal{L} dt [\text{fb}^{-1}]$ Mass limit Reference $\sqrt{s} = 7, 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$ $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_1^0$ 2-6 iets $m(\tilde{\chi}_1^0) < 100 \, GeV$ 1712.02332 0 Yes 36.1 36.1 x. 8x De 1.55 mono-iet 1-3 jets Yes [1x, 8x Deg 0.43 0.71 1711.03301 $m(\tilde{q})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}$ chas 0 2-6 iets 36.1 $m(\tilde{\chi}_1^0)$ <200 GeV 1712 02332 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ Yes 2.0 Forbidden 0.95-1.6 1712.02332 $m(\tilde{\chi}_{1}^{0})=900 \, GeV$ Spa 1706.03731 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$ 3 e. u 4 iets 36.1 1.85 m(X10)<800 GeV *ее, µµ* 2 jets Yes 36.1 1.2 1805.11381 $m(\tilde{q})-m(\tilde{\chi}_1^0)=50 \text{ GeV}$ 7-11 jets $m(\tilde{\chi}_{1}^{0}) < 400 \, GeV$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$ 0 Yes 36.1 1708 02794 3 e, µ 4 jets 36.1 0.98 1706.03731 $m(\tilde{g})-m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}$ 0-1 e,μ 3 e,μ $m(\tilde{\chi}_1^0)$ <200 GeV 1711.01901 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ 3hYes 36.1 2.0 4 jets 1.25 1706.03731 36.1 $m(\tilde{q})-m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}$ Multiple $m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BB(h\tilde{\chi}_{1}^{0})=1$ 1708.09266.1711.03301 $\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$ 36.1 Forbidden 0.9 Multiple 0.58-0.82 36.1 $m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=BR(t\tilde{\chi}_{1}^{\pm})=0.5$ 1708.09266 Multiple 36.1 0.7 $m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}, m(\tilde{\chi}_{1}^{\pm})=300 \text{ GeV}, BR(\tilde{\chi}_{1}^{\pm})=1$ 1706.03731 Multiple 1709 04183 1711 11520 1708 03247 $\tilde{b}_1 \tilde{b}_1, \tilde{t}_1 \tilde{t}_1, M_2 = 2 \times M_1$ 36.1 0.7 $m(\tilde{\chi}_1^0)=60 \text{ GeV}$ Multiple 0.9 1709.04183.1711.11520.1708.03247 36.1 $m(\tilde{\chi}_1^0)=200 \, GeV$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow Wb \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0$ 0-2 e, µ 0-2 jets/1-2 b Yes 36.1 1.0 $m(\tilde{\chi}_{1}^{0})=1 \text{ GeV}$ 1506 08616 1709 04183 1711 11520 1709.04183.1711.11520 $\tilde{t}_1 \tilde{t}_1, \tilde{H} LSP$ Multiple 0.4-0.9 $m(\tilde{\chi}_{1}^{0}) = 150 \text{ GeV} m(\tilde{\chi}_{1}^{\pm}) \cdot m(\tilde{\chi}_{1}^{0}) = 5 \text{ GeV} \tilde{\iota}_{1} \approx \tilde{\iota}_{1}$ 36.1 Multiple 36.1 0.6-0.8 1709.04183, 1711.11520 Forbidden $m(\tilde{\chi}_1^0)=300 \text{ GeV}, m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=5 \text{ GeV}, \tilde{t}_1 \approx \tilde{t}_L$ $\tilde{t}_1 \tilde{t}_1$, Well-Tempered LSP Multiple 36.1 0.48-0.84 $m(\tilde{\chi}_1^0)=150 \text{ GeV}, m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=5 \text{ GeV}, \tilde{t}_1 \approx \tilde{t}_L$ 1709.04183, 1711.11520 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$ 0 2cYes 36.1 0.85 $m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1805 01649 0.46 $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 50 \text{ GeV}$ 1805.01649 0 Yes 36.1 0.43 1711.03301 mono-jet $m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)=5$ GeV $\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$ 1-2 e, µ 4 b 36.1 0.32-0.88 1706.03986 Yes $m(\tilde{\chi}_{1}^{0})=0$ GeV, $m(\tilde{t}_{1})-m(\tilde{\chi}_{1}^{0})=180$ GeV $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via WZ2-3 e.u 0.6 Ves 36.1 $\begin{array}{c} \tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0\\ \tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0 \end{array}$ $m(\tilde{\chi}_{1}^{0})=0$ 1403.5294. 1806.02293 ее, µµ 0.17 > 1 Yes $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=10 \text{ GeV}$ 1712.08119 36.1 *ℓℓ/ℓγγ/ℓbb* $\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{2}^{0}$ via Wh Yes 20.3 $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.26 $m(\tilde{\chi}_{1}^{0})=0$ 1501.07110 $\begin{array}{c} \tilde{\chi}_1^{\pm} / \tilde{\chi}_2^0 \\ \tilde{\chi}_1^{\pm} / \tilde{\chi}_2^0 \end{array}$ 1708.07875 $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0, \tilde{\chi}_1^{+} \rightarrow \tilde{\tau} \nu(\tau \tilde{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\tau} \tau(\nu \tilde{\nu})$ 2τ Yes 36.1 0.76 $m(\tilde{\chi}_{1}^{0})=0, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ ĒΨ 0.22 $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=100 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ 1708.07875 2 e,µ 1803.02762 $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$ 0 Yes 36.1 0.5 $m(\tilde{\chi}_{1}^{0})=0$ 2 e, µ ≥ 1 Yes 36.1 0.18 $m(\tilde{\ell})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ 1712.08119 $\tilde{H}\tilde{H}$. $\tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$ 0.29-0.88 0 $\geq 3b$ Yes 36.1 0.13-0.23 $BR(\tilde{\chi}_{1}^{0} \rightarrow h\tilde{G})=1$ 1806.04030 0.3 $4 e, \mu$ 0 Yes 36.1 $BR(\tilde{\chi}_{1}^{0} \rightarrow Z\tilde{G})=1$ 1804 03602 Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ Disapp. trk 1 jet Yes 36.1 0.46 Pure Wind 1712.02118 Pure Higgsino 0 15 ATL-PHYS-PUB-2017-019 Stable 2 R-hadron SMP 3.2 1.6 1606.05129 Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$ Multiple 32.8 1710.04901. 1604.04520 2.4 $m(\tilde{\chi}_{1}^{0})=100 \text{ GeV}$ 0.44 GMSB, $\tilde{\chi}_{1}^{0} \rightarrow \gamma \tilde{G}$, long-lived $\tilde{\chi}_{1}^{0}$ 2γ Yes 20.3 $1 < \tau(\tilde{\chi}_1^0) < 3$ ns, SPS8 mode 1409.5542 $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow eev/e\mu v/\mu\mu v$ displ. ee/eµ/µµ 20.3 1.3 $6 \le c_{\tau}(\tilde{\chi}_{1}^{0}) \le 1000 \text{ mm} \text{ m}(\tilde{\chi}_{1}^{0}) = 1 \text{ TeV}$ 1504.05162 LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$ d'...=0.11. dua2/100/200=0.07 ец.ет.цт 32 1.9 1607 08079 $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$ 4 e, µ 0 Yes 36.1 1.33 $m(\tilde{\chi}_{1}^{0})=100 \text{ GeV}$ 1804.03602 $\tilde{\chi}_{2}^{0} = [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$ 1.9 2.0 1804.03568 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$ 0 4-5 large-R jets 36.1 1.3 Large X"... Multiple 36.1 1.05 $m(\tilde{\chi}_1^0)=200$ GeV, bino-like ATLAS-CONF-2018-003 J d E Multiple ATLAS-CONE-2018-003 $\tilde{g}\tilde{g}, \tilde{g} \to tbs / \tilde{g} \to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$ 36.1 1.8 2.1 $m(\tilde{\chi}_1^0)=200$ GeV, bino-like $\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$ Multiple 36.1 -2e-4 1e-2 0.55 1.05 $m(\tilde{\chi}_1^0)=200$ GeV, bino-like ATLAS-CONF-2018-003 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$ 0 2 iets + 2 b 36.7 0.42 0.61 1710.07171 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b\ell$ 0.4-1.45 $BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ 1710.05544 2 e, µ 2b36.1 *Only a selection of the available mass limits on new states or 10⁻¹ 1 Mass scale [TeV] phenomena is shown. Many of the limits are based on

simplified models, c.f. refs. for the assumptions made.

(From Albert De Roeck talk)

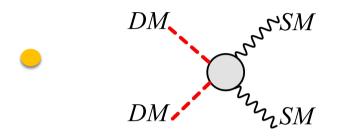
However, although a substantial annihilation rate in the early universe is necessary to get the correct relic abundance



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

There are mechanisms that suppress DD cross section

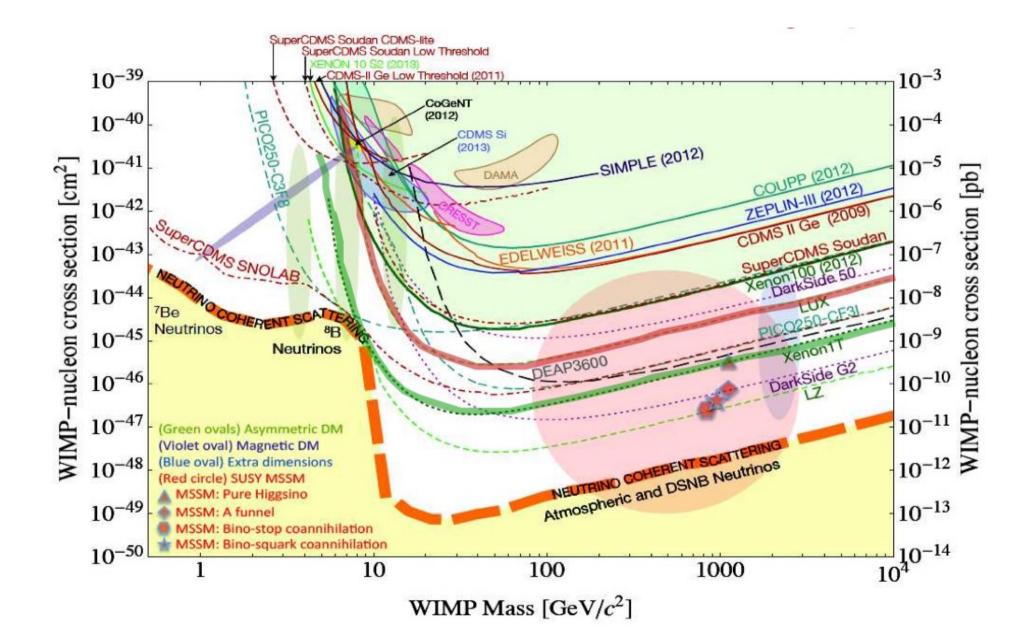
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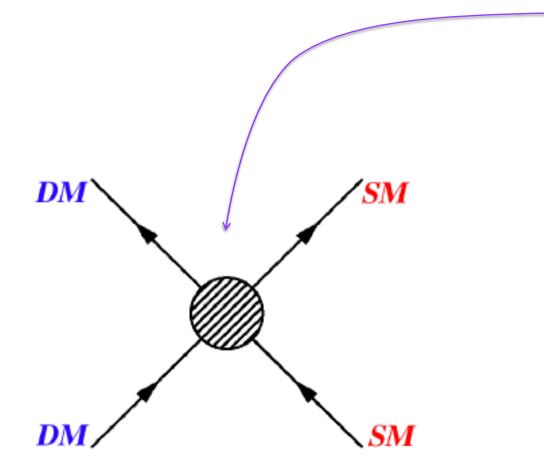
(see A. Belyaev's talk)

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

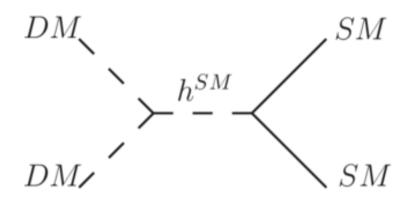
So, perhaps the DD tsunami is not that scary



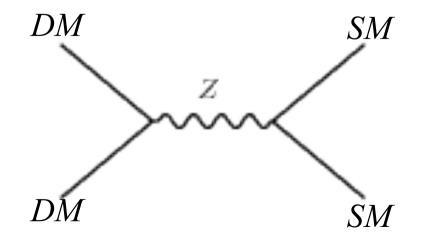
Essentially, everything depends on the content of the blob



Obvious possibilities



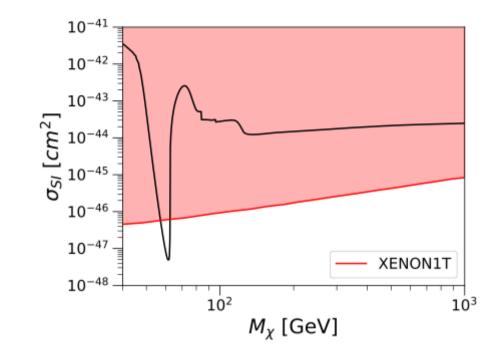
Higgs-portal



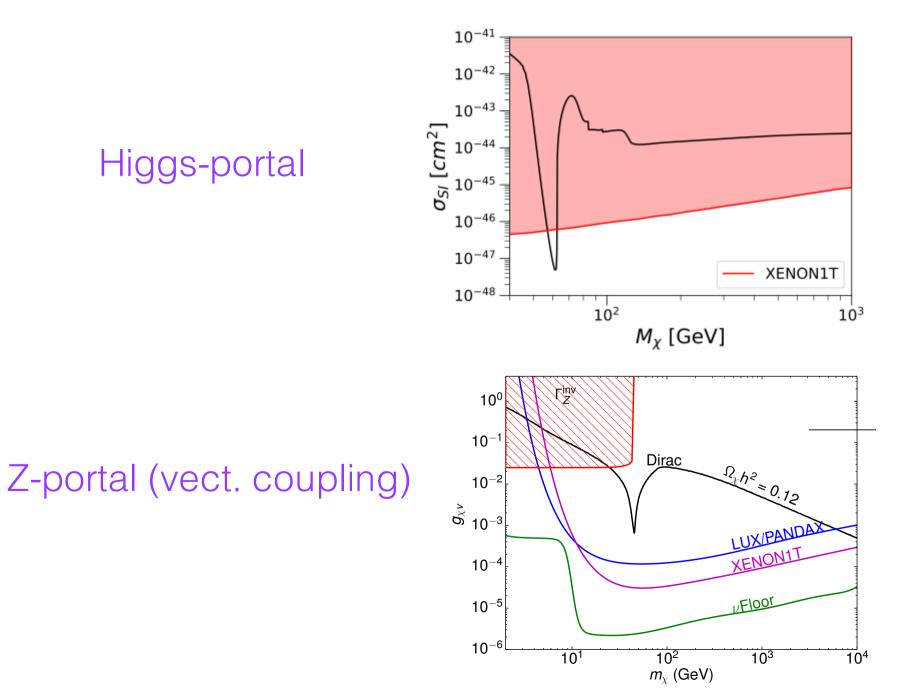
Z-portal

Both are in trouble with DD

Higgs-portal



Both are in trouble with DD

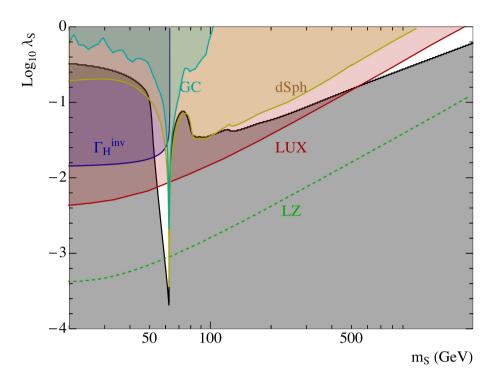


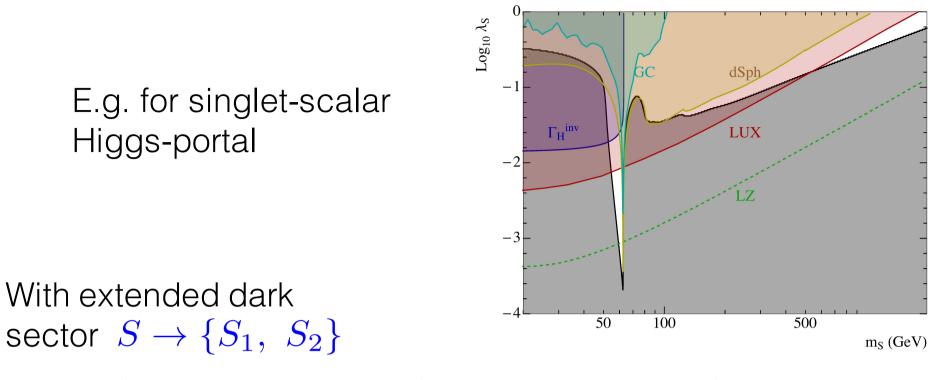
However, this scheme is probably oversimplified

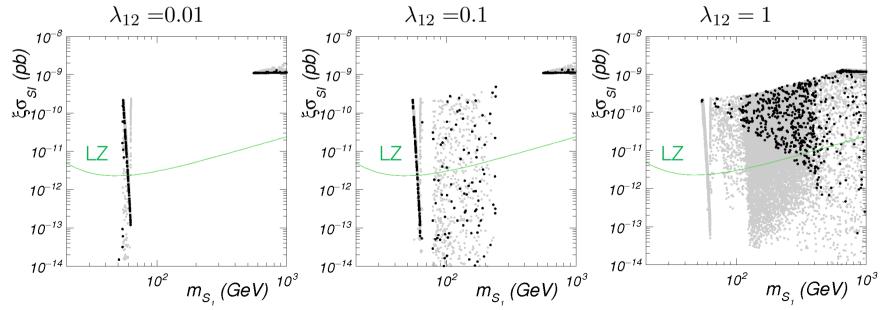
★ Dark sector may contain extra stuff

★ There may be other mediators

E.g. for singlet-scalar Higgs-portal

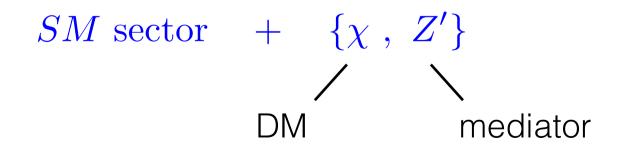






Let us focus now on new mediators, in particular on new gauge bosons (Z'), arising from extra U(1) factors in the symmetry group.

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



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 $y_i^e \bar{L}_i H e_i$: $Y'_H = 0$
- 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 $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)'$

Anomaly equations

 $U(1)_B$

$$\begin{split} SU(3)_C^2 \times U(1)' \text{ anomaly } &\longrightarrow \mathrm{Tr}[\{\mathcal{T}_i, \mathcal{T}_j\}Y'] = 0\\ SU(3)_C^2 \times U(1)_Y \text{ anomaly } &\longrightarrow \mathrm{Tr}[\{T_i, T_j\}Y] = 0\\ SU(2)_W^2 \times U(1)' \text{ anomaly } &\longrightarrow \mathrm{Tr}[\{T_i, T_j\}Y'] = 0\\ SU(2)_W^2 \times U(1)_Y \text{ anomaly } &\longrightarrow \mathrm{Tr}[\{T_i, T_j\}Y] = 0\\ U(1)_Y^2 \times U(1)' \text{ anomaly } &\longrightarrow \mathrm{Tr}[Y^2Y'] = 0\\ U(1)_Y \times U(1)'^2 \text{ anomaly } &\longrightarrow \mathrm{Tr}[YY'^2] = 0\\ U(1)_Y'^3 \text{ anomaly } &\longrightarrow \mathrm{Tr}[Y'^3] = 0\\ U(1)_Y^3 \text{ anomaly } &\longrightarrow \mathrm{Tr}[Y^3] = 0\\ \mathrm{Gauge \ gravity } &\longrightarrow \mathrm{Tr}[Y] = \mathrm{Tr}[Y'] = 0 \end{split}$$

(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

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

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

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) $_{Y^{\prime}}$ 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_{ψ}, Y_{η} 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:

$$\{Y_{\psi}, Y_{\eta}\} = \left\{\pm\frac{1}{2}, \pm 1\right\}, \ \left\{\pm\frac{7}{2}, \pm 5\right\}, \\ \left\{Y_{\psi_L}', Y_{\psi_R}', Y_{\eta_L}', Y_{\eta_R}', Y_{\chi_L}', Y_{\chi_R}'\right\} = \left\{-\frac{3}{2}, \frac{3}{2}, \frac{3}{2}, -\frac{3}{2}, \frac{3}{2}, -\frac{3}{2}\right\}.$$

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Minimal dark scalar-sector

Note: vectorial Z' couplings to quarks & axial coupling to DM DD effective operator is spindependent and velocitysuppressed



Fermionic content

+ 1 complex scalar

S (1, 0, -3)

which takes a VEV , giving mass to the new boson Z^{\prime} and the dark fermions

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



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



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

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

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

 $\epsilon \neq 0$ 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 $Z' \to \ell \ell$)

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

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

 λ_L , λ_R lead to the split of the two degrees of freedom of χ , thus spoiling the axial coupling of DM

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

$$\mathcal{L}_{\text{fer}} \supset -y_1 \bar{\psi}_L H \eta_R - y_2 \bar{\psi}_L \bar{H} \chi_R - y_3 \bar{\psi}_R H \eta_L - y_4 \bar{\psi}_R \bar{H} \chi_L - \lambda_{\psi} \bar{\psi}_L \psi_R S - \lambda_{\eta} \bar{\eta}_R \eta_L S - \lambda_{\chi} \bar{\chi}_R \chi_L S + (\text{h.c.}).$$

$$\mathcal{L}_{\text{fer}} \supset -y_1 \bar{\psi}_L H \eta_R - y_2 \bar{\psi}_L \bar{H} \chi_R - y_3 \bar{\psi}_R H \eta_L - y_4 \bar{\psi}_R \bar{H} \chi_L - \lambda_{\psi} \bar{\psi}_L \psi_R S - \lambda_{\eta} \bar{\eta}_R \eta_L S - \lambda_{\chi} \bar{\chi}_R \chi_L S + (\text{h.c.}).$$

The extra fermionic fields, ψ , η , 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.

$$\mathcal{L}_{\text{fer}} \supset -y_1 \bar{\psi}_L H \eta_R - y_2 \bar{\psi}_L \bar{H} \chi_R - y_3 \bar{\psi}_R H \eta_L - y_4 \bar{\psi}_R \bar{H} \chi_L - \lambda_{\psi} \bar{\psi}_L \psi_R S - \lambda_{\eta} \bar{\eta}_R \eta_L S - \lambda_{\chi} \bar{\chi}_R \chi_L S + (\text{h.c.}).$$

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

with
$$rac{1}{\Lambda}=rac{y_2y_4}{m_\psi}$$

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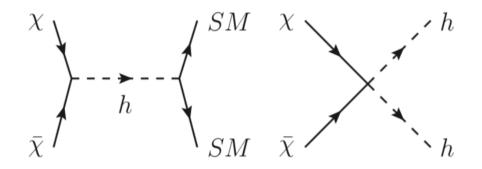


 \longrightarrow 3 annihilation channels: Z'-portal, s-portal and H-portal

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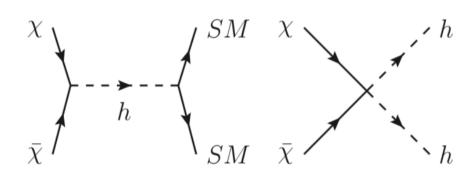


$$\mathcal{L}_{\text{eff}}^{\text{DM}} = \mathcal{L}_{\text{kin}} - \lambda_{\chi} \bar{\chi}_R \chi_L S + \frac{1}{\Lambda} \bar{\chi}_R \chi_L |H|^2 + \dots + (\text{h.c.})$$

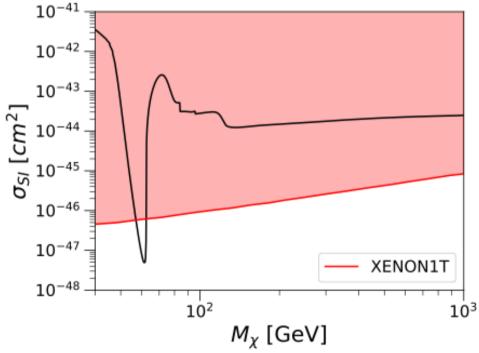
with $\frac{1}{\Lambda} = \frac{y_2 y_4}{m_{\psi}}$

 \rightarrow

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



Excluded except at the resonance



We will assume it is negligible

Finally

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

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

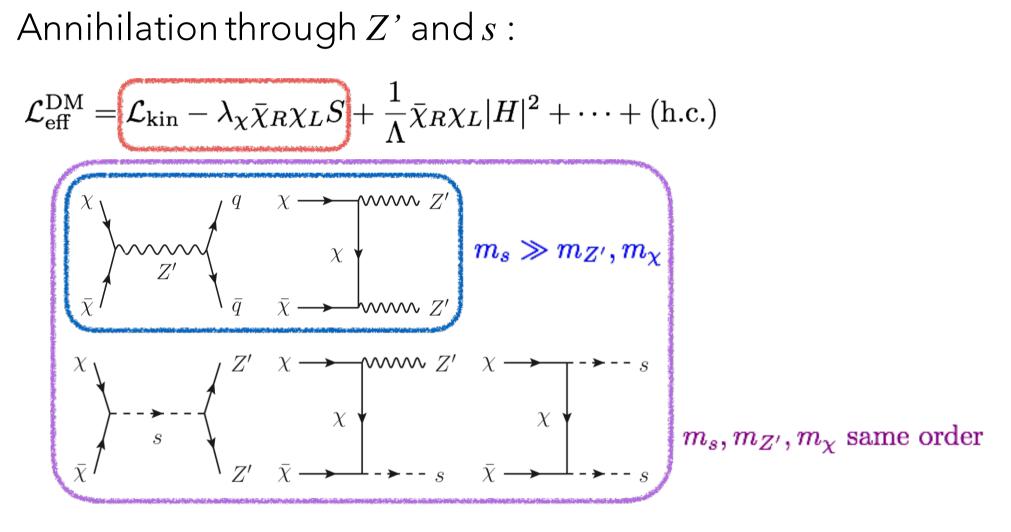
Relic density

Annihilation through Z' and s: $\mathcal{L}_{\text{eff}}^{\text{DM}} = \mathcal{L}_{\text{kin}} - \lambda_{\chi} \bar{\chi}_R \chi_L S + \frac{1}{\Lambda} \bar{\chi}_R \chi_L |H|^2 + \dots + (\text{h.c.})$

Relic density

Annihilation through Z' and s: $= \mathcal{L}_{\rm kin} - \lambda_{\chi} \bar{\chi}_R \chi_L S + \frac{1}{\Lambda} \bar{\chi}_R \chi_L |H|^2 + \dots + (\rm h.c.)$

Relic density



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

Note that the DM annihilation rate (and thus Ω^{DM}) depends on three parameters:

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

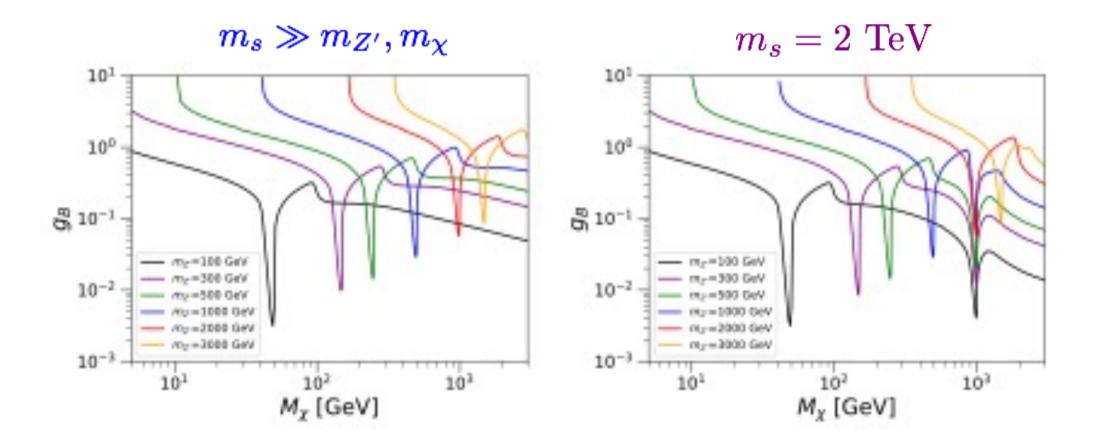
(plus m_s if the *s*-field is relevant)

Thus the model is more predictive than a SDMM

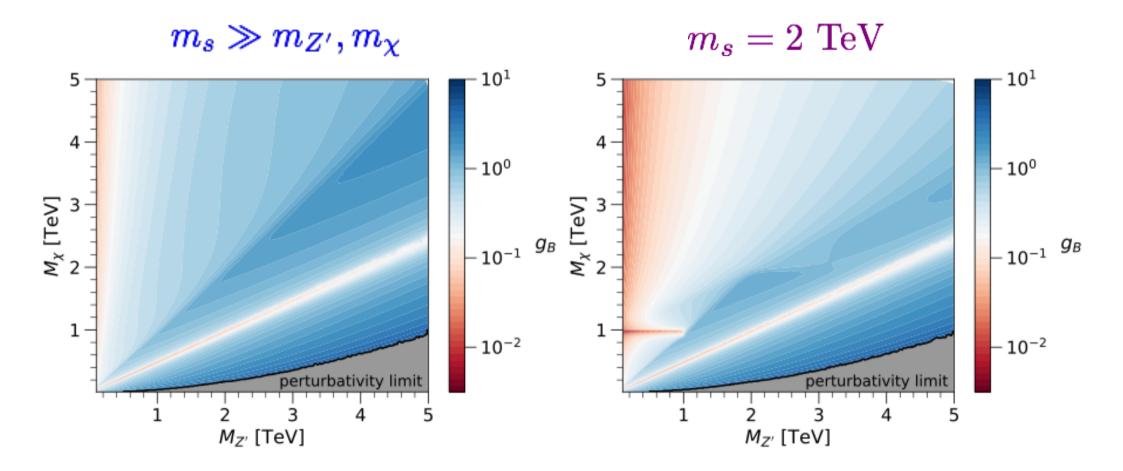
$$g_q = \frac{1}{3}g_B, \ g_{\rm DM} = \frac{3}{2}g_B$$

Notice that $g_q^2 \simeq \frac{1}{20} g_{\rm DM}^2$, 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 $\Omega_{\rm DM}^{\rm obs}$

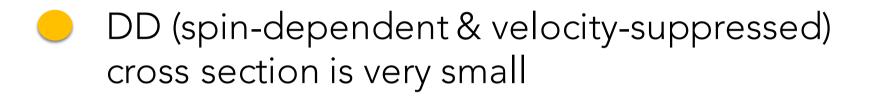


 $\Omega_{\rm DM} = \Omega_{\rm DM}^{\rm obs}$



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





D is velocity-suppressed as well



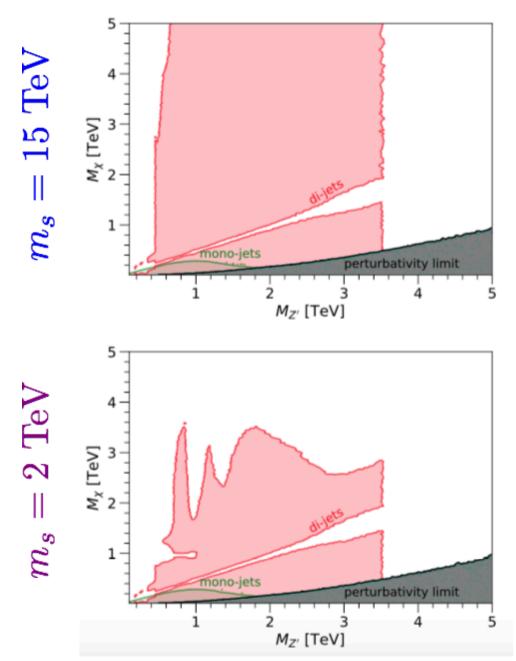
Main constraints come from colliders and EWPO



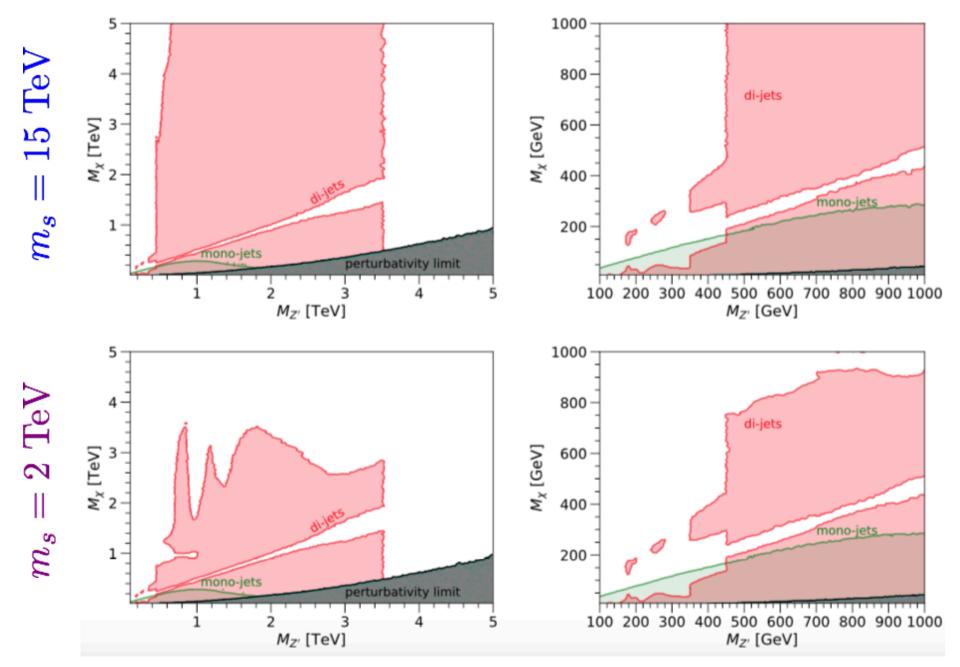
- ★ Di-lepton production at the LHC
- ★ Di-jet production

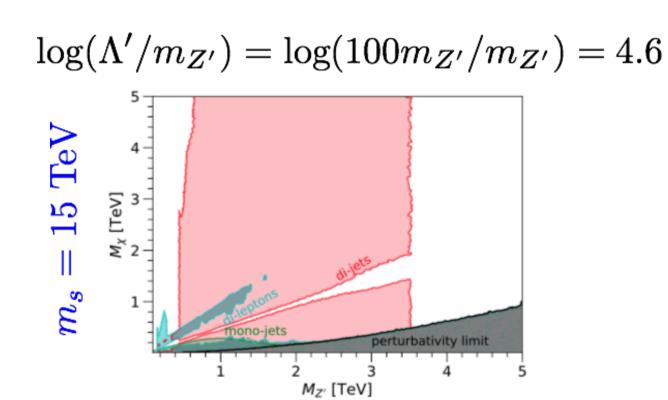


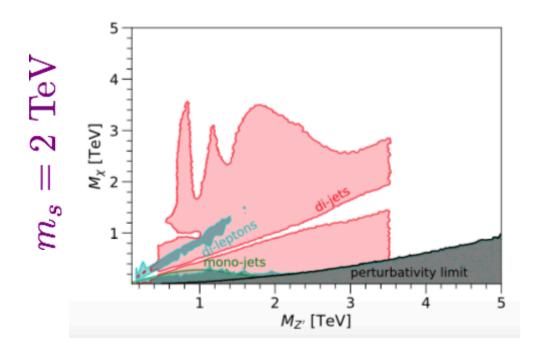
$$\log(\Lambda'/m_{Z'}) = 1$$

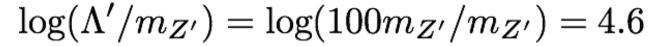


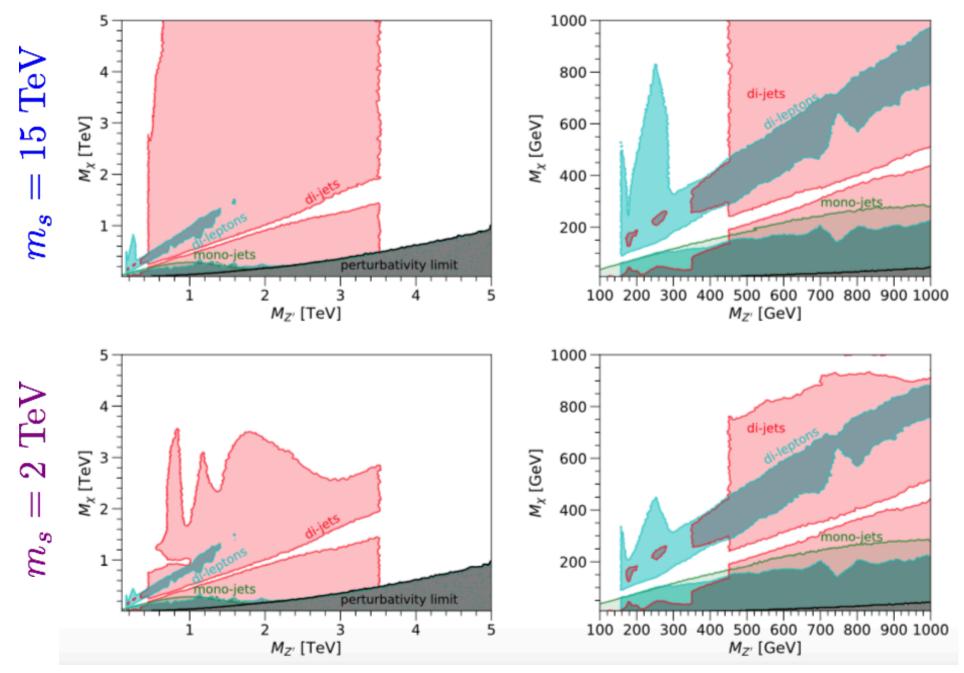
 $\log(\Lambda'/m_{Z'}) = 1$



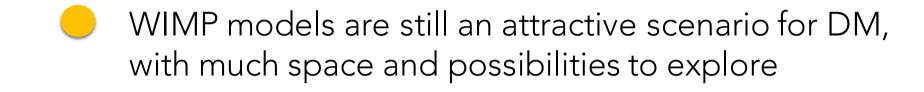












 Simplified DM models may be too simple. Typically, the dark sector can (must) be extended. There can be additional mediators.



- 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