A fermionic portal to a non-abelian dark sector

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Based on 2203.04681 and 2204.03510 with
A. Belyaev, A. Deandrea, S. Moretti and N. Thongyoi

A still unresolved issue

What is dark matter?

And if it is composed of new particle(s), what are their properties?

Thousands of papers, multiple experiments, no clue yet

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The SM is a gauge theory $\longrightarrow \begin{cases} \text{Dark sector} \longrightarrow \text{new gauge group} \\ \text{Dark matter} \longrightarrow \text{(massive) mediator of a new force} \end{cases}$

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Dark matter → (massive) mediator of a new force

Ingredients:

- **a new gauge symmetry**
- **a way to break it spontaneously** → massive gauge boson(s)
- **a residual conserved symmetry ($U(1)_D, \mathbb{Z}_2, \ldots$)**
  → the lightest particle transforming under it ($U(1)_D$-charged, $\mathbb{Z}_2$-odd …) is stable

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and that would be enough in theory. But we'd like to detect it...

- **a portal with the SM**

Which kind of gauge group?

Abelian

- A $U(1)_D$ group: $\mathcal{L} = V_{D\mu\nu}V_D^{\mu\nu}$

A problem:

Abelian ➔ kinetic mixing ➔ not stable

Solution:

- Sequester $U(1)_D$ ➔ an exact $\mathbb{Z}_2$

$$V_D^\mu \to -V_D^\mu \quad \text{(Charge conjugation)}$$

V_D is stable, now make it massive:

- SSB ➔ complex singlet S ($S \xrightarrow{\mathbb{Z}_2} S^*$)

$$\mathcal{L} = |D_\mu S|^2 + \mu_S^2|S|^2 - \lambda_S|S|^4$$
$$m_{V_D} = \sqrt{2}g_D v_D$$

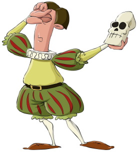
V_D^μ is a DM candidate

Need to interact with the SM:

- **Higgs portal** ➔ $V(\Phi_H, S) = \lambda|\Phi_H|^2|S|^2$

Widely studied

Lebedev, Lee & Mambrini 1111.4482,
Farzan & Akbarieh 1207.4272,
Baek, Ko, Park & Senaha 1212.2131, . . .



Non-abelian

- Various possible gauge groups

$$\mathcal{L} = V^a_{D\mu\nu}V_D^{\mu\nu a}$$

- No renormalizable kinetic mixing

Limiting to $SU(N)$:

- complete SSB with $N-1$ complex scalars ➔ preserved $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetries

Gross *et al* 1505.07480

$V_D^{\mu a}$ are all DM candidates

- Still can have **Higgs portal**

$$V(\Phi_H, S_{i,j,\dots}) = \sum_{i,j} \lambda_{ij}|\Phi_H|^2 S_i^\dagger S_j + h.c.$$

Also widely studied

Hambye 0811.0172, Diaz-Cruz & Ma 1007.2631,
Fraser, Ma & Zakeri 1409.1162, Ko & Tang 1609.02307, . . .

Minimal vector DM scenario
where the Higgs portal can be small or absent*?

Non-abelian with fermion portal

* No *need* to avoid Higgs portal, but new fermions can address current anomalies

Construction of the **Fermion Portal Vector Dark Matter** scenarios

Connecting the dark sector to the SM

$SU(2)_D$ $$\mathcal{V}_\mu^D = \begin{pmatrix} V^0_{D+} \\ V^0_{D0} \\ V^0_{D-} \end{pmatrix}$$

Massless $SU(2)_D$ gauge bosons
we need to give them mass

$SU(2)_L \times U(1)_Y$ $$\mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu \qquad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \begin{matrix} u_R \\ d_R \; e_R \end{matrix}$$

$$\mathcal{L} = -\frac{1}{4}(W^i_{\mu\nu})^2 - \frac{1}{4}(B_{\mu\nu})^2 + |D_\mu \Phi_H|^2 + \mu^2 \Phi_H^\dagger \Phi_H - \lambda(\Phi_H^\dagger \Phi_H)^2 + \bar{f}^{\mathrm{SM}}\, i\not{D}\, f^{\mathrm{SM}} - (y\, \bar{f}_L^{\mathrm{SM}}\, \Phi_H\, f_R^{\mathrm{SM}} + h.c.)$$
$$-\frac{1}{4}(\mathcal{V}^{Di}_{\mu\nu})^2$$

Connecting the dark sector to the SM

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SSB: $\langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_D \end{pmatrix}$

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Higgs portal: $\Phi_H^\dagger \Phi_H \Phi_D^\dagger \Phi_D$

- Not protected by any symmetry
- $V(\Phi_D)\ :\ SO(4) \xrightarrow{SSB} SU(2)_{\rm diag}$ unbroken global symmetry
- All the new gauge bosons are stable

Hambye 0811.0172

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$$-\lambda_{\Phi_H \Phi_D}\, \Phi_H^\dagger \Phi_H\ \Phi_D^\dagger \Phi_D$$

can be small

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$$\Big\updownarrow$$

Kinetic mixing: $\mathcal{V}_D^{\mu\nu a} W^b_{\mu\nu}$

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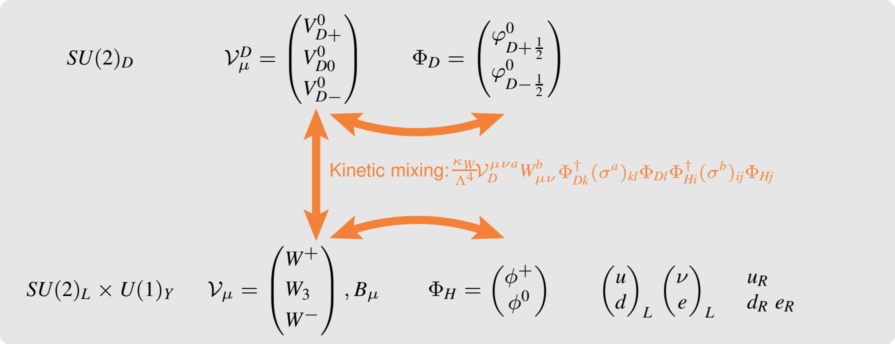

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Kinetic mixing: $\frac{\kappa_W}{\Lambda^4}\mathcal{V}_D^{\mu\nu a} W^b_{\mu\nu}\,\Phi^\dagger_{Dk}(\sigma^a)_{kl}\Phi_{Dl}\Phi^\dagger_{Hi}(\sigma^b)_{ij}\Phi_{Hj}$

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- **fundamental of $SU(2)_D$**
  → interacts with $\mathcal{V}^D_\mu$

Introducing a fermion

$SU(2)_L \times U(1)_Y$ $\quad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu$ $\quad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\quad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\quad u_R$, $d_R\ e_R$

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Introducing a fermion

- **fundamental of $SU(2)_D$**
  - → interacts with $\mathcal{V}^D_\mu$
- **Vector-like***
  - → no anomalies

* abelian case with VL fermions in DiFranzo, Fox & Tait 1512.06853

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$\boxed{-M_\Psi \bar{\Psi}\Psi}$

Introducing a fermion

- **fundamental of $SU(2)_D$**
  → interacts with $\mathcal{V}^D_\mu$
- **Vector-like**
  → no anomalies
- **Charged under $U(1)_Y$**
  → interacts with SM

doublet of $SU(2)_D$

singlets of $SU(2)_L$

$$SU(2)_L \times U(1)_Y \qquad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu \qquad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \begin{matrix} u_R \\ d_R \; e_R \end{matrix} \qquad \psi_D \; \psi$$

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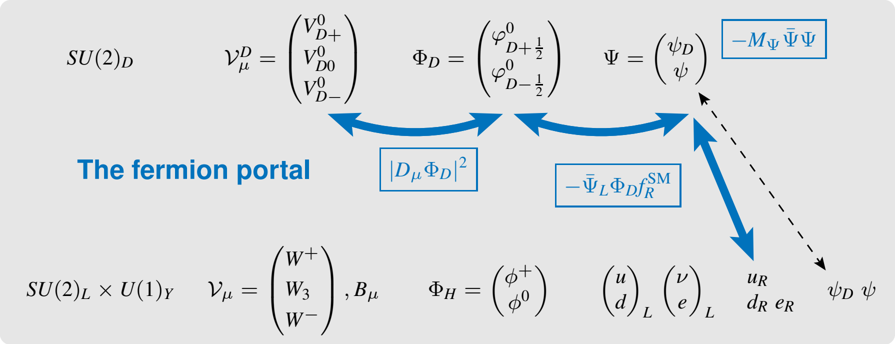

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The fermion portal

$\boxed{|D_\mu \Phi_D|^2}$

$\boxed{-\bar{\Psi}_L \Phi_D f_R^{\mathrm{SM}}}$

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A problem: $\boxed{-\bar{\Psi}_L \Phi^c_D f^{\mathrm{SM}}_R}$

- allowed because the fundamental of $SU(2)$ is pseudo-real
- explicitely breaks the global $SU(2)_{\mathrm{diag}}$

$$SU(2)_L \times U(1)_Y \qquad \mathcal{V}_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu \qquad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \begin{matrix} u_R \\ d_R \; e_R \end{matrix} \qquad \psi_D \; \psi$$

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~~A problem: $\boxed{\bar{\Psi}_L \Phi^c_D f^{\rm SM}_R}$~~ Impose $U(1)^{\rm glob}_D = e^{i\Lambda Y_D}$ with $Y_D \neq 0$ for $SU(2)_D$ doublets

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$$-\frac{1}{4}(\mathcal{V}^{Di}_{\mu\nu})^2 + |D_\mu \Phi_D|^2 + \mu^2_D \Phi^\dagger_D \Phi_D - \lambda_D(\Phi^\dagger_D \Phi_D)^2 + \bar{\Psi} i\not{D}\Psi - M_\Psi \bar{\Psi}\Psi - (y'\, \bar{\Psi}_L \Phi_D f^{\rm SM}_R + h.c)$$

$$-\lambda_{\Phi_H\Phi_D}\, \Phi^\dagger_H \Phi_H\; \Phi^\dagger_D \Phi_D - \mathcal{V}^{\mu\nu a}_D \Phi^\dagger_{Dk} (\sigma^a)_{kl} \Phi_{Dl} \left(\frac{\kappa_B}{\Lambda^2} B_{\mu\nu} \Phi^\dagger_H \Phi_H + \frac{\kappa_W}{\Lambda^4} W^b_{\mu\nu} \Phi^\dagger_{Hi} (\sigma^b)_{ij} \Phi_{Hj} \right)$$

can be small

suppressed

Connecting the dark sector to the SM

$$SU(2)_D \qquad \mathcal{V}^D_\mu = \begin{pmatrix} V^0_{D+} \\ V^0_{D0} \\ V^0_{D-} \end{pmatrix} \qquad \Phi_D = \begin{pmatrix} \varphi^0_{D+\frac{1}{2}} \\ \varphi^0_{D-\frac{1}{2}} \end{pmatrix} \qquad \Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix}$$

$\boxed{\text{When } \langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_D \end{pmatrix}}$ SSB: $SU(2)_D \times U(1)^{\text{glob}}_D \to U(1)^{\text{glob}}_{\text{diag}}$ with conserved $Q_D = T^3_D + Y_D$

(analogy to SM)

diagonal part

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If $Y_D = 1/2$ for $SU(2)_D$ doublets
and $Y_D = 0$ for $SU(2)_D$ triplets

$\boxed{\mathbb{Z}_2 = (-1)^{Q_D}}$ subgroup of $U(1)^{\text{glob}}_{\text{diag}}$

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The only* $\mathbb{Z}_2$-odd neutral massive particles are the D-charged gauge bosons $V^0_{D\pm}$

→ dark matter

* unless Ψ is a neutrino partner

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Gaugingthe global $U(1)$

A dark electroweak sector

Extend the dark sector with a $U(1)_{YD}$ (dark hypercharge). Same scalars Φ_H and Φ_D.

$$\mathcal{G} = \mathcal{G}_{\rm SM} \times \mathcal{G}_D = SU(2)_L \times U(1)_Y \times SU(2)_D \times U(1)_{YD} \longrightarrow U(1)_{\rm EM} \times U(1)_D$$

Conserved charge from the unbroken $U(1)_D$ symmetry: $Q_D = T_{3D} + Y_D$

One assumption: SM fields do not carry Q_D charge

The only Q_D-charged state is $V^0_{D\pm} \equiv W_D$ ➡ stable ➡ **DM candidate**

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Renormalizable, gauge-invariant kinetic mixing between $U(1)_Y$ and $U(1)_{YD}$ can be generated

$$-\mathcal{L}_{\text{KM}} = \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{4} B_{D\mu\nu} B_D^{\mu\nu} + \frac{\varepsilon}{2} B_{\mu\nu} B_D^{\mu\nu} \qquad \begin{pmatrix} B^\mu \\ B^{0\mu}_{D0} \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\varepsilon^2}} & 0 \\ -\frac{\varepsilon^2}{\sqrt{1-\varepsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_k & -\sin\theta_k \\ \sin\theta_k & \cos\theta_k \end{pmatrix} \begin{pmatrix} B_1^\mu \\ B_2^\mu \end{pmatrix}$$

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Mixing between all Q- and Q_D-neutral bosons

$$\begin{cases} m_\gamma = 0 \\ m_{\gamma_D} = 0 \end{cases} \qquad \begin{cases} m_Z^2 = \frac{v^2}{4}\left[g^2 + g'^2\left(1 + \frac{(g^2+g'^2)v^2 - g_D^2 v_D^2}{(g^2+g'^2)v^2 - (g_D^2+g_D'^2)v_D^2}\varepsilon^2\right)\right] + \mathcal{O}(\varepsilon^4) \\ m_{Z'}^2 = \frac{v_D^2}{4}\left[g_D^2 + g_D'^2\left(1 + \frac{g^2 v^2 - (g_D^2+g_D'^2)v_D^2}{(g^2+g'^2)v^2 - (g_D^2+g_D'^2)v_D^2}\varepsilon^2\right)\right] + \mathcal{O}(\varepsilon^4) \end{cases}$$

2 massless and 2 massive vectors

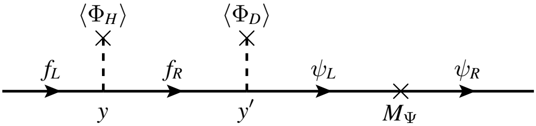
Connections with dark-photon phenomenology

The model components

The fermionic portal

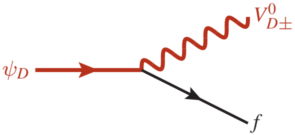
The $\mathbb{Z}_2$-even fermions mix due to the SM and new Yukawas

$$-\mathcal{L}_f = (y\, \bar{f}_L^{\mathrm{SM}}\, \Phi_H\, f_R^{\mathrm{SM}} + y'\, \bar{\Psi}_L \Phi_D f_R^{\mathrm{SM}} + h.c) + M_\Psi \bar{\Psi}\Psi \quad \text{with} \quad \Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix}$$



$$\mathcal{M}_F = \begin{pmatrix} y\frac{v}{\sqrt{2}} & 0 \\ y'\frac{v_D}{\sqrt{2}} & M_\Psi \end{pmatrix}$$

$\mathbb{Z}_2$-odd ψ_D is DM-SM mediator



$\mathbb{Z}_2$-even ψ mixes with SM

$$\begin{pmatrix} f^{\mathrm{SM}} \\ \psi \end{pmatrix}_{L,R} = \begin{pmatrix} \cos\theta_{fL,R} & \sin\theta_{fL,R} \\ -\sin\theta_{fL,R} & \cos\theta_{fL,R} \end{pmatrix} \begin{pmatrix} f \\ F \end{pmatrix}_{L,R}$$

The hierarchy between mass eigenstates is always $m_f < m_\psi \leq m_F$

The portal can be with any SM fermion(s) and with any number of VL fermions

maybe a portal in the lepton sector can explain anomalies and muon $(g-2)$?

The gauge sector

diagonal mass shifts

Φ_H and Φ_D are only charged under their gauge groups → No gauge mixing at tree-level

$$m_{V^0_{D\pm}} = m_{V^0_{D0}} = \frac{g_D}{2} v_D$$

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diagonal mass shifts

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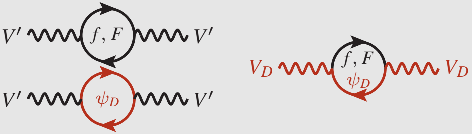
Different loop corrections:
($V^0_{D\pm} \equiv V_D$ and $V^0_{D0} \equiv V'$)



$$m_{V_D} - m_{V'} \simeq \frac{g_D^2}{32\pi^2} \frac{m_F^2 - m_{\psi_D}^2}{m_{V_D}} > 0 \quad \text{for} \quad m_F \gg m_f, m_{V_D}$$

The $\mathbb{Z}_2$-even gauge boson V' can only decay to $f\bar{f}$, or $V_D V_D^*$ if $m_F^2 - m_{\psi_D}^2$ is large enough

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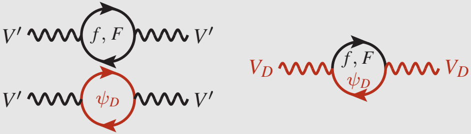

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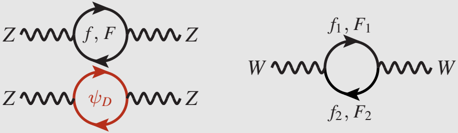
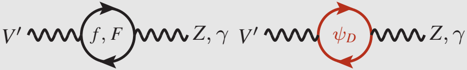
Modifications to SM
different for Z and W



Possible explanation of W mass discrepancy?

The gauge sector

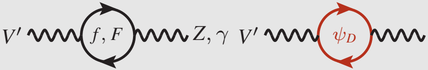
kinetic mixing in the broken phase



$$-\mathcal{L}_{\text{KM}} = \frac{\epsilon_{AV}}{4} V'_{\mu\nu} F^{\mu\nu} + \frac{\epsilon_{ZV}}{4} V'_{\mu\nu} Z^{\mu\nu}$$

The gauge sector

kinetic mixing in the broken phase



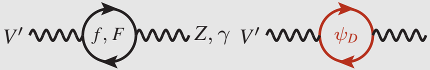
$$-\mathcal{L}_{\text{KM}} = \frac{\epsilon_{AV}}{4} V'_{\mu\nu} F^{\mu\nu} + \frac{\epsilon_{ZV}}{4} V'_{\mu\nu} Z^{\mu\nu}$$

The kinetic mixing matrix is function of fermion mass ratios $r_f = \frac{m_f}{m_{\psi_D}}$ and $r_{\psi_D} = \frac{m_{\psi_D}}{m_F}$:

$$V^{\text{KM}} = \begin{pmatrix} 1 & 0 & -\frac{\epsilon_{AV}}{\sqrt{1-\epsilon_{AV}^2-\epsilon_{ZV}^2}} \\ 0 & 1 & -\frac{\epsilon_{ZV}}{\sqrt{1-\epsilon_{AV}^2-\epsilon_{ZV}^2}} \\ 0 & 0 & \frac{1}{\sqrt{1-\epsilon_{AV}^2-\epsilon_{ZV}^2}} \end{pmatrix} \text{ with } \begin{cases} \epsilon_{AV} = \frac{g_D e Q_f}{16\pi^2} \left[\frac{m_{\psi_D}^4 - m_f^2 m_F^2}{(m_F^2 - m_f^2) m_{\psi_D}^2} \ln \frac{m_f^2}{m_F^2} + 2 \ln \frac{m_{\psi_D}^2}{m_f m_F} \right] \equiv \frac{g_D e Q_f}{16\pi^2} \mathcal{F}^{AV}(r_f, r_{\psi_D}) \\ \epsilon_{ZV} = \frac{g g_D}{64\pi^2 c_w} \left[\mathcal{F}^{ZV}_{qT1+qL}(r_f, r_{\psi_D}) + Q_f s_W^2 \mathcal{F}^{ZV}_{qT2}(r_f, r_{\psi_D}) \right] \end{cases}$$

The gauge sector

kinetic mixing in the broken phase



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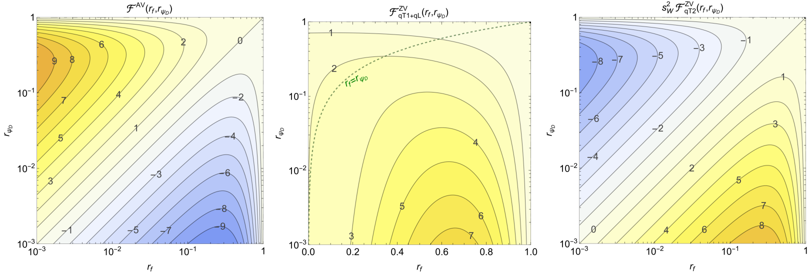
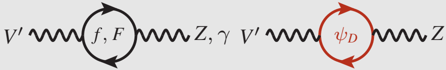


The gauge sector

kinetic mixing in the broken phase



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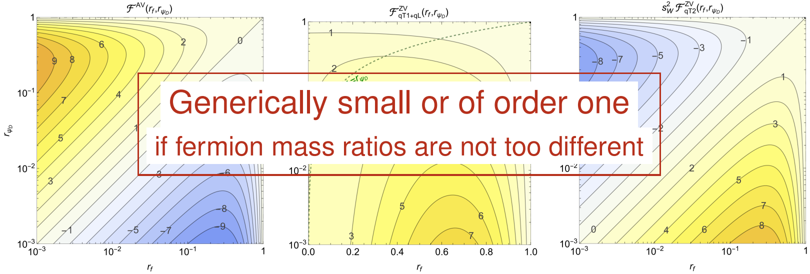
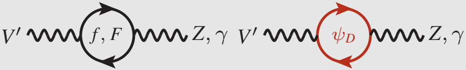


Generically small or of order one

if fermion mass ratios are not too different

The gauge sector

kinetic mixing in the broken phase



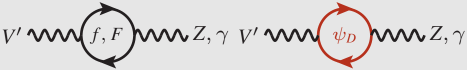
$$-\mathcal{L}_{\rm KM} = \frac{\epsilon_{AV}}{4} V'_{\mu\nu} F^{\mu\nu} + \frac{\epsilon_{ZV}}{4} V'_{\mu\nu} Z^{\mu\nu}$$

Z and V' mass mixing

Before KM: $\tilde{M}^2_{ZV} = \begin{pmatrix} \frac{1}{4}(g^2+g'^2)v^2 & \frac{1}{2} m_f^2 \epsilon^m_{ZV} \\ \frac{1}{2} m_f^2 \epsilon^m_{ZV} & \frac{1}{4} g_D^2 v_D^2 \end{pmatrix}$ with $\epsilon^m_{ZV} \equiv \frac{\Pi^{ZV}_{T+L}(q^2=0)}{m_f^2} = \frac{3 g g_D}{32\pi^2 c_w} \mathcal{F}^{ZV}_m(r_f, r_{\psi_D})$

The gauge sector

kinetic mixing in the broken phase



$$-\mathcal{L}_{\rm KM} = \frac{\epsilon_{AV}}{4} V'_{\mu\nu} F^{\mu\nu} + \frac{\epsilon_{ZV}}{4} V'_{\mu\nu} Z^{\mu\nu}$$

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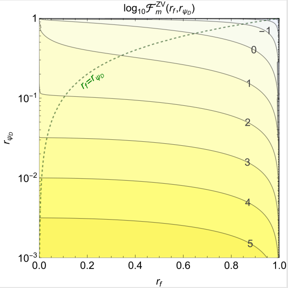
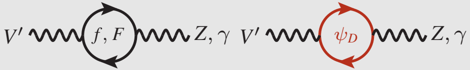


This can be dangerously large

(notice that the z-axis is in log scale)

The gauge sector

kinetic mixing in the broken phase



$$-\mathcal{L}_{\text{KM}} = \frac{\epsilon_{AV}}{4} V'_{\mu\nu} F^{\mu\nu} + \frac{\epsilon_{ZV}}{4} V'_{\mu\nu} Z^{\mu\nu}$$

Z and V' mass mixing

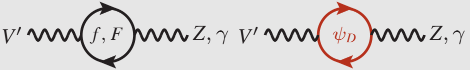
Before KM: $\tilde{M}^2_{ZV} = \begin{pmatrix} \frac{1}{4}(g^2 + g'^2)v^2 & \frac{1}{2} m_f^2 \epsilon^m_{ZV} \\ \frac{1}{2} m_f^2 \epsilon^m_{ZV} & \frac{1}{4} g_D^2 v_D^2 \end{pmatrix}$ with $\epsilon^m_{ZV} \equiv \frac{\Pi^{ZV}_{T+L}(q^2=0)}{m_f^2} = \frac{3 g g_D}{32\pi^2 c_W} \mathcal{F}^{ZV}_m(r_f, r_{\psi_D})$

After KM: $M^2_{ZV} = \left(V^{\text{KM}}\right)^T \tilde{M}^2_{ZV} V^{\text{KM}} = \frac{1}{4} \begin{pmatrix} (g^2 + g'^2)v^2 & -\frac{(g^2+g'^2)v^2 \epsilon_{ZV} - 2m_f^2 \epsilon^m_{ZV}}{\sqrt{1-\epsilon^2_{AV}-\epsilon^2_{ZV}}} \\ \text{symmetric} & \frac{g_D^2 v_D^2 + (g^2+g'^2)v^2 \epsilon^2_{ZV} - 4m_f^2 \epsilon_{ZV} \epsilon^m_{ZV}}{1-\epsilon^2_{AV}-\epsilon^2_{ZV}} \end{pmatrix}$

diagonalized for $\epsilon_{AV,ZV} \simeq \epsilon^m_{ZV} \simeq 0$ by $\tan 2\theta_{ZV} \simeq 2\theta_{ZV} \simeq \pm 2 \frac{2m_f^2 \epsilon^m_{ZV} - (g^2 + g'^2)v^2 \epsilon_{ZV}}{g_D^2 v_D^2 - (g^2 + g'^2)v^2}$

The gauge sector

kinetic mixing in the broken phase



$$-\mathcal{L}_{\rm KM} = \frac{\epsilon_{AV}}{4} V'_{\mu\nu} F^{\mu\nu} + \frac{\epsilon_{ZV}}{4} V'_{\mu\nu} Z^{\mu\nu}$$

Z and V' mass mixing

$$\tan 2\theta_{ZV} \simeq 2\theta_{ZV} \simeq \pm 2 \frac{2 m_f^2 \epsilon^m_{ZV} - (g^2 + g'^2) v^2 \epsilon_{ZV}}{g_D^2 v_D^2 - (g^2 + g'^2) v^2}$$

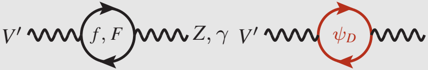
Mass eigenstates:

$$\begin{cases} m_Z^2 \simeq \frac{1}{4}(g^2 + g'^2) v^2 \left[1 + \theta_{ZV}^2 \left(1 - \frac{g_D^2 v_D^2}{(g^2 + g'^2) v^2}\right)\right] \\ m_{V'}^2 \simeq \frac{1}{4} g_D^2 v_D^2 \left[1 + \epsilon_{AV}^2 + (\theta_{ZV} - \epsilon_{ZV})^2 \left(1 - \frac{(g^2 + g'^2) v^2}{g_D^2 v_D^2}\right)\right] \end{cases}$$

modification to the SM Z mass

The gauge sector

kinetic mixing in the broken phase



$$-\mathcal{L}_{\text{KM}} = \frac{\epsilon_{AV}}{4} V'_{\mu\nu} F^{\mu\nu} + \frac{\epsilon_{ZV}}{4} V'_{\mu\nu} Z^{\mu\nu}$$

Z and V' mass mixing

$$\text{tan}2\theta_{ZV} \simeq 2\theta_{ZV} \simeq \pm 2 \frac{2m_f^2 \epsilon_{ZV}^m - (g^2 + g'^2) v^2 \epsilon_{ZV}}{g_D^2 v_D^2 - (g^2 + g'^2) v^2}$$

Mass eigenstates:

$$\begin{cases} m_Z^2 & \simeq \frac{1}{4}(g^2 + g'^2) v^2 \left[1 + \theta_{ZV}^2 \left(1 - \frac{g_D^2 v_D^2}{(g^2+g'^2)v^2} \right) \right] \\ m_{V'}^2 & \simeq \frac{1}{4} g_D^2 v_D^2 \left[1 + \epsilon_{AV}^2 + (\theta_{ZV} - \epsilon_{ZV})^2 \left(1 - \frac{(g^2+g'^2)v^2}{g_D^2 v_D^2} \right) \right] \end{cases}$$

modification to the SM Z mass

modified covariant derivative

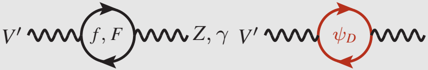
$$-ieQA_\mu - i \left[\frac{g}{c_w} (T_3 - Q s_W^2) - g_D T_D^3 \theta_{ZV} \right] Z_\mu - i \left[g_D T_D^3 - eQ\epsilon_{AV} + \frac{g}{c_w} (T_3 - Q s_W^2)(\theta_{ZV} - \epsilon_{ZV}) \right] V'_\mu$$

New Z interactions
with the dark sector

- V' interacts with all SM fermions
- EM multipole interactions of DM with atomic matter

The gauge sector

kinetic mixing in the broken phase



$$-\mathcal{L}_{\text{KM}} = \frac{\epsilon_{AV}}{4} V'_{\mu\nu} F^{\mu\nu} + \frac{\epsilon_{ZV}}{4} V'_{\mu\nu} Z^{\mu\nu}$$

Z and V' mass mixing

$$\tan 2\theta_{ZV} \simeq 2\theta_{ZV} \simeq \pm 2 \frac{2m_f^2 \epsilon^m_{ZV} - (g^2 + g'^2) v^2 \epsilon_{ZV}}{g_D^2 v_D^2 - (g^2 + g'^2) v^2}$$

Mass eigenstates:

$$\begin{cases} m_Z^2 & \simeq \frac{1}{4}(g^2 + g'^2) v^2 \left[1 + \theta_{ZV}^2 \left(1 - \frac{g_D^2 v_D^2}{(g^2 + g'^2) v^2} \right) \right] \\ m_{V'}^2 & \simeq \frac{1}{4} g_D^2 v_D^2 \left[1 + \epsilon_{AV}^2 + (\theta_{ZV} - \epsilon_{ZV})^2 \left(1 - \frac{(g^2 + g'^2) v^2}{g_D^2 v_D^2} \right) \right] \end{cases}$$

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Analogous (more complicate) mechanism in the gauged U$(1)_D$ scenario

The scalar sector

EW + Dark
symmetry breaking →

$$\begin{cases} v = \pm\sqrt{\frac{4\lambda_D\mu^2 - 2\lambda_{\Phi_H\Phi_D}\mu_D^2}{4\lambda\lambda_D - \lambda_{\Phi_H\Phi_D}^2}} \\ v_D = \pm\sqrt{\frac{4\lambda\mu_D^2 - 2\lambda_{\Phi_H\Phi_D}\mu^2}{4\lambda\lambda_D - \lambda_{\Phi_H\Phi_D}^2}} \end{cases}$$

8 degrees of freedom: 6 massive gauge bosons, 2 physical scalars h, H

The scalar sector

EW + Dark
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$$\begin{cases} v = \pm\sqrt{\frac{4\lambda_D\mu^2 - 2\lambda_{\Phi_H\Phi_D}\mu_D^2}{4\lambda\lambda_D - \lambda^2_{\Phi_H\Phi_D}}} \\ v_D = \pm\sqrt{\frac{4\lambda\mu_D^2 - 2\lambda_{\Phi_H\Phi_D}\mu^2}{4\lambda\lambda_D - \lambda^2_{\Phi_H\Phi_D}}} \end{cases}$$

8 degrees of freedom: 6 massive gauge bosons, 2 physical scalars h, H

Tree-level mass matrix

$$\mathcal{M}_S = \begin{pmatrix} \lambda v^2 & \frac{\lambda_{\Phi_H\Phi_D}}{2} v v_D \\ \frac{\lambda_{\Phi_H\Phi_D}}{2} v v_D & \lambda_D v_D^2 \end{pmatrix} \quad \sin\theta_S = \sqrt{2\frac{m_H^2 v^2 \lambda - m_h^2 v_D^2 \lambda_D}{m_H^4 - m_h^4}}$$

$$\boxed{m_{h,H}^2 = \lambda v^2 + \lambda_D v_D^2 \mp \sqrt{(\lambda v^2 - \lambda_D v_D^2)^2 + \lambda^2_{\Phi_H\Phi_D} v^2 v_D^2}}$$

The scalar sector

EW + Dark
symmetry breaking

$$\longrightarrow \begin{cases} v = \pm\sqrt{\dfrac{4\lambda_D\mu^2 - 2\lambda_{\Phi_H\Phi_D}\mu_D^2}{4\lambda\lambda_D - \lambda^2_{\Phi_H\Phi_D}}} \\ v_D = \pm\sqrt{\dfrac{4\lambda\mu_D^2 - 2\lambda_{\Phi_H\Phi_D}\mu^2}{4\lambda\lambda_D - \lambda^2_{\Phi_H\Phi_D}}} \end{cases}$$

8 degrees of freedom: 6 massive gauge bosons, 2 physical scalars h, H

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$$\boxed{m^2_{h,H} = \lambda v^2 + \lambda_D v_D^2 \mp \sqrt{(\lambda v^2 - \lambda_D v_D^2)^2 + \lambda^2_{\Phi_H\Phi_D} v^2 v_D^2}}$$

Loop mixing ALWAYS present (even if suppressed)

$$\begin{cases} H \text{ interacts with any massive SM state} \\ h \text{ interacts with the dark sector} \end{cases}$$

Summary of particle content

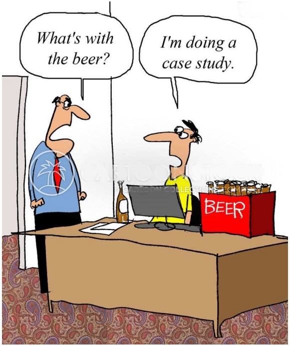
Scalars	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$\Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	**2**	$1/2$	**1**	$+$
$\Phi_D = \begin{pmatrix} \varphi^0_{D+\frac{1}{2}} \\ \varphi^0_{D-\frac{1}{2}} \end{pmatrix}$	**1**	0	**2**	$-$ $+$

Vectors	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$W_\mu = \begin{pmatrix} W^+_\mu \\ W^3_\mu \\ W^-_\mu \end{pmatrix}$	**3**	0	**1**	$+$ $+$ $+$
B_μ	**1**	0	**1**	$+$
$V^D_\mu = \begin{pmatrix} V^0_{D+\mu} \\ V^0_{D0\mu} \\ V^0_{D-\mu} \end{pmatrix}$	**1**	0	**3**	$-$ $+$ $-$

Fermions	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$f^{\rm SM}_L = \begin{pmatrix} f^{\rm SM}_{u,\nu} \\ f^{\rm SM}_{d,\ell} \end{pmatrix}_L$	**2**	$\frac{1}{6}, -\frac{1}{2}$	**1**	$+$
$u^{\rm SM}_R, \nu^{\rm SM}_R$	**1**	$\frac{2}{3}, 0$	**1**	$+$
$d^{\rm SM}_R, \ell^{\rm SM}_R$	**1**	$-\frac{1}{3}, -1$	**1**	$+$
$\Psi = \begin{pmatrix} \psi^D \\ \psi \end{pmatrix}$	**1**	Q	**2**	$-$ $+$

A case study

top portal without Higgs mixing at tree level



Case study: top portal w/o Higgs mixing

$\Psi = (t_D\ T)^T$ with $m_t < m_{t_D} \leq m_T$ and $\sin\theta_S = 0$

Case study: top portal w/o Higgs mixing

$\Psi = (t_D \; T)^T$ with $m_t < m_{t_D} \leq m_T$ and $\sin\theta_S = 0$

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 & \text{strong or weak cosmological constraints} \\ \left.\begin{matrix} m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{matrix}\right\} & \text{heavy enough to evade LHC constraints} \end{cases}$

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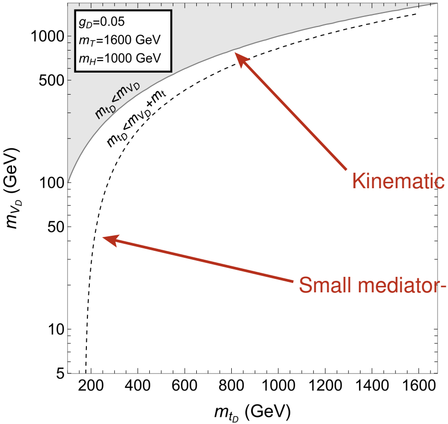
$$\text{Representative benchmarks: } \left\{\begin{array}{l} g_D = 0.05, 0.5 \quad \text{strong or weak cosmological constraints} \\ \left.\begin{array}{l} m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{array}\right\} \text{heavy enough to evade LHC constraints} \end{array}\right.$$



Kinematic limit

Small mediator-DM mass gap

Case study: top portal w/o Higgs mixing

$\Psi = (t_D\ T)^T$ with $m_t < m_{t_D} \le m_T$ and $\sin\theta_S = 0$

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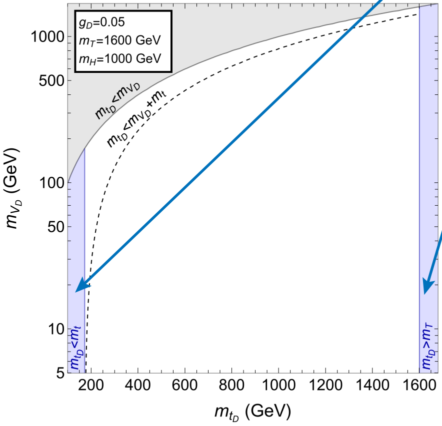

Mediator mass bounded from below and above

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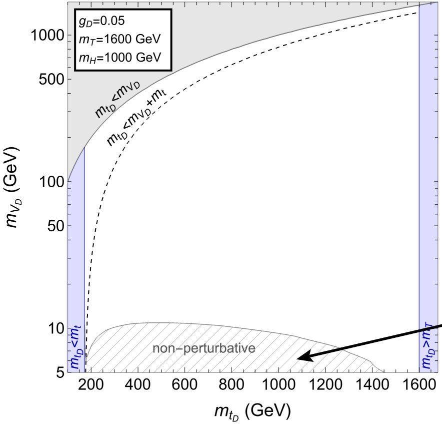
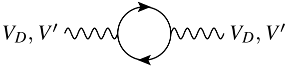
$\Psi = (t_D\ T)^T$ with $m_t < m_{t_D} \leq m_T$ and $\sin\theta_S = 0$

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 \\ m_T = 1600\ \text{GeV} \\ m_H = 1000\ \text{GeV} \end{cases}$ strong or weak cosmological constraints; m_T, m_H: heavy enough to evade LHC constraints



Mediator mass bounded from below and above

Light DM in non-perturbative region



$$\frac{m_V^{\text{pole}} - m_V}{m_V} > 50\%$$

Case study: top portal w/o Higgs mixing

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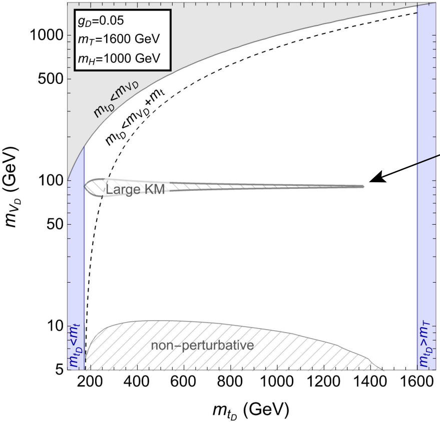
Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 \\ m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{cases}$ strong or weak cosmological constraints; m_T, m_H: heavy enough to evade LHC constraints



Mediator mass bounded from below and above

Light DM in non-perturbative region

Large kinetic mixing when $m_{V'} \simeq m_Z$

$\{\epsilon_{AV}$ or ϵ_{ZV} or $\theta_{ZV}\} > 0.1$

Case study: top portal w/o Higgs mixing

$\Psi = (t_D \; T)^T$ with $m_t < m_{t_D} \leq m_T$ and $\sin\theta_S = 0$

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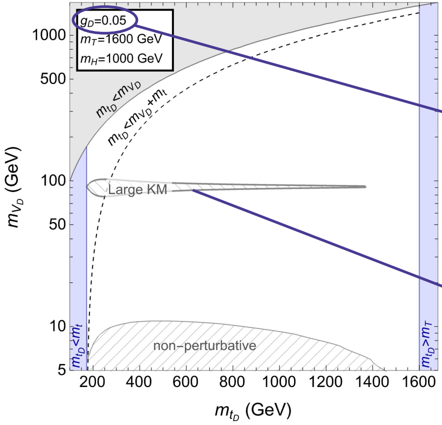
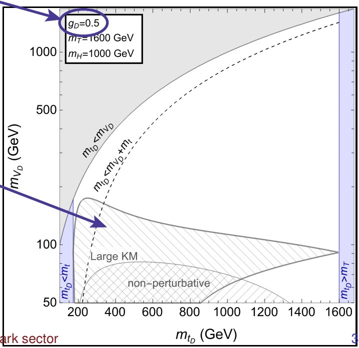


Mediator mass bounded from below and above

Light DM in non-perturbative region

Large kinetic mixing when $m_{V'} \simeq m_Z$ (but not only)

$\{\epsilon_{AV}$ or ϵ_{ZV} or $\theta_{ZV}\} > 0.1$



Case study: top portal w/o Higgs mixing

$$\Psi = (t_D\ T)^T \text{ with } m_t < m_{t_D} \leq m_T \quad \text{and} \quad \sin\theta_S = 0$$

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 \\ m_T = 1600 \text{ GeV} \\ m_H = 1000 \text{ GeV} \end{cases}$

$g_D = 0.05, 0.5$: strong or weak cosmological constraints

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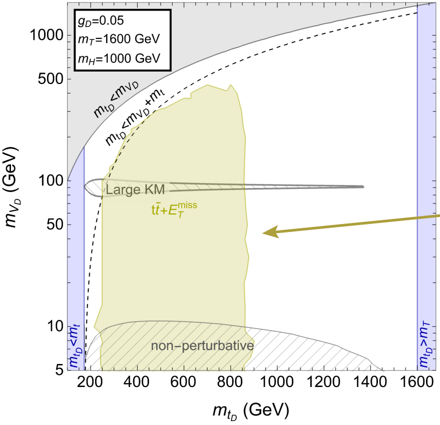
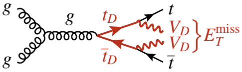


Mediator mass bounded from below and above

Light DM in non-perturbative region

Large kinetic mixing when $m_{V'} \simeq m_Z$ (but not only)

LHC constrains m_{t_D} for $m_{t_D} - m_{V_D} \gtrsim m_t$
(bounds almost independent on g_D, m_T and m_H)



Recast

A. M. Sirunyan *et al.* [CMS], **Search for top squarks and dark matter particles in opposite-charge dilepton final states at $\sqrt{s} = 13$ TeV**, Phys. Rev. D **97** (2018) no.3, 032009, arXiv:1711.00752 [hep-ex]

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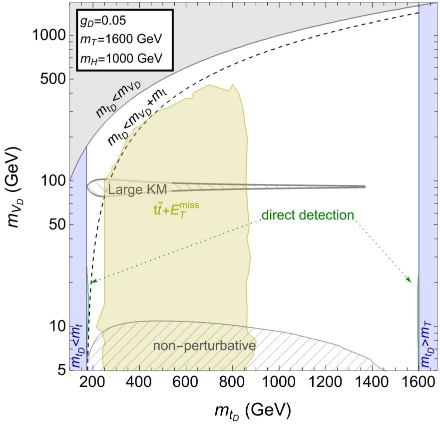

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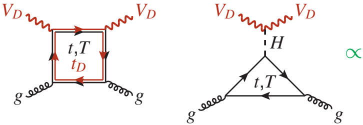
(bounds almost independent on g_D, m_T and m_H)

Very weak direct detection constraints
(mostly for $m_{t_D} \sim m_t$ or $m_{t_D} \sim m_T$ and light DM)



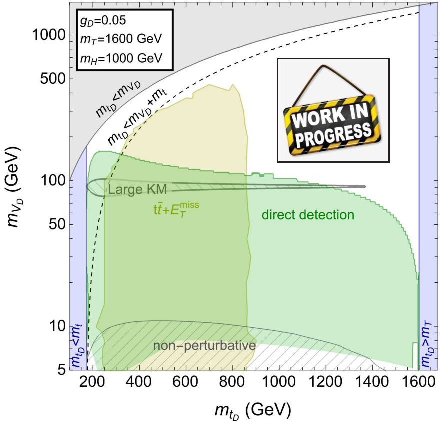
$\propto \frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm Planck}}$

E. Aprile *et al.* [XENON],
Dark Matter Search Results from a One Ton-Year Exposure of XENON1T,
Phys. Rev. Lett. **121** (2018) no.11, 111302, arXiv:1805.12562 [astro-ph.CO]

Case study: top portal w/o Higgs mixing

$\Psi = (t_D\ T)^T$ with $m_t < m_{t_D} \leq m_T$ and $\sin\theta_S = 0$

Representative benchmarks: $\left\{\begin{array}{l} g_D = 0.05, 0.5 \\ m_T = 1600\text{ GeV} \\ m_H = 1000\text{ GeV} \end{array}\right.$ g_D: strong or weak cosmological constraints; $\left.\begin{array}{l} m_T \\ m_H \end{array}\right\}$ heavy enough to evade LHC constraints



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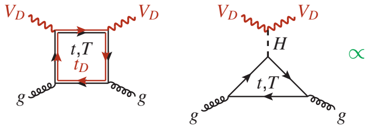
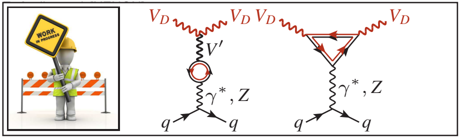
LHC constrains m_{t_D} for $m_{t_D} - m_{V_D} \gtrsim m_t$ (bounds almost independent on g_D, m_T and m_H)

Very weak direct detection constraints (mostly for $m_{t_D} \sim m_t$ or $m_{t_D} \sim m_T$ and light DM) ?



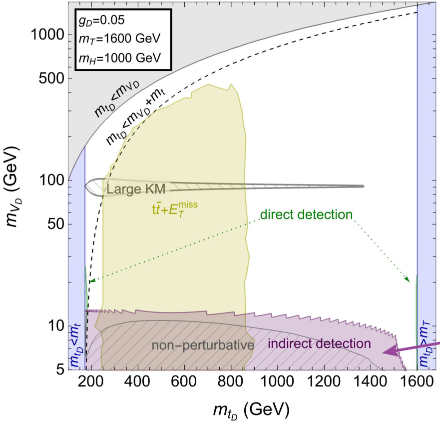
$\propto \frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm Planck}}$



Case study: top portal w/o Higgs mixing

$\Psi = (t_D\ T)^T$ with $m_t < m_{t_D} \leq m_T$ and $\sin\theta_S = 0$

Representative benchmarks: $\begin{cases} g_D = 0.05, 0.5 \\ m_T = 1600\text{ GeV} \\ m_H = 1000\text{ GeV} \end{cases}$ g_D: strong or weak cosmological constraints; m_T, m_H: heavy enough to evade LHC constraints



Mediator mass bounded from below and above

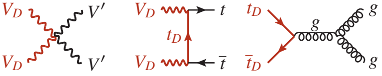
Light DM in non-perturbative region

Large kinetic mixing when $m_{V'} \simeq m_Z$ (but not only)

LHC constrains m_{t_D} for $m_{t_D} - m_{V_D} \gtrsim m_t$
(bounds almost independent on g_D, m_T and m_H)

Very weak direct detection constraints
(mostly for $m_{t_D} \sim m_t$ or $m_{t_D} \sim m_T$ and light DM) $\boxed{?}$

Indirect detection constrains light DM



$$\propto \left(\frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm Planck}}\right)^2$$

N. Aghanim *et al.* [Planck],
Planck 2018 results. VI. Cosmological parameters,
Astron. Astrophys. **641** (2020), A6, arXiv:1807.06209 [astro-ph.CO]

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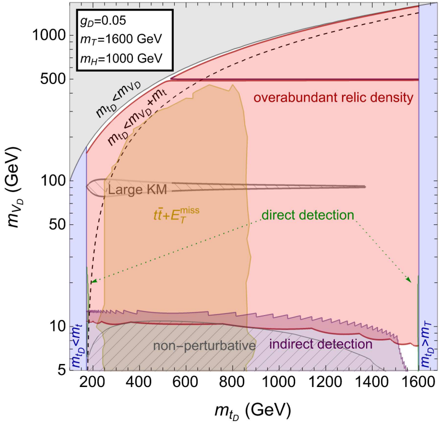

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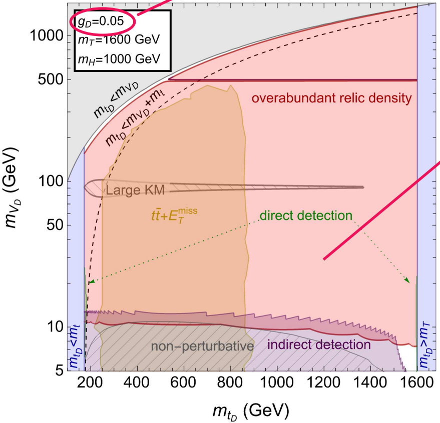

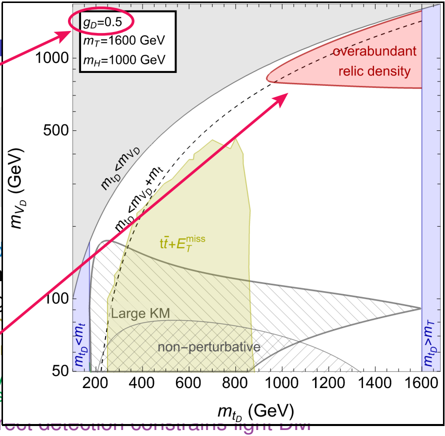

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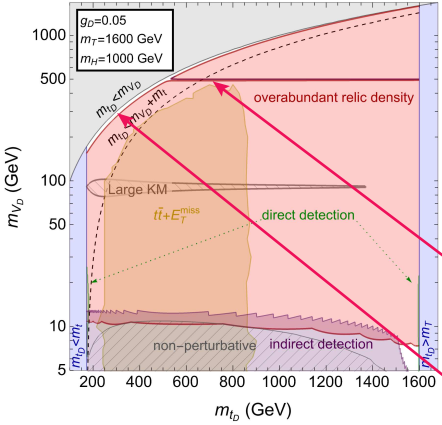

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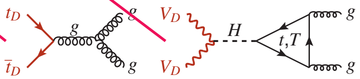

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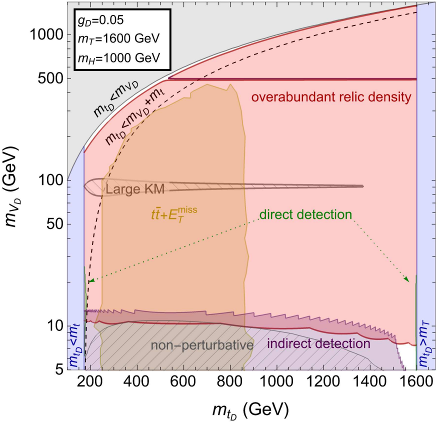

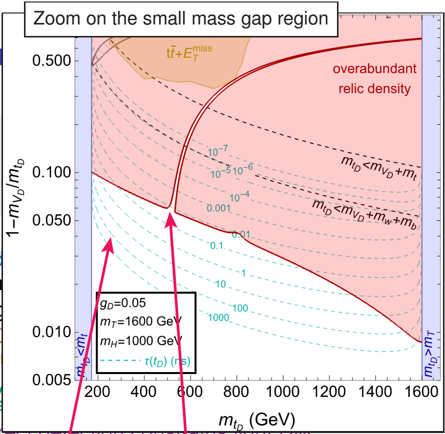

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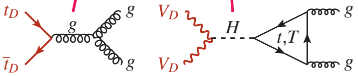

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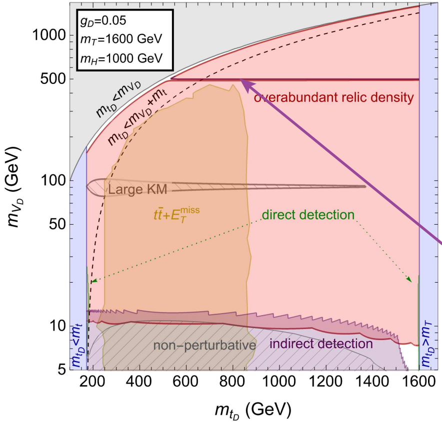

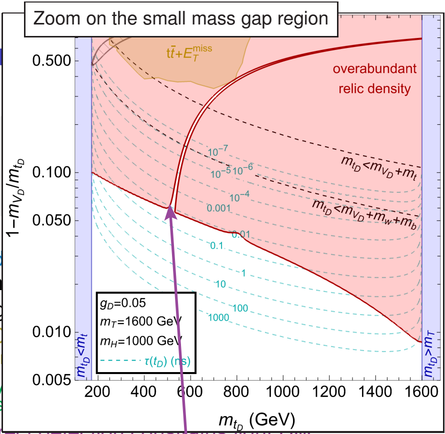

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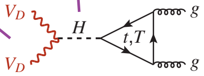

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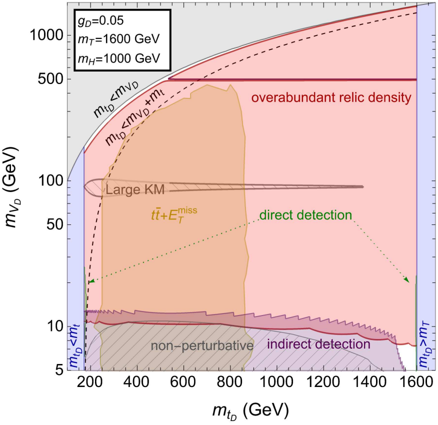

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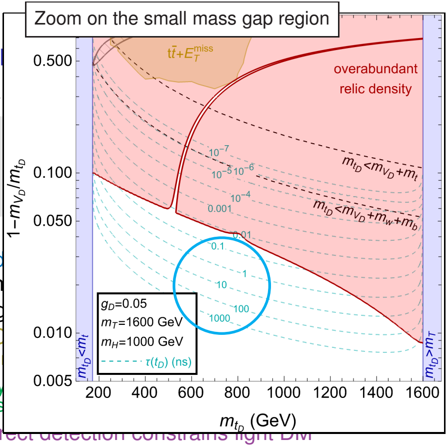
Zoom on the small mass gap region

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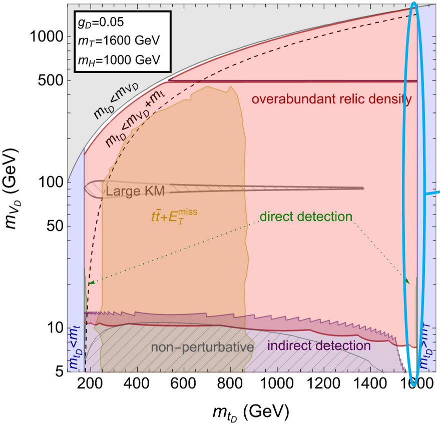

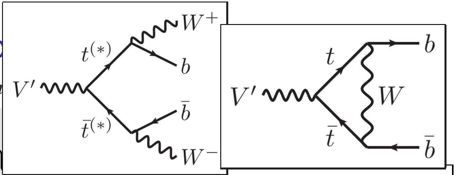

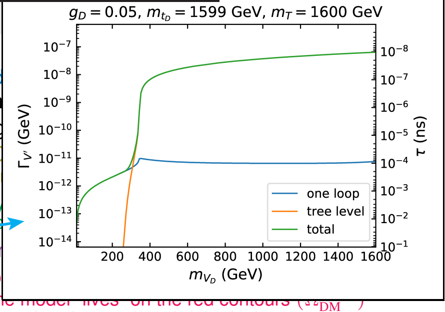

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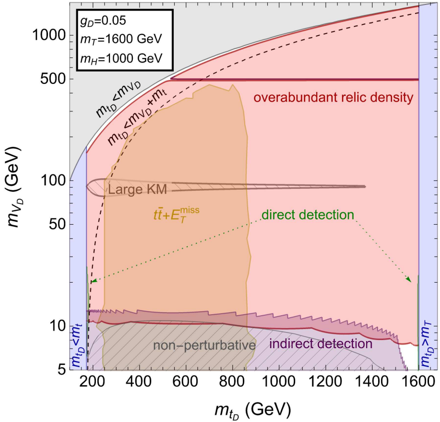

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just a simple realization of the model template
multiple features and signatures

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Full five-dimensional parameter space: $g_D, m_{V_D}, m_H, m_T, m_{t_D}$

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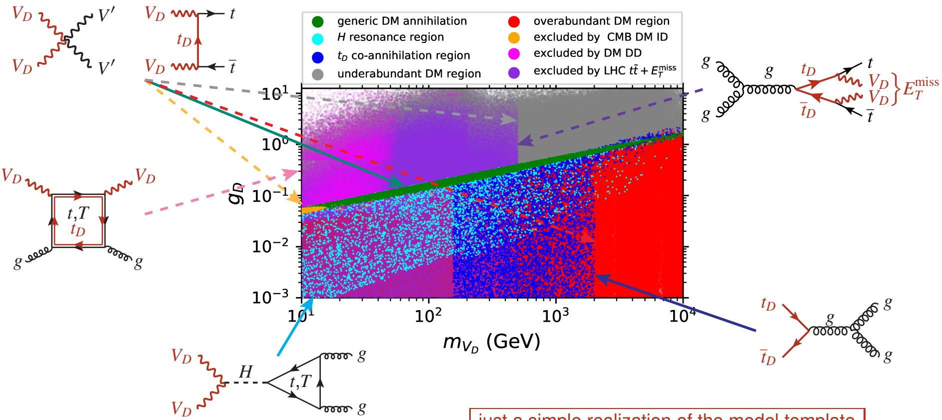

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Fermion Portal Vector Dark Matter

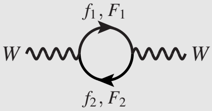
FPVDM

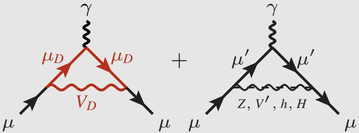
Summary

- ➜ A model of **non abelian vector DM** with a **fermion portal** which does not require the Higgs portal
- ➜ A **template scenario** with new collider and cosmological implications
- ➜ Case study in the **top sector** with multiple phenomenological predictions
- ➜ Different possible **origins of the $\mathbb{Z}_2$ parity**

Outlook

- ➜ **Different realizations** to study **current anomalies** (LFU, $(g-2)_\mu$, $m_W\dots$)





- ➜ Study of different **theoretical embeddings**
- ➜ Role of the new scalar in the **EW phase transition**
- ➜ Further analysis of **cosmological implications** and scenarios for **future colliders**
- ➜ Study of the gauged extension with the **dark photon**