Vector Dark Matter via a Fermionic Portal from a New Gauge Sector

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2203.04681 and 2204.03510 AB, Luca Panizzi, Aldo Deandrea, Stefano Moretti and Nakorn Thongyoi

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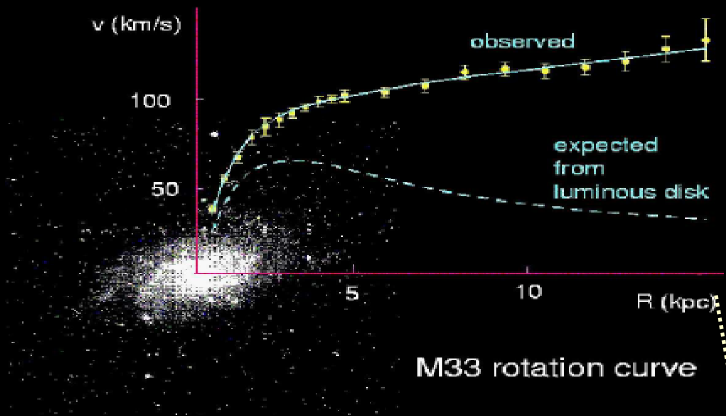
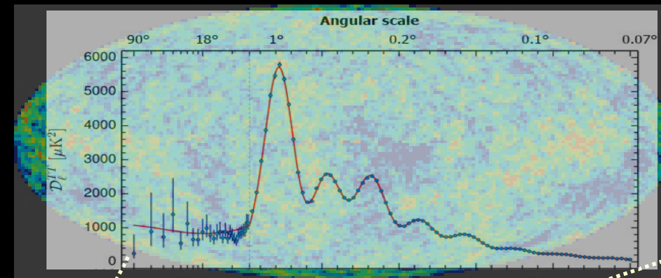
"Fundamental Forces from Colliders to Gravitational Waves"
20-24 June 2022 IP2I

The existence of Dark Matter is confirmed by several independent observations at cosmological scale

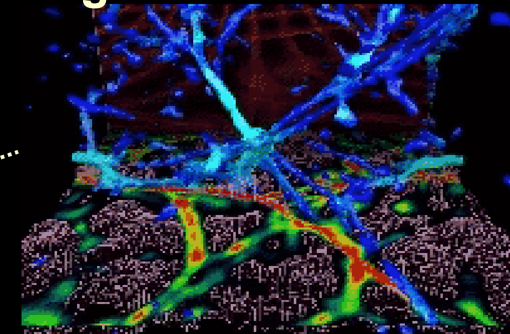
Galactic rotation curves

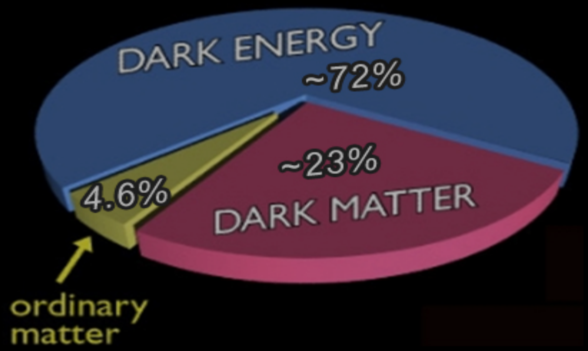


CMB: WMAP and PLANCK

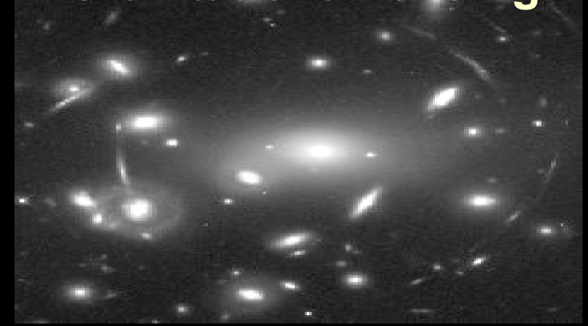


Large Scale Structures





Gravitational lensing



Bullet cluster

DM is very appealing even though we know almost nothing about it!

Spin ?

Mass ?

Stable

Yes ? No ?

symmetry behind stability ?

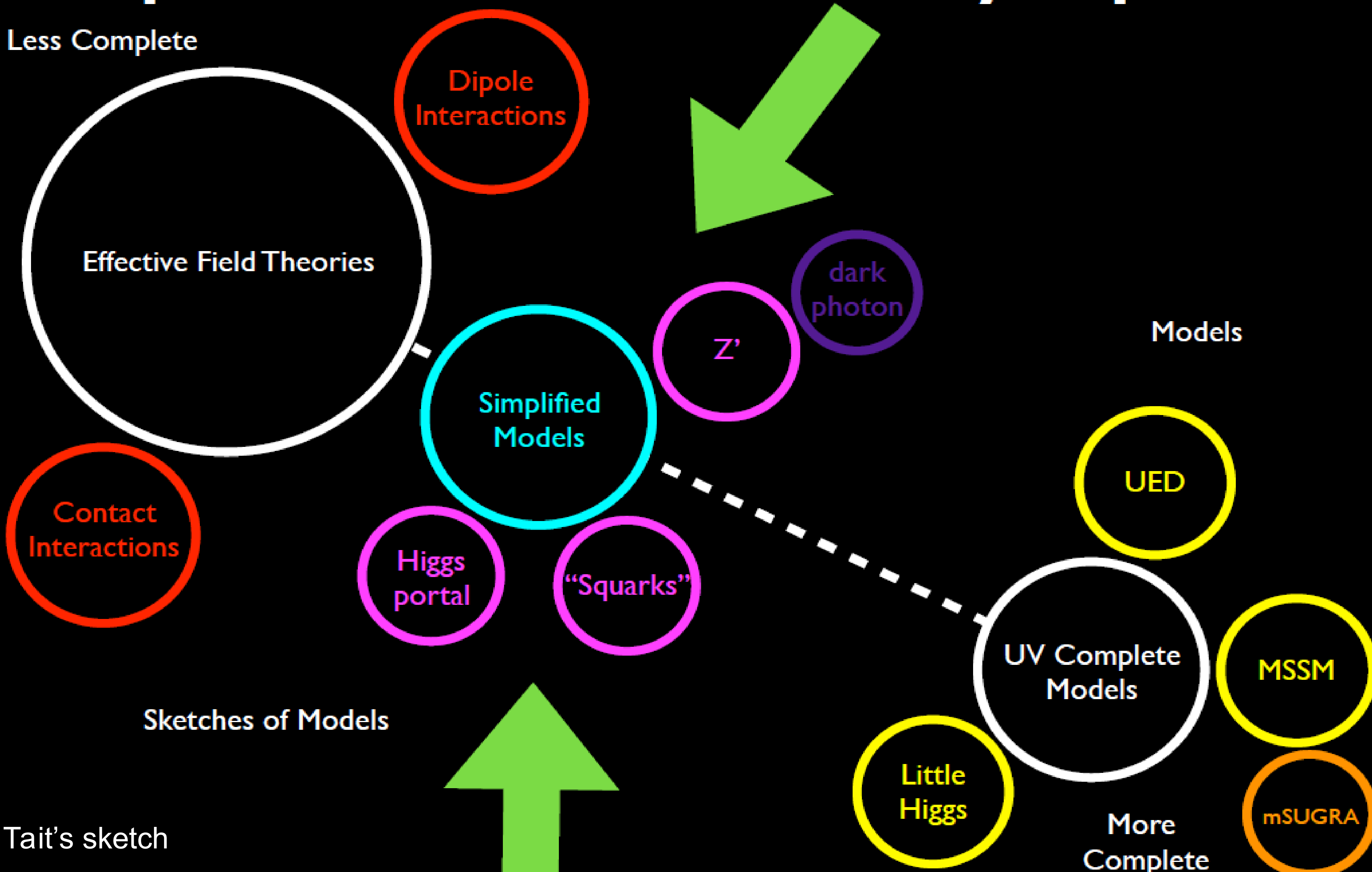
Couplings

gravity	V
weak	?
higgs	?
quarks/gluons	?
leptons	?
New mediators	?

Thermal relic

Yes ? No ?

Spectrum of Theory Space



Tim Tait’s sketch

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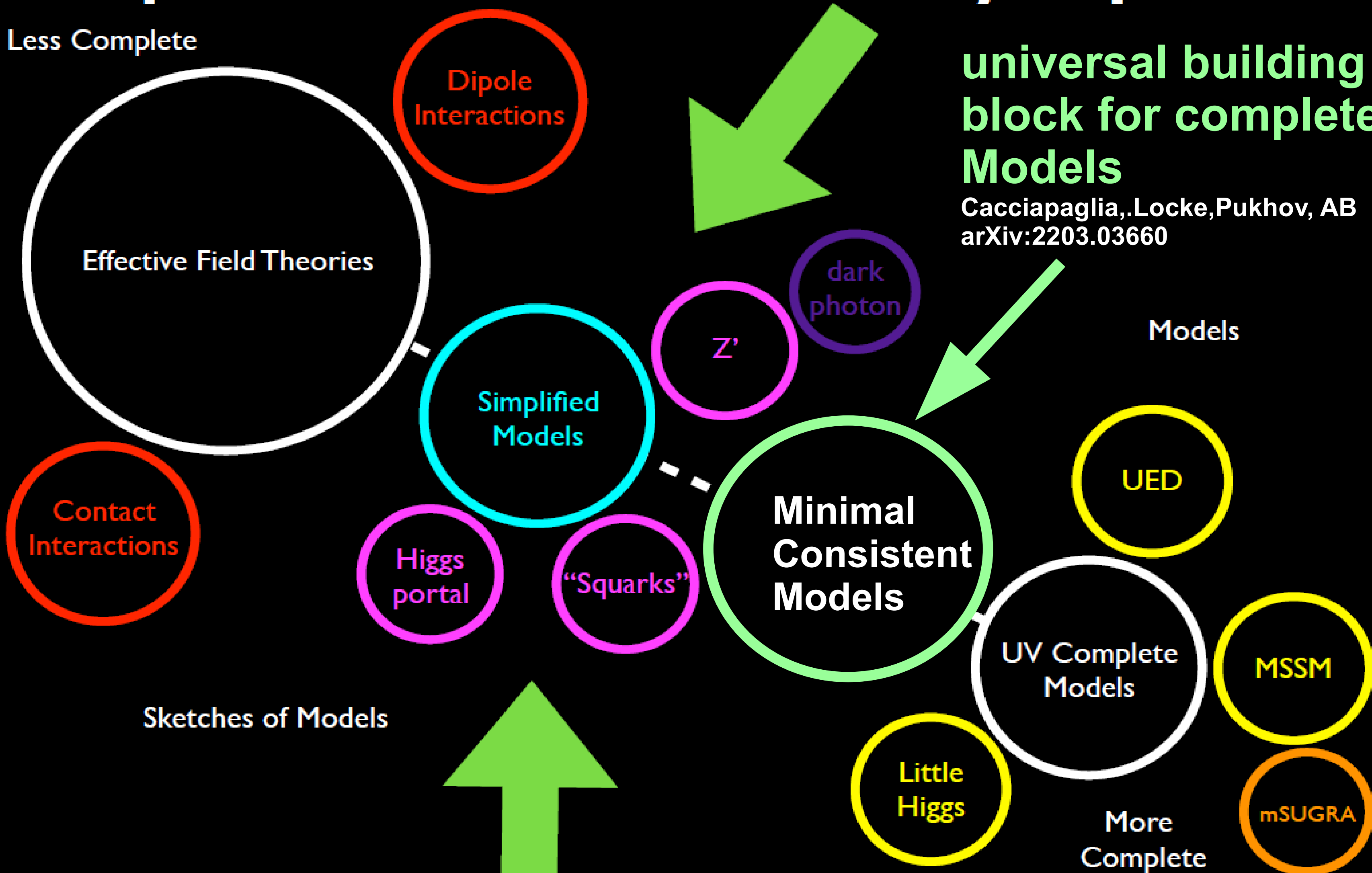

Vector DM

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  - $U(1)_D$ Group

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  - $V_D^\mu \leftrightarrow -V_D^\mu$ Explicit Z_2 symmetry plus a Higgs portal to provide the stability and the mass for VDM and connect it to the SM

$$\mathcal{L} \supset -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + (D_\mu\Phi)^\dagger (D^\mu\Phi) - V(\Phi) + \lambda_P \, |H|^2|\Phi|^2$$

with $D_\mu\Phi \equiv \partial_\mu\Phi - gQ_\Phi V_\mu\Phi$

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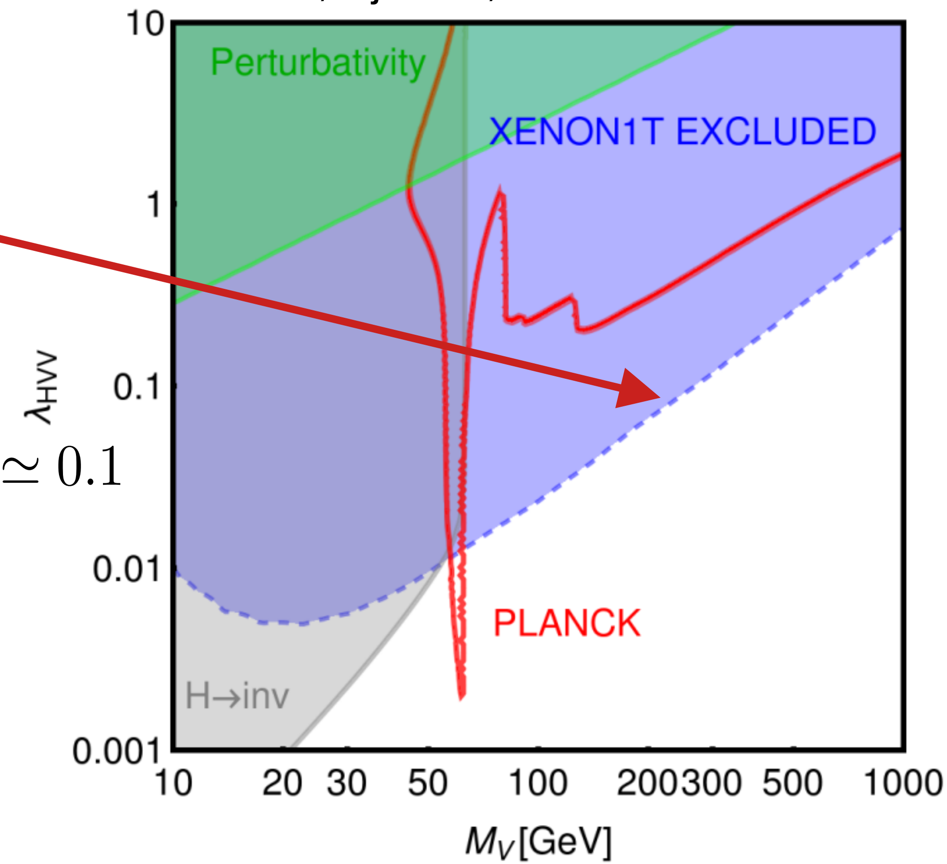
- Quite a few papers:
  - Lebedev, Lee, Mambrini 1111.4482,
  - Baek, Ko, Park , Senaha 1212.2131
  - DiFranzo, Fox,Tait 1512.06853
  - Farzan, Akbarieh 1207.4272
  - Duch, Grzadkowski, McGarrie 1506.08805
  - …………………………..

Vector DM with the Higgs portal

- Since VDM 'talks' to SM via Higgs, V_DV_DH coupling is **limited from above** by DM direct detection and H→ DM DM Br

Arcadi, Djouadi, Kado 2001.10750



$$\Omega h^2 \simeq 0.1$$

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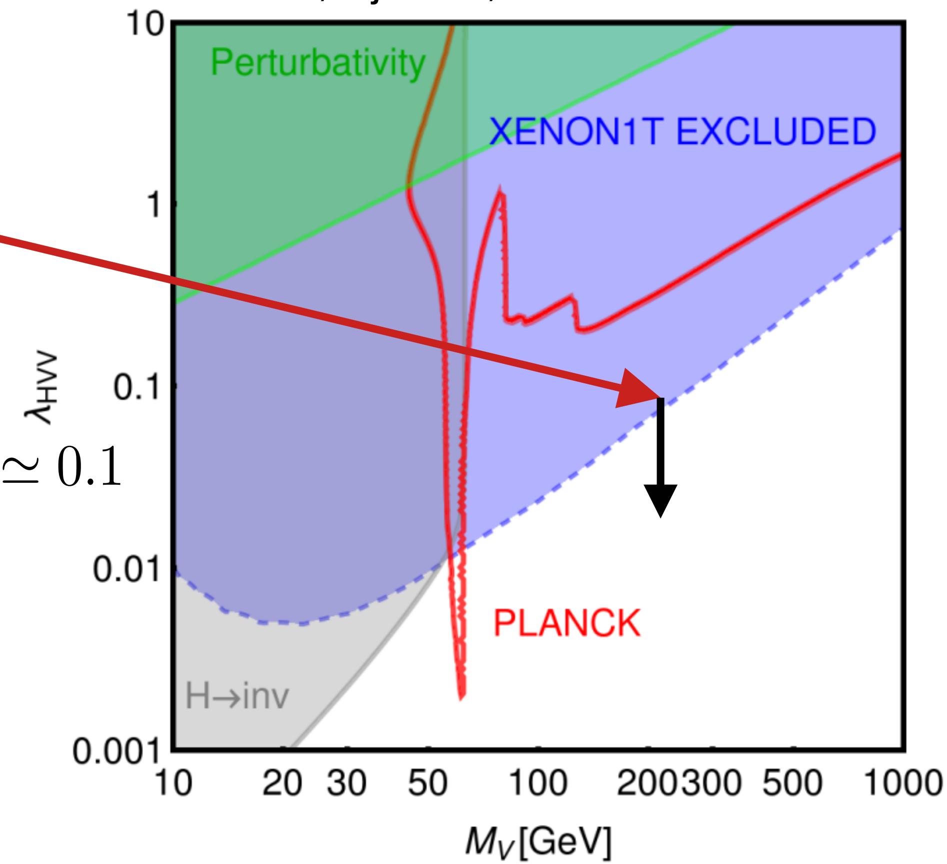

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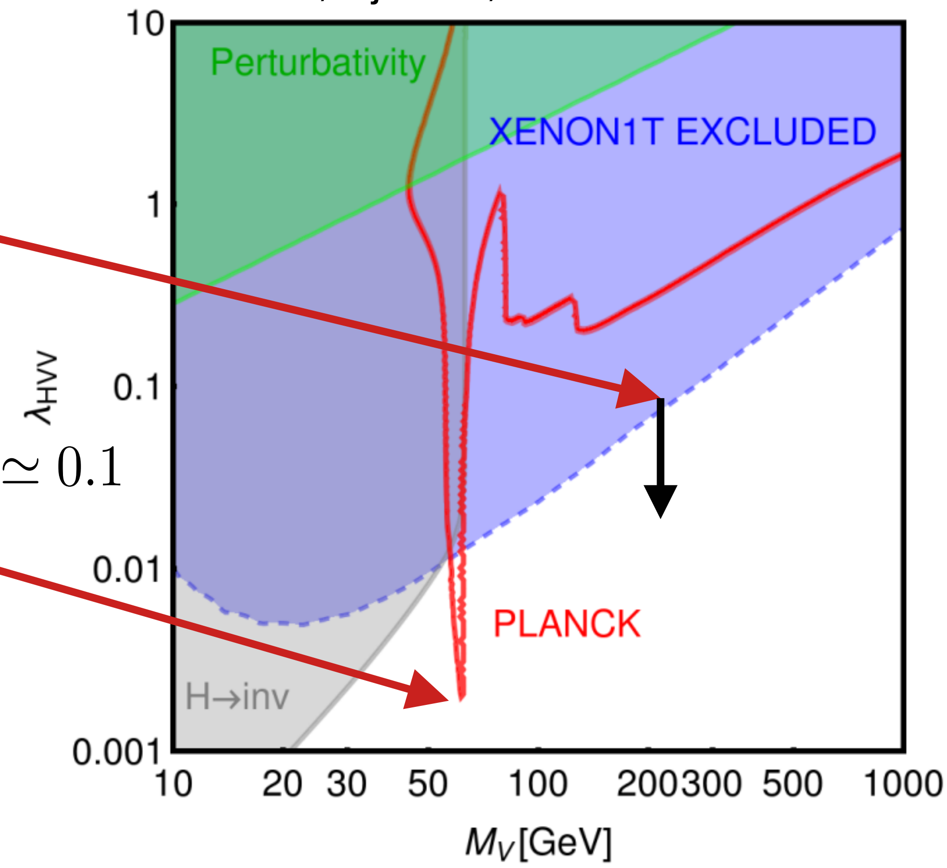

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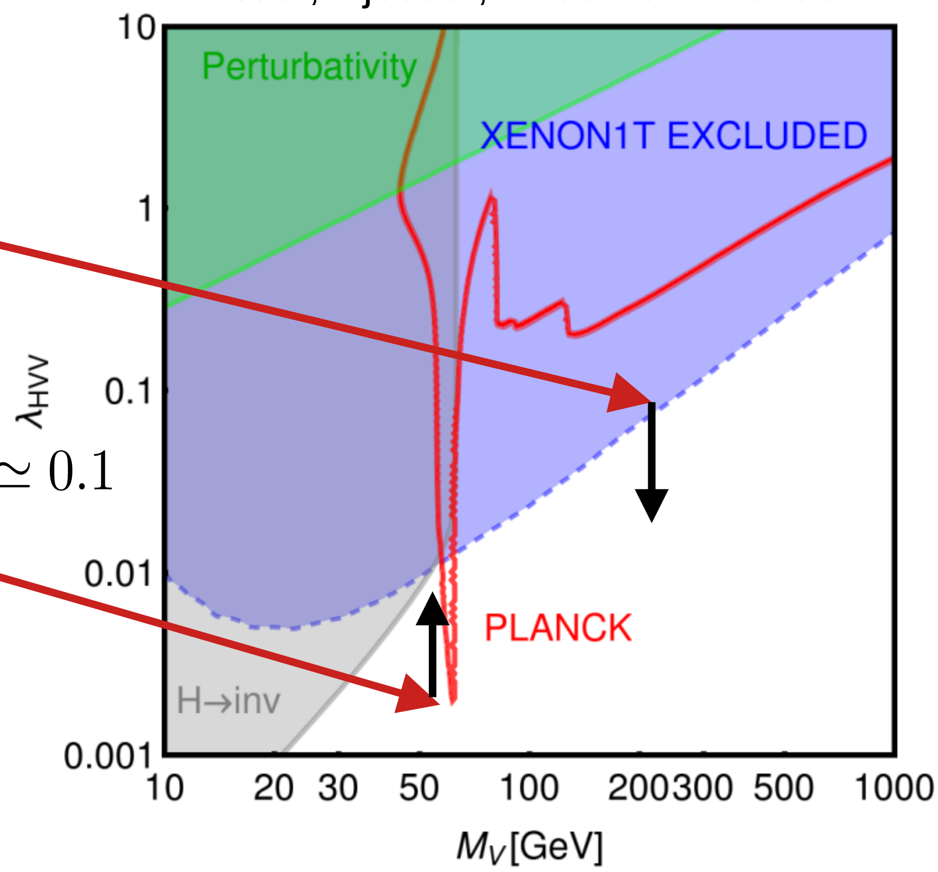

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- The Higgs portal VDM parameter space is very limited by interplay of collider, DD and DM relic density

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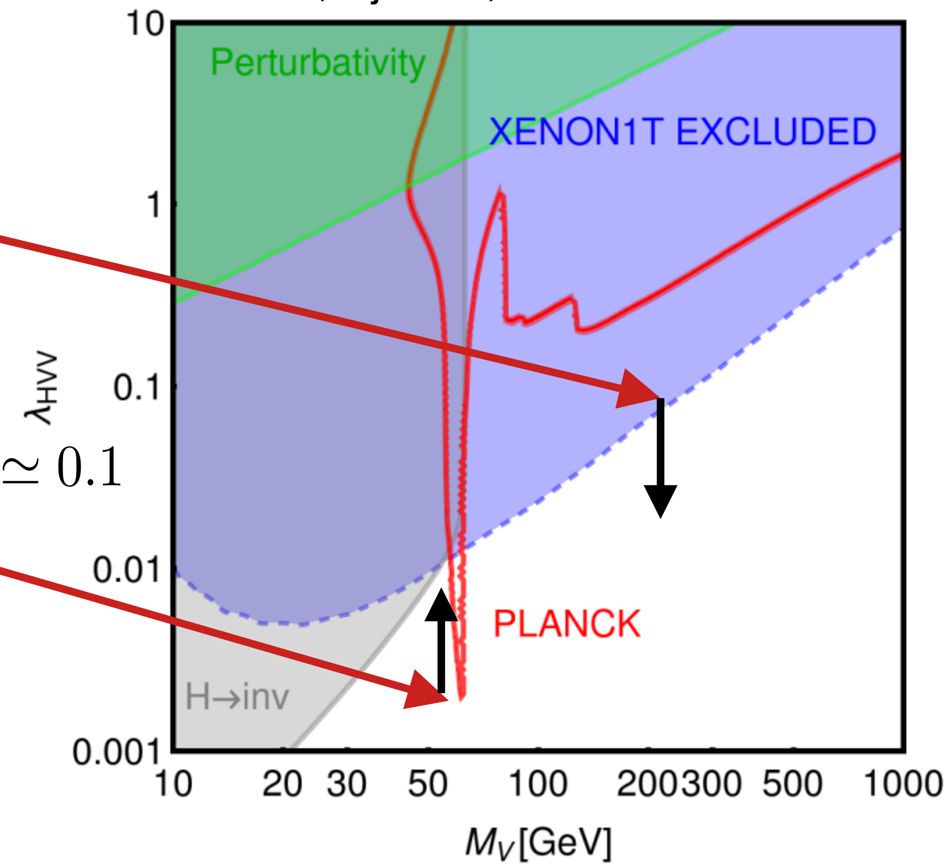

Vector DM with the Higgs portal

- Non-abelian case
  - Generalisation to SU(N) case:

    Gross, Lebedev, Mambrini 1505.07480

    SSB with N-1 complex scalar N-plets in fundamental rep of SU(N) – gives mass to VDM and predicts $(N\text{-}1)^2$ scalars

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    $\mathrm{SU}(2)_0\times\mathrm{SU}(2)_1\times\mathrm{SU}(2)_2\times\mathrm{U}(1)_Y$: $SU(2)_0 \leftrightarrow SU(2)_2$ symmetry provides stability for VDM, so there are VDM triplet + vector triplet of unstable W'/Z' bosons

$$\begin{aligned}V_{\rm scalar} =& m^2 H^\dagger H + m_\Phi^2 \mathrm{tr}\left(\Phi_1^\dagger\Phi_1\right) + m_\Phi^2 \mathrm{tr}\left(\Phi_2^\dagger\Phi_2\right) \\ &+ \lambda(H^\dagger H)^2 + \lambda_\Phi\left(\mathrm{tr}\left(\Phi_1^\dagger\Phi_1\right)\right)^2 + \lambda_\Phi\left(\mathrm{tr}\left(\Phi_2^\dagger\Phi_2\right)\right)^2 \\ &+ \lambda_{h\Phi} H^\dagger H \mathrm{tr}\left(\Phi_1^\dagger\Phi_1\right) + \lambda_{h\Phi} H^\dagger H \mathrm{tr}\left(\Phi_2^\dagger\Phi_2\right) + \lambda_{12}\mathrm{tr}\left(\Phi_1^\dagger\Phi_1\right)\mathrm{tr}\left(\Phi_2^\dagger\Phi_2\right)\end{aligned}$$

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$$

quite a non-minimal model

Vector like fermion Portal for Vector DM

- Higgs portal is very-well studied and the parameter space for minimal scenarios is almost excluded
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We consider SM + three ingredients:

- $SU(2)_D$: Dark non-abelian gauge group
- Complex scalar doublet charged under $SU(2)_D$
- VL fermion doublet of $SU(2)_D$

	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$
$\Phi_D = \begin{pmatrix} \varphi^0_{D+\frac{1}{2}} \\ \varphi^0_{D-\frac{1}{2}} \end{pmatrix}$	$\mathbf{1}$	0	$\mathbf{2}$
$\Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix}$	$\mathbf{1}$	Q	$\mathbf{2}$
$V^D_\mu = \begin{pmatrix} V^0_{D+\mu} \\ V^0_{D0\mu} \\ V^0_{D-\mu} \end{pmatrix}$	$\mathbf{1}$	0	$\mathbf{3}$

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- this means that one of the components of the vector triplet is Z_2-even
- this construction allows the $y' \bar{\Psi}_L \Phi_D f_R^{\rm SM}$ term, connecting dark scalar and VL fermion and SM RH fermion, meaning that one component of VL fermion doublet must be Z_2-even and the other - Z_2-odd

Building Vector Like Fermion(VLF) Portal for Vector DM

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

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

$\mathbb{Z}_2 : \{+, -\}$

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

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

Building VLF Portal for Vector DM: Higgs portal is possible but not required

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

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

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$$-\frac{1}{4}(\mathcal{V}^{Di}_{\mu\nu})^2 + |D_\mu \Phi_D|^2 + \mu_D^2 \Phi_D^\dagger \Phi_D - \lambda_D (\Phi_D^\dagger \Phi_D)^2$$

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

Building VLF Portal for Vector DM: kinetic mixing is generated at higher loops

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

$\mathbb{Z}_2 : \{+, -\}$

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

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

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$$-\frac{1}{4}(\mathcal{V}^{Di}_{\mu\nu})^2 + |D_\mu\Phi_D|^2 + \mu_D^2\Phi^\dagger_D\Phi_D - \lambda_D(\Phi^\dagger_D\Phi_D)^2$$

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

Building VLF Portal for Vector DM: VLF plays the central role

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

$\mathbb{Z}_2 : \{+, -\}$

Introducing a fermion

- **fundamental of $SU(2)_D$**
  $\rightarrow$ interacts with V^D_μ
- **Vector-like**
  $\rightarrow$ no anomalies
- **Charged under $U(1)_Y$**
  $\rightarrow$ interacts with SM

doublet of $SU(2)_D$

singlets of $SU(2)_L$

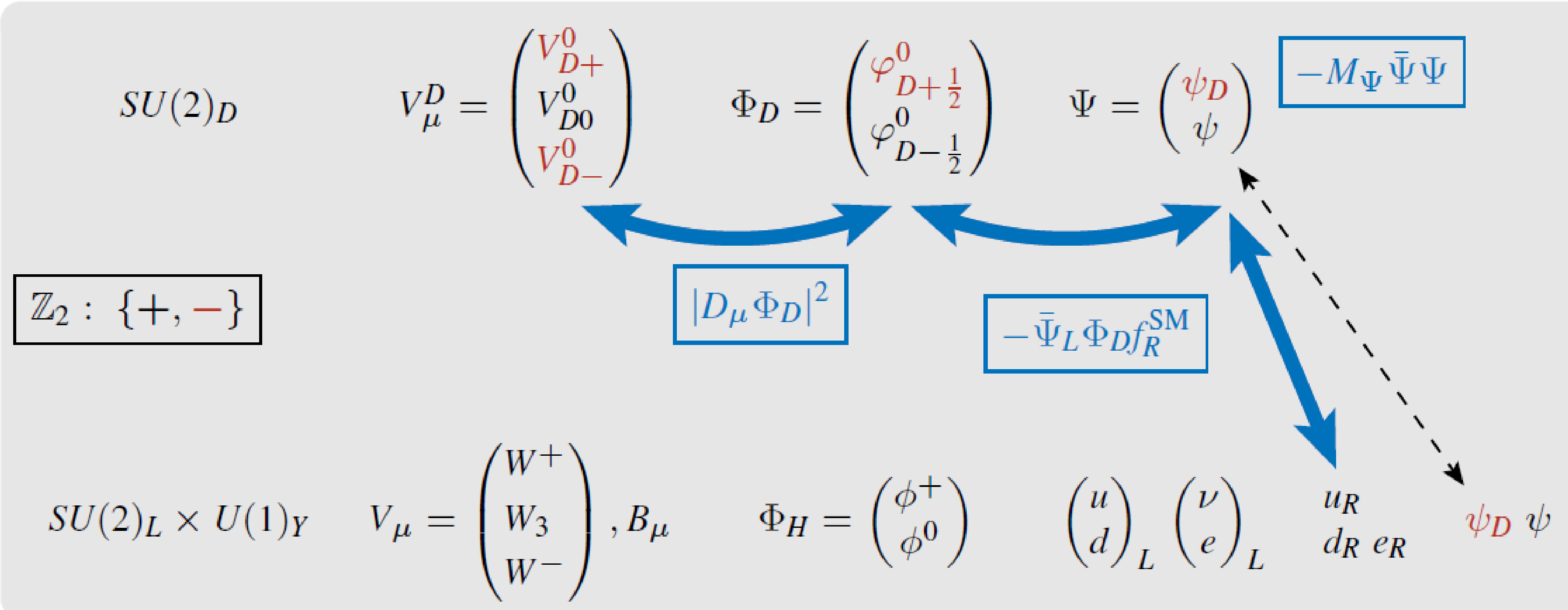
$SU(2)_L \times U(1)_Y$ $\quad V_\mu = \begin{pmatrix} W^+ \\ W_3 \\ W^- \end{pmatrix}, B_\mu$ $\quad \Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\quad \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ $\quad u_R \; d_R \; e_R$ $\quad \psi_D \; \psi$

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

$$-\frac{1}{4}(V^{Di}_{\mu\nu})^2 + |D_\mu \Phi_D|^2 + \mu_D^2 \Phi_D^\dagger \Phi_D - \lambda_D(\Phi_D^\dagger \Phi_D)^2 + \bar{\Psi} i\not{D}\Psi - M_\Psi \bar{\Psi}\Psi$$

$$-\lambda_{\Phi_H \Phi_D} \Phi_H^\dagger \Phi_H \; \Phi_D^\dagger \Phi_D - V_D^{\mu\nu a} \Phi_{Dk}^\dagger (\sigma^a)_{kl} \Phi_{Dl} \left(\frac{\kappa_W}{\Lambda^4} W^b_{\mu\nu} \Phi_{Hi}^\dagger (\sigma^b)_{ij} \Phi_{Hj} + \frac{\kappa_B}{\Lambda^4} B_{\mu\nu} \Phi_H^\dagger \Phi_H \right)$$

Building VLF Portal for Vector DM: VLF couples to $SU(2)_D$ scalar and RH SM F



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

$$-\frac{1}{4}(V^{Di}_{\mu\nu})^2 + |D_\mu\Phi_D|^2 + \mu_D^2\Phi_D^\dagger\Phi_D - \lambda_D(\Phi_D^\dagger\Phi_D)^2 + \bar{\Psi}i\not{D}\Psi - M_\Psi\bar{\Psi}\Psi - (y'\,\bar{\Psi}_L\Phi_D f_R^{SM} + h.c)$$

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

Building VLF Portal for Vector DM: V^0_{D+} / V^0_{D-} is Dark Matter

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

$\mathbb{Z}_2 : \{+, -\}$

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

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

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

$$-\frac{1}{4}(V^{Di}_{\mu\nu})^2 + |D_\mu \Phi_D|^2 + \mu_D^2 \Phi_D^\dagger \Phi_D - \lambda_D(\Phi_D^\dagger \Phi_D)^2 + \bar{\Psi} i\not{D} \Psi - M_\Psi \bar{\Psi}\Psi - (y' \bar{\Psi}_L \Phi_D f_R^{SM} + h.c)$$

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

Building VLF Portal for Vector DM: on the origin of Z_2 symmetry

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

If $y' = 0$ the Φ_D potential has a global custodial symmetry $SU(2)'_D$

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

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

$$-\frac{1}{4}(V^{Di}_{\mu\nu})^2 + |D_\mu \Phi_D|^2 + \mu_D^2 \Phi_D^\dagger \Phi_D - \lambda_D(\Phi_D^\dagger \Phi_D)^2 + \bar{\Psi} i\not{D}\Psi - M_\Psi \bar{\Psi}\Psi - \cancel{(y' \bar{\Psi}_L \Phi_D f_R^{SM} + h.c)}$$

$$-\lambda_{\Phi_H \Phi_D} \Phi_H^\dagger \Phi_H\ \Phi_D^\dagger \Phi_D - V_D^{\mu\nu a} \Phi_{Dk}^\dagger (\sigma^a)_{kl} \Phi_{Dl} \left(\frac{\kappa_W}{\Lambda^4} W^b_{\mu\nu} \Phi^\dagger_{Hi} (\sigma^b)_{ij} \Phi_{Hj} + \frac{\kappa_B}{\Lambda^4} B_{\mu\nu} \Phi_H^\dagger \Phi_H \right)$$

Building VLF Portal for Vector DM: on the origin of Z_2 symmetry

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

When $y' \neq 0$ Explicit breaking: $SU(2)'_D \to U(1)_c$

global charge conjugation

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

$$\mathcal{L} = -\frac{1}{4}(W^i_{\mu\nu})^2 - \frac{1}{4}(B_{\mu\nu})^2 + |D_\mu \Phi_H|^2 + \mu^2 \Phi_H^\dagger \Phi_H - \lambda(\Phi_H^\dagger \Phi_H)^2 + \bar{f}^{SM}\, i\not{D}\, f^{SM} - (y\, \bar{f}_L^{SM}\, \Phi_H\, f_R^{SM} + h.c.)$$
$$-\frac{1}{4}(V^{Di}_{\mu\nu})^2 + |D_\mu \Phi_D|^2 + \mu_D^2 \Phi_D^\dagger \Phi_D - \lambda_D(\Phi_D^\dagger \Phi_D)^2 + \bar{\Psi} i\not{D} \Psi - M_\Psi \bar{\Psi}\Psi - (y'\, \bar{\Psi}_L \Phi_D f_R^{SM} + h.c)$$
$$-\lambda_{\Phi_H \Phi_D} \Phi_H^\dagger \Phi_H\ \Phi_D^\dagger \Phi_D - V_D^{\mu\nu a} \Phi_{Dk}^\dagger (\sigma^a)_{kl} \Phi_{Dl} \left(\frac{\kappa_W}{\Lambda^4} W^b_{\mu\nu} \Phi_{Hi}^\dagger (\sigma^b)_{ij} \Phi_{Hj} + \frac{\kappa_B}{\Lambda^4} B_{\mu\nu} \Phi_H^\dagger \Phi_H \right)$$

Building VLF Portal for Vector DM: the origin of Z_2 – the conservation of dark charge

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

When $\langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_D \end{pmatrix}$ SSB: $SU(2)_D \times U(1)_c \to$ global $U(1)$ — diagonal part

$\mathbb{Z}_2$ is a subgroup of $U(1)$

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

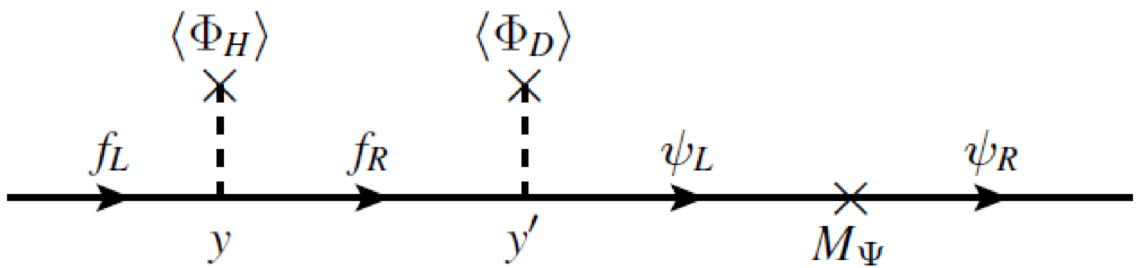
$$\mathcal{L} = -\frac{1}{4}(W^i_{\mu\nu})^2 - \frac{1}{4}(B_{\mu\nu})^2 + |D_\mu \Phi_H|^2 + \mu^2 \Phi_H^\dagger \Phi_H - \lambda(\Phi_H^\dagger \Phi_H)^2 + \bar{f}^{SM} \, i\not{D} \, f^{SM} - (y \, \bar{f}_L^{SM} \, \Phi_H \, f_R^{SM} + h.c.)$$

$$-\frac{1}{4}(V^{Di}_{\mu\nu})^2 + |D_\mu \Phi_D|^2 + \mu_D^2 \Phi_D^\dagger \Phi_D - \lambda_D(\Phi_D^\dagger \Phi_D)^2 + \bar{\Psi} i\not{D} \Psi - M_\Psi \bar{\Psi}\Psi - (y' \, \bar{\Psi}_L \Phi_D f_R^{SM} + h.c)$$

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

VLF portal: Z_2-even fermions – RH SM ones and VL ones – mix

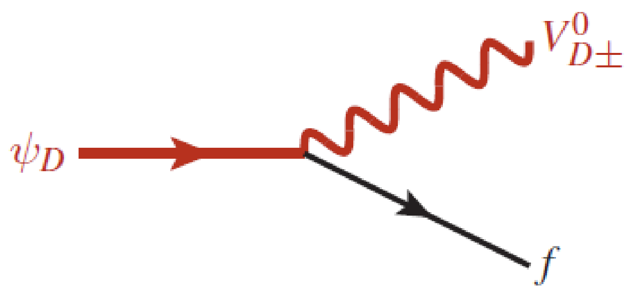
$$-\mathcal{L}_f = (y\, \bar{f}_L^{\rm SM}\, \Phi_H\, f_R^{\rm SM} + y' \bar{\Psi}_L \Phi_D f_R^{\rm SM} + h.c) + M_\Psi \bar{\Psi}\Psi \quad \text{with} \quad \Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix}$$



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

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

$\mathbb{Z}_2$-even ψ mixes with SM

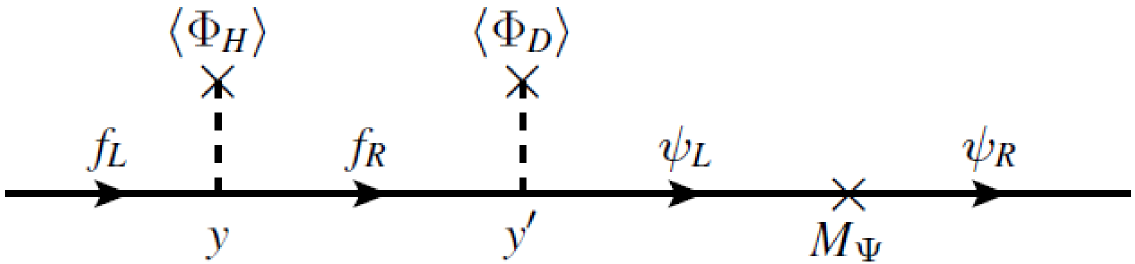


$$\begin{pmatrix} f^{\rm SM} \\ \psi \end{pmatrix}_{L,R} = \begin{pmatrix} \cos\theta_{fL,R} & \sin\theta_{fL,R} \\ -\sin\theta_{fL,R} & \cos\theta_{fL,R} \end{pmatrix} \begin{pmatrix} f \\ F \end{pmatrix}_{L,R}$$

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

VLF portal: Z₂-even fermions – RH SM ones and VL ones – mix

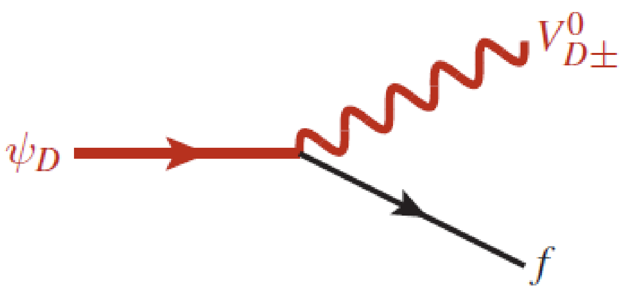
$$-\mathcal{L}_f = (y\,\bar{f}_L^{SM}\,\Phi_H\,f_R^{SM} + y'\,\bar{\Psi}_L\Phi_D f_R^{SM} + h.c) + M_\Psi\bar{\Psi}\Psi \quad \text{with} \quad \Psi = \begin{pmatrix}\psi_D\\ \psi\end{pmatrix}$$



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

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

$\mathbb{Z}_2$-even ψ mixes with SM



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

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

Potential to introduce flavour structure(s) with VL fermions, including VL leptons to explain various flavour anomalies, including (g-2)μ !

The gauge sector: V' / V_D radiative mass split, no tree-level V' – Z mixing

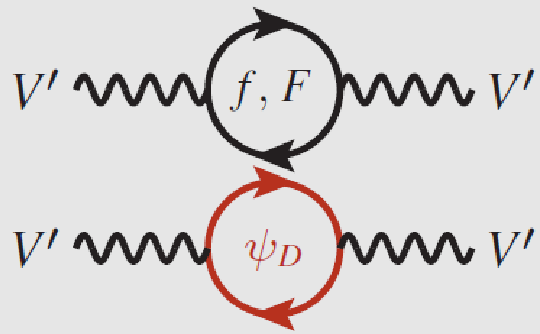
- **At tree-level:** $$m_{V^0_{D\pm}} = m_{V^0_{D0}} = \frac{g_D}{2} v_D$$

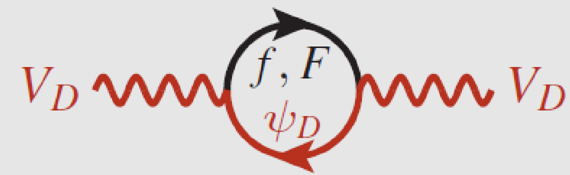
The gauge sector: V' / V_D radiative mass split, no tree-level V' – Z mixing

- **At tree-level:** $m_{V^0_{D\pm}} = m_{V^0_{D0}} = \frac{g_D}{2} v_D$

- **At loop-level:**

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





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

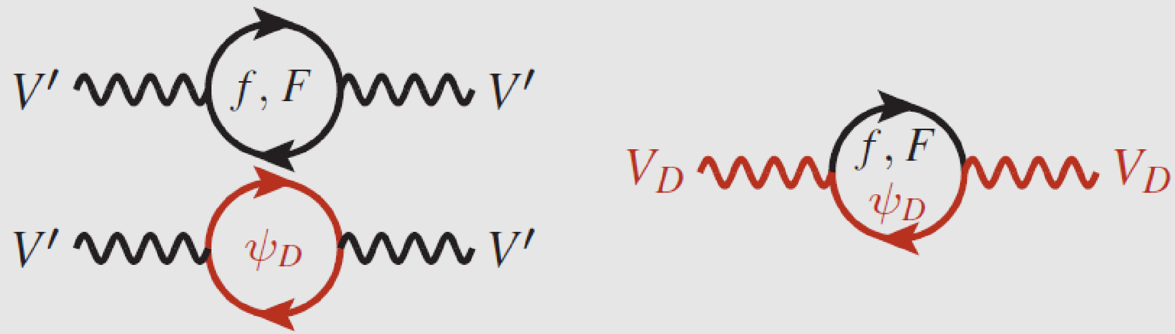
The $\mathbb{Z}_2$-even gauge boson V' can only decay to $f\bar{f}$, or $V_D V_D^*$ if $m_F^2 - m_{\psi_D}^2$ is large enough

The gauge sector: V′ / V_D radiative mass split, no tree-level V′ – Z mixing

- **At tree-level:** $$m_{V^0_{D\pm}} = m_{V^0_{D0}} = \frac{g_D}{2} v_D$$

- **At loop-level:**

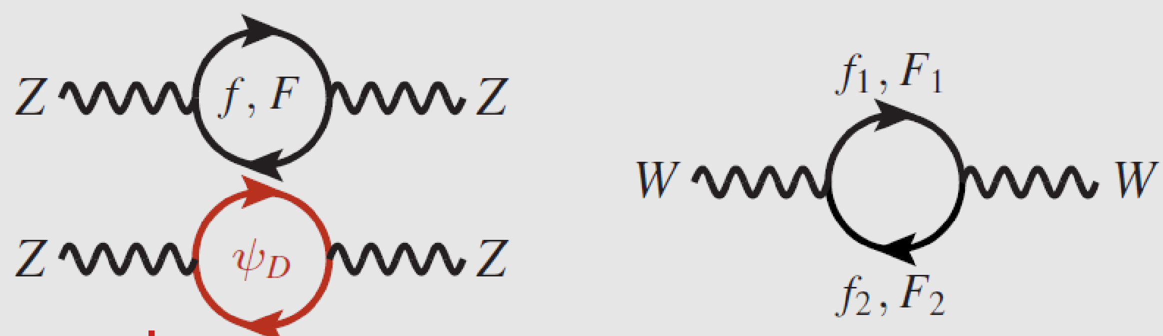
Different loop corrections:
($V^0_{D\pm} \equiv V_D$ and $V^0_{D0} \equiv V'$)



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

- **Effect for W/Z boson masses**

Modifications to SM
different for Z and W



Potential to explain W-boson mass anomaly

The scalar sector: when the higgs portal is absent, the interactions become minimal

EW + Dark symmetry breaking →

Including Higgs portal

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

Without Higgs portal

$$\begin{cases} v = \pm\sqrt{\dfrac{\mu^2}{\lambda}} \\ v_D = \pm\sqrt{\dfrac{\mu_D^2}{\lambda_D}} \end{cases}$$

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

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

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

The scalar sector: when the higgs portal is absent, the interactions become minimal

EW + Dark symmetry breaking →

Including Higgs portal

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

Without Higgs portal

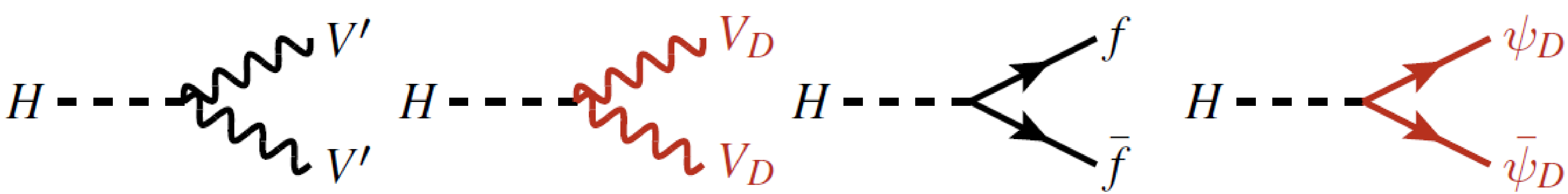
$$\begin{cases} v = \pm\sqrt{\dfrac{\mu^2}{\lambda}} \\ v_D = \pm\sqrt{\dfrac{\mu_D^2}{\lambda_D}} \end{cases}$$

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

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

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

If no Higgs portal, the interactions of the new scalar H are limited to:



VL portal VDM: the summary of particle content

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

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**	$+$
$\Phi_D = \begin{pmatrix} \varphi_{D+\frac{1}{2}}^0 \\ \varphi_{D-\frac{1}{2}}^0 \end{pmatrix}$	**1**	0	**2**	$-$ $+$

Fermions	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$f_L^{\text{SM}} = \begin{pmatrix} f_{u,\nu}^{\text{SM}} \\ f_{d,\ell}^{\text{SM}} \end{pmatrix}_L$	**2**	$\frac{1}{6}, -\frac{1}{2}$	**1**	$+$
$u_R^{\text{SM}}, \nu_R^{\text{SM}}$	**1**	$\frac{2}{3}, 0$	**1**	$+$
$d_R^{\text{SM}}, \ell_R^{\text{SM}}$	**1**	$-\frac{1}{3}, -1$	**1**	$+$
$\Psi = \begin{pmatrix} \psi^D \\ \psi \end{pmatrix}$	**1**	Q	**2**	$-$ $+$

VL portal VDM: the summary of particle content

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

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

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

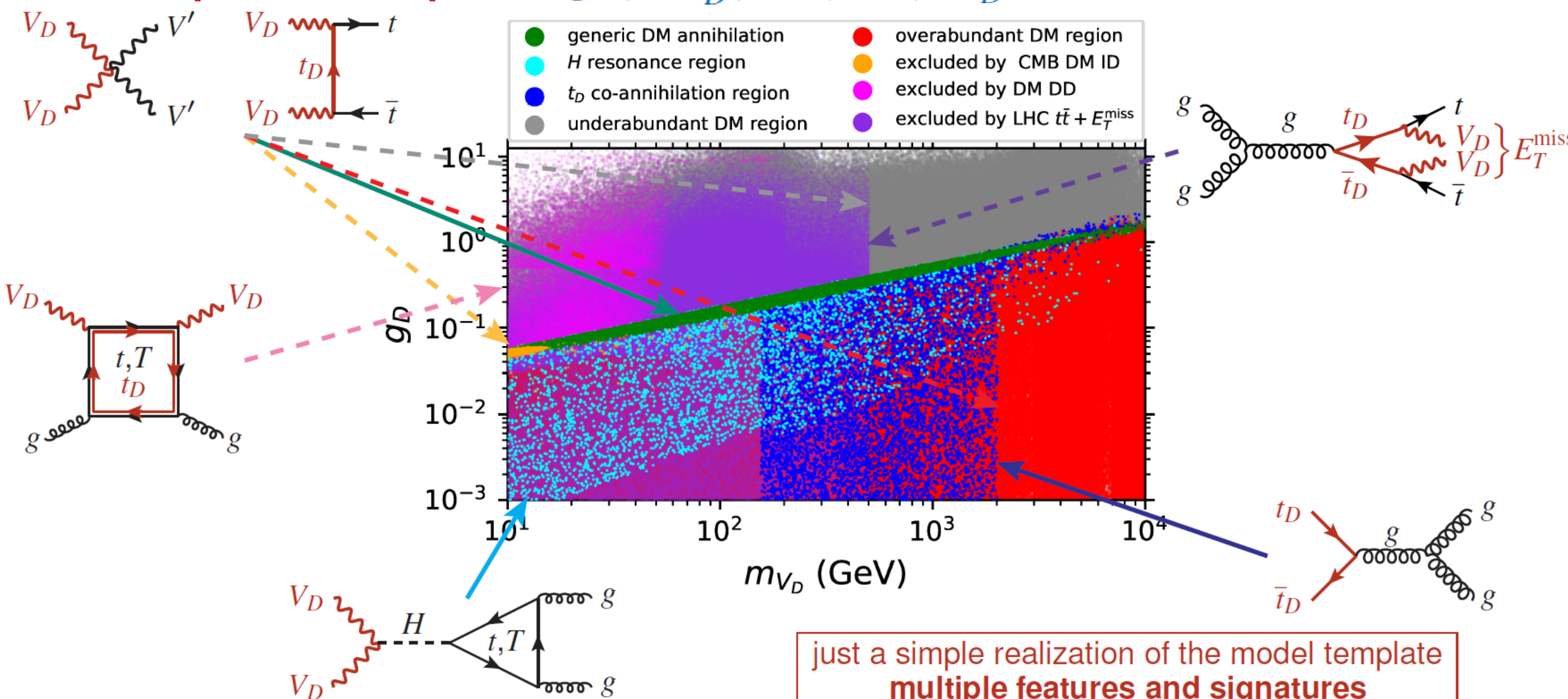
Minimal VL top portal VDM: VL top portal without mixing

The VL fermion is composed of top partners and there is no mixing between scalars

$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{t_D} \le m_T$$

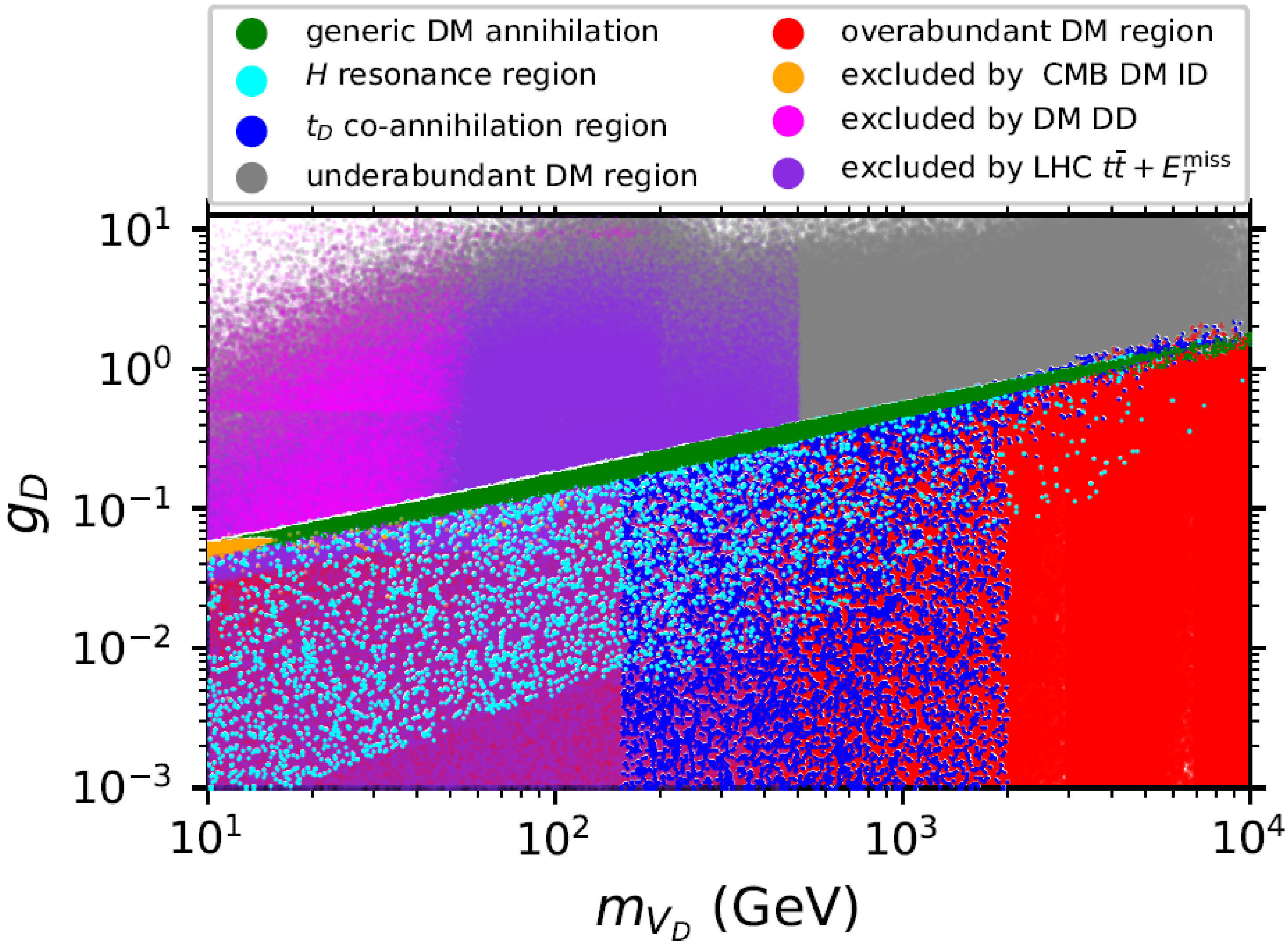
$$\sin\theta_S = 0$$

5D parameter space: $g_D\,,m_{V_D}\,,m_H\,,m_T\,,m_{t_D}$



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

Minimal VL top portal VDM: projections of 5D scan in $g_D, m_{V_D}, m_H, m_T, m_{t_D}$



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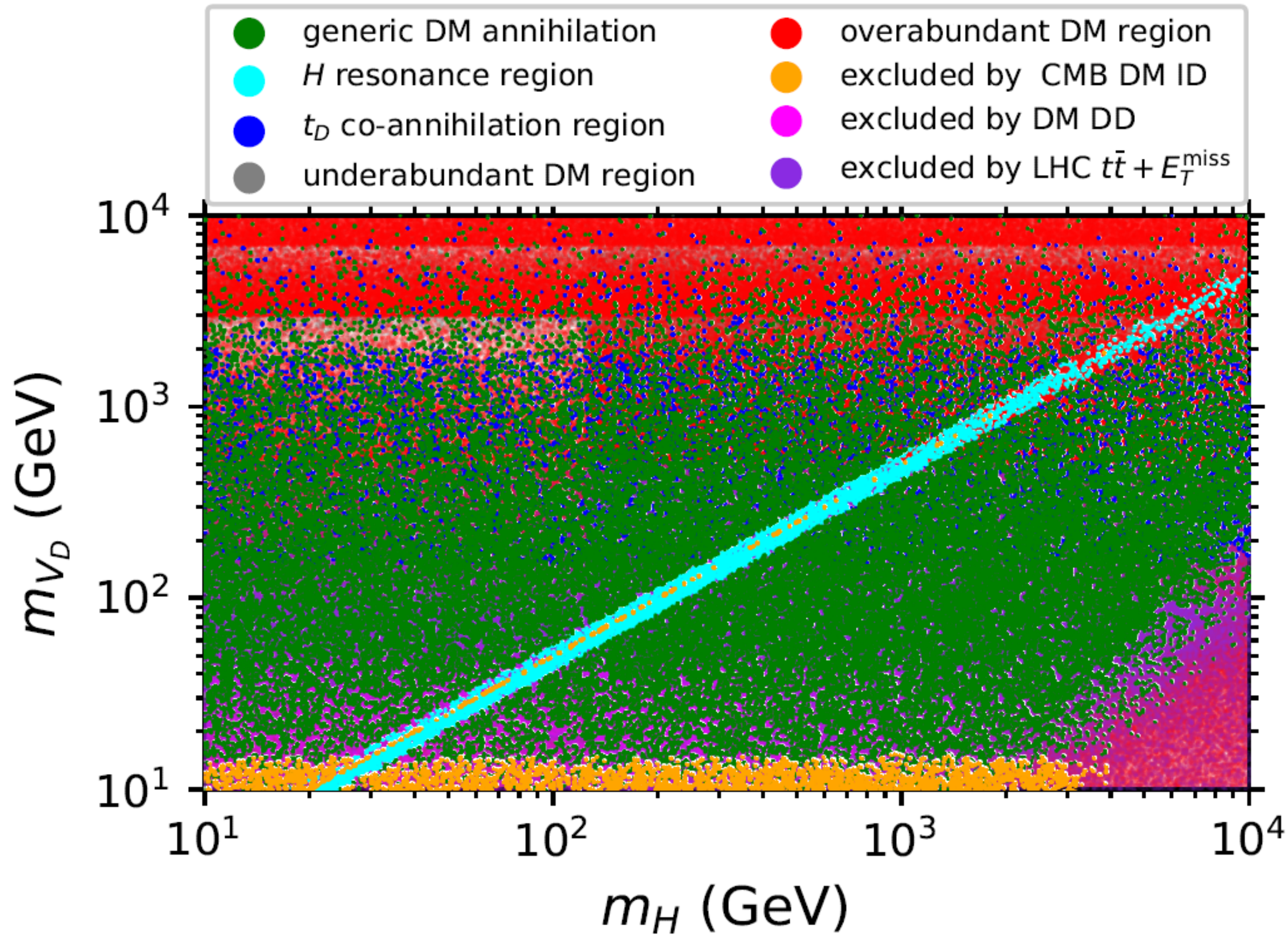

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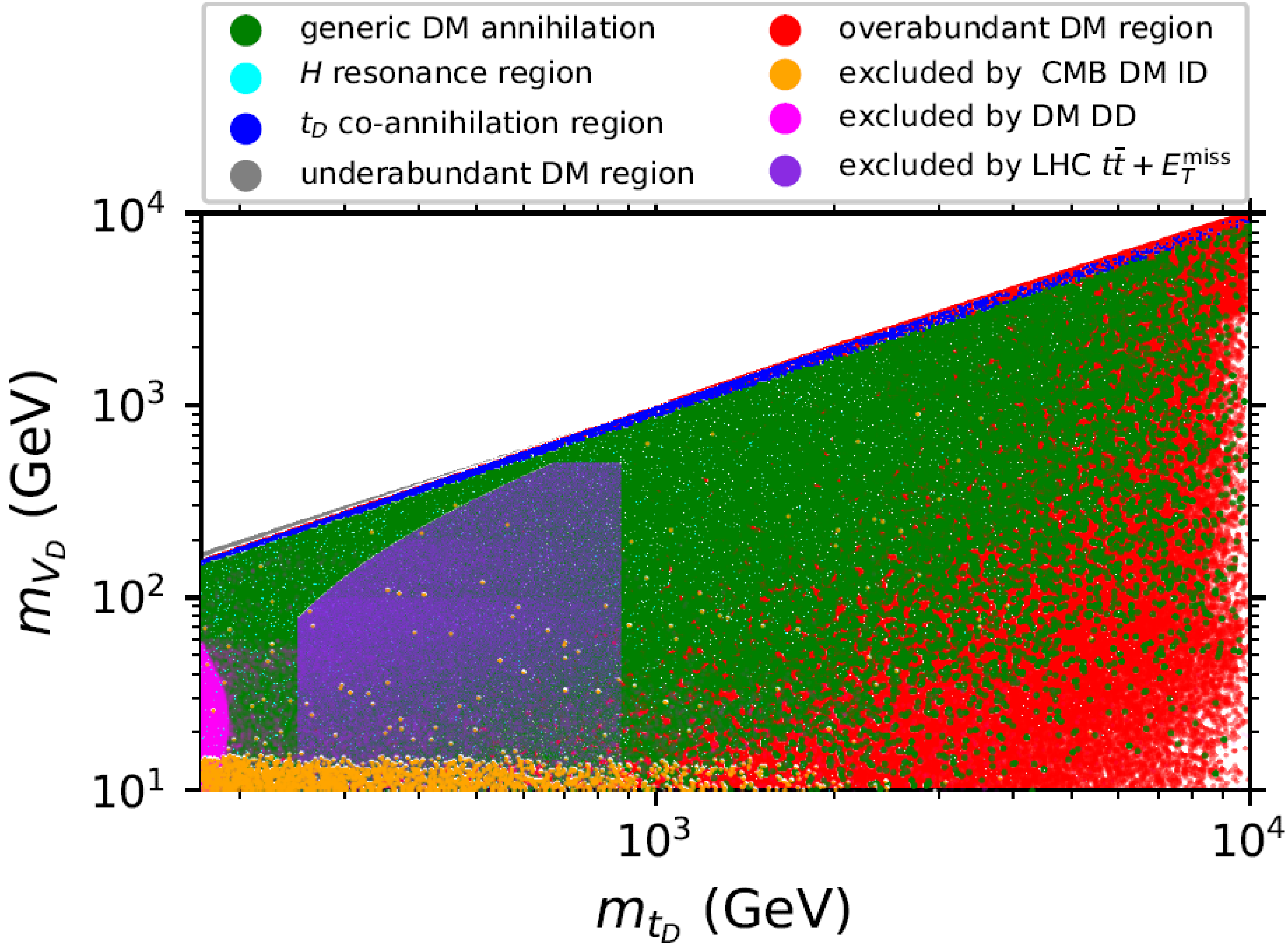

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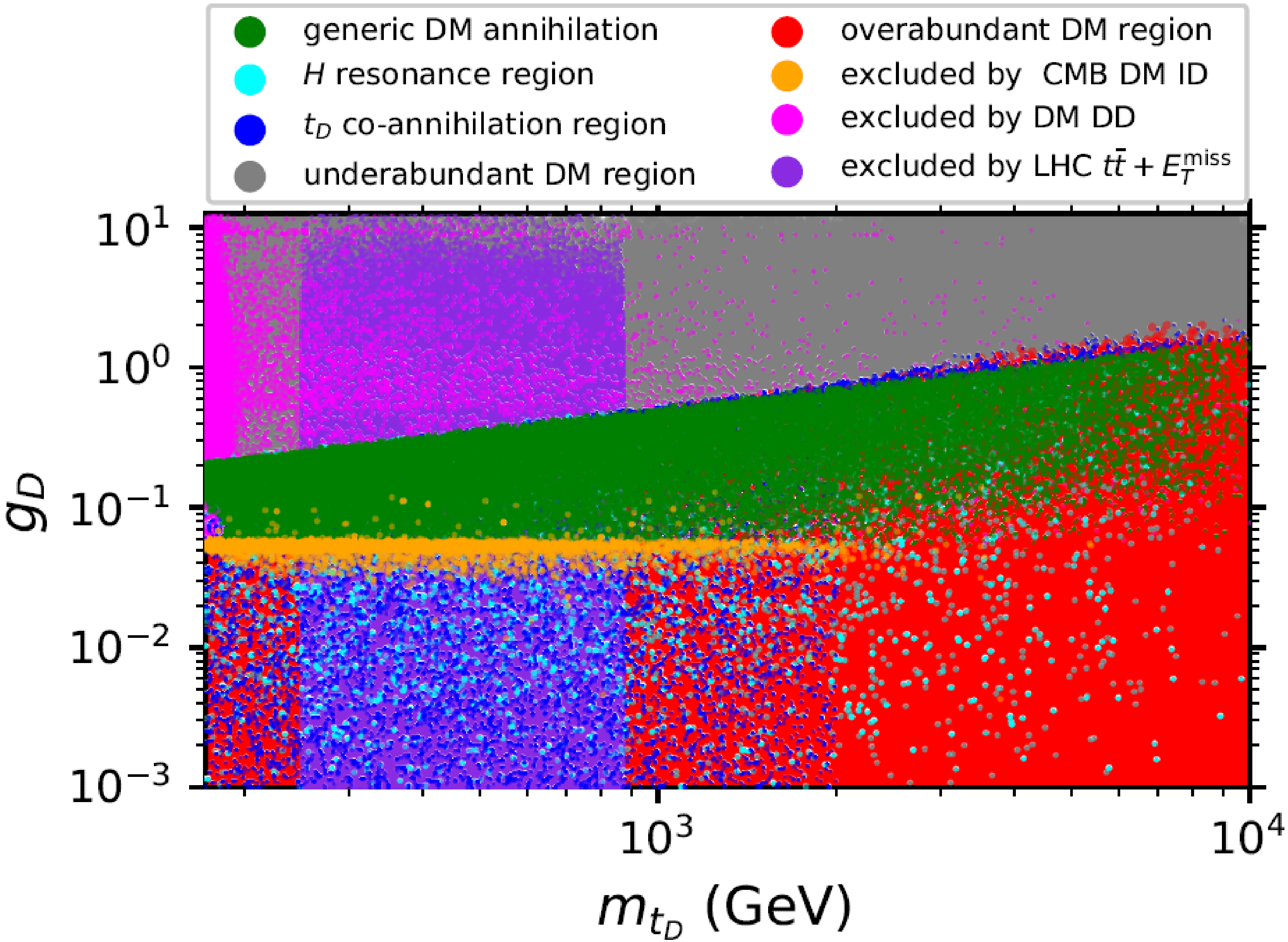

Minimal VL top portal VDM: details of 2D space for chosen benchmarks

The VL fermion is composed of top partners and there is no mixing between scalars

$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{t_D} \leq m_T$$

$$\sin\theta_S = 0$$

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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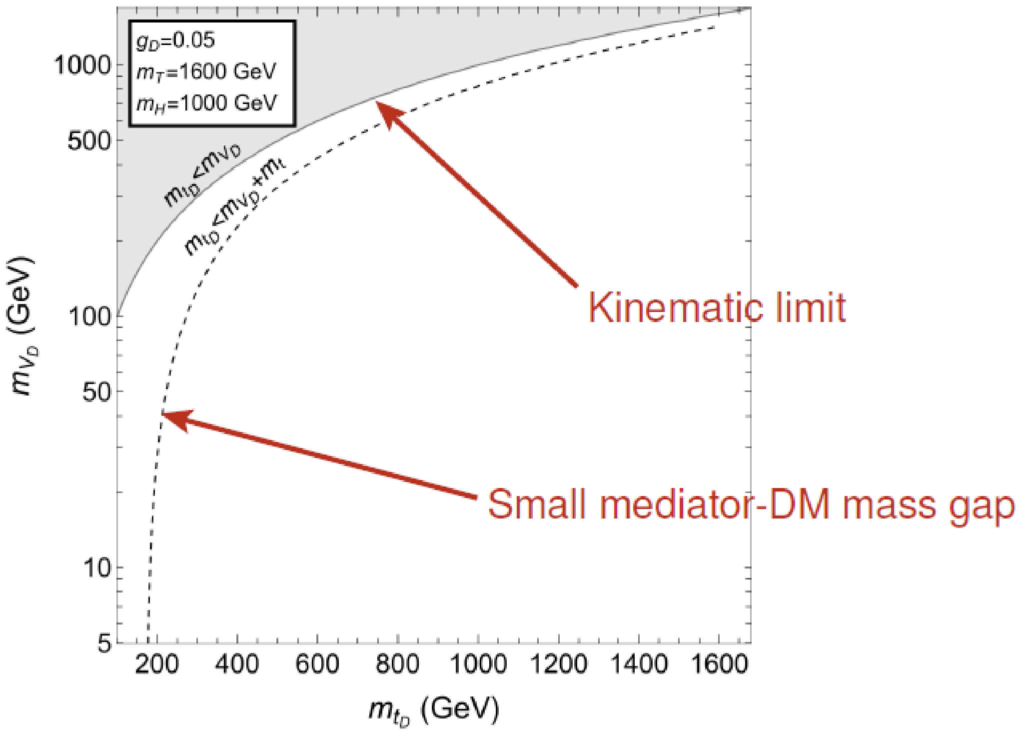

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The VL fermion is composed of top partners and there is no mixing between scalars

$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix}$ with $m_t < m_{t_D} \le m_T$

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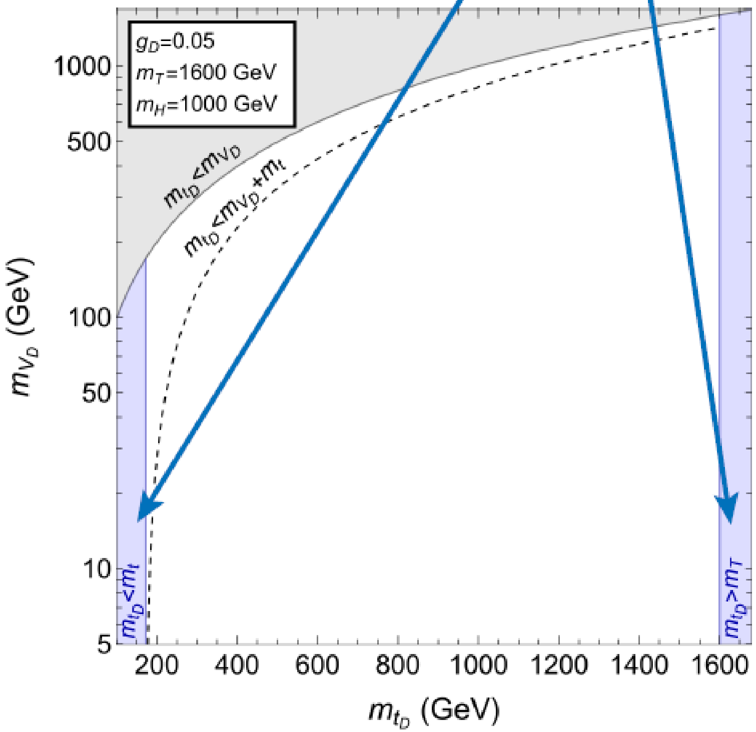

Mediator mass bounded from below and above

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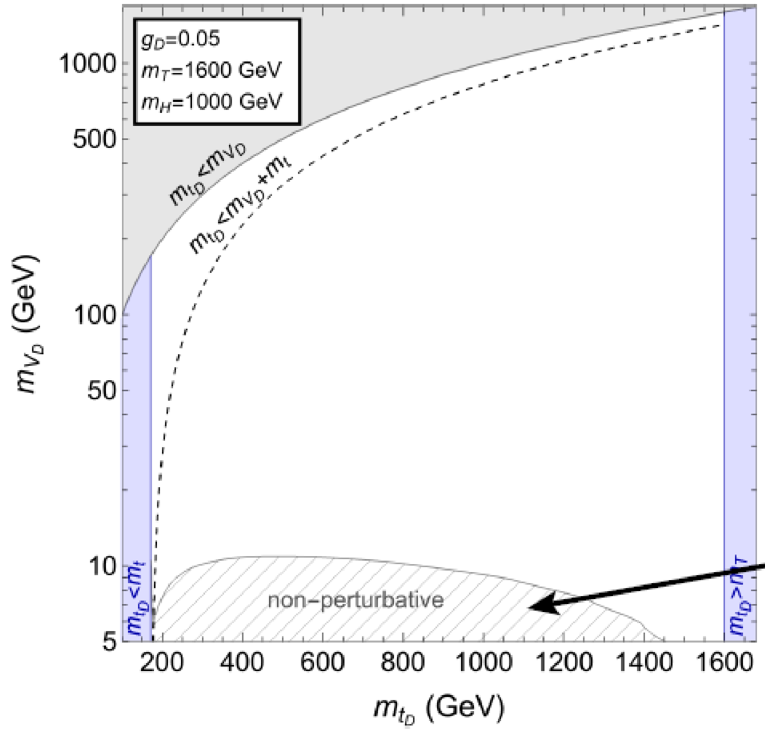

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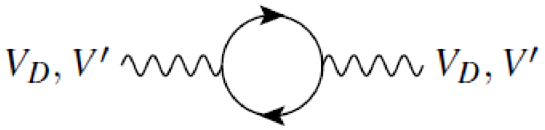
Light DM in non-perturbative region



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

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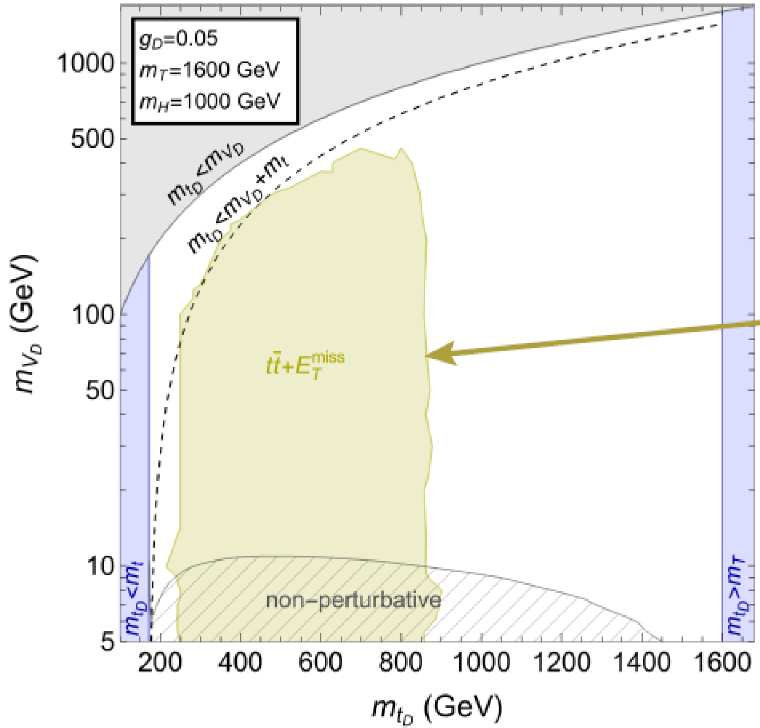

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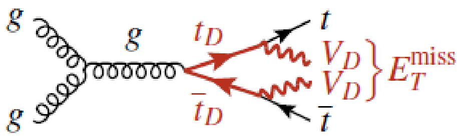

Recast

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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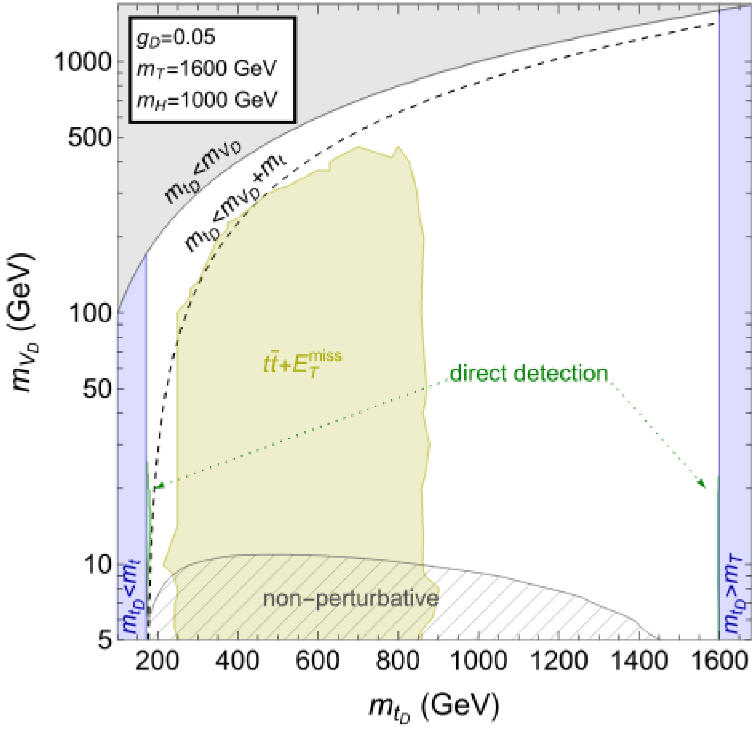

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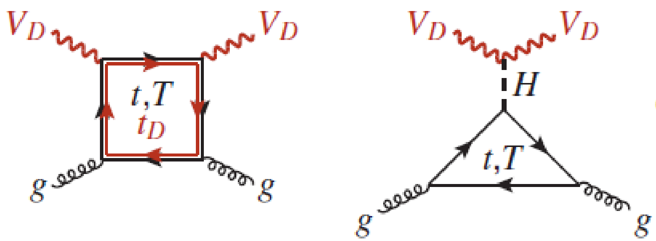

$\propto \frac{\Omega_{DM}}{\Omega_{DM}^{Planck}}$

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]

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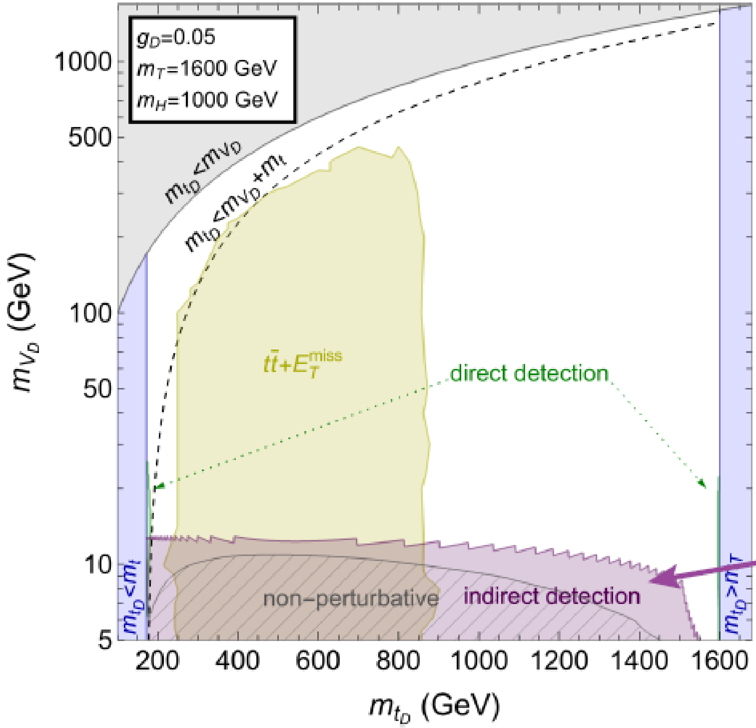

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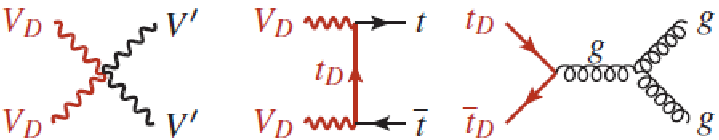

$$\propto \left(\frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm Planck}}\right)^2$$

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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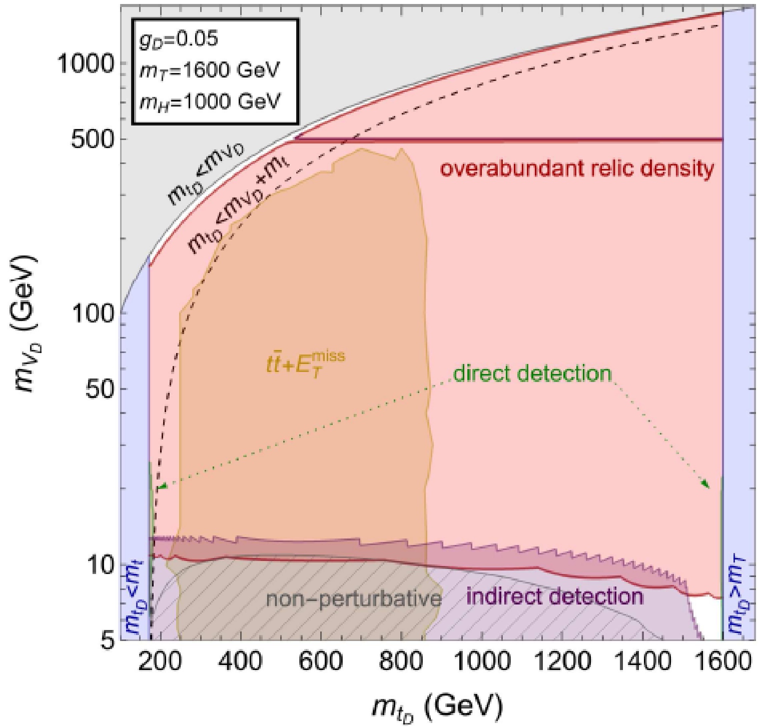

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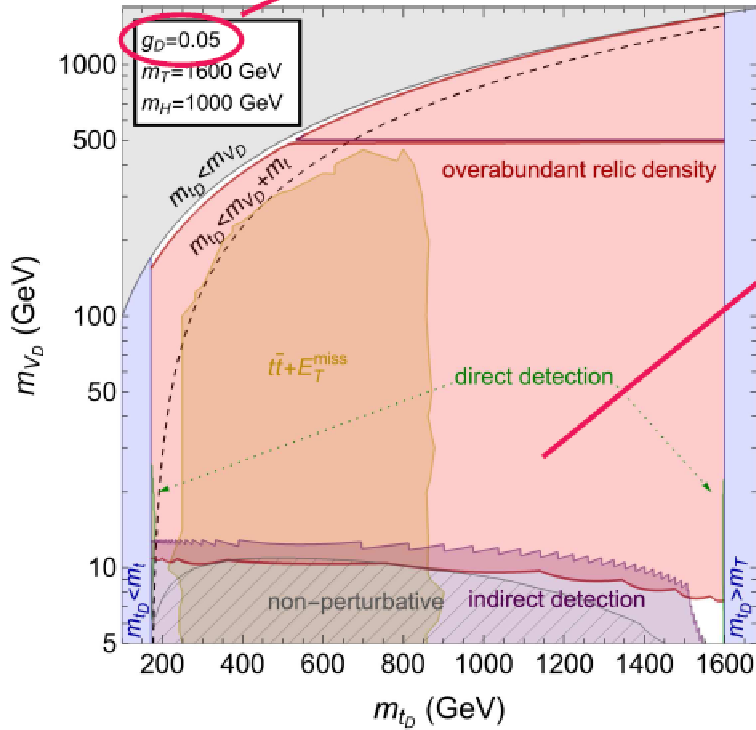

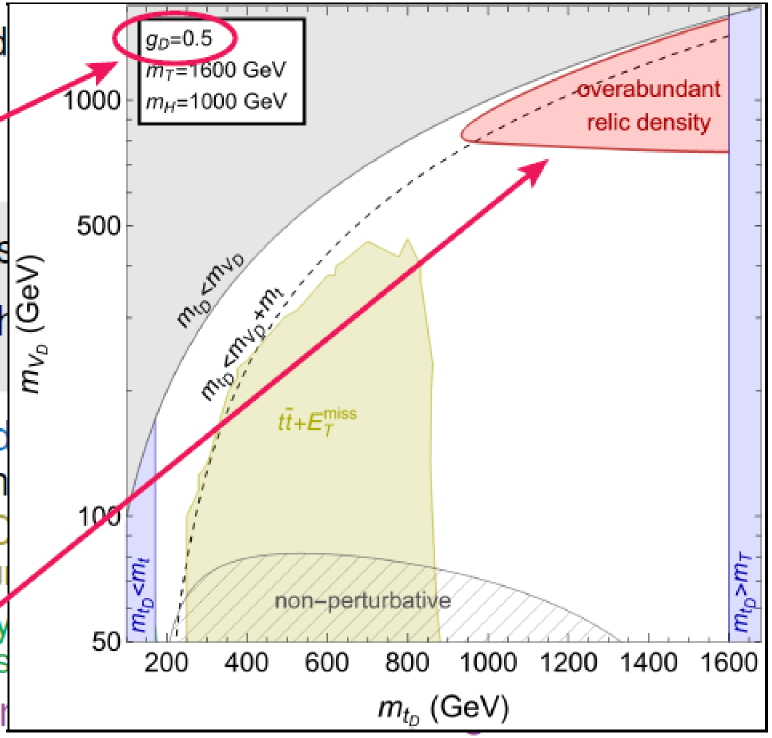

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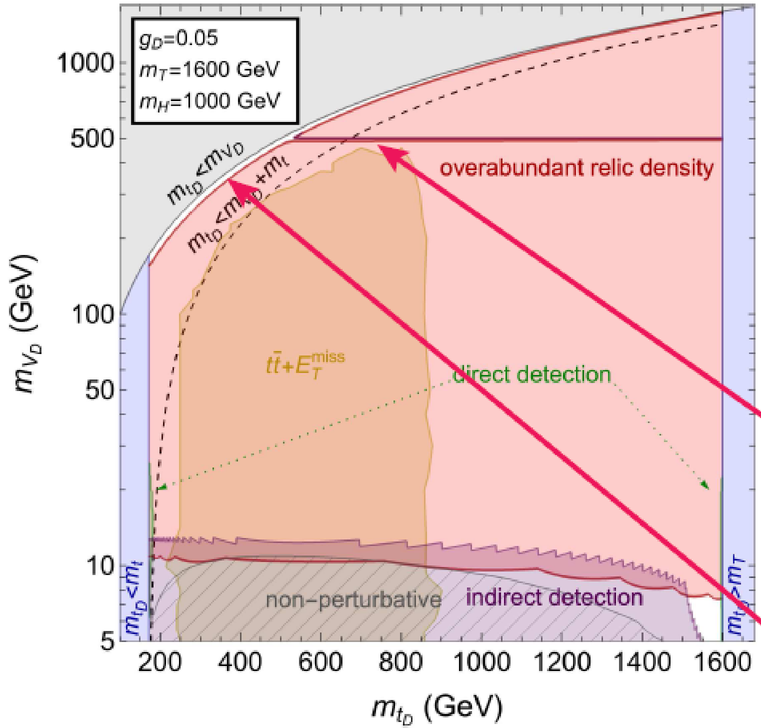

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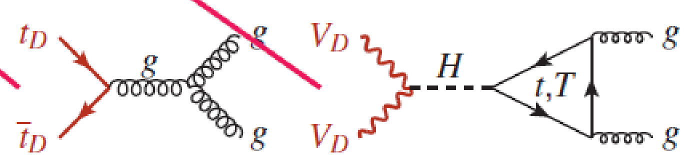

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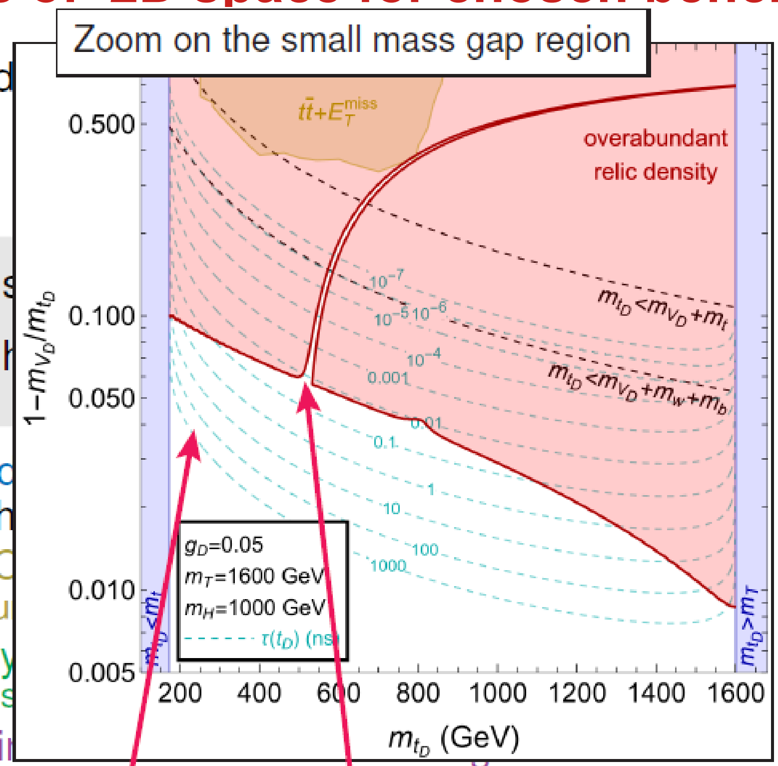

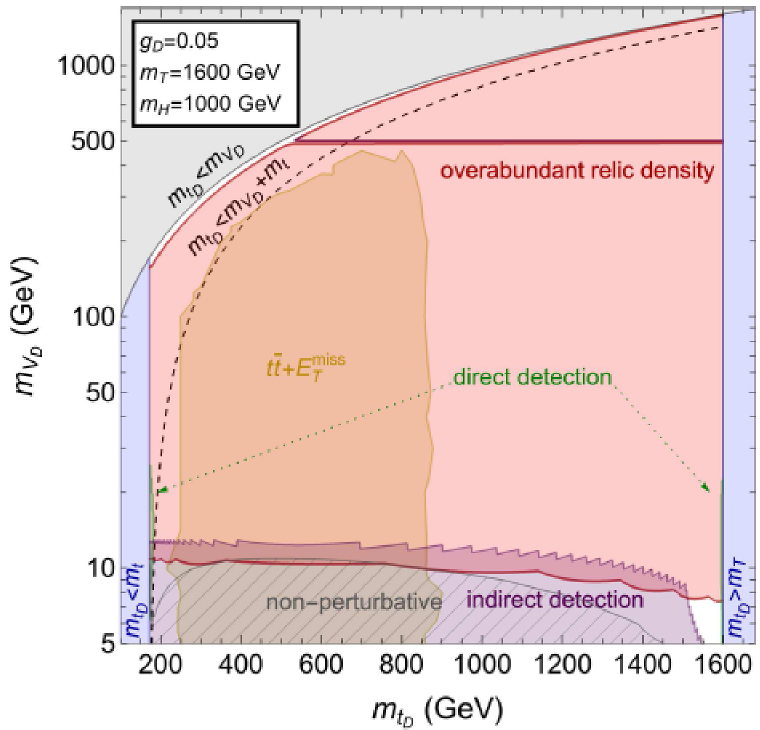

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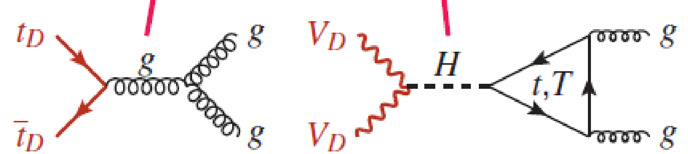

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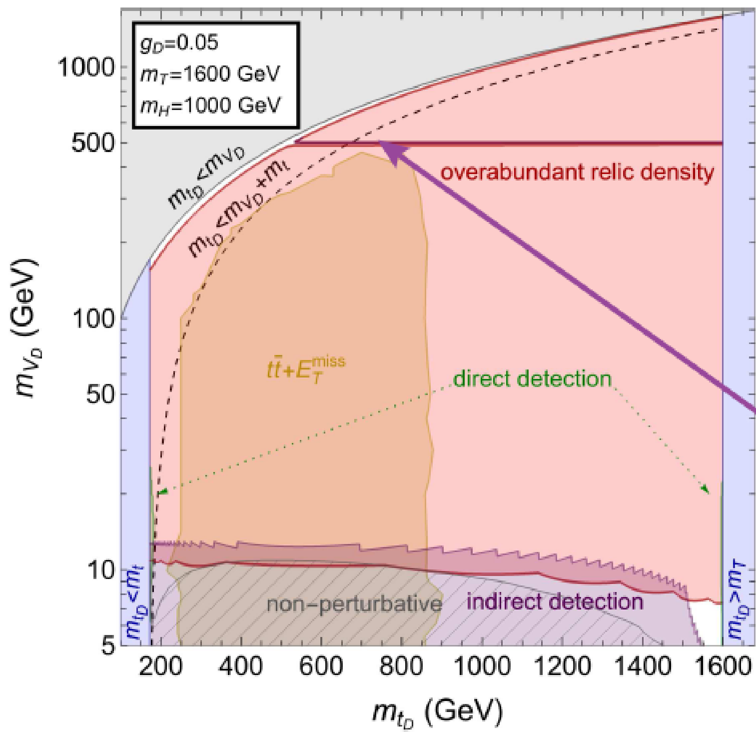

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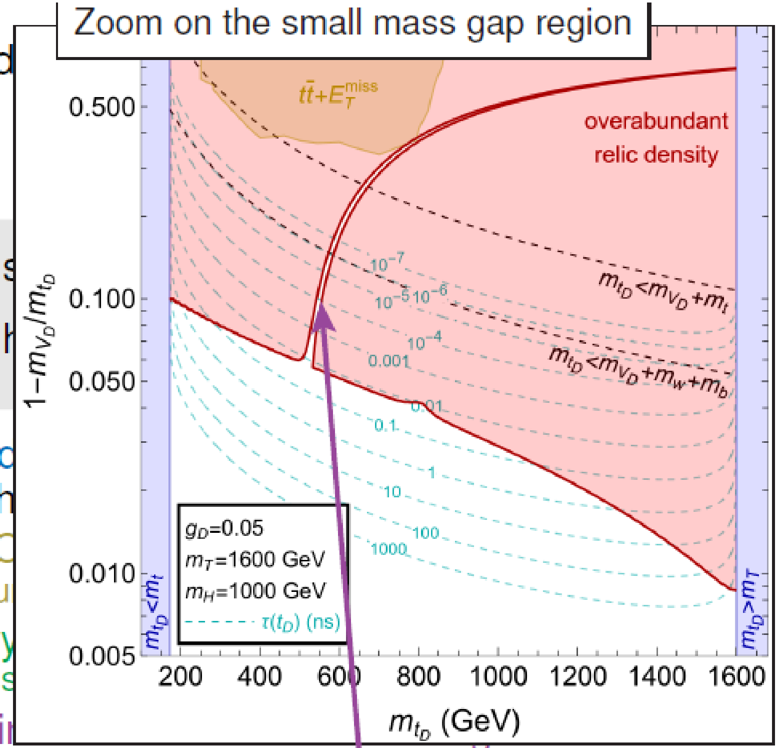

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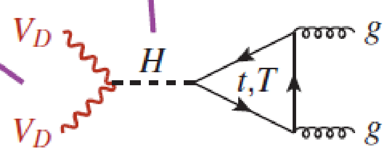

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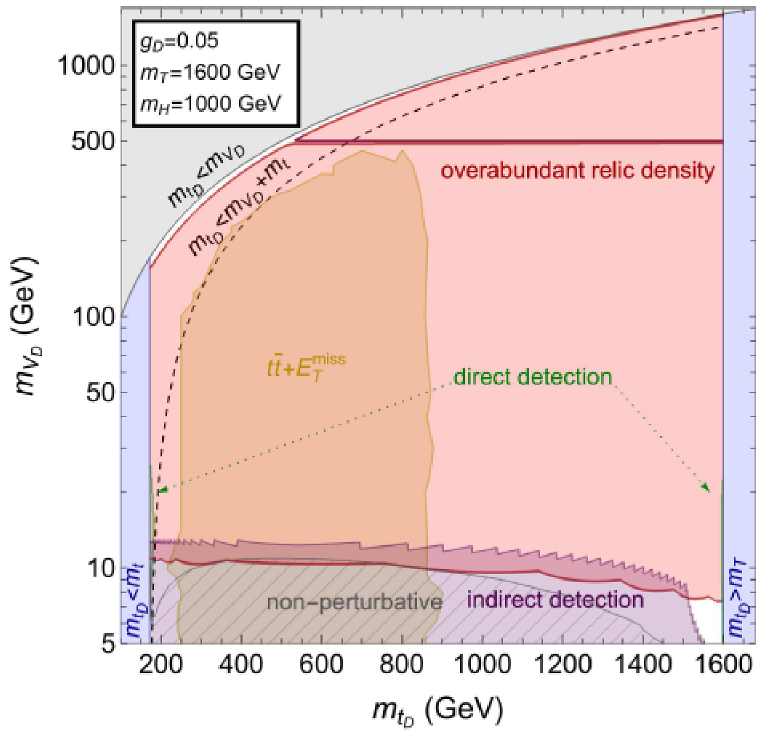

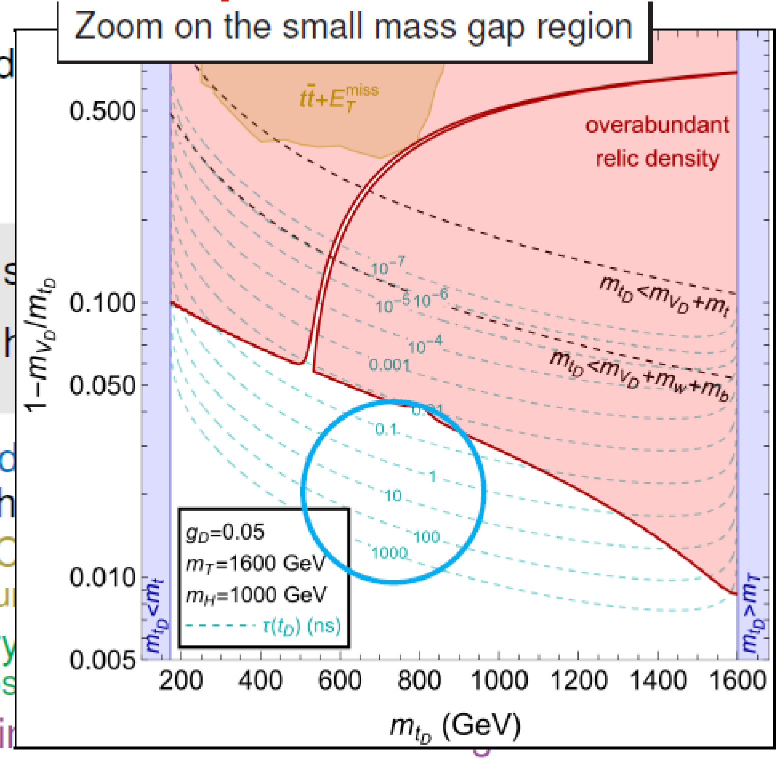

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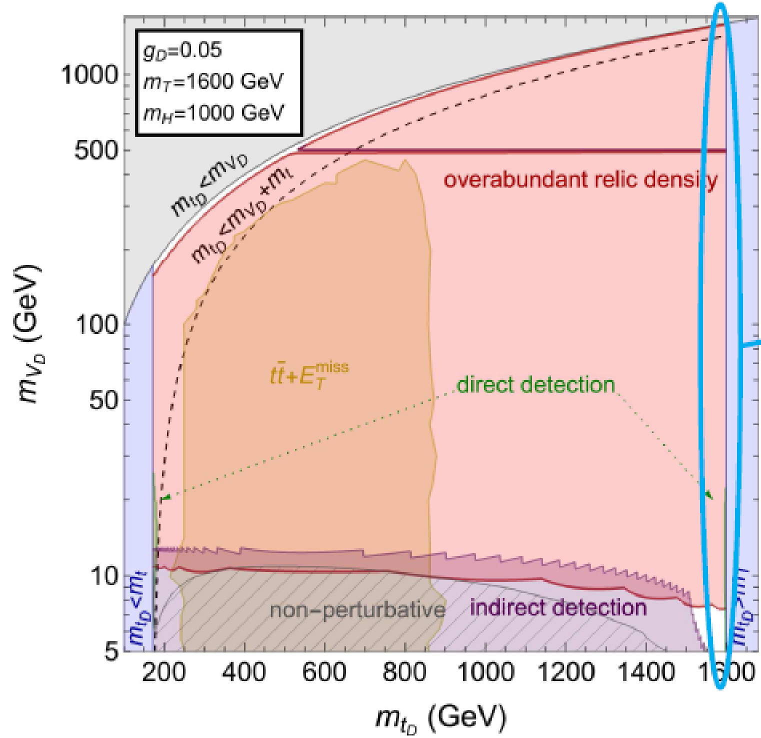

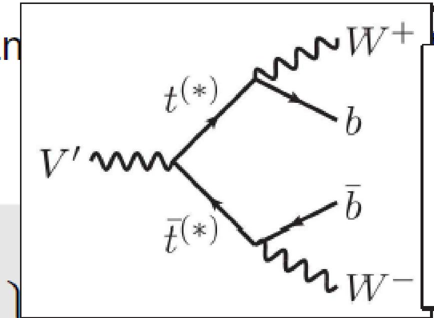

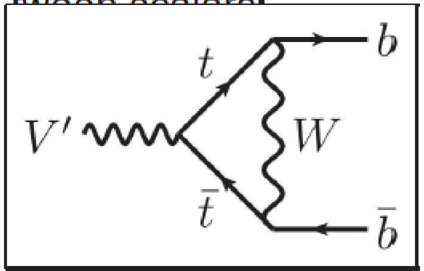

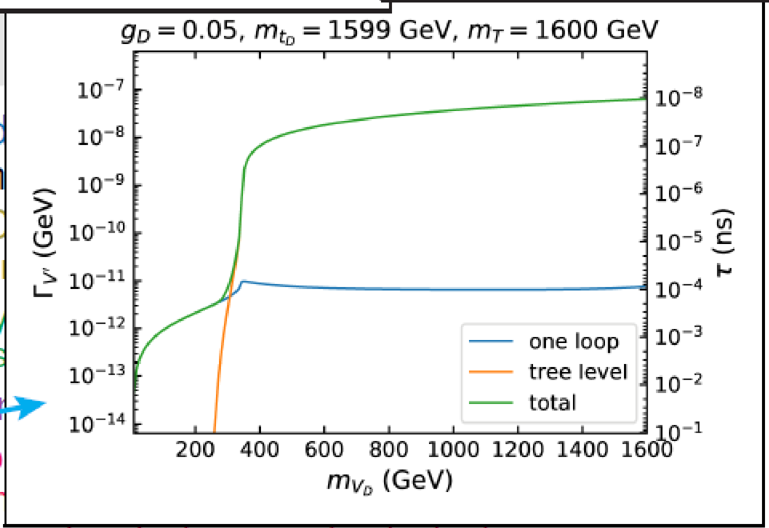

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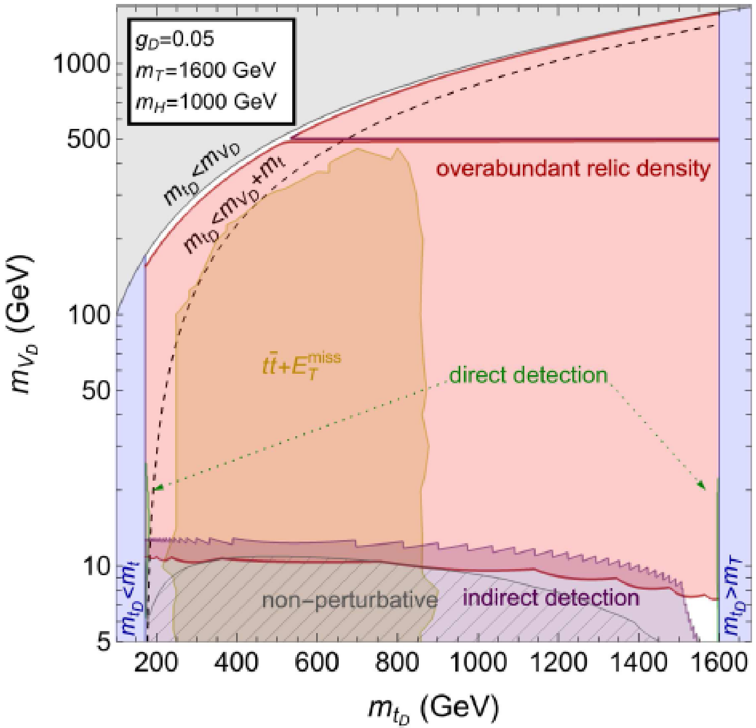

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just a simple realization of the model template
multiple features and signatures

Summary on Fermion Portal Vector Dark Matter (FPVDM)

- FPVDM is a new framework which does not require the Higgs portal
- Incorporates many possibilities with new collider and cosmological implications
- Case study in the top sector with multiple phenomenological predictions

Great potential to explore flavour and DM phenomena!

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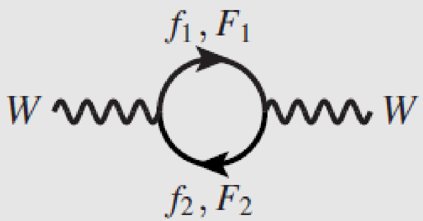
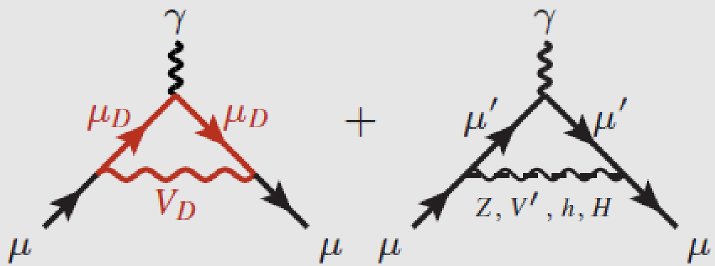
Outlook

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





→ Study of different **theoretical embeddings**

→ Further analysis of **cosmological implications** and scenarios for **future colliders**

Backup slides

Gauging the 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.

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

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**

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

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

Mixing between all Q- and Q_D-neutral bosons

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

2 massless and 2 massive vectors

Connections with dark-photon phenomenology