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

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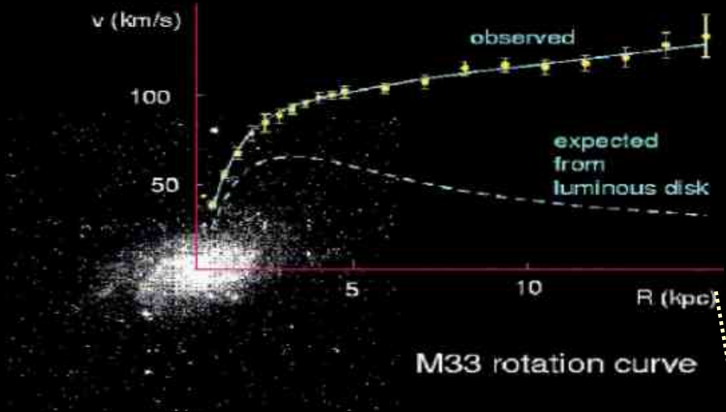
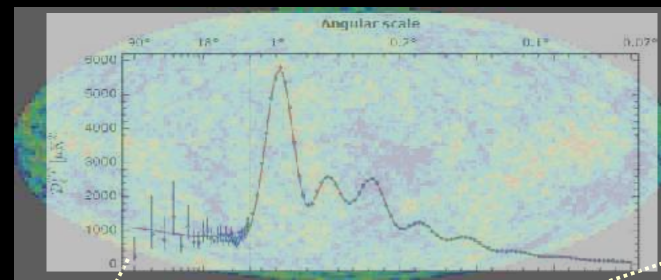
Workshop on the Standard Model and Beyond
August 28 – September 8, 2022

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

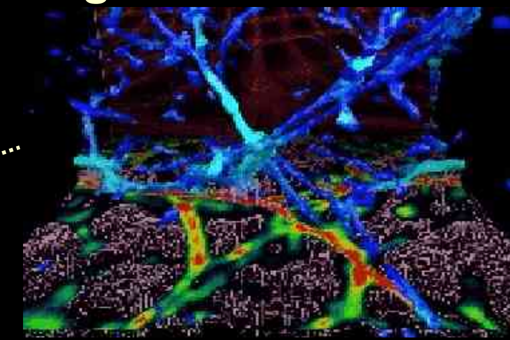
Galactic rotation curves

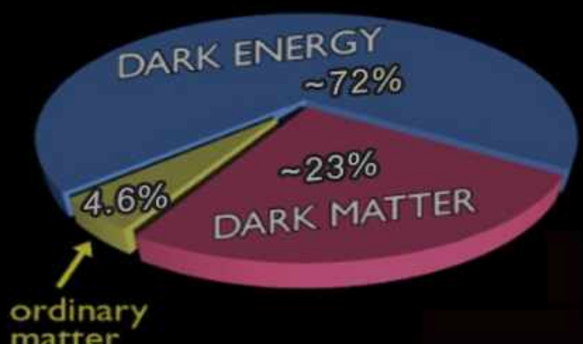


CMB: WMAP and PLANCK



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 ?

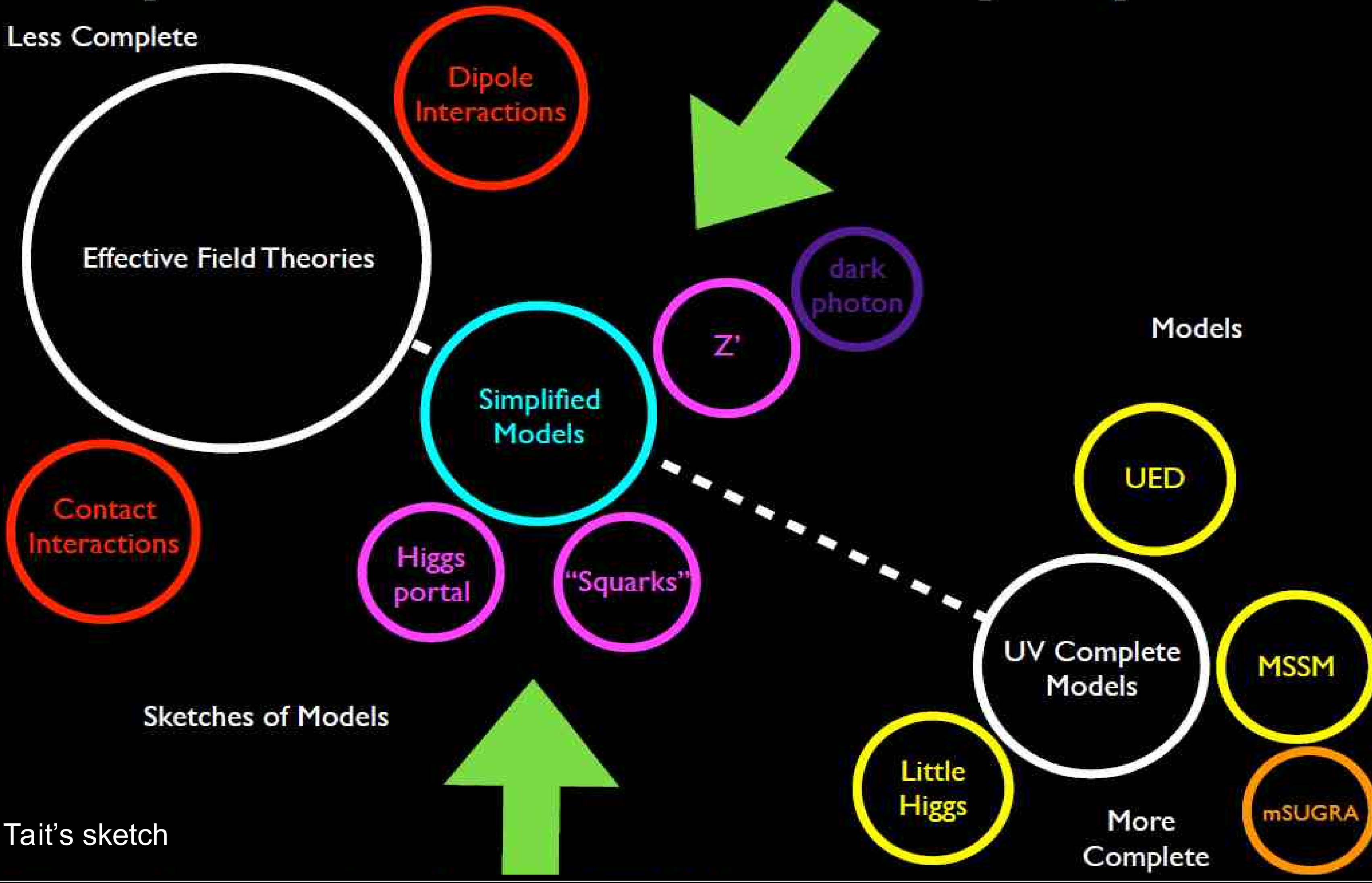
Couplings

- 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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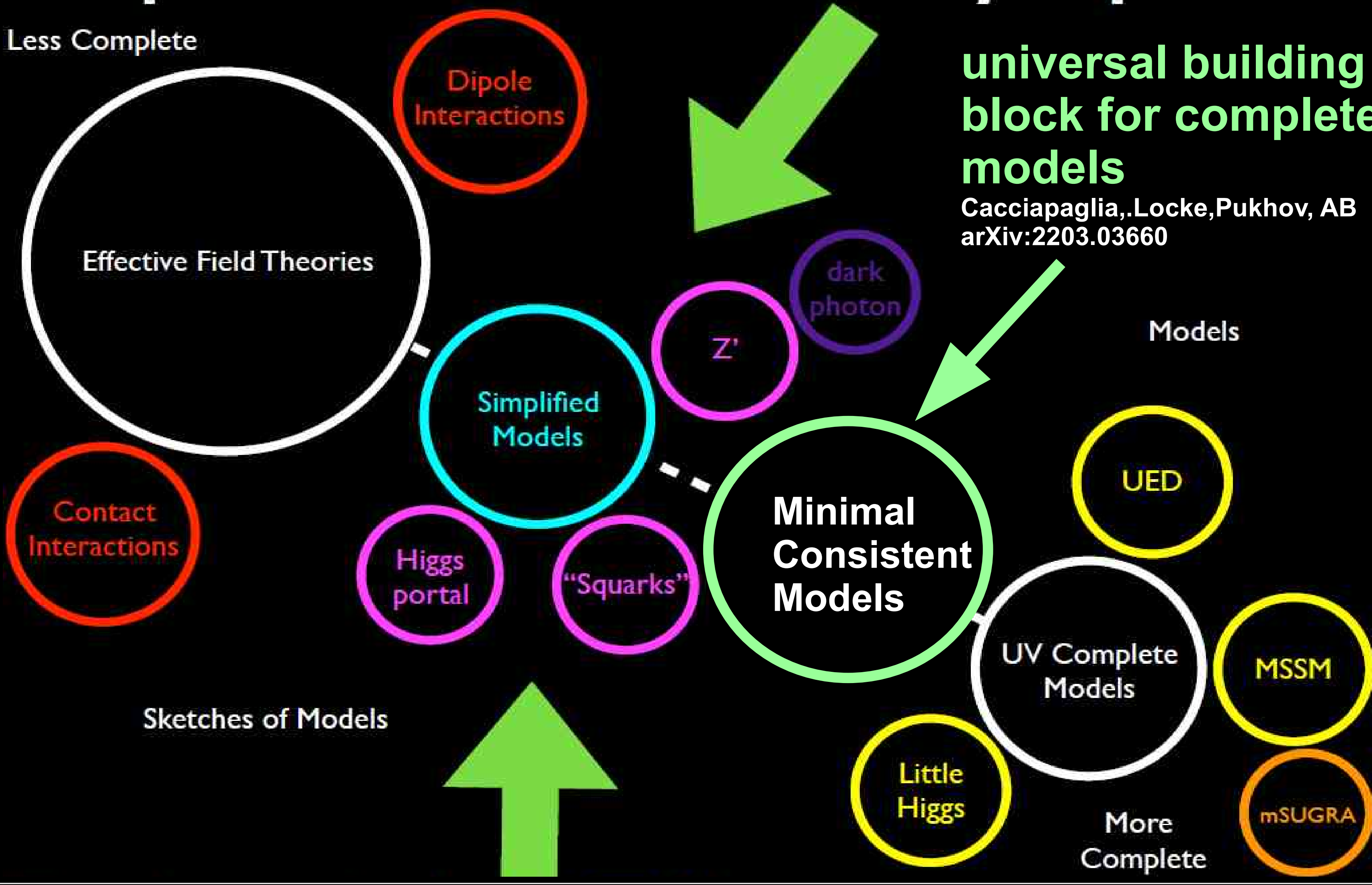

Vector DM

- The abelian/non-abelian Vector DM with Higgs portal
  - $U(1)_D$ Group

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  - $U(1)_D$ Group
  - $V_D^\mu \leftrightarrow -V_D^\mu$ 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 $D_\mu \Phi \equiv \partial_\mu \Phi - g Q_\Phi V_\mu \Phi$

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so one has $m_V^2 = g^2 Q_\Phi^2 \; v_\phi^2$

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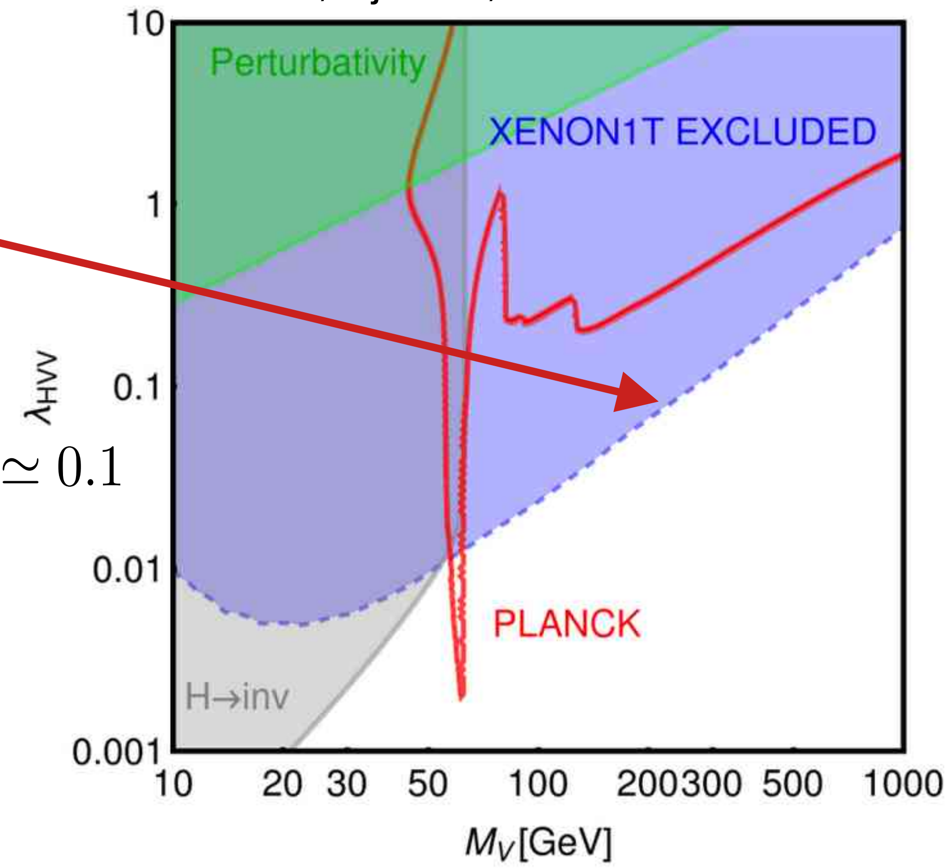
  - Quite a few papers:
    - Lebedev, Lee, Mambrini 1111.4482,
    - Baek, Ko, Park , Senaha 1212.2131
    - DiFranzo, Fox,Tait 1512.06853
    - Farzan, Akbarieh 1207.4272
    - Duch, Grzadkowski, McGarrie 1506.08805
    - ....

Vector DM with the Higgs portal

- Since VDM ‘talks’ to SM via Higgs, $V_D V_D H$ 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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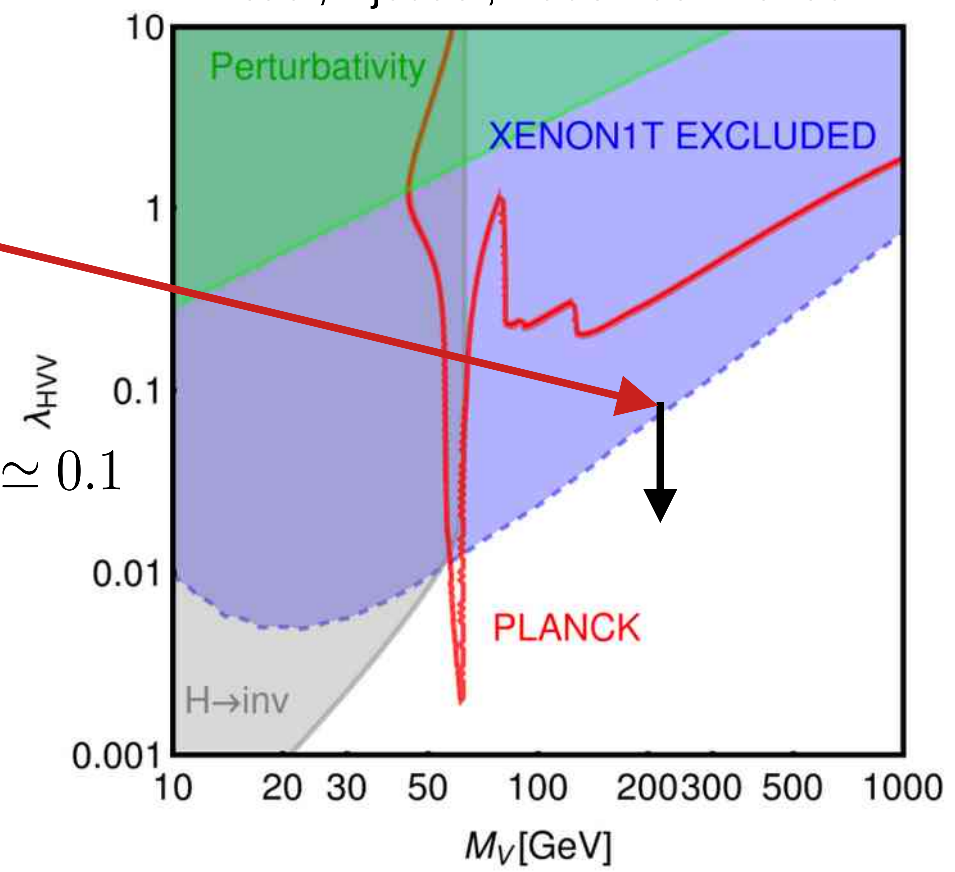

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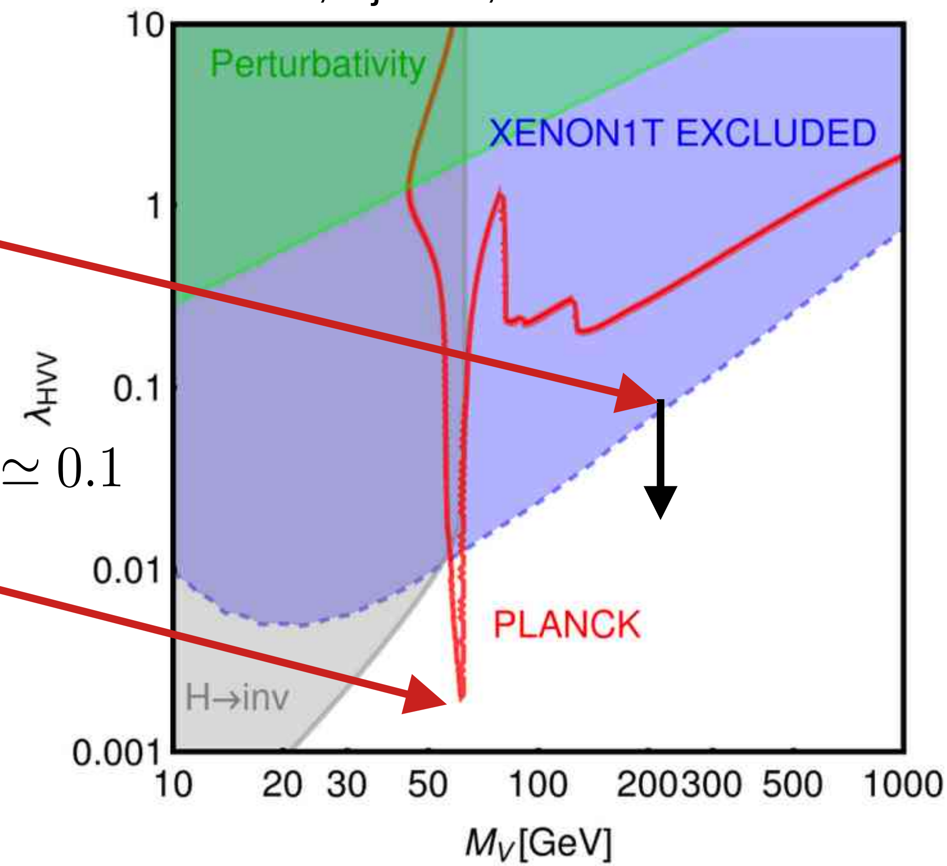

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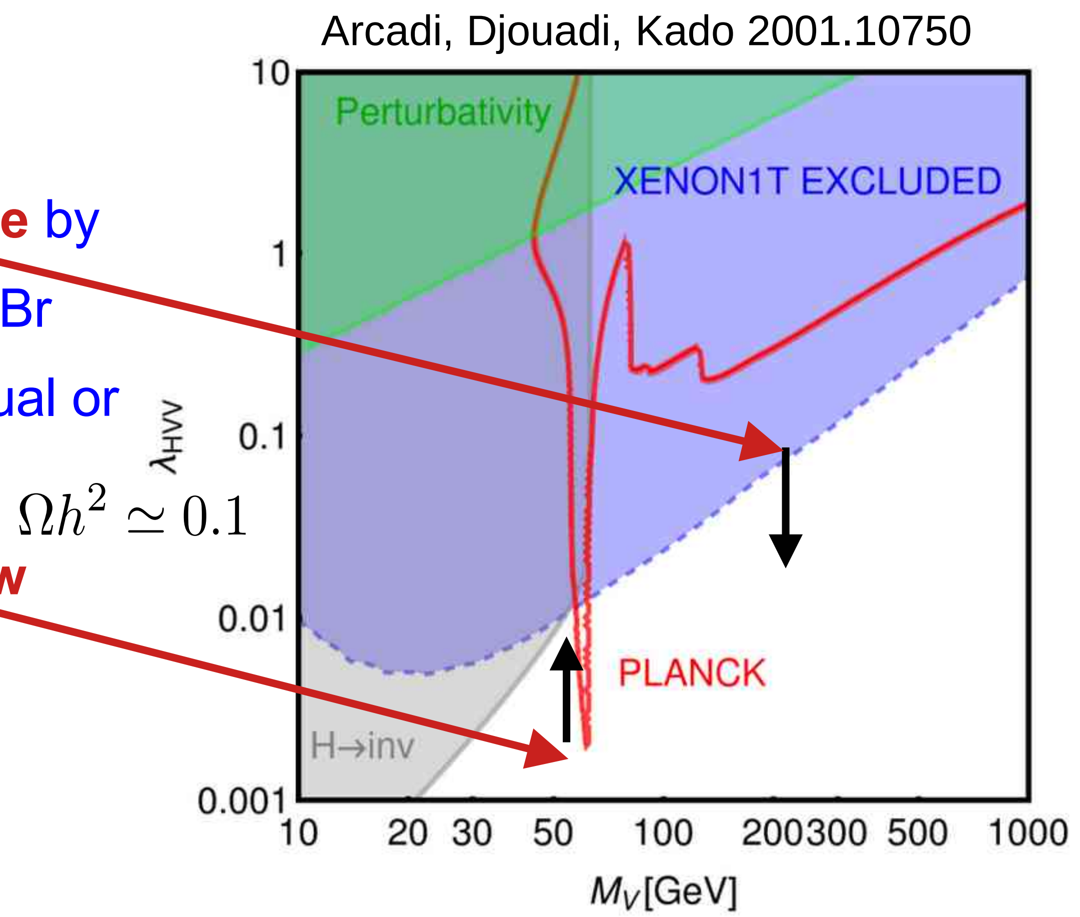

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- The Higgs portal VDM parameter space is very limited by interplay of collider, DD and DM relic density

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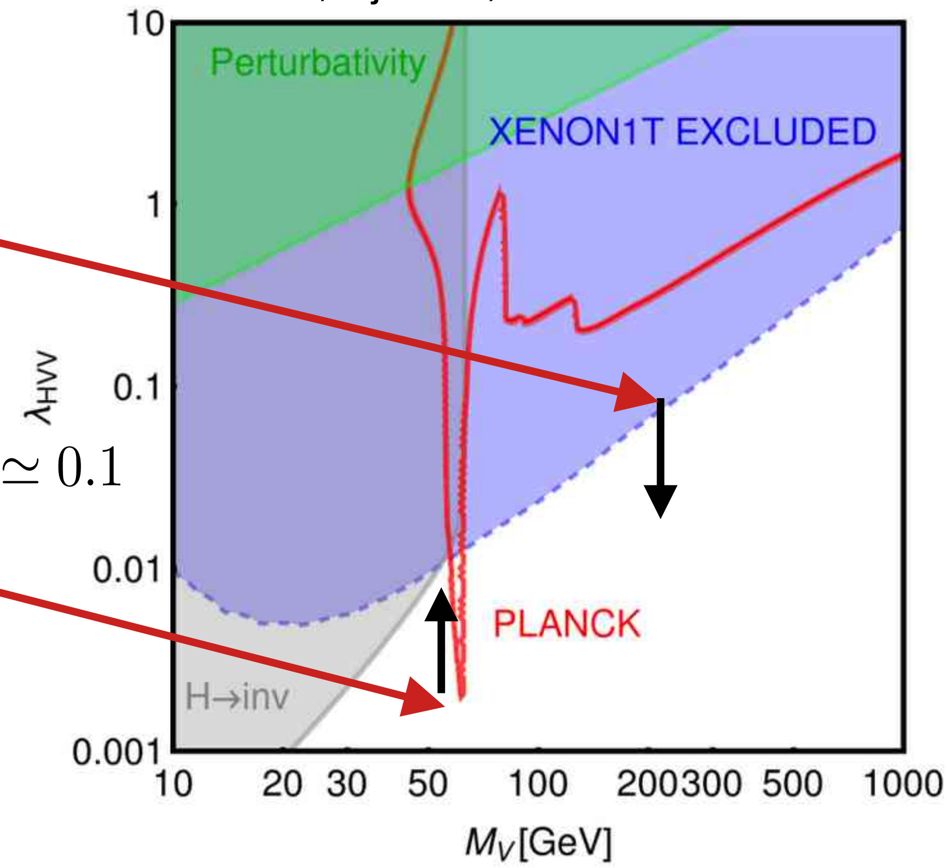

Vector DM with the Higgs portal

- 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 $(N-1)^2$ scalars

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  - electroweakly interacting non-abelian vector dark matter:

    Abea, Fujiwara, Hisano, Matsushita 2004.00884

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

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

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
- **We are driven by curiosity and simplicity to find an alternative portal for Vector Dark Matter**

SM + three ingredients:

- $SU(2)_D$ new (dark) non-abelian new gauge group V_μ^D
- Complex scalar doublet charged under $SU(2)_D$ Φ_D
- Vector-Like fermion doublet of $SU(2)_D$ Ψ

Vector like fermion Portal for Vector DM

- The general form of the Yukawa terms of the new fermion sector reads

$$-\mathcal{L}_f = M_\Psi \bar{\Psi}\Psi + (y' \bar{\Psi}_L \Phi_D f_R^{\rm SM} + y'' \bar{\Psi}_L \Phi_D^c f_R^{\rm SM} + h.c) \ ,$$

where $\Phi_D^c = i\tau_2\Phi^*$, while y' and y'' are new Yukawas, connecting SM fermions and new VL fermions

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- If we assign the "dark charge" to the components of the doublets, e.g. $Q_D = T_D^3 + Y_D$ and require its conservation, we will get
  - $SU(2)_D \times U(1)_{\rm glob} \to U(1)_{\rm glob}^d$ pattern of dark sector breaking
  - $\mathbb{Z}_2$ Subgroup can be defined as $\mathbb{Z}_2 : (-1)^{Q_D}$
  - for Φ_D we choose, e.g, $Y_D = 1/2$, then y'' is eliminated, stabilizing VDM

Vector like fermion Portal for Vector DM

- So, we have: $SU(2)_D \times U(1)_{\rm glob} \to U(1)^d_{\rm glob}$, $\mathbb{Z}_2 : (-1)^{Q_D}$, $Q_D = T^3_D + Y_D$

$Y_D = 1/2$ for the doublet and $Y_D = 0$ for the triplet

- Different components of the doublet and triplet will have different parities:

  - two scalar degrees of the doublet (i.e upper part of the doublet) are Z_2 - odd – they become longitudinal component of DM the lower part of scalar doublet is Z_2-even, it contains vev
  - this means that one of the components of the vector triplet is Z_2-even
  - the term, connecting dark scalar and VL fermion and SM RH fermion:

$$y' \bar{\Psi}_L \Phi_D f_R^{\rm SM}$$

one component of VL fermion doublet is Z_2-even and the other - Z_2-odd

$$\Phi_D = \begin{pmatrix} \varphi^0_{D+1/2} \\ \varphi^0_{D-1/2} \end{pmatrix} \longrightarrow \langle \Phi_D \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_D \end{pmatrix}$$

	$SU(2)_L$	$U(1)_Y$	$SU(2)_{\rm D}$	$\mathbb{Z}_2$
$\Phi_D = \begin{pmatrix} \varphi^0_{D+\frac{1}{2}} \\ \varphi^0_{D-\frac{1}{2}} \end{pmatrix}$	**1**	0	**2**	$\begin{matrix} - \\ + \end{matrix}$
$\Psi = \begin{pmatrix} \psi_D \\ \psi \end{pmatrix}$	**1**	Q	**2**	$\begin{matrix} - \\ + \end{matrix}$
$V^D_\mu = \begin{pmatrix} V^0_{D+\mu} \\ V^0_{D0\mu} \\ V^0_{D-\mu} \end{pmatrix}$	**1**	0	**3**	$\begin{matrix} - \\ + \\ - \end{matrix}$

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

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

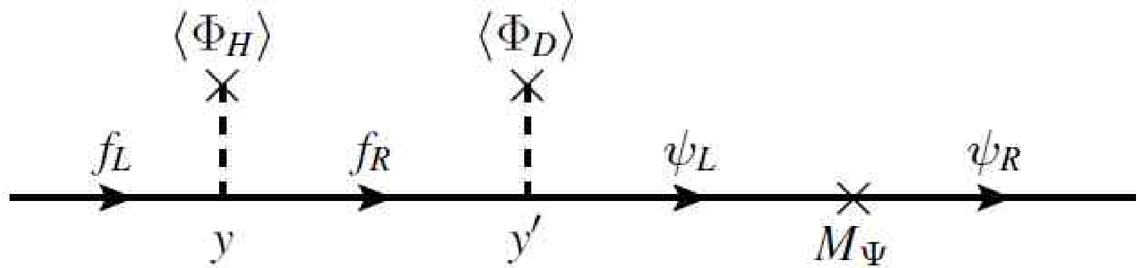
$$\mathcal{L} = -\frac{1}{4}(W^i_{\mu\nu})^2 - \frac{1}{4}(B_{\mu\nu})^2 + |D_\mu \Phi_H|^2 + \mu^2 \Phi_H^\dagger \Phi_H - \lambda(\Phi_H^\dagger \Phi_H)^2 + \bar{f}^{SM}\, i\not{D}\, f^{SM} - (y\, \bar{f}_L^{SM}\, \Phi_H\, f_R^{SM} + h.c.)$$

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

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

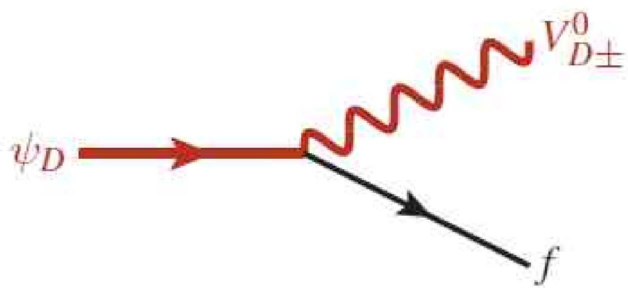
VLF portal: Z_2-even fermions – RH SM ones and VL ones – mix

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



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

$\mathbb{Z}_2$-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 $m_f < m_\psi \leq m_F$

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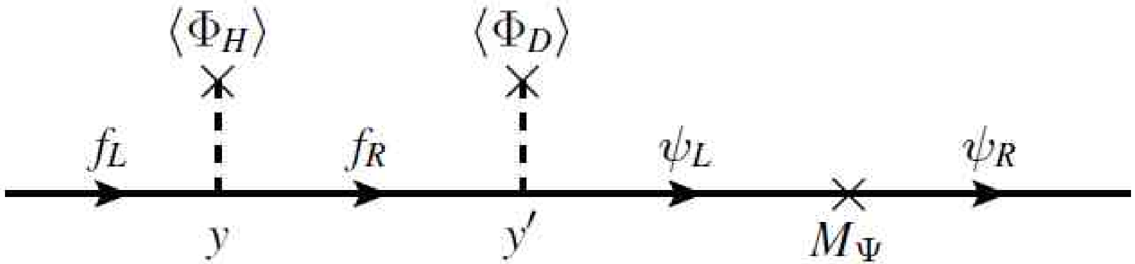

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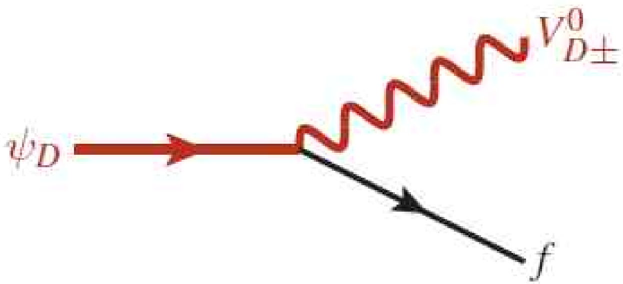

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Potential to introduce flavour structure(s) with VL fermions, including VL leptons to explain various flavour anomalies, including $(g-2)_\mu$!

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

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

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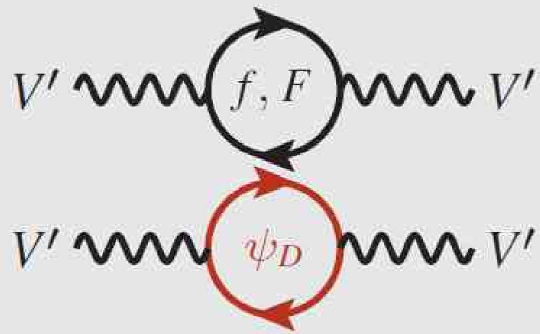
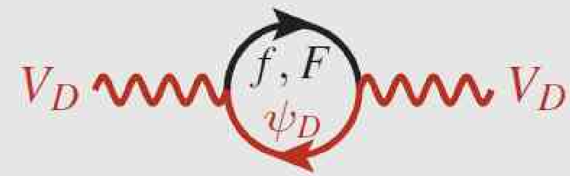
- **At loop-level:**

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





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

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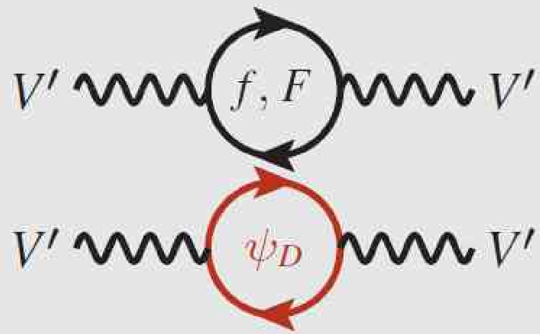

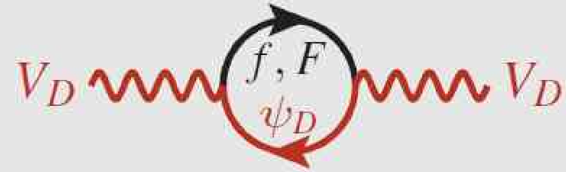

Similar diagrams appear for Kinetic mixing (backup slides)

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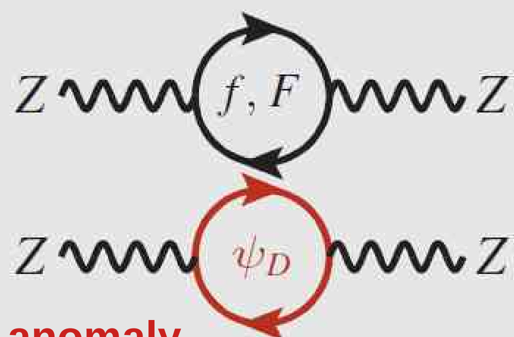
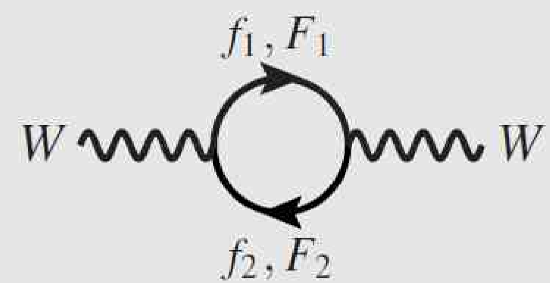
- **Effect for W/Z boson masses**

Modifications to SM
different for Z and W





Potential to explain W-boson mass anomaly

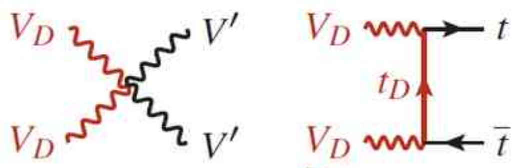
Minimal VL top portal VDM: VL top portal without higgs portal mixing

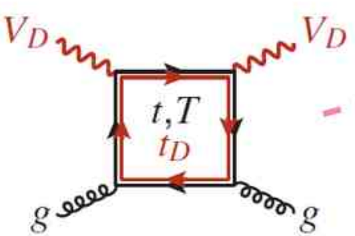
The VL fermion is composed of top partners and there is no mixing between scalars

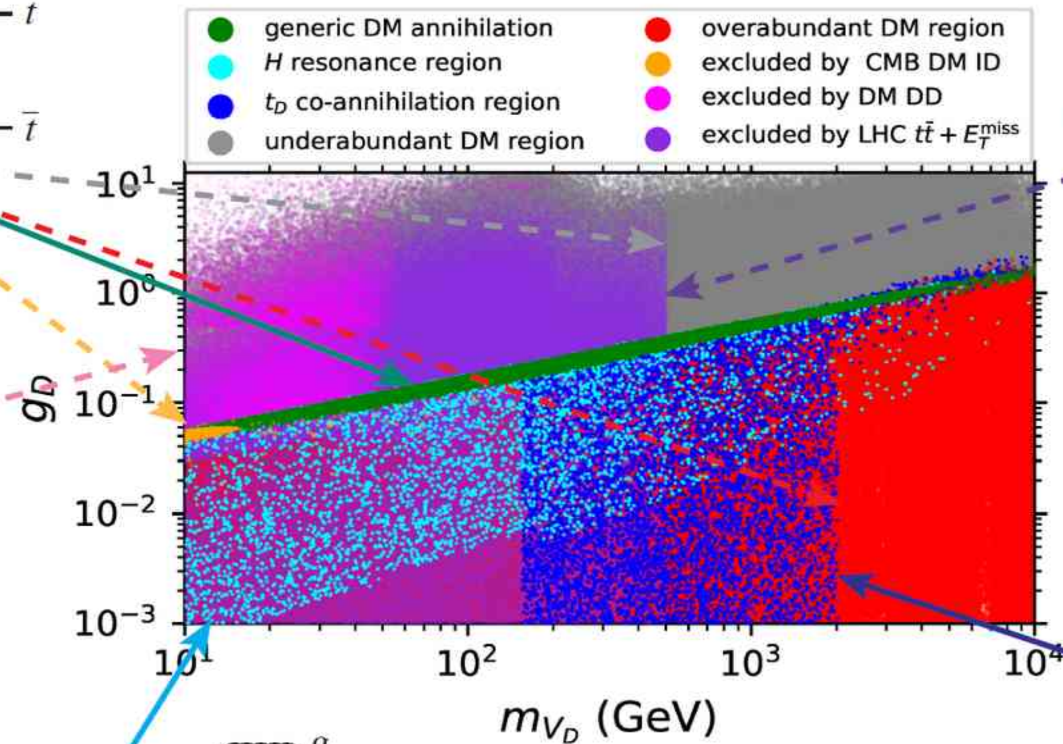
$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{t_D} \leq m_T$$

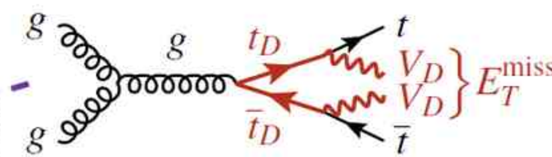
$$\sin\theta_S = 0$$

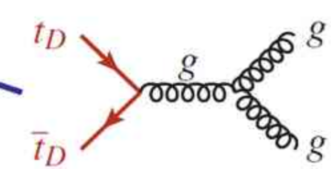
5D parameter space: $g_D, m_{V_D}, m_H, m_T, m_{t_D}$

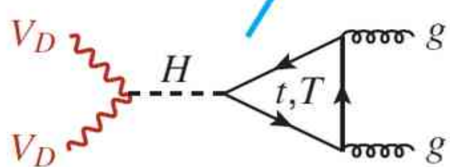






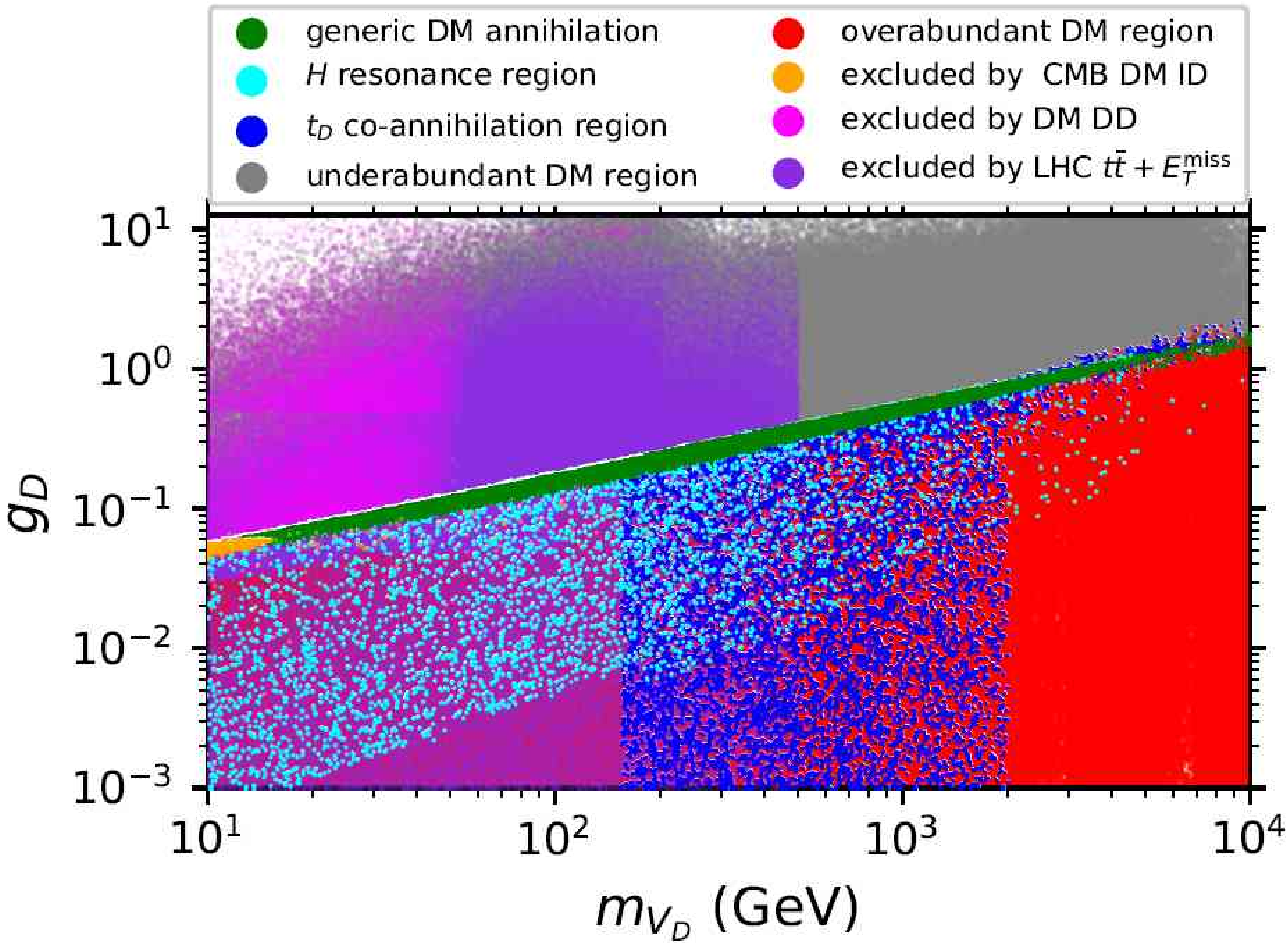






just a simple realization of the model template
multiple features and signatures

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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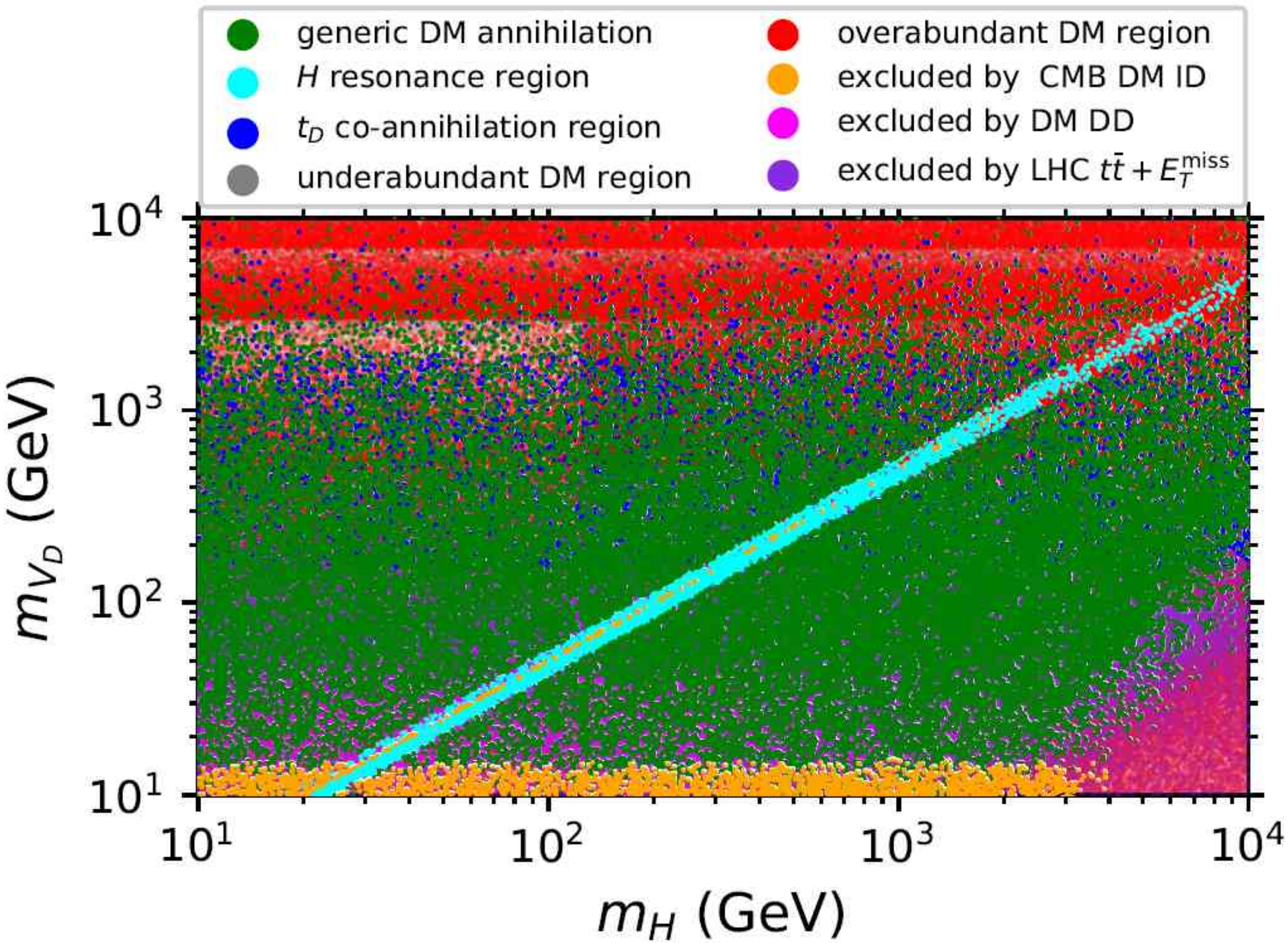

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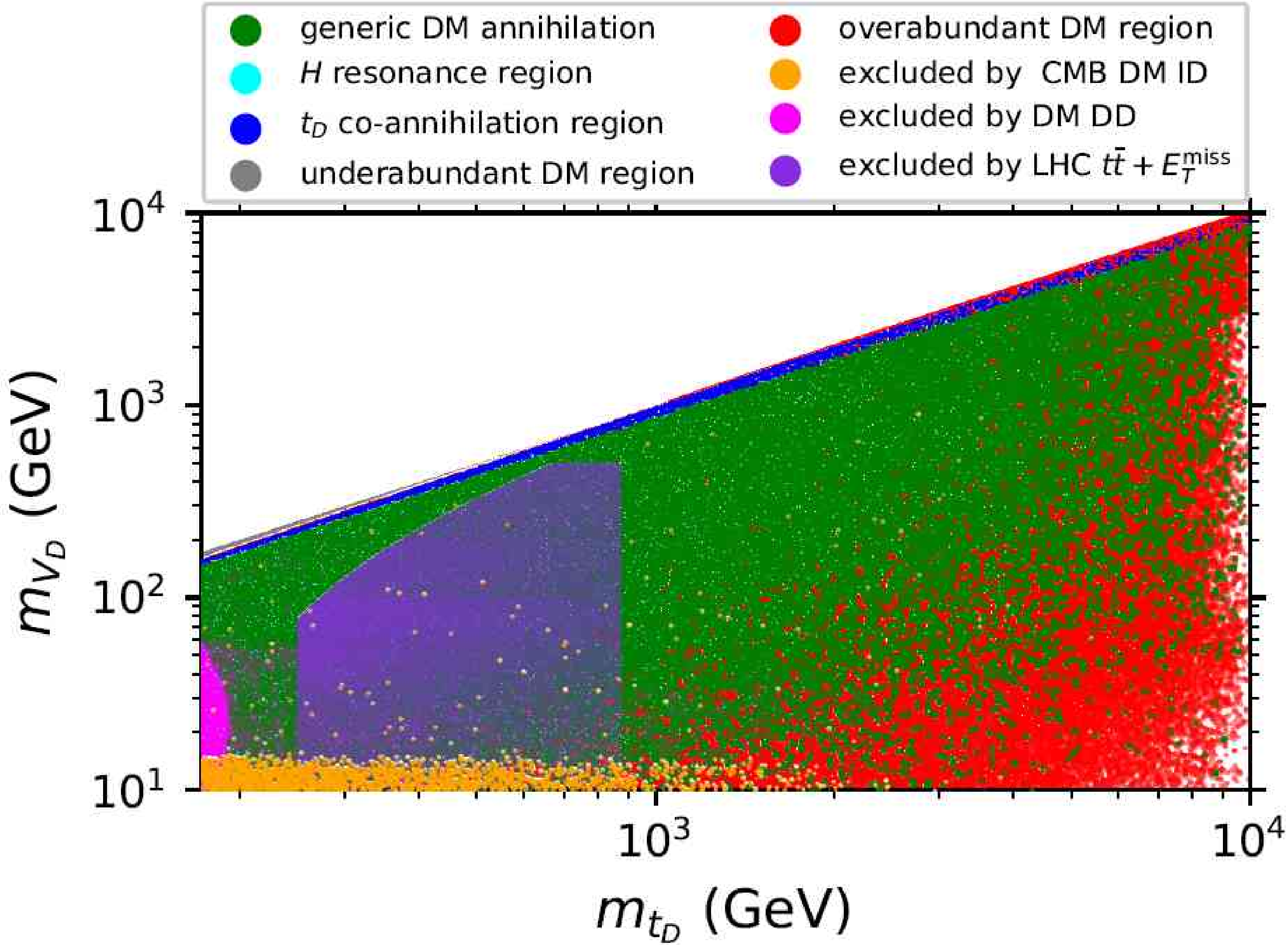
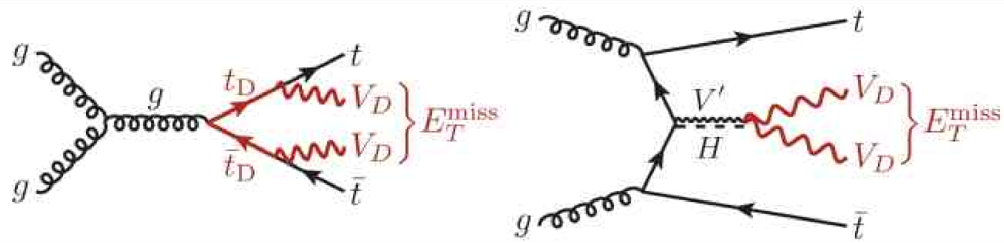
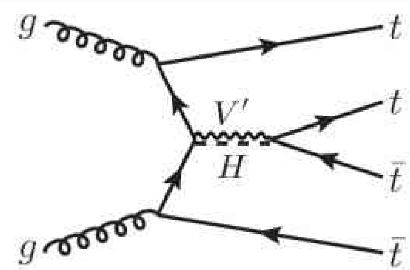
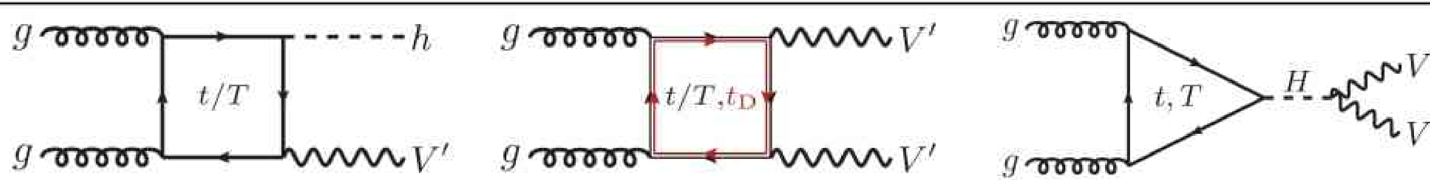


Minimal VL top portal VDM: collider signatures

Process	Representative diagrams
mono-jet (only loop)	 + jet from ISR or from loop
$t\bar{t} + E_T^{miss}$	
$t\bar{t}t\bar{t}$	
hV' and $V'V'$ (only loop)	

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

The VL fermion is composed of top partners

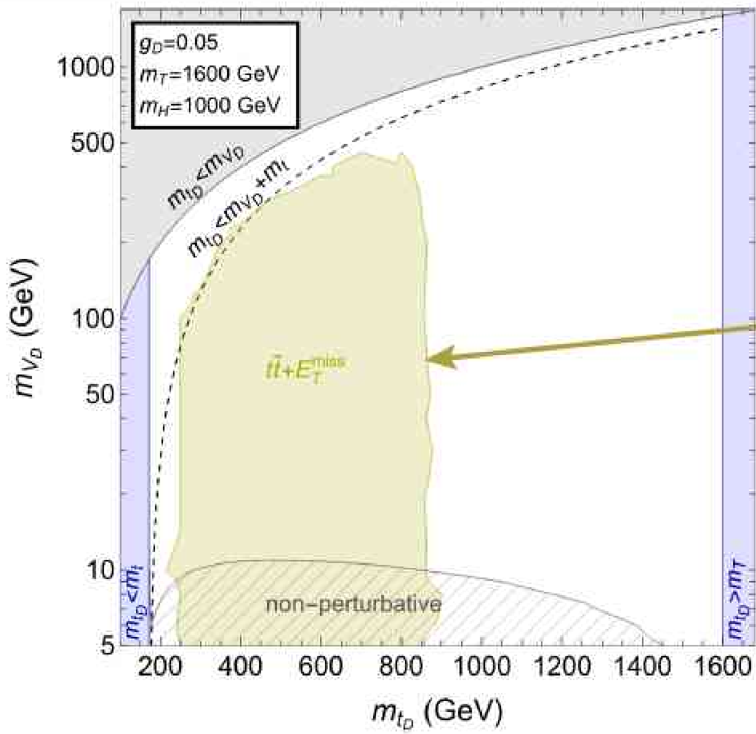
$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{t_D} \leq m_T$$

and there is no mixing between scalars

$$\sin\theta_S = 0$$

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

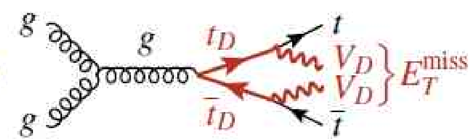
- $g_D = 0.05, 0.5$ — strong or weak cosmological constraints
- $m_T = 1600$ GeV, $m_H = 1000$ GeV — heavy enough to evade LHC constraints



Mediator mass bounded from below and above

Light DM in non-perturbative region

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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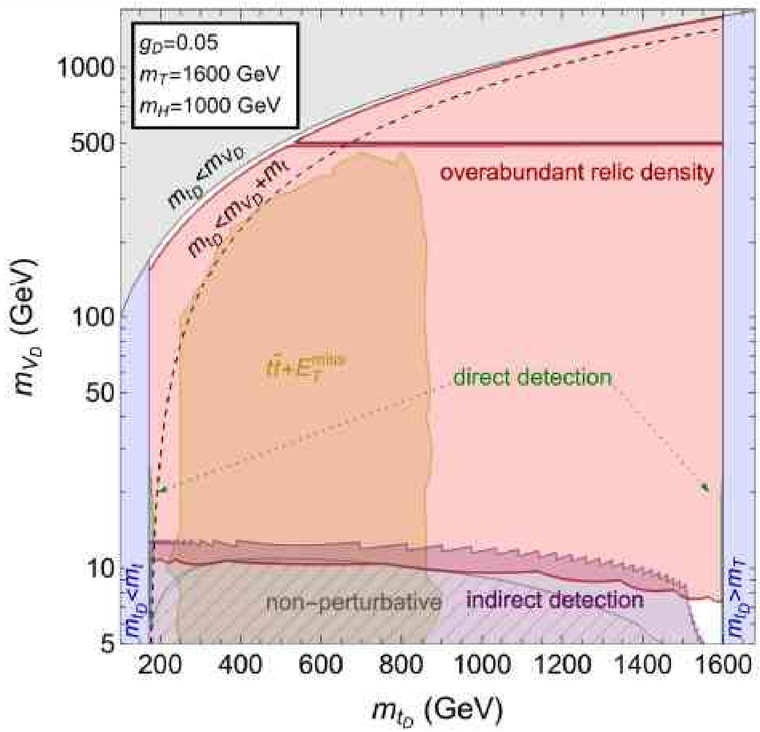

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Very weak direct detection constraints
(mostly for $m_{t_D} \sim m_t$ or $m_{t_D} \sim m_T$ and light DM)

Indirect detection constrains light DM

Strong constrain from relic density
→ the model "lives" on the red contours ($\Omega_{\rm DM}^{\rm Planck}$)

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

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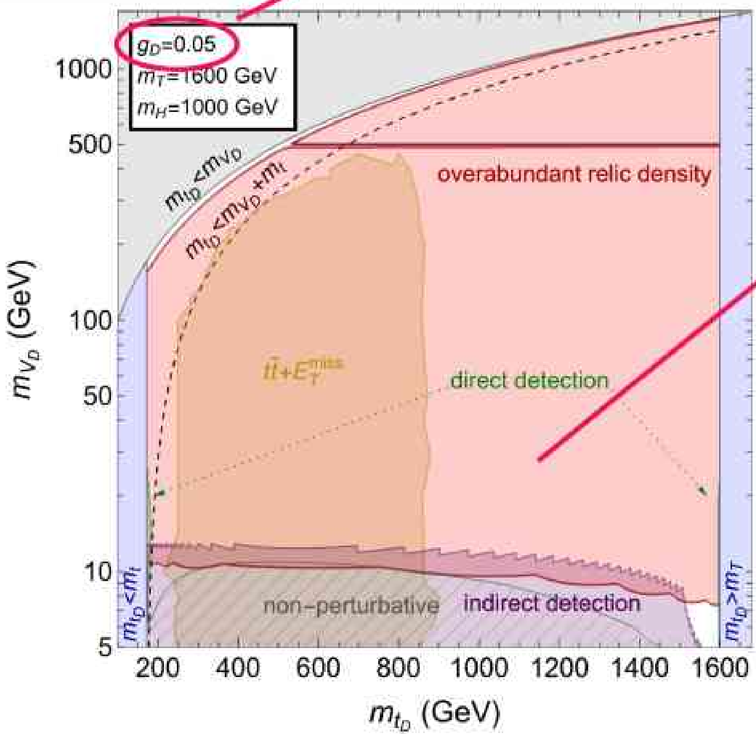

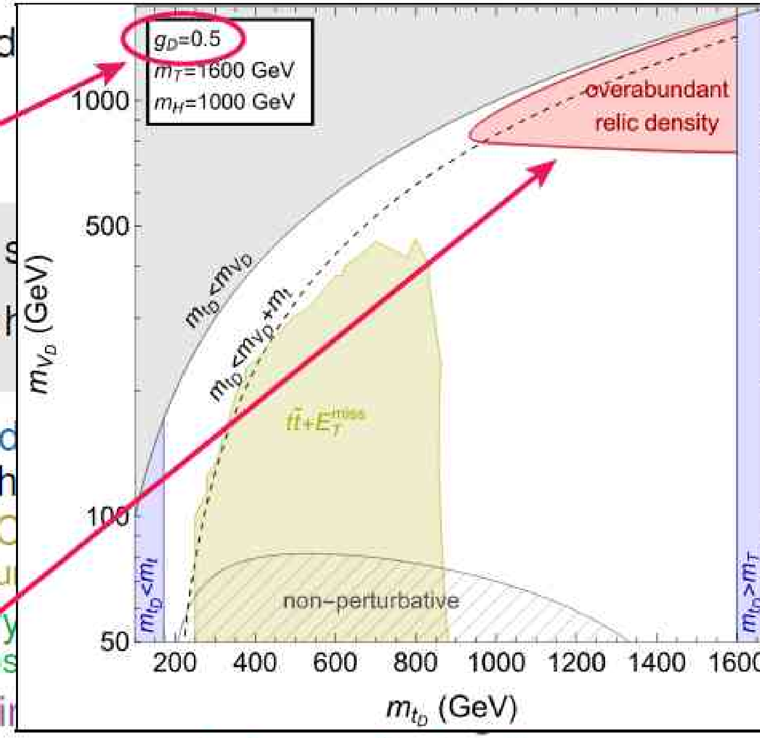

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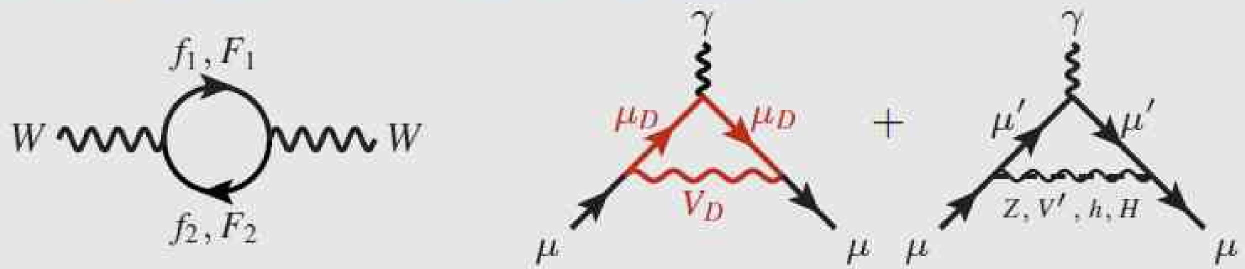
Strong constrain from relic density
→ the model “lives” on the red contours ($\Omega^{\text{Planck}}_{\text{DM}}$)
→ overabundant region shrinks for larger g_D
→ and ID constraints vanish

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 with the top sector – multiple phenomenological predictions
  - great potential to explain dark matter
  - collider signatures: tt+miss, Z', Z'H, long-lived Z'
  - great potential to explore flavour, was deliberately designed for this!

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.

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

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**

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

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

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

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

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

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

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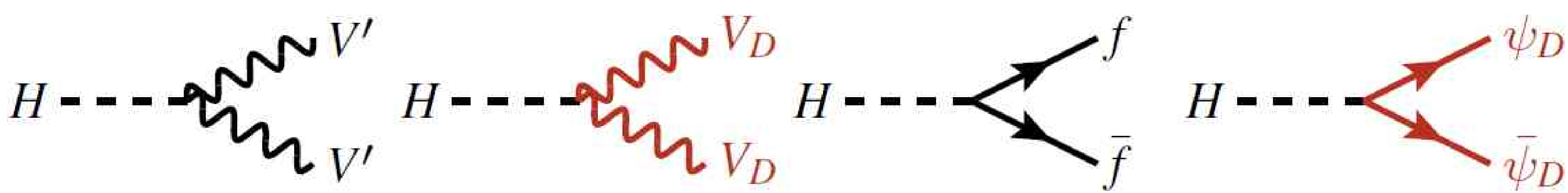
If no Higgs portal, the interactions of the new scalar H are limited to:



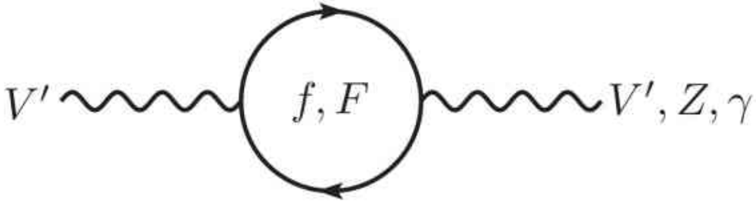
VL portal VDM: the summary of particle content

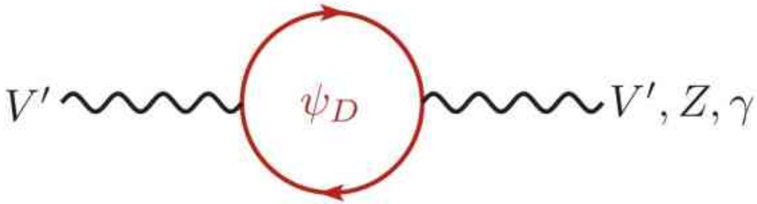
Vectors	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$W_\mu = \begin{pmatrix} W^+_\mu \\ W^3_\mu \\ W^-_\mu \end{pmatrix}$	$\mathbf{3}$	0	$\mathbf{1}$	$+$ $+$ $+$
B_μ	$\mathbf{1}$	0	$\mathbf{1}$	$+$
$V^D_\mu = \begin{pmatrix} V^0_{D+\mu} \\ V^0_{D0\mu} \\ V^0_{D-\mu} \end{pmatrix}$	$\mathbf{1}$	0	$\mathbf{3}$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

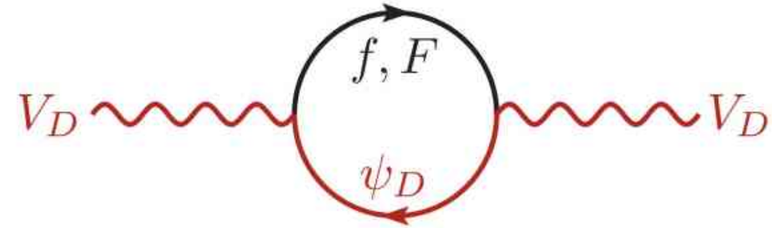
Scalars	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$\Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$\mathbf{2}$	$1/2$	$\mathbf{1}$	$+$
$\Phi_D = \begin{pmatrix} \varphi^0_{D+\frac{1}{2}} \\ \varphi^0_{D-\frac{1}{2}} \end{pmatrix}$	$\mathbf{1}$	0	$\mathbf{2}$	$-$ $+$

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, ν^{SM}_R	$\mathbf{1}$	$\frac{2}{3}, 0$	$\mathbf{1}$	$+$
d^{SM}_R, ℓ^{SM}_R	$\mathbf{1}$	$-\frac{1}{3}, -1$	$\mathbf{1}$	$+$
$\Psi = \begin{pmatrix} \psi^D \\ \psi \end{pmatrix}$	$\mathbf{1}$	Q	$\mathbf{2}$	$-$ $+$

Kinetic Mixing in FPVDM models





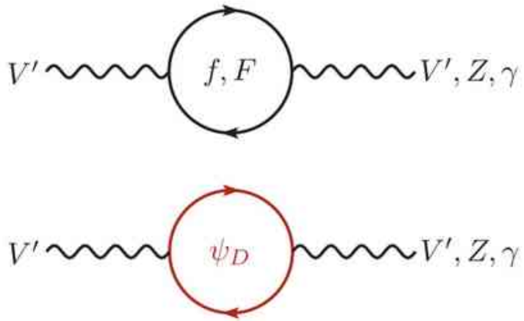


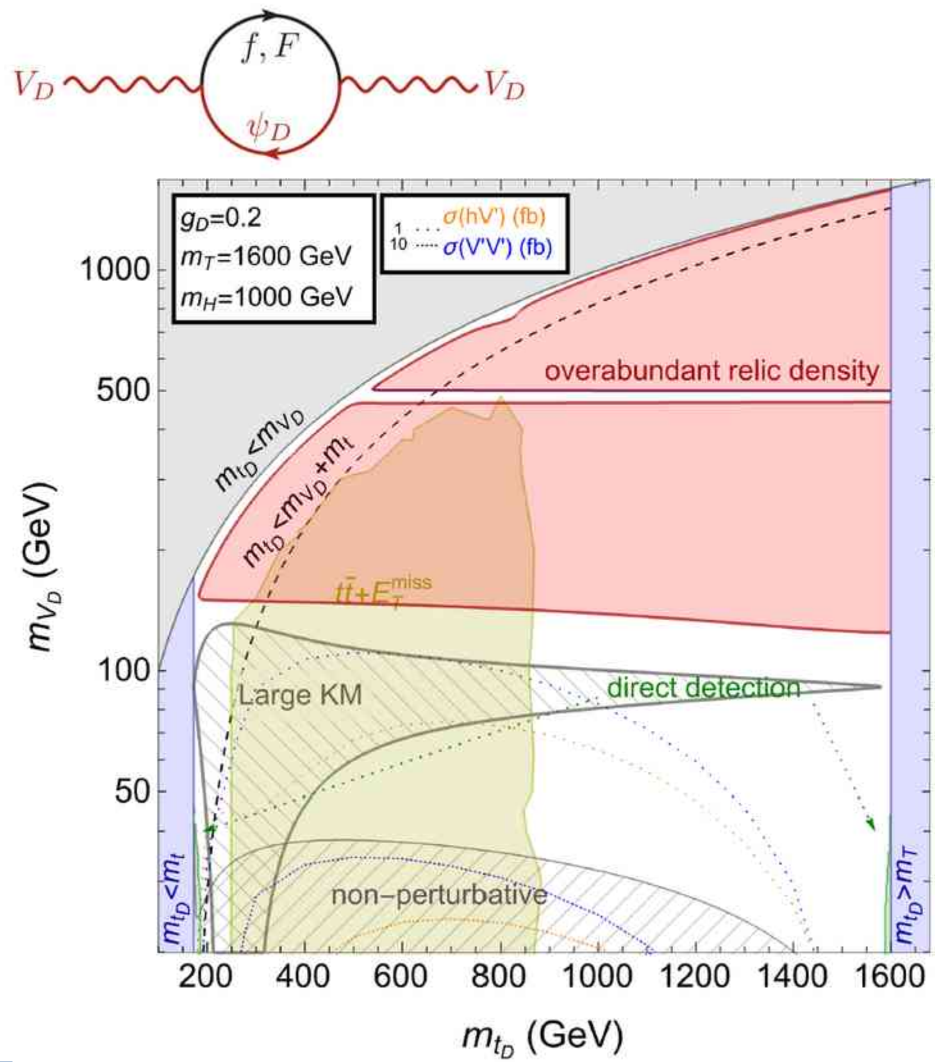
$$\epsilon_{ZV} = \frac{g g_D}{16\pi^2 c_w}\left(\mathcal{F}^{ZV}_{qT1+qL}(r_f, r_{\psi_D}) + Q_f s_W^2 \mathcal{F}^{ZV}_{qT2}(r_f, r_{\psi_D})\right)$$

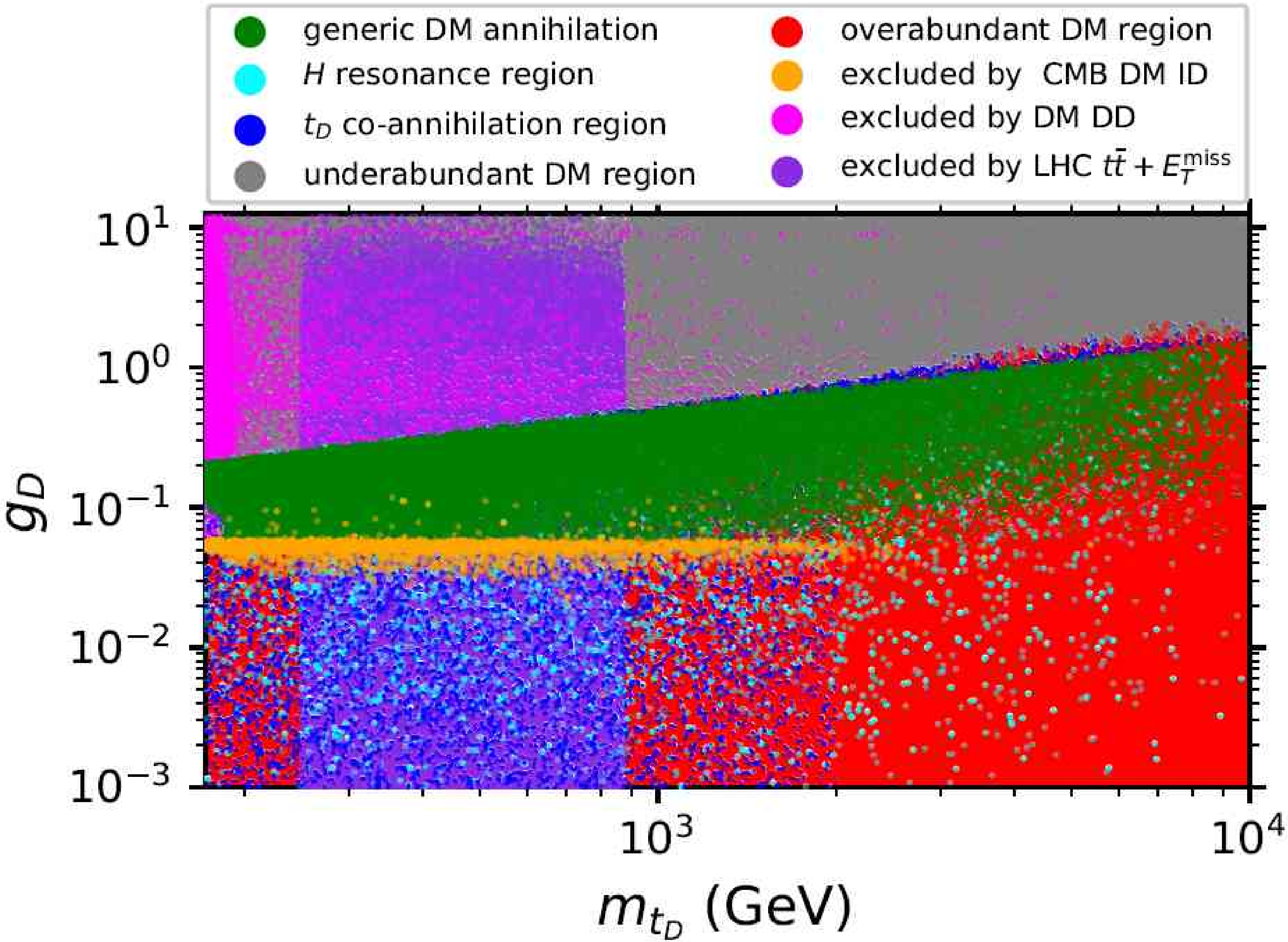
$$V^{\rm KM} = \begin{pmatrix} 1 & 0 & -\frac{\epsilon_{AV}}{\sqrt{1-\epsilon_{AV}^2-\epsilon_{ZV}^2}} \\ 0 & 1 & -\frac{\epsilon_{ZV}}{\sqrt{1-\epsilon_{AV}^2-\epsilon_{ZV}^2}} \\ 0 & 0 & \frac{1}{\sqrt{1-\epsilon_{AV}^2-\epsilon_{ZV}^2}} \end{pmatrix}$$

$$\epsilon_{AV} = \frac{g_D e Q_f}{4\pi^2}\mathcal{F}^{AV}(r_f, r_{\psi_D})$$

Kinetic Mixing in FPVDM models





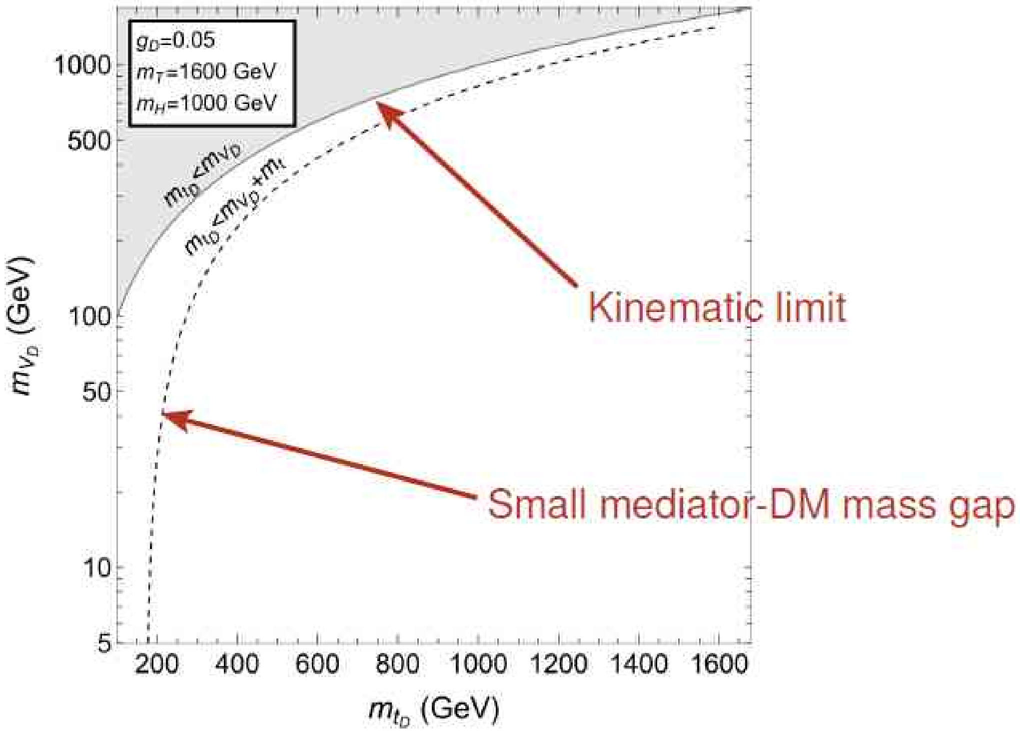

generic DM annihilation
H resonance region
t_D co-annihilation region
underabundant DM region
overabundant DM region
excluded by CMB DM ID
excluded by DM DD
excluded by LHC $t\bar{t} + E_T^{miss}$
g_D
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^3
10^4
m_{t_D} (GeV)

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

$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{t_D} \leq m_T \qquad\qquad \sin\theta_S = 0$$

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



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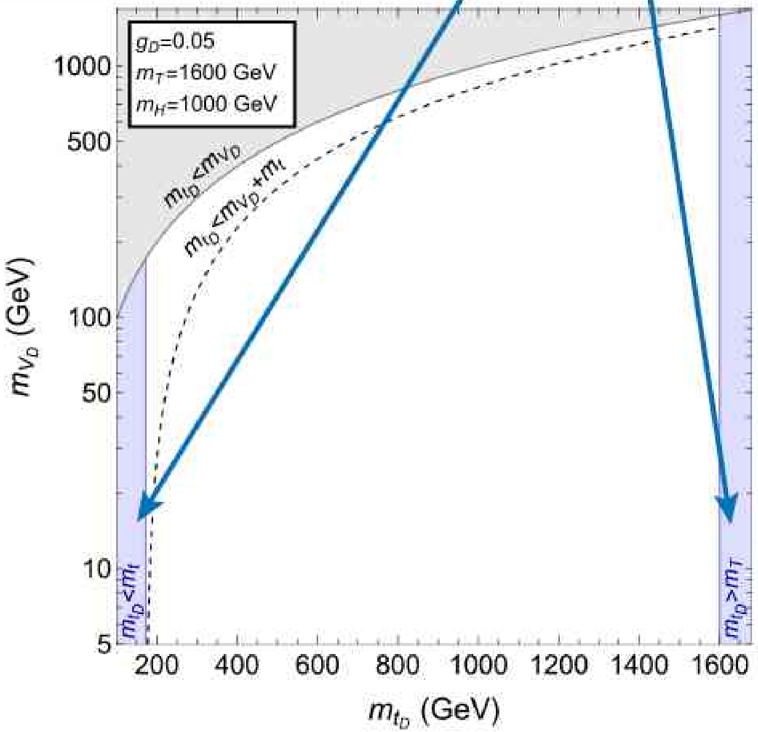
(m_T, m_H:) heavy enough to evade LHC constraints



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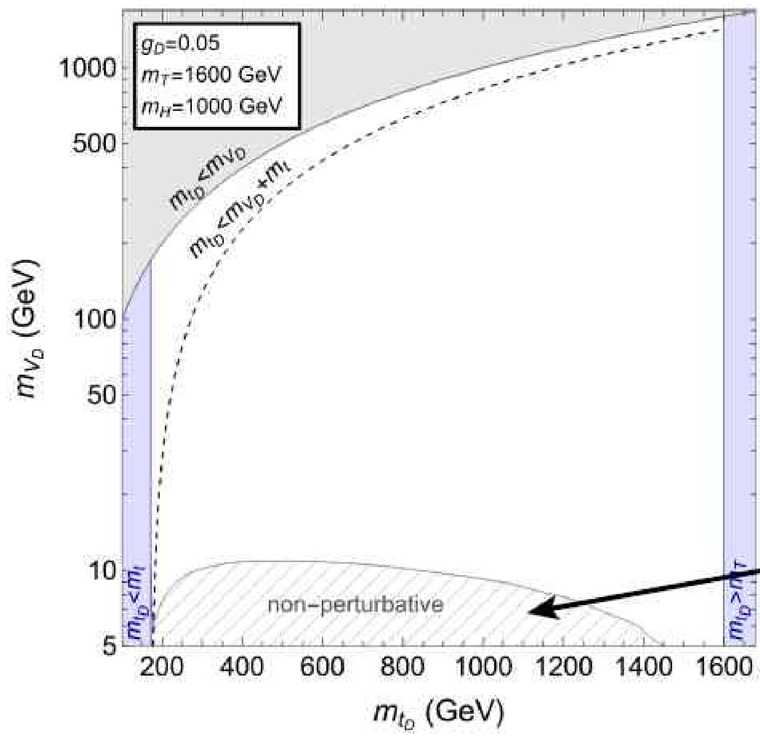
m_T and m_H: heavy enough to evade LHC constraints



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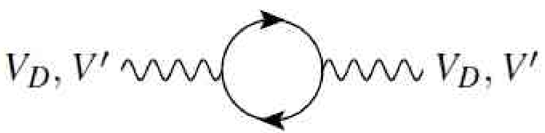

$$\frac{m_V^{\text{pole}} - m_V}{m_V} > 50\%$$

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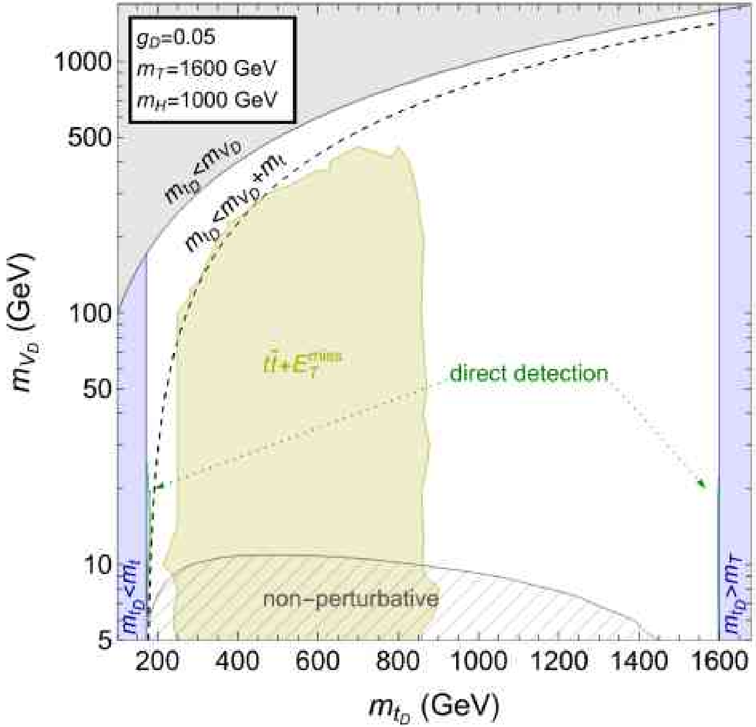

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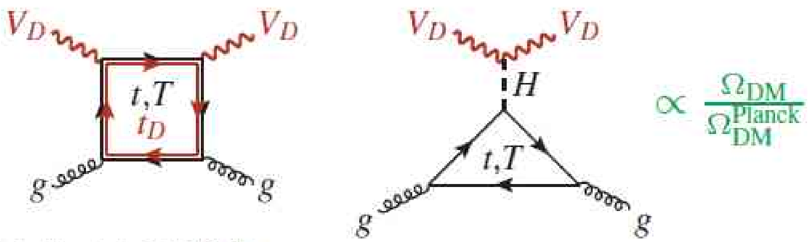

E. Aprile *et al.* [XENON],
Dark Matter Search Results from a One Ton-Year Exposure of XENON1T,
Phys. Rev. Lett. **121** (2018) no.11, 111302, arXiv:1805.12562 [astro-ph.CO]

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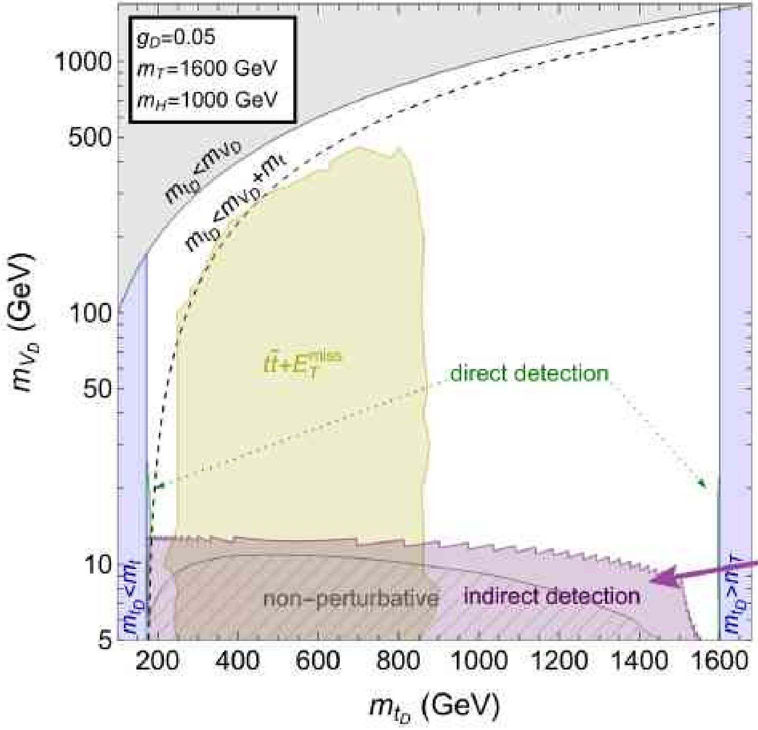

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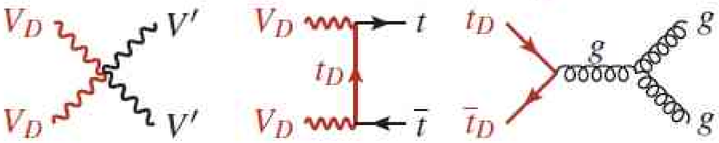
Indirect detection constrains light DM



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

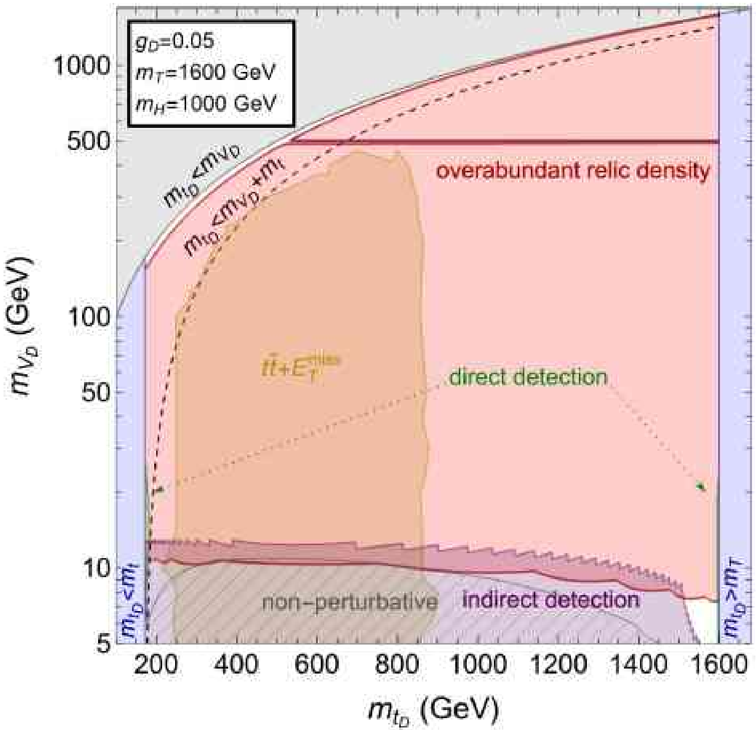
N. Aghanim *et al.* [Planck], **Planck 2018 results. VI. Cosmological parameters,** Astron. Astrophys. **641** (2020), A6, arXiv:1807.06209 [astro-ph.CO]

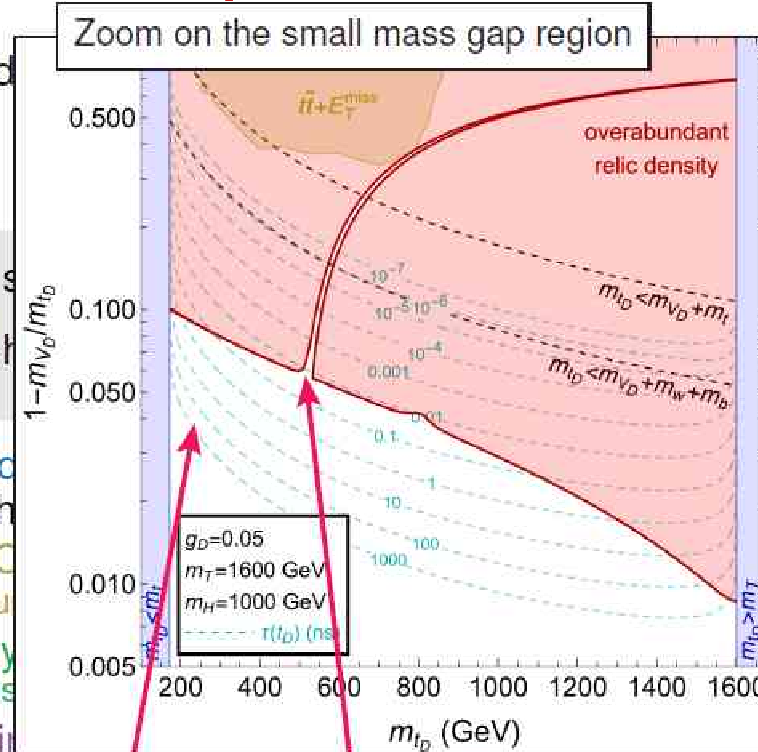
Minimal VL top portal VDM: details of 2D space for chosen benchmarks

The VL fermion is composed of top partners and

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

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





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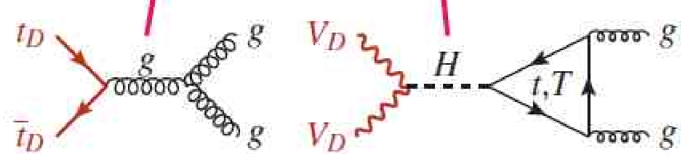
Strong constrain from relic density

→ the model "lives" on the red contours (Ω_{DM}^{Planck})

→ overabundant region shrinks for larger g_D

→ and ID constraints vanish

→ effective (co-)annihilation processes



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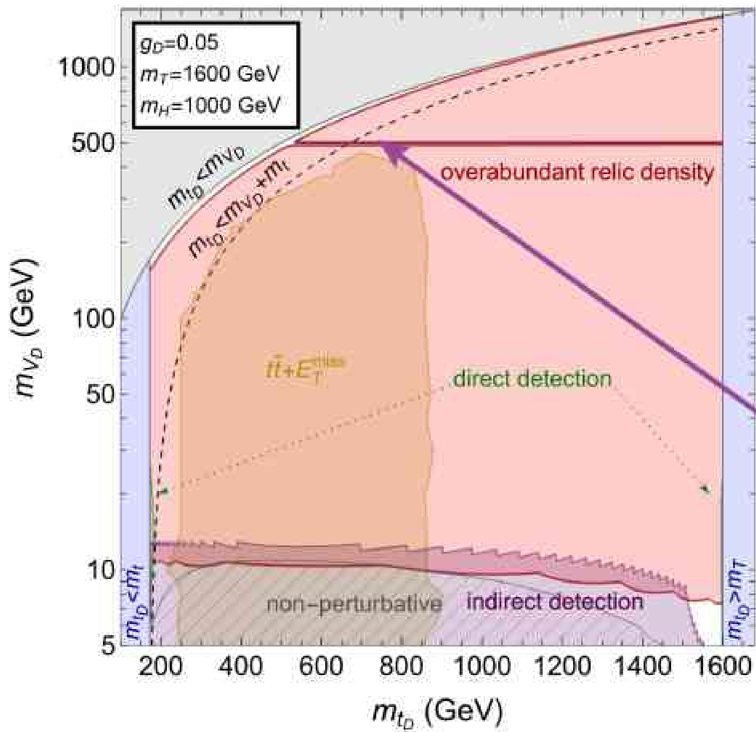

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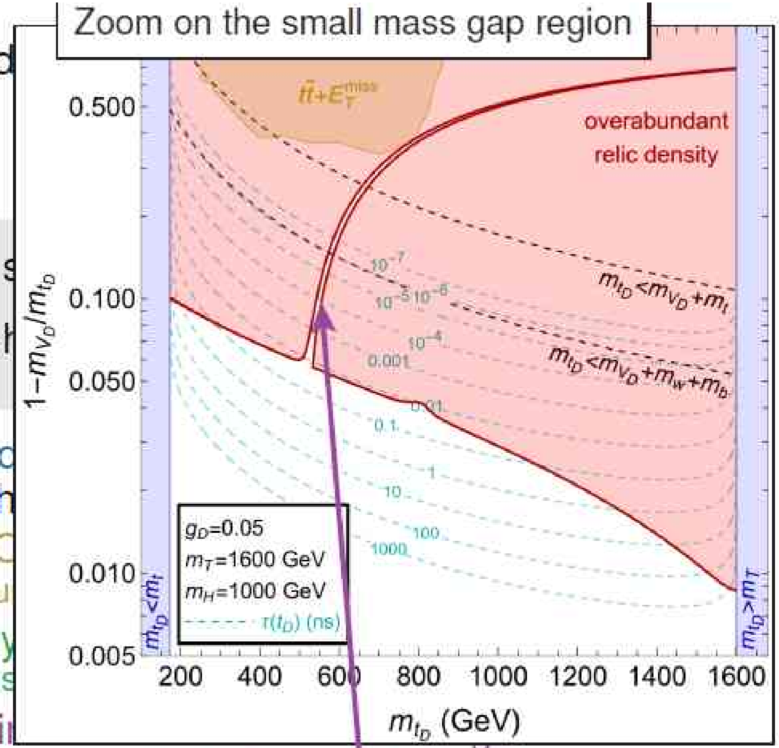

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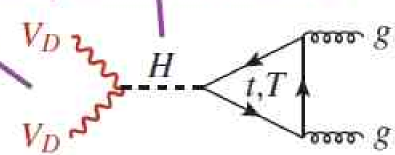

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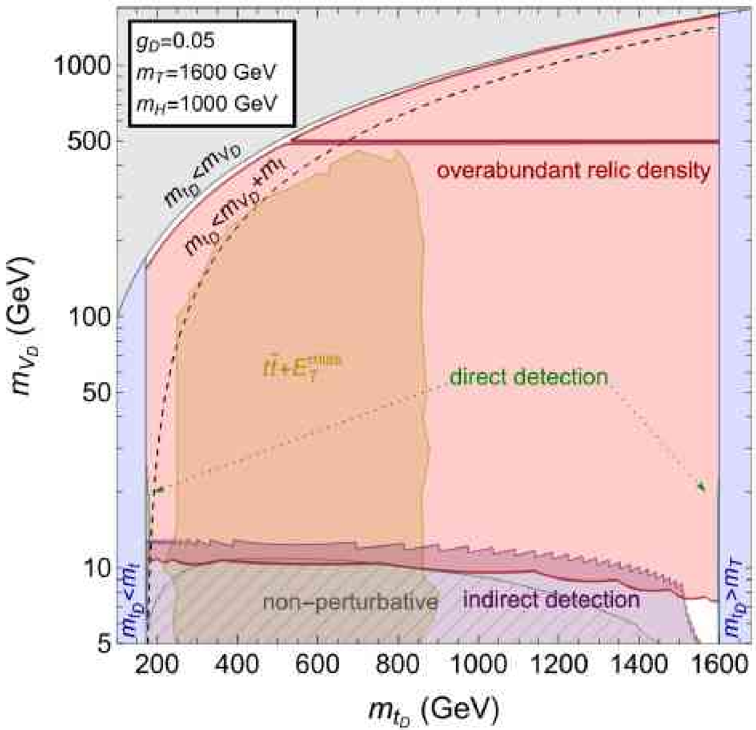

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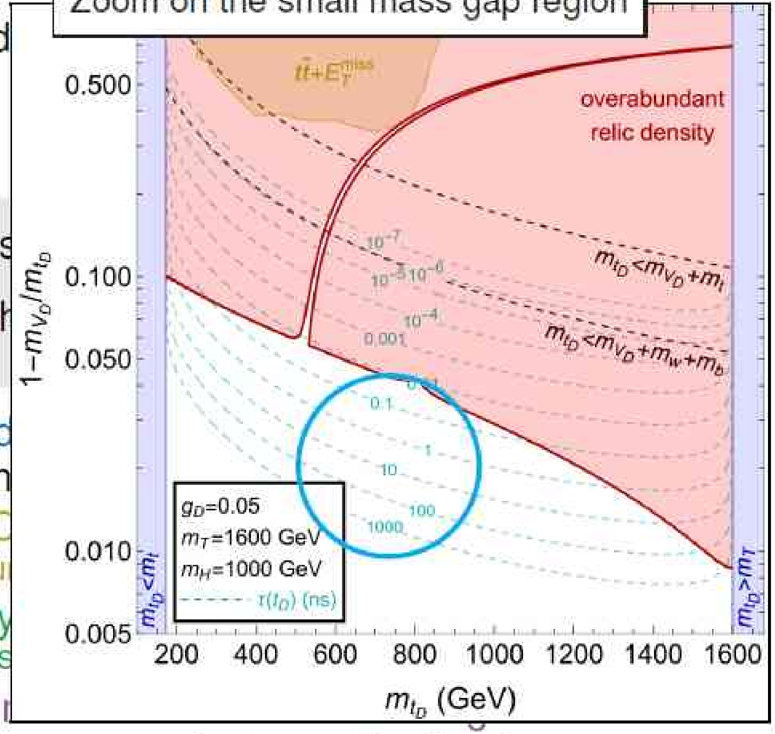
Zoom on the small mass gap region



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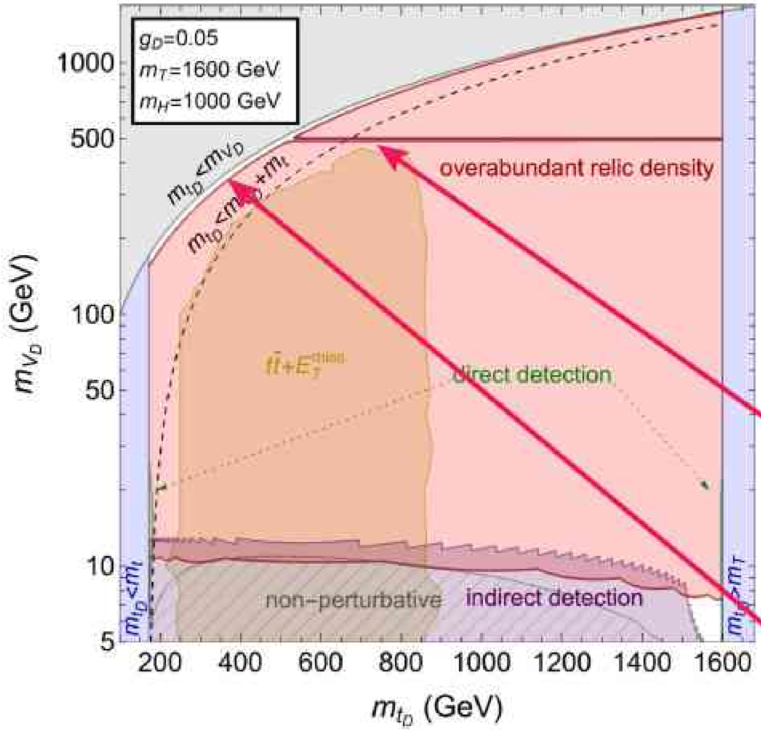
The mediator t_D can be long lived

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

$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{t_D} \leq m_T \qquad\qquad \sin\theta_S = 0$$

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



- Mediator mass bounded from below and above
- Light DM in non-perturbative region
- 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)
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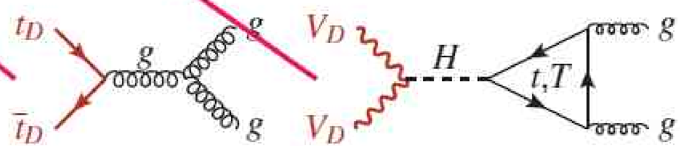
  - → the model "lives" on the red contours ($\Omega_{\rm DM}^{\rm Planck}$)
  - → overabundant region shrinks for larger g_D
    - → and ID constraints vanish
  - → effective (co-)annihilation processes



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

The VL fermion is composed of top partners an… …tween scalars

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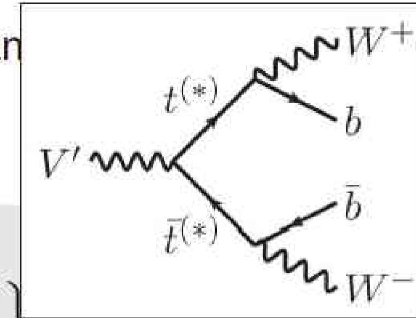

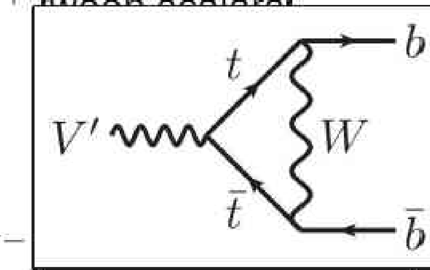

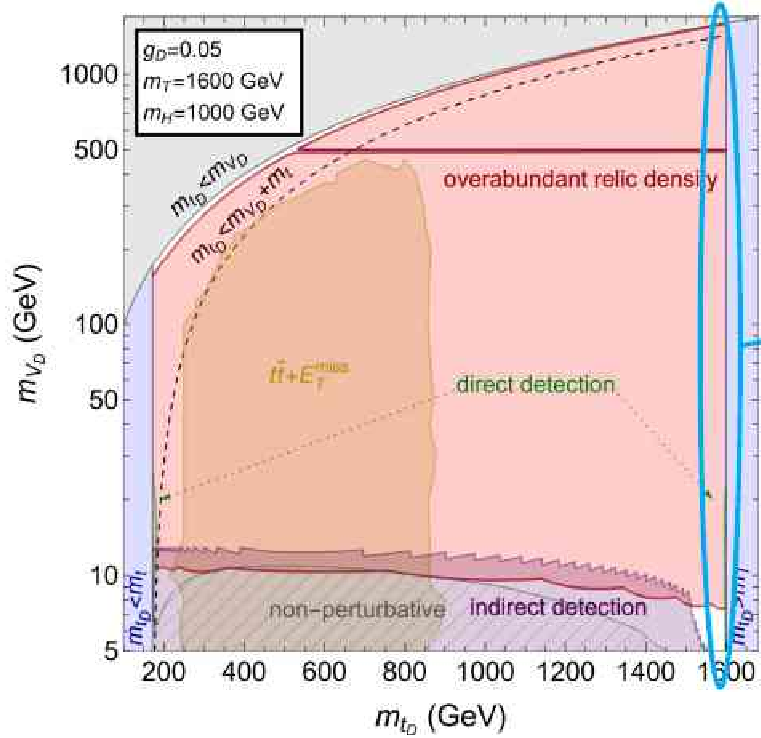

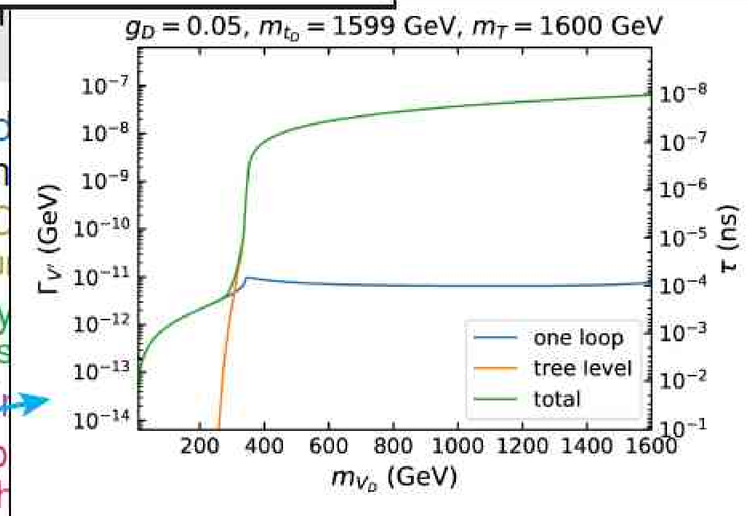

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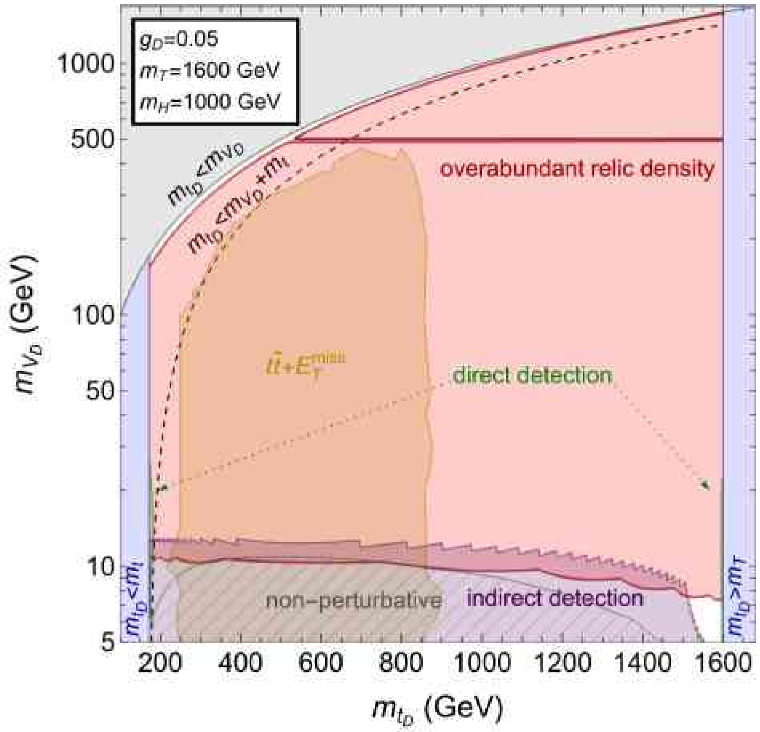
- $g_D = 0.05, 0.5$: strong or weak cosmological constraints
- $m_T = 1600$ GeV, $m_H = 1000$ GeV: heavy enough to evade LHC constraints



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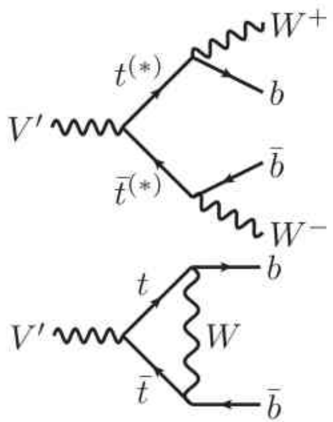
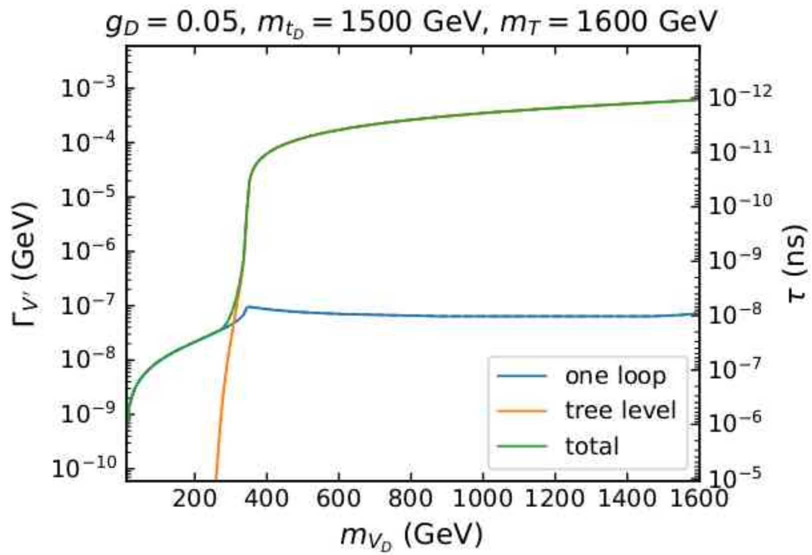
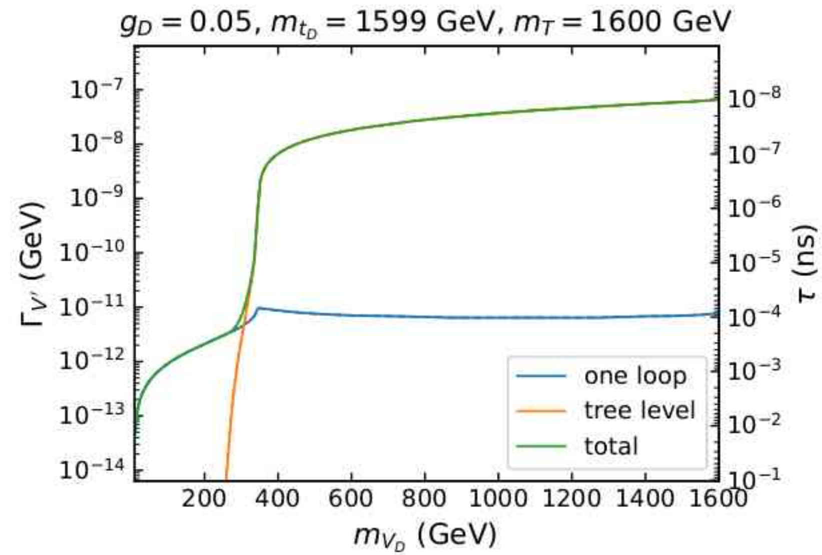
just a simple realization of the model template
multiple features and signatures


W^+
$t^{(*)}$
b
V'
$\bar{b}$
$\bar{t}^{(*)}$
W^-
b
t
V'
W
$\bar{t}$
$\bar{b}$


$g_D = 0.05$, $m_{t_D} = 1500$ GeV, $m_T = 1600$ GeV
$\Gamma_{V'}$ (GeV)
τ (ns)
m_{V_D} (GeV)
one loop
tree level
total


$g_D = 0.05$, $m_{t_D} = 1599$ GeV, $m_T = 1600$ GeV
$\Gamma_{V'}$ (GeV)
τ (ns)
m_{V_D} (GeV)
one loop
tree level
total