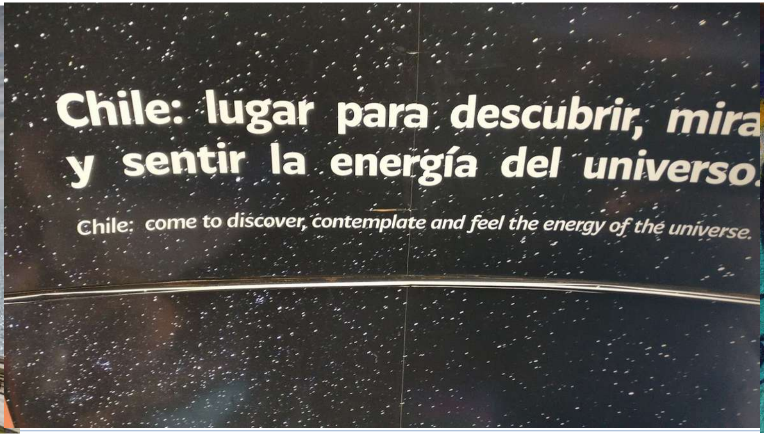
Vector Dark Matter via a Fermionic Portal from a New Gauge Sector

Alexander Belyaev

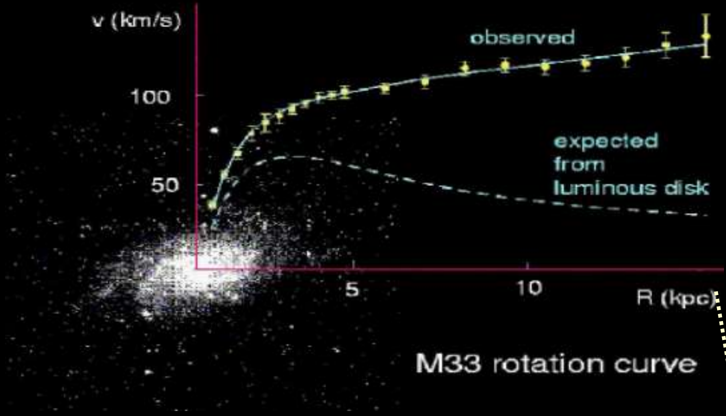
Southampton University & Rutherford Appleton Laboratory

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

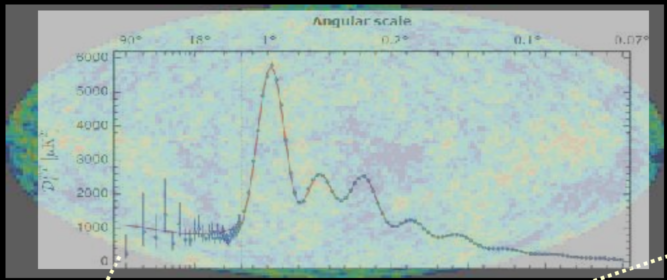


The existence of Dark Matter is confirmed by several independent observations at cosmological scale

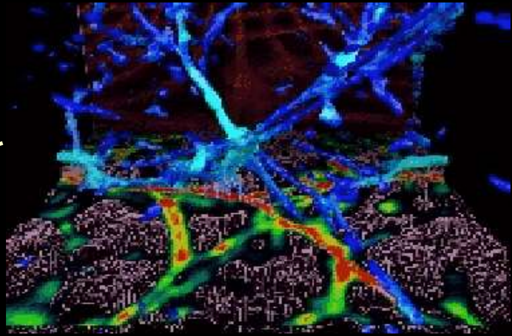
Galactic rotation curves

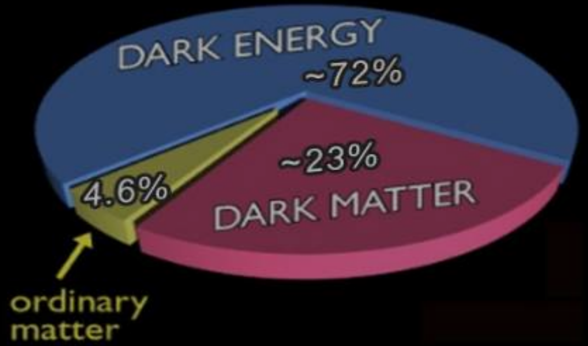


CMB: WMAP and PLANCK



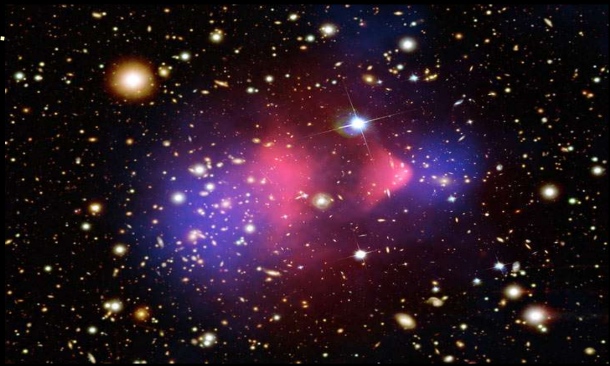
Large Scale Structures





Gravitational lensing

Bullet cluster



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

Spin ?

Mass ?

Stable

Yes ? No ?

symmetry behind stability ?

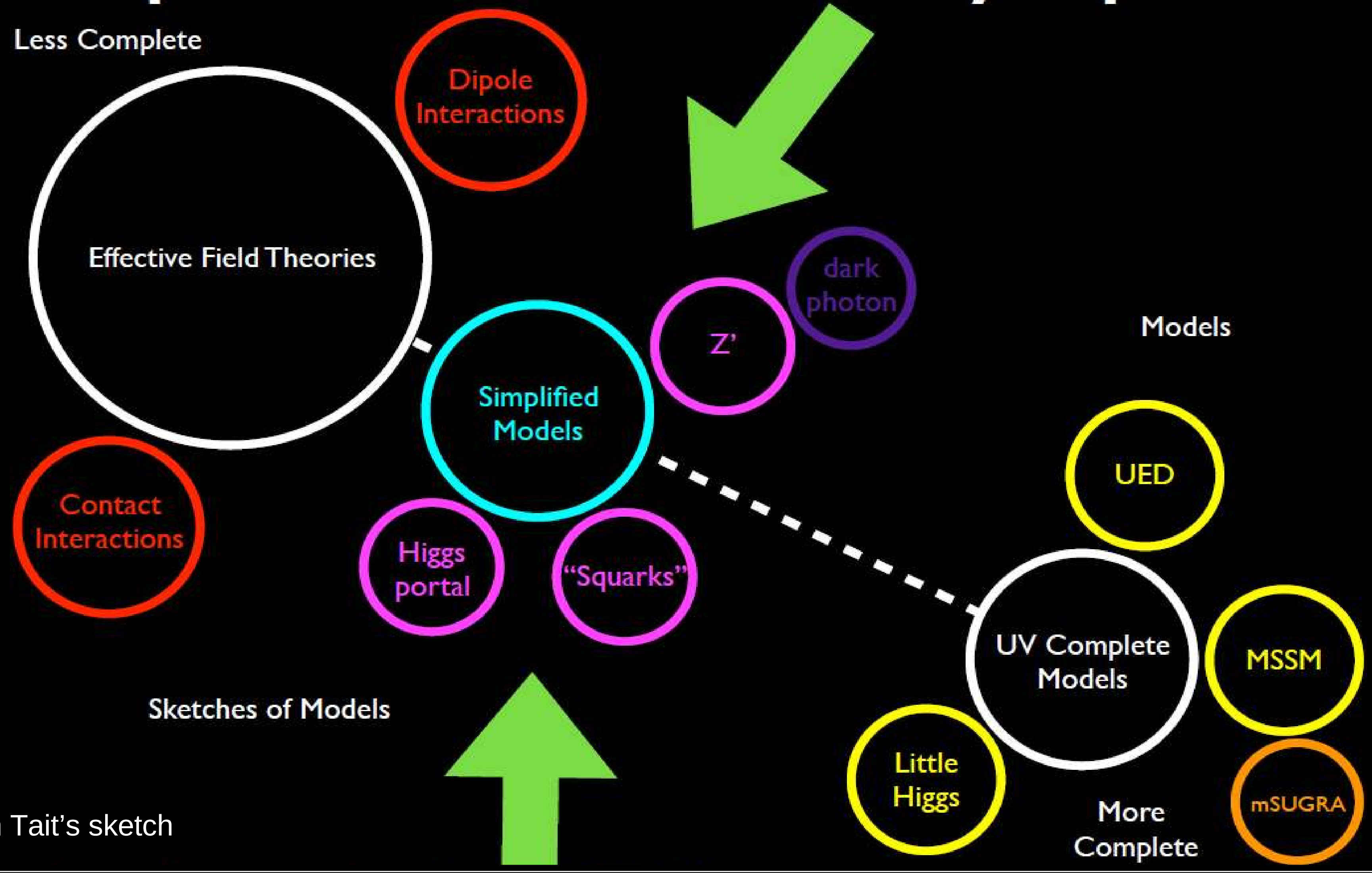
Couplings

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

Thermal relic

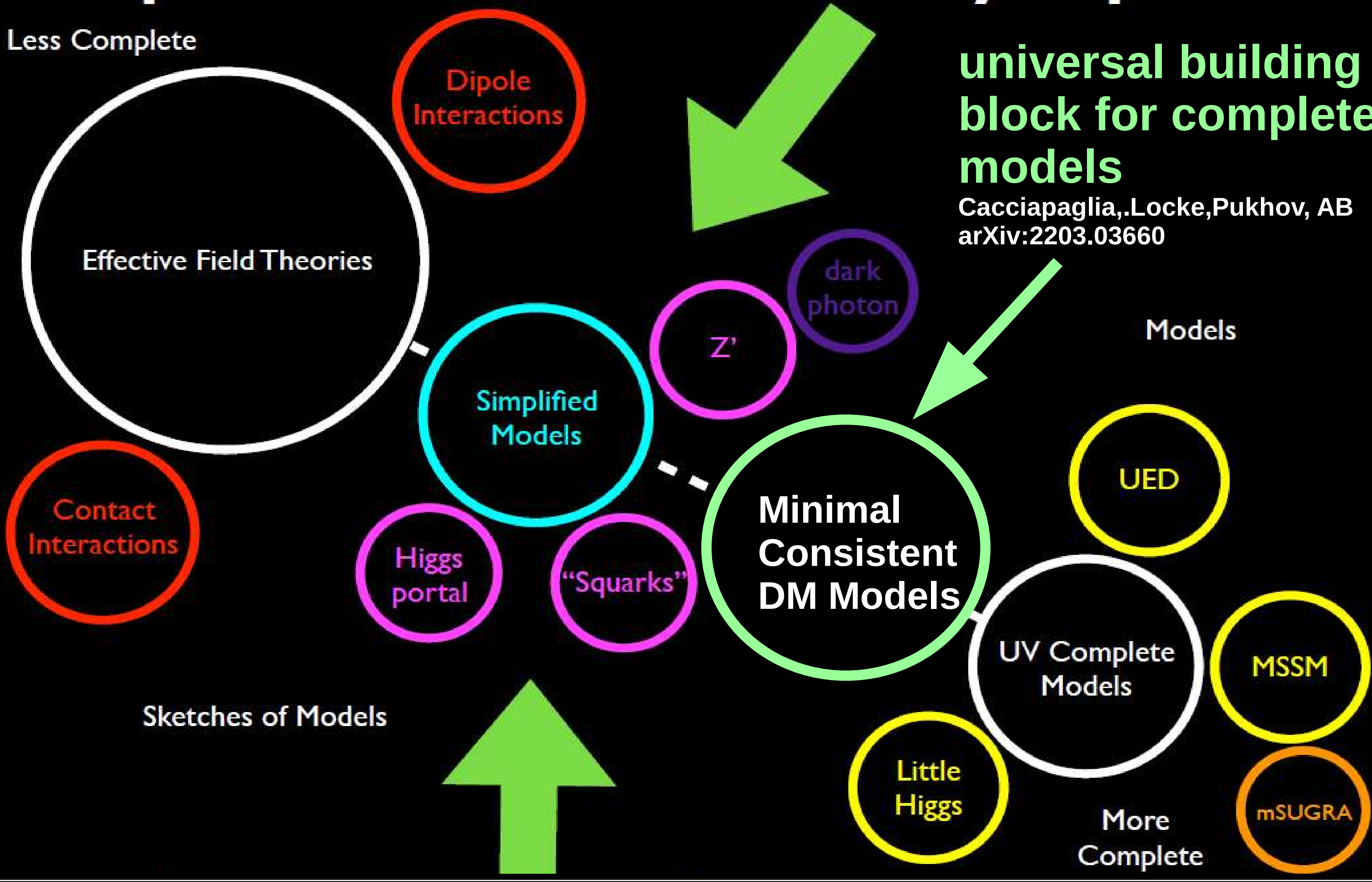
Yes ? No ?

Spectrum of Theory Space

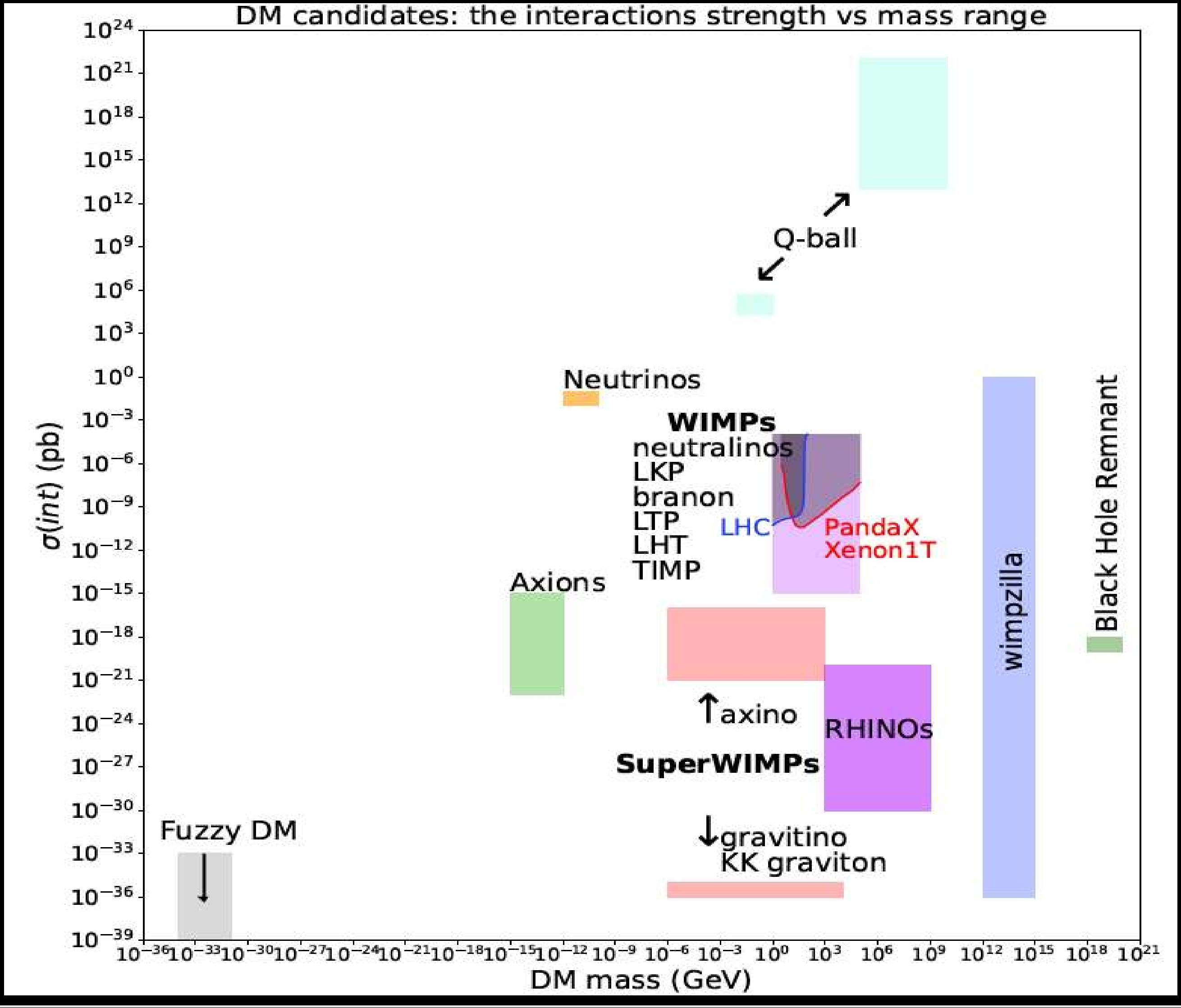


Tim Tait's sketch

Spectrum of Theory Space



DM candidates: interaction vs mass



Planck mass BH remnants: tiny black holes protected by gravity effects [Chen '04] from decay via Hawking radiation

Wimpzillas: very massive non-thermal WIMPs [Kolb,Chung,Riotto'98]

Q-balls: topological solitons that occur in QFT [Coleman '86]

EW scale WIMPs, protected by parity – LSP, LKP, LTP particles

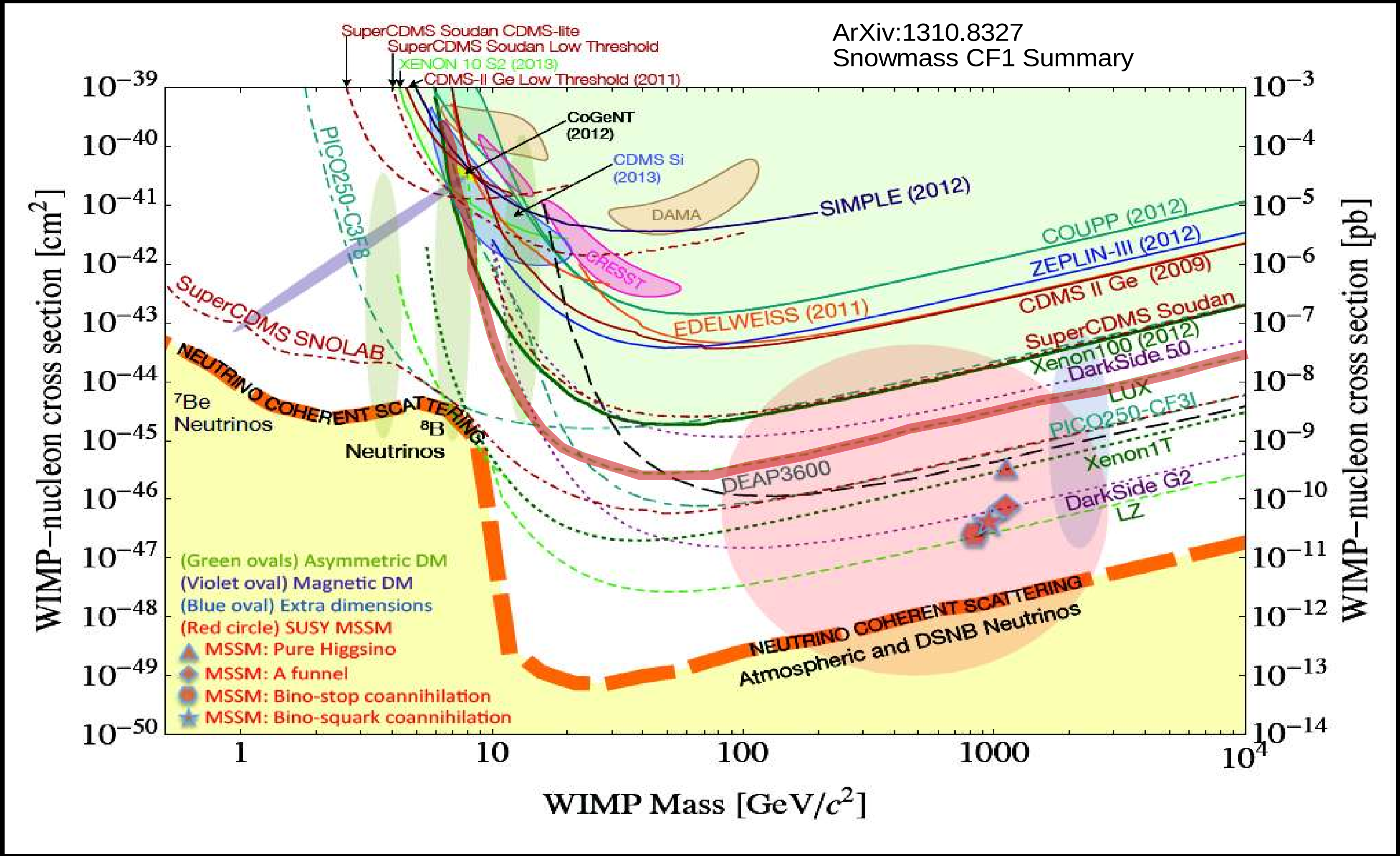
SuperWIMPs: electrically and color neutral DM interacting with much smaller strength (perhaps only gravitationally)

Neutrinos: usual neutrinos are too light-HDM, subdominant component only (to be consistent with large scale structures); but heavier gauge singlet neutrinos can be CDM

Axions: $\frac{\theta_{QCD}}{32pi^2} F^{\mu\nu} \tilde{F}^{\mu\nu}$

θ_{QCD} is replaced by a quantum field, the potential energy allows the field to relax to near zero strength, axion as a consequence

Direct DM search: testing DM interactions rate versus mass



- Improvements in technology have given impressive limits on properties of DM
- But nothing conclusive yet … However DM can be around the corner !

DM Observables: the power of WIMP

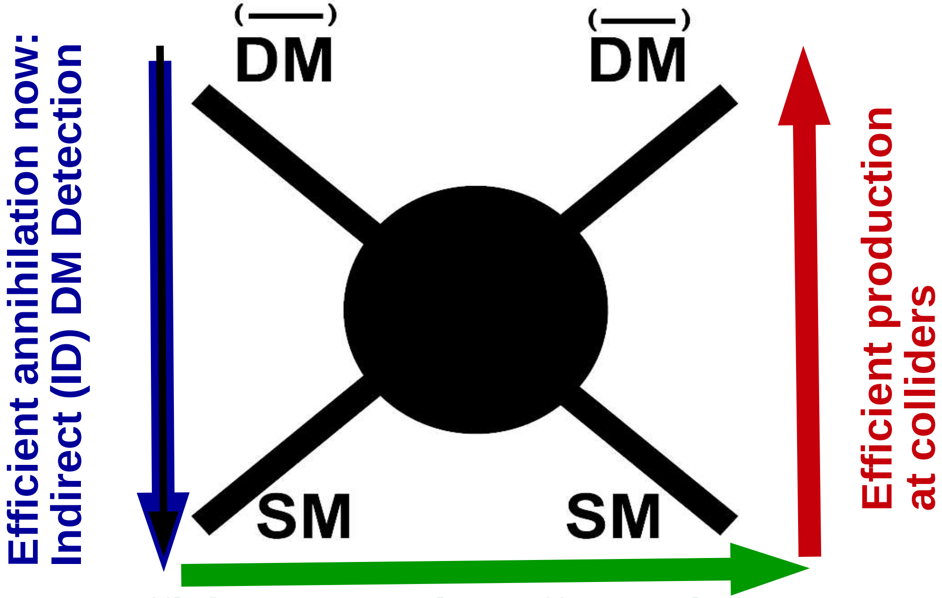
Correct Relic density: efficient (co) annihilation
WMAP, Planck ; annihilation to photons can affect CMB

Signatures from neutralino annihilation in halo, core of the Earth and Sun

- **photons,**
- **Anti-protons**
- **positrons,**
- **Neutrinos**

Neutrino telescopes:

- **Amanda**
- **Icecube**
- **Antares**



Efficient scattering off nuclei:
DM Direct Detection (DD)

Signature from energy deposition from nuclei recoil: LUX, XENON, WARP,

LHC signatures

- **mono-jet**
- **mono-photon**
- **mono-Z**
- **mono Higgs**

- **VBF+MET**
- **soft leptons+MET**
- **....**

Note: there is no 100%correlation between signatures above. For example, the high rate of annihilation does not always guarantee high rate for DD!

Actually there is a great complementarity in this:

- **In case of NO DM Signal – we can efficiently exclude DM models**
- **In case of DM signal – we can efficiently determine the nature of DM**

Vector DM

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

Vector DM

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

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

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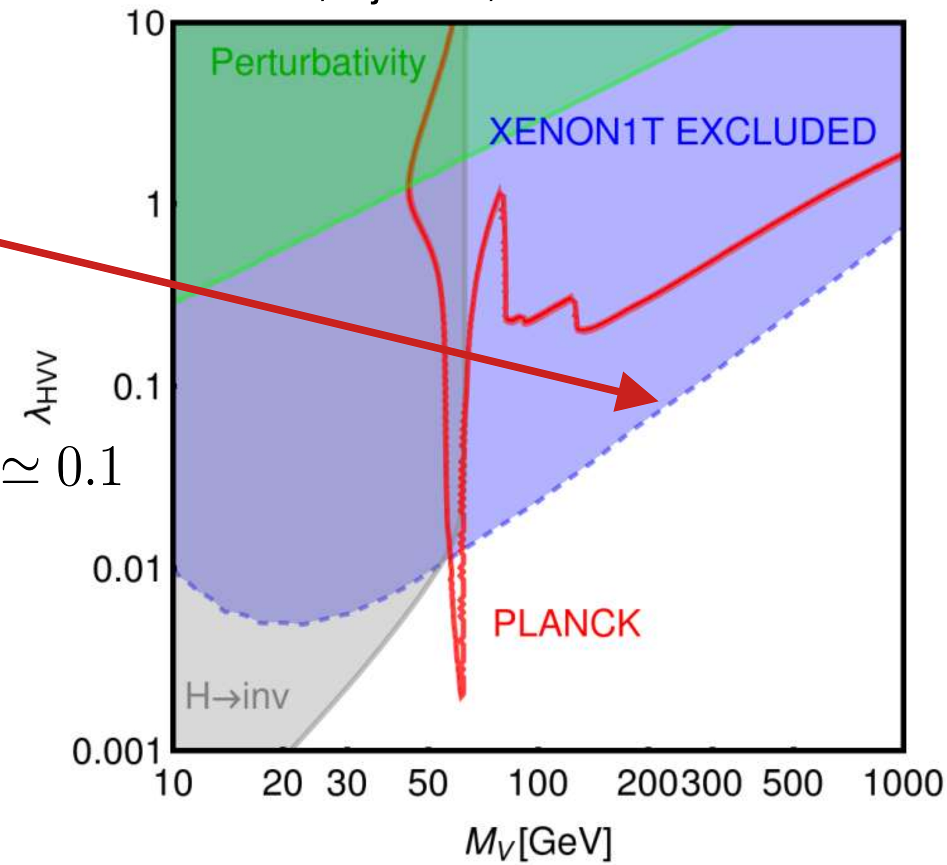
- Quite a few papers:

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



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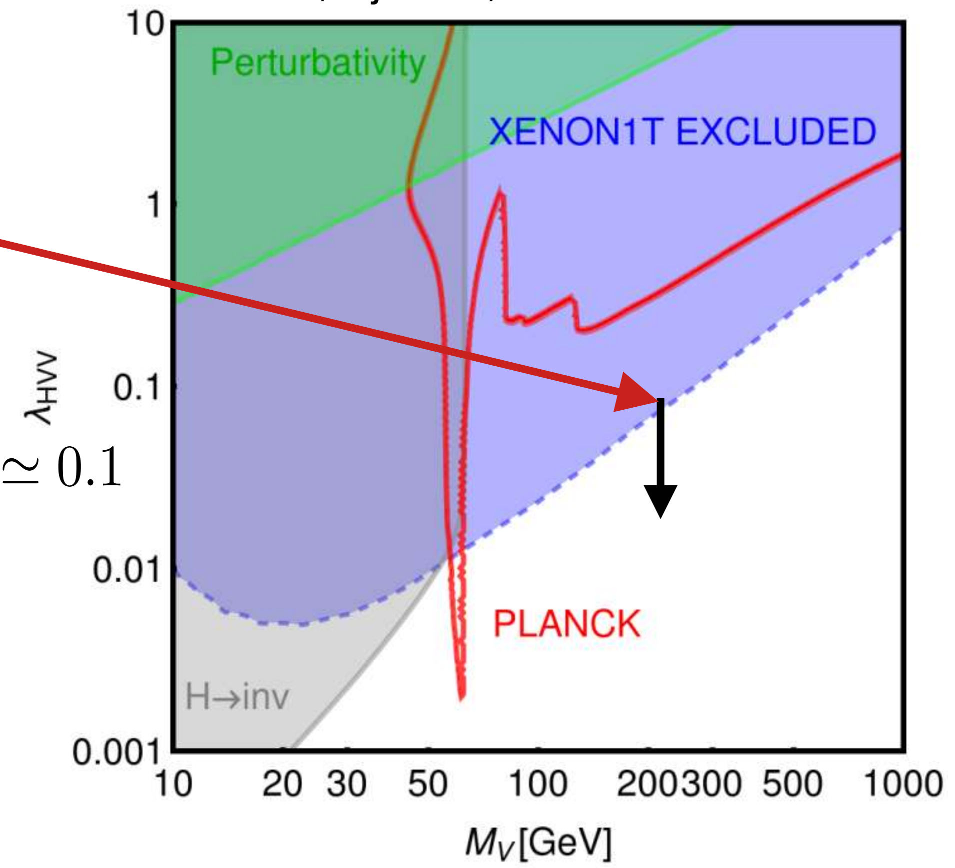

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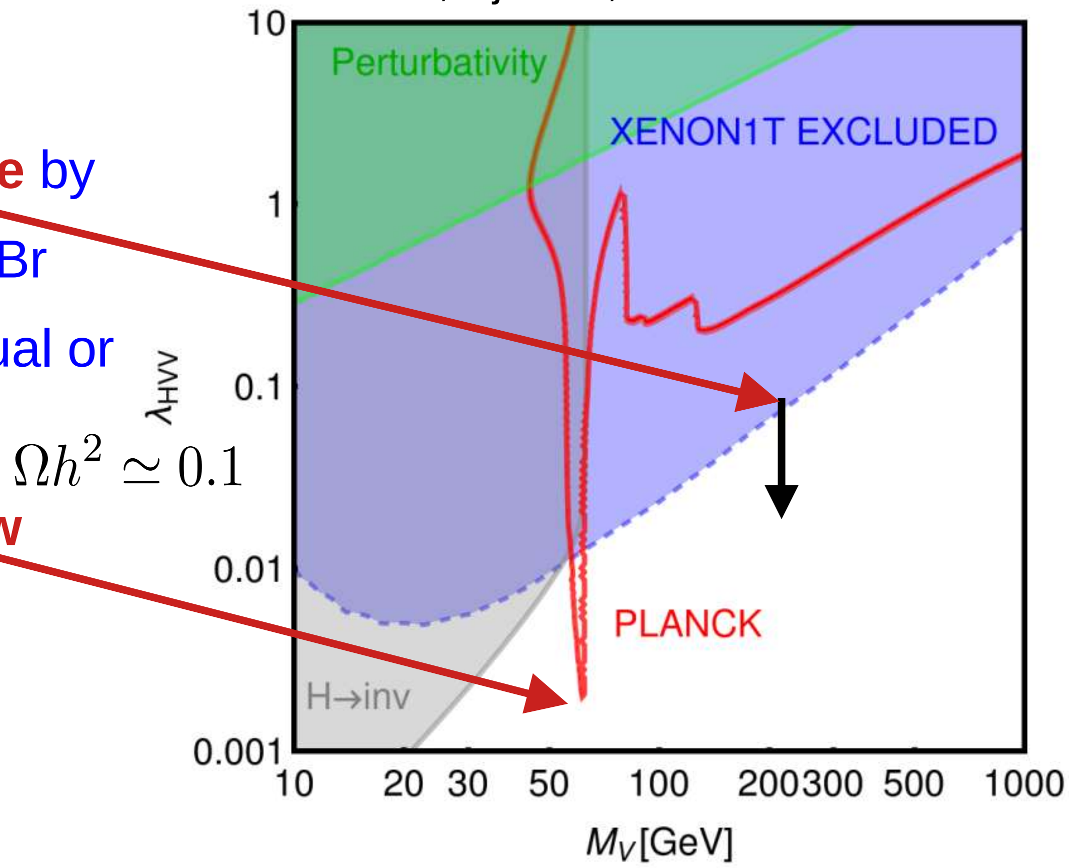

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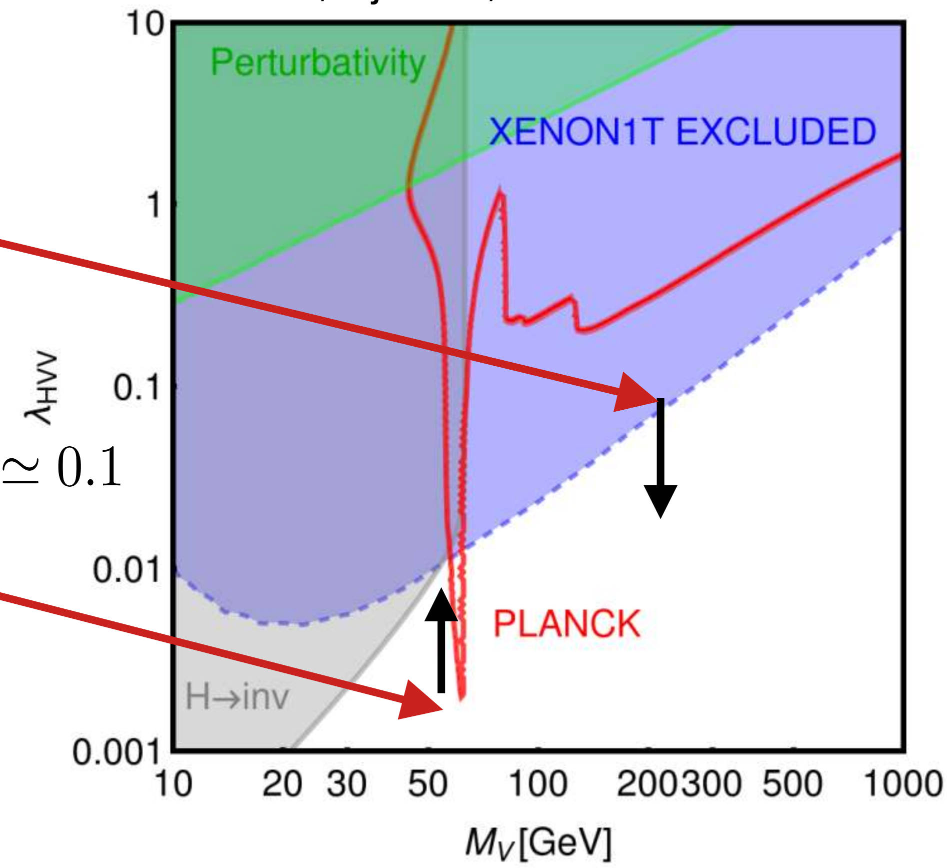

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- Since DM Relic density should be equal or below the PLANCK relic density limit $V_D V_D H$ coupling is **limited from below**
- The Higgs portal VDM parameter space is very limited by interplay of collider, DD and DM relic density

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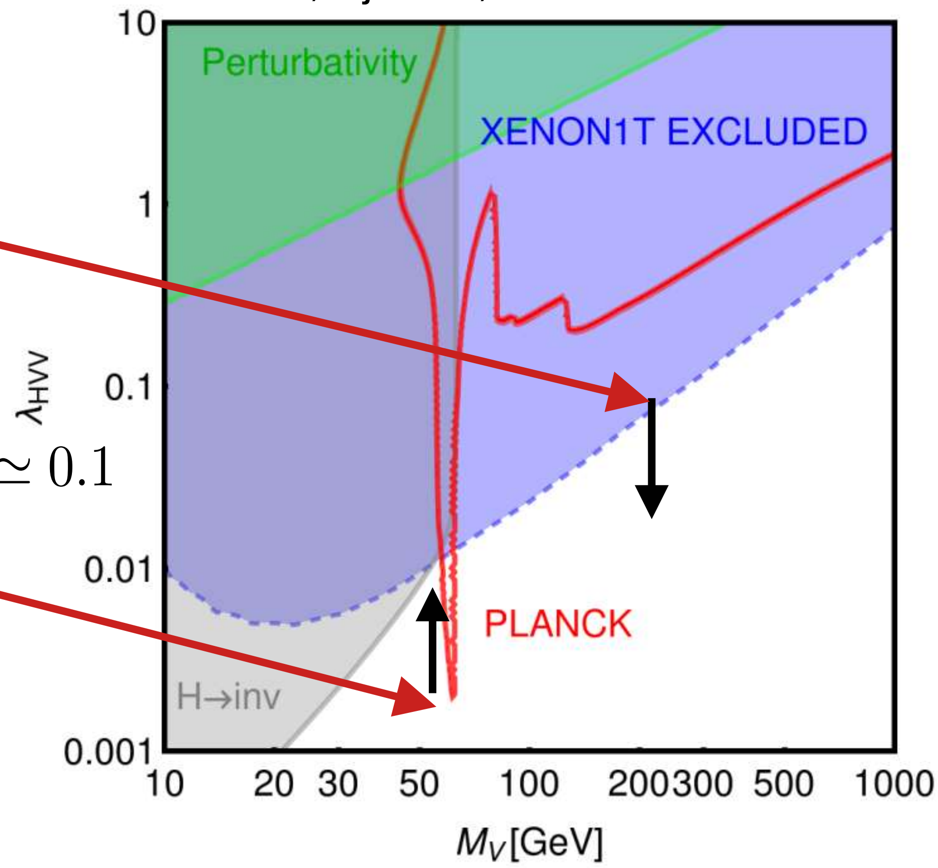

Vector DM with the Higgs portal

- 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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  - 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

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

quite a non-minimal model

Vector like (VL) 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 (VL) fermion Portal for Vector DM

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

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

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
  - $SU(2)_D \times U(1)_{\rm glob} \to U(1)^d_{\rm glob}$ 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 0/1 dark charge, so +/- Z_2

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

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

- 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

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

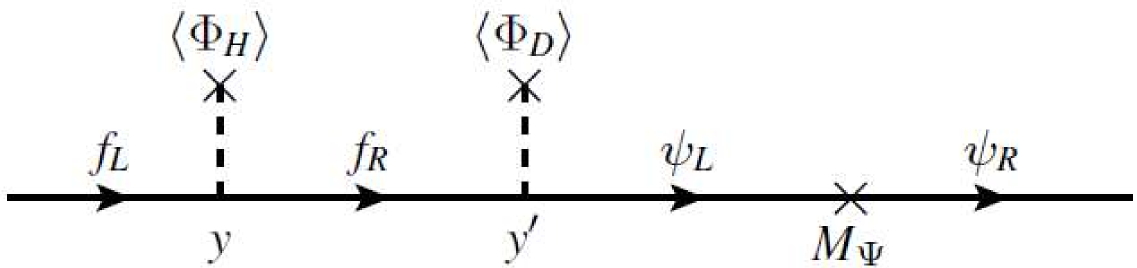
* unless Ψ is a neutrino partner

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

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

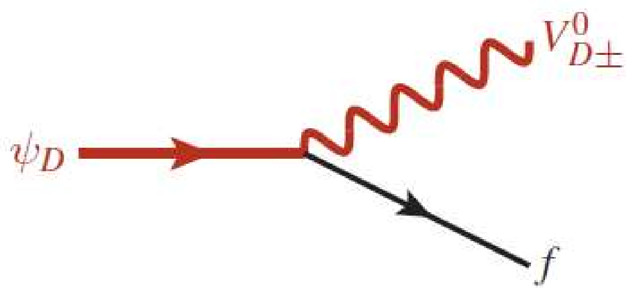
VLF portal: Z_2-even fermions – RH SM ones and VL ones – mix

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



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

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

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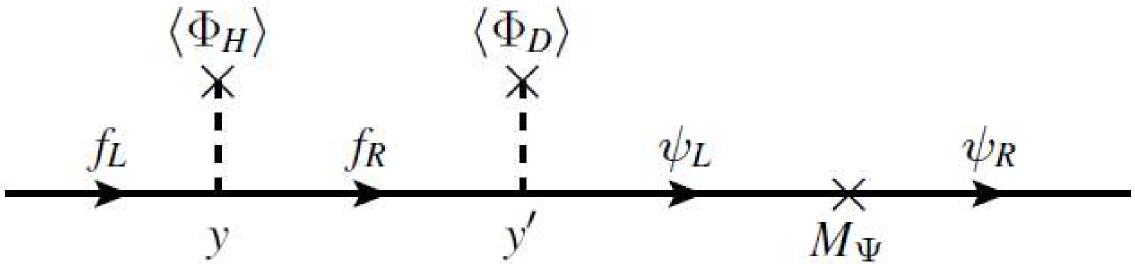

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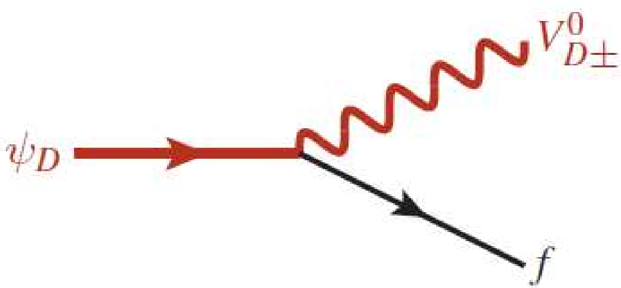

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Potential to introduce flavour structure(s) with VL fermions, including VL leptons to explain various flavour anomalies, including (g-2)μ !

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

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

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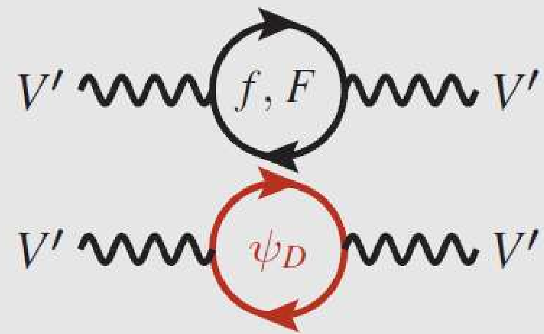
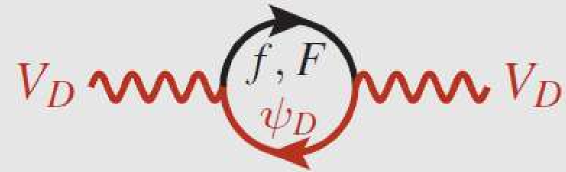
- **At loop-level:**

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





Similar diagrams appear for Kinetic mixing (backup slides)

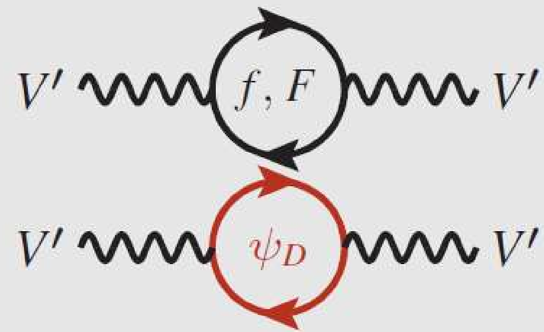
$$m_{V_D} - m_{V'} \simeq \frac{g_D^2}{32\pi^2} \frac{m_F^2 - m_{\psi_D}^2}{m_{V_D}} > 0 \quad \text{for} \quad m_F \gg m_f, m_{V_D}$$

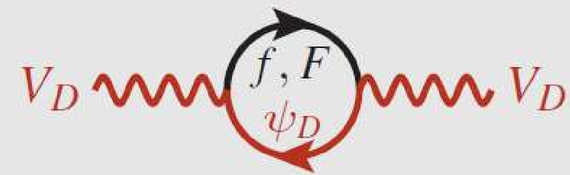
The gauge sector: V′ / V_D radiative mass split, no tree-level V′ – Z mixing

- **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 $V^0_{D0} \equiv V')$





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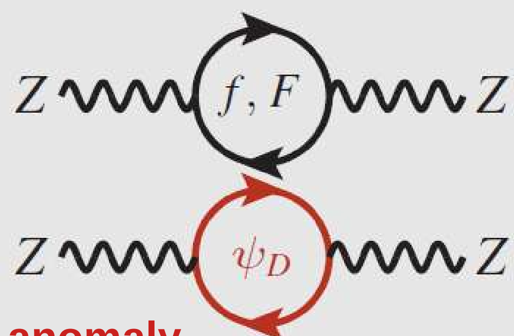
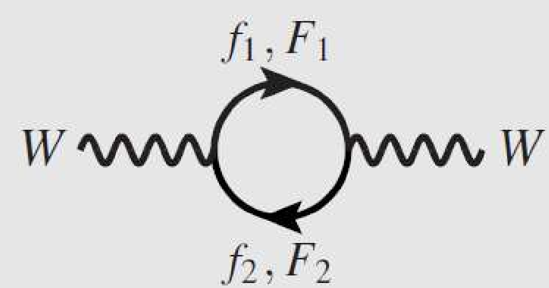
- **Effect for W/Z boson masses**

Modifications to SM
different for Z and W





Potential to explain W-boson mass anomaly

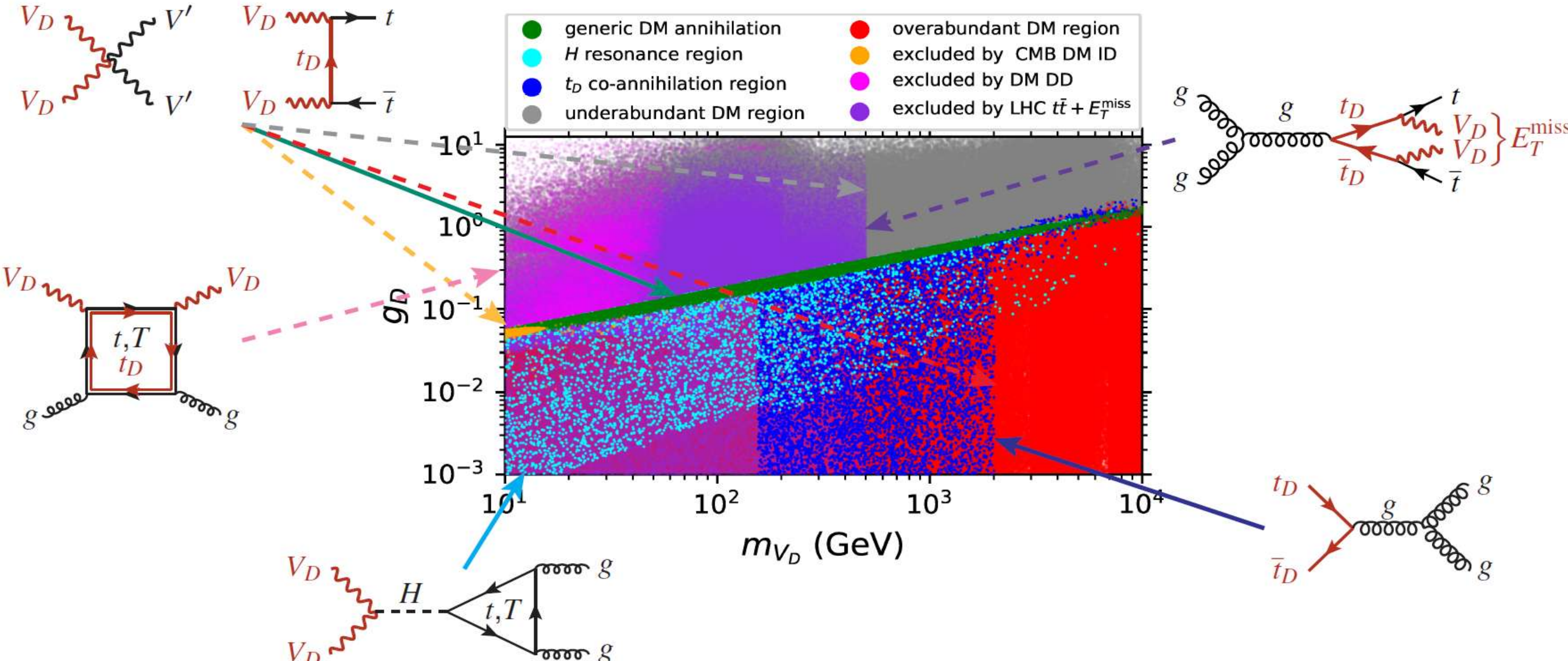
Minimal VL top portal VDM: VL top portal without higgs portal mixing

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: $g_D, m_{V_D}, m_H, m_T, m_{t_D}$



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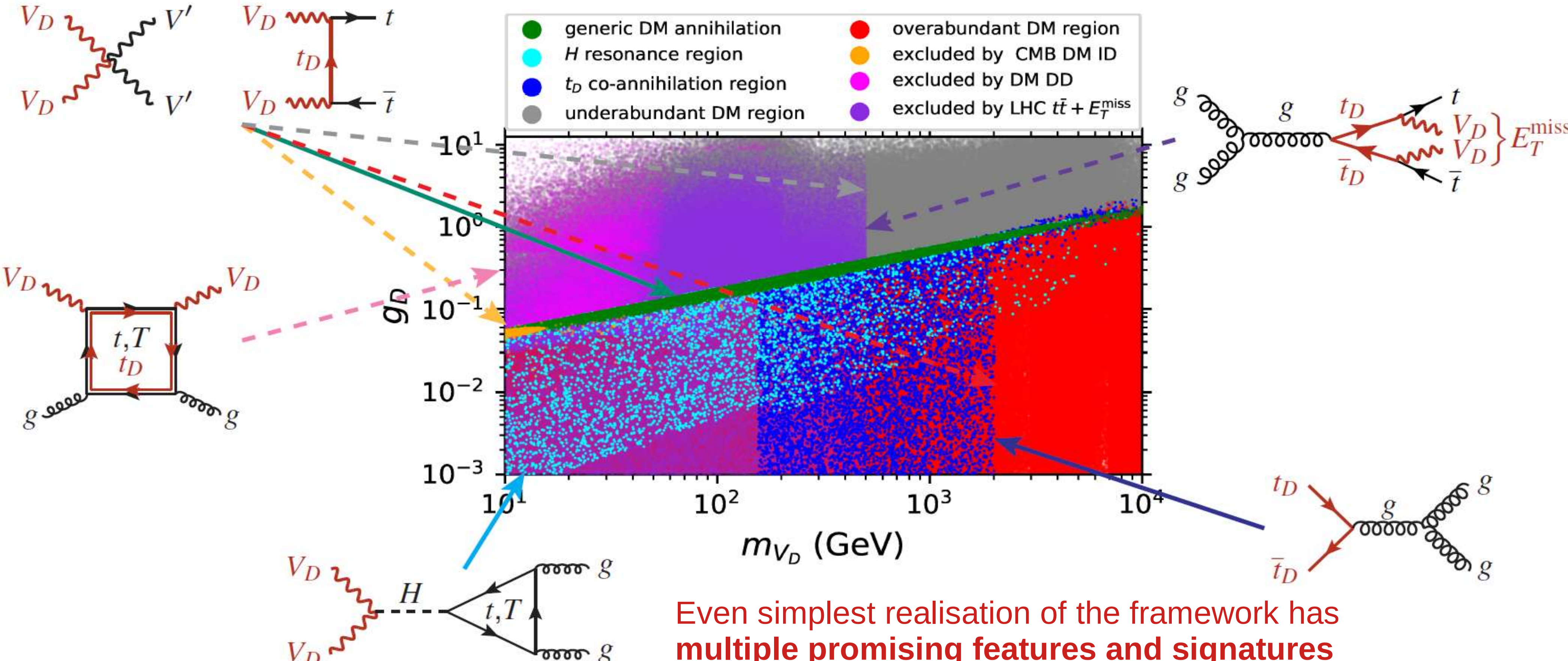
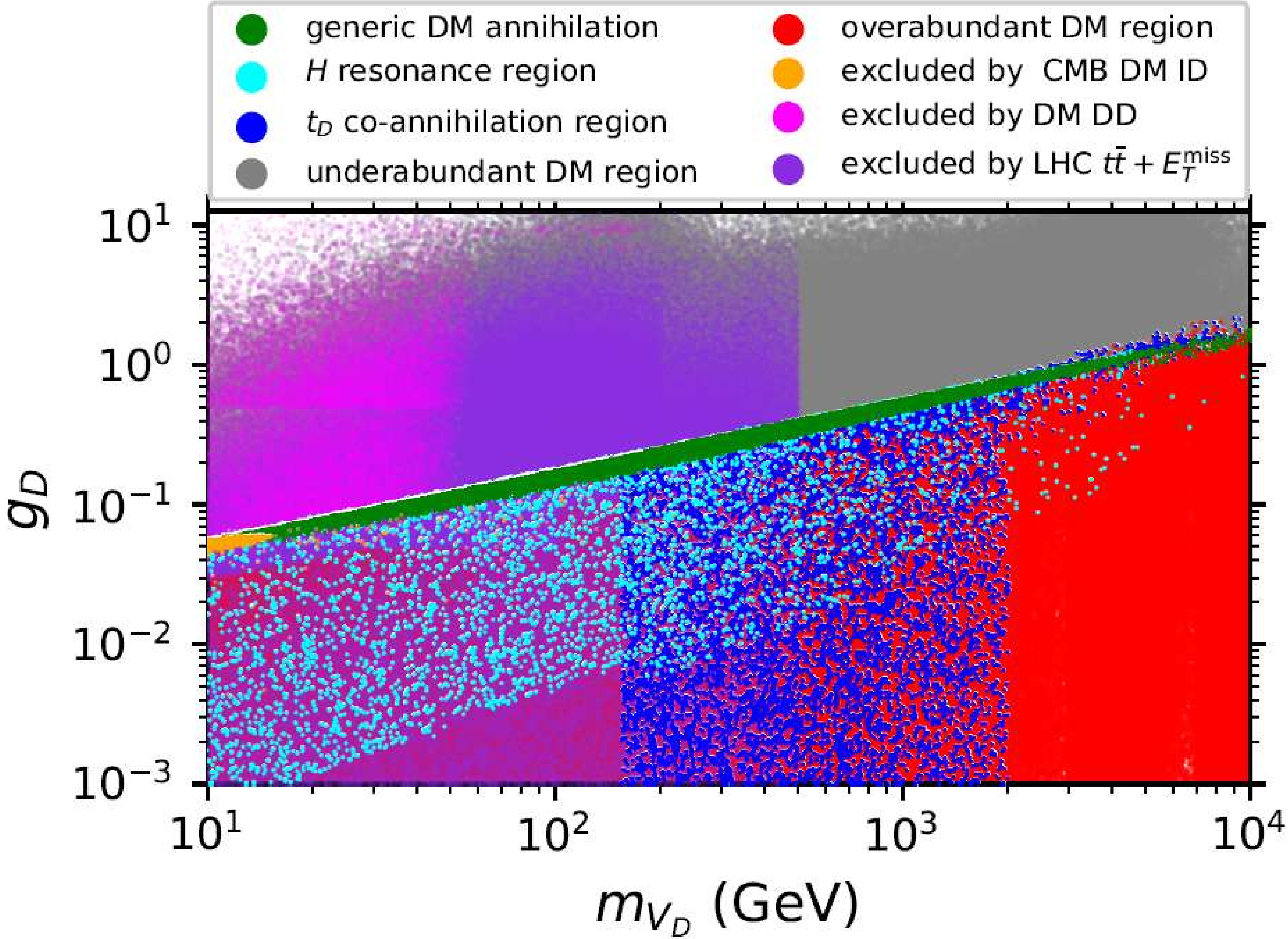


Even simplest realisation of the framework has **multiple promising features and signatures**

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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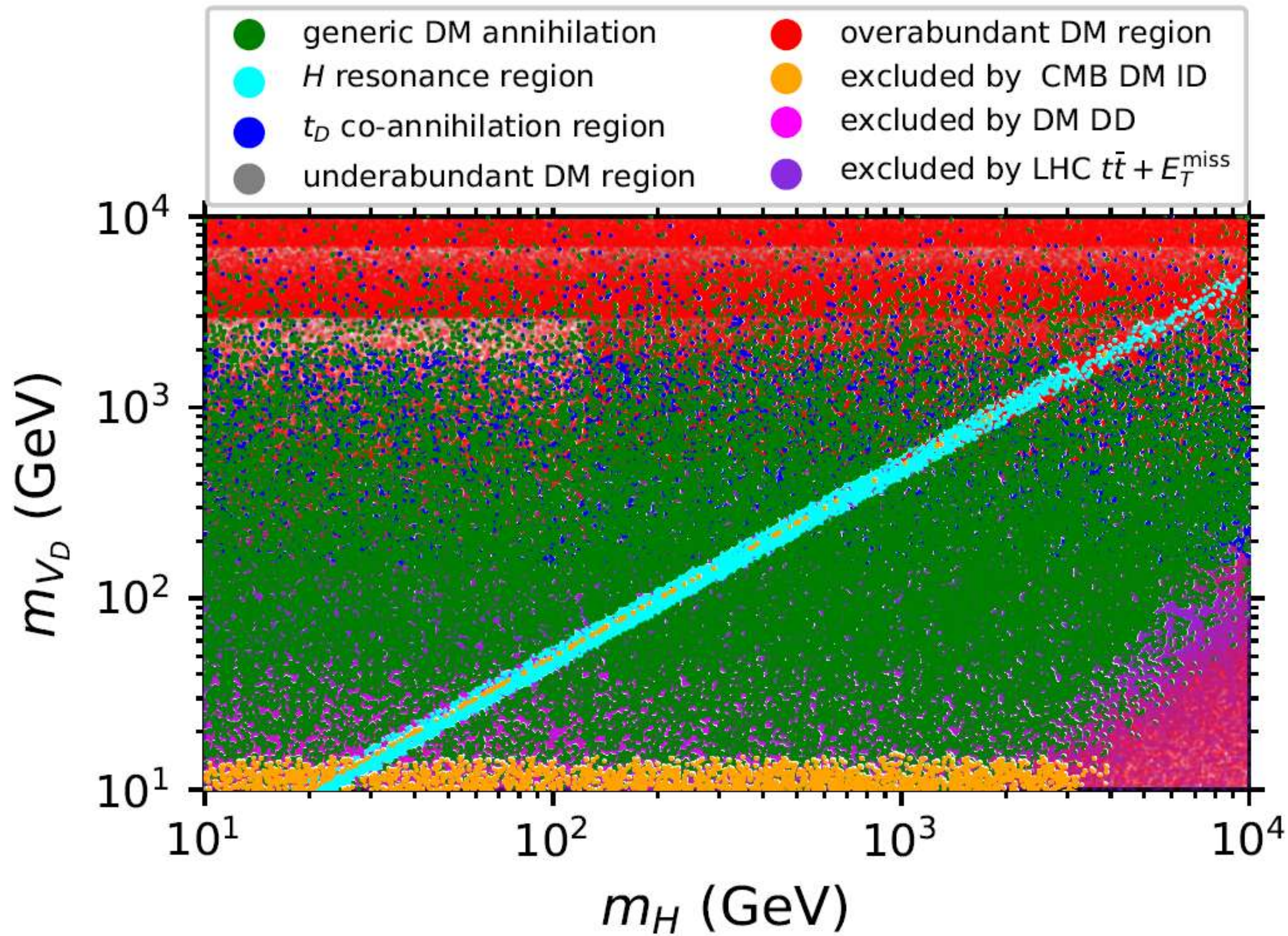

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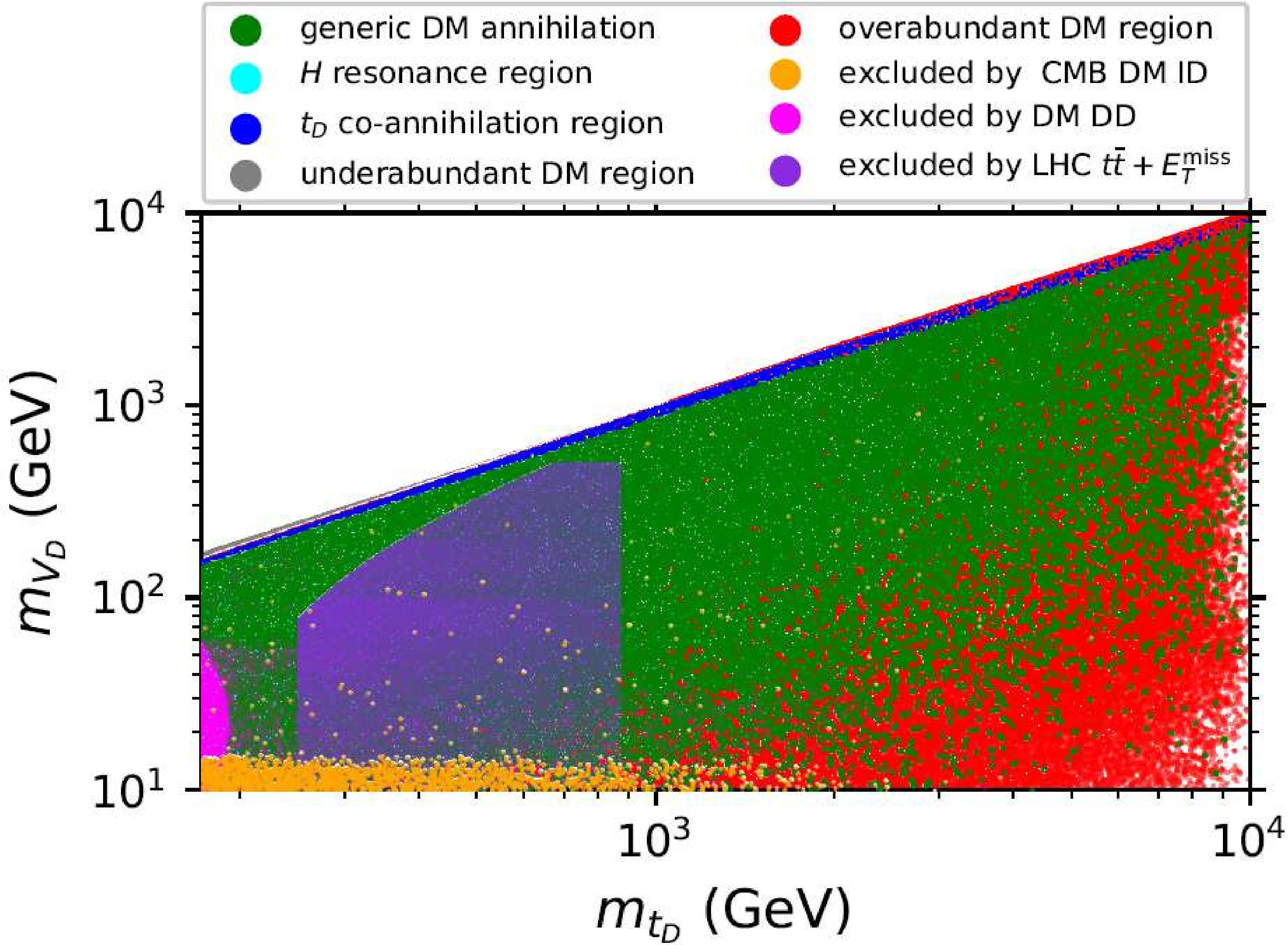
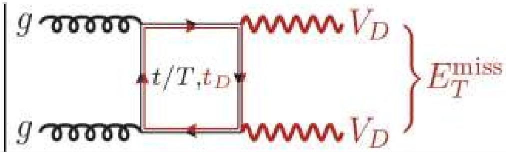
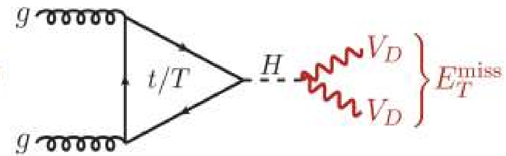
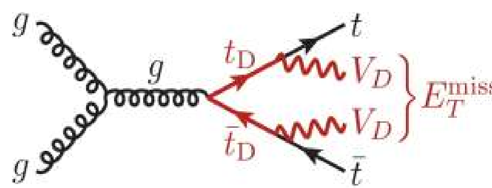
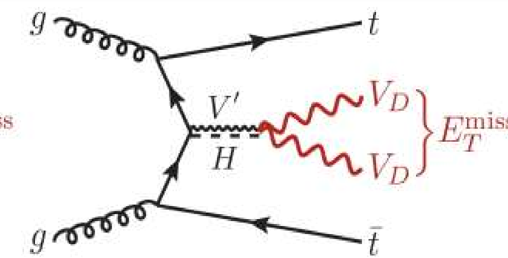
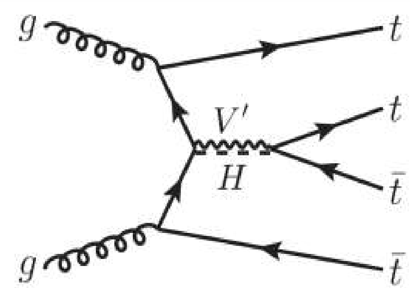
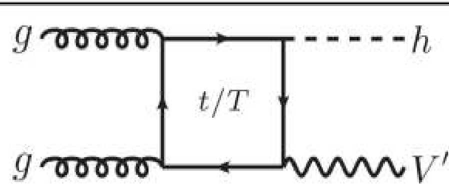
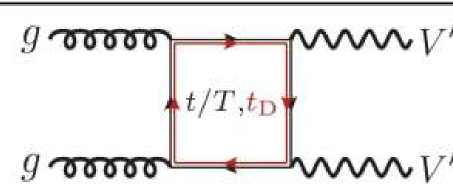
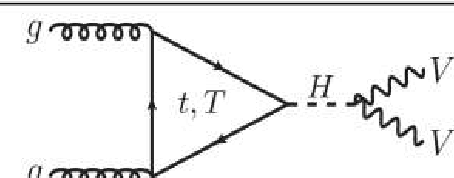


Minimal VL top portal VDM: collider signatures

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

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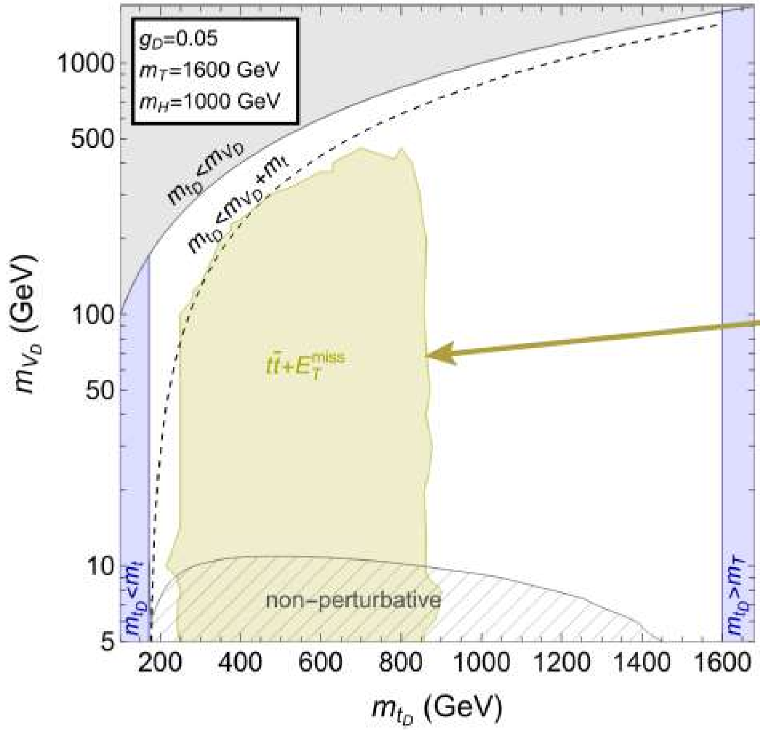
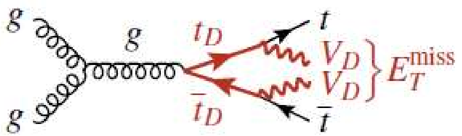
Representative benchmarks:
$g_D = 0.05, 0.5$ — strong or weak cosmological constraints
$m_T = 1600$ GeV, $m_H = 1000$ GeV — heavy enough to evade LHC constraints



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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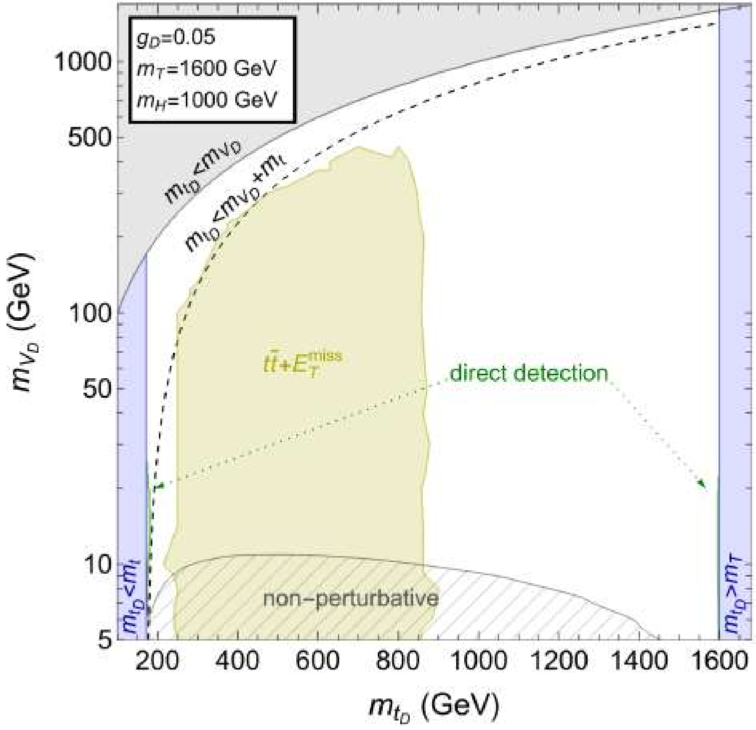

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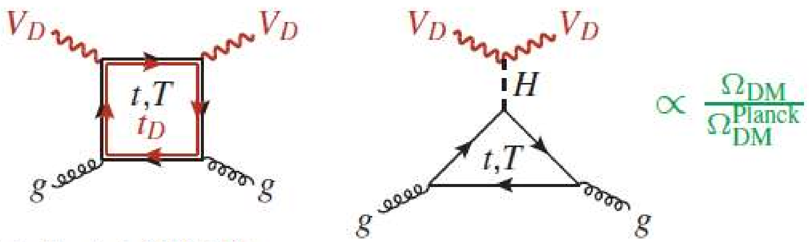
Very weak direct detection constraints
(mostly for $m_{t_D} \sim m_t$ or $m_{t_D} \sim m_T$ and light DM)



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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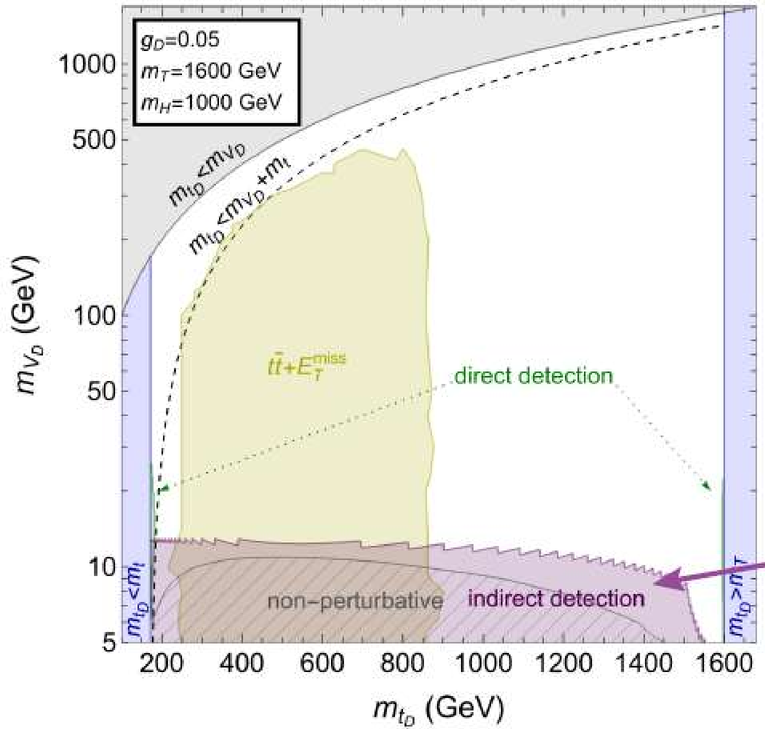

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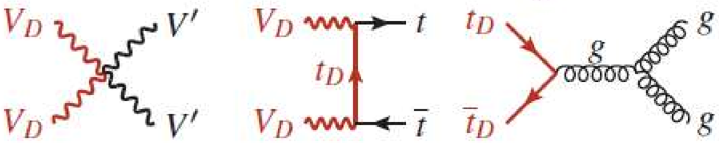
Indirect detection constrains light DM



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

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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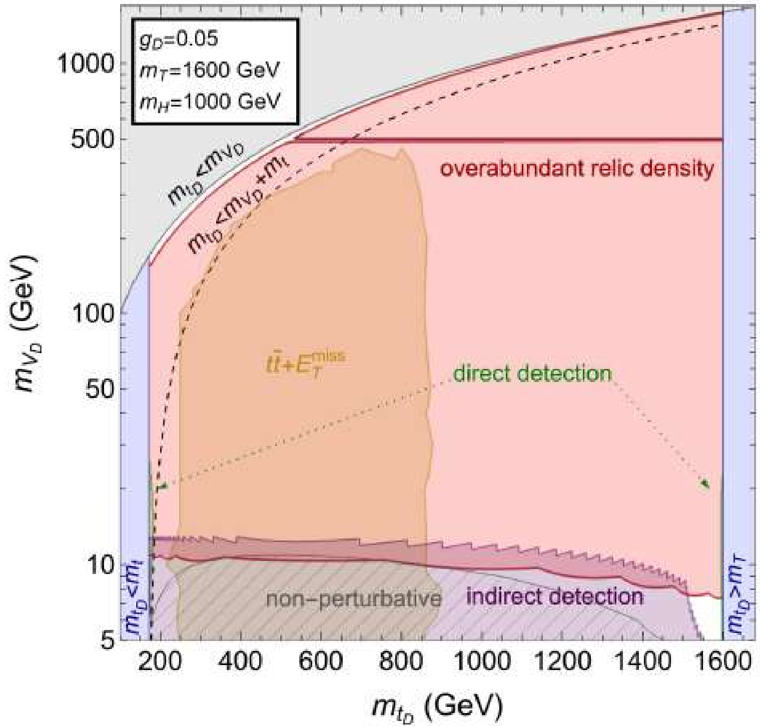

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Strong constrain from relic density
$\rightarrow$ the model "lives" on the red contours ($\Omega_{\rm DM}^{\rm Planck}$)

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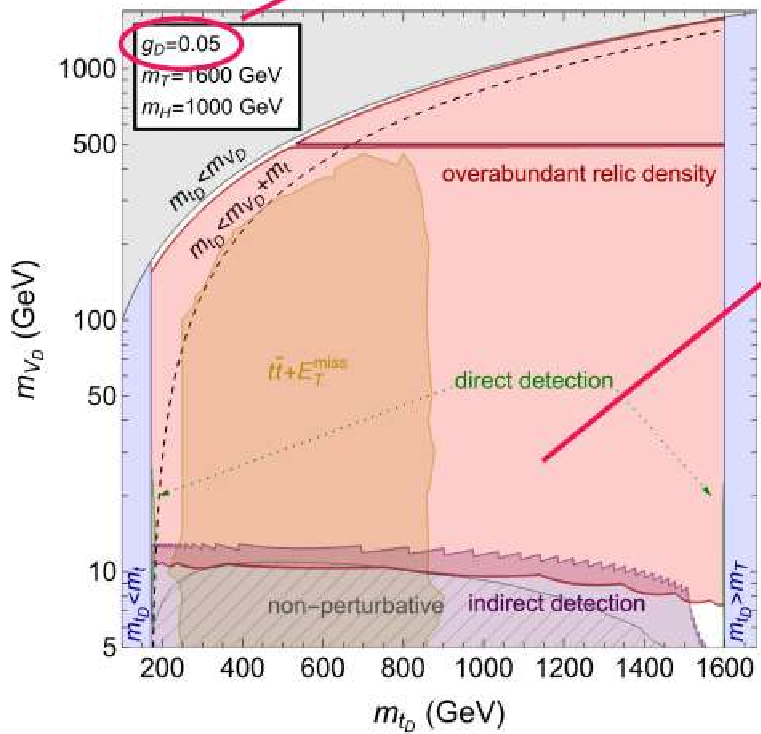

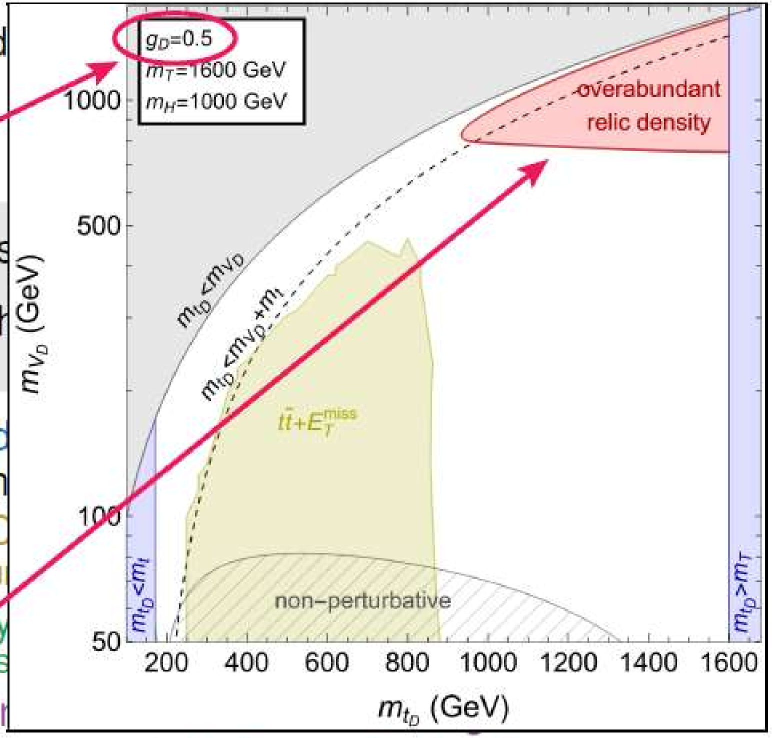

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Strong constrain from relic density
→ the model "lives" on the red contours (Ω_{DM}^{Planck})
→ overabundant region shrinks for larger g_D
→ and ID constraints vanish

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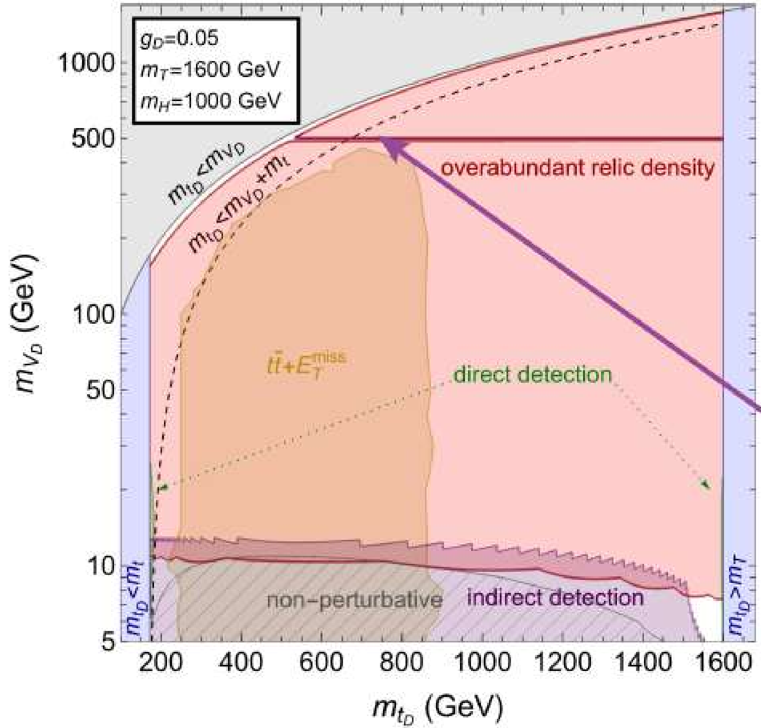

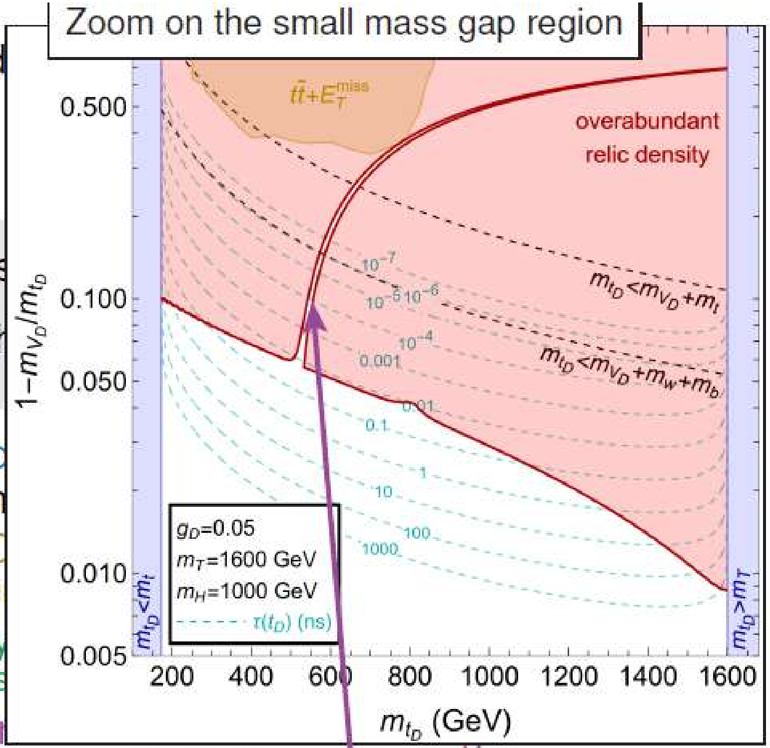

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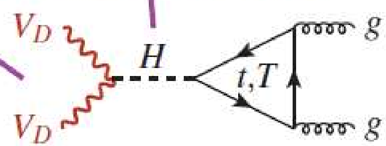
→ on the H_D pole, exclusion from ID



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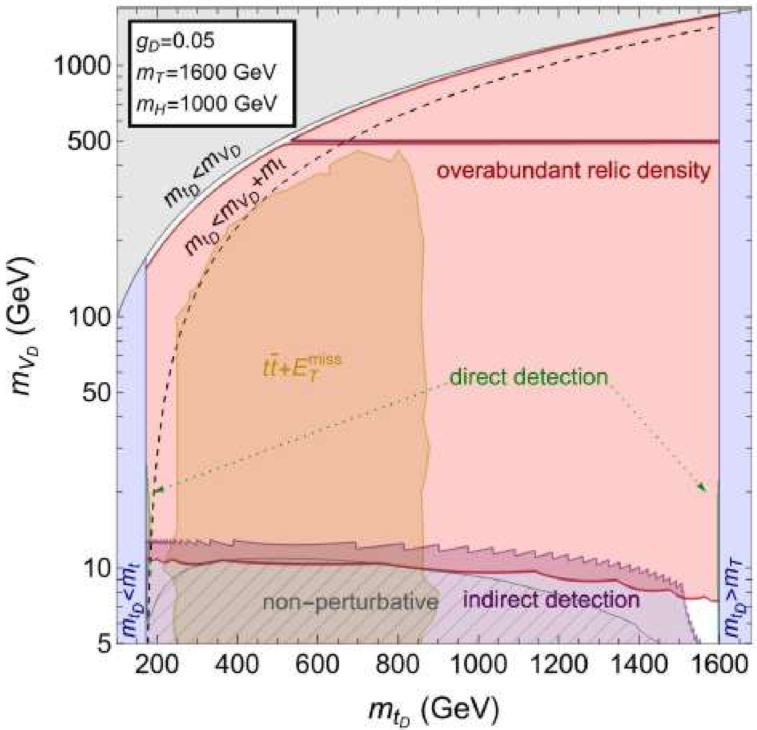

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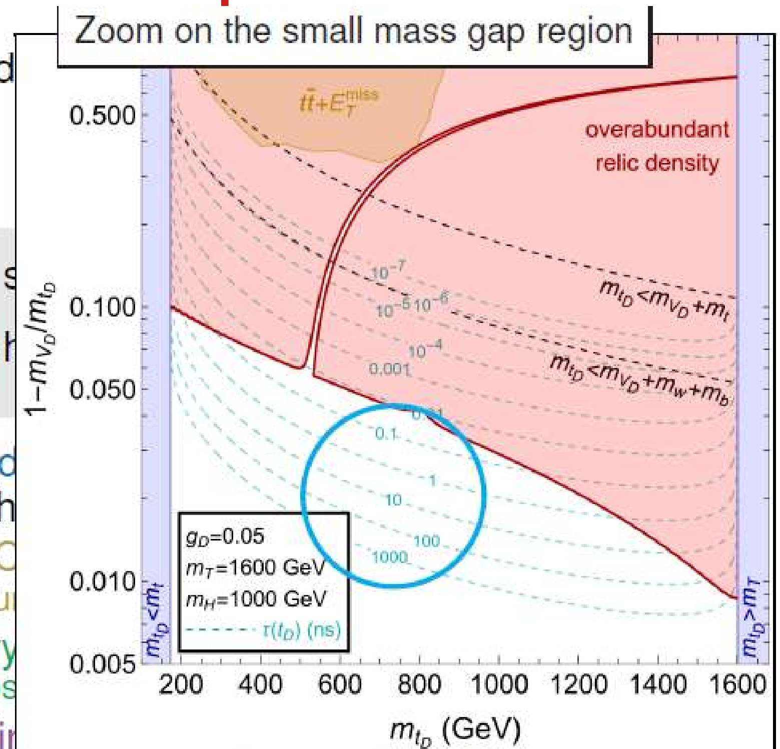

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The mediator t_D can be long lived

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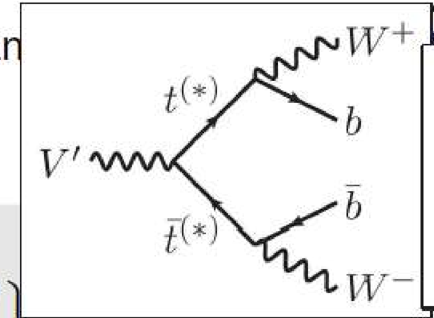

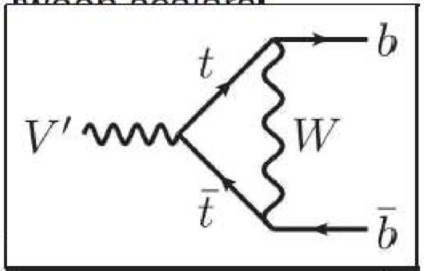

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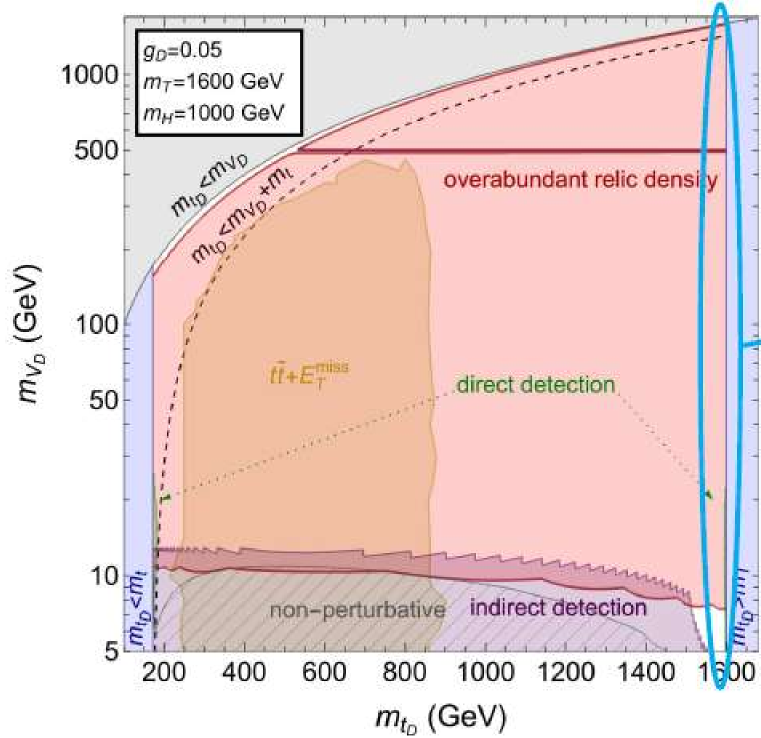

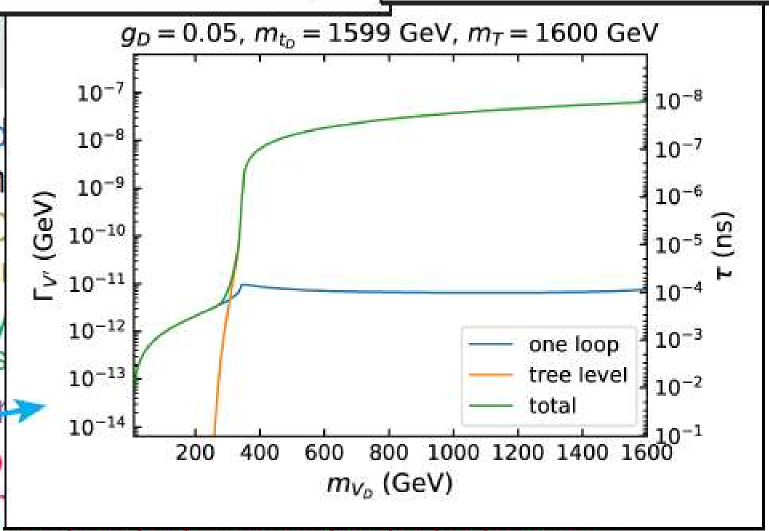

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The mediator t_D can be long lived, and V' too

Summary on Fermion Portal Vector Dark Matter (FPVDM)

- FPVDM is a new framework which does not require the Higgs portal
- Has new features with new collider and cosmological implications
- Simple realisation of the top sector – several promising predictions and signatures
  - great potential to explain dark matter
  - collider signatures: tt+miss, Z′, Z′H, long-lived Z′

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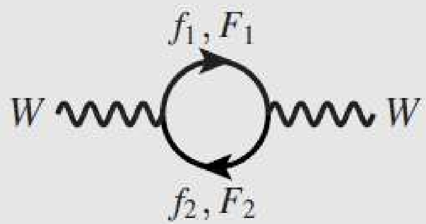
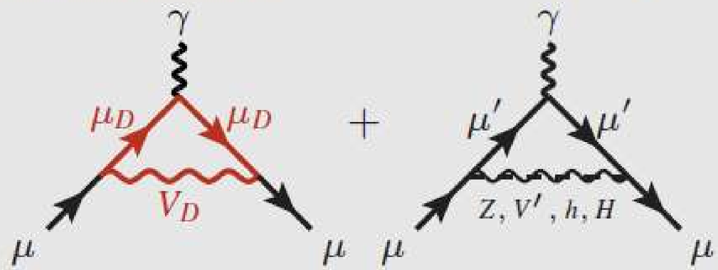
Outlook

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

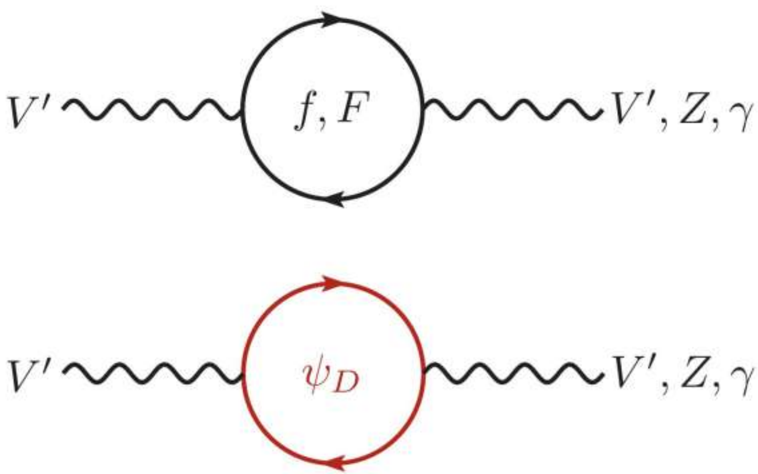




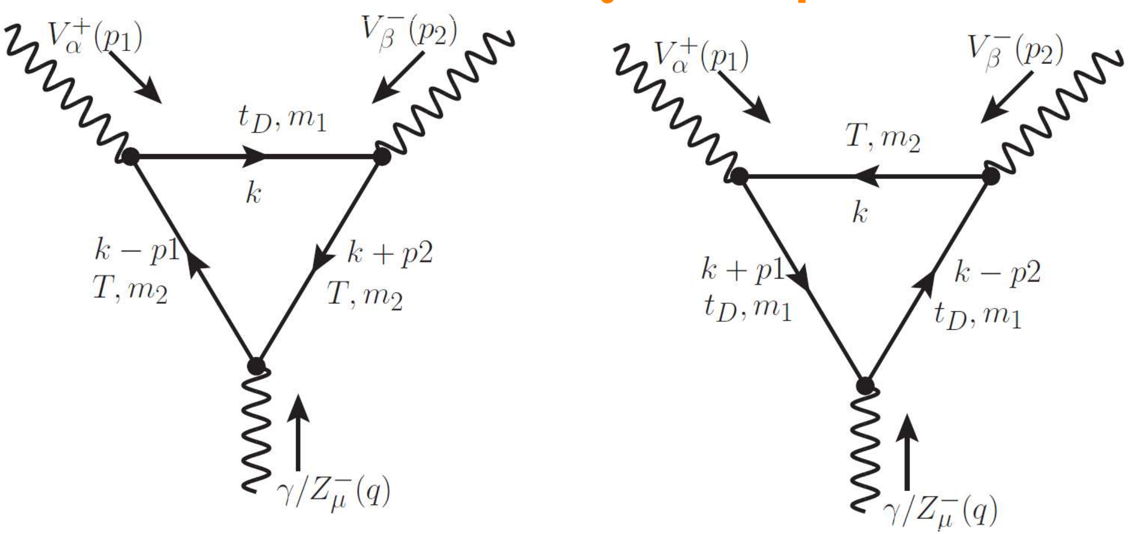
→ Study of different theoretical embeddings

→ Further analysis of cosmological implications and scenarios for future colliders

V' Kinetic mixing



DM interaction with Z/γ at loop level



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Thank you!

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

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

2 massless and 2 massive vectors

Connections with dark-photon phenomenology

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

EW + Dark symmetry breaking →

Including Higgs portal

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

Without Higgs portal

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

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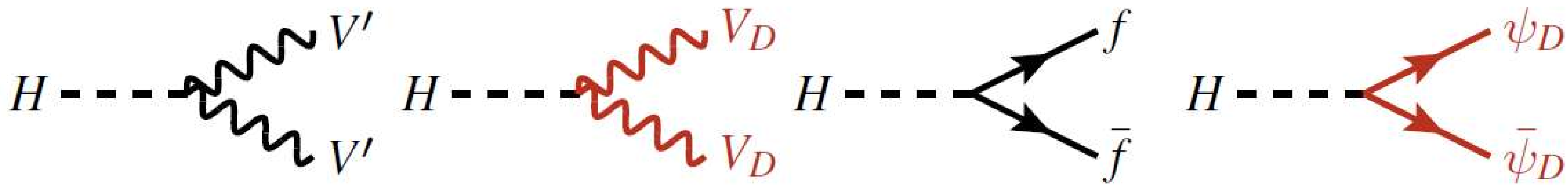
If no Higgs portal, the interactions of the new scalar H are limited to:



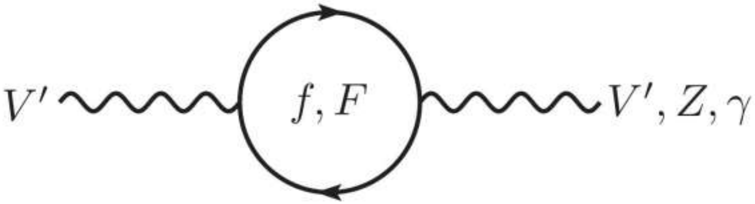
VL portal VDM: the summary of particle content

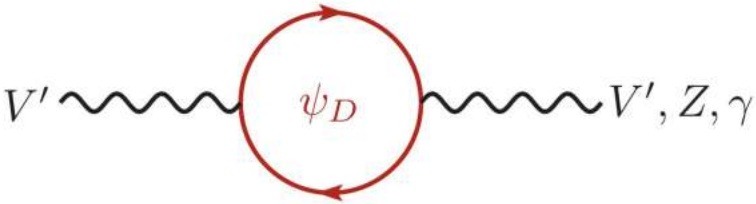
Vectors	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$W_\mu = \begin{pmatrix} W^+_\mu \\ W^3_\mu \\ W^-_\mu \end{pmatrix}$	$\mathbf{3}$	0	$\mathbf{1}$	$+$ $+$ $+$
B_μ	$\mathbf{1}$	0	$\mathbf{1}$	$+$
$V^D_\mu = \begin{pmatrix} V^0_{D+\mu} \\ V^0_{D0\mu} \\ V^0_{D-\mu} \end{pmatrix}$	$\mathbf{1}$	0	$\mathbf{3}$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

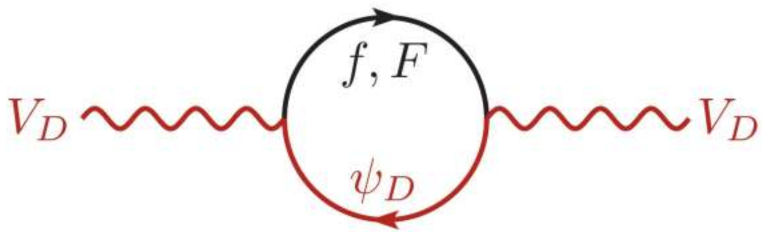
Scalars	$SU(2)_L$	$U(1)_Y$	$SU(2)_D$	$\mathbb{Z}_2$
$\Phi_H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	$\mathbf{2}$	$1/2$	$\mathbf{1}$	$+$
$\Phi_D = \begin{pmatrix} \varphi^0_{D+\frac{1}{2}} \\ \varphi^0_{D-\frac{1}{2}} \end{pmatrix}$	$\mathbf{1}$	0	$\mathbf{2}$	$-$ $+$

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





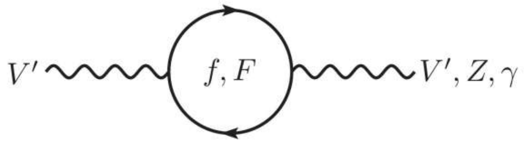


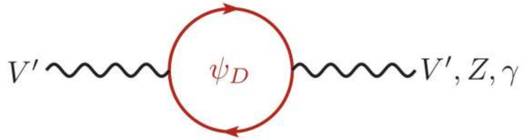
$$\epsilon_{ZV} = \frac{g g_D}{16\pi^2 c_w}\left(\mathcal{F}^{ZV}_{qT1+qL}(r_f, r_{\psi_D}) + Q_f s^2_W \mathcal{F}^{ZV}_{qT2}(r_f, r_{\psi_D})\right)$$

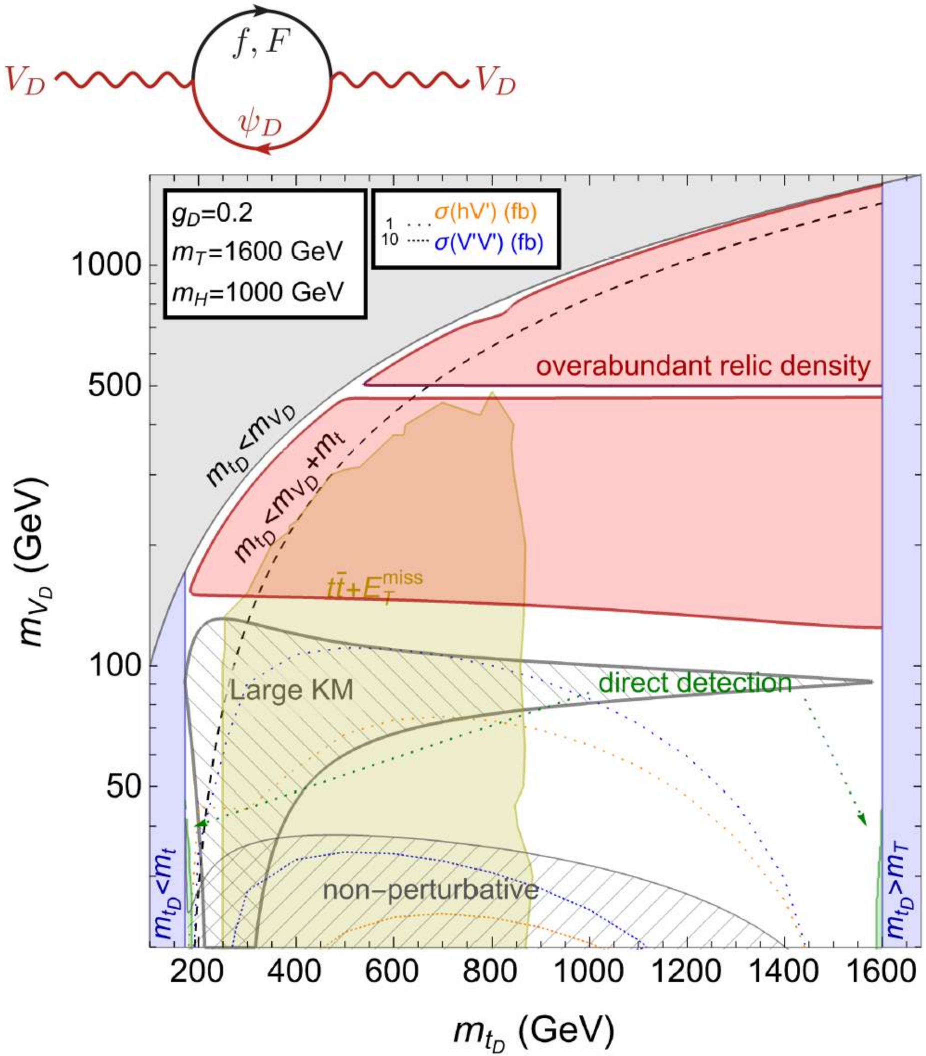
$$V^{\mathrm{KM}} = \begin{pmatrix} 1 & 0 & -\frac{\epsilon_{AV}}{\sqrt{1-\epsilon^2_{AV}-\epsilon^2_{ZV}}} \\ 0 & 1 & -\frac{\epsilon_{ZV}}{\sqrt{1-\epsilon^2_{AV}-\epsilon^2_{ZV}}} \\ 0 & 0 & \frac{1}{\sqrt{1-\epsilon^2_{AV}-\epsilon^2_{ZV}}} \end{pmatrix}$$

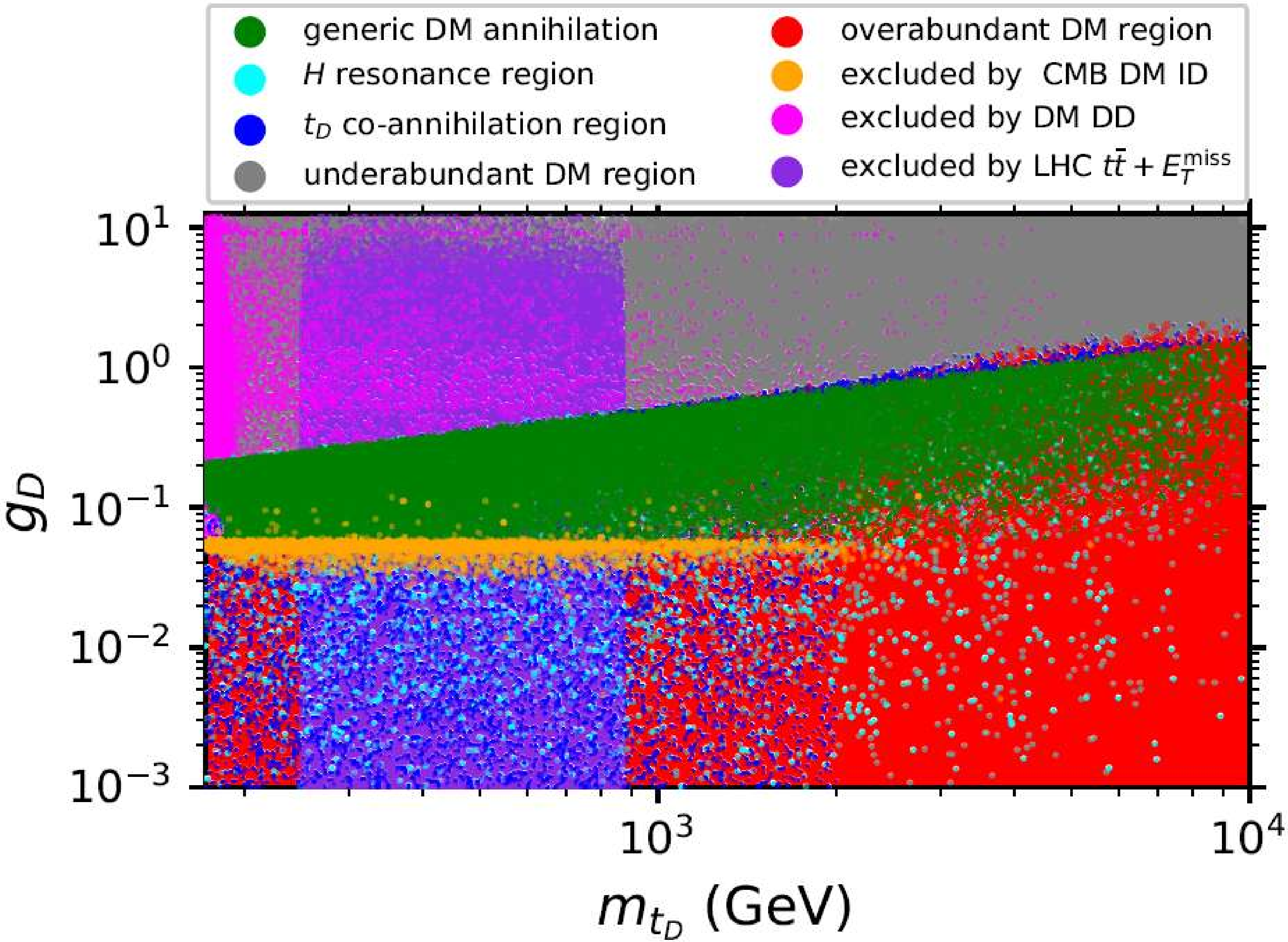
$$\epsilon_{AV} = \frac{g_D e Q_f}{4\pi^2}\mathcal{F}^{AV}(r_f, r_{\psi_D})$$

Kinetic Mixing in FPVDM models









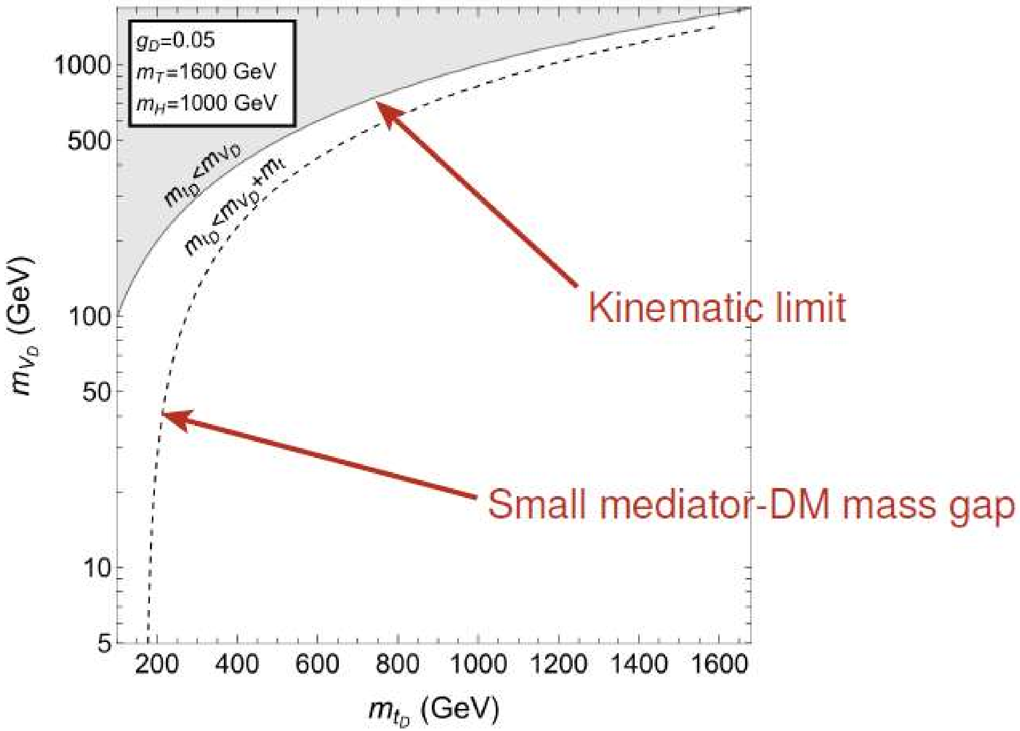
generic DM annihilation
H resonance region
t_D co-annihilation region
underabundant DM region
overabundant DM region
excluded by CMB DM ID
excluded by DM DD
excluded by LHC $t\bar{t}+E_T^{miss}$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
g_D
10^3
10^4
m_{t_D} (GeV)

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

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

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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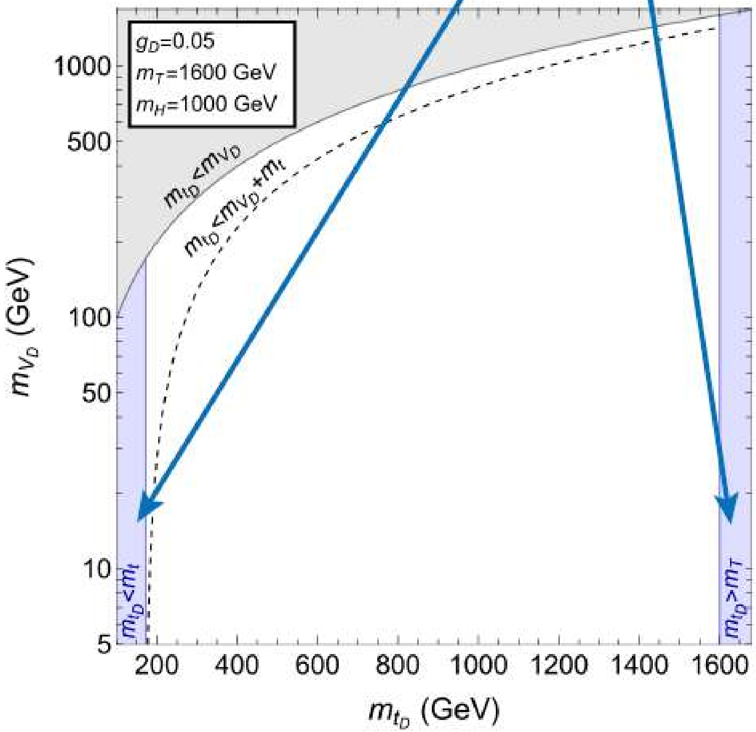

Mediator mass bounded from below and above

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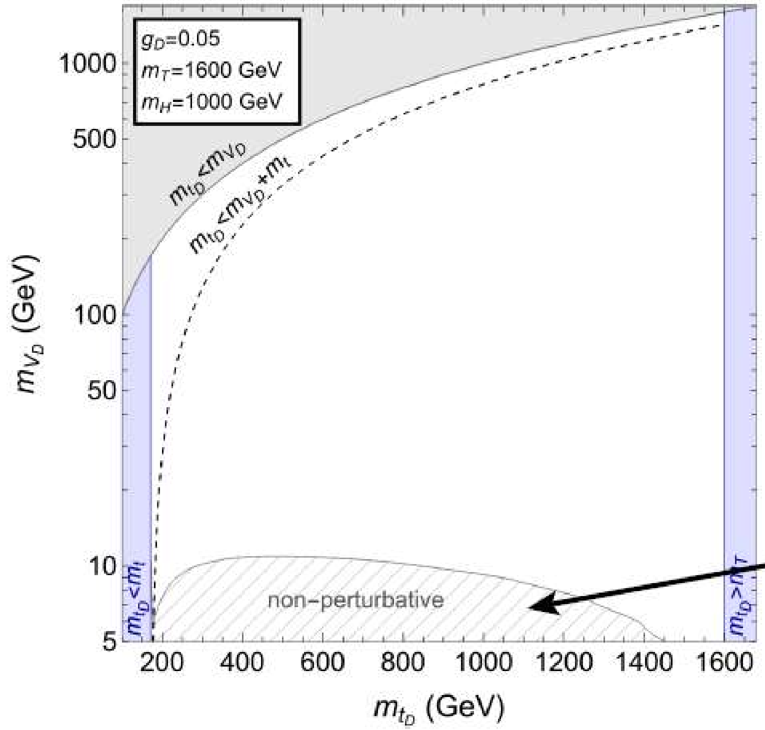

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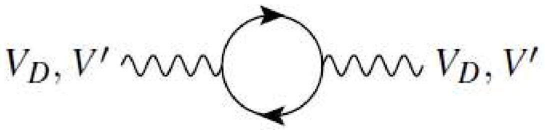
Light DM in non-perturbative region



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

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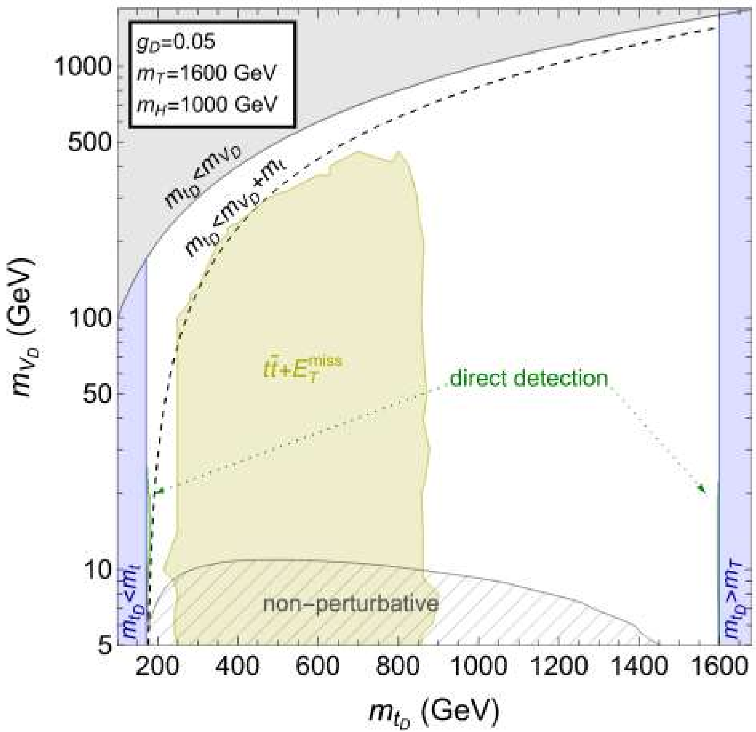

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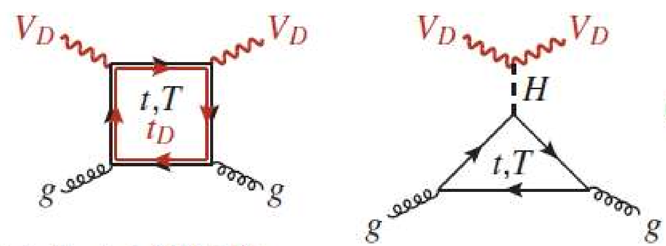
LHC constrains m_{t_D} for $m_{t_D} - m_{V_D} \gtrsim m_t$
(bounds almost independent on g_D, m_T and m_H)

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



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

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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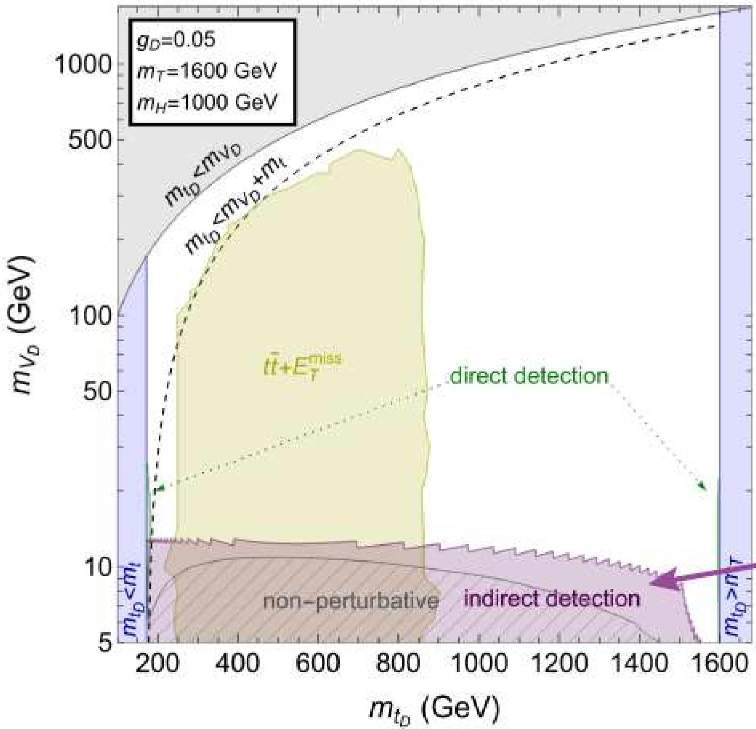

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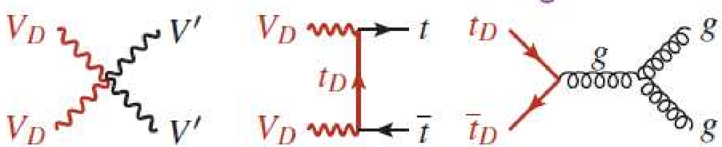

$$\propto \left(\frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm Planck}}\right)^2$$

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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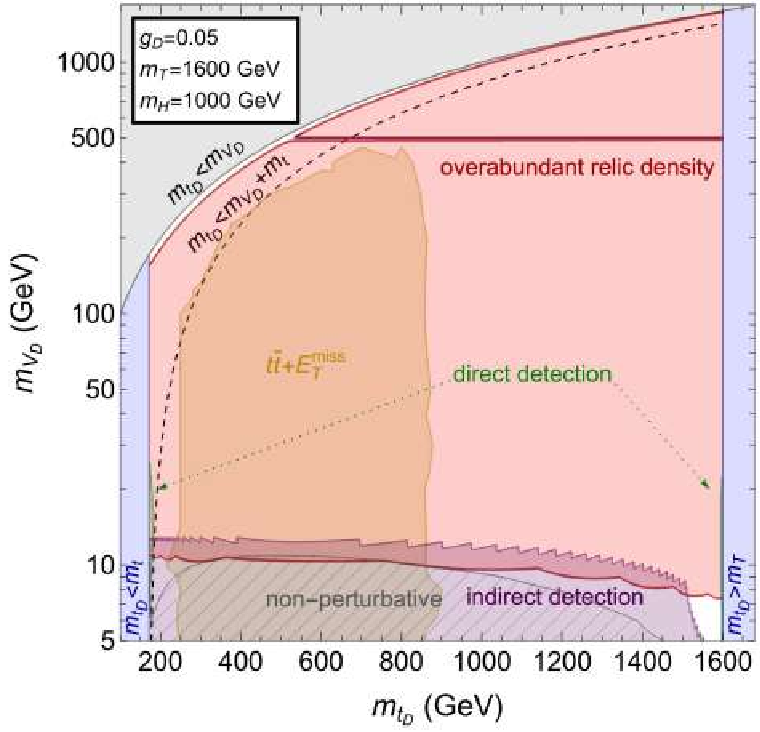

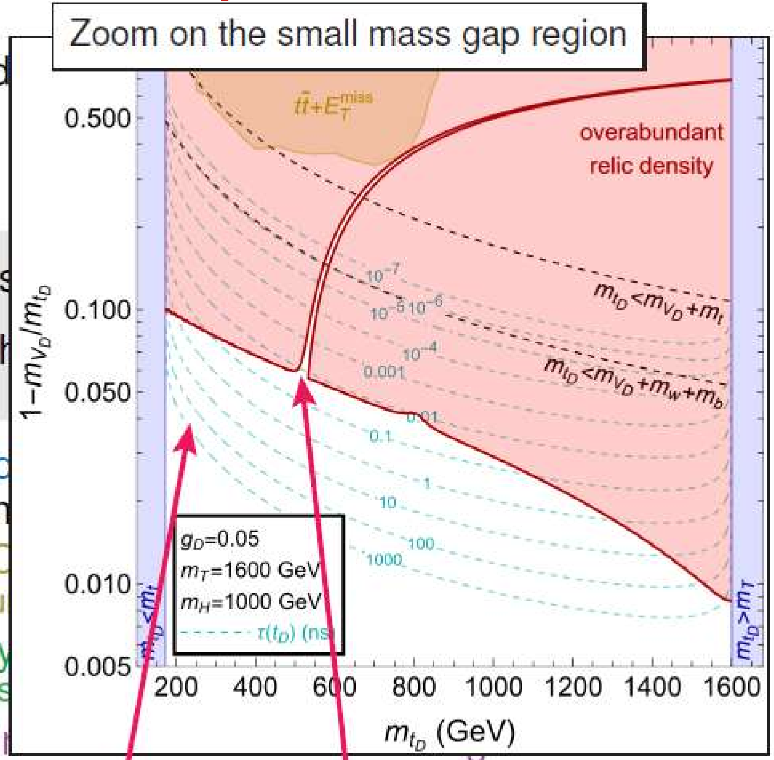

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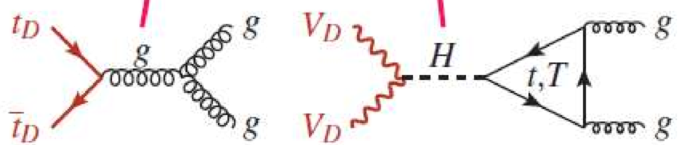
Strong constrain from relic density
→ the model "lives" on the red contours (Ω_{DM}^{Planck})
→ overabundant region shrinks for larger g_D
→ and ID constraints vanish
→ effective (co-)annihilation processes



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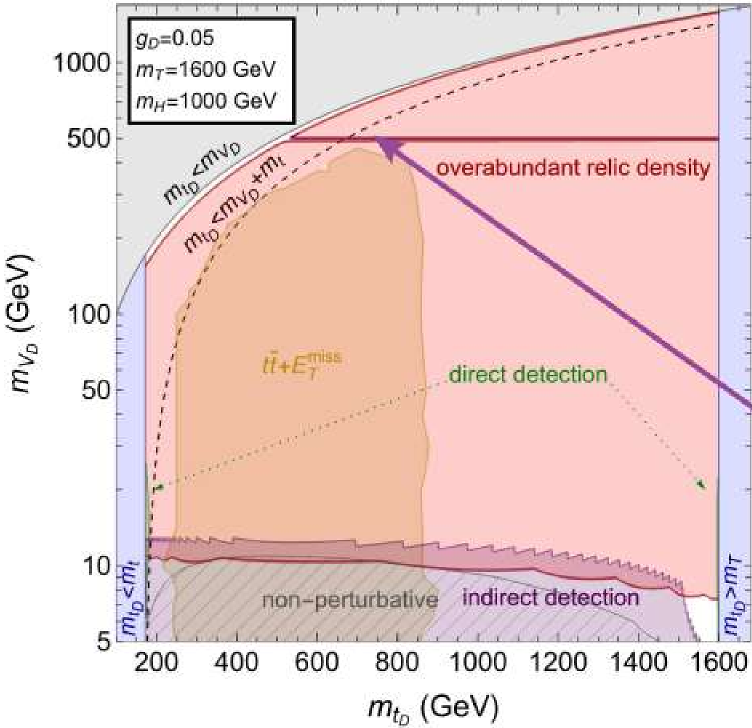

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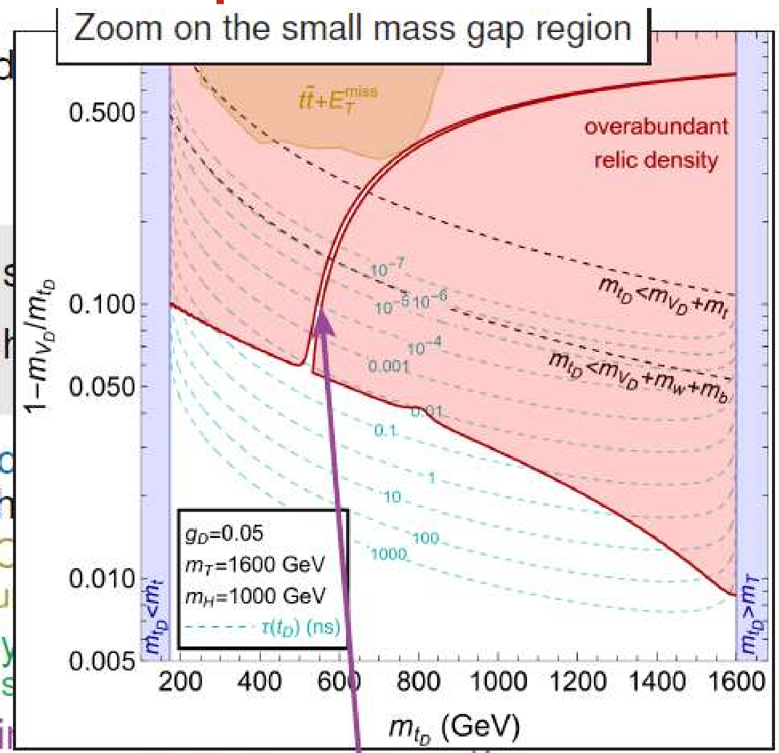

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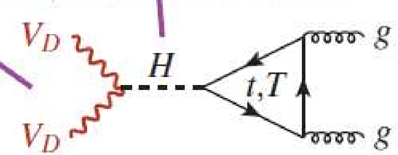

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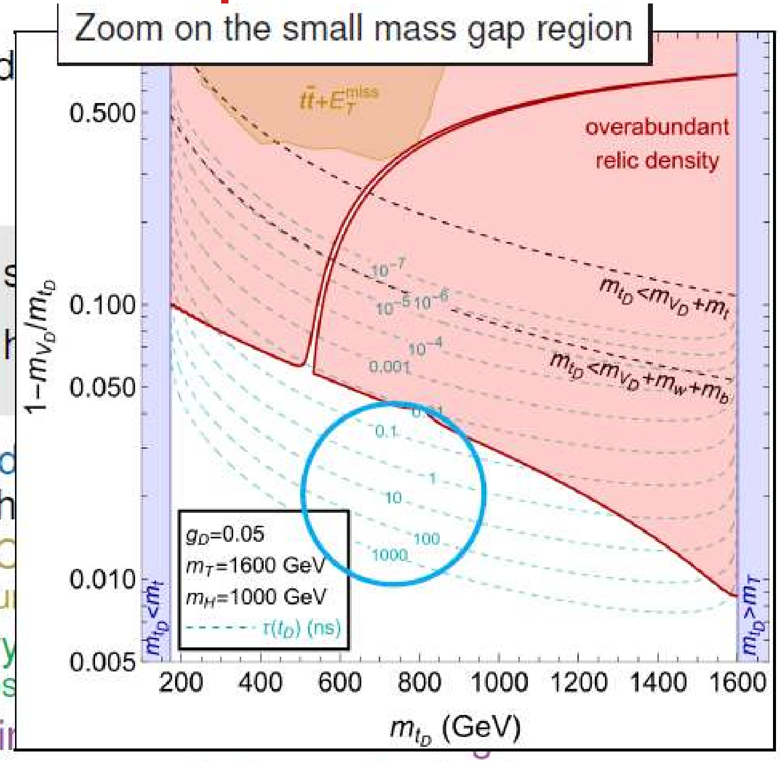

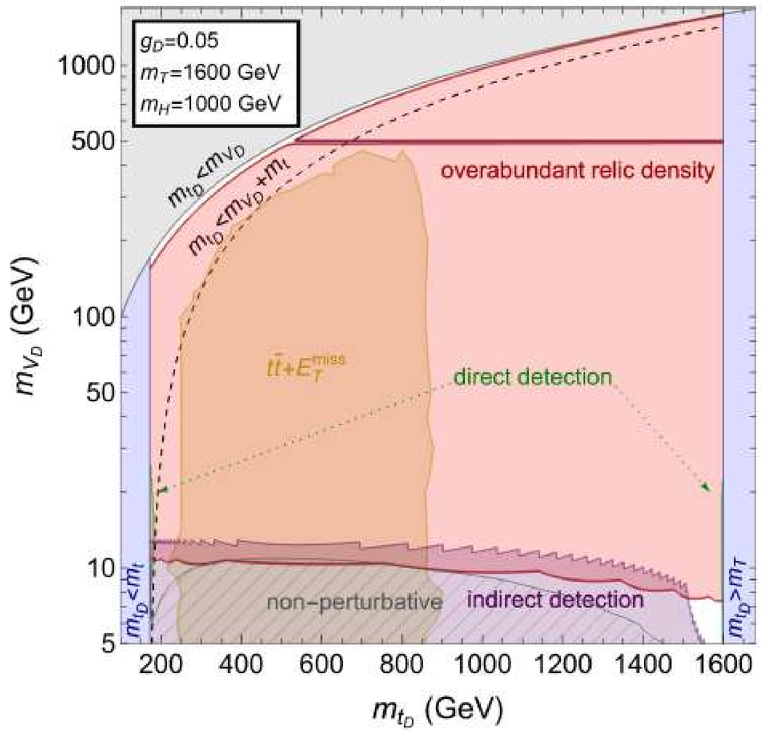

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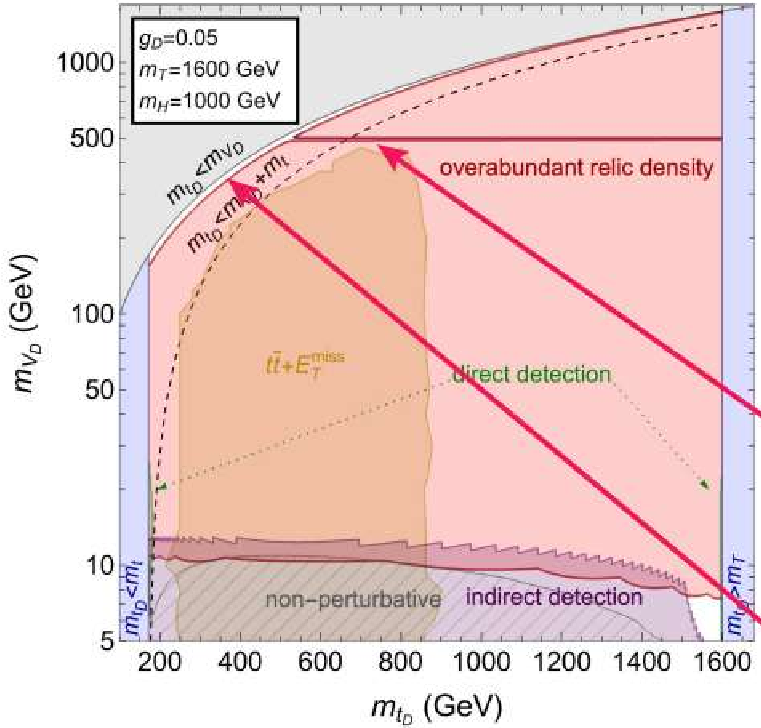

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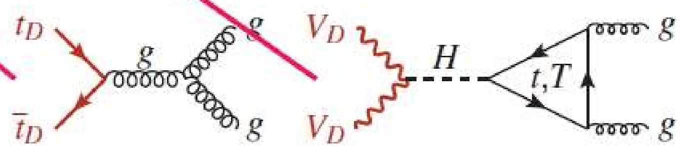

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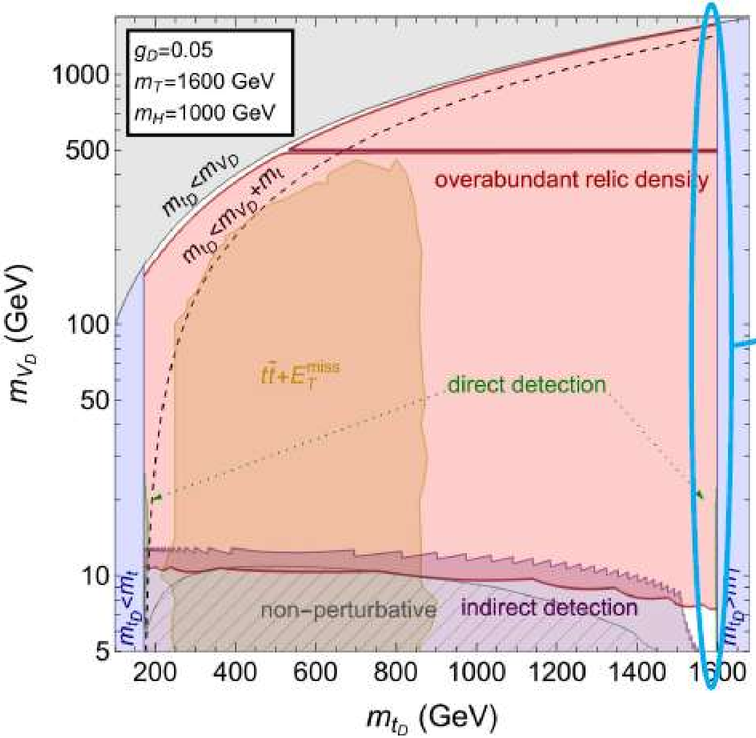

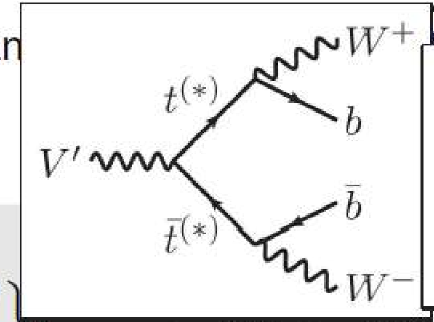

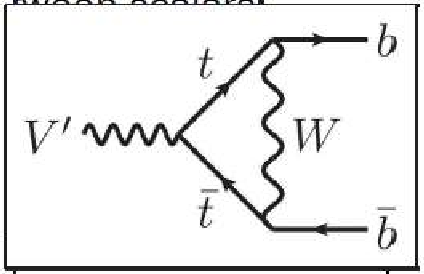

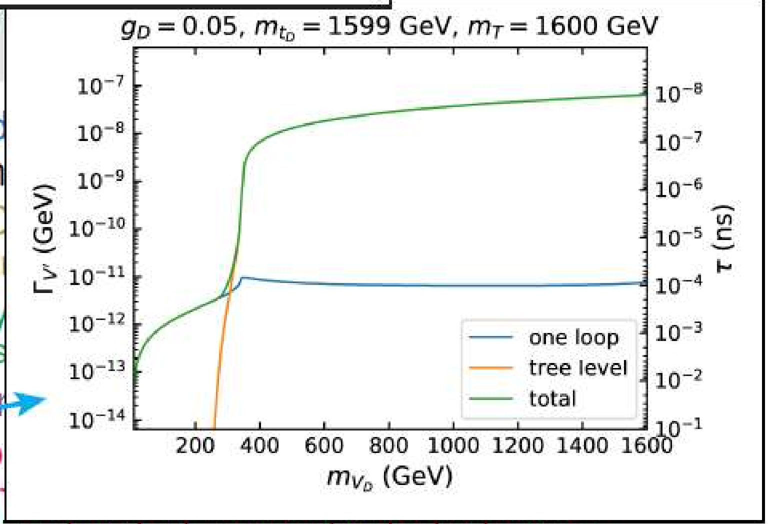

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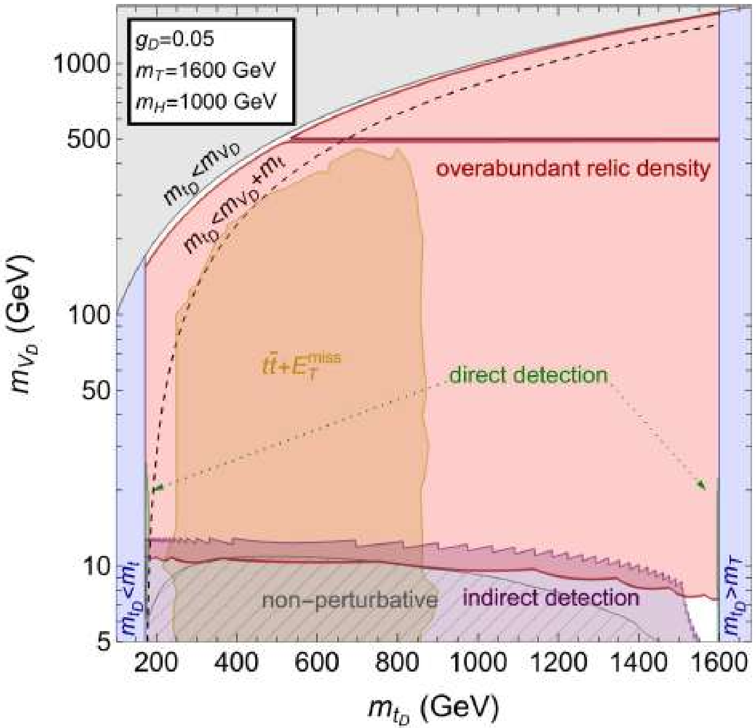
$$\Psi = \begin{pmatrix} t_D \\ T \end{pmatrix} \quad \text{with} \quad m_t < m_{t_D} \leq m_T \qquad\qquad \sin\theta_S = 0$$

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)

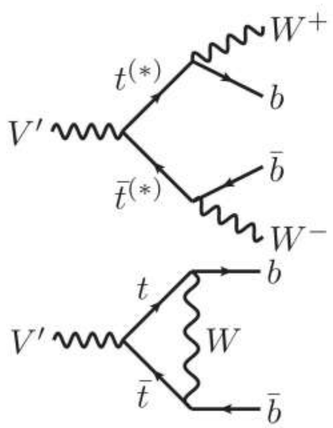
Very weak direct detection constraints (mostly for $m_{t_D} \sim m_t$ or $m_{t_D} \sim m_T$ and light DM)

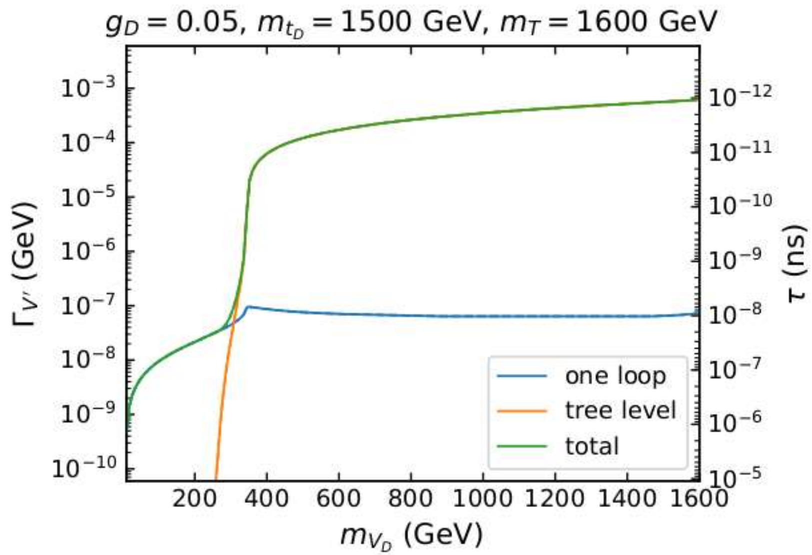
Indirect detection constrains light DM

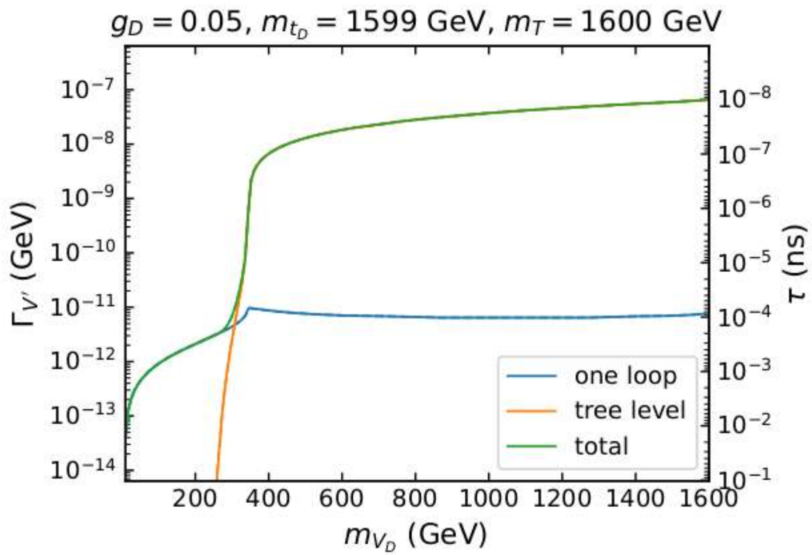
Strong constrain from relic density
- → the model "lives" on the red contours ($\Omega_{\rm DM}^{\rm Planck}$)
- → overabundant region shrinks for larger g_D
  - → and ID constraints vanish
- → effective (co-)annihilation processes
  - → on the H_D pole, exclusion from ID

The mediator t_D can be long lived, and V' too

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


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