# $(g\text{-}2)_\mu$ from the Fermionic Portal to Vector Dark Matter

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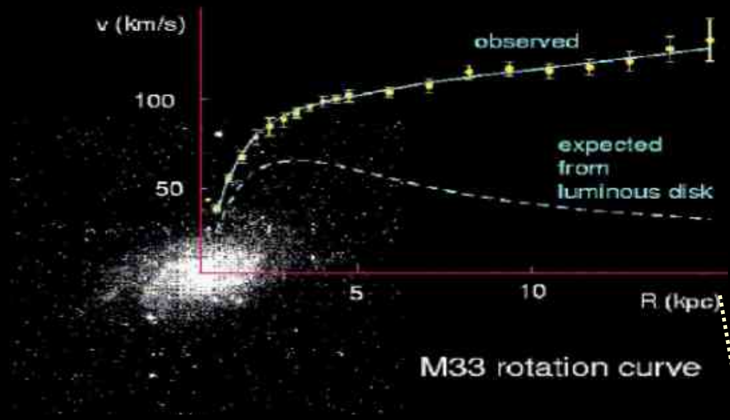
in collaboration with Luca Panizzi, Nakorn Thongyoi and Franz Wilhelm (work in progress)

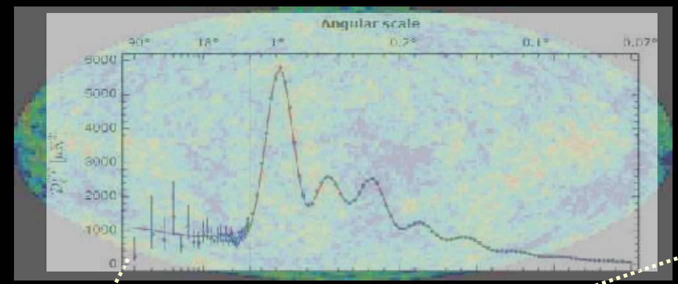
**Workshop on the Standard Model and Beyond**
**August 27 – September 7, 2023**


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

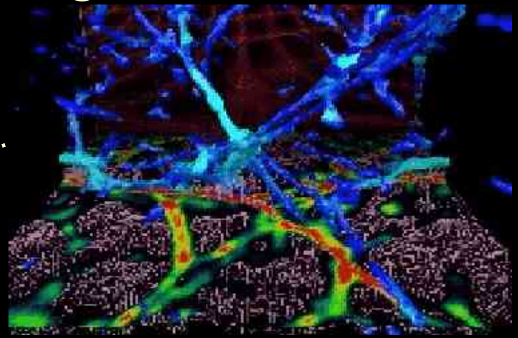
## Galactic rotation curves

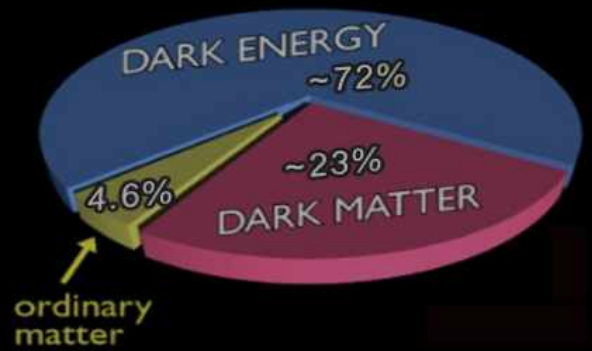



## CMB: WMAP and PLANCK



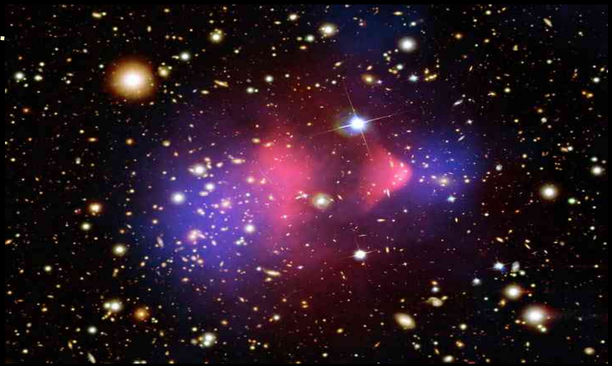

## Large Scale Structures



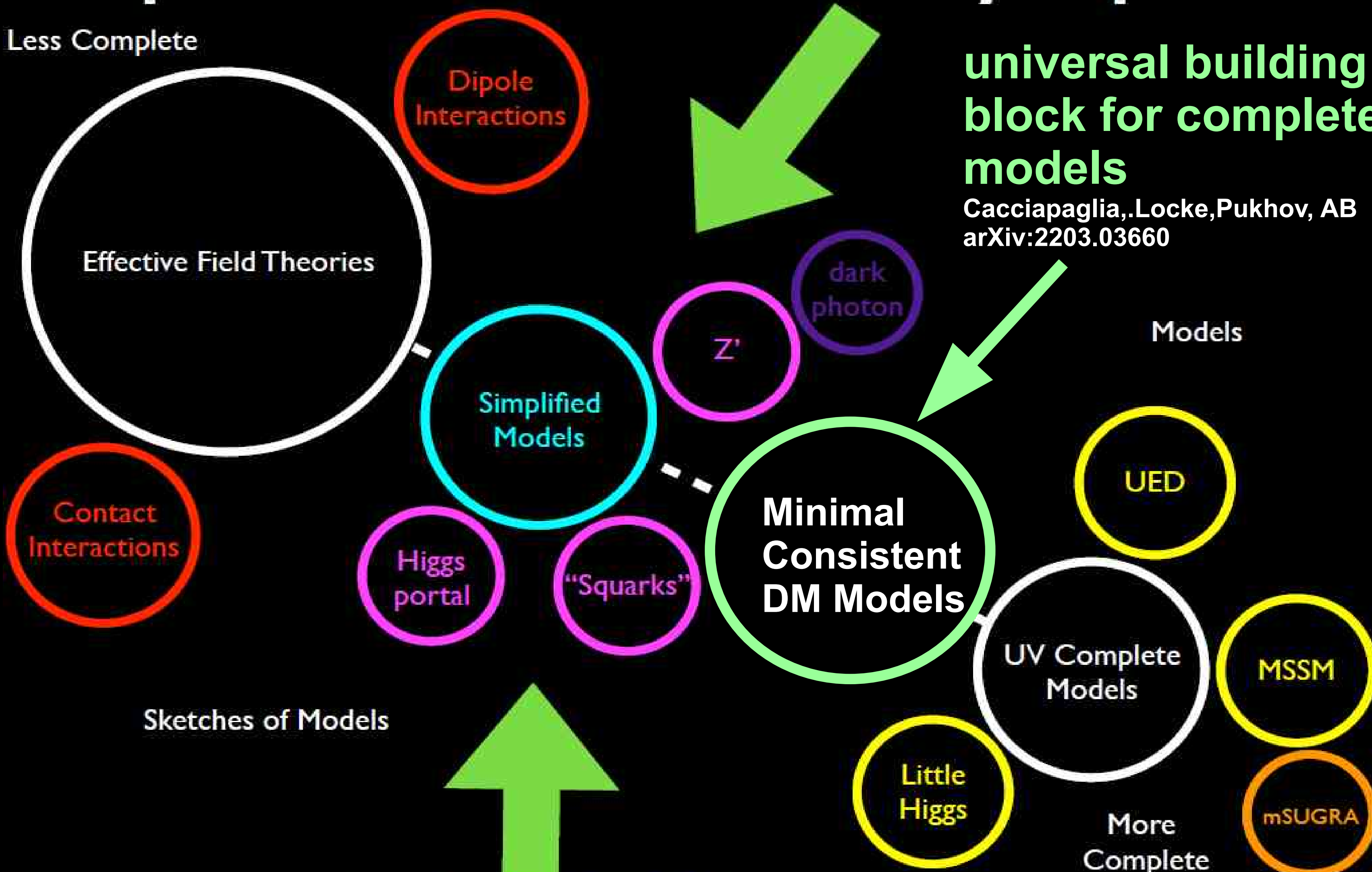



## Gravitational lensing

## Bullet cluster



# Spectrum of Theory Space



# Vector DM and Vector-Like Fermionic Portal

- Higgs portal : the parameter space for minimal scenarios is almost excluded
- **Vector Like(VL) fermionic portal for Vector Dark Matter** (also in Nakorn's talk)
  - $SU(2)_D$ gauge triplet (new dark gauge) $V_\mu^D$
  - Complex scalar doublet charged under $SU(2)_D$ $\Phi_D$ – to break gauge group
  - Vector-Like fermion doublet of $SU(2)_D$ $\Psi$ – to "talk" to SM

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  - we assign the "dark charge" to the components of the doublets, e.g. $Q_D = T_D^3 + Y_D$ and require its conservation
  - $SU(2)_D \times U(1)_{\text{glob}} \to U(1)^d_{\text{glob}}$ pattern of dark sector breaking
  - $\mathbb{Z}_2$ subgroup can be defined as: $(-1)^{Q_D}$

# Vector DM and Vector-Like Fermionic Portal

| | $SU(2)_L$ | $U(1)_Y$ | $SU(2)_D$ | $Q_D$ | $Z_2$ |
|---|---|---|---|---|---|
| $\Phi_D = \begin{pmatrix}\varphi_D^{+\frac{1}{2}} \\ \varphi_D^{-\frac{1}{2}}\end{pmatrix} \to \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ H_D + v_D\end{pmatrix}$ | 1 | 0 | 2 | $+1$<br>$0$ | $-$<br>$+$ |
| $\Psi = \begin{pmatrix}\psi_D \\ \psi\end{pmatrix} = \begin{pmatrix}\tilde{F} \\ F\end{pmatrix}$ | 1 | $Q_{EM}$ | 2 | $+1$<br>$0$ | $-$<br>$+$ |
| $V_\mu^D = \begin{pmatrix}V_\mu^{D+} \\ V_\mu^{D0} \\ V_\mu^{D-}\end{pmatrix} = \begin{pmatrix}\tilde{V}_D^+ \\ V' \\ \tilde{V}_D^-\end{pmatrix}$ | 1 | 0 | 3 | $+1$<br>$0$<br>$-1$ | $-$<br>$+$<br>$-$ |

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- If we chose $Y_D = +1/2$ for $\Phi_D$ and $\Psi$ then we have

$$y' \bar{\Psi}_L \Phi_D f_R^{\rm SM} + \cancel{y'' \bar{\Psi}_L \Phi_D^c f_R^{\rm SM}} + h.c$$

$y''$ **eliminated, DM is stabilised!**

# Fermionic Portal for Vector Dark Matter (FPVDM)

- It is the framework, representing the class of models
  (Deandrea, Moretti, Panizzi, Ross, Thongyoi, AB – arXiv:2204.03510,2203.04681)

- Various realisations are possible, including one or several VL fermions

$$\mathcal{L}_{FPVDM} = -\frac{1}{4}(V^i_{D\mu\nu})^2 + \bar{\Psi} i \not{D} \Psi + |D_\mu \Phi_D|^2 - V(\Phi_H, \Phi_D)$$
$$- \underline{(y'_{\alpha\beta} \bar{\Psi}^{i\alpha}_L \Phi_D f^{\mathrm{SM}\beta}_R} + h.c) - M_\Psi{}^{ij} \bar{\Psi}^i \Psi^j$$

$$V(\Phi_H, \Phi_D) = -\mu_H^2 \Phi_H^\dagger \Phi_H - \mu_D^2 \Phi_D^\dagger \Phi_D + \lambda_H (\Phi_H^\dagger \Phi_H)^2$$
$$+\lambda_D (\Phi_D^\dagger \Phi_D)^2 + \lambda_{HD} (\Phi_H^\dagger \Phi_H)(\Phi_D^\dagger \Phi_D)$$

- $y'_{\alpha\beta}$ can have a flavour structure – to explain flavour anomalies
- $\lambda_{HD}$ can be zero at tree-level, DM can be well-generated via FP

- the model with $\Psi = \begin{pmatrix} \tilde{T} \\ T \end{pmatrix}$ and $\lambda_{HD} = 0$ was explored and discussed already (Nakorn's talk)

## FPVDM model with $\Psi_M = \begin{pmatrix} \tilde{M} \\ M' \end{pmatrix}$, the partner of muon

$$\mathcal{L}_{\mu PVDM} \supset -y'\bar{\Psi}_{ML}\Phi_D \mu_R + h.c \qquad \text{with} \quad \tilde{V}_D, \quad V', \quad H_D, \quad M', \quad \tilde{M}$$

- has potential to explain DM relic density and $(g\text{-}2)_\mu$ anomaly

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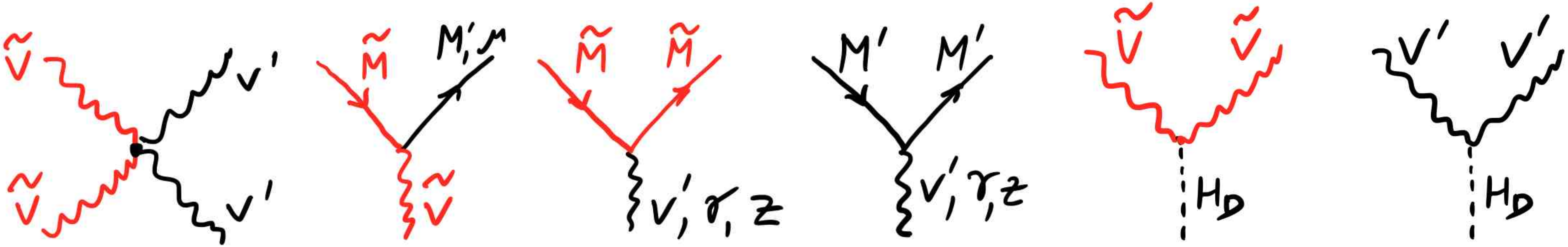
- Interactions:



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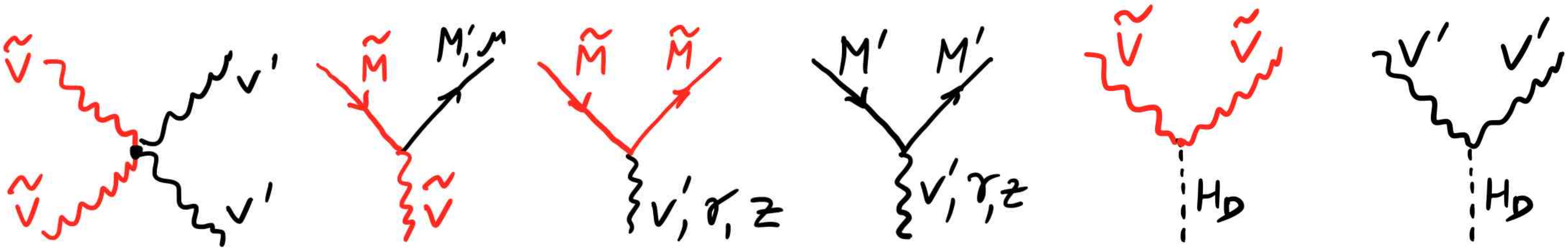
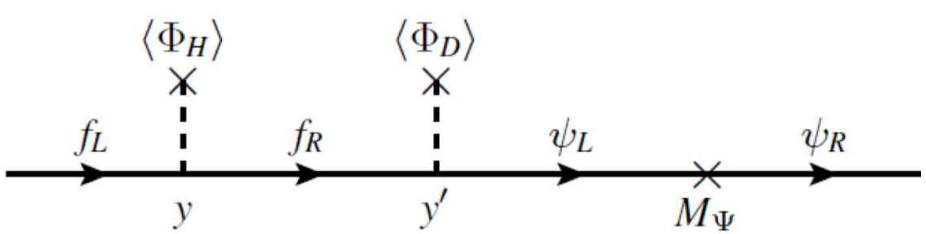
- Interactions+mixing:



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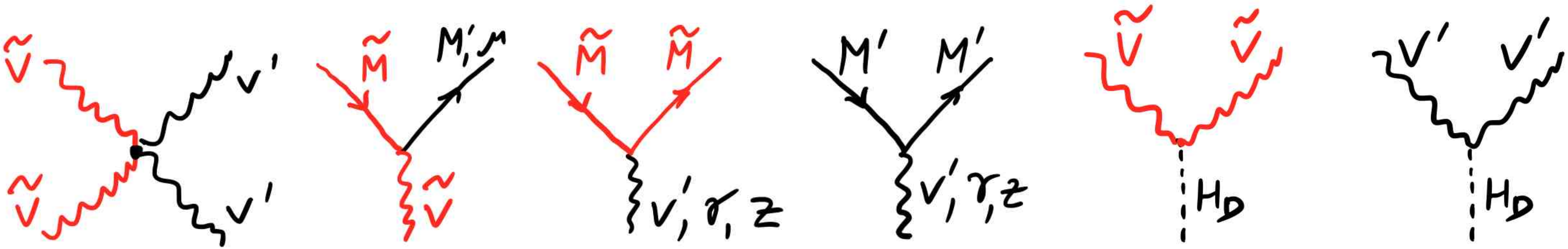
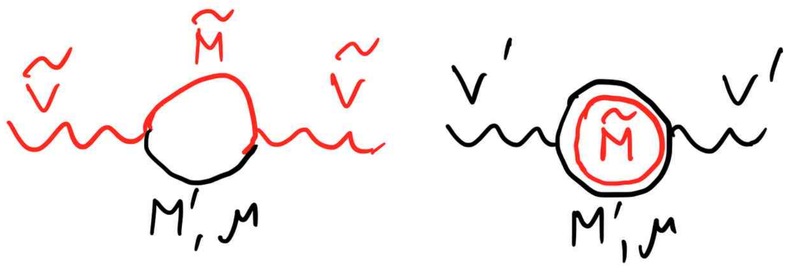
- Interactions+mass corrections:




$$m_{V_D} - m_{V'} = \frac{g_D^2 m_{M'}^2}{32\pi^2 m_{V_D}} \left( \frac{m_{M'}^2 - m_{\tilde{M}}^2}{m_{M'}^2} \right)^2$$

# The status of $(g\text{-}2)_\mu$ and our approach here

- The combined experimental value from BNL +FNAL(from August 2023):

$$a_\mu^{\rm EXP} = 116592059(22) \times 10^{-11}$$

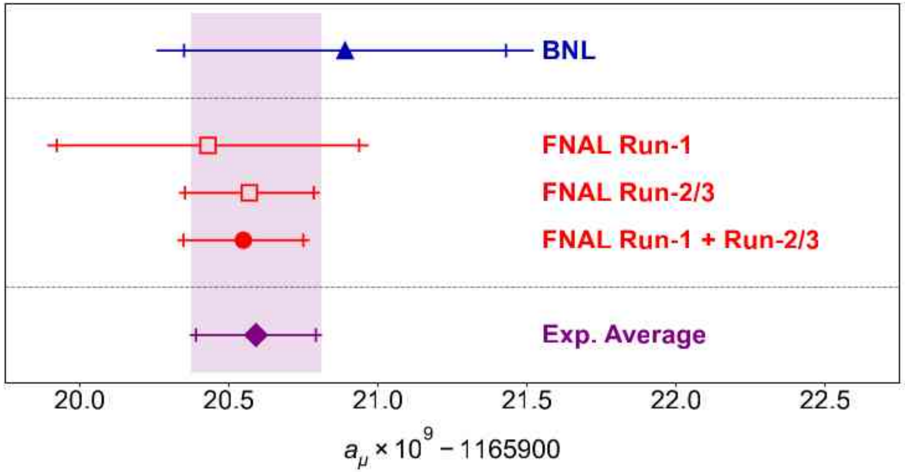
- The SM Theory Initiative 2020 prediction [arXiv:2006.04822] provides

$$a_\mu^{\rm SM} = 116591810(43) \times 10^{-11}$$

- Combining above numbers, one concludes one finds 5.1σ SM vs EXP discrepancy

$$\Delta a_\mu = a_\mu^{\rm EXP} - a_\mu^{\rm SM} = 249(48) \times 10^{-11}$$

FNAL, (g-2)m , August 2023, arXiv:2308.06230



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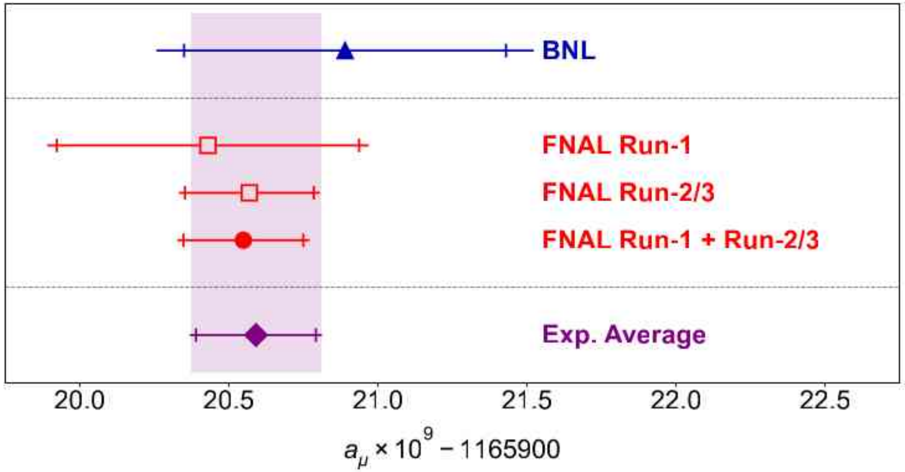


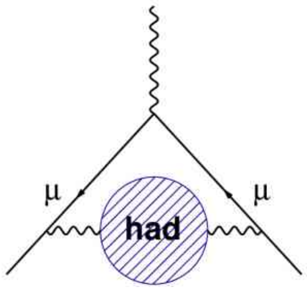


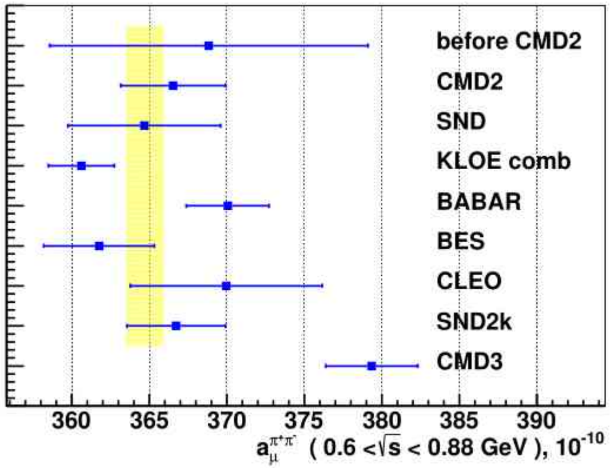

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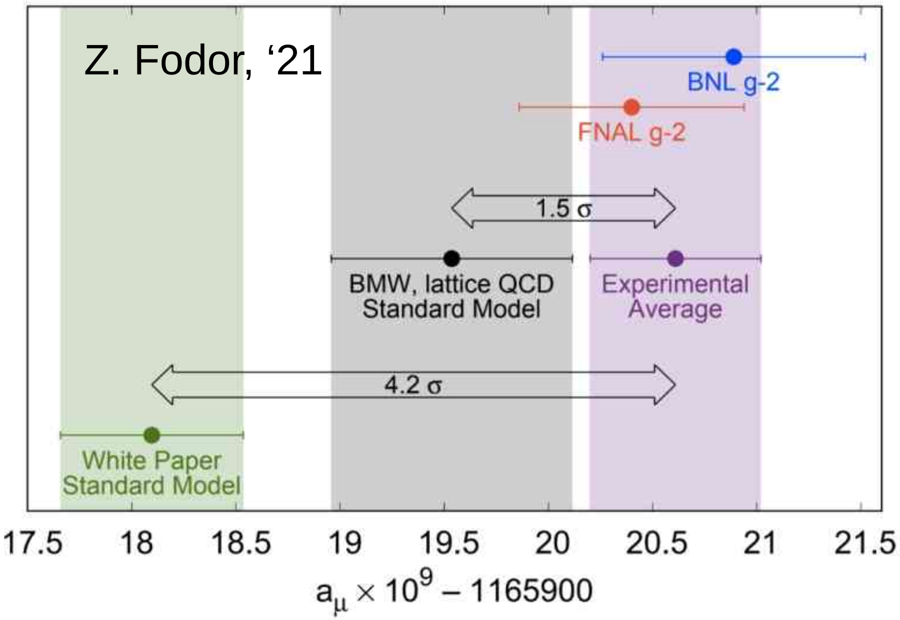
- Of course recent Lattice results from BMW [Nature 593, 51 (2021)] must be add here



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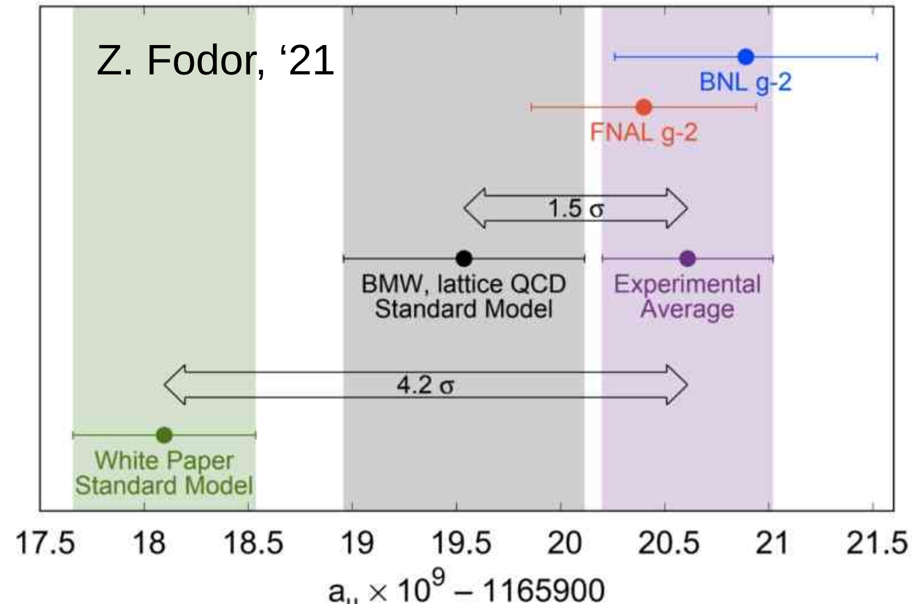
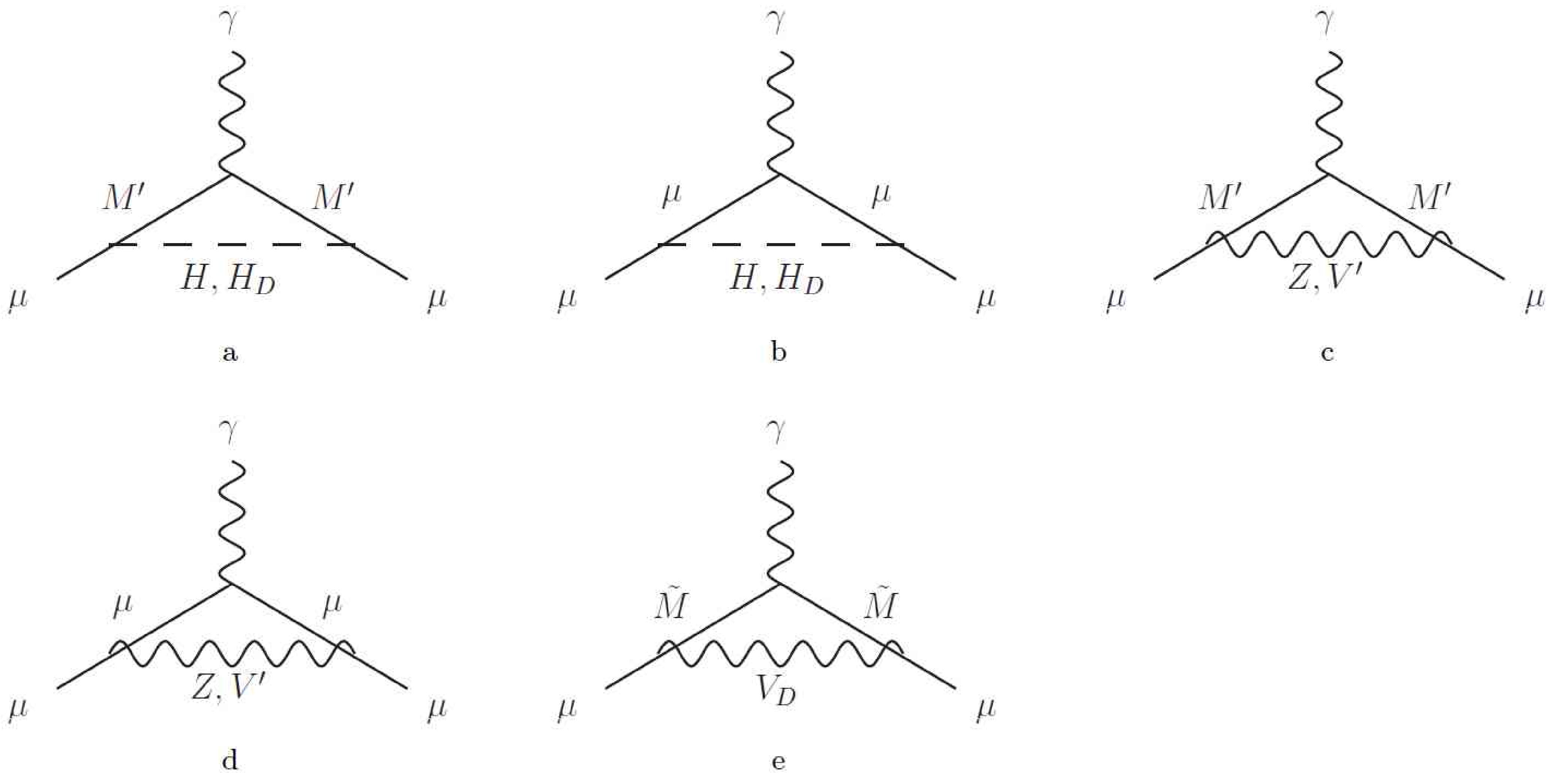
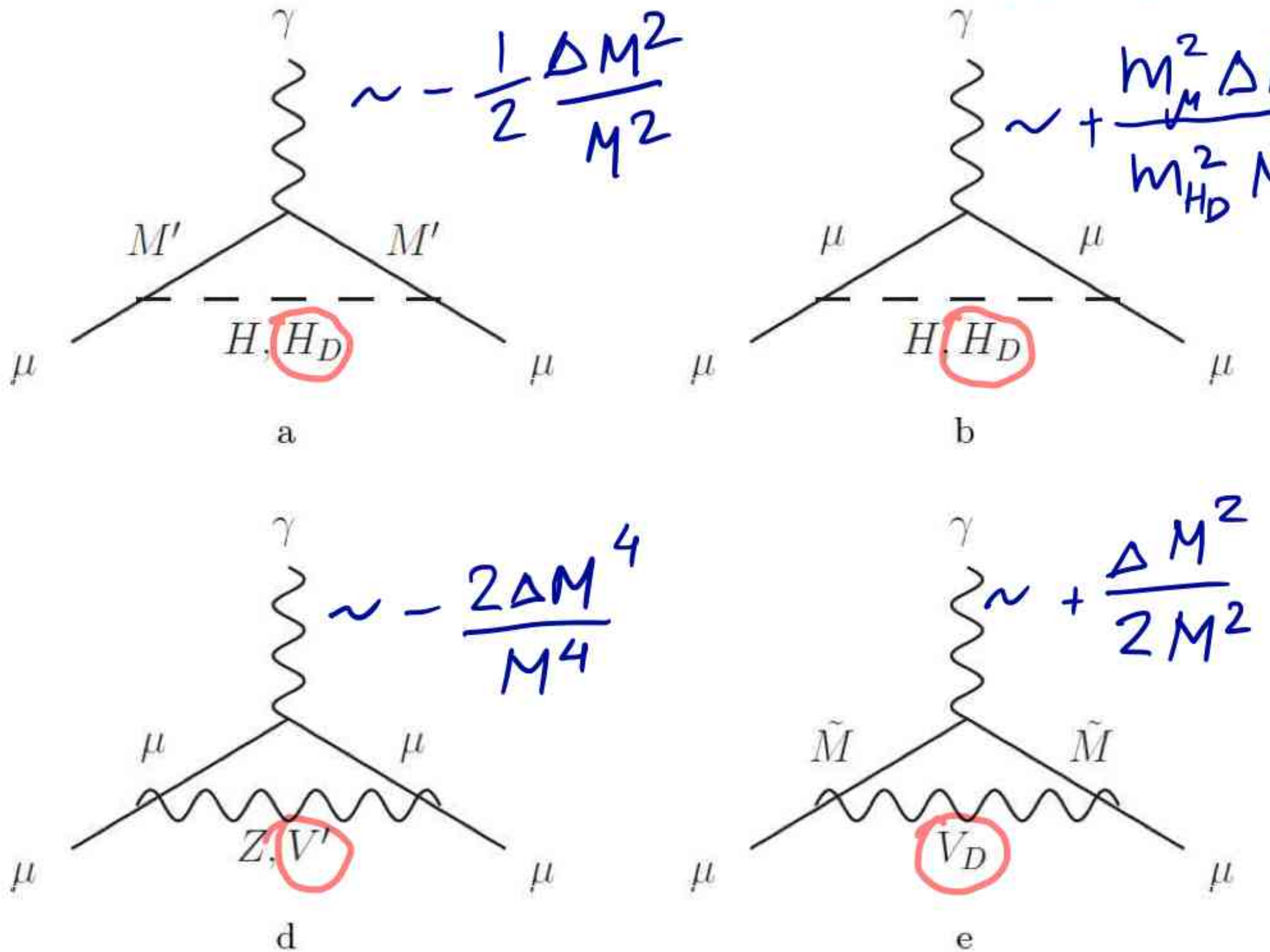



- $(g\text{-}2)\mu$ is an important puzzle to be solved including discrepancy between HVP from e+e- data and Lattice
- In our study we take $\Delta a_\mu$ as a real effect to be explained within our μFPVDM model

# The contribution to (g-2)$_\mu$ from $\mu$PVDM



# The contribution to $(g\text{-}2)_\mu$ from $\mu$PVDM x $\boxed{\frac{g_D^2}{96\pi^2}\frac{m_\mu^2}{m_{V_D}^2}}$




a: $\sim -\frac{1}{2}\frac{\Delta M^2}{M^2}$

b: $\sim +\frac{m_\mu^2 \Delta M^4}{m_{H_D}^2 M^4}$

c: $\sim +\frac{1}{4}\frac{\Delta M^2}{M^2}$

d: $\sim -\frac{2\Delta M^4}{M^4}$

e: $\sim +\frac{\Delta M^2}{2M^2}$

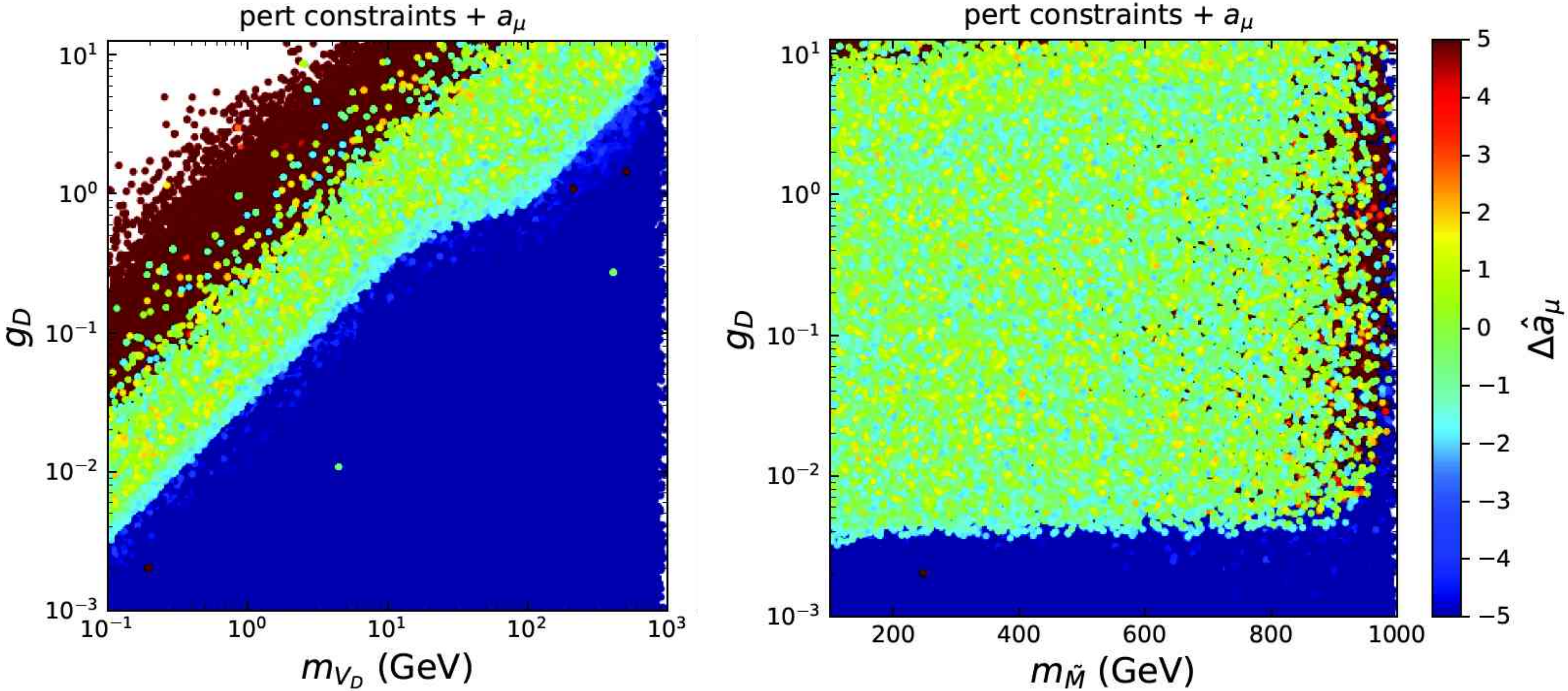
$$\Delta M^2 = m_{M'}^2 - m_{\tilde{M}}^2$$

$$M = m_{M'}$$

$M \gg m_{V_D}$ was used

# (g-2)$_\mu$ results from scan of $\boxed{g_D, m_{V_D}, m_{H_D}, m_{M'}, m_{\tilde{M}}}$ space

$$\Delta\hat{a}_\mu = \Delta a_\mu^{\mu PVDM} - \Delta a_\mu \equiv \Delta a_\mu^{\mu PVDM} - 249 \times 10^{-11}$$

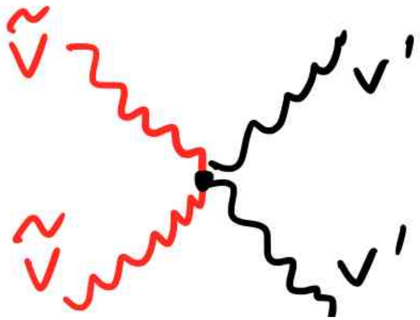



- $\Delta a_\mu$ can be explained within μFPVDM model $(g_D/m_{V_D} \sim 0.1)$
- $g_D - m_{V_D}$ correlation can be clearly observed as predicted by analytical calculations
- For $m_{M'} > 1$ TeV it is hard to explain $\Delta a_\mu$ because of $1/m_{M'}^2$ suppression

# We also aim to explain DM relic density & to be consistent with DM DD and ID as well as with collider searches

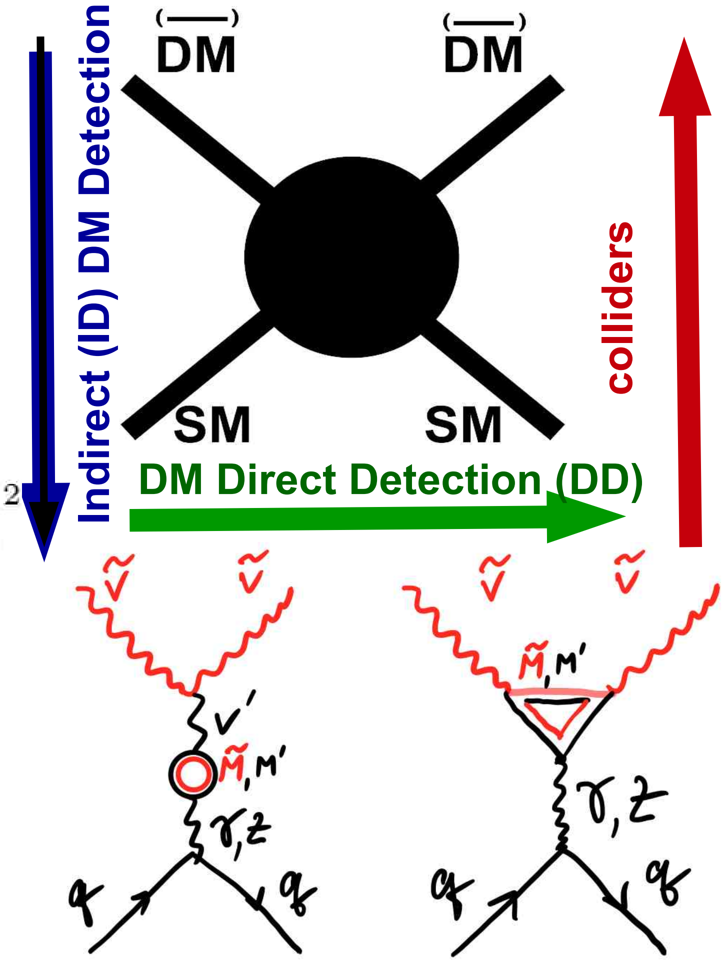
**Correct Relic density: efficient (co) annihilation**
**annihilation to photons can affect CMB**

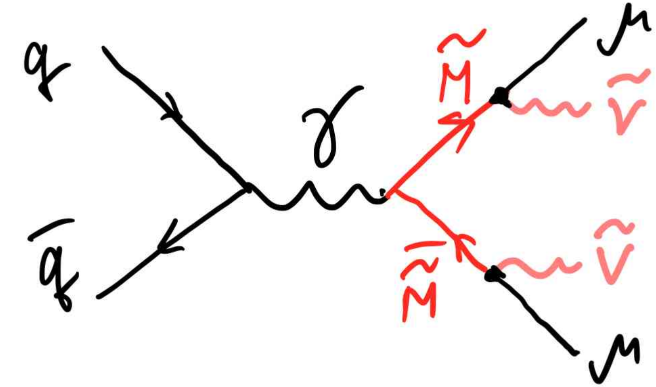
$$\Omega_{\rm DM}^{\rm Planck} h^2 = 0.12 \pm 0.0012$$




$$P_{\rm ann} < 3.2 \times 10^{-28}\, \frac{\rm cm^3}{\rm s\,GeV}$$

$$P_{\rm ann} = \sum_j \frac{f_j^{\rm eff} \langle \sigma v \rangle_j}{M_{\rm DM}} \left( \frac{\Omega_{\rm DM}}{\Omega_{\rm DM}^{\rm Planck}} \right)^2$$



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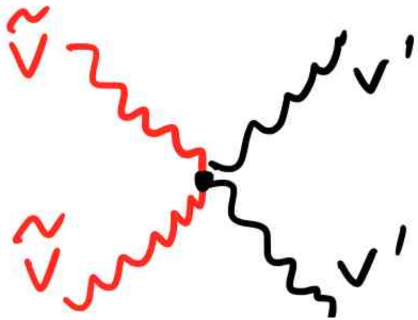


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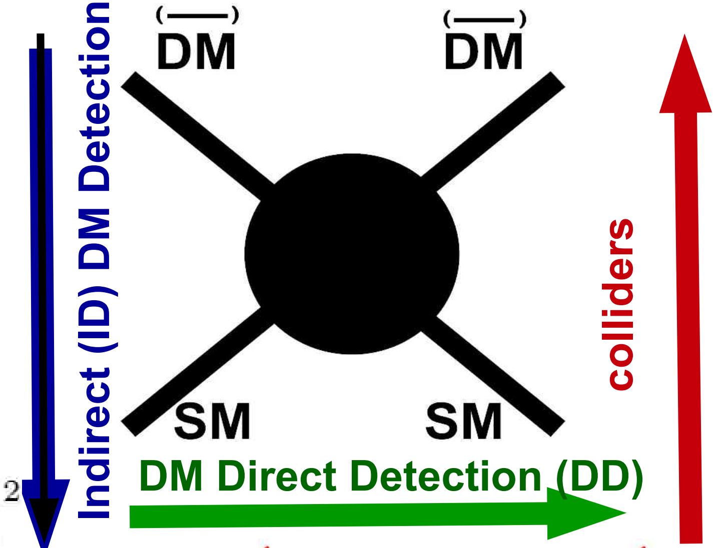
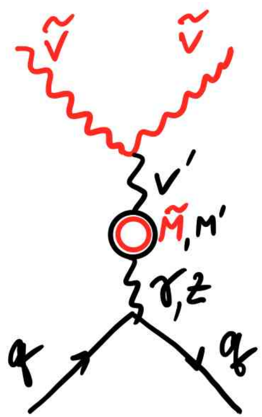
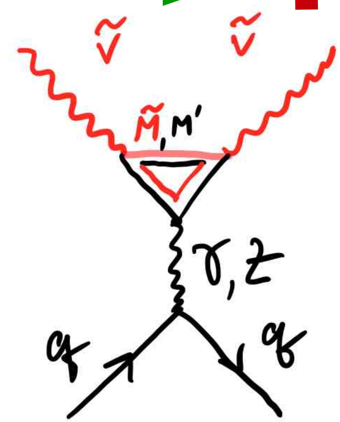
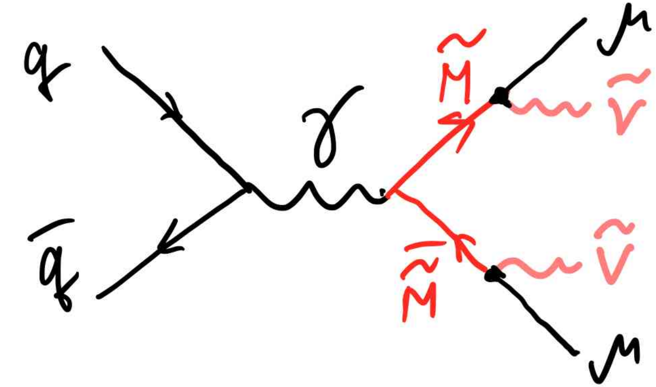



**Tools used**

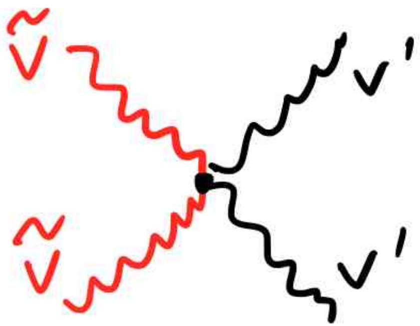
- **DM DD, ID, Relic density**

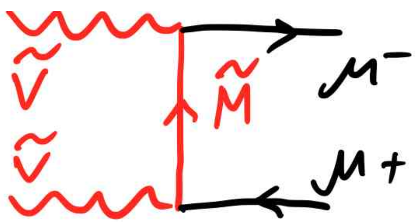
  **LanHEP, CalcHEP, micrOMEGAs**

- **Collider searches**

  **CalcHEP, MC@NLO, PYTHIA, DELPHES, MadAnalysis, CHECKMATE**

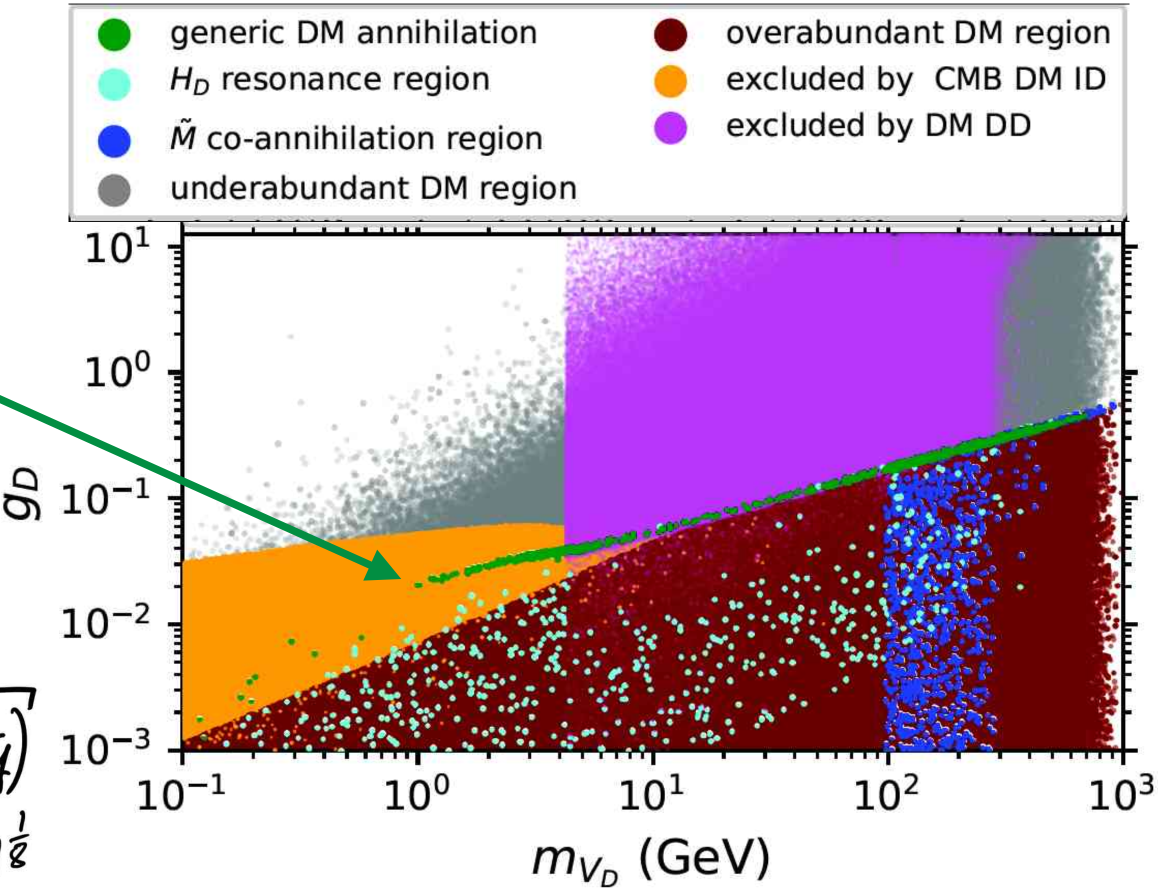
# Cosmological constraints on μPVDM parameter space




$$\Omega h^2 \propto \frac{M_{V_D}^2}{g_D^4} \frac{1}{\sqrt{g_{eff}(T_f)}}$$

$$g_D \sim \sqrt{M_{V_D}} / [g_{eff}(T_f)]^{\frac{1}{8}}$$



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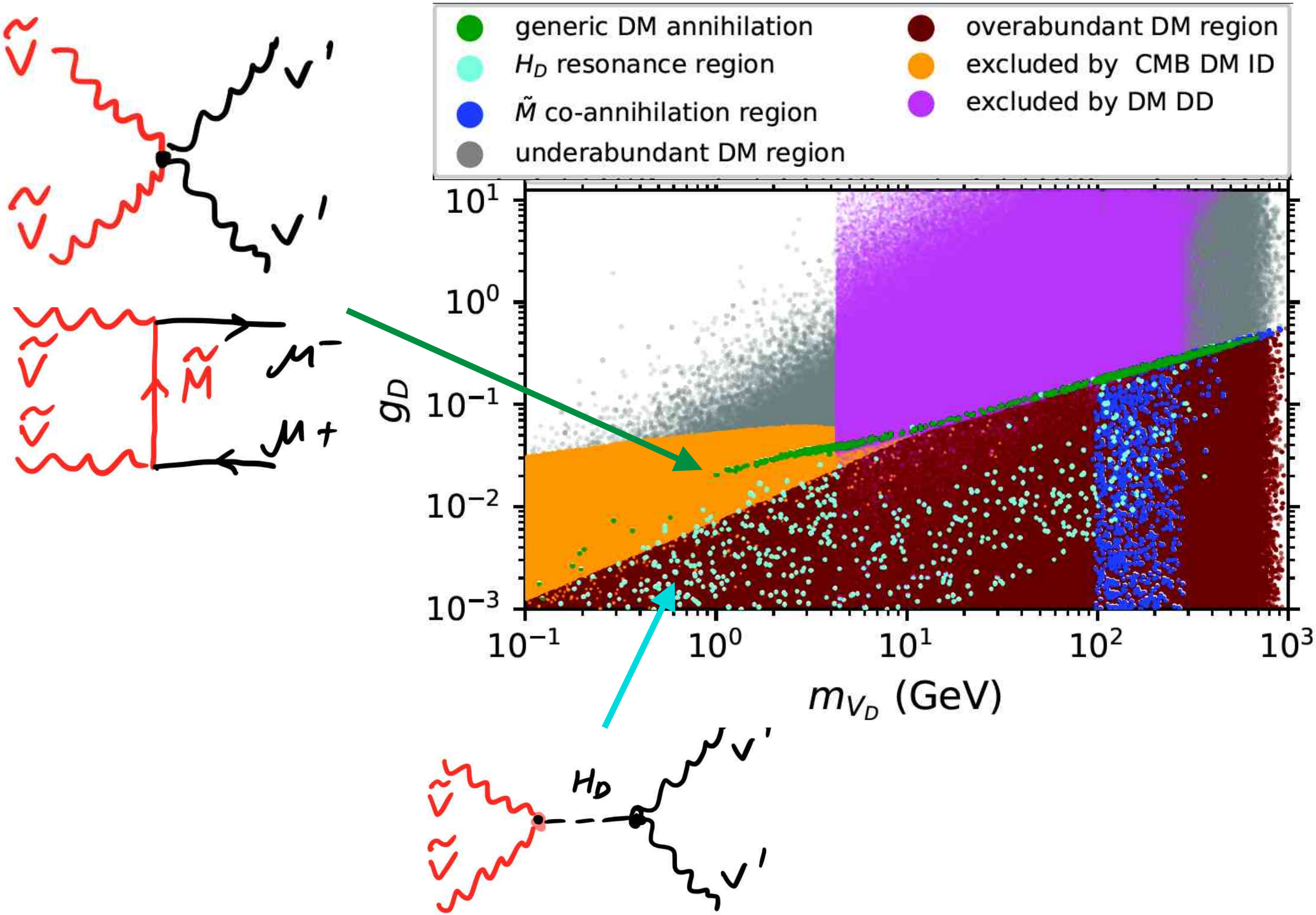

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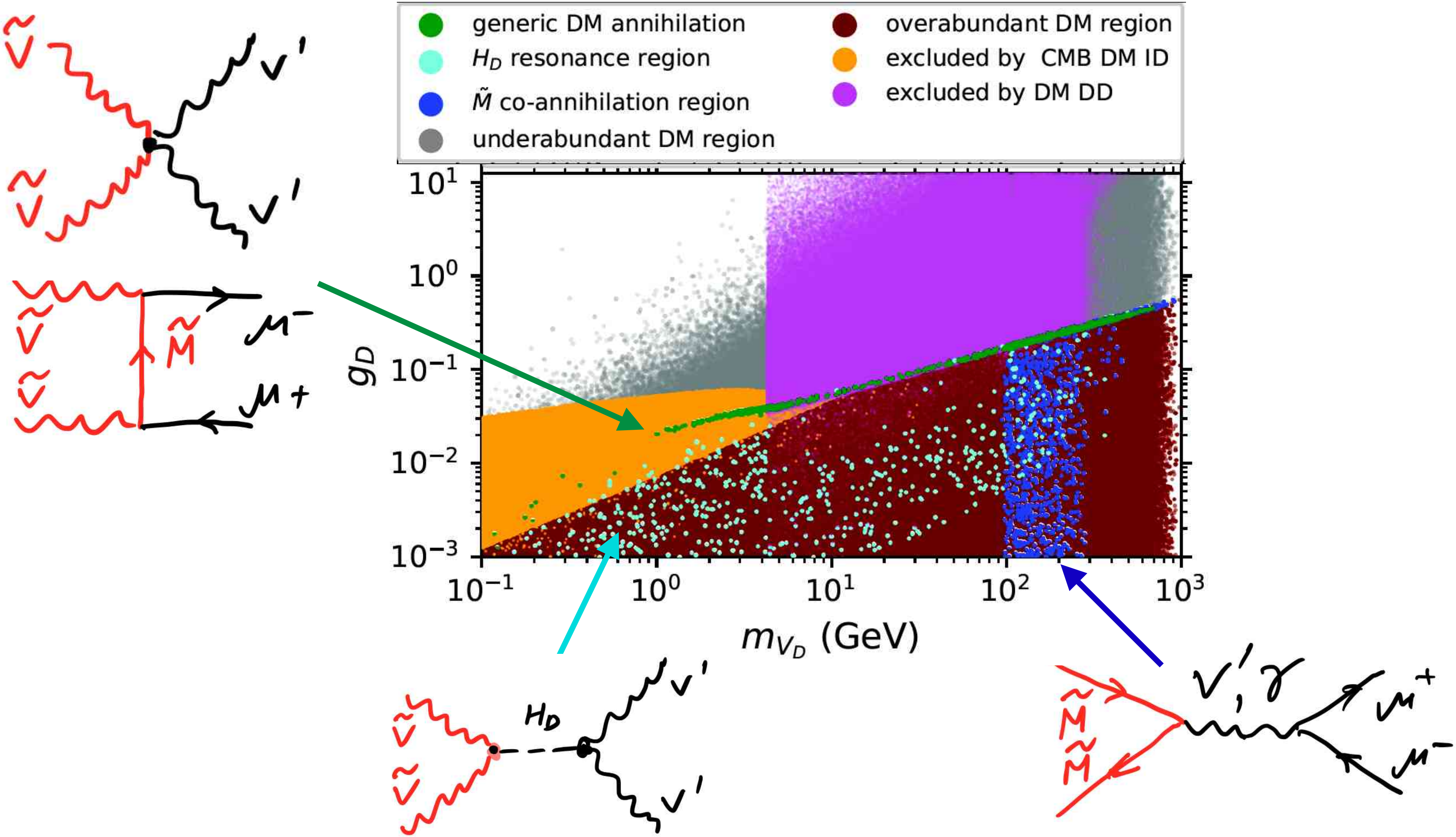
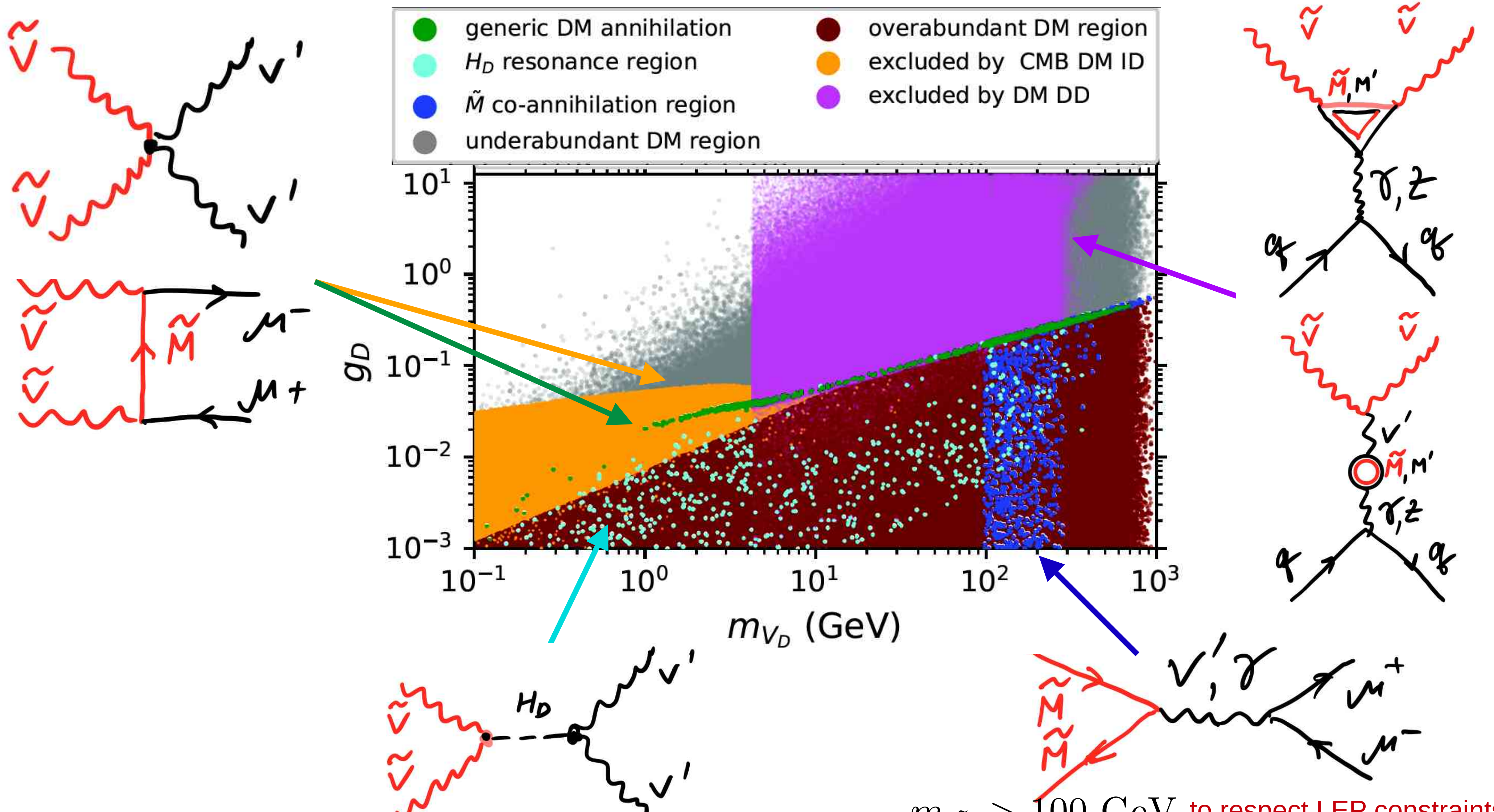
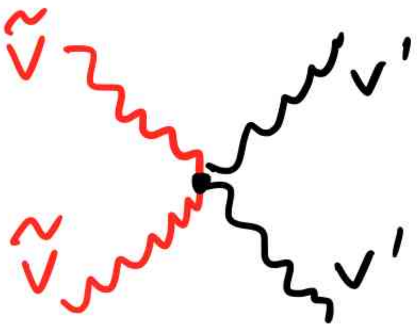


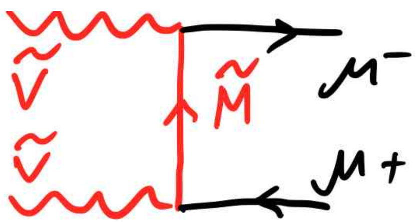
# Cosmological constraints on μPVDM parameter space

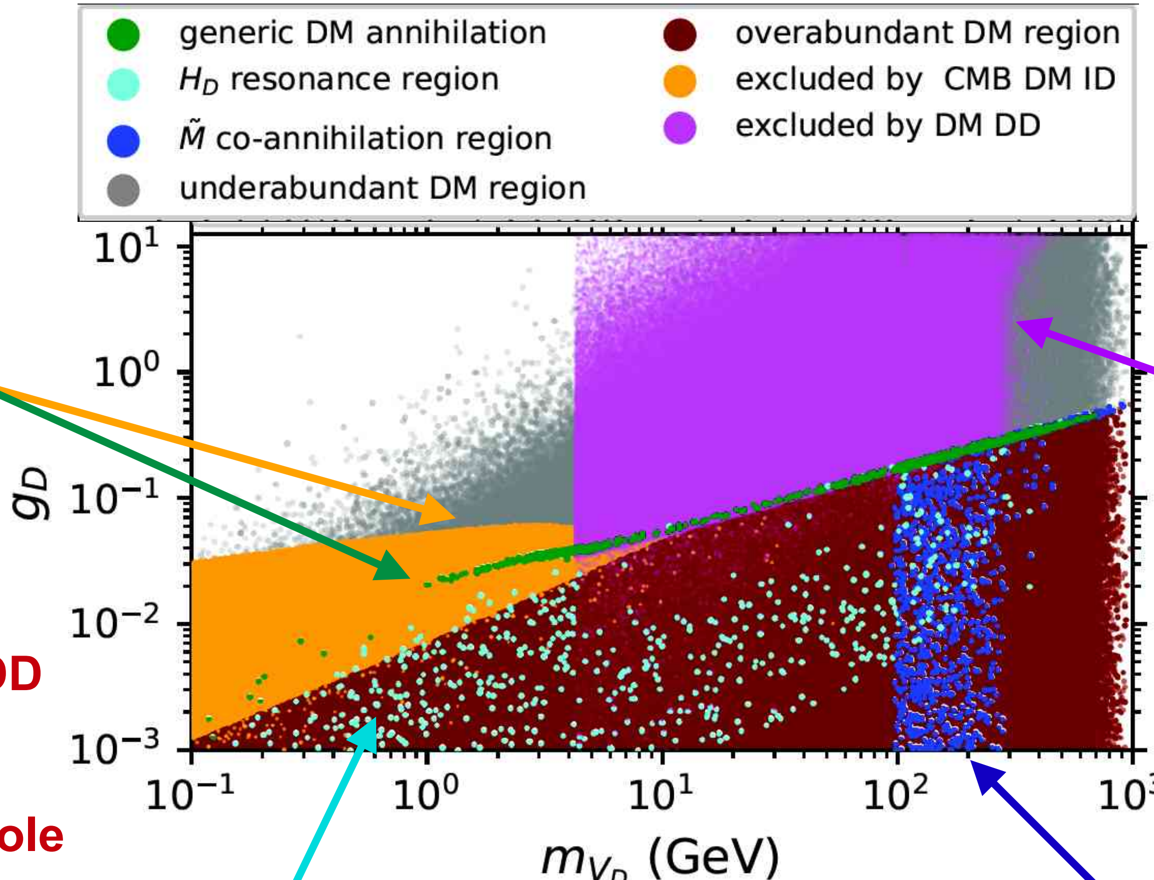


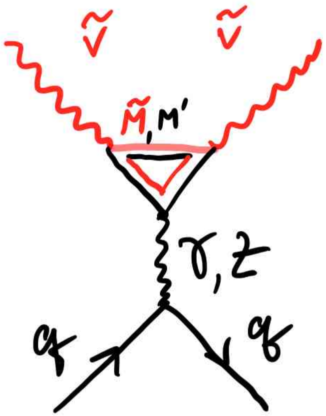

$m_{\tilde{M}} > 100$ GeV to respect LEP constraints

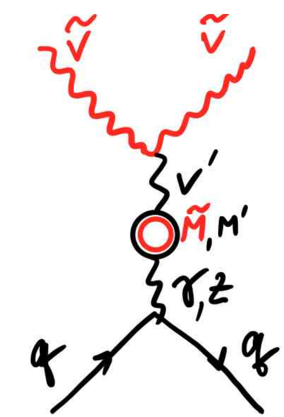
# Cosmological constraints on μPVDM parameter space



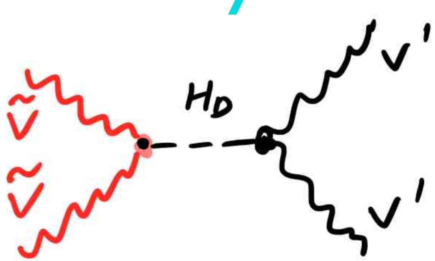



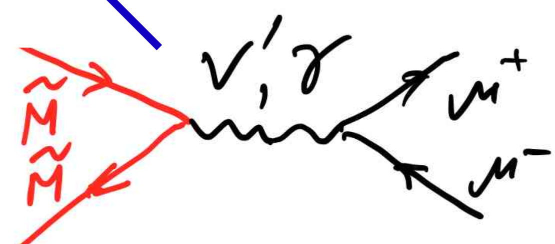



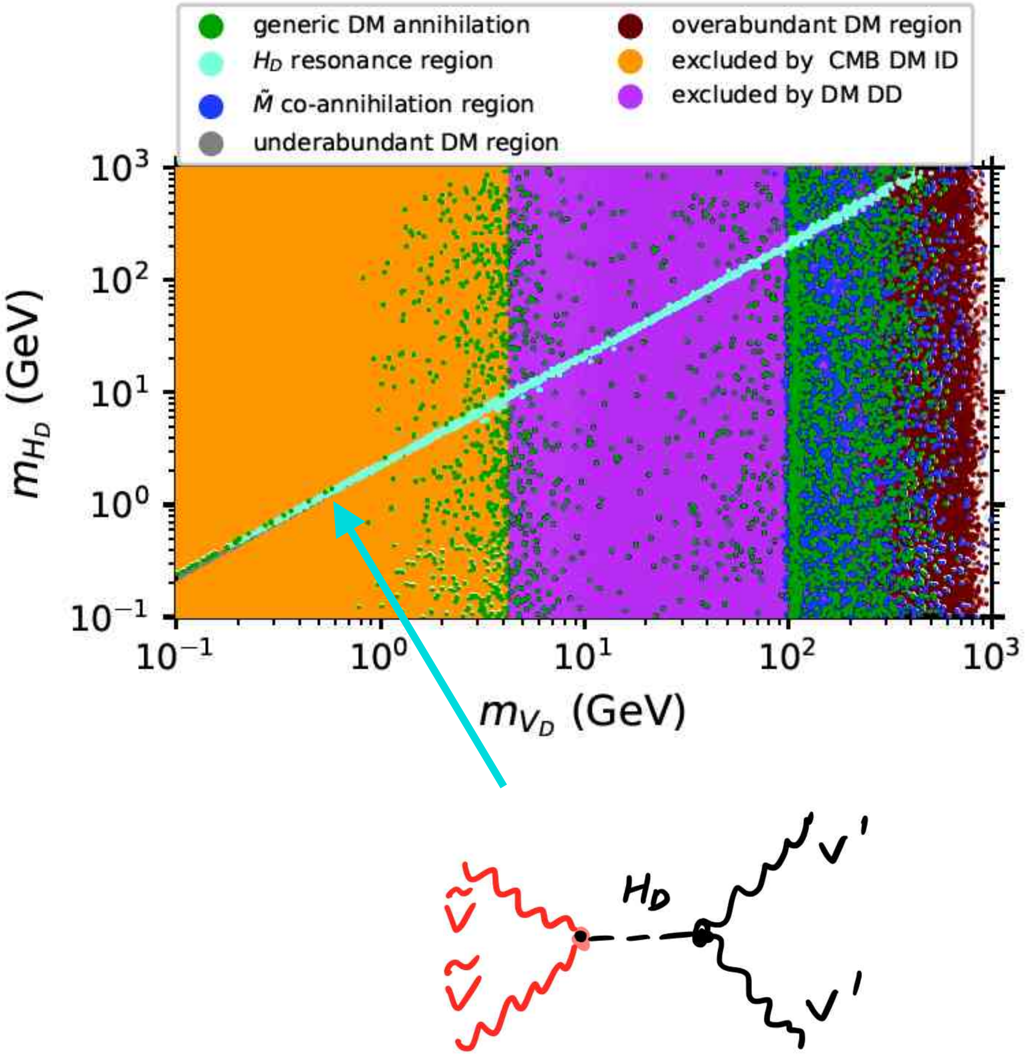

- **both DM ID and DD exclusions play important complementary role**

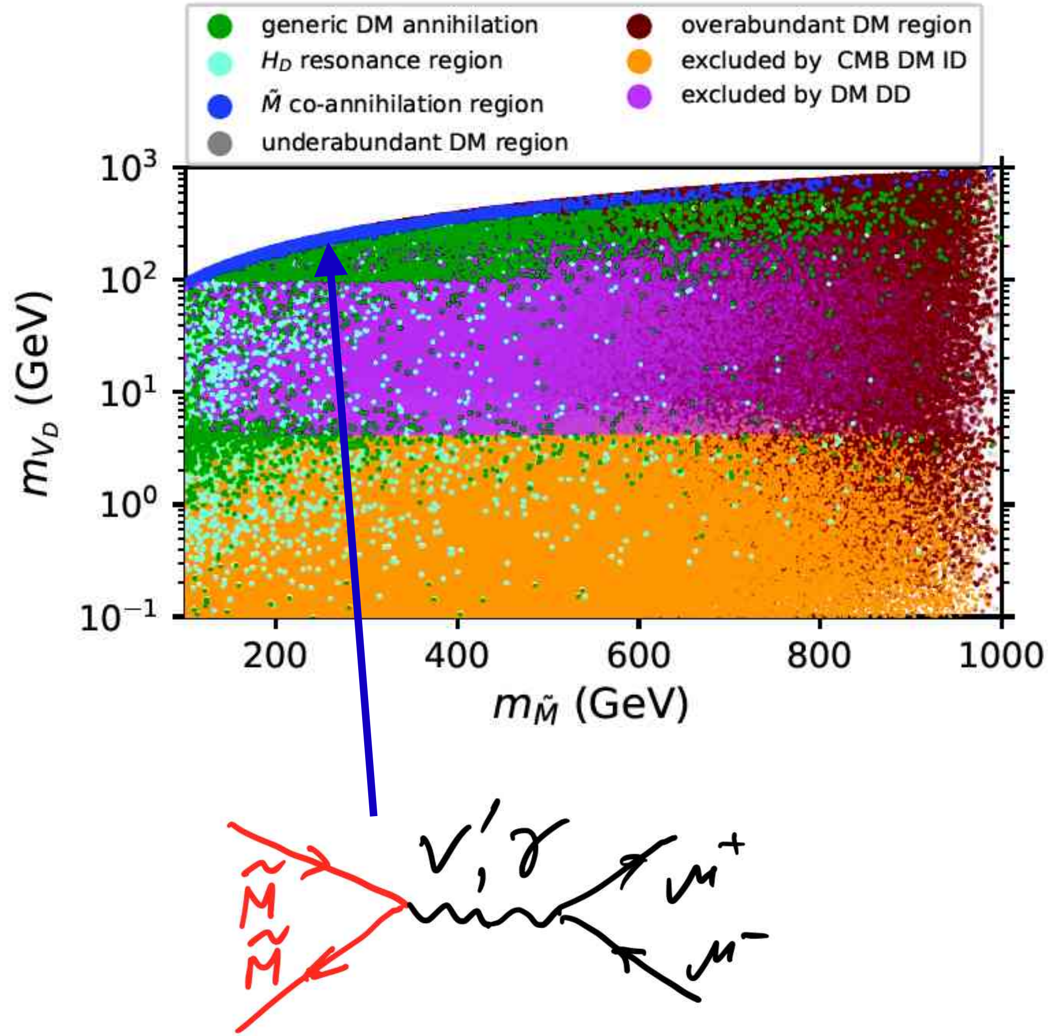


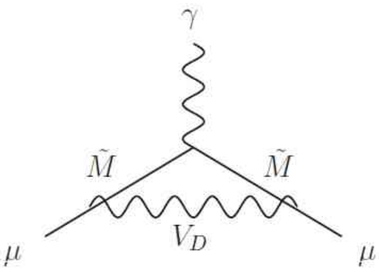

$m_{\tilde{M}} > 100$ GeV to respect LEP constraints

# $m_{HD}$ vs $m_{VD}$ and $m_{VD}$ vs $m_M$ planes



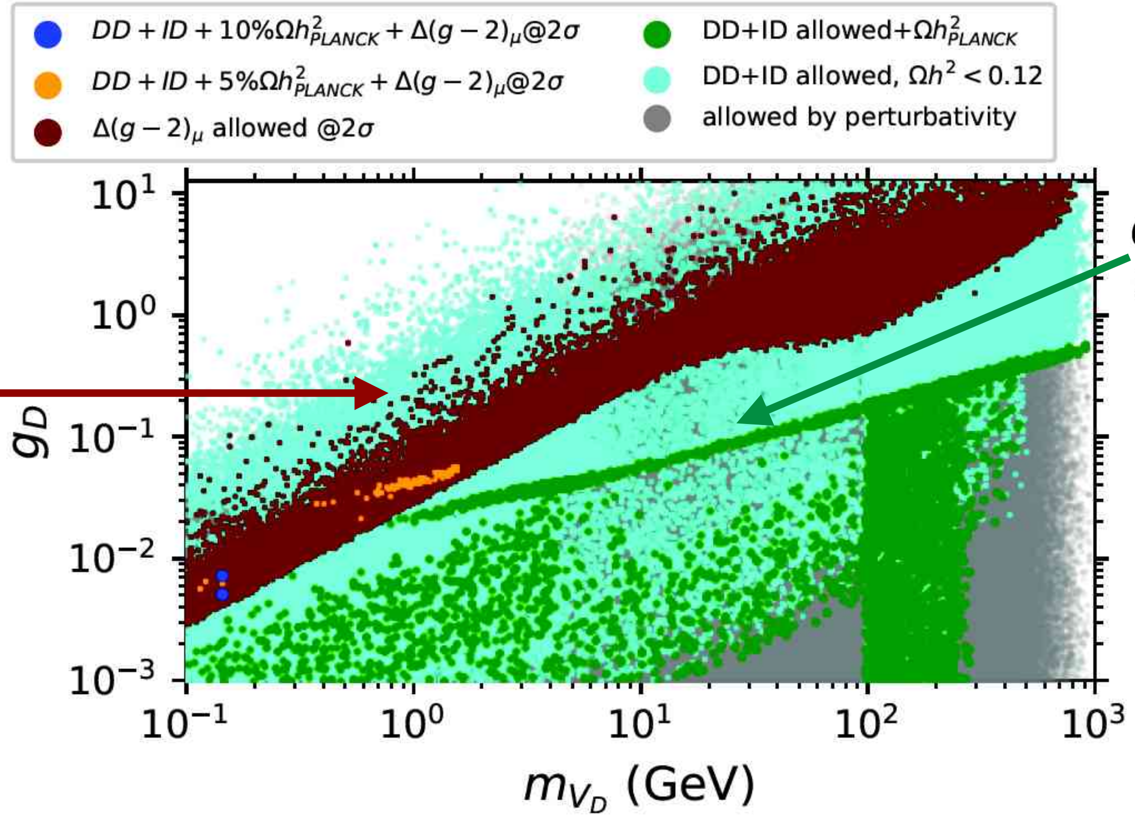



# Combining $(g\text{-}2)_\mu$ and DM constraints




$$g_D \sim m_{V_D}$$

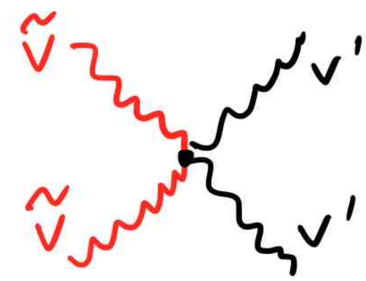
"trajectory" to explain $\Delta a_\mu$



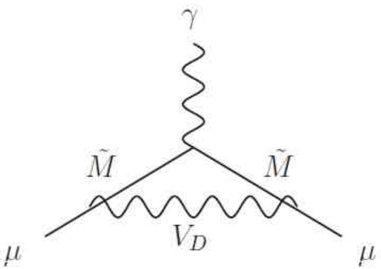

$$\Omega h^2 \propto \frac{M_{V_D}^2}{g_D^4} \frac{1}{\sqrt{g_{eff}(T_f)}}$$

$$g_D \sim \sqrt{M_{V_D}} / [g_{eff}(T_f)]^{\frac{1}{8}}$$

$\Omega h^2_{PLANCK}$
"trajectory" to explain DM relic density



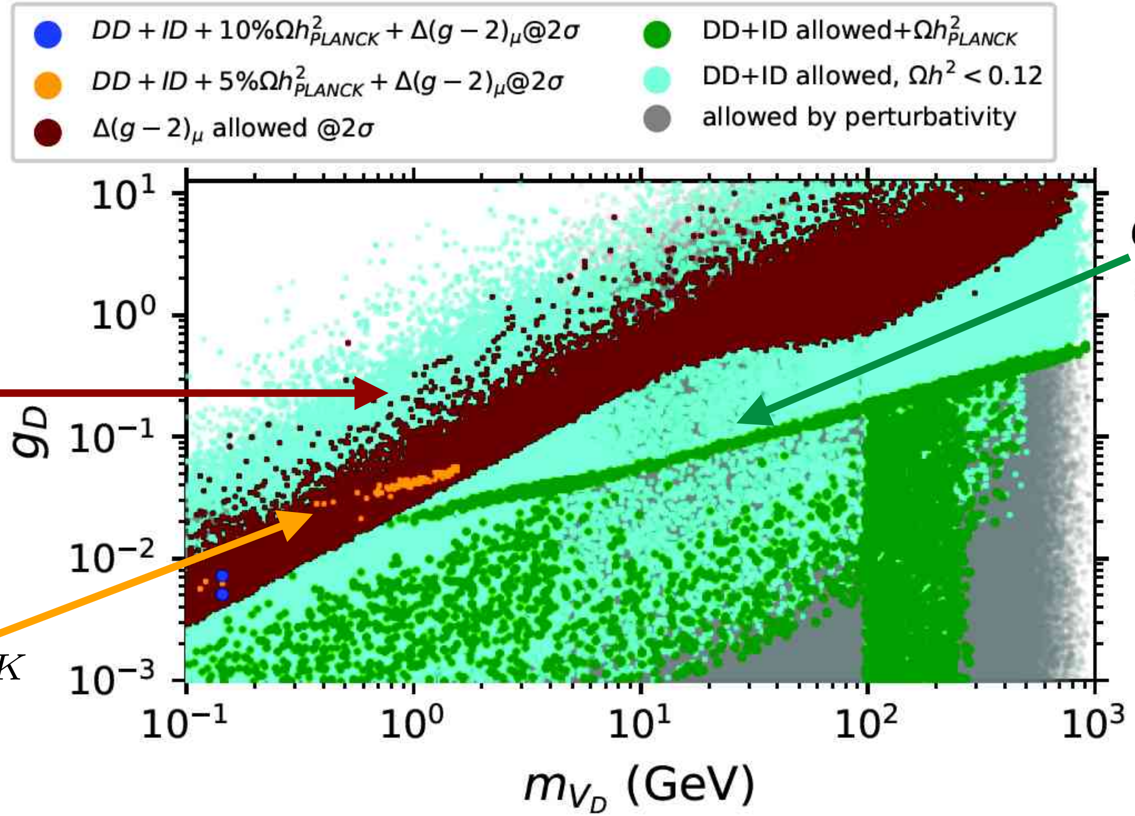
# Combining $(g\text{-}2)_\mu$ and DM constraints




$g_D \sim m_{V_D}$

"trajectory" to explain $\Delta a_\mu$

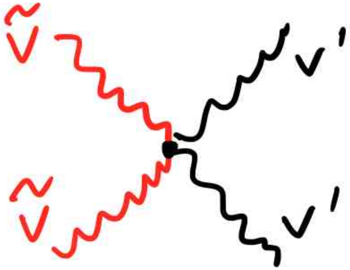
$5\% \Omega h^2_{PLANCK}$




$\Omega h^2 \propto \frac{M_{V_D}^2}{g_D^4} \frac{1}{\sqrt{g_{eff}(T_f)}}$

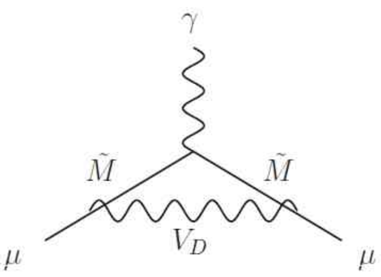
$g_D \sim \sqrt{M_{V_D}} / [g_{eff}(T_f)]^{\frac{1}{8}}$

$\Omega h^2_{PLANCK}$
"trajectory" to explain DM relic density




- (g-2) and DM relic density allowed bands have different slopes, so they should cross!
- Their crossing happens for DM mass in the **0.1 – 1 GeV region** – very intriguing to explore further for GW effects and explaining NANOGrav results

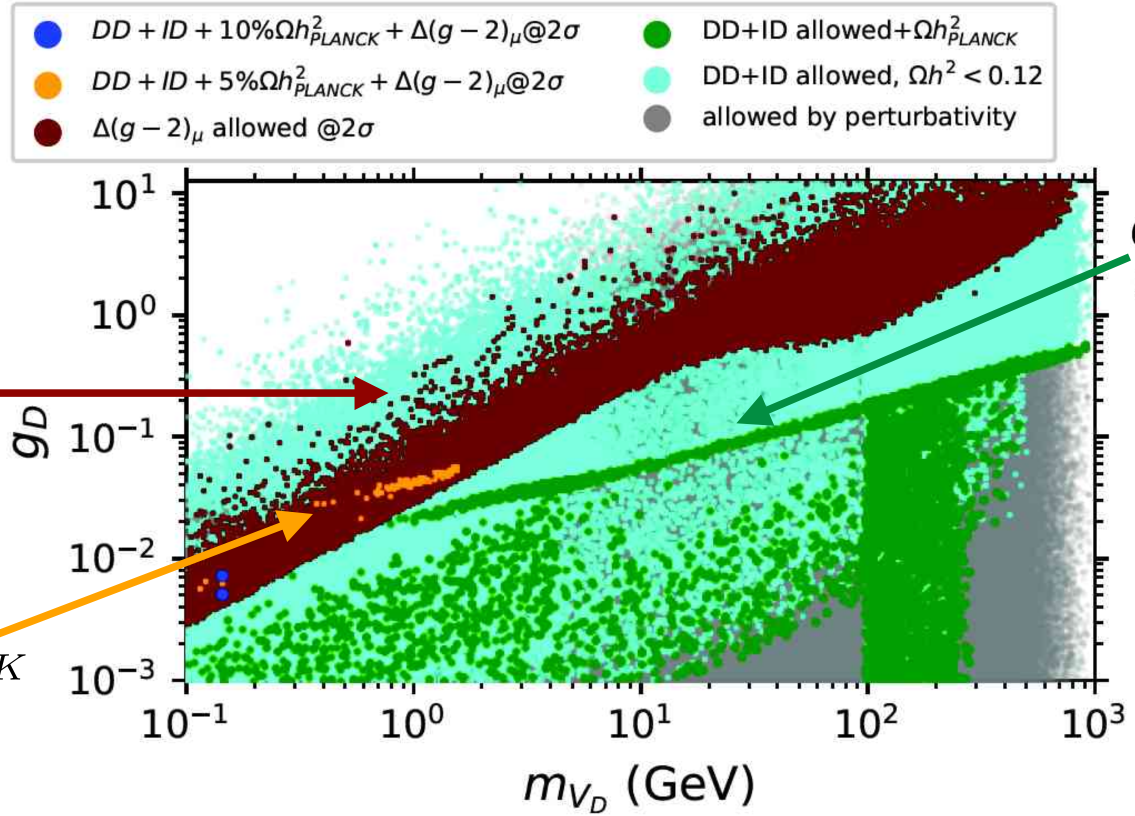
# Combining $(g\text{-}2)_\mu$ and DM constraints




$g_D \sim m_{V_D}$

"trajectory" to explain $\Delta a_\mu$

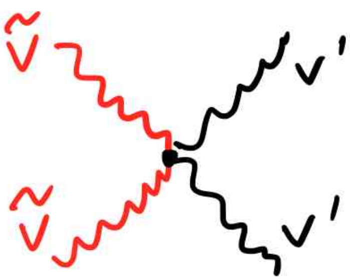
$5\%\Omega h^2_{PLANCK}$




$$\Omega h^2 \propto \frac{M_{V_D}^2}{g_D^4}\frac{1}{\sqrt{g_{eff}(T_f)}}$$

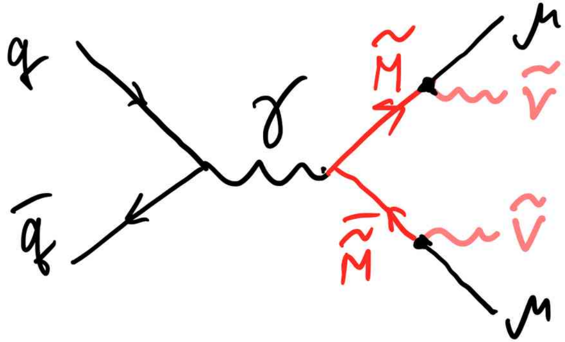
$$g_D \sim \sqrt{M_{V_D}}\,/[g_{eff}(T_f)]^{\frac{1}{8}}$$

$\Omega h^2_{PLANCK}$
"trajectory" to explain DM relic density



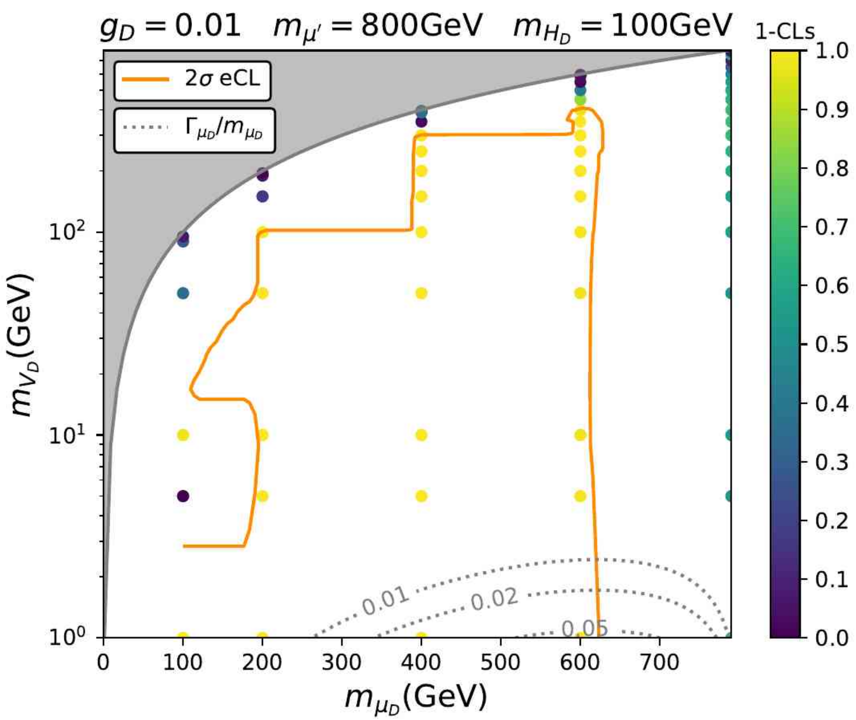

- (g-2) and DM relic density allowed bands have different slopes, so they should cross!
- Their crossing happens for DM mass in the **0.1 – 1 GeV region** – very intriguing to explore further for GW effects and explaining NANOGrav results
- Iin this region **only upto 10% relic density can be explained** – the region with higher relic density is excluded by CMB constraints

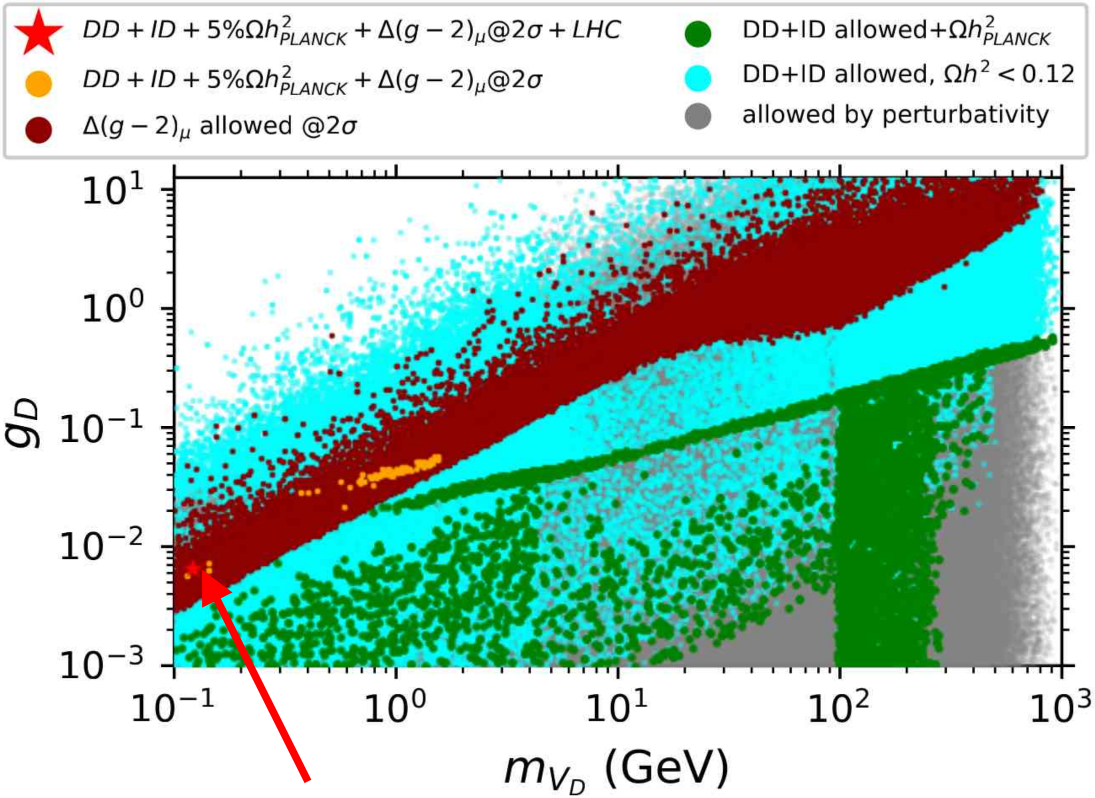
# Final set and very important constraints: colliders




$$pp \to \tilde{M}^-\tilde{M}^+ \to \tilde{V}_D\tilde{V}_D\mu^+\mu^-$$

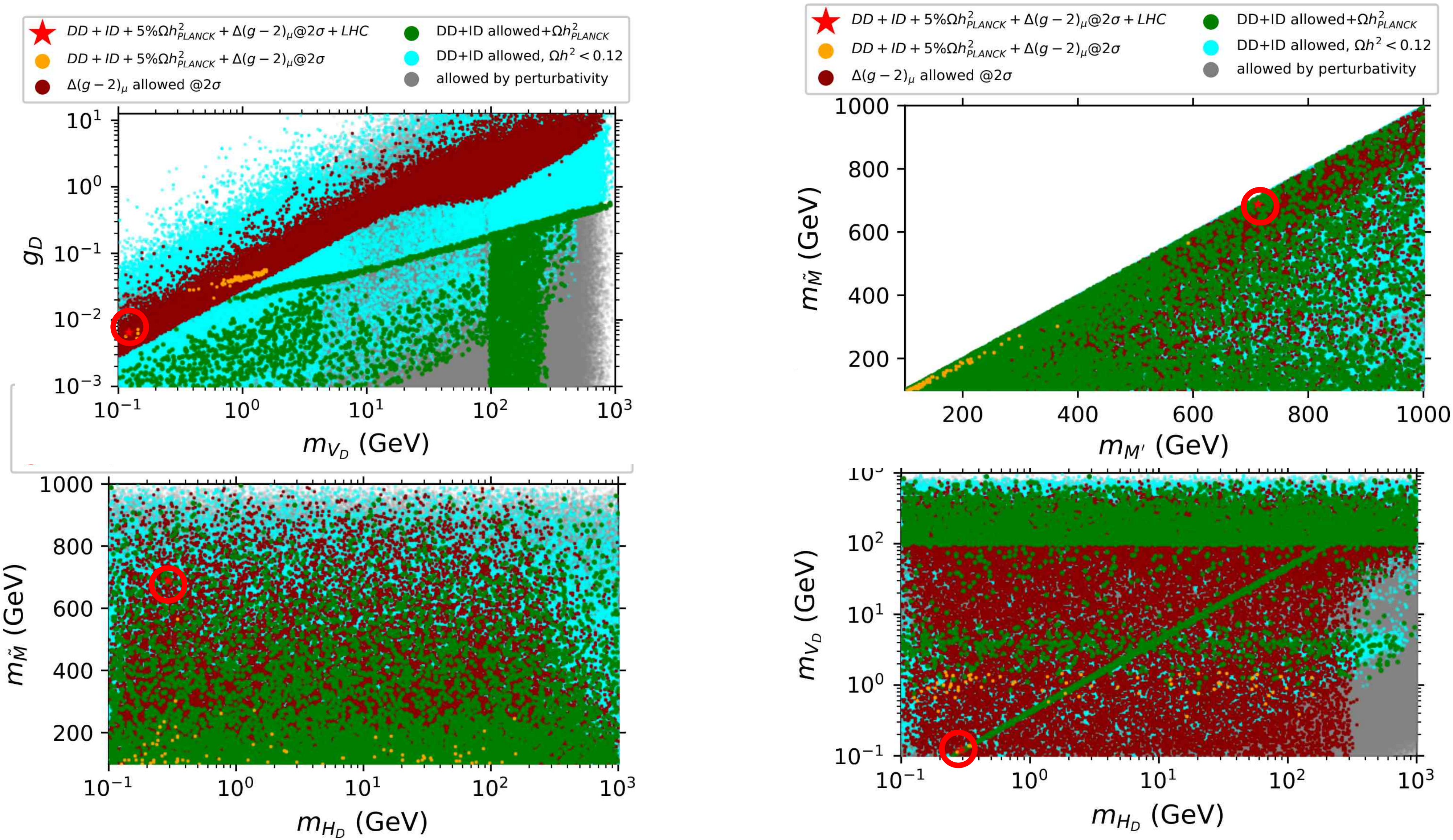
- Madgraph + PTHIA+Delphes + Madanalysis
- $\tilde{M} > 600\ \mathrm{GeV}$ comes from the main $\mu^+\mu^- +\ MET$




- surviving region
- Δaμ parameter space is further constrained

# Various projections of the parameter space after all constraints



# Summary on $\mu$PVDM

- FPVDM is a very promising new framework for VDM, not requiring Higgs portal
- Incorporates many possibilities with new collider and cosmological implications
  - great potential to explain dark matter
  - collider signatures: ff+ET miss, V', Z'H, long-lived V'
- great potential to explore flavour, was not deliberately designed for this

- The model with VL partner of muon – **$\mu$PVDM**– is presented (work in progress)
  - **can explain relic density and $\Delta a_\mu$**
  - collider constraints + simultaneous explanation of DM requires a very specific parameter space: **$M_{DM}$~ 0.2 GeV, $M_{HD}$ ~ 2 $M_{DM}$, $g_D$ ~ 0.01** to avoid DM ID (CMB constraints)
  - typically In this parameter space DM relic density is below 0.12
  - The low DM mass range makes it interesting for the connection to GW data from NANOGrav

**The very definite, though very restricted region of the parameter space is actually good and predictive.**
**It is enough to find just one spot which Nature prefers!**