Dark Matter from a Vector Field in a non-trivial representation of SU(2)_L

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DEPARTAMENTO DE FÍSICA

Plan of the Talk

- Motivation
- The Minimal Isotriplet Vector Dark Matter model and its phenomenology
- A Vector in the fundamental representation of $SU(2)_L$
- Conclusions

Motivation

$$\begin{aligned}\mathcal{L} &= -\frac{1}{2}Tr\left\{G_{\mu\nu}G^{\mu\nu}\right\} - Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\} \\ &\quad -\frac{g^2}{2}Tr\left\{\left[V_\mu, V_\nu\right]\left[V^\mu, V^\nu\right]\right\} \\ &\quad -igTr\left\{G_{\mu\nu}\left[V^\mu, V^\nu\right]\right\} + M^2 Tr\{V_\nu V^\nu\}\end{aligned}$$

V is a massive vector field in the adjoint representation of a local SU(N)

This Lagrangian is consistent with perturbative unitarity at tree level due to two crucial facts:

- It has an accidental Z_2 symmetry
- There is only one coupling constant: the gauge coupling constant

A. Zerwekh Int.J.Mod.Phys. A28 (2013) 1350054

The Minimal Isotriplet Vector Dark Matter Model

A.Belyaev, G. Cacciapaglia, J. McKey, D. Marin and A. Zerwekh
ArXiv:1808.10464

$$
\begin{aligned}
\mathcal{L} \quad = \quad & \mathcal{L}_{SM} - Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\} \\
& -\frac{g^2}{2} Tr\left\{\left[V_\mu, V_\nu\right]\left[V^\mu, V^\nu\right]\right\} \\
& -igTr\left\{W_{\mu\nu}\left[V^\mu, V^\nu\right]\right\} + \tilde{M}^2 Tr\{V_\nu V^\nu\} \\
& +a\left(\Phi^\dagger\Phi\right) Tr\{V_\nu V^\nu\}
\end{aligned}
$$

Higgs doublet

D_μ is the covariant derivative of SU(2)

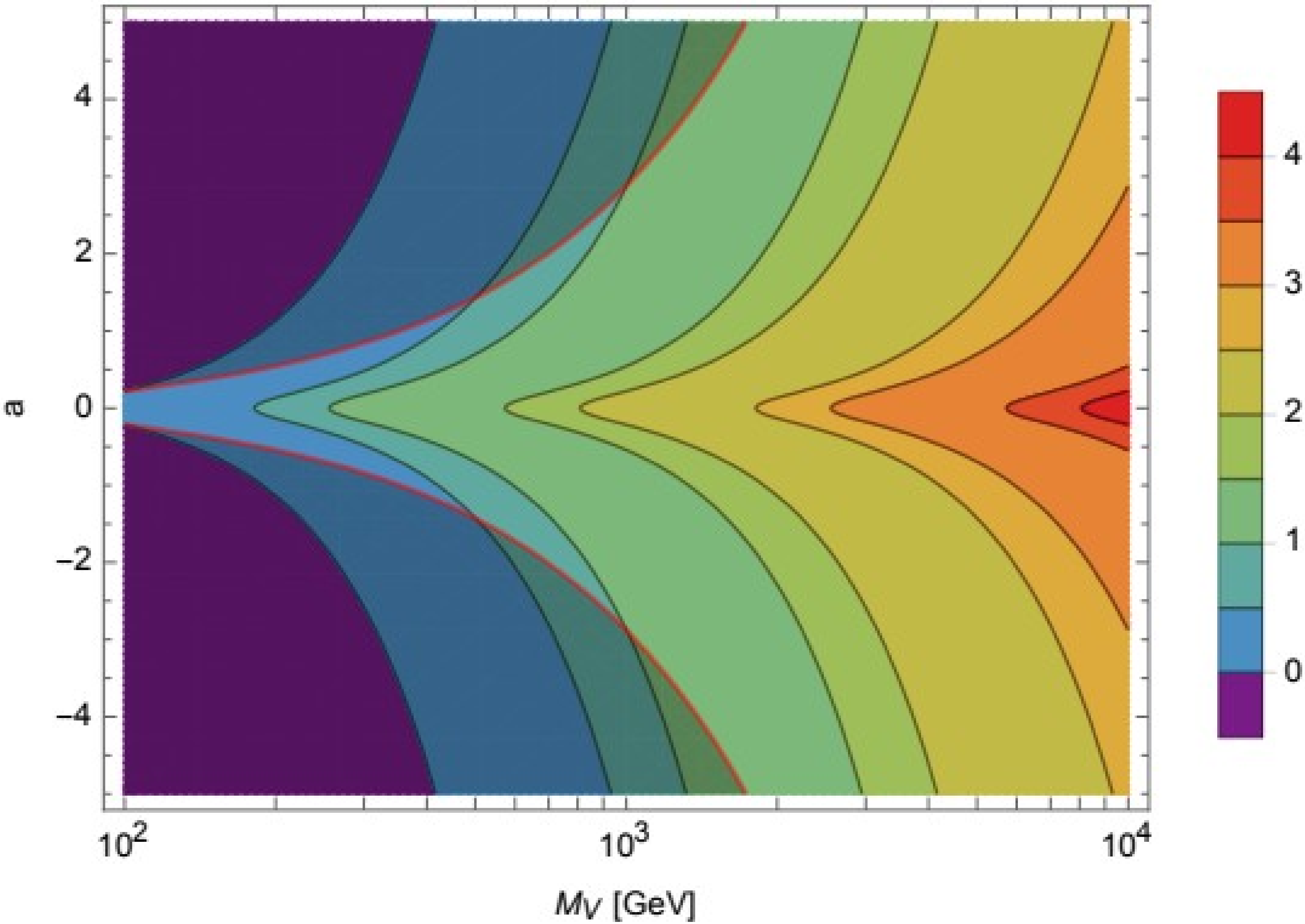
Only two free parameters: a and M

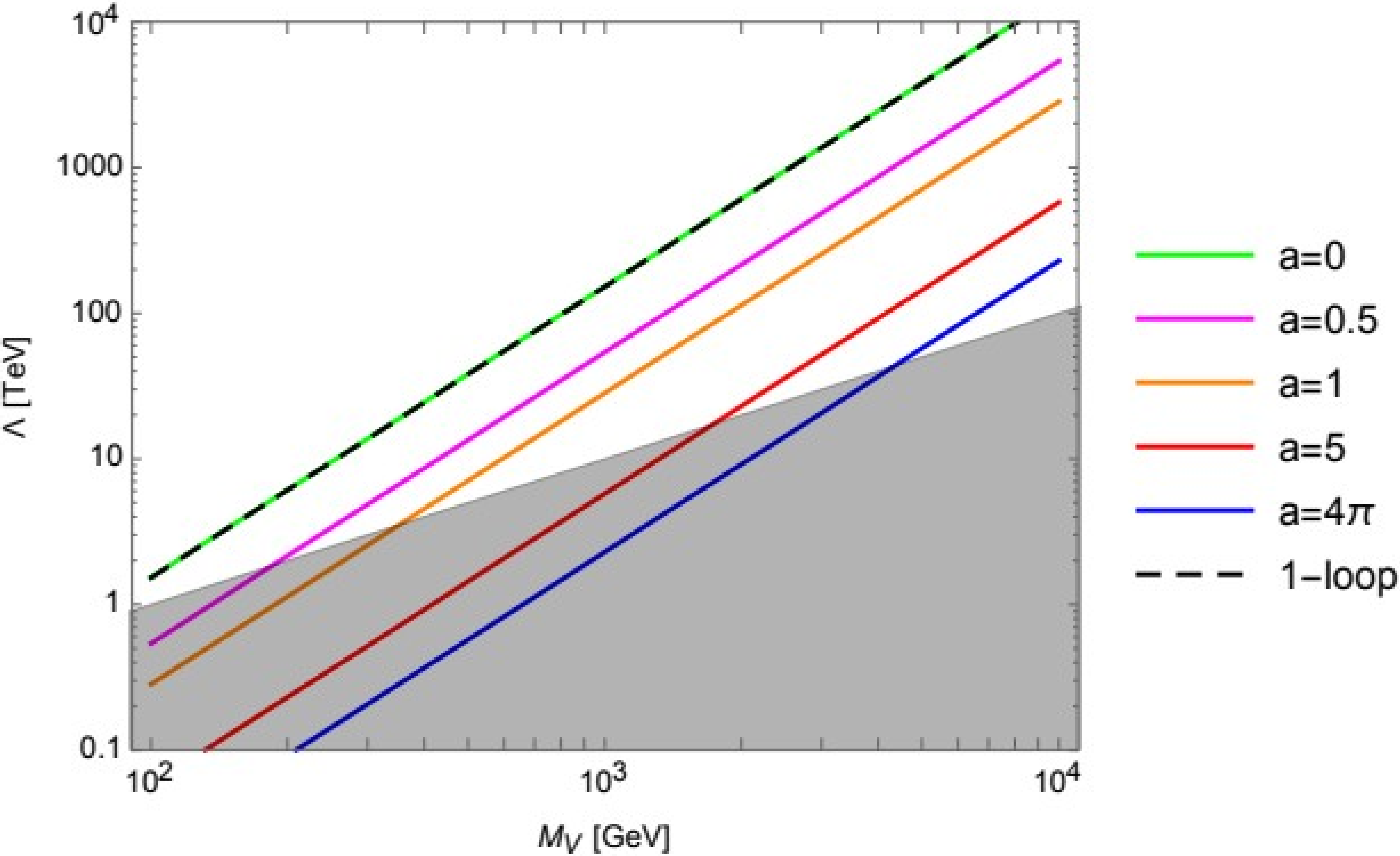
$$
a^{1-\mathrm{loop}} = -3\frac{\alpha^2}{\sin\theta_W^4}\ln\frac{\Lambda}{M_V} \approx -0.0037\ \ln\frac{\Lambda}{M_V}
$$

Unitarity

$$\sigma_l(k) \leq \frac{4\pi\left(2l+1\right)}{k^2}$$

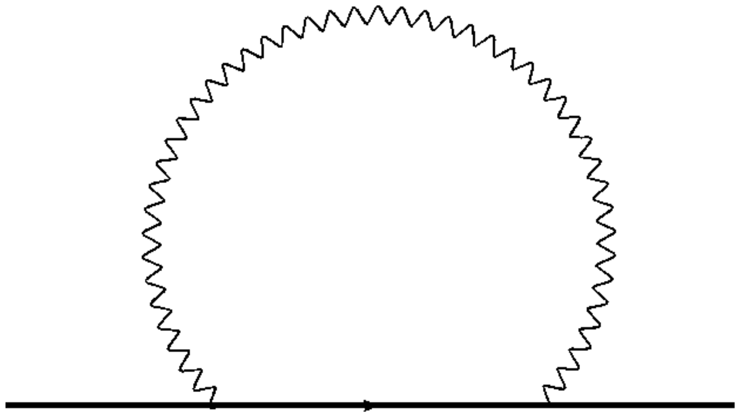
$$\Lambda \approx \frac{8\sqrt{\pi}M_V^2}{\sqrt{4a^2v^2+3g^2M_W^2}}$$

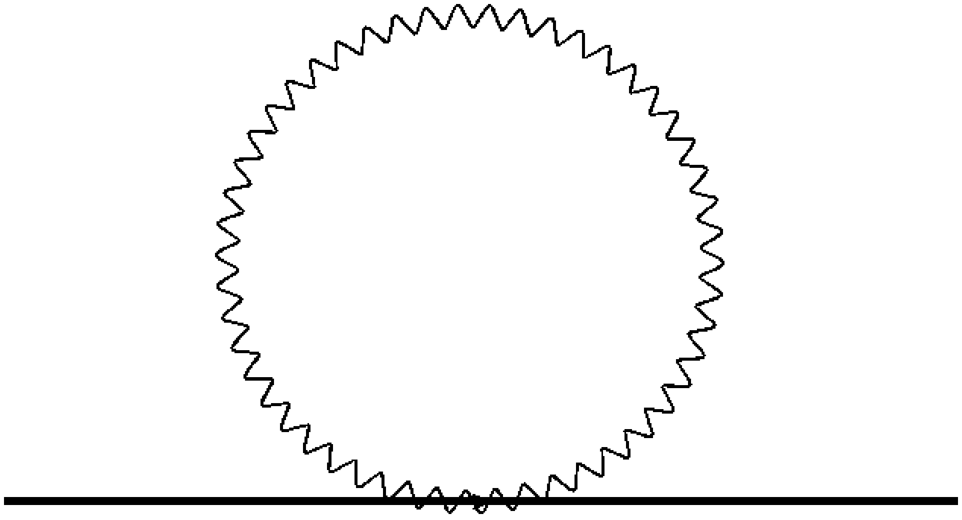

4
2
0
−2
−4
a
10^2
10^3
10^4
M_V [GeV]
4
3
2
1
0



10^4
1000
100
10
1
0.1
Λ [TeV]
10^2
10^3
10^4
M_V [GeV]
a=0
a=0.5
a=1
a=5
a=4π
1–loop

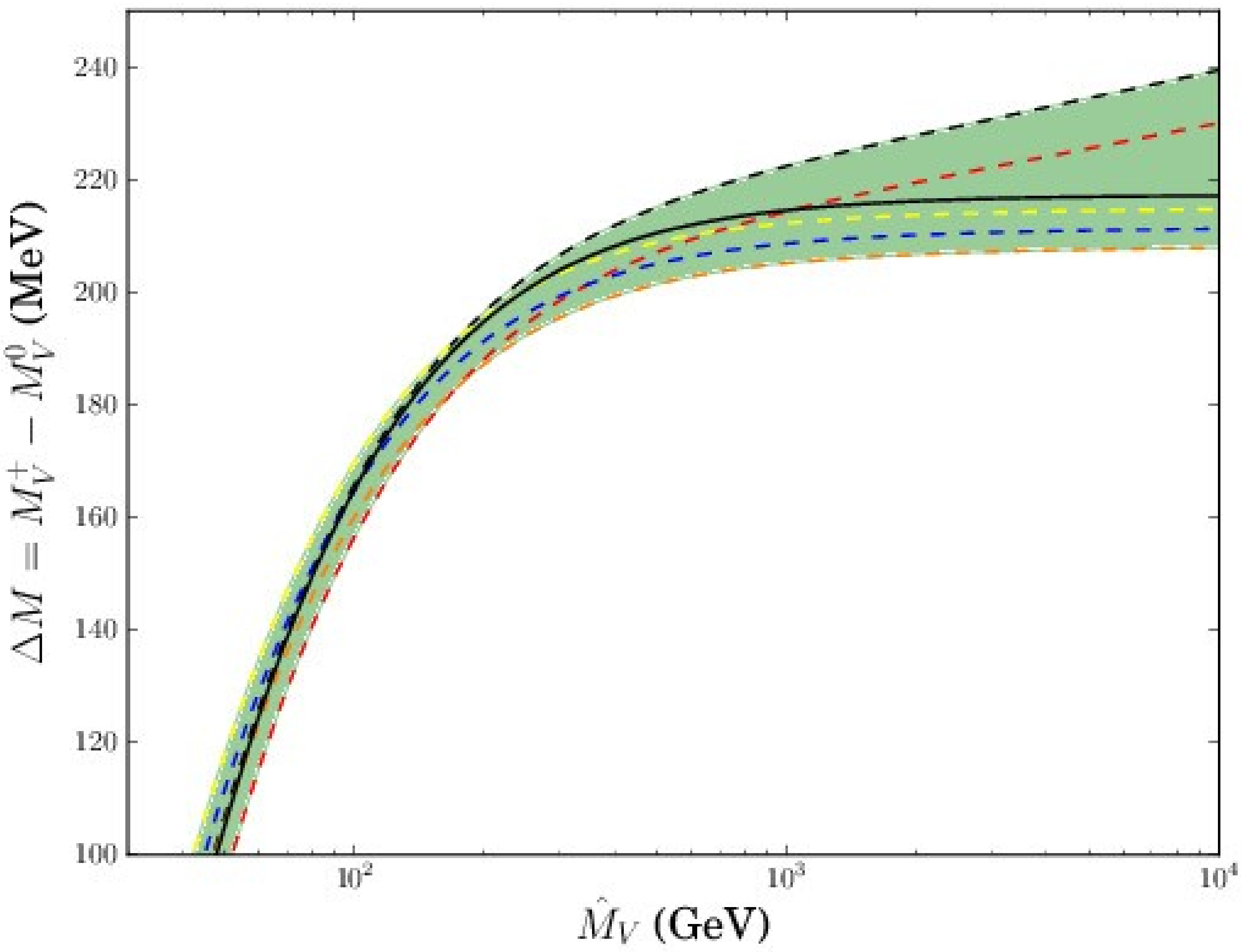
Radiative corrections produce mass splitting



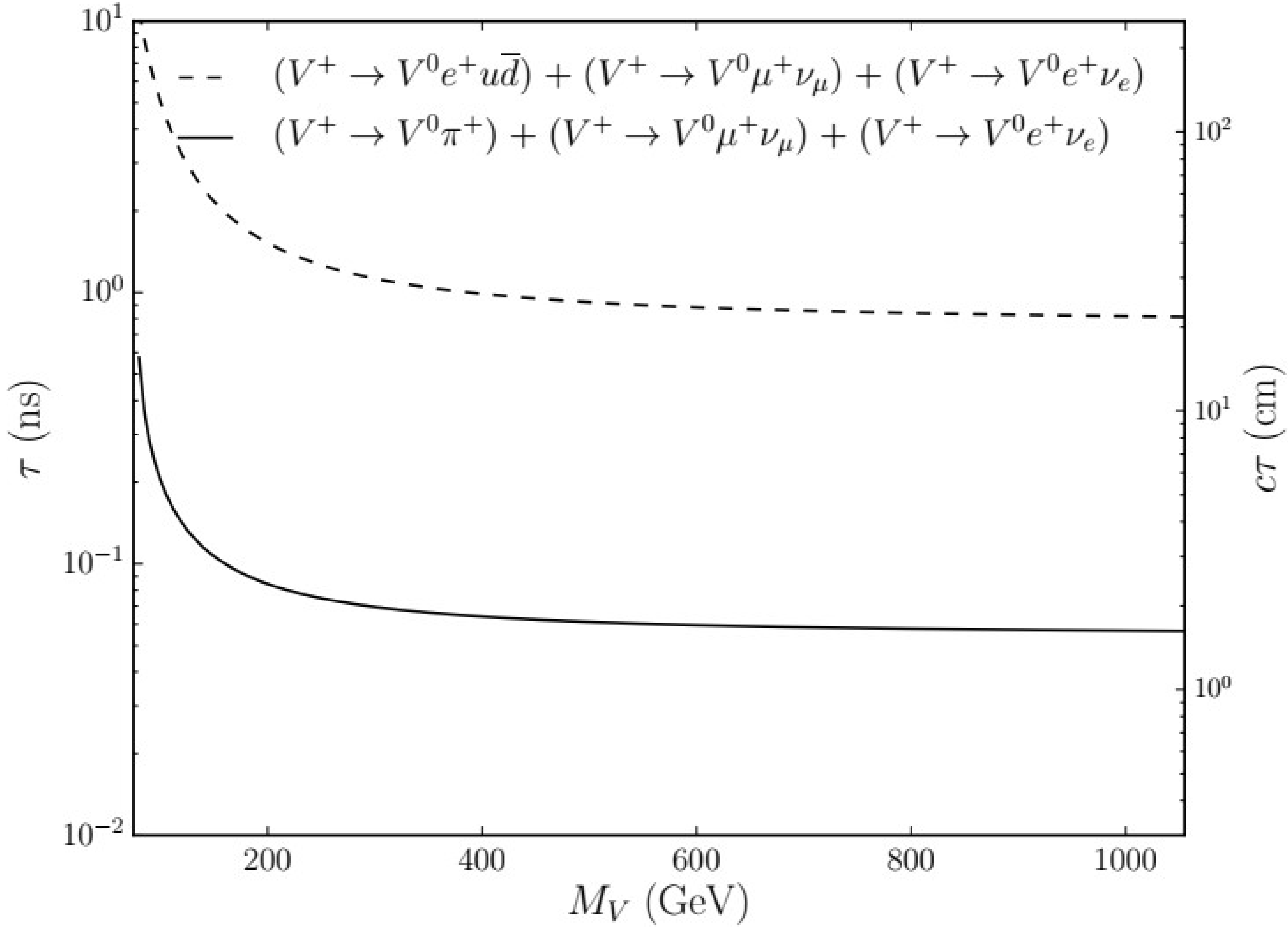


$$\Delta M \approx 210 MeV$$

$$V^{\pm} \to V^0 e^{\pm} \nu \qquad V^{\pm} \to V^0 \pi^{\pm}$$

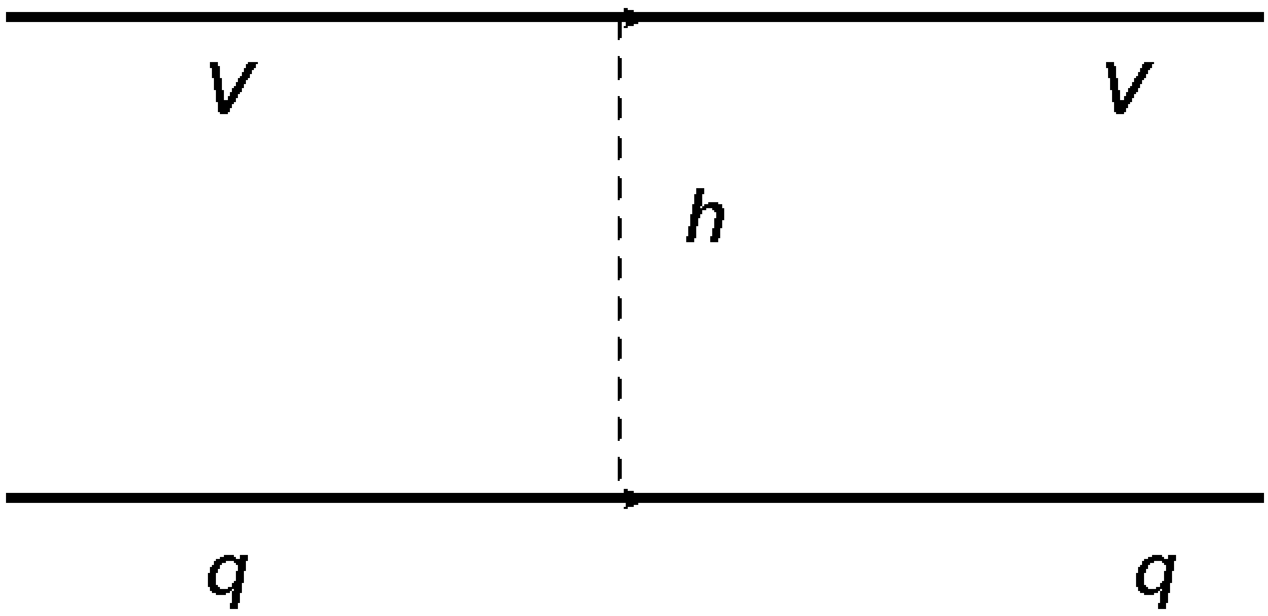


240
220
200
180
160
140
120
100
$\Delta M = M_V^+ - M_V^0$ (MeV)
10^2
10^3
10^4
$\hat{M}_V$ (GeV)

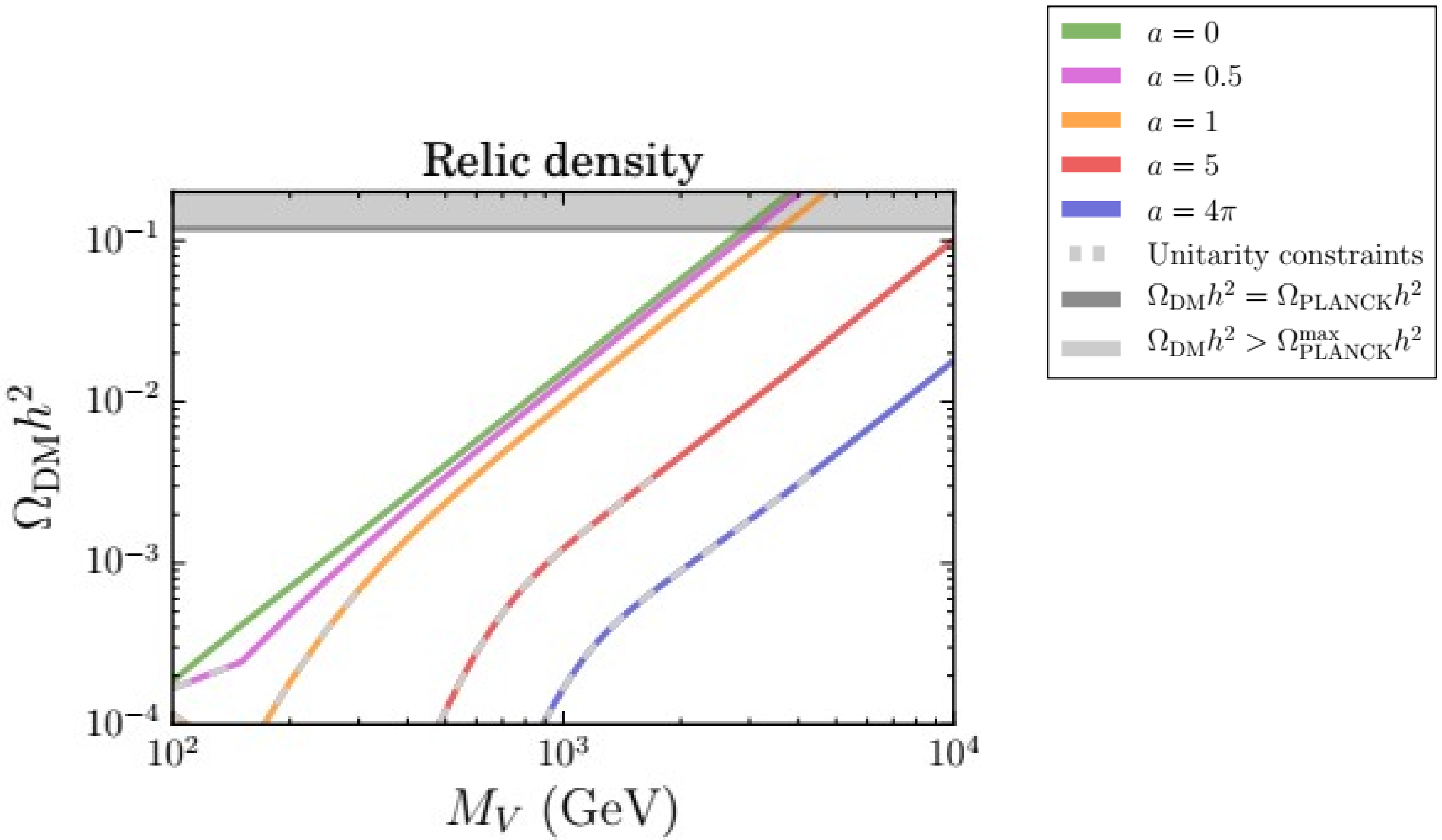


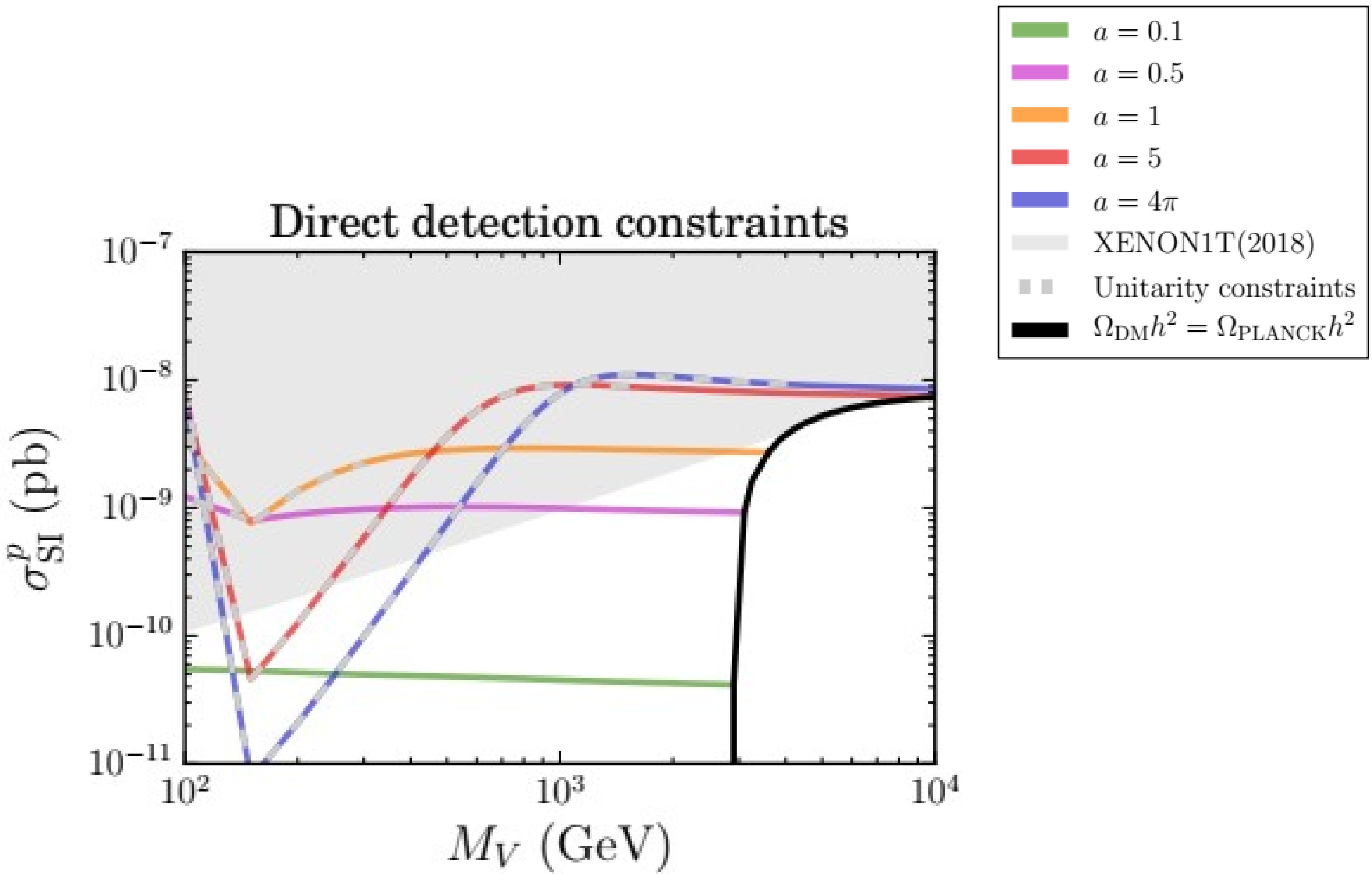
$(V^+ \to V^0 e^+ u\bar{d}) + (V^+ \to V^0 \mu^+ \nu_\mu) + (V^+ \to V^0 e^+ \nu_e)$
$(V^+ \to V^0 \pi^+) + (V^+ \to V^0 \mu^+ \nu_\mu) + (V^+ \to V^0 e^+ \nu_e)$
τ (ns)
$c\tau$ (cm)
M_V (GeV)
10^1
10^0
10^{-1}
10^{-2}
10^2
10^1
10^0
200
400
600
800
1000

Interaction between V^0 and quarks (low energy)

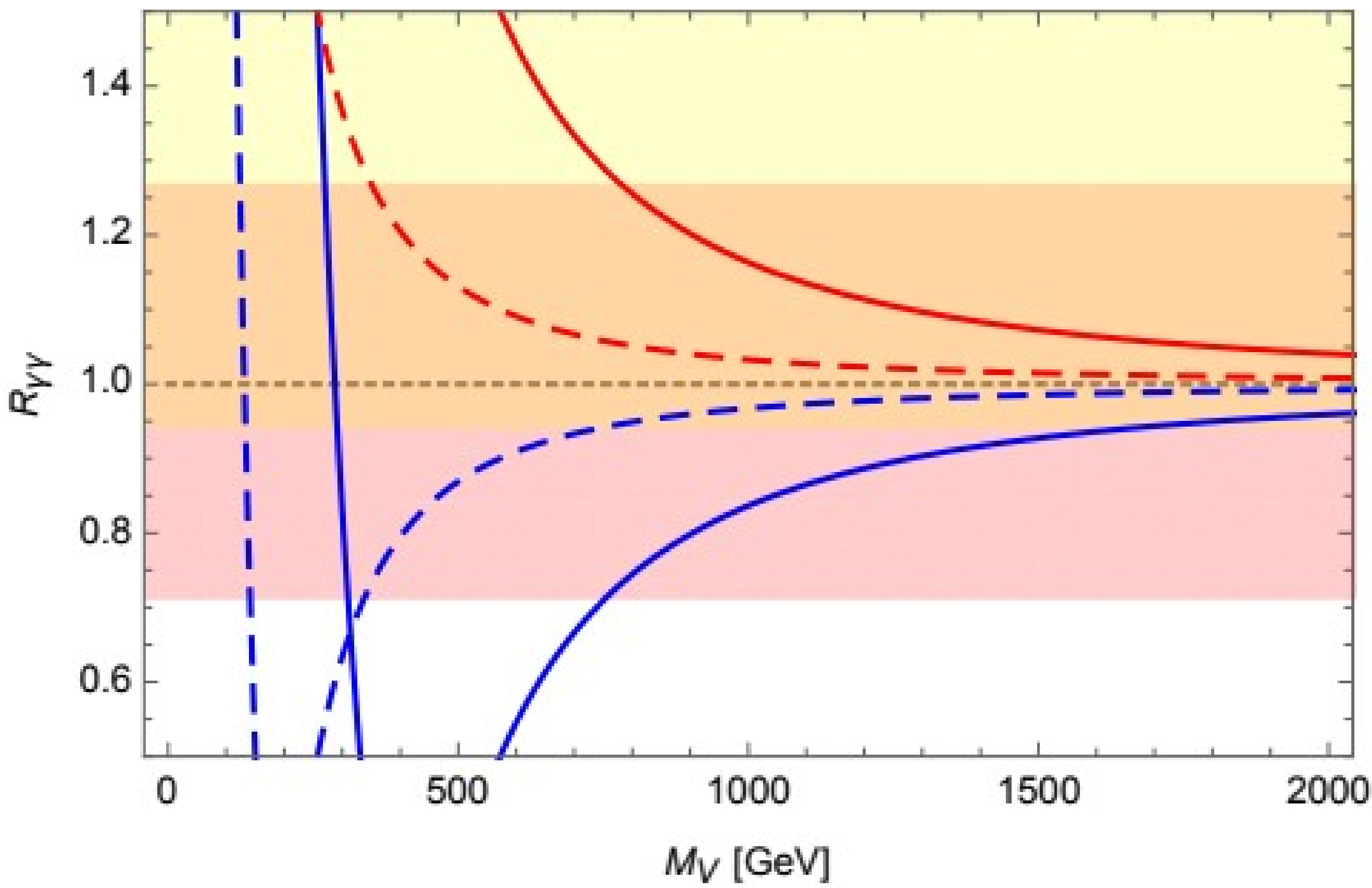


Experimental Constrains

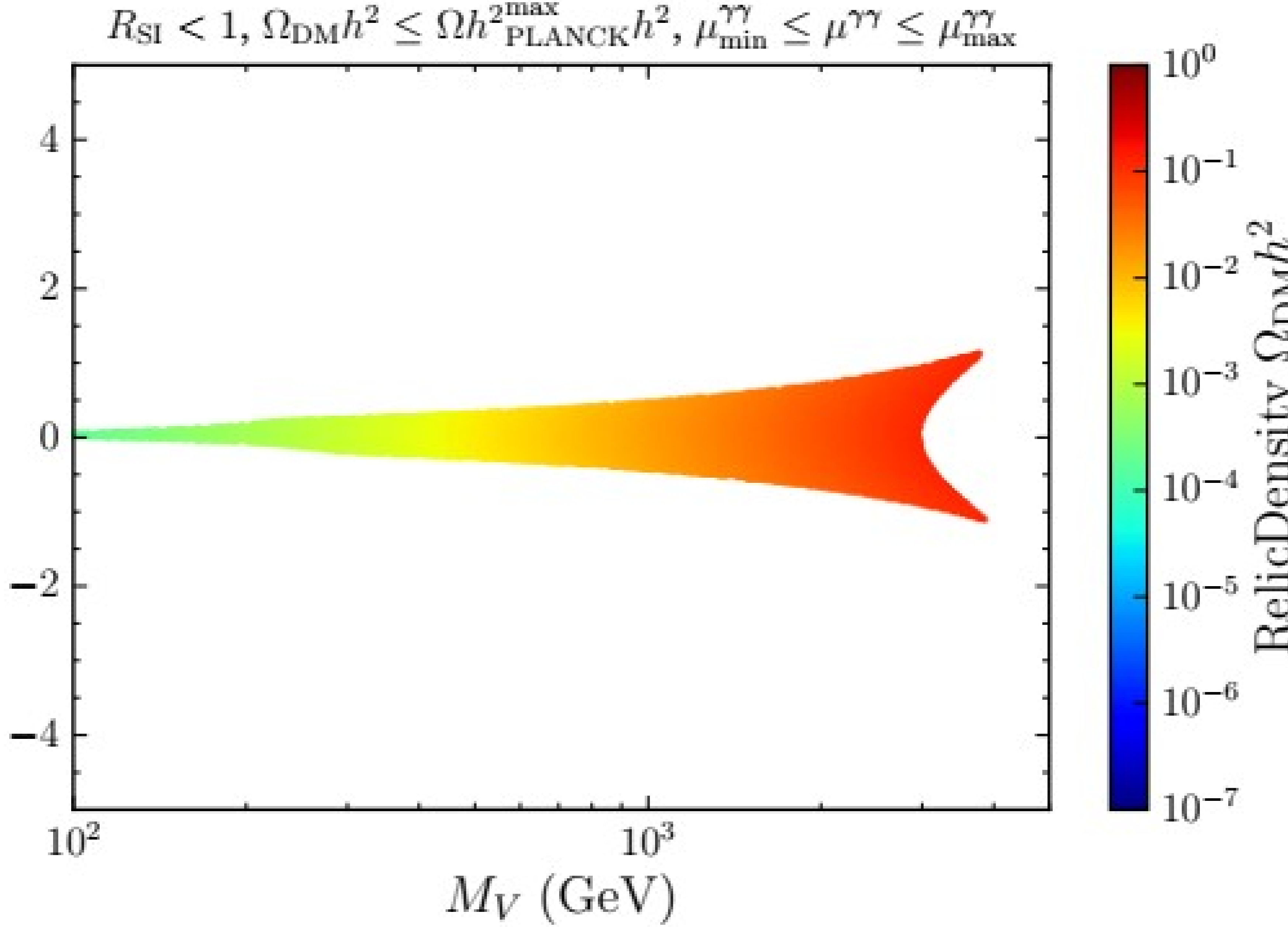

Relic density
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\Omega_{\rm DM} h^2$
10^2
10^3
10^4
M_V (GeV)
$a = 0$
$a = 0.5$
$a = 1$
$a = 5$
$a = 4\pi$
Unitarity constraints
$\Omega_{\rm DM} h^2 = \Omega_{\rm PLANCK} h^2$
$\Omega_{\rm DM} h^2 > \Omega_{\rm PLANCK}^{\rm max} h^2$



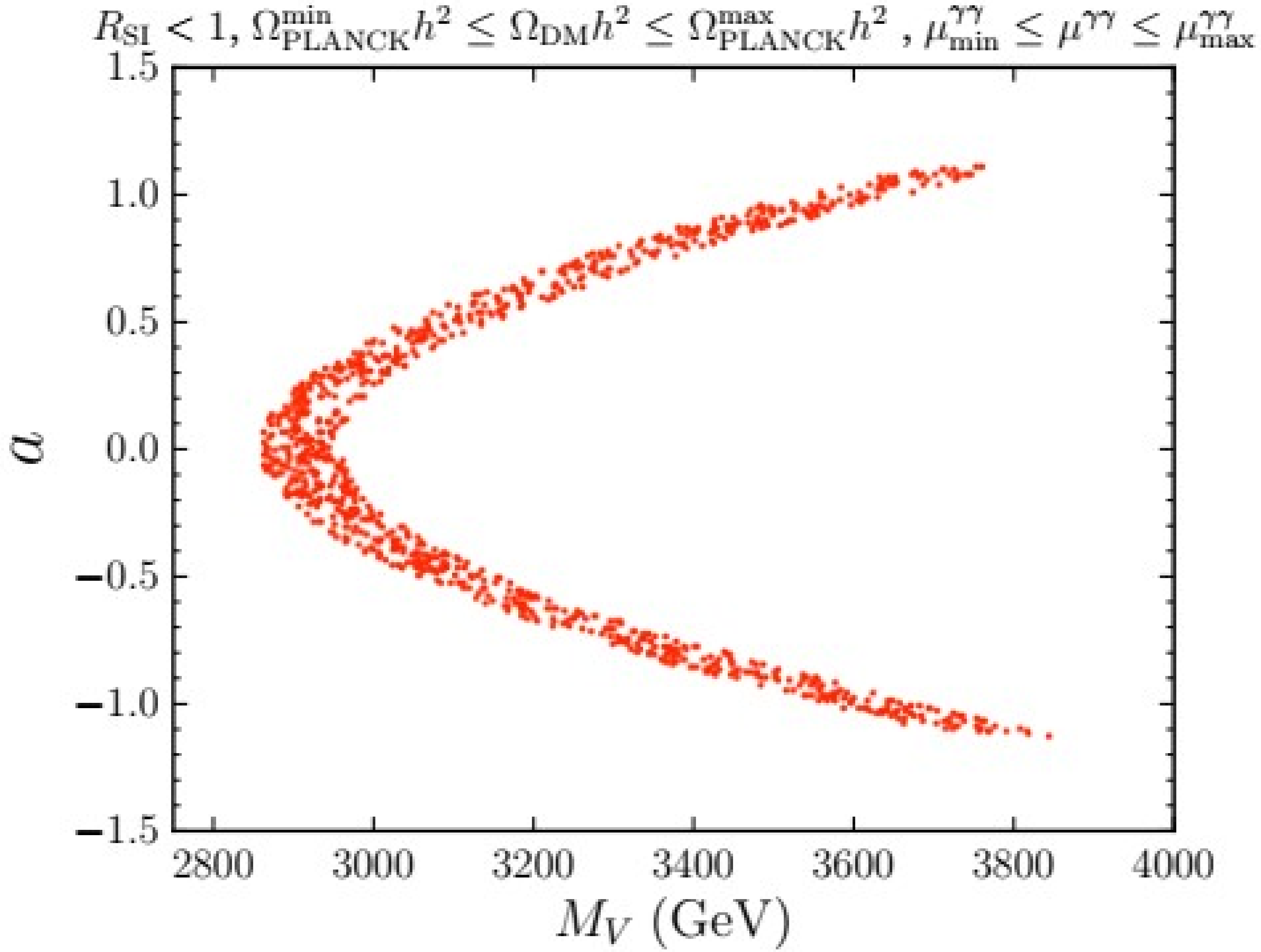
Direct detection constraints
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$\sigma^p_{\rm SI}$ (pb)
10^2
10^3
10^4
M_V (GeV)
$a = 0.1$
$a = 0.5$
$a = 1$
$a = 5$
$a = 4\pi$
XENON1T(2018)
Unitarity constraints
$\Omega_{\rm DM}h^2 = \Omega_{\rm PLANCK}h^2$



a = +/- 1(dashed) and a = +/- 5
The colour code uses red for positive values and blue for negative. The coloured bands are the experimentally allowed regions at 95 % CL from ATLAS (pink) and CMS (yellow), while the orange band shows the overlap

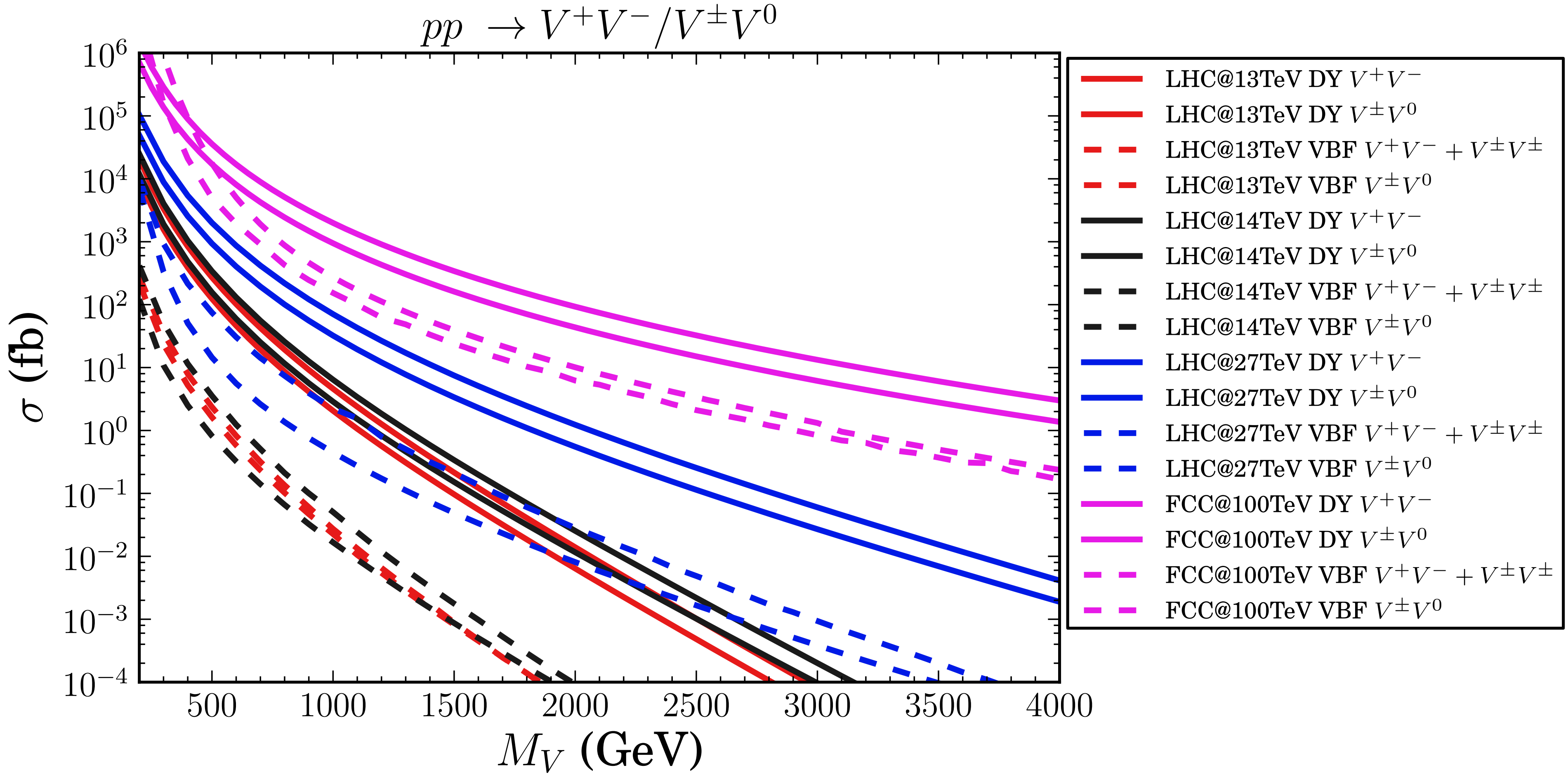


$R_{\rm SI} < 1$, $\Omega_{\rm DM}h^2 \le \Omega h^{2\,\rm max}_{\rm PLANCK} h^2$, $\mu^{\gamma\gamma}_{\rm min} \le \mu^{\gamma\gamma} \le \mu^{\gamma\gamma}_{\rm max}$
4
2
0
-2
-4
10^2
10^3
M_V (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
RelicDensity $\Omega_{\rm DM}h^2$



$R_{\rm SI} < 1$, $\Omega^{\rm min}_{\rm PLANCK} h^2 \leq \Omega_{\rm DM} h^2 \leq \Omega^{\rm max}_{\rm PLANCK} h^2$, $\mu^{\gamma\gamma}_{\rm min} \leq \mu^{\gamma\gamma} \leq \mu^{\gamma\gamma}_{\rm max}$
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
a
2800
3000
3200
3400
3600
3800
4000
M_V (GeV)

What about the LHC ?



A Vector in the fundamental representation of $SU(2)_L$

Bastián Díaz, Marcela González, Felipe Rojas, A. Z.

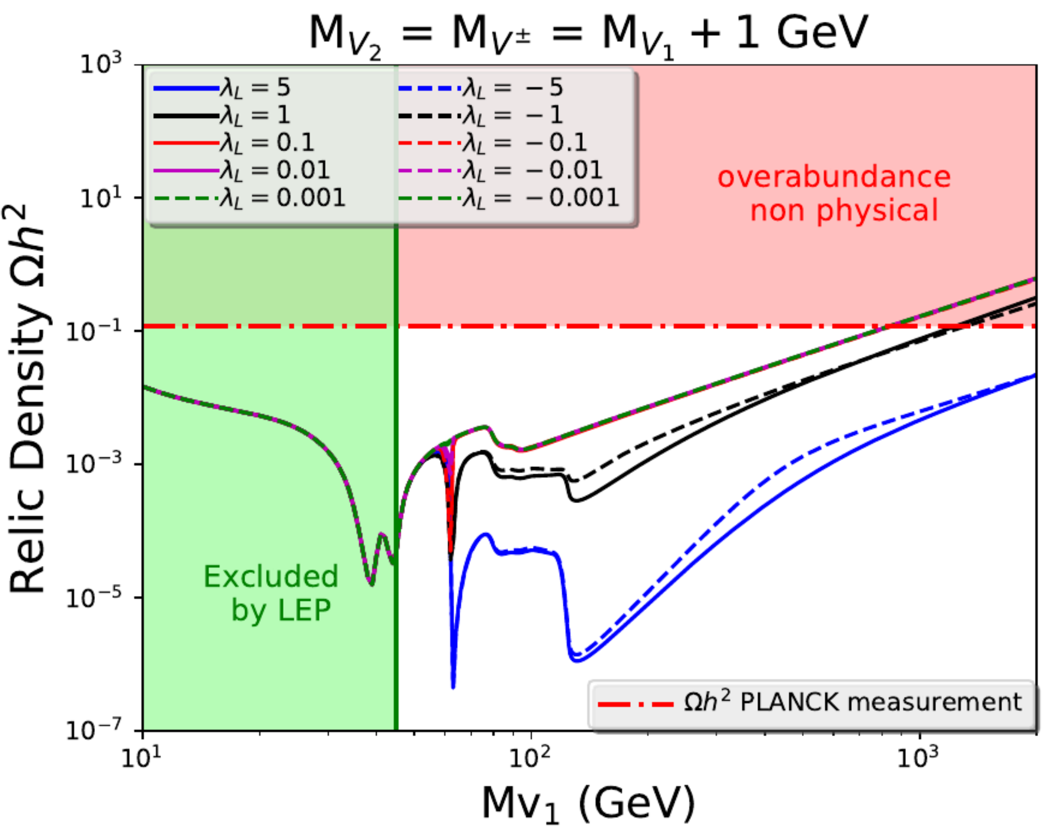
Arxiv: 1810.06375

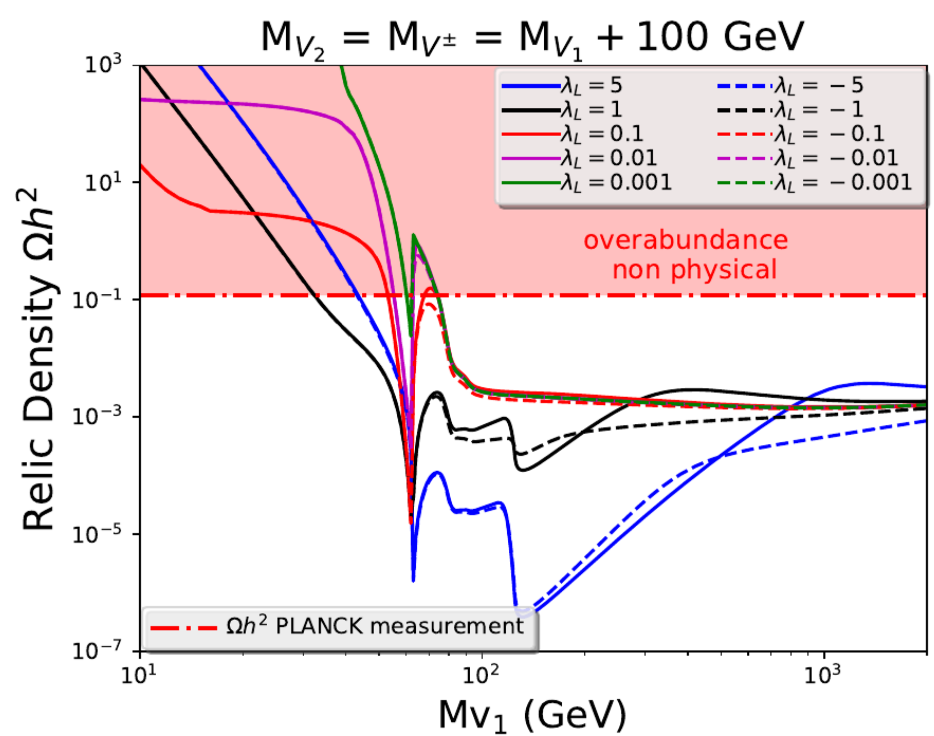
$$
\begin{aligned}
L \;=\; & (D_\mu V_\nu - D_\nu V_\mu)^\dagger (D^\mu V^\nu - D^\nu V^\mu) \\
& + \frac{1}{2} M^2 V_\mu^\dagger V^\mu + \lambda_2 (\phi^\dagger \phi)(V_\mu^\dagger V^\mu) \\
& + \lambda_3 (\phi^\dagger V_\mu)(V^{\mu\dagger} \phi) + \lambda_4 (V_\mu^\dagger \phi)(\phi^\dagger V^\mu) \\
& + \alpha_1 \left[\phi^\dagger D_\mu V^\mu + (D_\mu V^\mu)^\dagger \phi\right] + \alpha_2 \left[V_\mu^\dagger (D^\mu \phi) + (D_\mu \phi)^\dagger V^{\mu\dagger}\right] \\
& + \alpha_3 (V_\mu^\dagger V^\mu)(V_\nu^\dagger V^\nu) + \alpha_4 (V_\mu^\dagger V^\nu)(V_\nu^\dagger V^\mu)
\end{aligned}
$$

$$
V_\mu \;=\; \begin{pmatrix} V_\mu^+ \\ V_\mu^0 + i V_\mu^1 \end{pmatrix}
$$

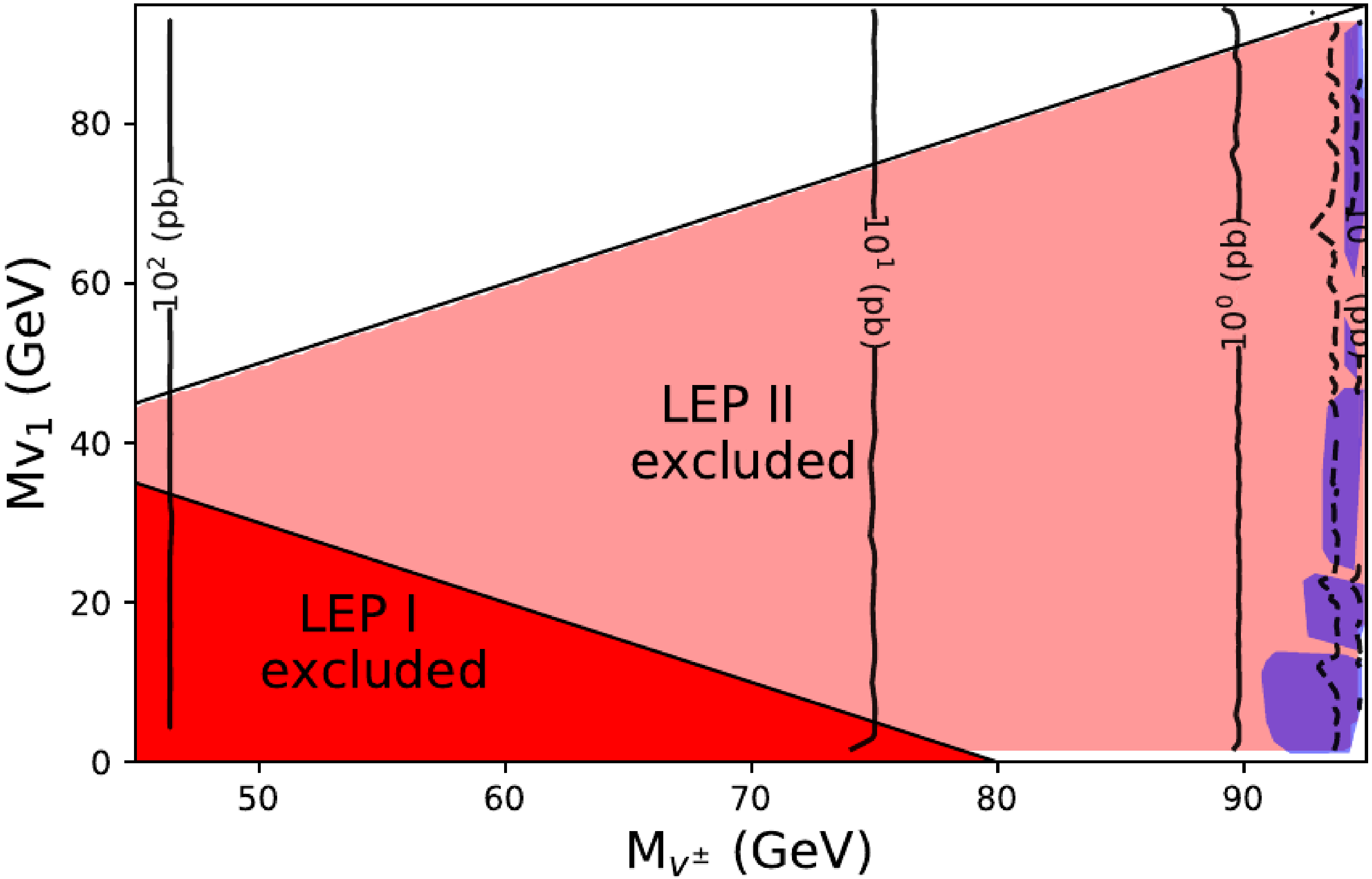
It is not possible to couple V to standard fermions without introducing exotic vector-like fermions

Very nice but already invented by M.V. Chizhov and G. Dvali, PLB 703 (2011) 593


$M_{V_2} = M_{V^\pm} = M_{V_1} + 1$ GeV
$\lambda_L = 5$
$\lambda_L = 1$
$\lambda_L = 0.1$
$\lambda_L = 0.01$
$\lambda_L = 0.001$
$\lambda_L = -5$
$\lambda_L = -1$
$\lambda_L = -0.1$
$\lambda_L = -0.01$
$\lambda_L = -0.001$
overabundance
non physical
Excluded
by LEP
Ωh^2 PLANCK measurement
Relic Density Ωh^2
Mv_1 (GeV)

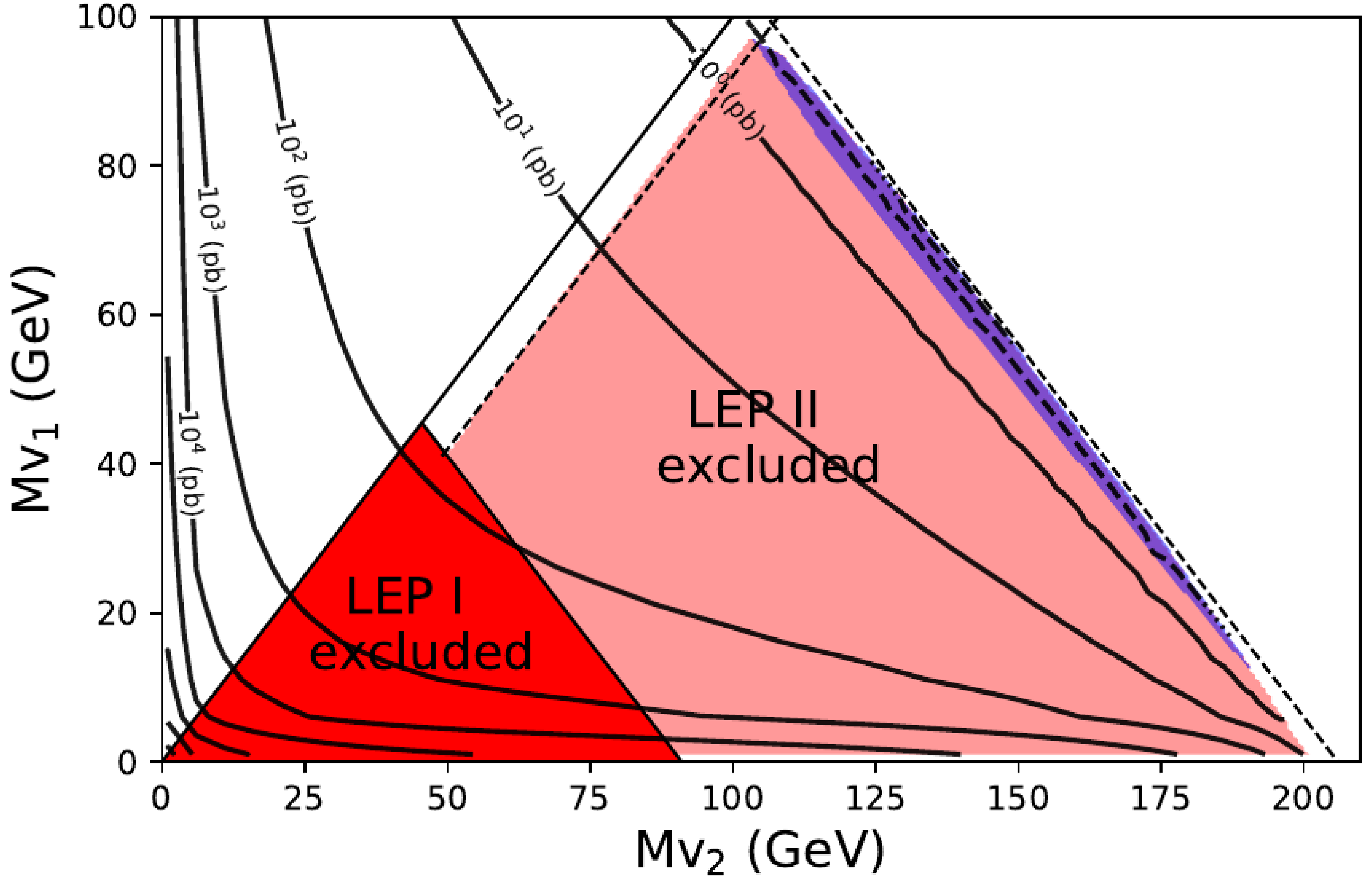

$M_{V_2} = M_{V^\pm} = M_{V_1} + 100$ GeV
$\lambda_L = 5$
$\lambda_L = 1$
$\lambda_L = 0.1$
$\lambda_L = 0.01$
$\lambda_L = 0.001$
$\lambda_L = -5$
$\lambda_L = -1$
$\lambda_L = -0.1$
$\lambda_L = -0.01$
$\lambda_L = -0.001$
overabundance
non physical
Ωh^2 PLANCK measurement
Relic Density Ωh^2
Mv_1 (GeV)

LEP

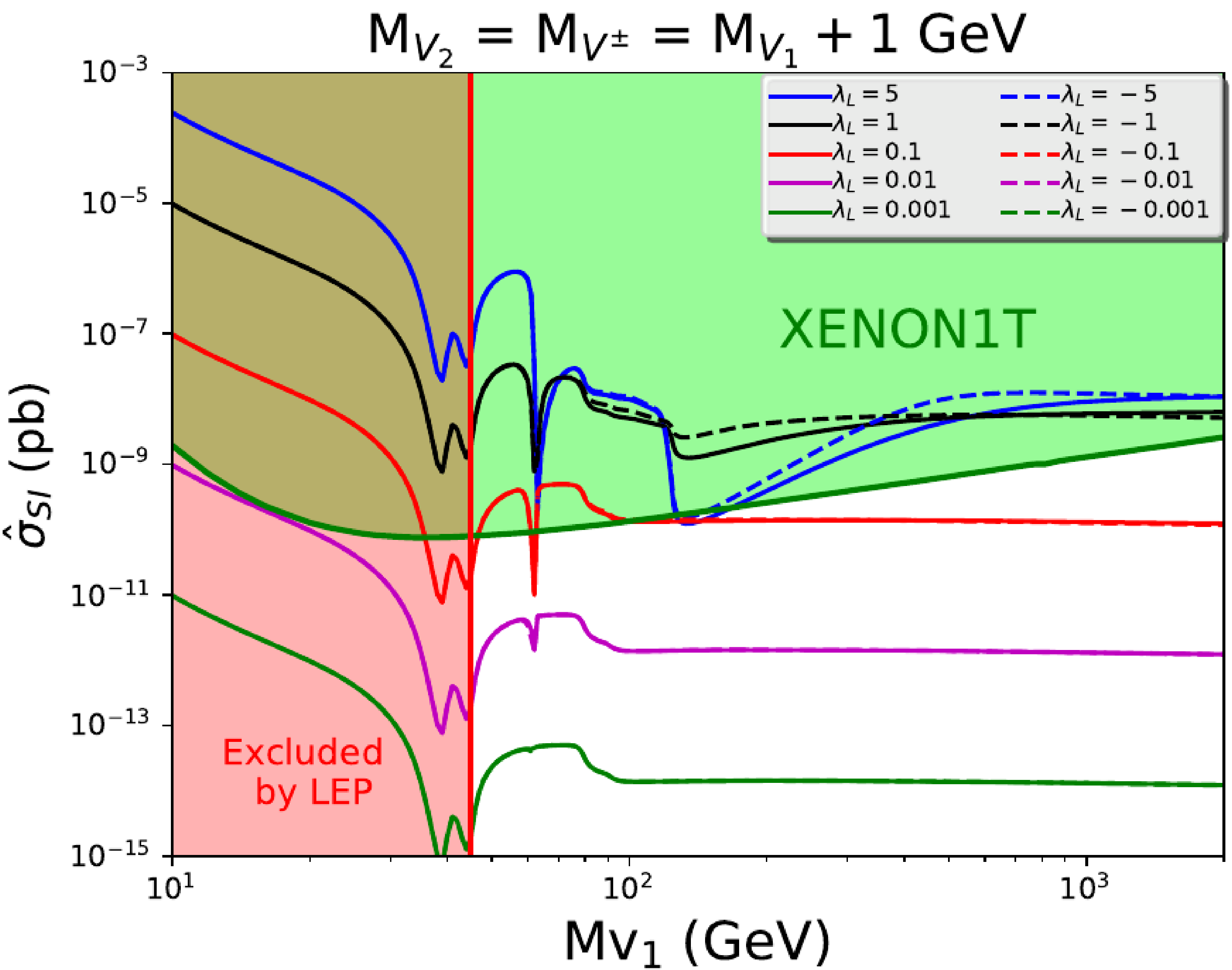


LEP II
excluded
LEP I
excluded
10^2 (pb)
10^1 (pb)
10^0 (pb)
M_{v_1} (GeV)
$M_{v^\pm}$ (GeV)
0
20
40
60
80
50
60
70
80
90

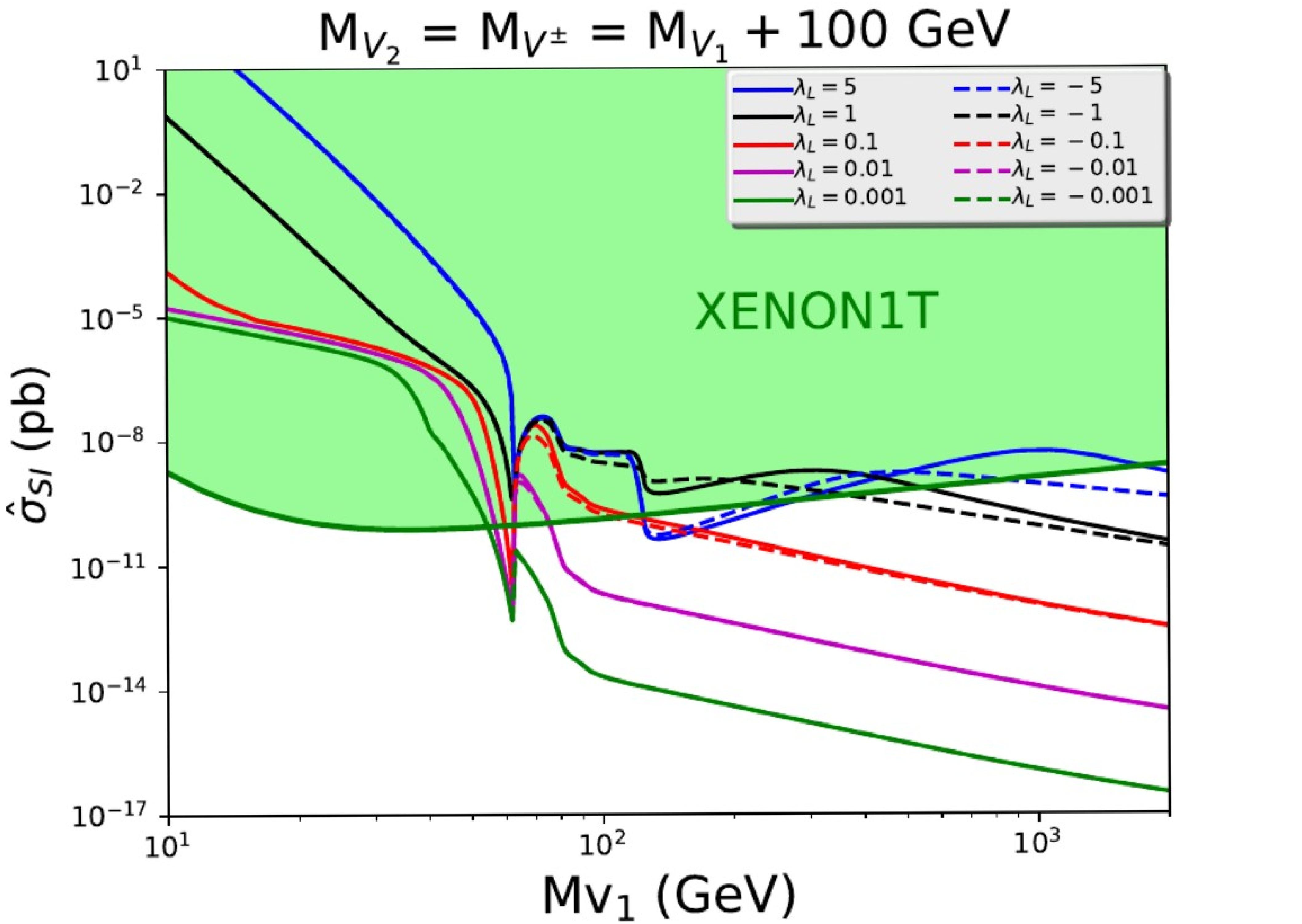
LEP



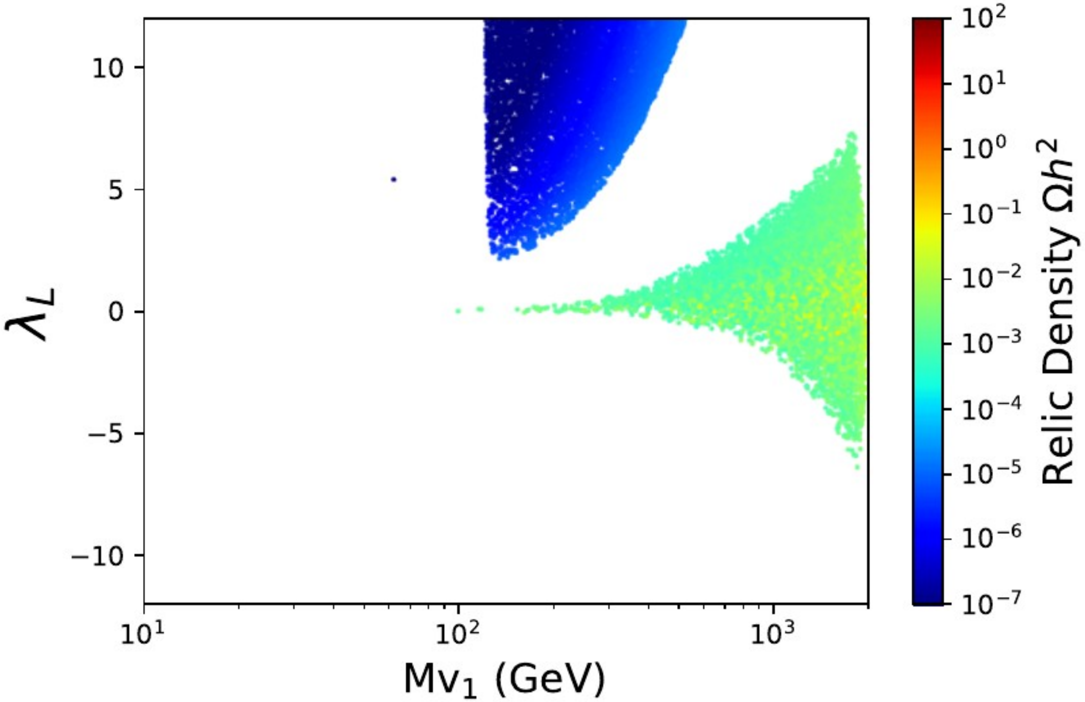
LEP II
excluded
LEP I
excluded
10^4 (pb)
10^3 (pb)
10^2 (pb)
10^1 (pb)
10^0 (pb)
Mv_1 (GeV)
Mv_2 (GeV)
0
20
40
60
80
100
0
25
50
75
100
125
150
175
200

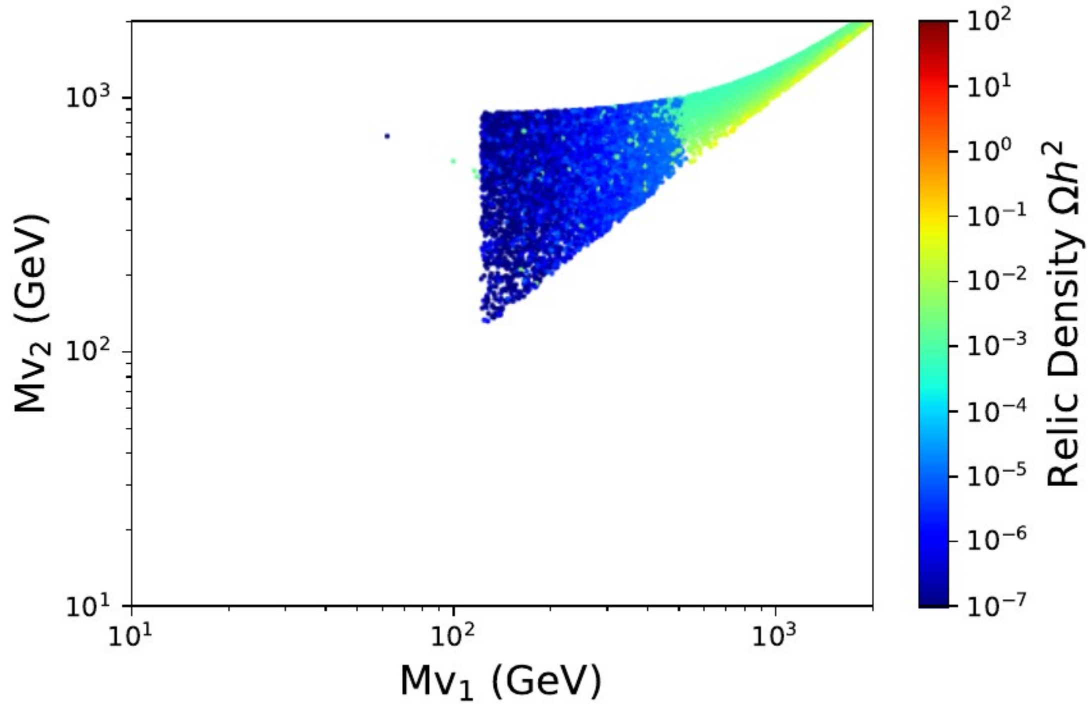


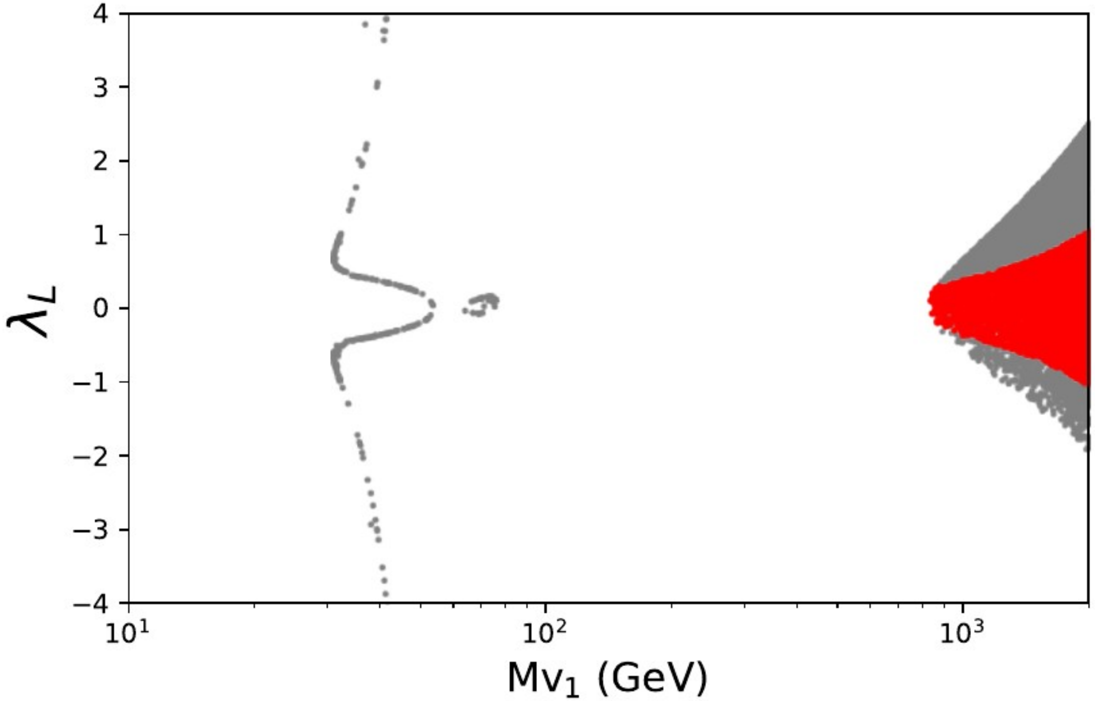
$M_{V_2} = M_{V^\pm} = M_{V_1} + 1$ GeV
$\lambda_L = 5$
$\lambda_L = -5$
$\lambda_L = 1$
$\lambda_L = -1$
$\lambda_L = 0.1$
$\lambda_L = -0.1$
$\lambda_L = 0.01$
$\lambda_L = -0.01$
$\lambda_L = 0.001$
$\lambda_L = -0.001$
XENON1T
Excluded by LEP
$\hat{\sigma}_{SI}$ (pb)
Mv_1 (GeV)
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{1}
10^{2}
10^{3}



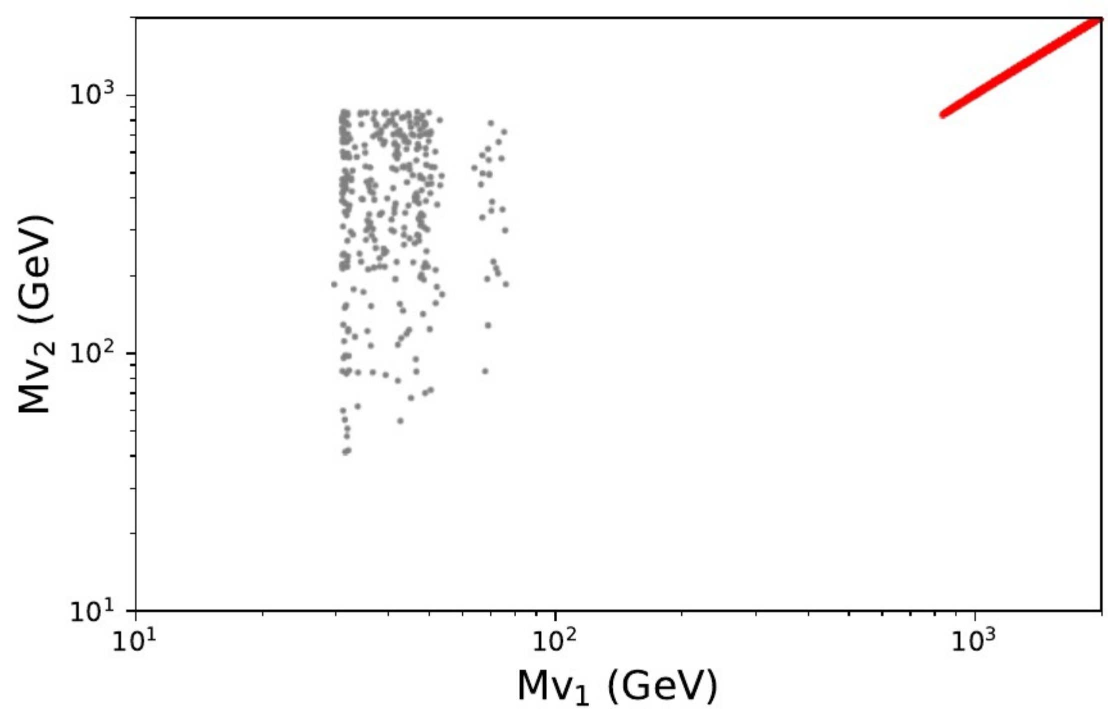
$M_{V_2} = M_{V^\pm} = M_{V_1} + 100$ GeV
$\lambda_L = 5$
$\lambda_L = -5$
$\lambda_L = 1$
$\lambda_L = -1$
$\lambda_L = 0.1$
$\lambda_L = -0.1$
$\lambda_L = 0.01$
$\lambda_L = -0.01$
$\lambda_L = 0.001$
$\lambda_L = -0.001$
XENON1T
$\hat{\sigma}_{SI}$ (pb)
Mv_1 (GeV)
10^{1}
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{1}
10^{2}
10^{3}


λ_L
10
5
0
−5
−10
10^1
10^2
10^3
Mv_1 (GeV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Relic Density Ωh^2


Mv_2 (GeV)
10^3
10^2
10^1
10^1
10^2
10^3
Mv_1 (GeV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Relic Density Ωh^2



λ_L
Mv$_1$ (GeV)

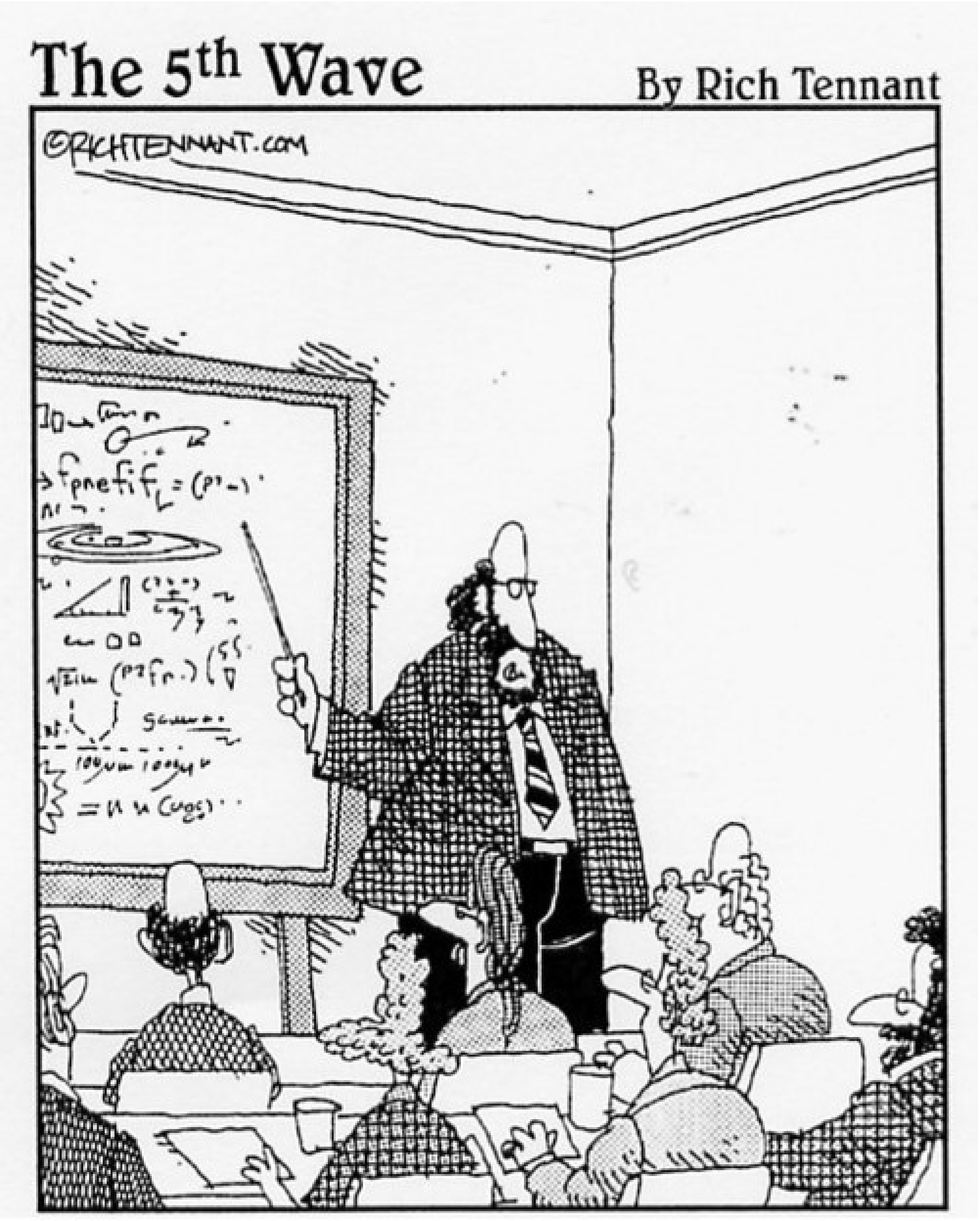


Mv$_2$ (GeV)
Mv$_1$ (GeV)

Conclusions

- We have found a consistent theoretical construction to couple a massive vector matter field to a gauge field
- We built an extension of the SM incorporating the new vector matter field and the model contains a natural dark matter candidate.
- The new Z_2 symmetry is motivated by theory and not imposed by hand.
- The model is consistent with collider and cosmological data
- A Vector in the Fundamental Representation offers a nice DM candidate but the model is more strongly challenged by data and by unitarity contrains

A typical case of “doesn’t matter”



“After the discovery of ‘antimatter’ and ‘dark matter’, we have just confirmed the existence of ‘doesn’t matter’, which does not have any influence on the Universe whatsoever.”

Thank you