Theory and Motivations of Dark Higgs Bosons

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More variegated collider signals with respect to simplified models.

Allow for consistent DM models with limited number of free parameters

Dark Higgs bosons

Extension to further directions. E.g: Generation of Neutrino Masses, Gravitational Waves from First Order Phase Transitions.

Dark Higgs boson as origin of spin-1 portal

M. Duerr, A. Grohsjean, F. Kahlhoefer, B. Penning, K. Schmidt-Hoberg, C. Schwaneberger JHEP 04 (2017) 143
see also
F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz and S. Vogl, JHEP 02 (2016) 016, JHEP 09 (2016) 042.

$$L = (D^\mu \phi)^\dagger (D_\mu \phi) + \mu_\phi^2 \phi^\dagger \phi - \lambda_\phi (\phi^\dagger \phi)^2 - \lambda_{H\phi} \phi^\dagger \phi H^\dagger H$$
$$- g_X X_\mu \bar{f} \gamma^\mu (V_f - \gamma_5 A_f) f - \frac{1}{4} X^{\mu\nu} X_{\mu\nu} - \frac{1}{2} \sin\delta X^{\mu\nu} B_{\mu\nu}$$

$$m_X = 2 g_X \omega \longrightarrow$$

$$M_{Z'}^2 = m_X^2 + (Contributions\ from\ mixing\ with\ the\ Z)$$

Mixing with a Dark Higgs

$$V(H,\phi) = \frac{\lambda_H}{4}\left|H^\dagger H\right|^2 + \frac{\lambda_{H\phi}}{4}|\phi|^2|H|^2 + \frac{\lambda_\phi}{4}|S|^4 + \frac{1}{2}\mu_H^2 H^\dagger H + \frac{1}{2}\mu_\phi^2|\phi|^2$$

$$O^T M^2 O = diag(M_{H_1}^2, M_{H_2}^2)$$

$$O = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad M^2 = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H\phi} v\omega \\ \lambda_{H\phi} v\omega & 2\lambda_\phi \omega^2 \end{pmatrix} \longrightarrow \qquad \tan 2\theta = \frac{\lambda_{H\phi} v\omega}{\lambda_\phi \omega^2 - \lambda_\phi v^2}$$

$$L_{\phi H,SM} = \frac{H_1\cos\theta + H_2\sin\theta}{v}\left(2M_W^2 W_\mu^+ W^{-\mu} + M_Z^2 Z_\mu Z^\mu - m_f \bar{f} f\right)$$

$$\begin{pmatrix} B_\mu \\ W_\mu^3 \\ X_\mu \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\tan\delta \\ 0 & 1 & 0 \\ 0 & 0 & 1/\cos\delta \end{pmatrix} \begin{pmatrix} c_W & -s_W\cos\xi & s_W\sin\xi \\ s_W & c_W\cos\xi & -c_W\sin\xi \\ 0 & \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

$$M_Z^2 = m_{Z_0}^2(1 + s_W \tan\xi \tan\delta)$$

$$M_{Z'}^2 = \frac{m_X^2 + \delta m^2(s_W \sin\delta - \cos\delta\ tan\xi)}{\cos^2\delta(1 + s_W tan\delta tan\xi)}$$

$$\tan 2\xi = \frac{-2\cos\delta\left(\delta m^2 + m_{Z_0}^2 s_W \sin\delta\right)}{m_X^2 - m_{Z_0}^2\cos^2\delta + m_{Z_0}^2 s_W^2 \sin^2\delta + 2\delta m^2 s_W \sin\delta}$$

$$\lambda_H = \frac{1}{4v^2}\left[M_{H_1}^2 + M_{H_2}^2 + \left(M_{H_1}^2 - M_{H_2}^2\right)\cos 2\theta\right]$$

$$\lambda_\phi = \frac{g_X^2}{m_X^2}\left[M_{H_1}^2 + M_{H_2}^2 + \left(M_{H_2}^2 - M_{H_1}^2\right)\cos 2\theta\right]$$

$$\lambda_{H\phi} = \frac{g_X}{m_X v}\left(M_{H_1}^2 - M_{H_2}^2\right)\sin 2\theta$$

$$L_{DM} = -\frac{y_{N_1}}{2\sqrt{2}}\rho N_1 N_1 - \frac{1}{2} g_X X^\mu \overline{N_1}\gamma_\mu\gamma_5 N_1 + \frac{1}{2} g_X^2 X_\mu X^\mu (\rho^2 + 2\rho\omega)$$

Majorana DM

$$\frac{y_{N_1}}{2\sqrt{2}} \rightarrow g_X \frac{m_{N_1}}{m_X}$$

Relic density due to:

$$N_1 N_1 \rightarrow \bar{f} f, \quad \mathrm{N_1 N_1} \rightarrow \rho Z', N_1 N_1 \rightarrow Z' Z', N_1 N_1 \rightarrow \rho\rho$$

In presence of $h/\rho, Z/Z'$ mixing we have

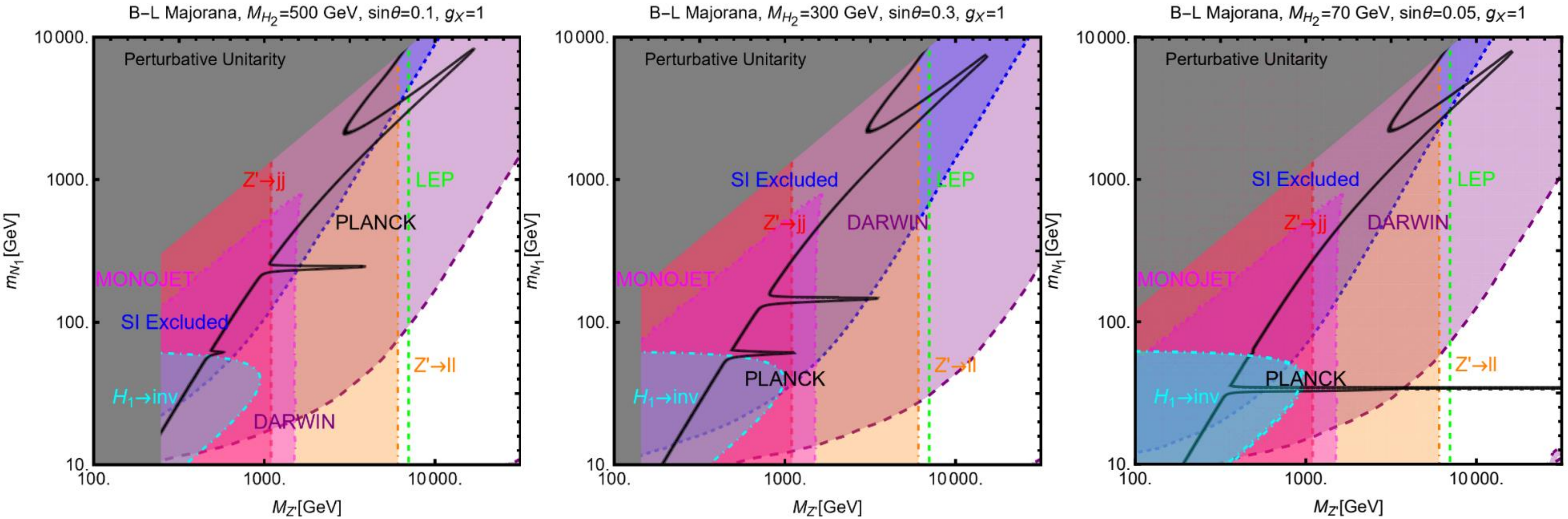
$$N_1 N_1 \rightarrow \bar{f} f, \qquad \mathrm{N_1 N_1} \rightarrow ZZ, ZZ', Z'Z', N_1 N_1 \rightarrow W^+ W^-, N_1 N_1 \rightarrow H_{1,2} H_{1,2}$$

Direct Detection

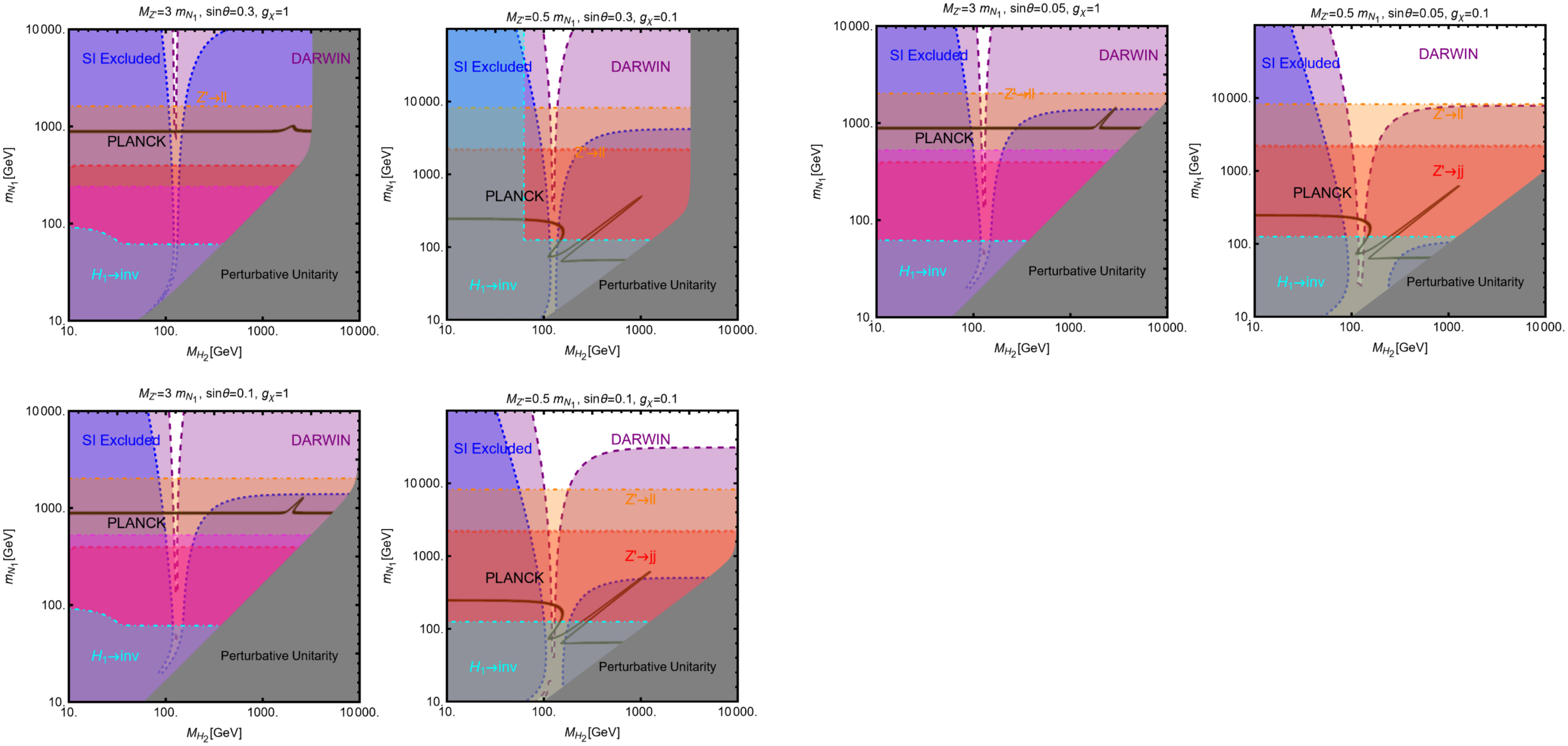
$$\sigma_{N_1 p}^{SI} = \frac{4\mu_{N_1 p}^2}{\pi}\left\{\frac{y_{N_1} m_p}{v}\sin\theta\cos\theta\left(\frac{1}{M_{H_1}^2}-\frac{1}{M_{H_2}^2}\right)\left[\sum_{q=u,d,s} f_q^p + \frac{2}{27} f_{TG}\right] + \right.$$

$$\left. m_p \sum_{q=u,d,s} f_q^p f_q + \sum_{q=u,d,s,c,b} \frac{3}{4} m_p (q(2)+\bar{q}(2))\left(g_q^{(1)}+g_q^{(2)}\right) - \frac{8\pi}{9\alpha_s} f_{TG} f_G \right\}^2$$

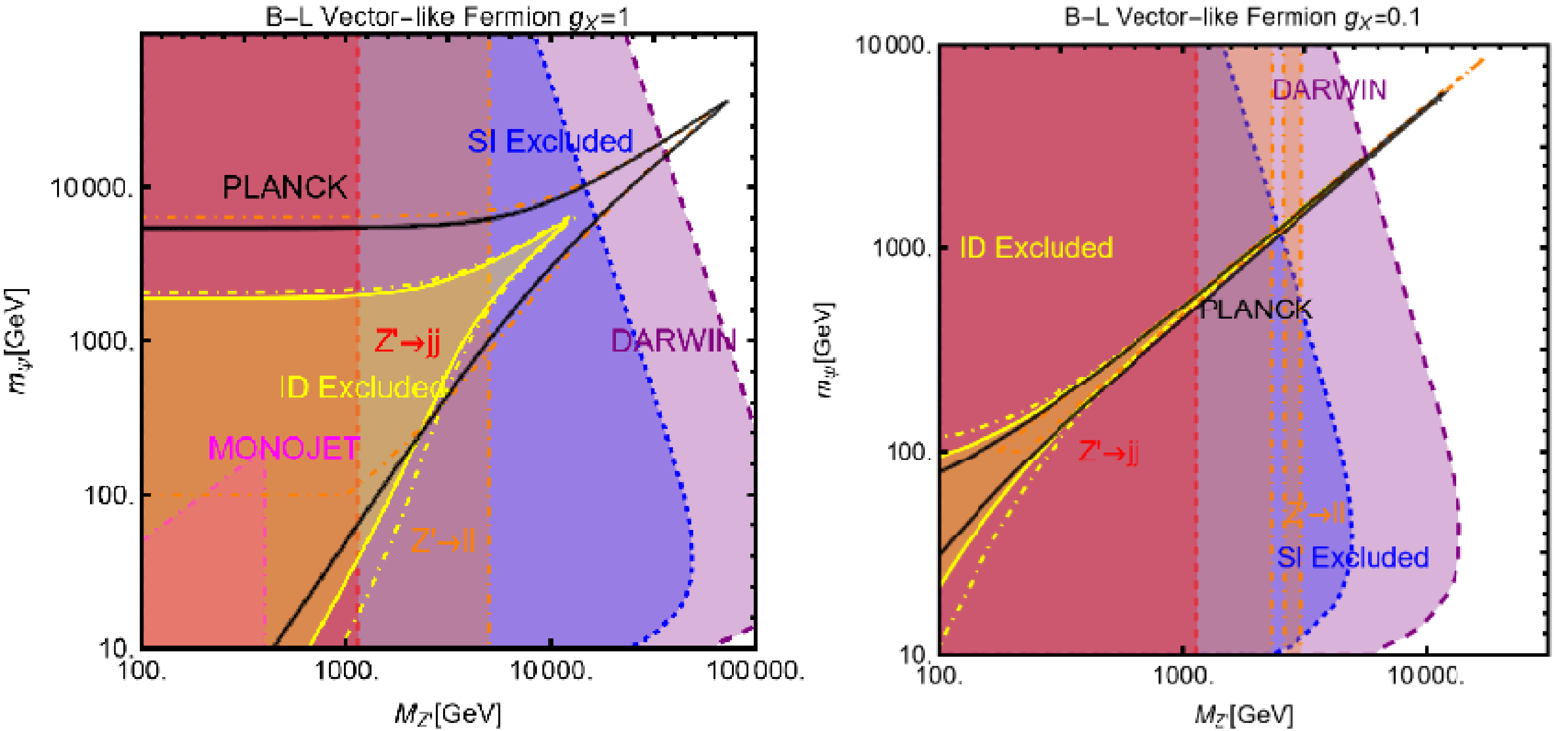
$$\sigma_{N_1 p}^{SD} = \frac{3\mu_{N_1 p}^{\ 2}}{\pi} g_X^4 \left\{\frac{\left[A_u^Z \Delta_u^p + A_d^Z\left(\Delta_d^p + \Delta_s^p\right)\right]}{M_Z^2} + \frac{\left[A_u^{Z'} \Delta_u^p + A_d^{Z'}\left(\Delta_d^p + \Delta_s^p\right)\right]}{M_{Z'}^2}\right\}^2$$



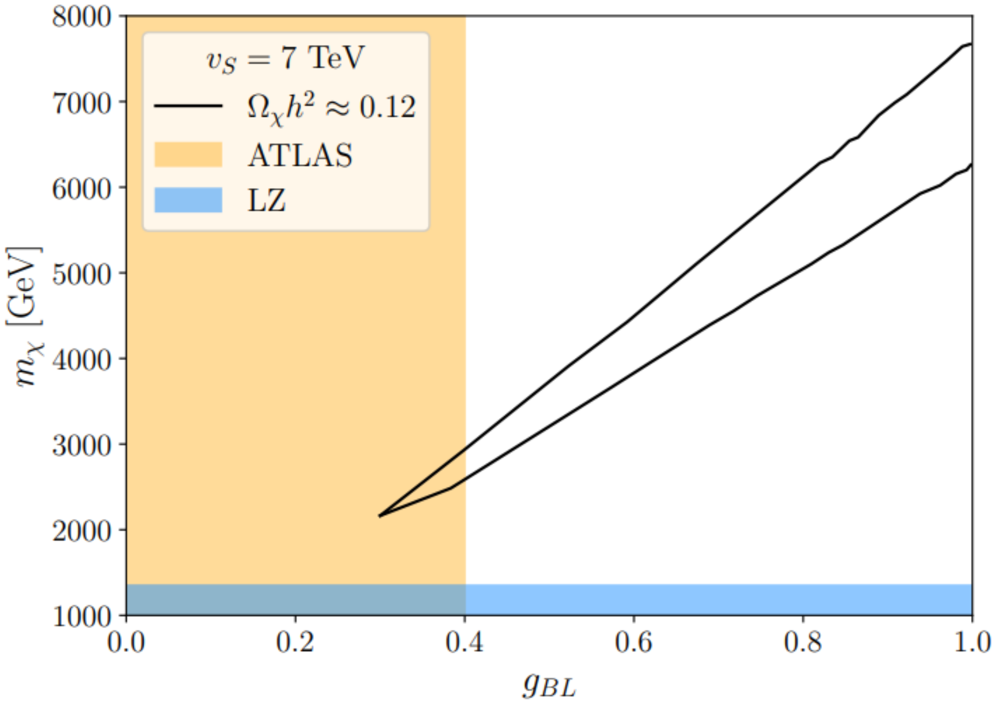
G.A. et al, arXiv: 2403.15860

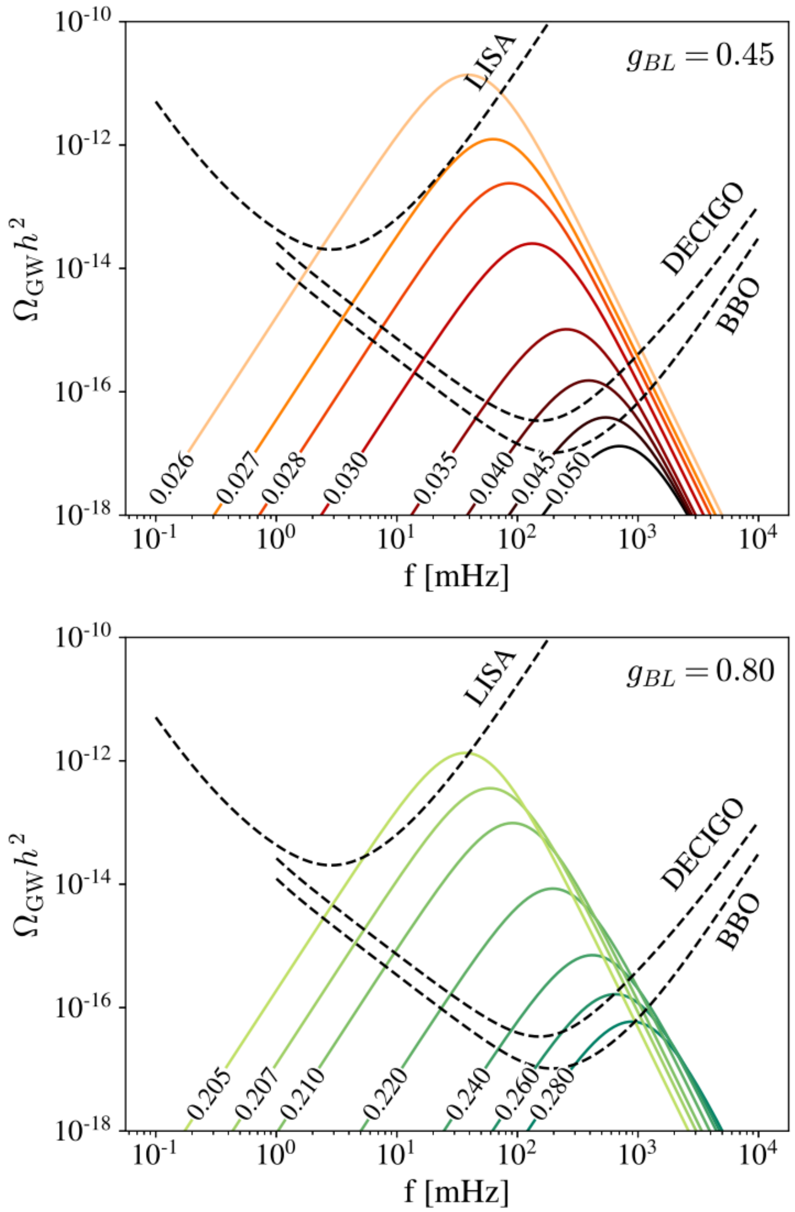


$M_{Z'}=3\ m_{N_1}$, sinθ=0.3, g_X=1
$M_{Z'}=0.5\ m_{N_1}$, sinθ=0.3, g_X=0.1
$M_{Z'}=3\ m_{N_1}$, sinθ=0.05, g_X=1
$M_{Z'}=0.5\ m_{N_1}$, sinθ=0.05, g_X=0.1
$M_{Z'}=3\ m_{N_1}$, sinθ=0.1, g_X=1
$M_{Z'}=0.5\ m_{N_1}$, sinθ=0.1, g_X=0.1
SI Excluded
DARWIN
Z'→ll
Z'→jj
PLANCK
H_1→inv
Perturbative Unitarity
m_{N_1}[GeV]
M_{H_2}[GeV]


B−L Vector−like Fermion g_X=1
SI Excluded
PLANCK
DARWIN
Z'→jj
ID Excluded
MONOJET
Z'→ll
m_ψ[GeV]
$M_{Z'}$[GeV]
B−L Vector−like Fermion g_X=0.1
DARWIN
ID Excluded
PLANCK
Z'→jj
Z'→ll
SI Excluded

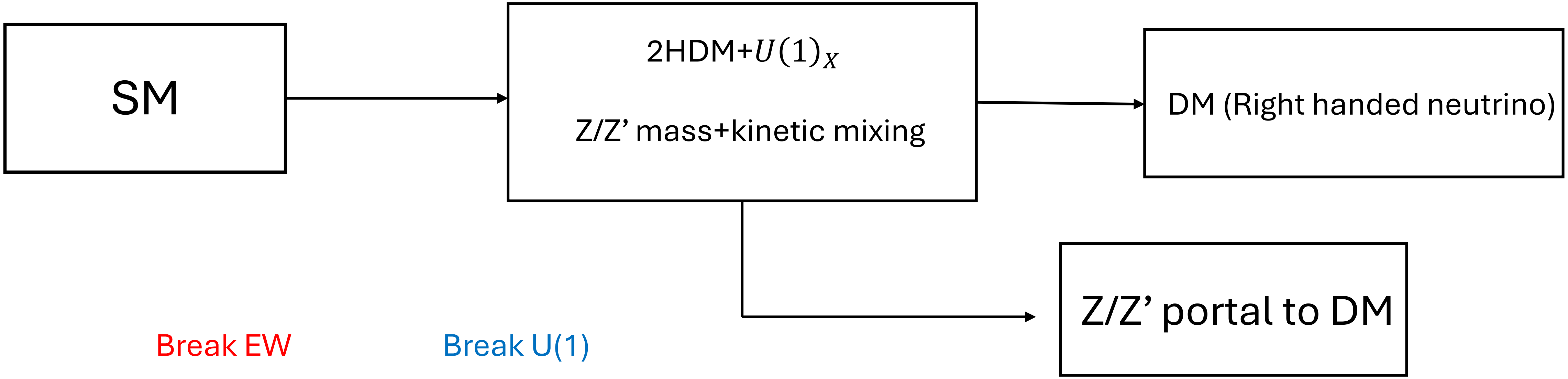
Connection with GW





G.A., G. C. Dorsch, J. P. Neto, F. S. Queiroz, Y. M. Oviedo Torres Phys. Lett. B848 (2024) 138382

2HDM+$U(1)_X$

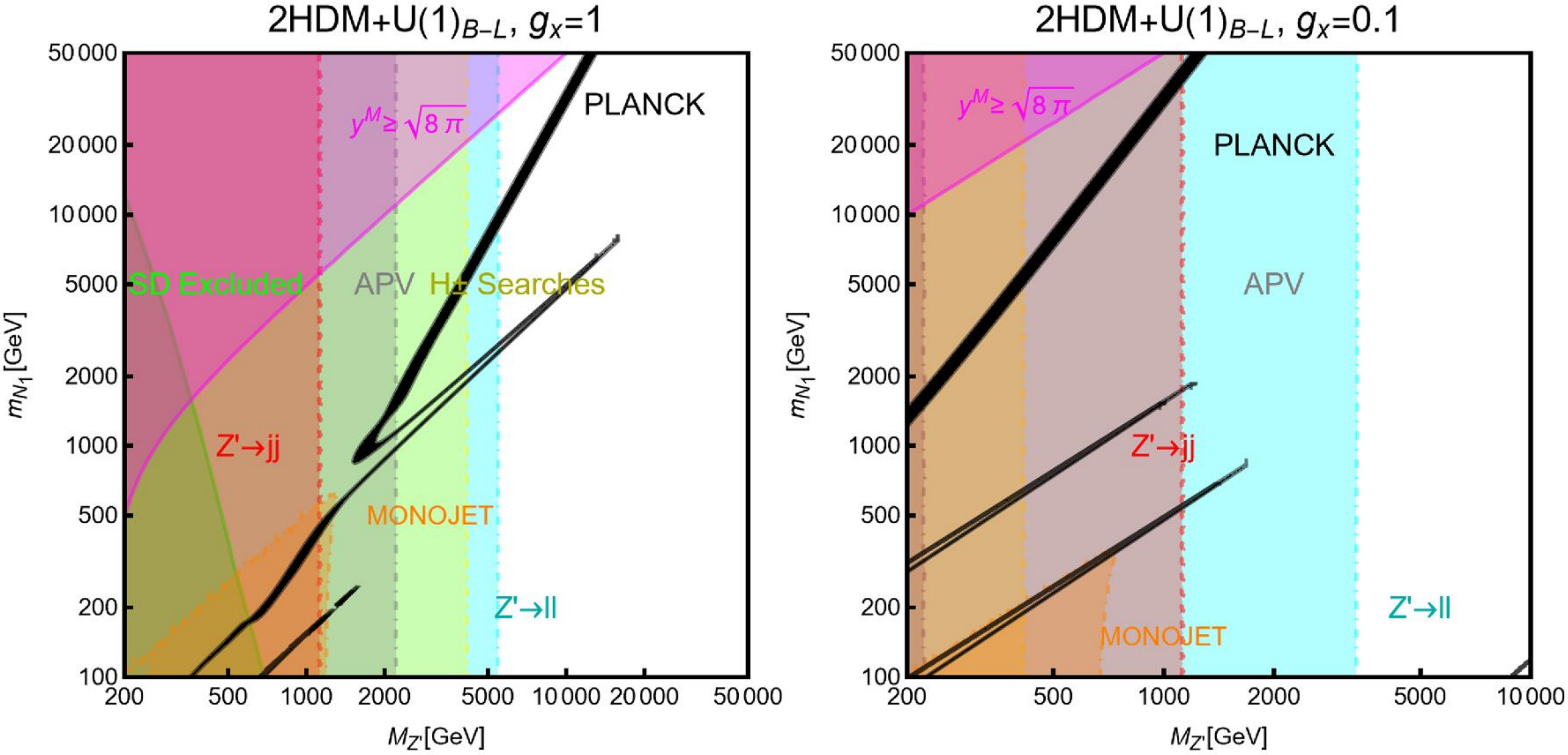


Break EW

Break U(1)

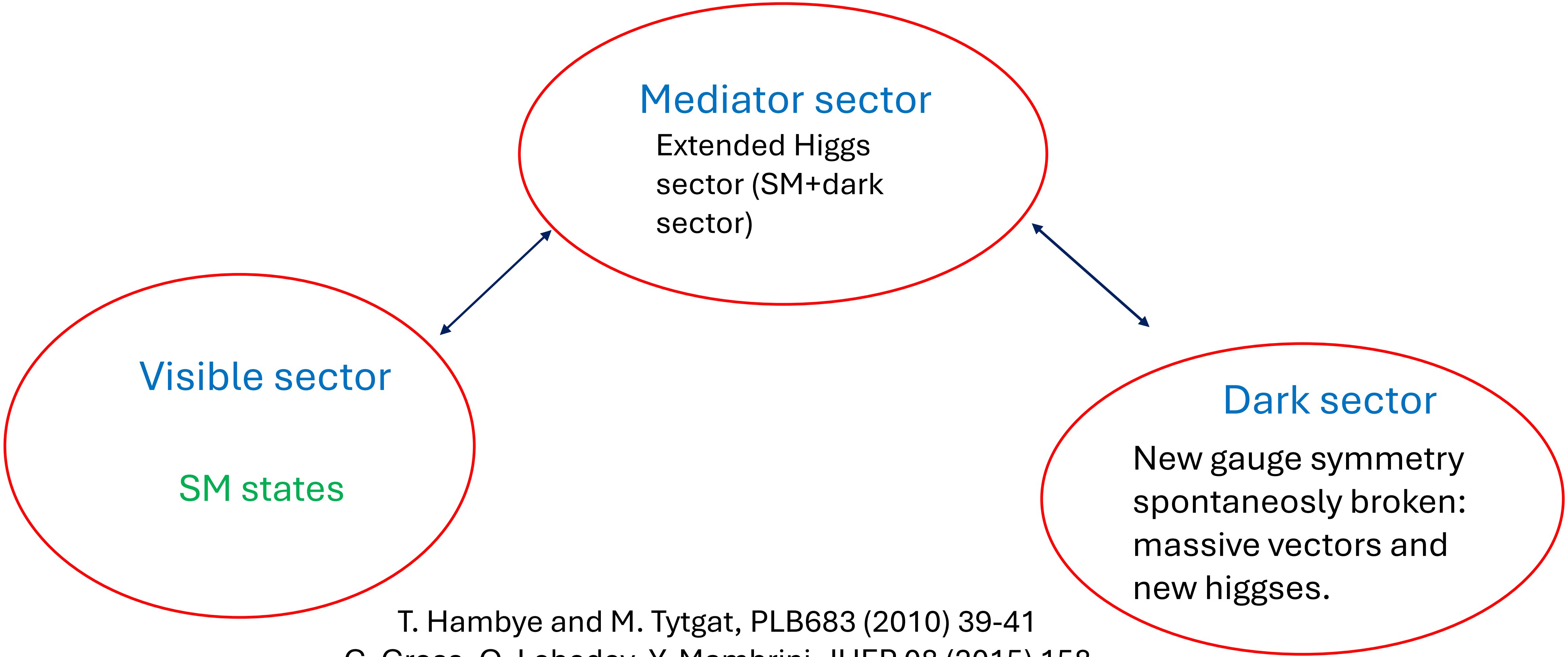
$$\mathcal{L} = (D^\mu\phi_1)^\dagger(D_\mu\phi_1) + (D^\mu\phi_2)^\dagger(D_\mu\phi_2) + (D^\mu\phi_s)^\dagger(D_\mu\phi_s) =$$
$$+\frac{1}{4}g^2v^2W^{-\mu}W^+_\mu + \frac{1}{8}g_Z^2v^2Z^{0\mu}Z^0_\mu - \frac{1}{4}g_Z(G_{X_1}v_1^2 + G_{X_2}v_2^2)Z^{0\mu}X_\mu$$
$$+\frac{1}{8}(v_1^2G_{X_1}^2 + v_2^2G_{X_2}^2v_2^2 + v_s^2Q_{X_s}^2g_X^2)X^\mu X_\mu$$

$$\mathcal{L}_{\rm NC} = -eJ^\mu_{\rm em}A_\mu - \frac{g}{2\cos\theta_W}\cos\xi J^\mu_{NC}Z_\mu - \sin\xi\left(\epsilon e J^\mu_{em} + \epsilon_Z\frac{g}{2\cos\theta_W}J^\mu_{NC}\right)Z'_\mu +$$
$$+\frac{1}{4}g_X\sin\xi\left[\left(Q^R_{Xf}+Q^L_{Xf}\right)\bar\psi_f\gamma^\mu\psi_f + \left(Q^R_{Xf}-Q^L_{Xf}\right)\bar\psi_f\gamma^\mu\gamma_5\psi_f\right]Z_\mu +$$
$$-\frac{1}{4}g_X\cos\xi\left[\left(Q^R_{Xf}+Q^L_{Xf}\right)\bar\psi_f\gamma^\mu\psi_f - \left(Q^L_{Xf}-Q^R_{Xf}\right)\bar\psi_f\gamma^\mu\gamma_5\psi_f\right]Z'_\mu +$$
$$-\frac{1}{4}Q_{N_1}g_X\cos\xi\cos\xi N_1\gamma^\mu\gamma_5N_1Z'_\mu + \frac{1}{4}Q_{N_1}g_X\sin\xi N_1\gamma^\mu\gamma_5N_1Z_\mu,$$



2HDM+U(1)$_{B-L}$, g_X=1
PLANCK
$y^M \geq \sqrt{8\pi}$
SD Excluded
APV
H± Searches
Z'→jj
MONOJET
Z'→ll
m_{N_1}[GeV]
$M_{Z'}$[GeV]
2HDM+U(1)$_{B-L}$, g_X=0.1
PLANCK
$y^M \geq \sqrt{8\pi}$
APV
Z'→jj
MONOJET
Z'→ll
m_{N_1}[GeV]
$M_{Z'}$[GeV]

Dark Matter from gauge symmetry



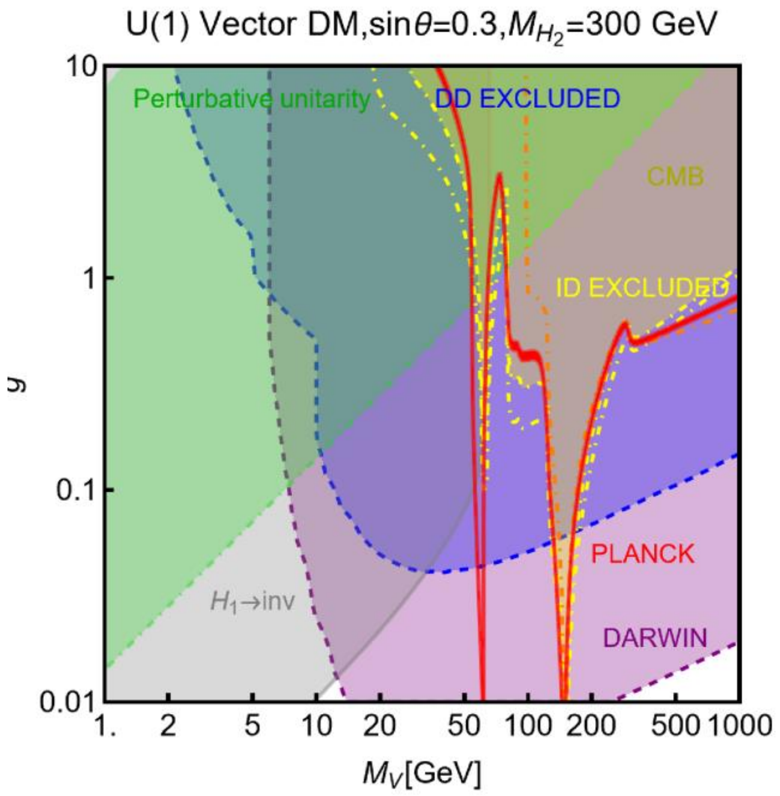
T. Hambye and M. Tytgat, PLB683 (2010) 39-41
C. Gross, O. Lebedev, Y. Mambrini, JHEP 08 (2015) 158
G.A. , C. Gross, O. Lebedev, Y. Mambrini, S. Pokorski, T. Toma, JHEP 12 (2016) 081

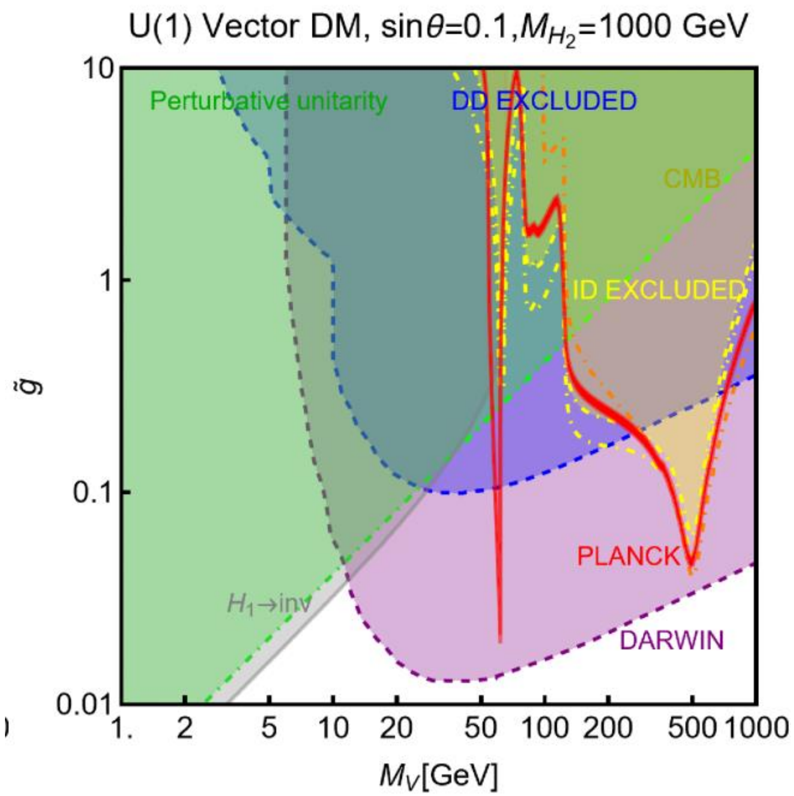
Vector DM from U(1)

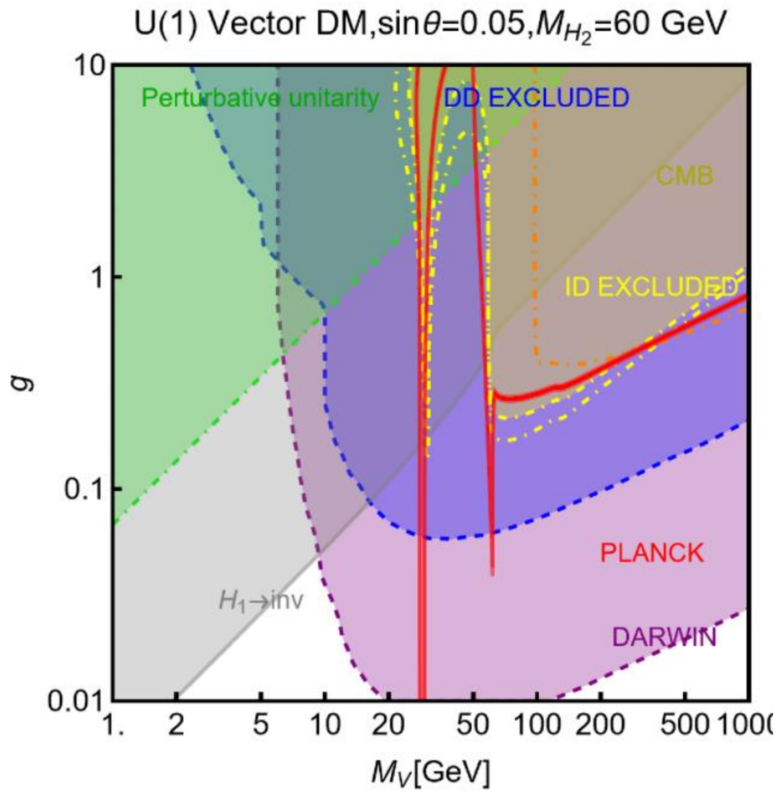
$$L_{U(1)} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi,H)$$

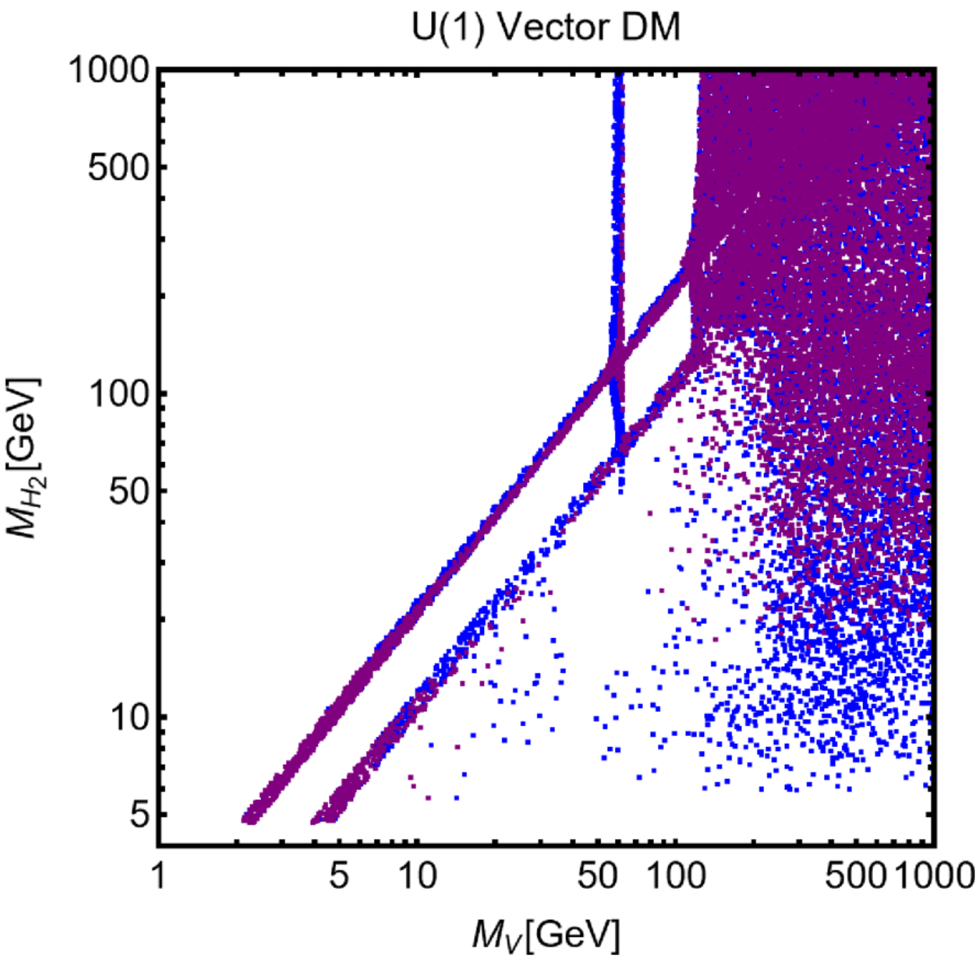
U(1) spontaneosly broken → Residual Z_2 symmetry $V_\mu \to -V_\mu$

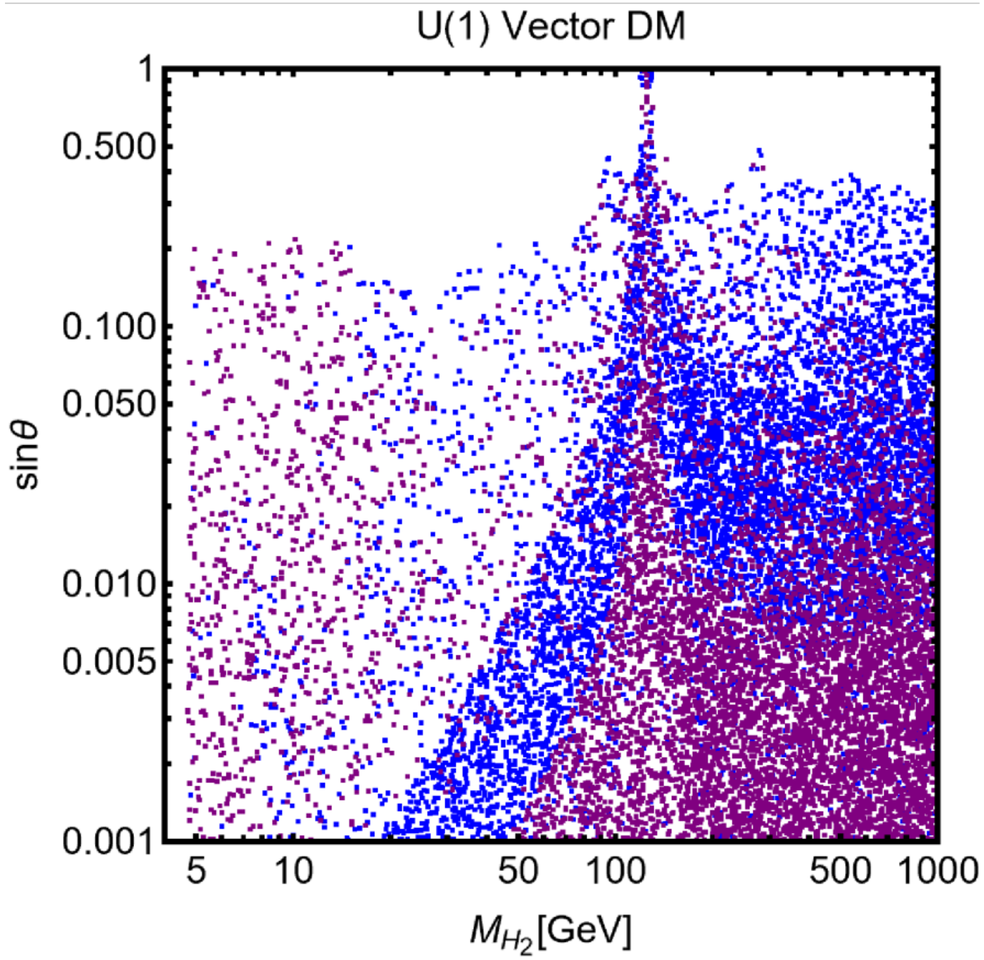
$$\Delta L = \frac{\tilde{g}^2}{4}\omega\rho V_\mu V^\mu + \frac{\tilde{g}^2}{8}\rho^2 V_\mu V^\mu \qquad M_V^2 = \frac{1}{2}\tilde{g}^2\omega^2$$








U(1) Vector DM
1000
500
100
50
10
5
1
5
10
50
100
500
1000
M_{H_2}[GeV]
M_V[GeV]


U(1) Vector DM
1
0.500
0.100
0.050
0.010
0.005
0.001
5
10
50
100
500
1000
sinθ
M_{H_2}[GeV]

Dark SU(3) dark symmetry

$$\mathcal{L}_{\text{Higgs}} = -\frac{\lambda_H}{2}|\phi|^4 - m_H^2|\phi|^2$$

$$\mathcal{L}_{\text{portal}} = -\lambda_{H11}|\phi|^2\phi_1^2 - \lambda_{H22}|\phi|^2\phi_2^2 + \left(|\phi|^2\phi_1^\dagger\phi_2 + \text{h.c}\right)$$

$$\mathcal{L}_{\text{hidden}} = -\frac{1}{2}\text{Tr}\left\{V_{\mu\nu}V^{\mu\nu}\right\} + |D_\mu\phi_1|^2 + |D_\mu\phi_2|^2 - V_{\text{hidden}}$$

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ v_1 + h_1 \end{pmatrix}$$

$$\phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 + h_2 \\ v_3 + h_3 + i\left(v_4 + h_4\right) \end{pmatrix}$$

SU(3) completely broken by two Higgses in the fundamental representation

$$V_{\text{hidden}} = m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2\left(\phi_1^\dagger\phi_2 + \text{h.c.}\right) + \left[\frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \lambda_6|\phi_1|^2\left(\phi_1^\dagger\phi_2\right) + \lambda_7|\phi_2|^2\left(\phi_1^\dagger\phi_2\right) + \text{h.c.}\right]$$

$$+\frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2$$

Vector (and Scalar DM) from SU(3)

In a simplified limit we can define the following Lagrangian:

$$
\begin{aligned}
\mathcal{L} = & \frac{\tilde{g} M_V}{2} \left(-\sin\theta H_1 + \cos\theta H_2\right) \left(\sum_{a=1,2} V_\mu^a V^{\mu\, a} + \left(\cos\alpha - \frac{\sin\alpha}{\sqrt{3}}\right)^2 V_\mu^3 V^{\mu\, 3} \right) \\
& + \tilde{g}\cos\alpha \sum_{a,b,c} \epsilon_{abc} \partial_\mu V_\nu V_\nu^a V^{b\,\mu} V^{c\,\nu} - \frac{\tilde{g}^2}{2}\cos^2\alpha \sum_{a=1,2} \left(V_\mu^a V^{a\,\mu} V_\nu^3 V^{3\,\nu} - \left(V_\mu^a V^{a\,\mu}\right)^2 \right) \\
& - \frac{1}{2} m_\psi^2 \psi^2 + \left[\frac{\tilde{g}}{2 M_V} \left(-\sin\theta H_1 + \cos\theta H_2\right) - \frac{1}{4} \left(\lambda_{\psi\psi 11} H_1^2 + 2\lambda_{\psi\psi 12} H_1 H_2 + \lambda_{\psi\psi 22} H_2^2 \right) \right] \psi^2 \\
& - \frac{k_{111}}{2} v H_1^3 - \frac{k_{112}}{2} H_1^2 H_2 v \sin\theta - \frac{\kappa_{221}}{2} H_1 H_2^2 v \cos\theta - \frac{\kappa_{222}}{2} H_2^3 v \\
& + \frac{H_1 \cos\theta + H_2 \sin\theta}{v} \left(2 M_W^2 W_\mu^+ W^{\mu -} + M_Z^2 Z_\mu Z^\mu - m_f \bar{f} f \right)
\end{aligned}
$$

Single component DM

CP-violated tiny violated

$Z_2 x Z_2$' acts only on the vector states.

We can distinguish CP-even and CP-odd states but χ is unstable.

Single component Dark Matter with increased annihilation channels

Multi component DM

CP-conserved

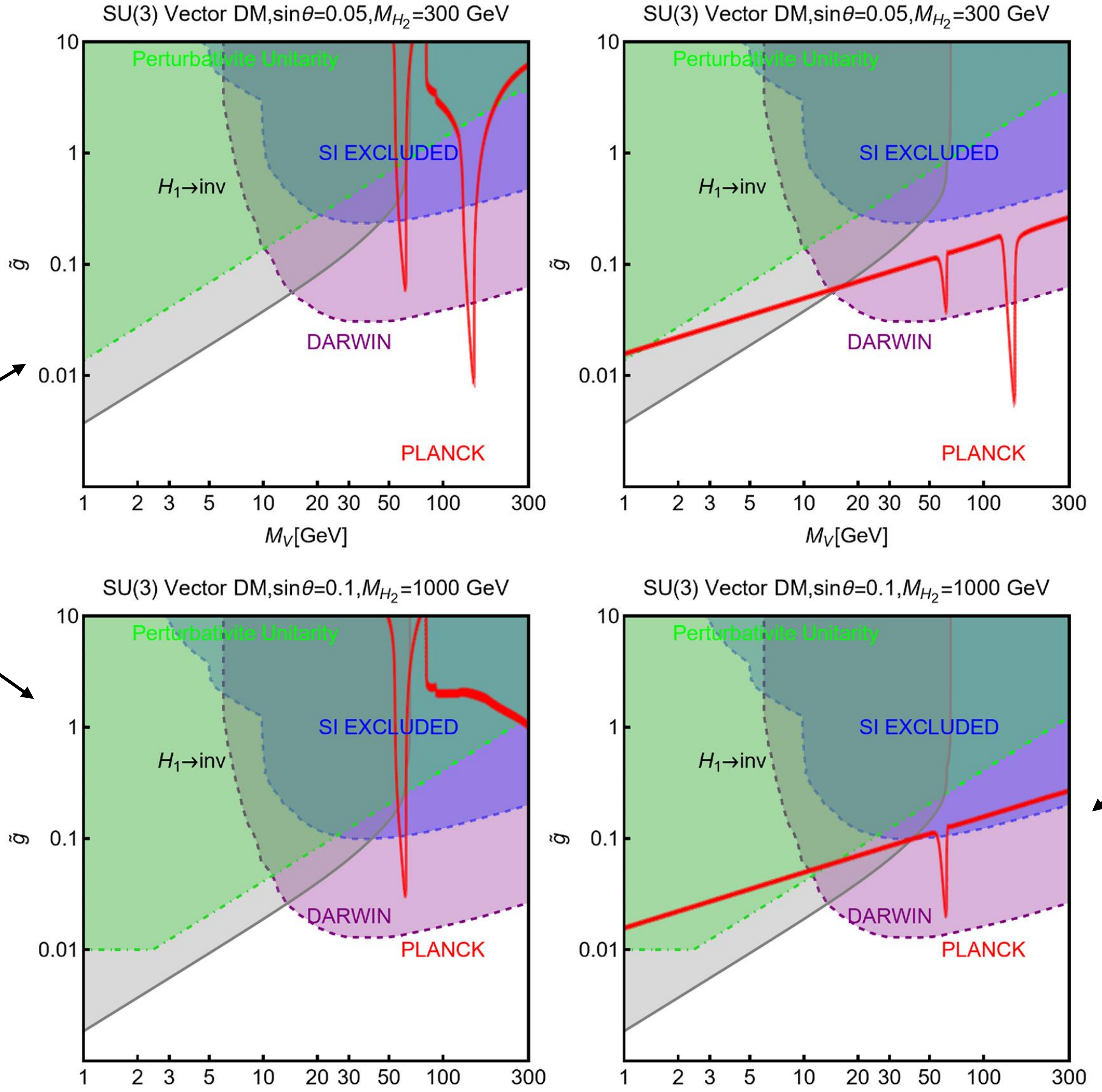
$Z_2 x Z_2$' extends also to the scalar sector.

Two cases of multicomponent DM:

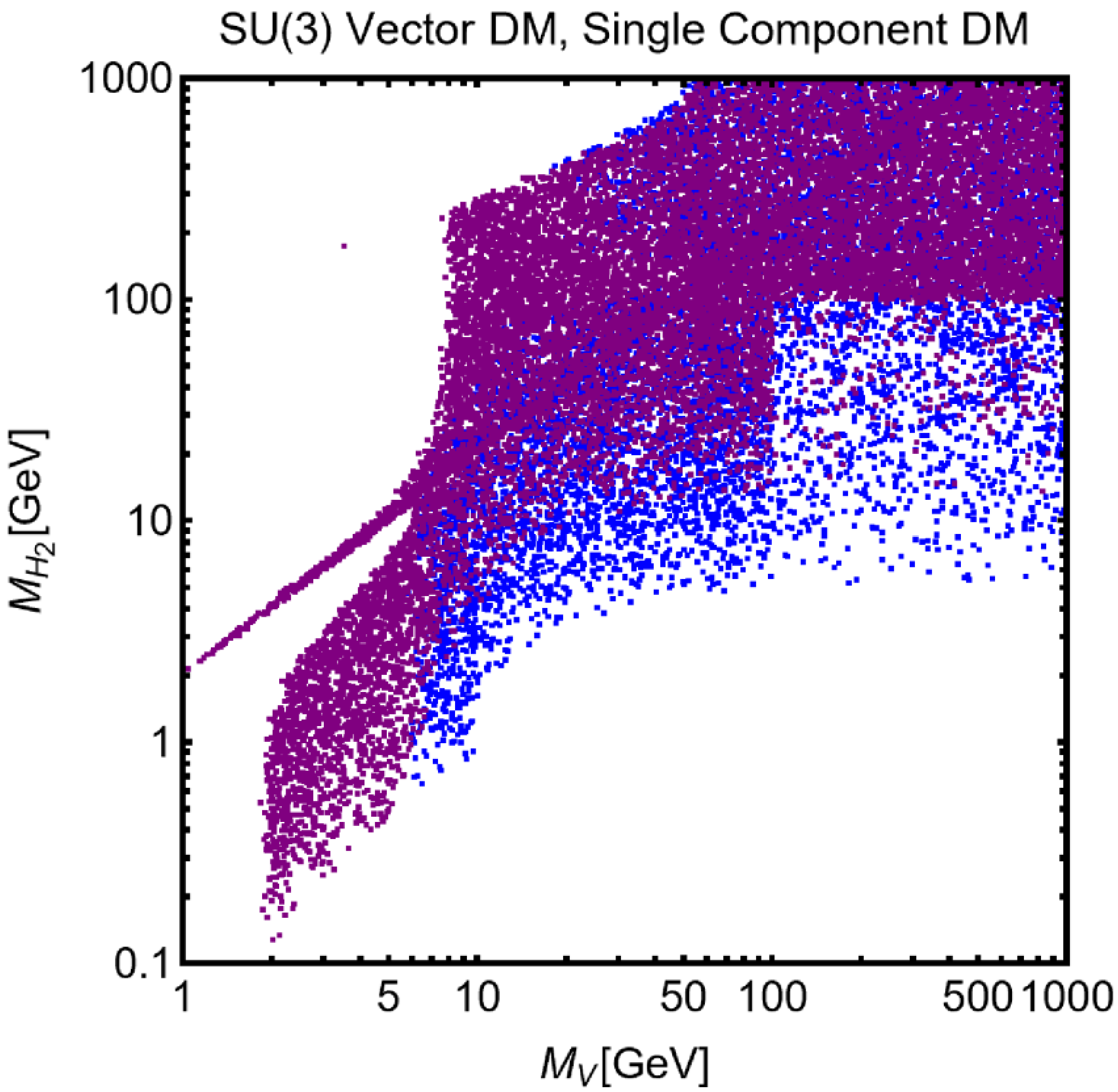
Spin-0/Spin-1 (V,χ)

Spin-1/Spin-1 (V,V^3)

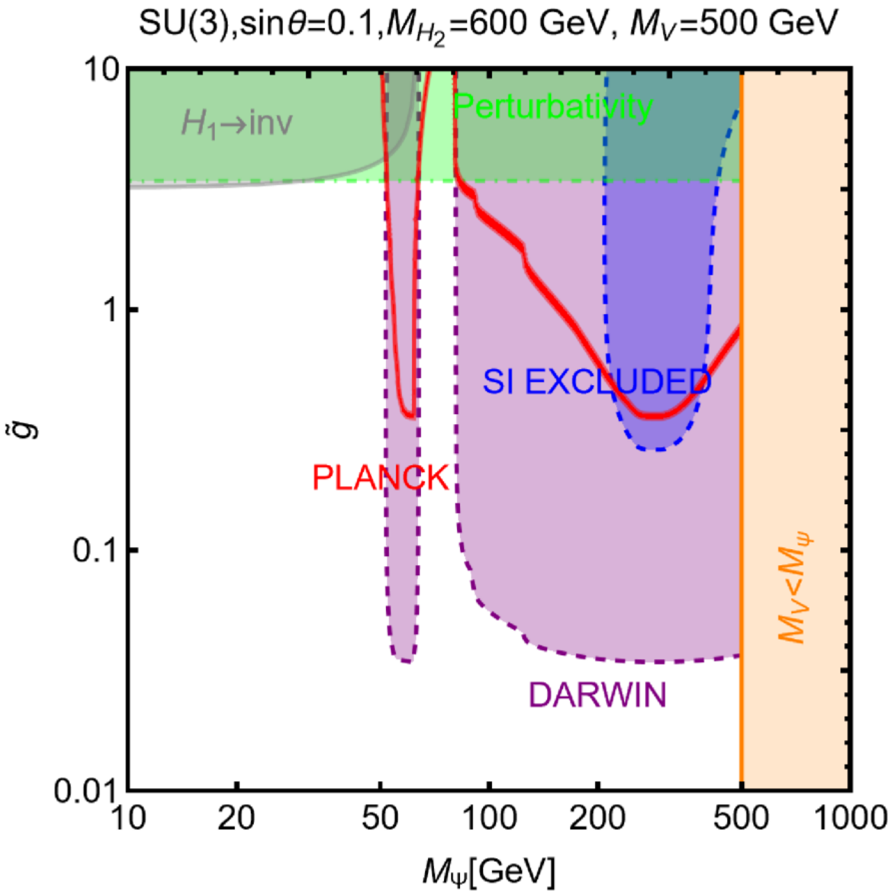
Two-component Vector DM

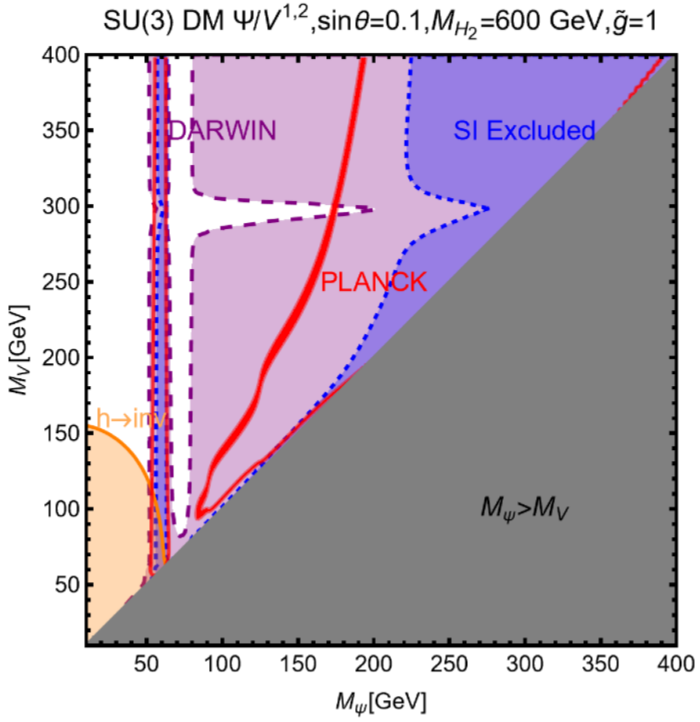


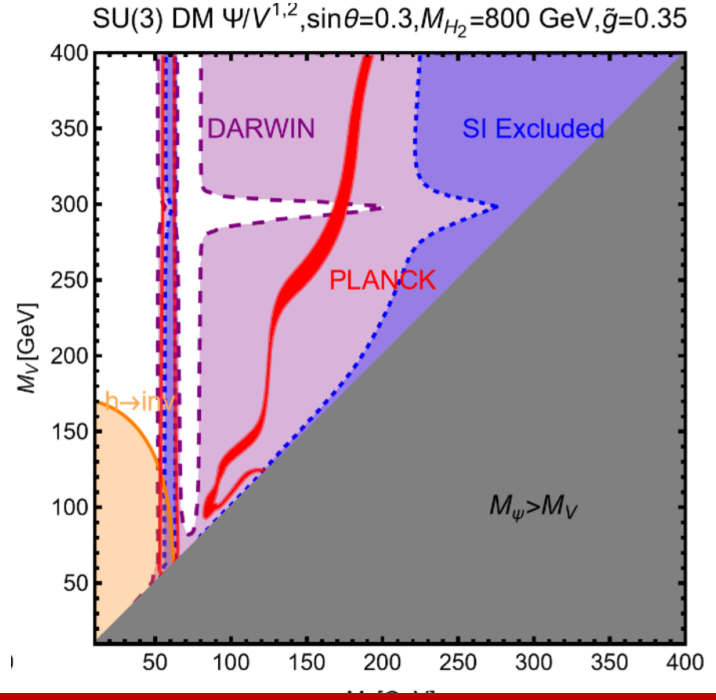
Single component DM with light metastable vector


SU(3) Vector DM, Single Component DM
1000
100
10
1
0.1
M_{H_2}[GeV]
1
5
10
50
100
500
1000
M_V[GeV]

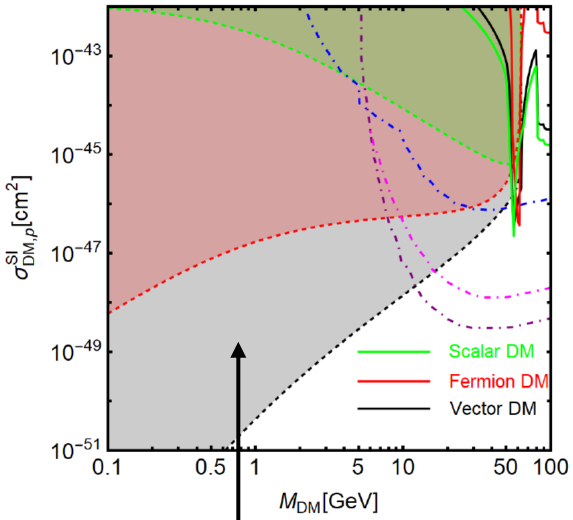
Two component scalar/vector DM







Consistency of the correlation plot for Higgs-to-invisible search

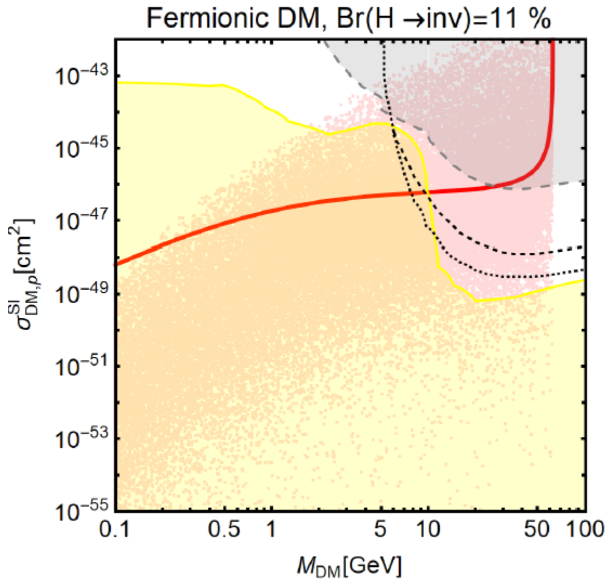


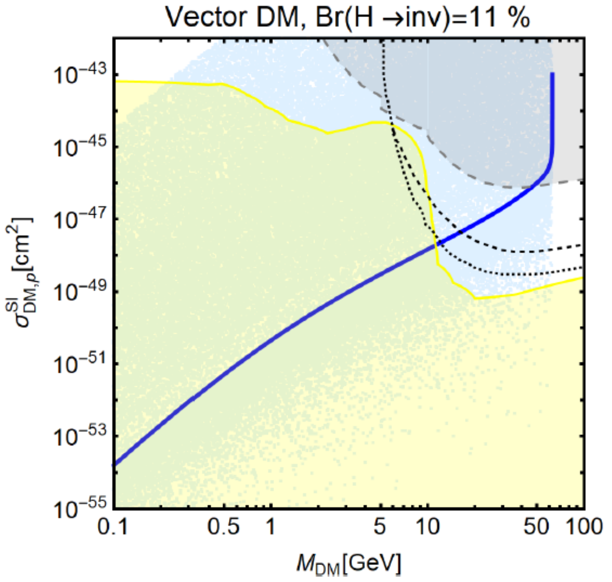
Effective Higgs portal

More realistic completion through mixing

$$\sigma_{DM,p} \propto \left(\frac{1}{M_{H_1}^2} - \frac{1}{M_{H_2}^2}\right)^2$$

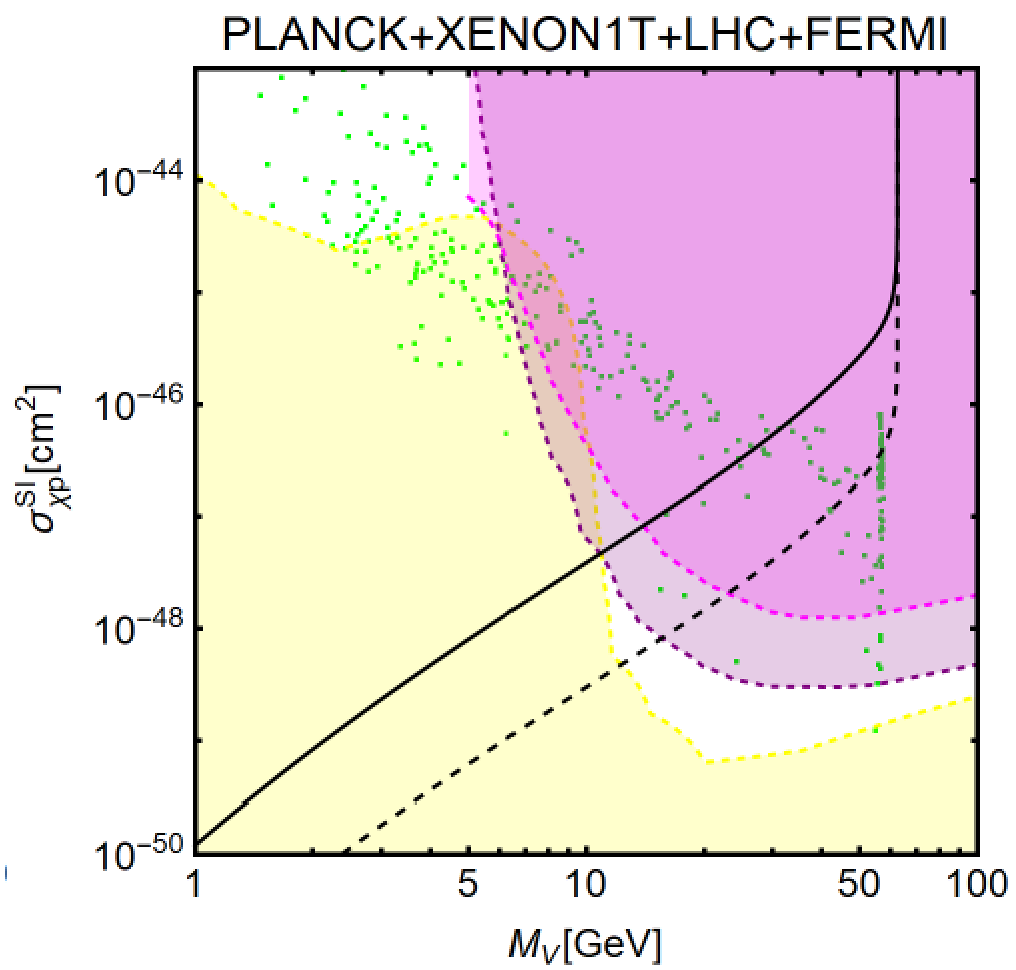
The additional degree of freedom crucially alters the LHC correlation plot.

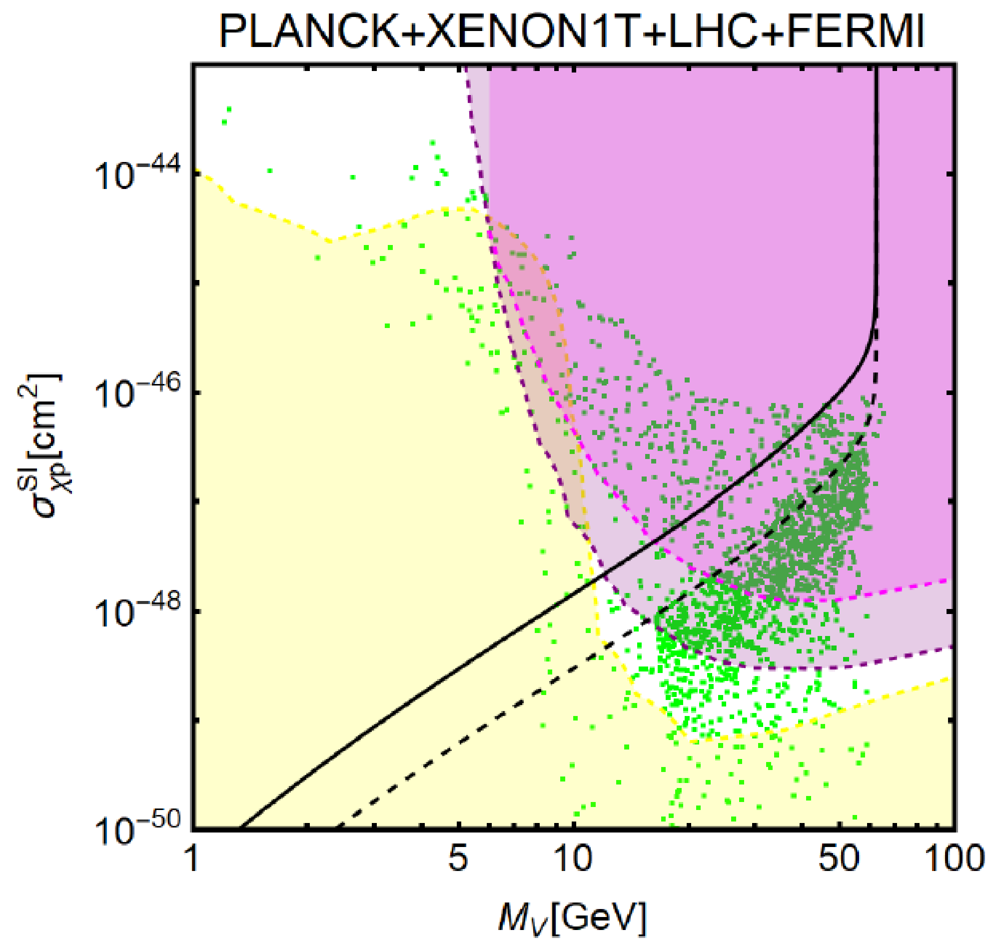




See also:
S. Baek et al. JHEP 05 (2013) 036
S. Baek et al. Phys. Rev. D90 (2014) 055015

Correlation plots for Vector DM





Conclusions

We have provided an overview of theoretical models based on the existence of Dark Higgs Bosons.

Two main scenarios considered:

- Dark Higgs boson of an abelian symmetry dynamically generating the mass of the a Z' mediator and fermionic DM.

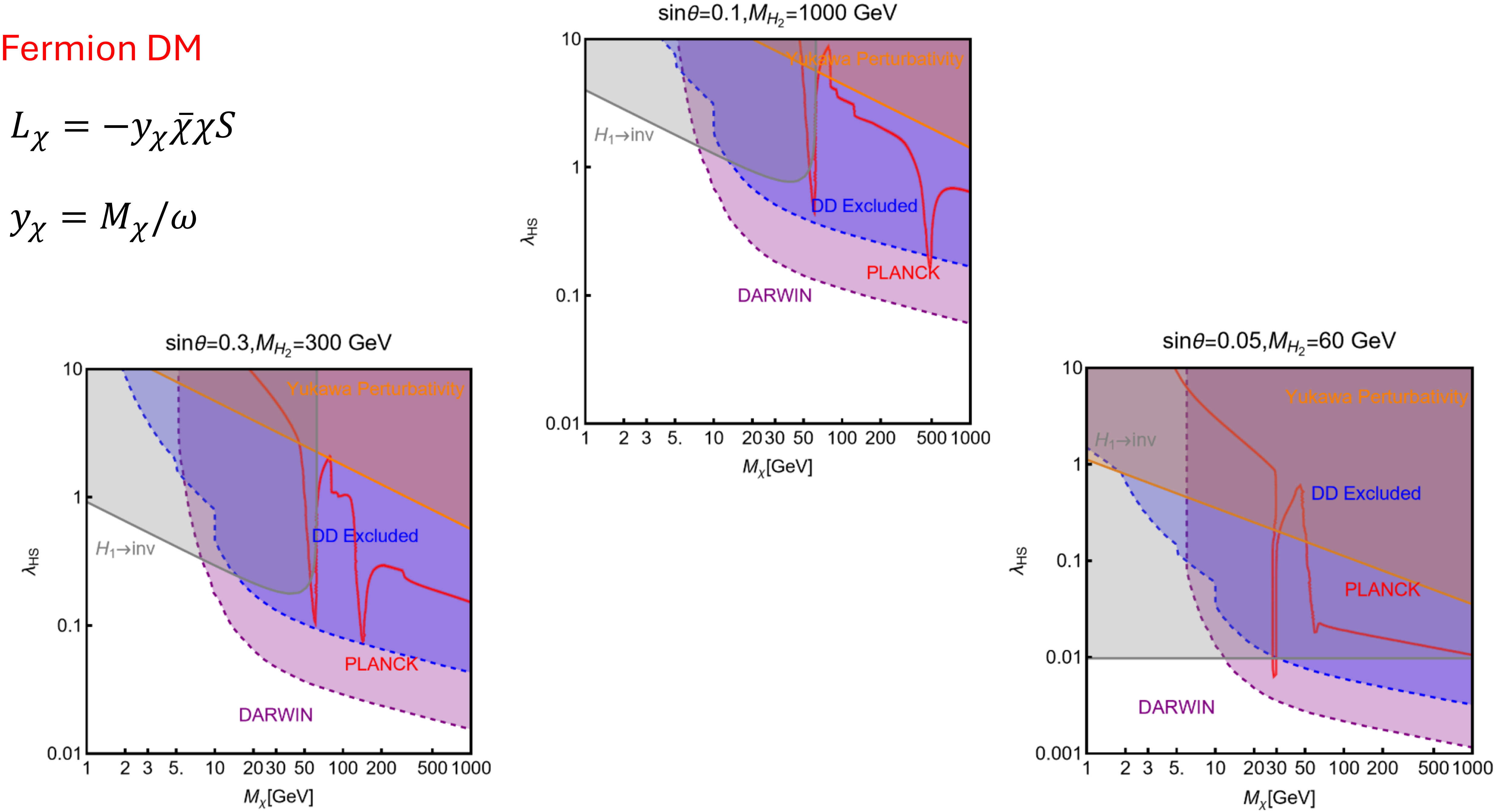
- Dark Higgs boson from Abelian/non Abelian symmetry dynamically generating mass of vector DM.

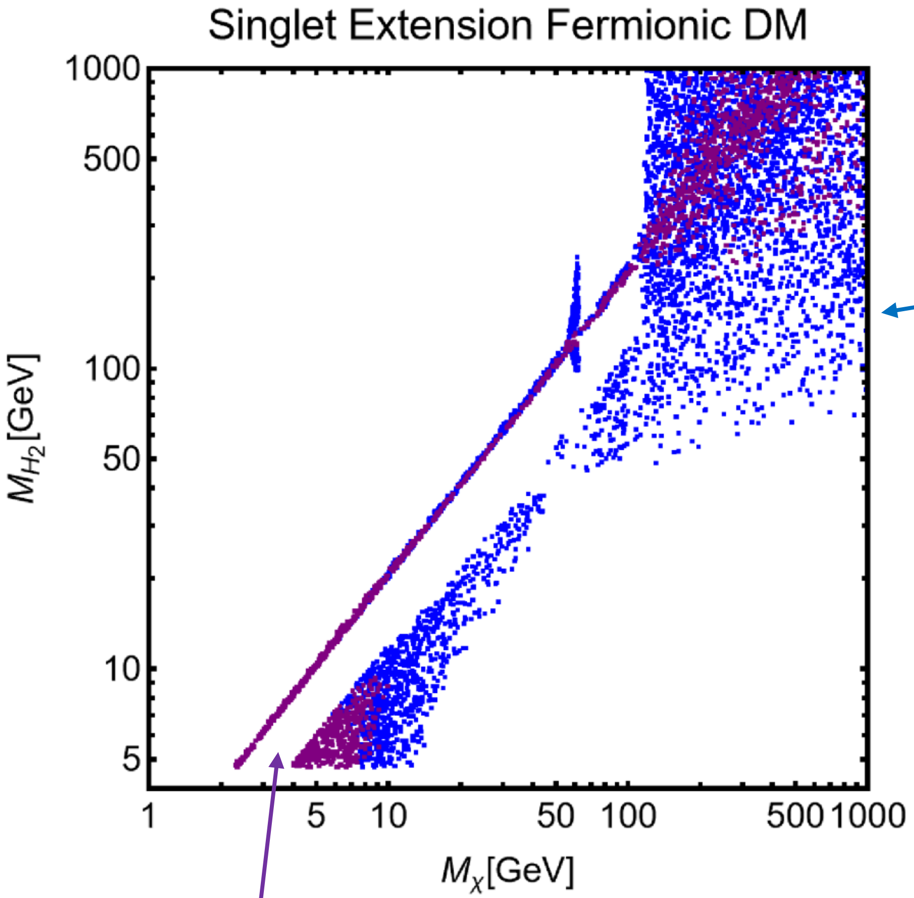
Back up

Fermion DM

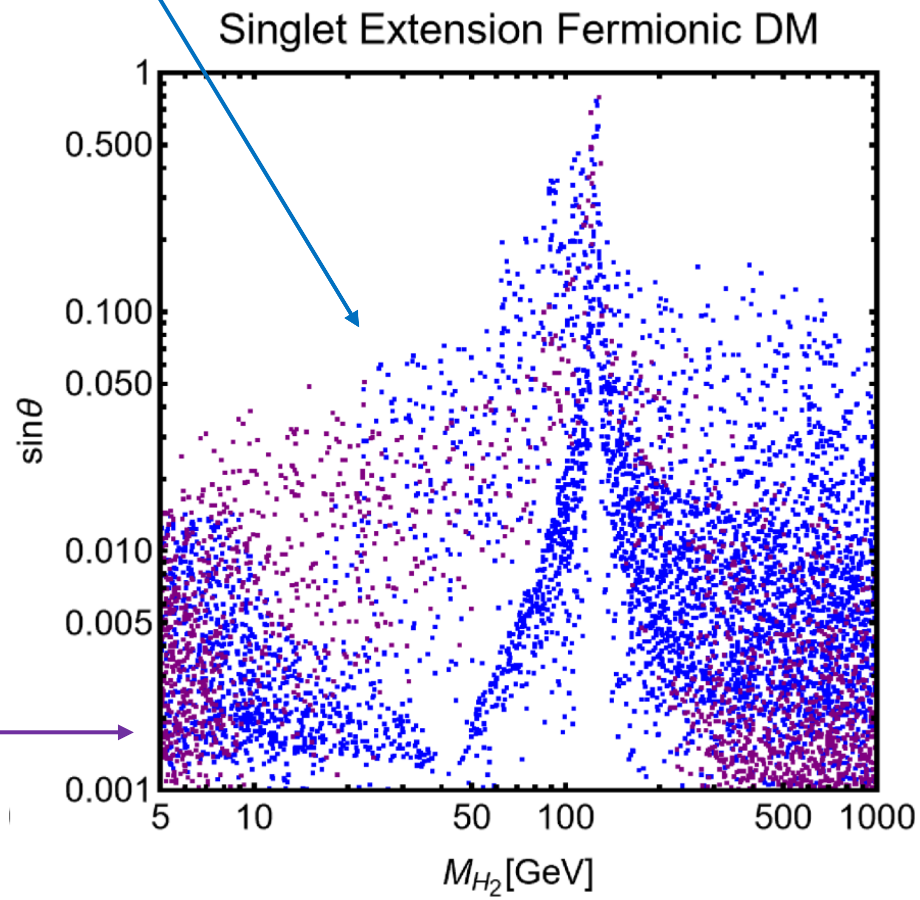
$$L_\chi = -y_\chi \bar{\chi}\chi S$$

$$y_\chi = M_\chi/\omega$$

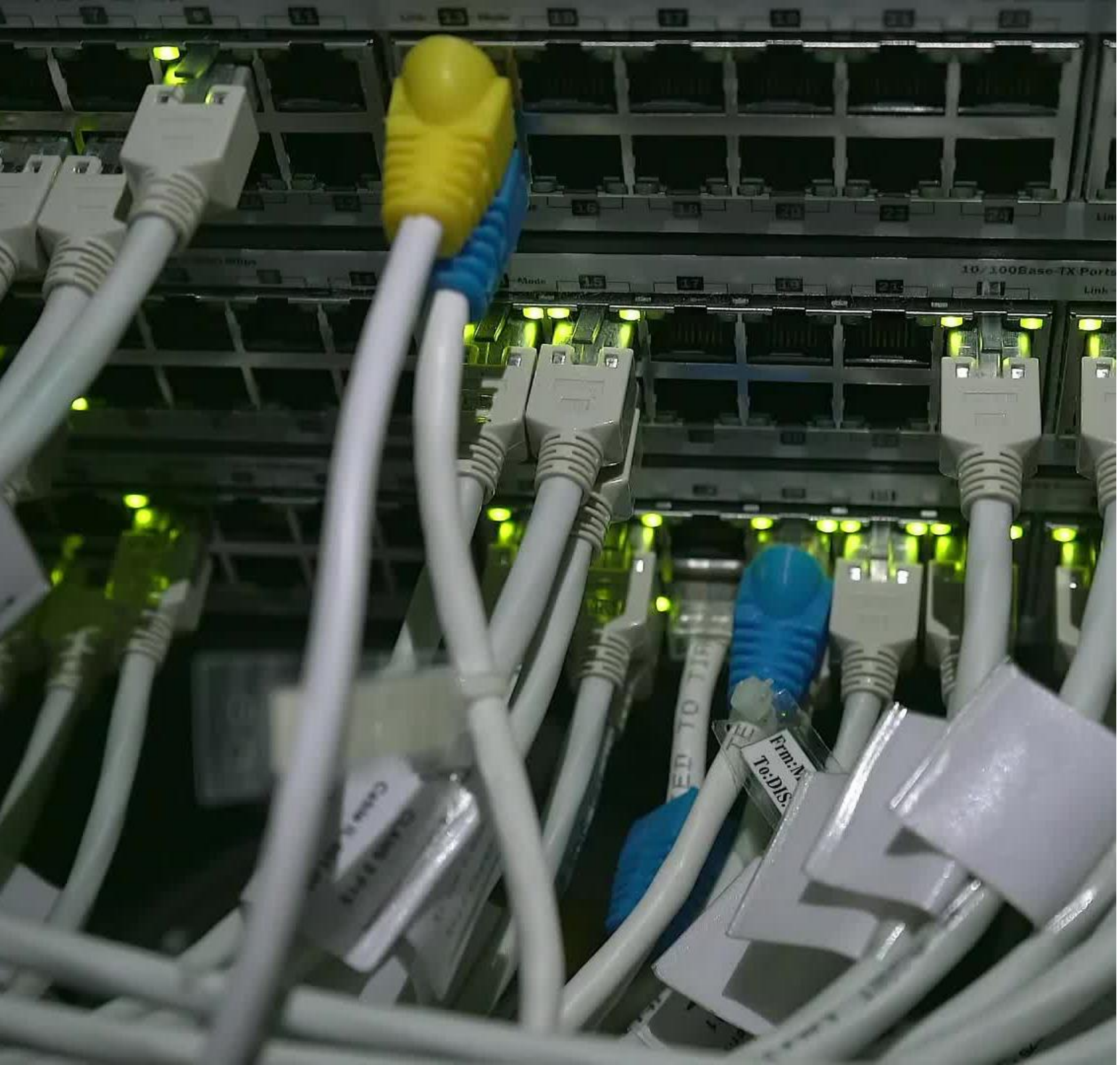




Model points compatible with present constraints



Model points passing possible bounds from DARWIN



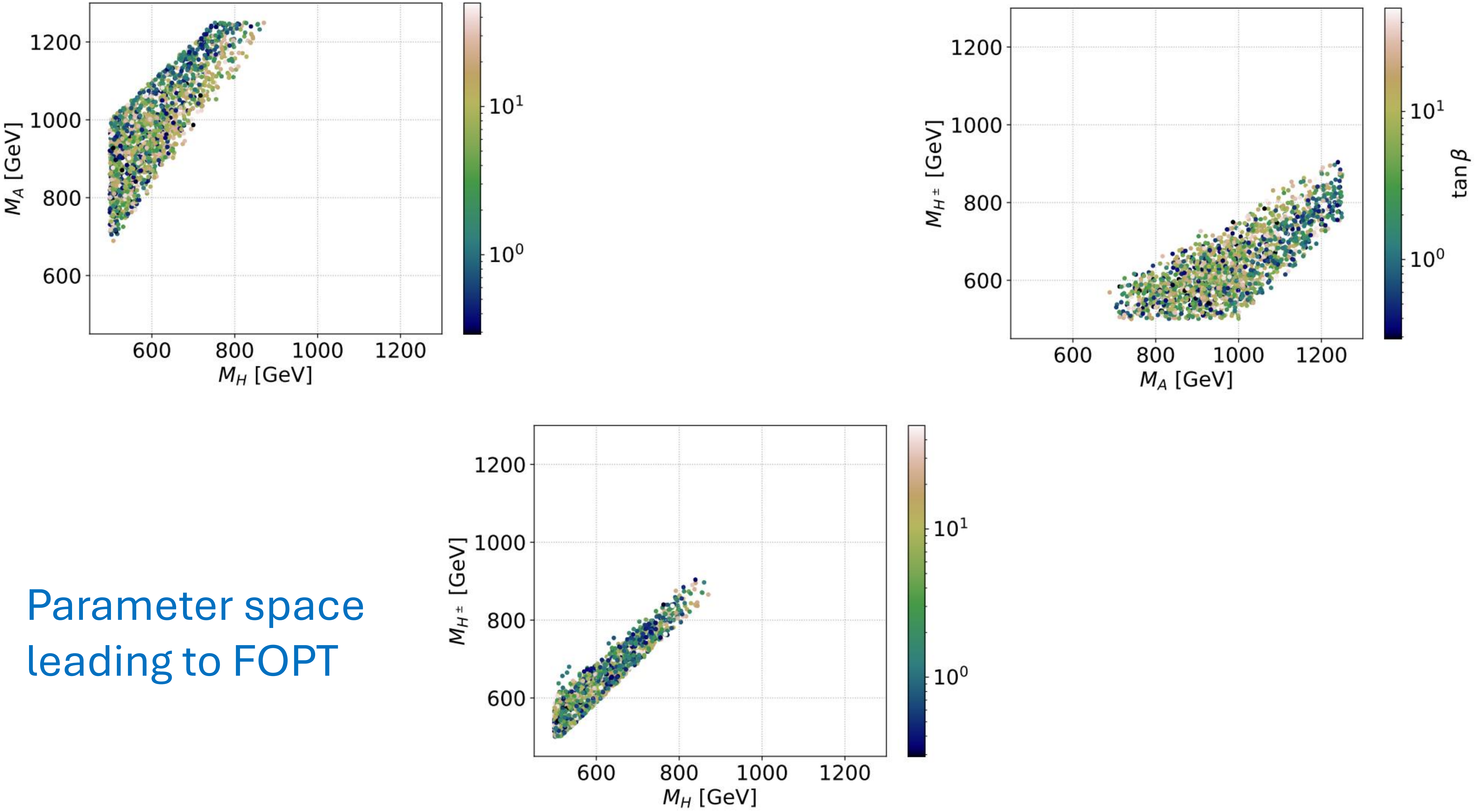
Connections with GW Signals

FOPT and GW in the 2HDM+a

One-loop thermal effective potential

$$V_{eff}(h^0, H^0, T) = V_0 + V_{CW} + V_{CT} + V_T$$

- V_{CW} → One loop quantum corrections
- V_T → Thermal corrections
- V_{CT} → Counterterms (to compensate the shift from V_{CW} to the vevs)
- V_0 → Tree-level potential



Parameter space leading to FOPT

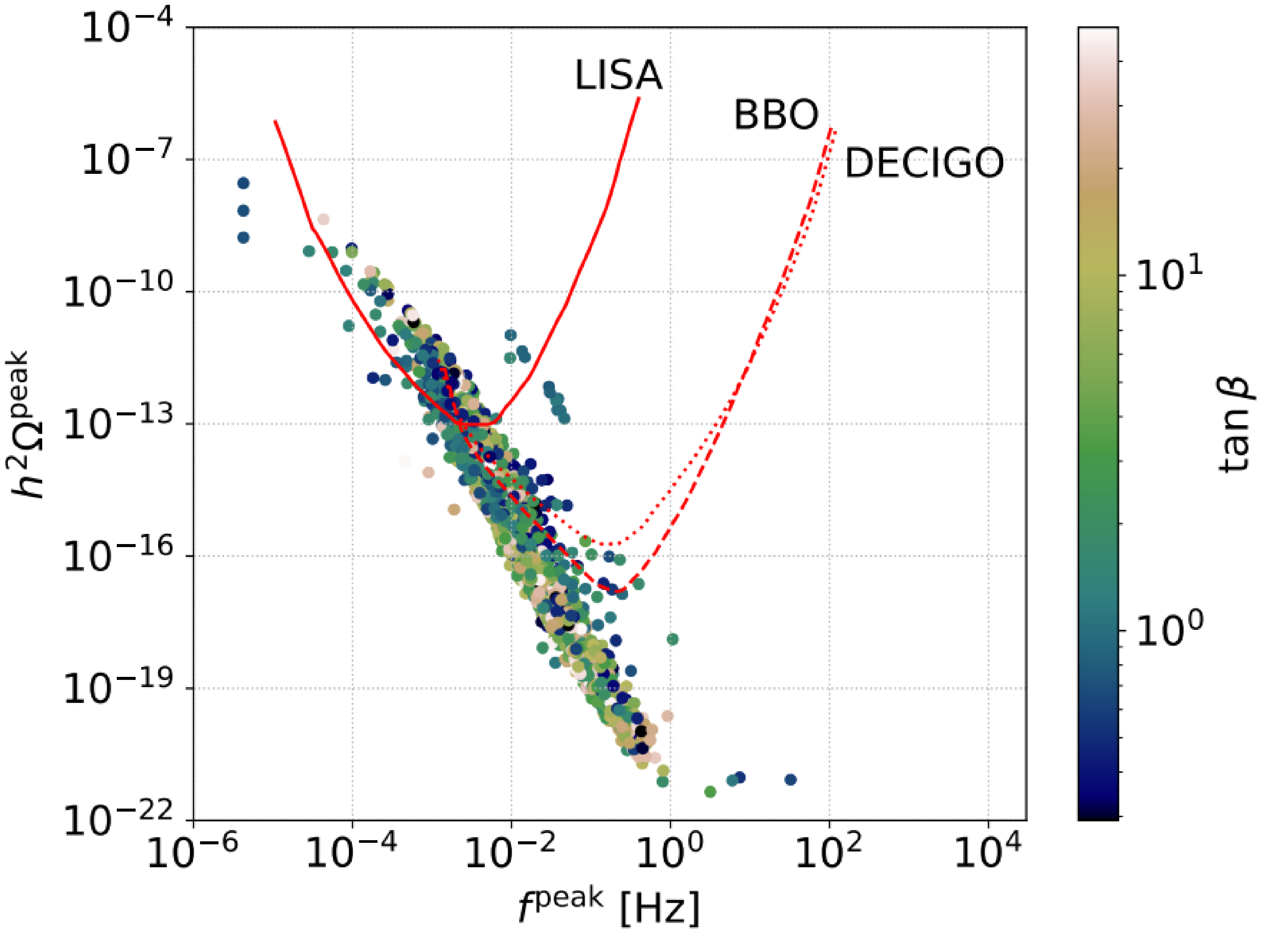
GW Signal

GW background is typically the (linear) combination of three kinds of contributions

C. Caprini et al JCAP 04 (2016) 001

$$h^2\Omega_{GW} \simeq h^2\Omega_{col} + h^2\Omega_{sw} + h^2\Omega_{turb}$$

- $h^2\Omega_{sw}$: Contribution from sound wave overlap
- $h^2\Omega_{turb}$: Contribution from Magneto-Hydrodynamical (MHD) turbolence
- $h^2\Omega_{col}$: Contribution from bubble collisions



G.A, N. Benincasa, A. Djouadi, K. Kannike, *Phys.Rev.D* 108 (2023) 5, 055010

95 GeV Excess

95 GeV Excess

CMS Collaboration JHEP 07 (2023) 073
CMS Collaboration Phys. Lett. B793 (2019)
ATLAS Collaboration ATLAS-CONF-2023-035

$$\mu_{\tau\tau} = \frac{\sigma_\phi Br(\phi \to \tau\tau)}{\sigma_{\phi,SM} Br(\phi \to \tau\tau)_{SM}} = R_{gg} R_{\tau\tau} = \frac{\Gamma(\phi \to gg)}{\Gamma(\phi \to gg)_{SM}} \frac{\Gamma(\phi \to \tau\tau)}{\Gamma(\phi \to \tau\tau)_{SM}}$$

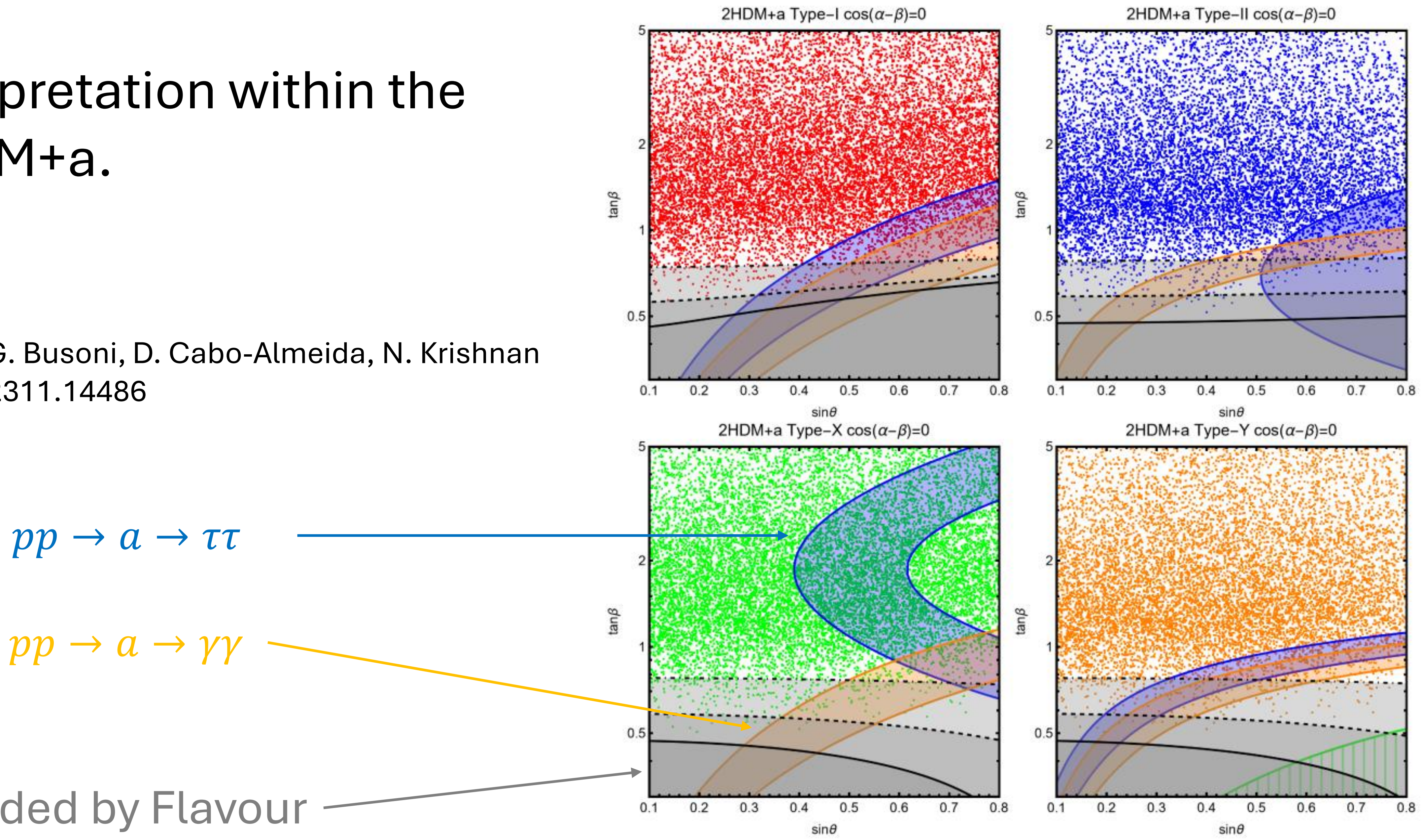
$$\mu_{\gamma\gamma} = \frac{\sigma_\phi Br(\phi \to \gamma\gamma)}{\sigma_{\phi,SM} Br(\phi \to \gamma\gamma)_{SM}} = \begin{cases} R_{gg} R_{\gamma\gamma} \dfrac{\sigma_{gg\phi,SM}}{\sigma_{\phi,SM}} \; (PS) \\ \dfrac{R_{gg}\sigma_{gg\phi,SM} + R_V \sigma_{V,BF} + R_{tt}\sigma_{tt\phi,SM}}{\sigma_{\phi,SM}} R_{\gamma\gamma} \; (S) \end{cases}$$

For our study we have used:

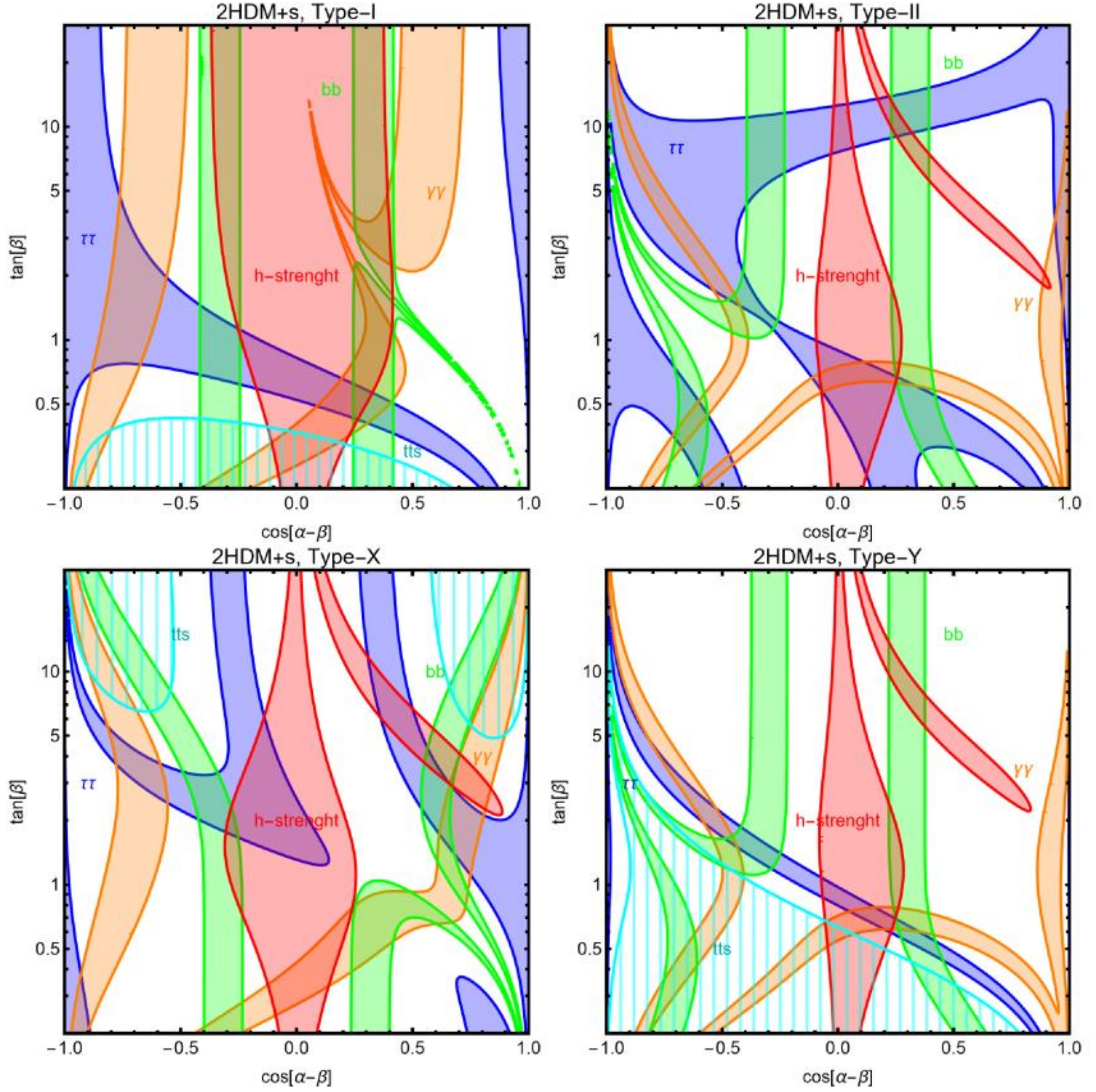
$$0.73 < \mu_{\tau\tau} < 1.83$$
$$0.17 < \mu_{\gamma\gamma} < 0.37$$

Interpretation within the 2HDM+a.

G.A., G. Busoni, D. Cabo-Almeida, N. Krishnan
arXiv:2311.14486

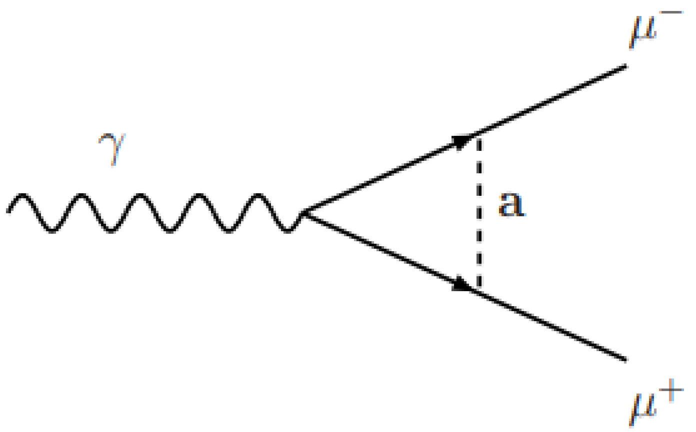


Interpretation within the 2HDM+s.

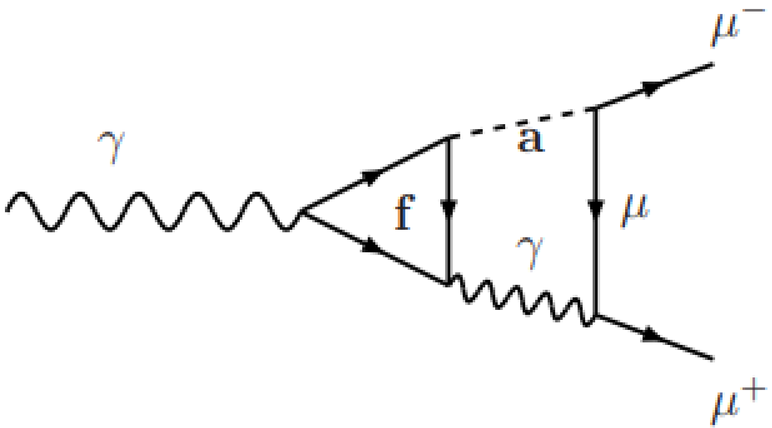



Connection with g-2

Interpretation of g-2 in the 2HDM+PS



$$\Delta a_\mu^{1-loop} \approx -\frac{\alpha}{8\pi \sin^2\theta_W}\frac{m_\mu^4}{M_W^2 M_a^2} g_{a\mu\mu}^2\left[\log\left(\frac{M_a^2}{m_\mu^2}\right)-\frac{11}{6}\right]$$

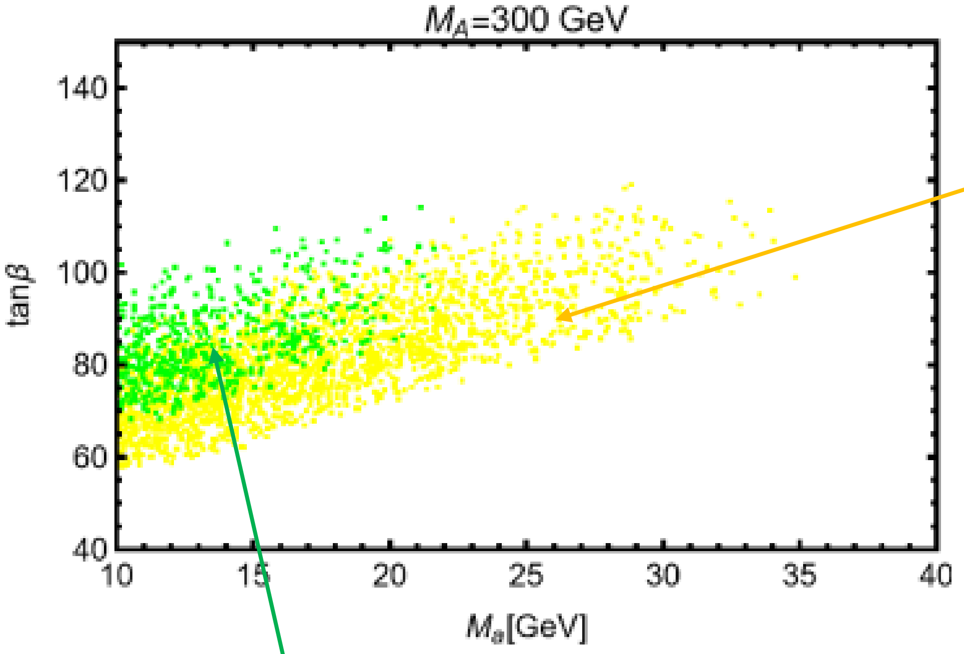


$$\Delta a_\mu^{2-loop} = \frac{\alpha^2}{8\pi^2 \sin^2\theta_W}\frac{m_\mu^2}{M_W^2} g_{a\mu\mu}\sum_f g_{aff} N_c^f Q_f \frac{m_f^2}{M_a^2} F\left(\frac{m_f^2}{M_a^2}\right)$$

$$F(r) = \int_0^1 dx \frac{\log(r)-\log[x(1-x)]}{r-x(1-r)}$$

To have a sizable Δa_μ we need $g_{a\mu\mu} \propto tan\beta$. We need to go for Type-II or Type-X configurations.

g-2 in the Type-X 2HDM+a

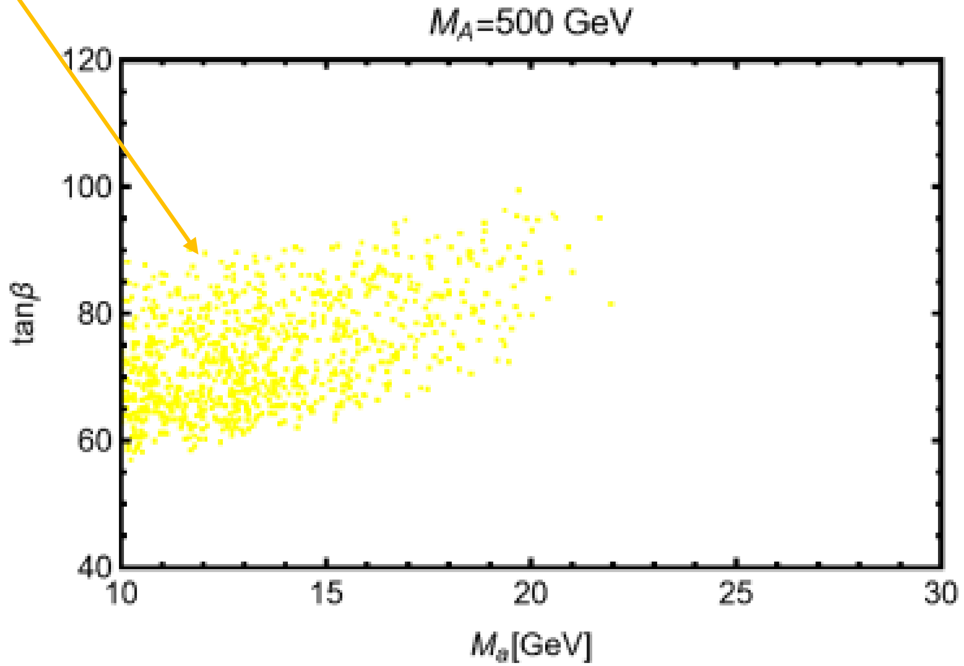


$\Delta a_\mu (2\,\sigma)$

$\Delta a_\mu (1\,\sigma)$

Viable parameter space limited by lepton universality in decays of Z-boson and τ lepton. (see next slides).

Abe et al. JHEP 07 (2015) 064
E. Jin Chun et al JHEP 07 (2016) 110



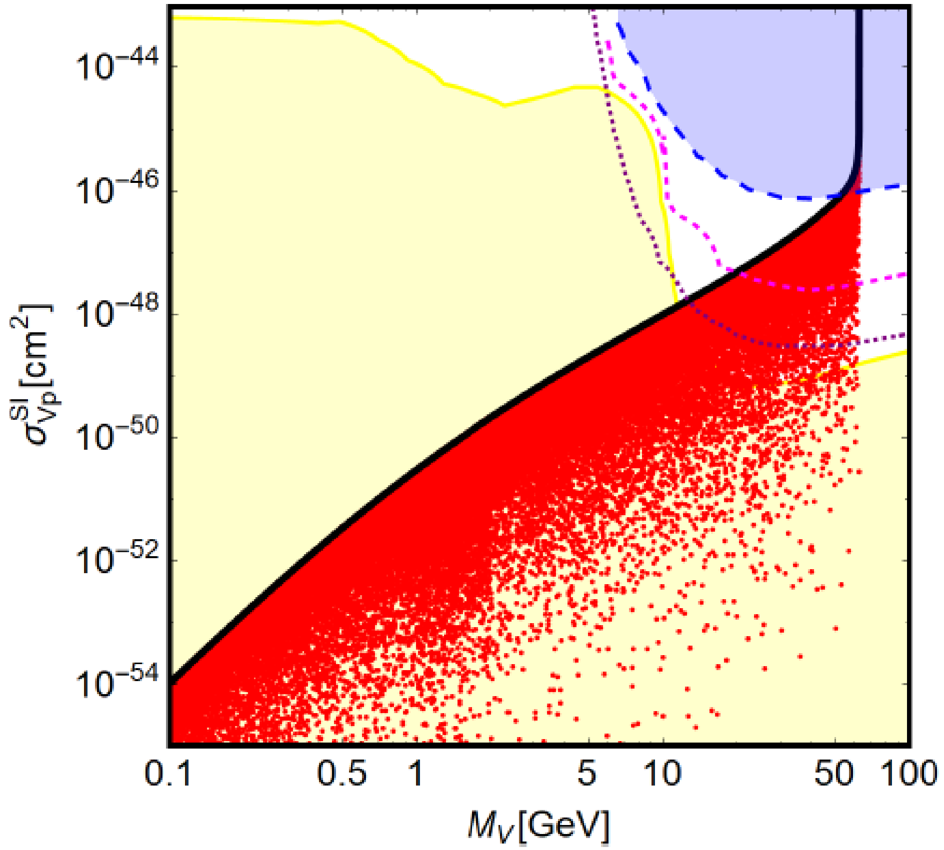
G.A. and A. Djouadi, *Phys.Rev.D* 106 (2022) 9, 095008

As can be imagined, for $M_{H_2} \gg M_{H_1}$

$$\sigma_{Vp}^{SI}\Big|_{EFT} = 32\mu_{Vp}^2 \frac{M_V^2}{M_H^3}\frac{Br(H\to VV)\Gamma_{\rm H}^{\rm tot}}{\beta_{VH}}\frac{1}{M_H^4}\frac{m_p^2}{v^2}|f_p|^2$$

$$\sigma_{Vp}^{SI}\Big|_{U(1)} = 32\cos^2\theta\mu_{Vp}^2 \frac{M_V^2}{M_{H_1}^3}\frac{Br(H\to VV)\Gamma_{\rm H_1}^{tot}}{\beta_{VH_1}}\left(\frac{1}{M_{H_2}^2}-\frac{1}{M_{H_1}^2}\right)^2\frac{m_p^2}{v^2}|f_p|^2$$

$$r = \frac{\sigma_{U(1)}^{SI}}{\sigma_{EFT}^{SI}} = 1 \longrightarrow \cos^2\theta\left(\frac{1}{M_{H_2}^2}-\frac{1}{M_{H_1}^2}\right)\approx 1$$



Perturbative Unitarity

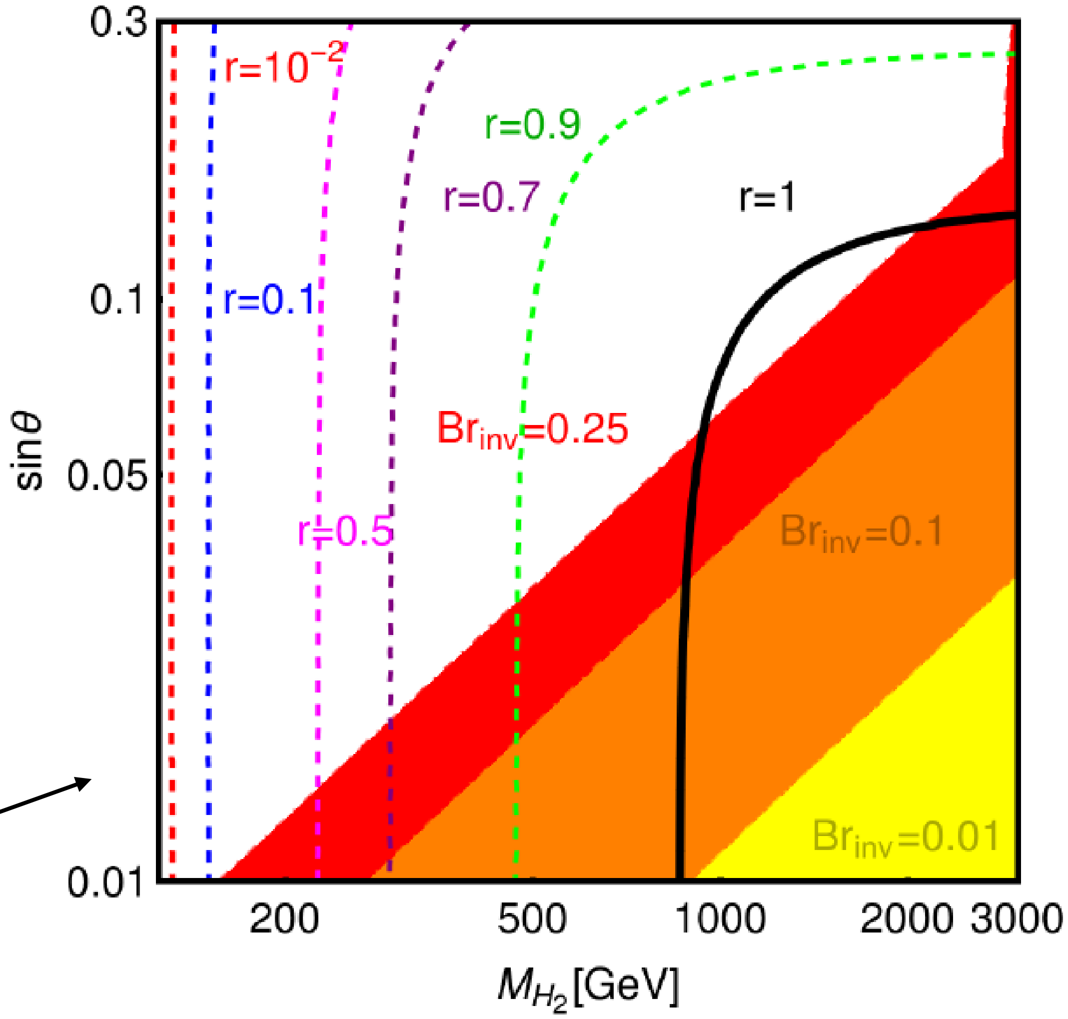
$$\lambda_{HS} \leq \frac{4\pi}{3} \Longrightarrow \text{BR}(H_1 \to VV) \lesssim 0.25 \left(\frac{3\,\text{TeV}}{M_{H_2}}\right)^4 ,$$

$$\lambda_S \leq \frac{4\pi}{3} \Longrightarrow \text{BR}(H_1 \to VV) \lesssim 0.35 \left(\frac{\sin\theta}{0.1}\right)^2 \left(\frac{3\,\text{TeV}}{M_{H_2}}\right)^2$$

$$\sigma^{\text{SI}}_{Vp}|_{\text{EFT}} = 8\mu^2_{Vp} \frac{M_V^2}{M_H^3} \frac{\text{BR}\,(H \to VV)\,\Gamma_H^{\text{tot}}}{\beta_{VH}} \frac{1}{M_H^4} \frac{m_p^2}{v^2} |f_p|^2 ,$$

$$\sigma^{\text{SI}}_{Vp}|_{\text{U(1)}} = 8\cos^2\theta \mu^2_{Vp} \frac{M_V^2}{M_{H_1}^3} \frac{\text{BR}\,(H_1 \to VV)\,\Gamma_{H_1}^{\text{tot}}}{\beta_{VH_1}} \left(\frac{1}{M_{H_2}^2} - \frac{1}{M_{H_1}^2}\right)^2 \frac{m_p^2}{v^2} |f_p|^2$$

$$r = \frac{\sigma^{SI}_{U(1)}}{\sigma^{SI}_{EFT}}$$



Dark SU(3) dark symmetry

$$\mathcal{L}_{\text{Higgs}} = -\frac{\lambda_H}{2}|\phi|^4 - m_H^2|\phi|^2$$

$$\mathcal{L}_{\text{portal}} = -\lambda_{H11}|\phi|^2\phi_1^2 - \lambda_{H22}|\phi|^2\phi_2^2 + \left(|\phi|^2\phi_1^\dagger\phi_2 + \text{h.c}\right)$$

$$\mathcal{L}_{\text{hidden}} = -\frac{1}{2}\text{Tr}\left\{V_{\mu\nu}V^{\mu\nu}\right\} + |D_\mu\phi_1|^2 + |D_\mu\phi_2|^2 - V_{\text{hidden}}$$

$$\phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ v_1 + h_1 \end{pmatrix}$$

$$\phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 + h_2 \\ v_3 + h_3 + i\left(v_4 + h_4\right) \end{pmatrix}$$

SU(3) completely broken by two Higgses in the fundamental representation

$$V_{\text{hidden}} = m_{11}^2|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2\left(\phi_1^\dagger\phi_2 + \text{h.c.}\right) + \left[\frac{\lambda_5}{2}\left(\phi_1^\dagger\phi_2\right)^2 + \lambda_6|\phi_1|^2\left(\phi_1^\dagger\phi_2\right) + \lambda_7|\phi_2|^2\left(\phi_1^\dagger\phi_2\right) + \text{h.c.}\right]$$

$$+\frac{\lambda_1}{2}|\phi_1|^4 + \frac{\lambda_2}{2}|\phi_2|^4 + \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2$$

Scalar mass spectrum

$$\mathcal{L} = -\frac{1}{2}\Phi^T \mathcal{M}^2_{\text{CP}-\text{even}}\Phi - \frac{1}{4}(\lambda_4 - \lambda_5)(v_1^2 + v_2^2)\psi^2$$

$$\mathcal{M}^2_{\text{CP}-\text{even}} = \begin{pmatrix} \lambda_H v^2 & \lambda_{H11} v v_1 & \lambda_{H22} v v_2 & 0 \\ \lambda_{H11} v v_1 & \lambda_1 v_1^2 & \lambda_3 v_1 v_3 & 0 \\ \lambda_{H22} v v_2 & \lambda_3 v_1 v_3 & \lambda_2 v_2^2 & 0 \\ 0 & 0 & 0 & \frac{1}{2}(\lambda_4 + \lambda_5)(v_1^2 + v_2^2) \end{pmatrix}$$

$$H_1 \simeq \cos\theta H - \sin\theta h_2$$

$$H_2 \simeq \sin\theta H + \cos\theta h_2$$

$$H_3 \simeq h_3$$

$$H_4 \simeq h_1$$

$$M^2_{H_1,H_2} \simeq \frac{1}{2}(\lambda_2 v_2^2 + \lambda_H v^2) \mp \frac{\lambda_2 v_2^2 - \lambda_H v^2}{2\cos 2\theta}$$

$$M^2_{H_3} = \frac{1}{2}(\lambda_4 + \lambda_5)(v_1^2 + v_2^2)$$

$$\tan 2\theta \simeq \frac{2\lambda_{H22} v v_2}{\lambda_2 v_2^2 - \lambda_H v^2}$$

$$M^2_{H_4} = \lambda_1 v_1^2$$

Higgs Portal Embedding in Dark SU(3)

We can reduce the model to an extended Higgs portal in the limit:

$$v_3 \ll v_2 \ll v_1$$

$$\begin{aligned}
\mathcal{L} =& \frac{\tilde{g} M_V}{2}\left(-\sin\theta H_1 + \cos\theta H_2\right)\left(\sum_{a=1,2} V_\mu^a V^{\mu\, a} + \left(\cos\alpha - \frac{\sin\alpha}{\sqrt{3}}\right)^2 V_\mu^3 V^{\mu\, 3}\right) \\
&+ \tilde{g}\cos\alpha \sum_{a,b,c} \epsilon_{abc}\partial_\mu V_\nu V_\nu^a V^{b\,\mu} V^{c\,\nu} - \frac{\tilde{g}^2}{2}\cos^2\alpha \sum_{a=1,2}\left(V_\mu^a V^{a\,\mu} V_\nu^3 V^{3\,\nu} - \left(V_\mu^a V^{a\,\mu}\right)^2\right) \\
&- \frac{1}{2} m_\psi^2 \psi^2 + \left[\frac{\tilde{g}}{2M_V}\left(-\sin\theta H_1 + \cos\theta H_2\right) - \frac{1}{4}\left(\lambda_{\psi\psi 11} H_1^2 + 2\lambda_{\psi\psi 12} H_1 H_2 + \lambda_{\psi\psi 22} H_2^2\right)\right]\psi^2 \\
&- \frac{k_{111}}{2} v H_1^3 - \frac{k_{112}}{2} H_1^2 H_2 v \sin\theta - \frac{\kappa_{221}}{2} H_1 H_2^2 v \cos\theta - \frac{\kappa_{222}}{2} H_2^3 v \\
&+ \frac{H_1\cos\theta + H_2\sin\theta}{v}\left(2M_W^2 W_\mu^+ W^{\mu -} + M_Z^2 Z_\mu Z^\mu - m_f \bar{f} f\right)
\end{aligned}$$

gauge eigenstates	mass eigenstates	$\mathbb{Z}_2 \times \mathbb{Z}_2'$
$h, h_1, h_2, h_3, A^7_\mu$	$H_1, H_2, H_3, H_4, \tilde{V}^7_\mu$	$(+,+)$
V^1_μ, V^4_μ	V^1_μ, V^4_μ	$(-,-)$
V^2_μ, V^5_μ	V^2_μ, V^5_μ	$(-,+)$
$h_4, V^3_\mu, V^6_\mu, V^8_\mu$	$\psi, V'^3_\mu, V^6_\mu, V'^8_\mu$	$(+,-)$

$$M^2_{V_1} = M^2_{V_2} = \frac{1}{4}\tilde{g}^2 v_2^2$$

$$M^2_{V_4} = M^2_{V_5} = \frac{1}{4}\tilde{g}^2 v_1^2$$

$$M^2_{V_6} = M^2_{V_7} = \frac{1}{4}\tilde{g}^2 (v_1^2 + v_2^2)$$

$$V_8' = -V_3 \sin\alpha + V_8 \cos\alpha \qquad V_3' = V_3 \cos\alpha + V_8 \sin\alpha$$

$$M^2_{V_3'} = \frac{\tilde{g}^2 v_2^2}{4}\left(1 - \frac{\tan\alpha}{\sqrt{3}}\right)$$

$$M^2_{V_8'} = \frac{\tilde{g}^2 v_1^2}{4}\frac{1}{(1 - \tan\alpha/\sqrt{3})}$$

	Case I	Case II	Case III	Case IV
dark matter	(V^1_μ, V^2_μ, ψ)	(V^4_μ, V^5_μ, ψ)	$(V^1_\mu, V^2_\mu, V'^3_\mu)$	$(V^4_\mu, V^5_\mu, V'^3_\mu)$
parameter	$v_2/v_1 < 1$	$v_2/v_1 > 1$	$v_2/v_1 < 1$	$v_2/v_1 > 1$
choice	$\lambda_4 - \lambda_5 \ll 1$	$\lambda_4 - \lambda_5 \ll 1$	$\lambda_4 - \lambda_5 = \mathcal{O}(1)$	$\lambda_4 - \lambda_5 = \mathcal{O}(1)$

$$L_{Yukawa} = -\sum_{n=h,H} \left(Y_n^u Q_L u_R \tilde{\Phi}_n + Y_n^d Q_L d_R \Phi_n + Y_n^l L_L e_R \Phi_n \right)$$

2HDM+s $\longrightarrow$ (Φ_1, Φ_2, S) $\longrightarrow$ $(h, S_1, S_2, A, H^\pm)$

2HDM+a $\longrightarrow$ (Φ_1, Φ_2, P) $\longrightarrow$ $(h, a, H, A, H^\pm)$

2HDM+S

$$Y_h^i = g_{hii} Y_{h,SM}^i$$

$$Y_{S_1}^i = g_{Hii} \cos\theta \, Y_{h,SM}^i$$

$$Y_{S_2}^i = -g_{Hii} \sin\theta \, Y_{h,SM}^i$$

$$Y_A^i = g_{Aii} Y_{h,SM}^i$$

2HDM+PS

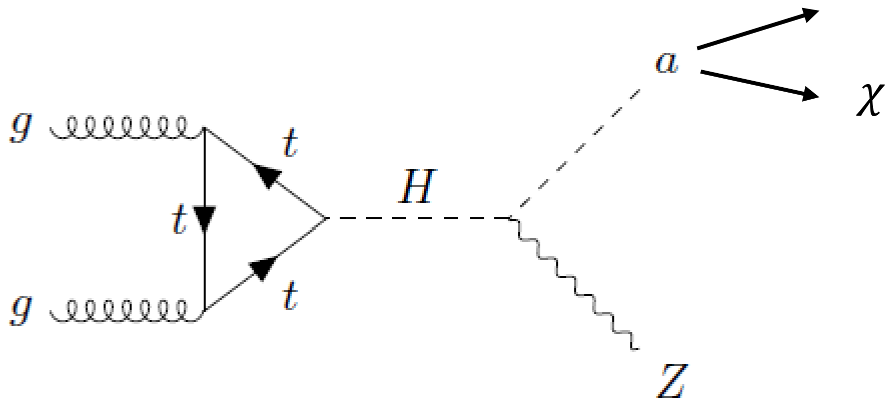
$$Y_h^i = g_{hii} Y_{h,SM}^i$$

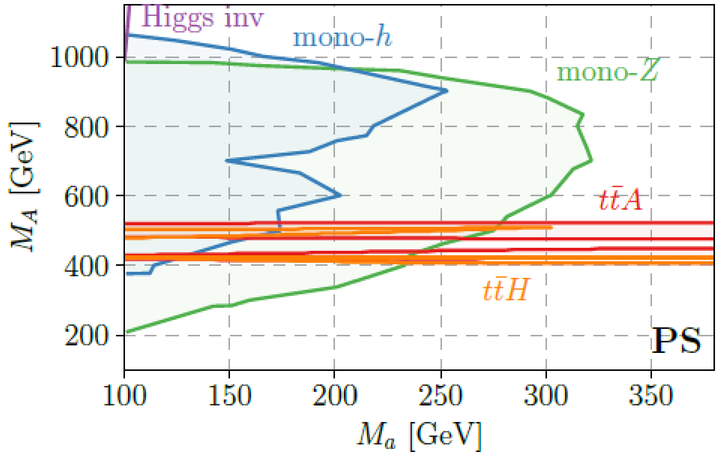
$$Y_H^i = g_{Hii} \cos\theta \, Y_{h,SM}^i$$

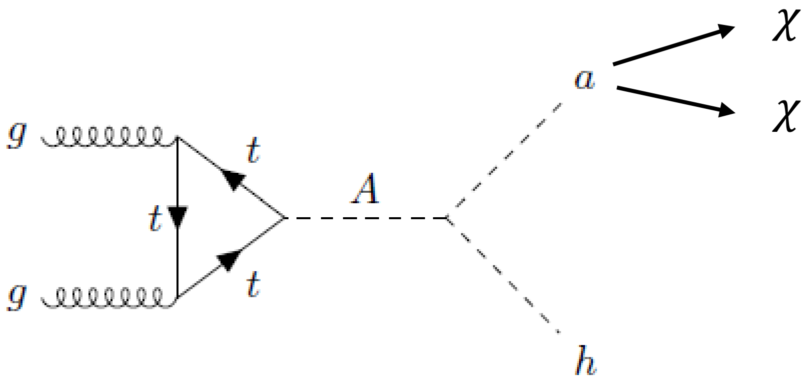
$$Y_A^i = g_{Aii} \cos\theta \, Y_{h,SM}^i$$

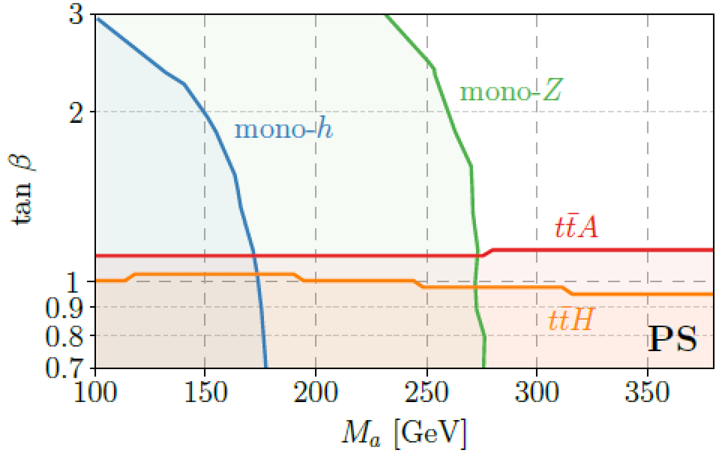
$$Y_a^i = -g_{Aii} \sin\theta \, Y_{h,SM}^i$$

	Type I	Type II	Type-X/Lepton-specific	Type-Y/Flipped
g_{huu}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$
g_{hdd}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$
g_{hll}	$\frac{\cos\alpha}{\sin\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$-\frac{\sin\alpha}{\cos\beta} \to 1$	$\frac{\cos\alpha}{\sin\beta} \to 1$
g_{Huu}	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$
g_{Hdd}	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$
g_{Hll}	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\cos\alpha}{\cos\beta} \to \tan\beta$	$\frac{\sin\alpha}{\sin\beta} \to -\frac{1}{\tan\beta}$
g_{Auu}	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$
g_{Add}	$-\frac{1}{\tan\beta}$	$\tan\beta$	$-\frac{1}{\tan\beta}$	$\tan\beta$
g_{All}	$-\frac{1}{\tan\beta}$	$\tan\beta$	$\tan\beta$	$-\frac{1}{\tan\beta}$



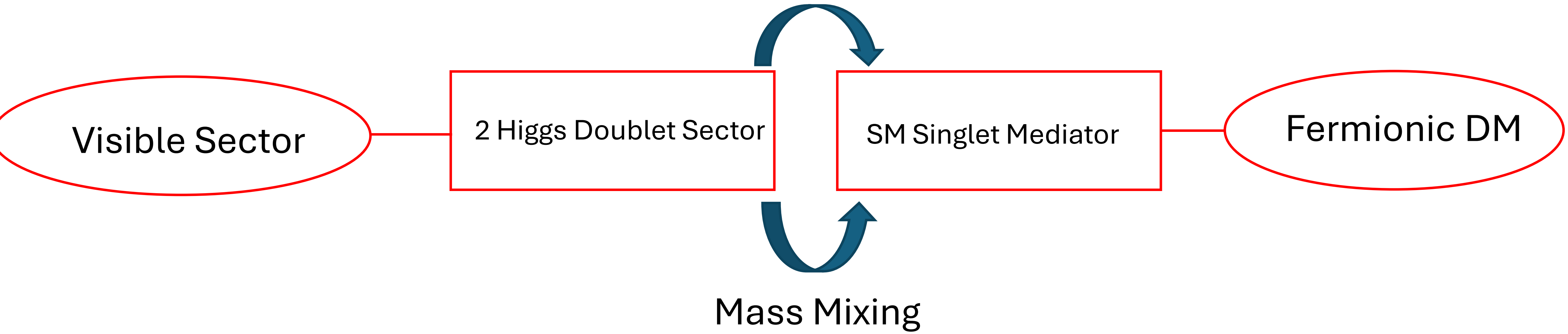






G. A., G. Busoni, T. Hugle and V. Tenorth; JHEP 06 (2020) 098

Third Scenario:Dark Higgs coupled 2HD



$$V_S(S) = \frac{1}{2} M_{SS}^2 S^2 + \frac{1}{3}\mu_S S^3 + \frac{1}{4}\lambda_S S^4$$

$$V_{S,2HDM}(\Phi_1,\Phi_2,S)$$
$$= \mu_{11S}\left(\Phi_1\Phi_1^\dagger\right)S + \mu_{22S}\left(\Phi_2\Phi_2^\dagger\right)S + \left(\mu_{12S}\Phi_1\Phi_2^\dagger S + h.c.\right)$$
$$+ \frac{\lambda_{11S}}{2}\left(\Phi_1\Phi_1^\dagger\right)S^2 + \frac{\lambda_{22S}}{2}\left(\Phi_2\Phi_2^\dagger\right)S^2 + \frac{1}{2}\left(\lambda_{12S}\Phi_1\Phi_2^\dagger S^2 + h.c.\right)$$

Conventional 2HDM Potential

$$V(\Phi_1,\Phi_2,S/P) = V_{2HDM}(\Phi_1,\Phi_2) + V_{self}(S/P) + V_{S/P,2HDM}(\Phi_1,\Phi_2,S/P)$$

Self Interaction lagrangian

Singlet Doublet Interaction Lagrangian

$$V_P(P) = \frac{1}{2} M_{PP}^2 P^2 + \frac{1}{4}\lambda_P P^4$$

$$V_{P,2HDM}(P) = \frac{\lambda_{11P}}{2}\left(\Phi_1\Phi_1^\dagger\right)P^2 + \frac{\lambda_{22P}}{2}\left(\Phi_2\Phi_2^\dagger\right)P^2 + \mu_{12P}P\left(i\Phi_1^\dagger\Phi_2 + h.c.\right)$$

Dark Matter Phenomenology

2HDM+S

N. Bell, G. Busoni, I. W. Sanderson; JCAP 08 (2018) 017

2HDM+PS

G.A. et al; JCAP 03 (2018) 042
F. Ertas and F. Kahlhoefer; JHEP 06 (2019) 052
T. Abe, M. Fujiwara and J. Hisano, JHEP 02 (2019)

Relic Density

P-wave dominated annihilation cross-section.

S-wave dominated annihilation cross-section.

Direct Detection

Sizable (tree-level) Spin Independent DM/nucleon cross-section.

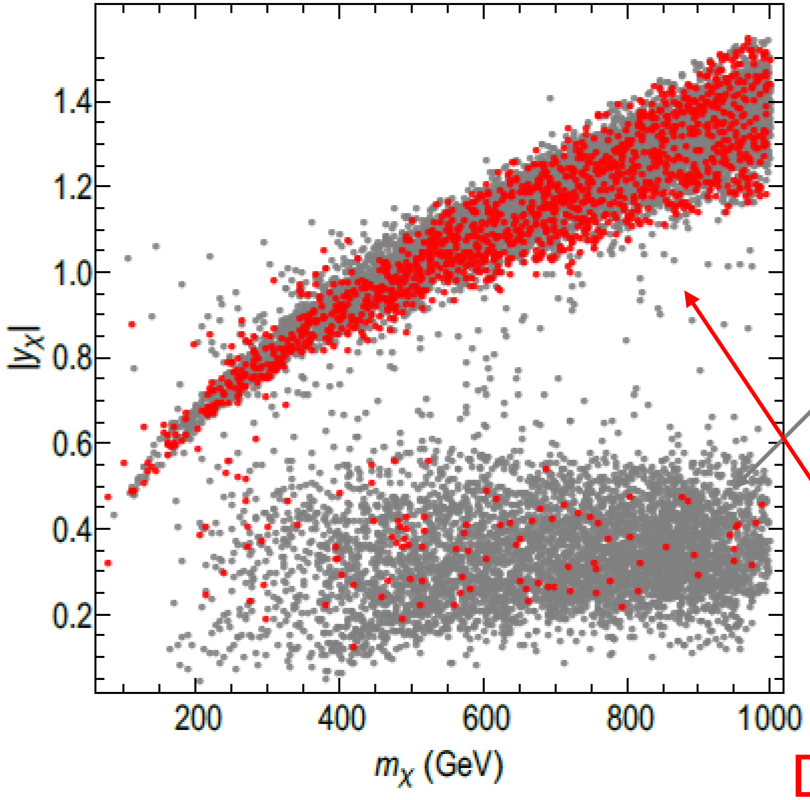
$$\sigma_{\chi p}^{SI} \propto \frac{y_\chi^2}{v^2} \sin^2\theta \cos^2\theta \left(\frac{1}{M_{S_1}^2} - \frac{1}{M_{S_2}^2}\right)^2$$

Very suppressed (Spin Dependent-like) tree level cross-section.
SI cross induced at the loop level (can be probed by next generation detectors)

2HDM+s Model

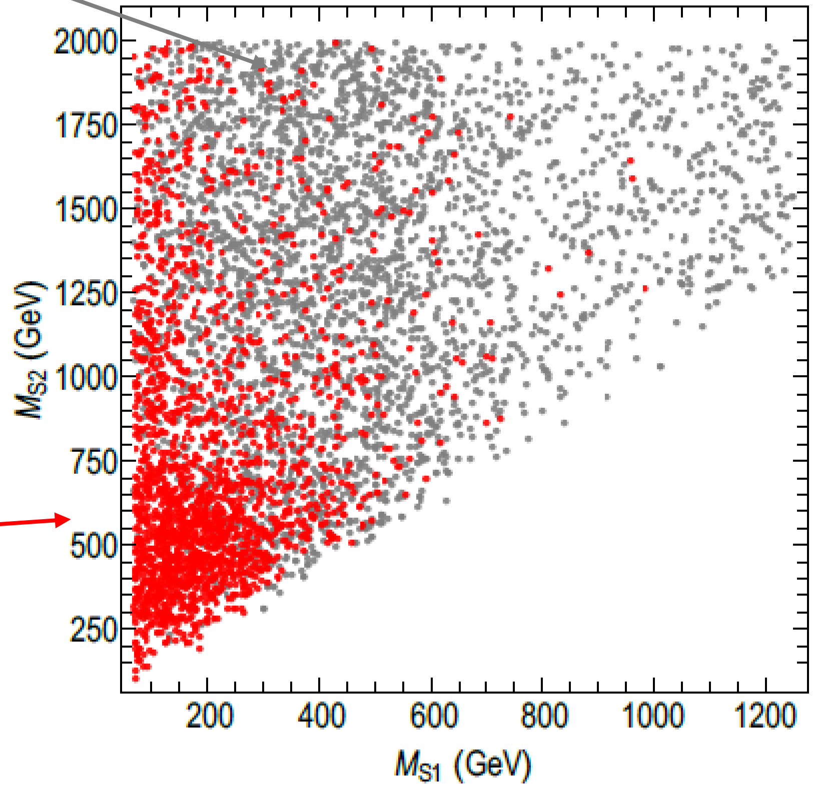
S-originates from a Dark Boson

$$y_\chi \propto m_\chi / v_S$$



DD Allowed

DD Ruled-out



N. F. Bell, G. Busoni, I. W. Sanderson JCAP 01 (2018) 015

DM Phenomenology of the 2HDM+a

$$L_{DM} = i y_\chi \bar{\chi}\gamma_5\chi a_0 \longrightarrow i y_\chi (a\cos\theta + A\sin\theta)\bar{\chi}\gamma_5\chi$$

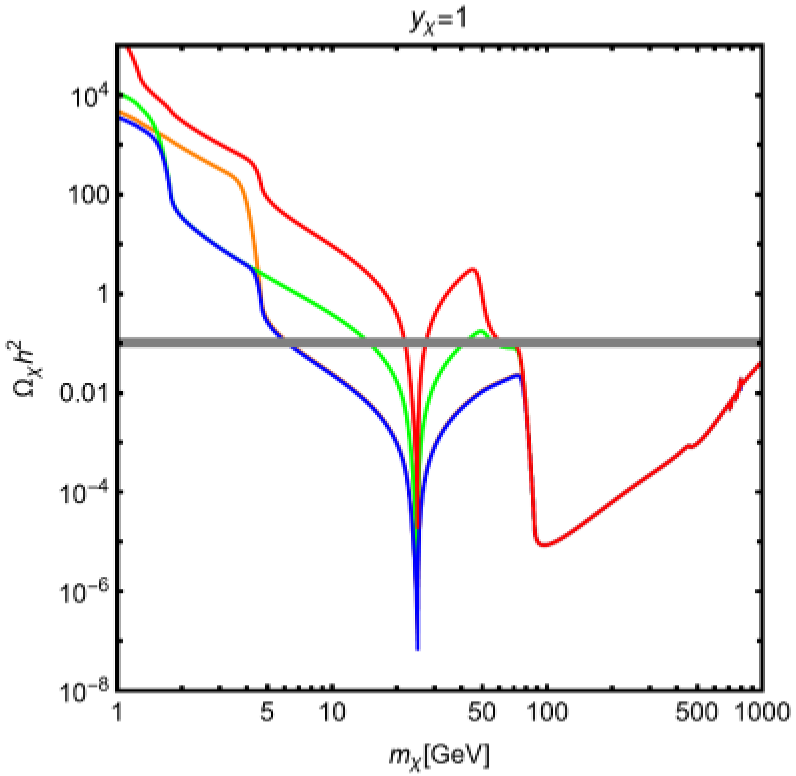
$$\langle\sigma v\rangle$$

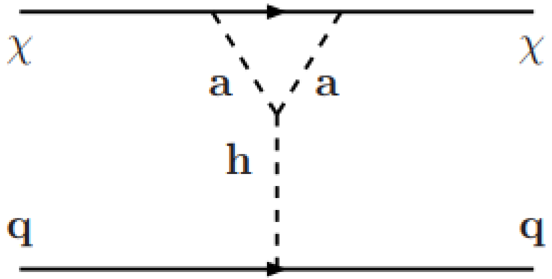
$$\bar{\chi}\chi \to a/A \to \bar{f}f$$

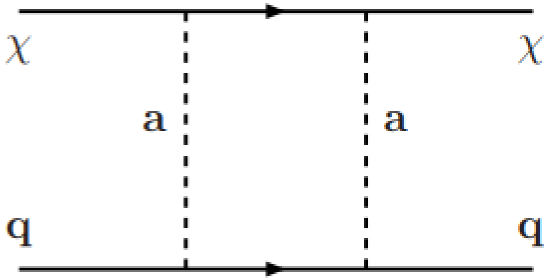
$$\bar{\chi}\chi \to a/A \to ha(A)$$

$$\bar{\chi}\chi \to a/A \to a(A)a(A)$$

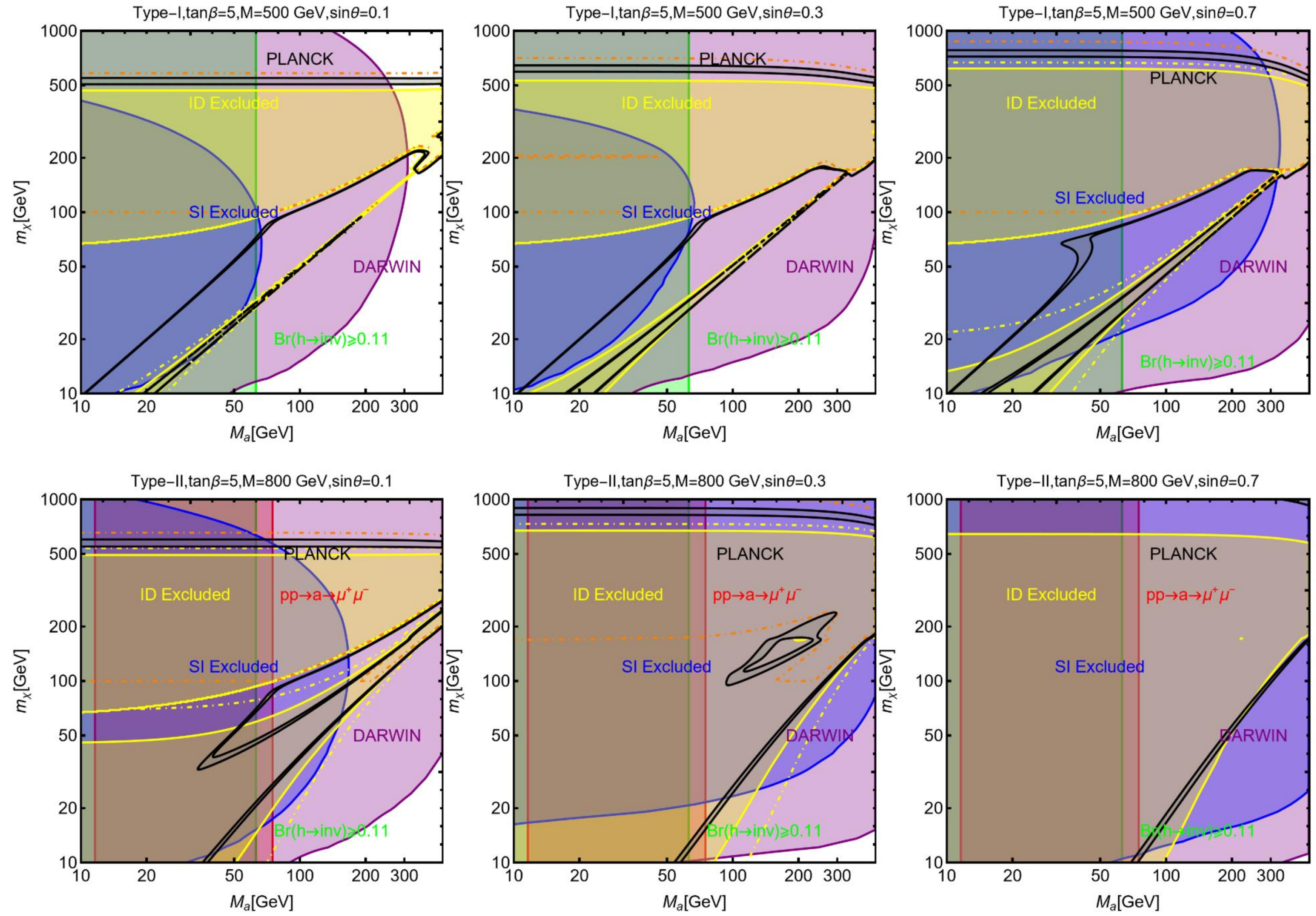
$$\Omega h^2 \propto \frac{1}{\langle\sigma v\rangle}$$







Induced at one-loop


Type−I,tanβ=5,M=500 GeV,sinθ=0.1
Type−I,tanβ=5,M=500 GeV,sinθ=0.3
Type−I,tanβ=5,M=500 GeV,sinθ=0.7
Type−II,tanβ=5,M=800 GeV,sinθ=0.1
Type−II,tanβ=5,M=800 GeV,sinθ=0.3
Type−II,tanβ=5,M=800 GeV,sinθ=0.7
PLANCK
ID Excluded
SI Excluded
DARWIN
Br(h→inv)≥0.11
pp→a→μ⁺μ⁻
m_χ[GeV]
M_a[GeV]