

# Dark Matter and Gravitational Waves in the 2HDM+a

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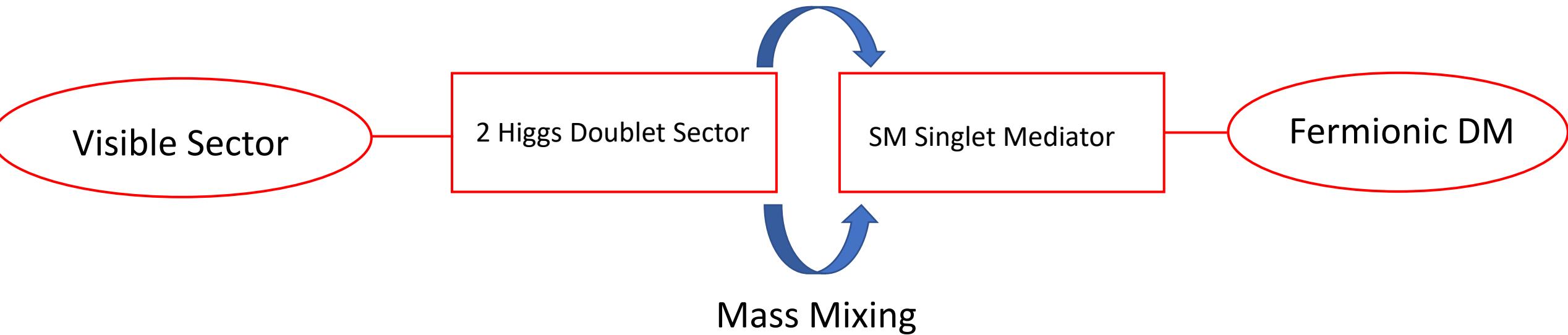
Based on

G.A., N. Benincasa, A. Djouadi, K. Kannike  
PRD in press

# 2HDM+a belongs to the so called Next generation simplified models

LHC Dark Matter Working Group: Phys. Dark. Univ. 27 (2020) 100351

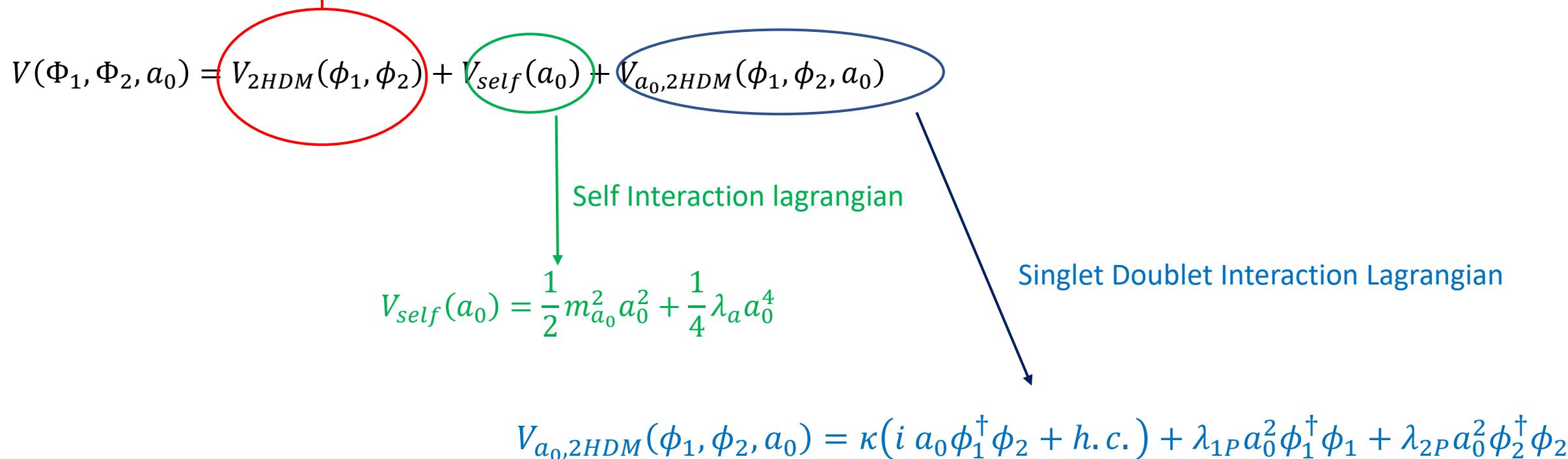
(see also e.g. M. Bauer et al. *JHEP* 05 (2017) 138, T. Robens *Symmetry* 13 (2021) 12, 2341)



Good compromise between theoretical consistency and predictivity (still limited number of free parameters);  
Benchmark for a large variety of collider studies;  
Interesting Dark Matter phenomenology.  
Possibility of triggering First Order Phase Transition (FOPT).

## Conventional ( $Z_2$ symmetric) 2HDM Potential

$$V_{2HDM} = m_1^2 \phi_1^\dagger \phi_1 + m_2^2 m_1^2 \phi_2^\dagger \phi_2 - m_3^2 (\phi_1^\dagger \phi_2 + h.c.) + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \frac{1}{2} \lambda_5 \left( (\phi_1^\dagger \phi_2)^2 + h.c. \right) \\ + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1)$$



## EW Symmetry Breaking

$$\langle \phi_1 \rangle = v_1$$

$$\langle \phi_2 \rangle = v_2 \quad \frac{v_2}{v_1} = \tan\beta$$

$$(\phi_1, \phi_2, a_0) \longrightarrow (h, a, H, A, H^\pm)$$

### Mixing between pseudoscalar states

$$\begin{pmatrix} A^0 \\ a^0 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A \\ a \end{pmatrix}$$

$$L_{Yuk} = \sum_f \frac{m_f}{v} [g_{hff} h \bar{f} f + g_{Hff} H \bar{f} f - i g_{aff} a \bar{f} \gamma_5 f - i g_{Aaff} A \bar{f} \gamma_5 f]$$

$$g_{hff} = 1 \quad g_{Aff} = \cos\theta g_{A^0 ff}$$

$$g_{aff} = \sin\theta g_{A^0 ff}$$

	Type I	Type II	Type X	Type Y
$g_{htt}$	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$
$g_{hbb}$	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$	$-\frac{\sin\alpha}{\cos\beta} \rightarrow 1$	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$	$-\frac{\sin\alpha}{\cos\beta} \rightarrow 1$
$g_{h\tau\tau}$	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$	$-\frac{\sin\alpha}{\cos\beta} \rightarrow 1$	$-\frac{\sin\alpha}{\cos\beta} \rightarrow 1$	$\frac{\cos\alpha}{\sin\beta} \rightarrow 1$
$g_{Htt}$	$\frac{\sin\alpha}{\sin\beta} \rightarrow -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \rightarrow -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \rightarrow -\frac{1}{\tan\beta}$	$\frac{\sin\alpha}{\sin\beta} \rightarrow -\frac{1}{\tan\beta}$
$g_{Hbb}$	$\frac{\sin\alpha}{\sin\beta} \rightarrow -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \rightarrow \tan\beta$	$\frac{\sin\alpha}{\sin\beta} \rightarrow -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \rightarrow \tan\beta$
$g_{H\tau\tau}$	$\frac{\sin\alpha}{\sin\beta} \rightarrow -\frac{1}{\tan\beta}$	$\frac{\cos\alpha}{\cos\beta} \rightarrow \tan\beta$	$\frac{\cos\alpha}{\cos\beta} \rightarrow \tan\beta$	$\frac{\sin\alpha}{\sin\beta} \rightarrow -\frac{1}{\tan\beta}$
$g_{A^0 tt}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$	$\frac{1}{\tan\beta}$
$g_{A^0 bb}$	$-\frac{1}{\tan\beta}$	$\tan\beta$	$-\frac{1}{\tan\beta}$	$\tan\beta$
$g_{A^0 \tau\tau}$	$-\frac{1}{\tan\beta}$	$\tan\beta$	$\tan\beta$	$-\frac{1}{\tan\beta}$

# Summary scan

$$\tan\beta \in [1,60], |\cos(\beta - \alpha)| \leq 0.2$$

$$(M_H, M_A, M_{H^\pm}) \in [(125, 90, 80) \text{ GeV}, 1 \text{ TeV}]$$

$$M_a \in [10, 400] \text{ GeV}$$

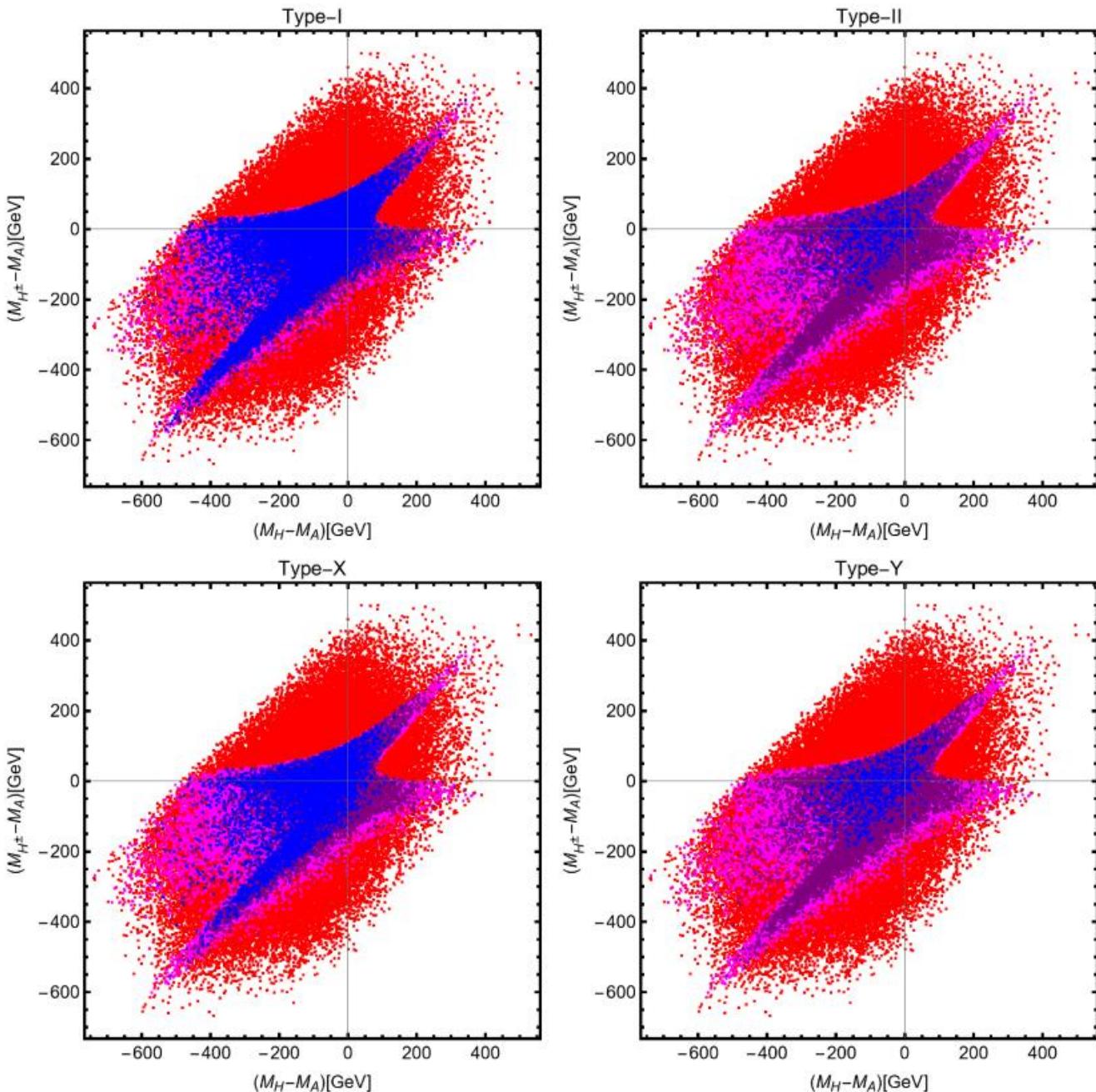
$$|\lambda_3, \lambda_{1P}, \lambda_{2P}| \leq 4\pi$$

Theoretical constraints

EWPT

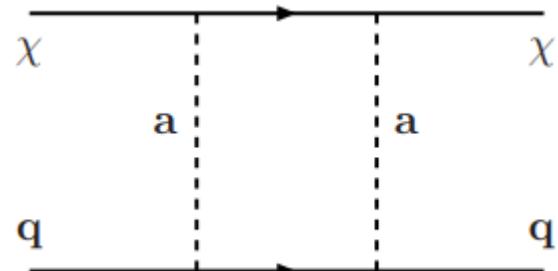
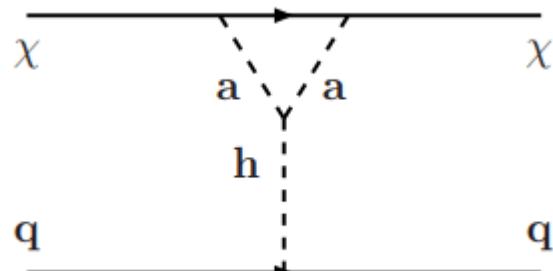
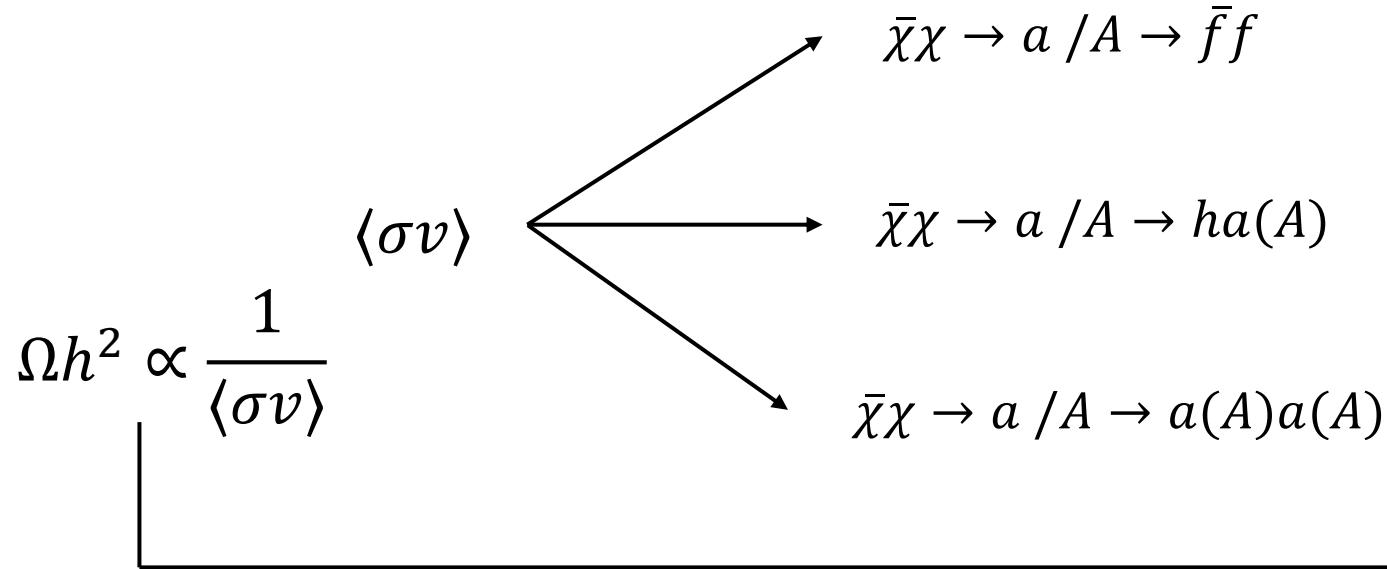
Higgs Signal Strength

Flavour

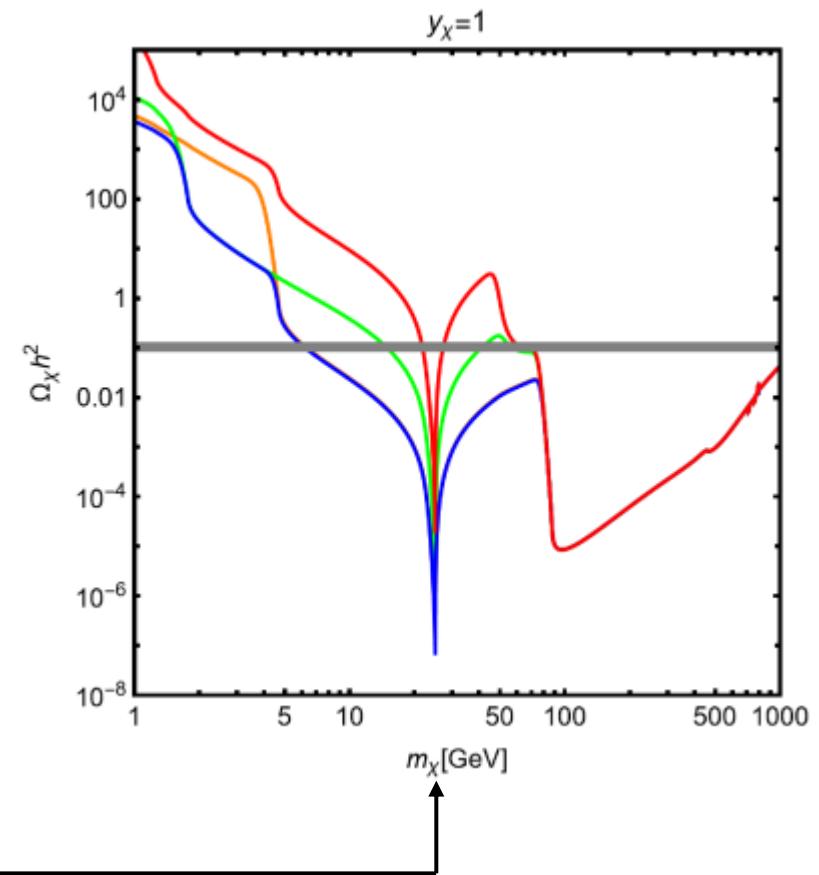


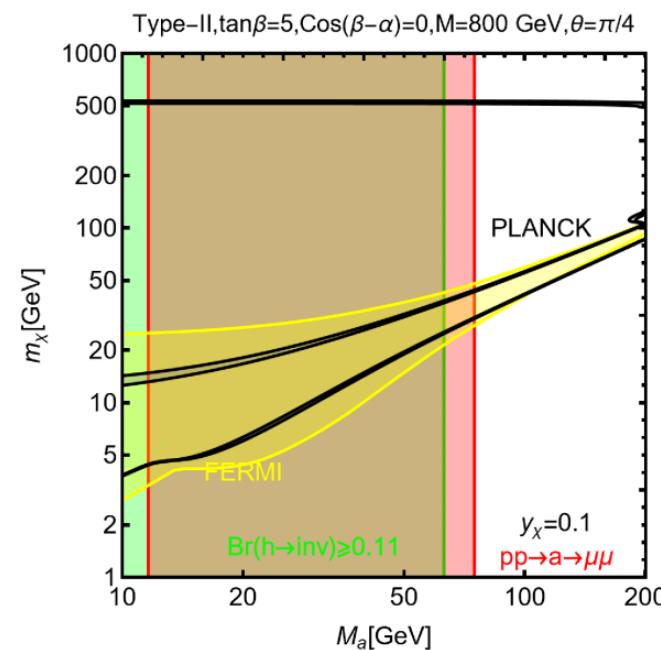
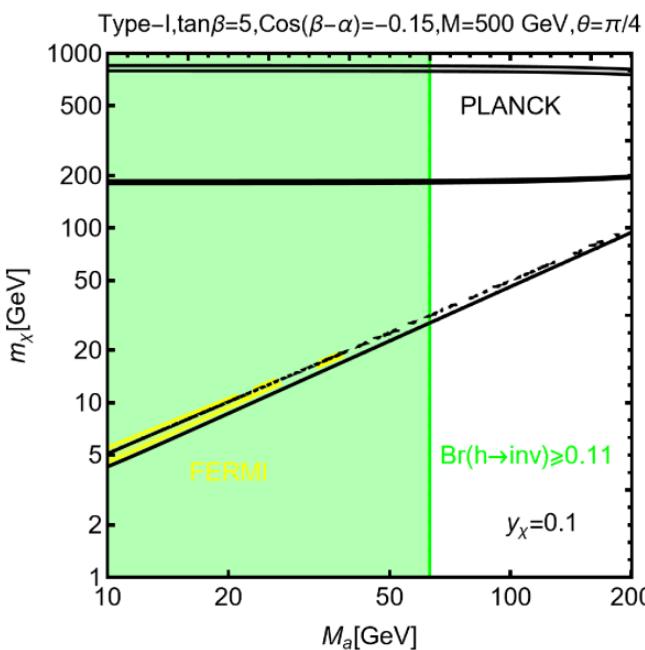
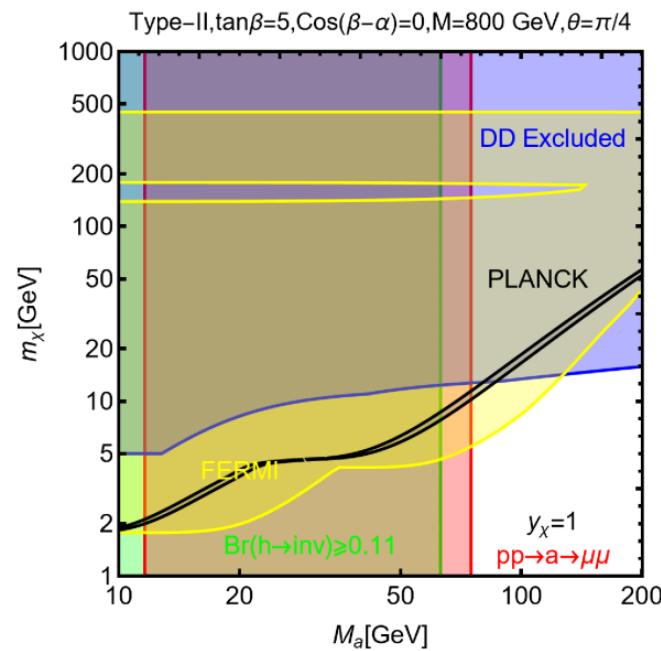
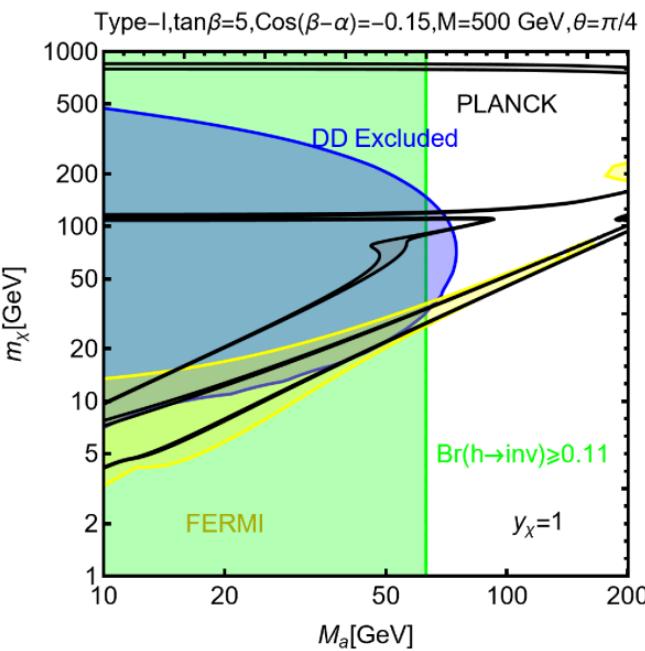
# DM Phenomenology

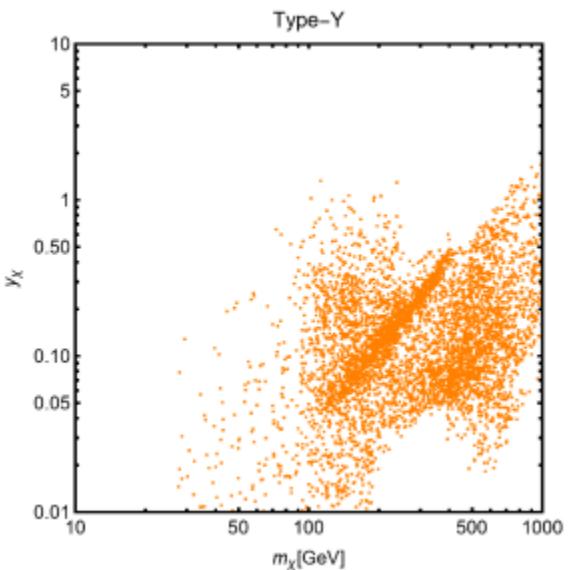
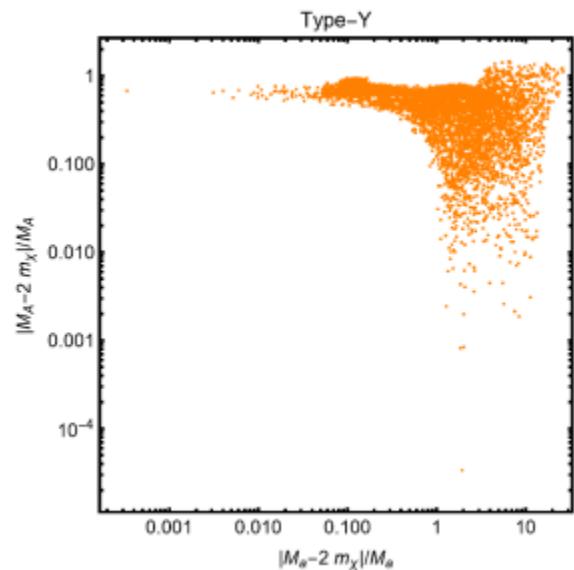
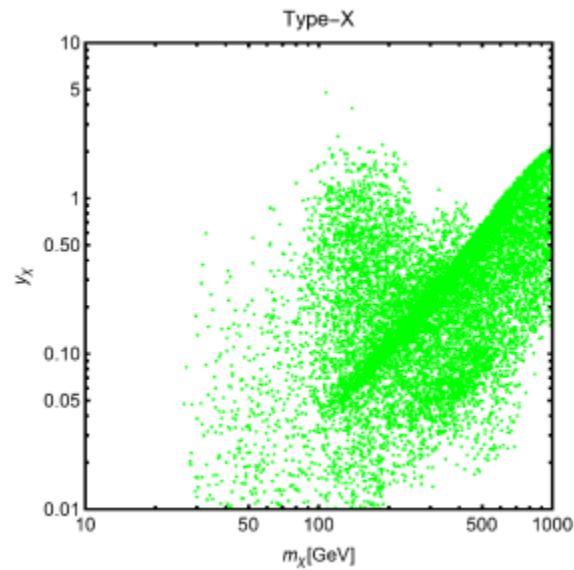
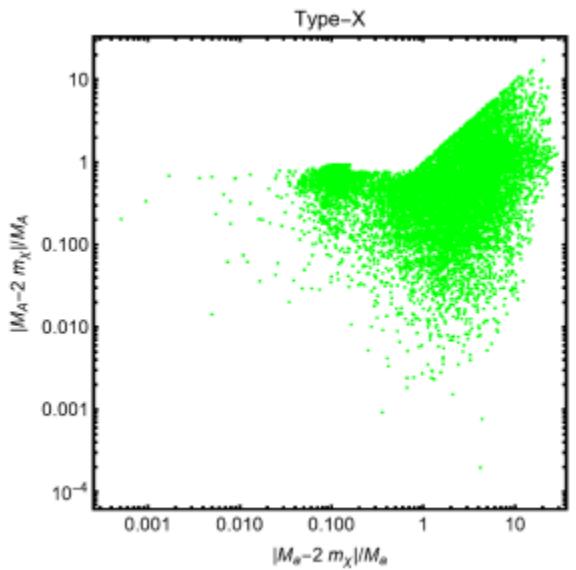
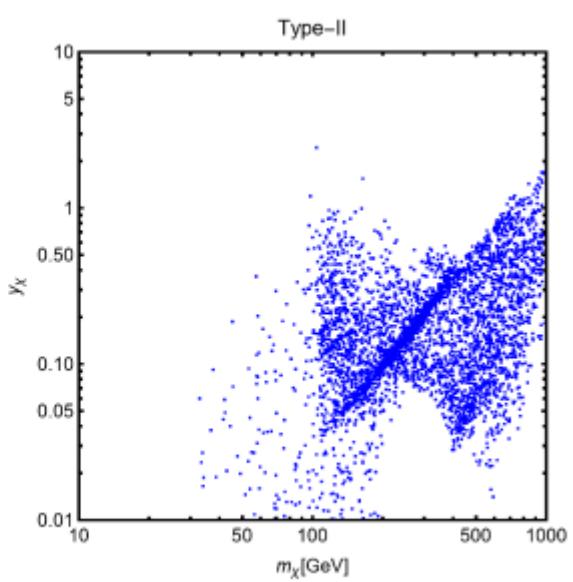
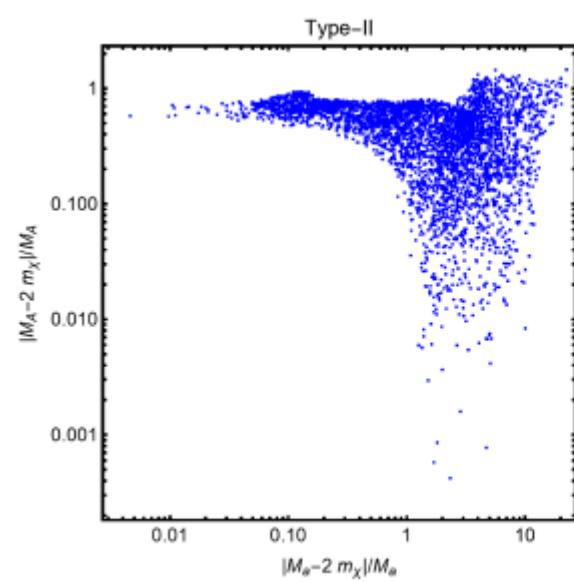
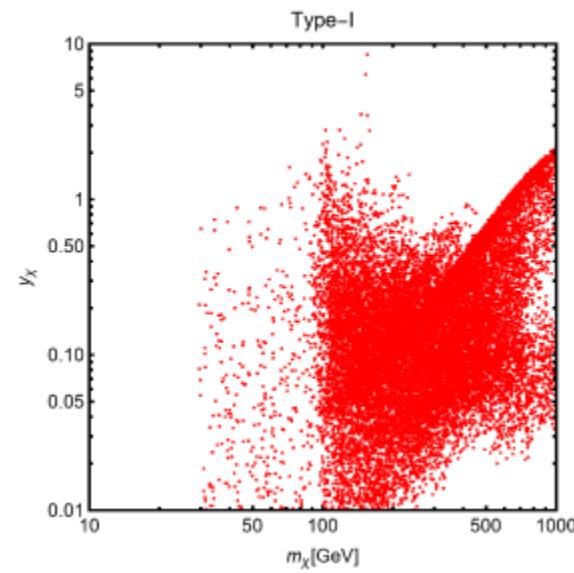
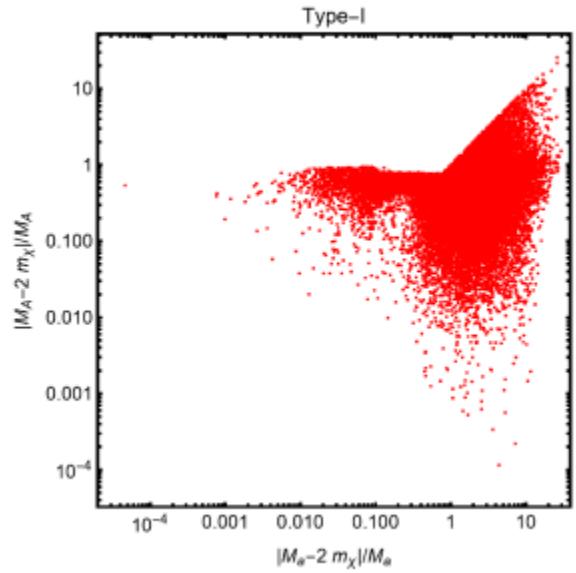
$$L_{DM} = iy_\chi \bar{\chi} \gamma_5 \chi a_0 \longrightarrow iy_\chi (a \cos \theta + A \sin \theta) \bar{\chi} \gamma_5 \chi$$



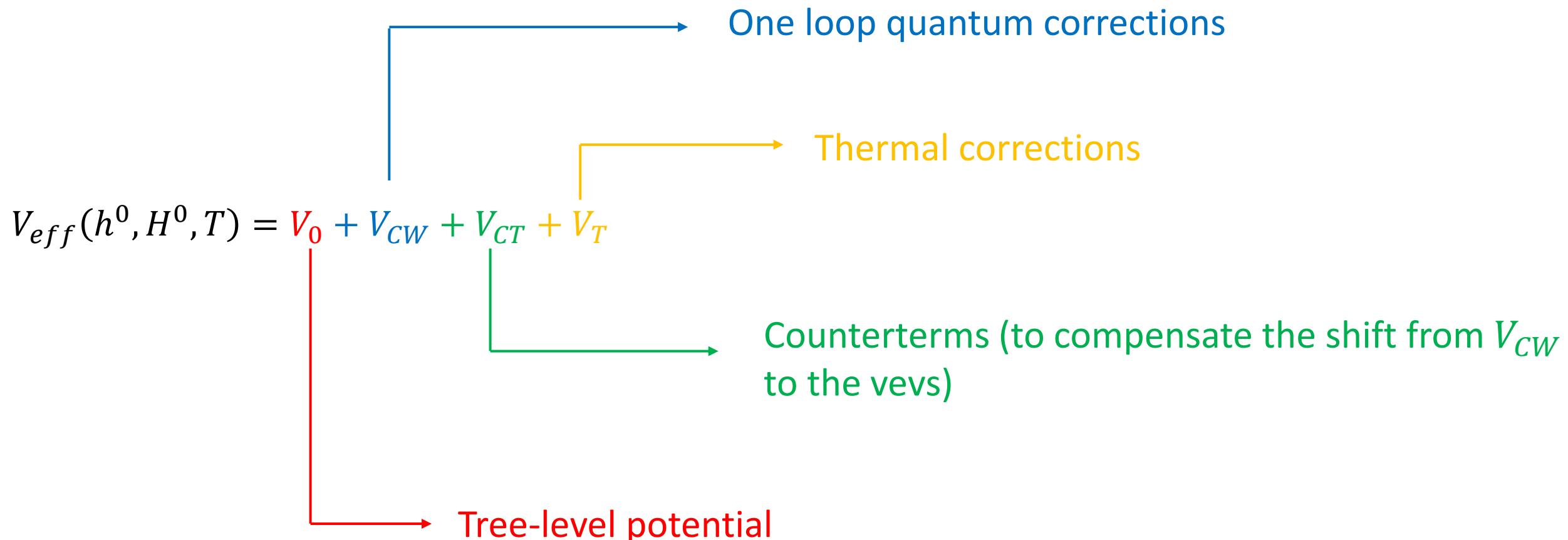
Induced at one-loop







# One-loop thermal effective potential

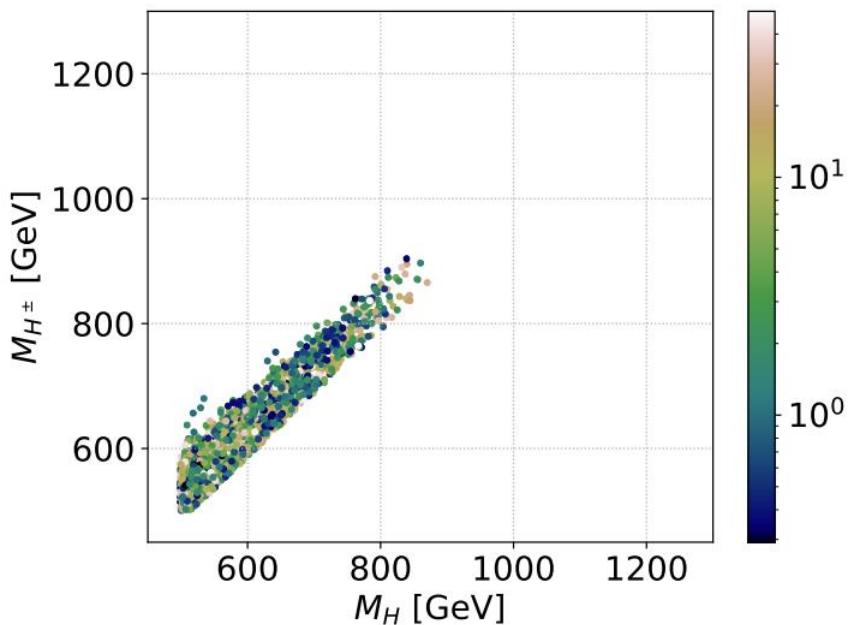
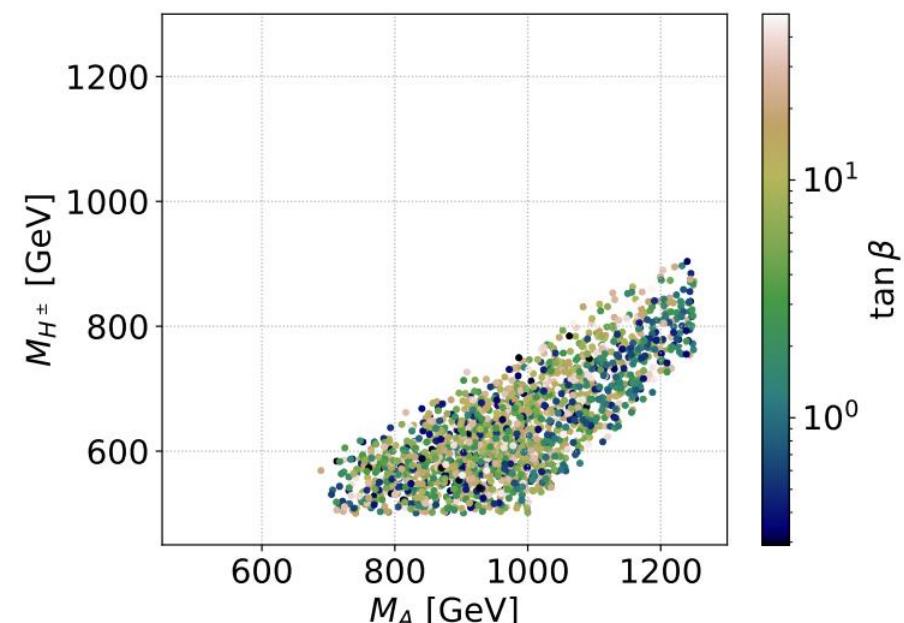
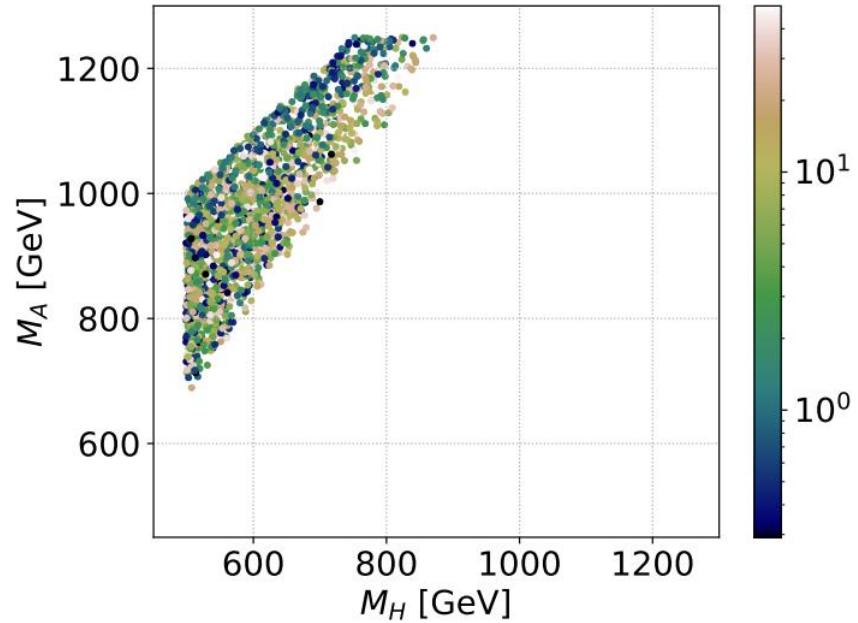


$$V_0 = \frac{m_{11}^2}{2}(h^0)^2 + \frac{m_{22}^2}{2}(H^0)^2 - m_{12}^2 h^0 H^0 + \frac{\lambda_1}{8}(h^0)^4 + \frac{\lambda_2}{8}(H^0)^4 + \frac{\lambda_3 + \lambda_4 + \lambda_5}{2}(h^0)^2(H^0)^2$$

$$V_{CW} = \frac{1}{64\pi^2} \sum_i n_i m_i^4 \left( \log \frac{m_i^2}{\mu^2} - c_i \right)$$

$$V_{CT} = \delta m_{11}^2 (h^0)^2 + \delta m_{22}^2 (H^0)^2 + \delta m_{12}^2 h^0 H^0 + \delta \lambda_1 (h^0)^4 + \delta \lambda_2 (H^0)^4$$

$$V_T = \frac{T^4}{2\pi^4} \sum_i n_i J\left(\frac{m_i^2}{T^2}\right) \quad J(y^2) = \int_0^\infty dx \, x^2 \log(1 + (-1)^B \exp[-\sqrt{x^2 + y^2}])$$



Parameter space  
leading to FOPT

For reference the plot refers to Type-I.  
No substantial differences for the other  
Yukawa configurations though.

# GW Signal

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

C. Caprini et al JCAP 04 (2016) 001

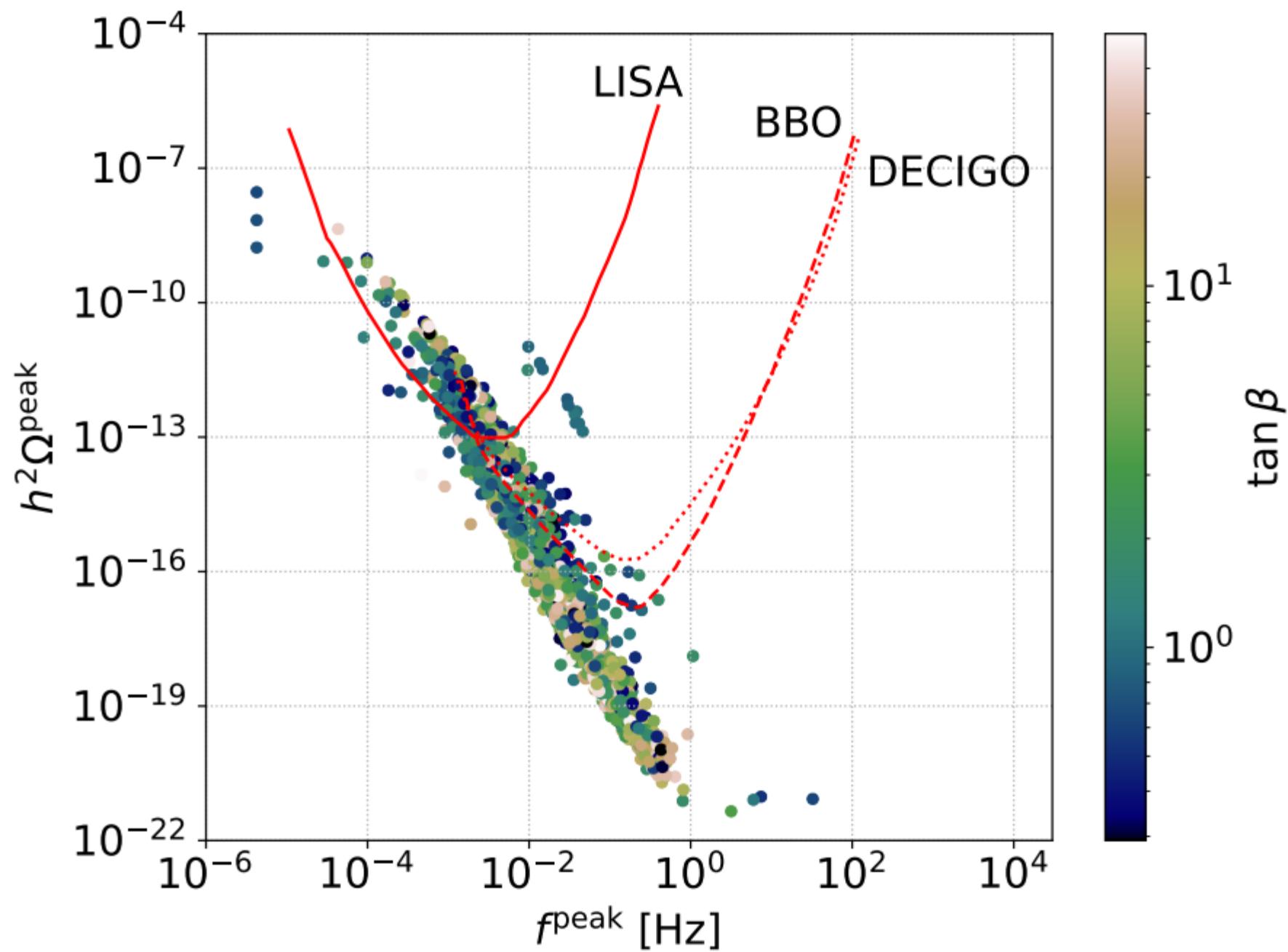
$$h^2 \Omega_{GW} \simeq h^2 \Omega_{col} + h^2 \Omega_{sw} + h^2 \Omega_{turb}$$

The diagram illustrates the decomposition of the gravitational wave signal. A horizontal line at the bottom represents the total signal  $h^2 \Omega_{GW}$ . Three arrows point from this line to the right, each representing a contribution. The top arrow is blue and points to the text "Contribution from sound wave overlap". The middle arrow is green and points to the text "Contribution from Magneto-Hydrodynamical (MHD) turbulence". The bottom arrow is red and points to the text "Contribution from bubble collisions".

Contribution from sound wave overlap

Contribution from Magneto-Hydrodynamical (MHD) turbulence

Contribution from bubble collisions



# Conclusions

The 2HDM+a is an economical but consistent extension of the SM.

It features viable DM phenomenology and can accommodate a FOPT with a potentially detectable signal for some regions of the parameter space.

# Back up

## Constraints from decay of the Higgs

$$\Gamma(h \rightarrow aa) = \frac{|\lambda_{haa}|^2}{32 \pi M_h} \sqrt{1 - \frac{4M_a^2}{M_h^2}}$$

$$\lambda_{haa} = \frac{1}{v} [(M_h^2 - 2M_H^2 + 4M_{H^\pm}^2 - 2M_a^2 - 2\lambda_3 v^2) \sin^2 \theta - 2(\lambda_{1P} \cos^2 \beta + \lambda_{2P} \sin^2 \beta) v^2 \cos^2 \theta]$$

$M_a < \frac{M_h}{2}$  excluded unless one imposes:

$$\frac{\lambda_{haa}}{M_h} \leq O(10^{-3})$$

# Collider Constraints

Applied constraints:

$$pp \rightarrow H, A \rightarrow \tau^+ \tau^-$$

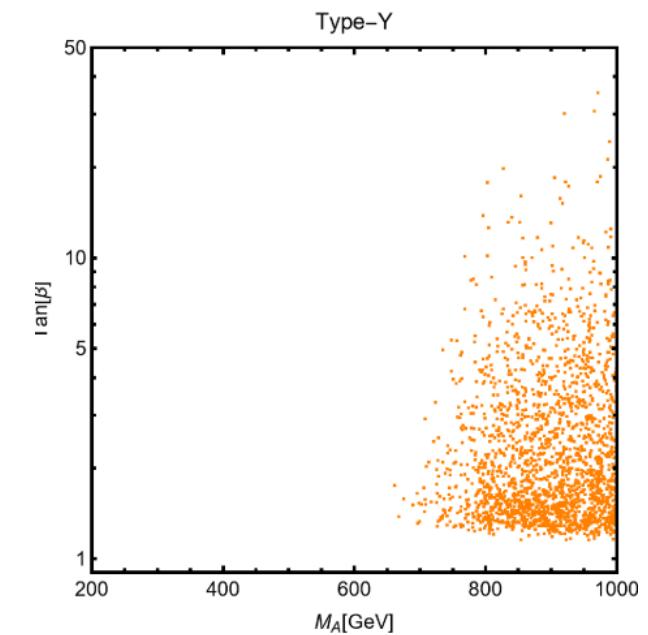
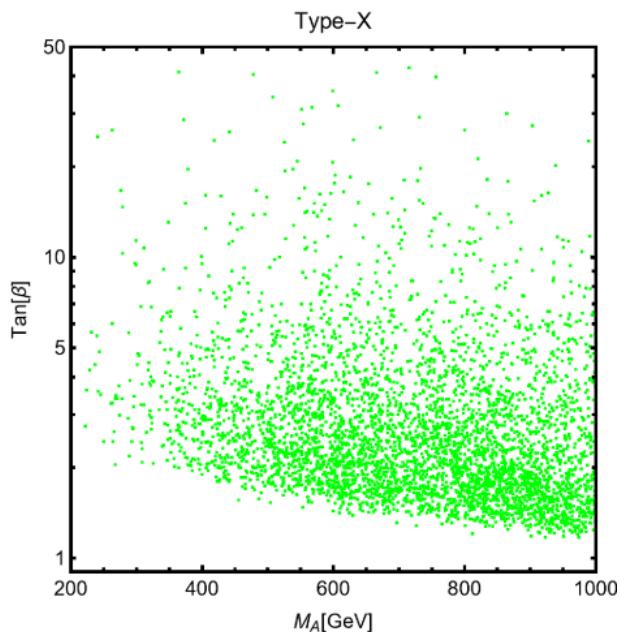
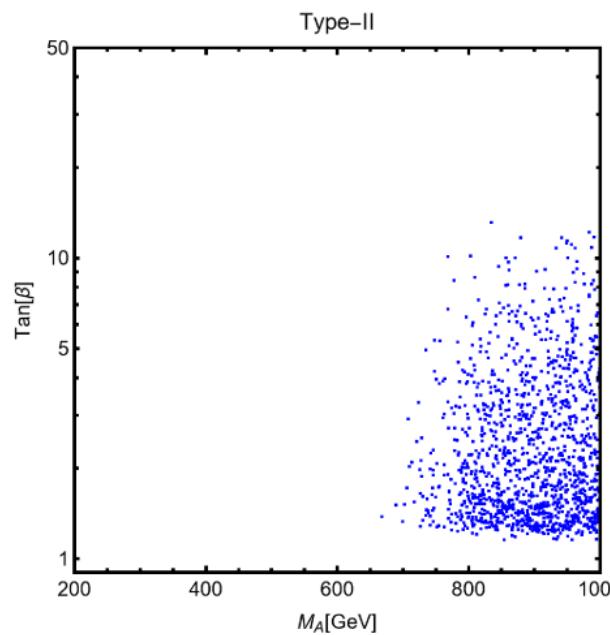
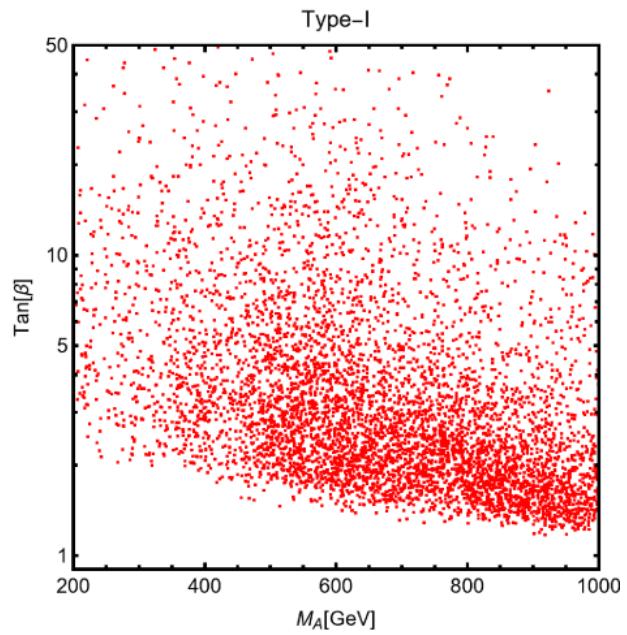
$$pp \rightarrow H \rightarrow ZA, Za \quad (A, a \rightarrow \chi\chi)$$

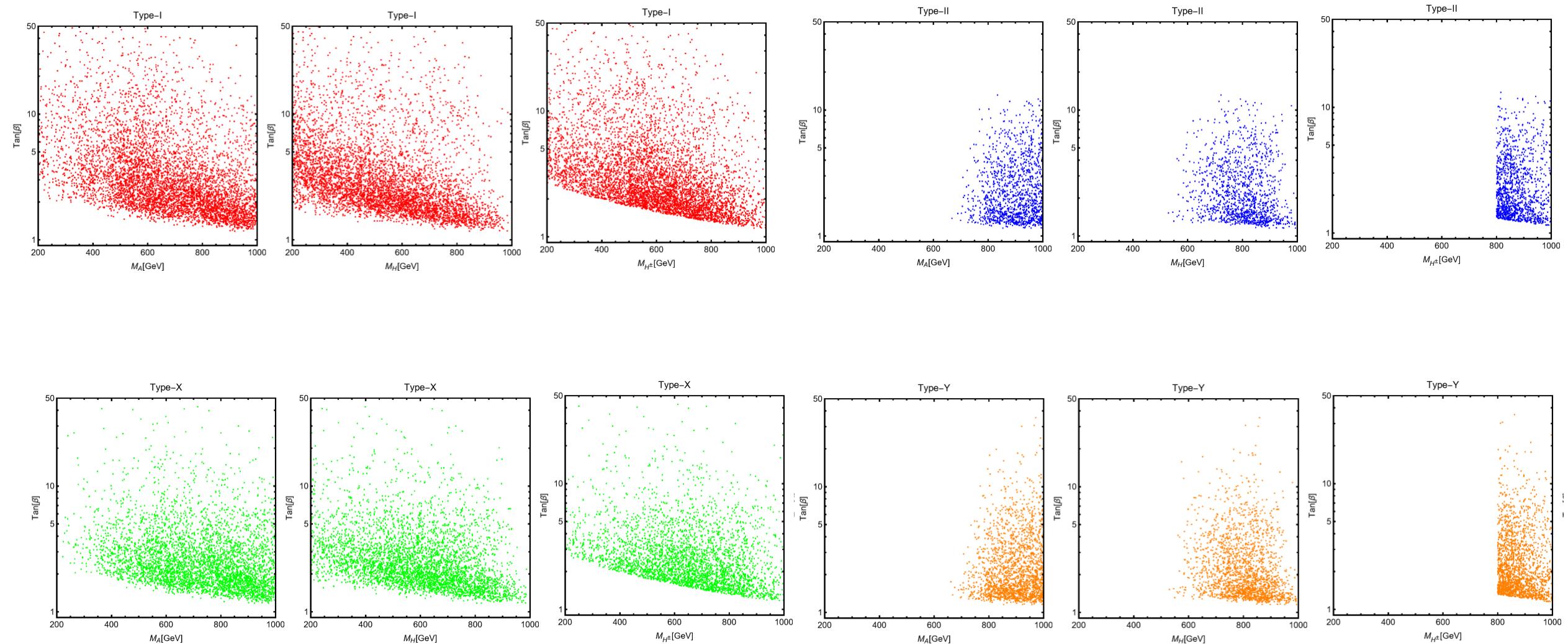
$$pp \rightarrow a \rightarrow \mu^+ \mu^-$$

$$pp \rightarrow A \rightarrow ha \quad (a \rightarrow \chi\chi)$$

$$pp \rightarrow A \rightarrow ZH, Zh$$

$$pp \rightarrow H \rightarrow ZA, Za \quad (A, a \rightarrow SM)$$





# GW Signal

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

$$h^2 \Omega_{col}(f) = h^2 \Omega_{col}^{peak} S_{col}(f)$$

$$h^2 \Omega_{col}^{peak} = 1.67 \times 10^{-5} \left( \frac{H_n}{\beta} \right)^2 \left( \frac{\kappa_{col} \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_n} \right)^{1/3} \left( \frac{0.11 v_w^3}{0.42 + v_w^2} \right)$$

$$S_{col} = \frac{3.8 (f/f_{col})^{2.8}}{1 + 2.8 (f/f_{col})^{3.8}}$$

$$h^2 \Omega_{sw}(f) = h^2 \Omega_{sw}^{peak} S_{sw}(f)$$

$$h^2 \Omega_{sw}^{peak} = 1.23 \times 10^{-6} \left( \frac{H_n}{\beta} \right) \left( \frac{\kappa_{sw} \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_n} \right)^{1/3} v_w \Upsilon$$

$$\Upsilon = 1 - \frac{1}{\sqrt{2\tau_{sw} H_n + 1}}$$

$$S_{sw} = \left( \frac{f}{f_{sw}} \right)^3 \left( \frac{7}{4 + 3 \left( \frac{f}{f_{sw}} \right)^2} \right)^{7/2}$$

$$h^2 \Omega_{turb}(f) = h^2 \Omega_{turb}^{peak} S_{turb}(f) \quad h^2 \Omega_{turb}^{peak} = 3.35 \times 10^{-4} \left( \frac{H_n}{\beta} \right) \left( \frac{\kappa_{turb} \alpha}{1 + \alpha} \right)^{3/2} \left( \frac{100}{g_n} \right)^{1/3} v_w \frac{1}{N_{turb}}$$

$$S_{turb} = \frac{\left( \frac{f}{f_{turb}} \right)^3}{\left[ 1 + \left( \frac{f}{f_{turb}} \right) \right]^{11/3}} \frac{N_{turb}}{1 + 8\pi f/h_n}$$

$$N_{turb} = 2^{11/3} (1 + 8\pi f_{turb}/h_n)$$

