Dark Matter and Gravitational Waves in the 2HDM+a

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Based on G.A., N Benicasa,
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Conventional (Z_2 symmetric)2HDM Potential

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

$$V(\Phi_1,\Phi_2,a_0) = V_{2HDM}(\phi_1,\phi_2) + V_{self}(a_0) + V_{a_0,2HDM}(\phi_1,\phi_2,a_0)$$

Self Interaction lagrangian

$$V_{self}(a_0) = \frac{1}{2}m_{a_0}^2 a_0^2 + \frac{1}{4}\lambda_a a_0^4$$

Singlet Doublet Interaction Lagrangian

$$V_{a_0,2HDM}(\phi_1,\phi_2,a_0) = \kappa(i\,a_0\phi_1^\dagger\phi_2 + h.c.) + \lambda_{1P}a_0^2\phi_1^\dagger\phi_1 + \lambda_{2P}a_0^2\phi_2^\dagger\phi_2$$

EW Symmetry Breaking

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

$$\langle \phi_2 \rangle = v_2$$

$$\frac{v_2}{v_1} = tan\beta$$

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

Mixing between pseudoscalar states

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

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

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

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

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

Summary scan

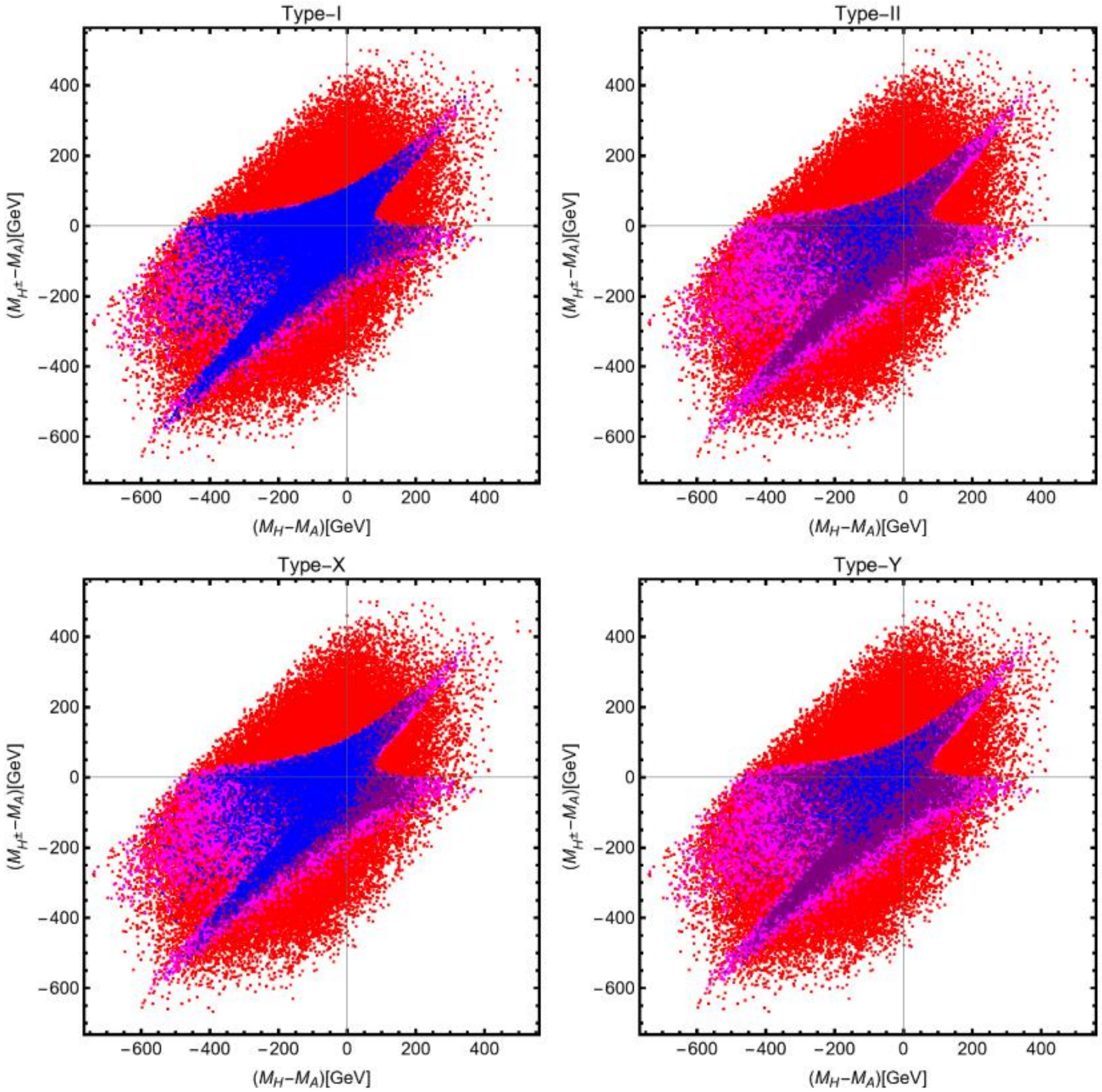
$tan\beta \in [1,60], |\cos(\beta - \alpha)| \leq 0.2$

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

$M_a \in [10,400]\ GeV$

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

Theoretical constraints
EWPT
Higgs Signal Strength
Flavour



Summary of collider constraints

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

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

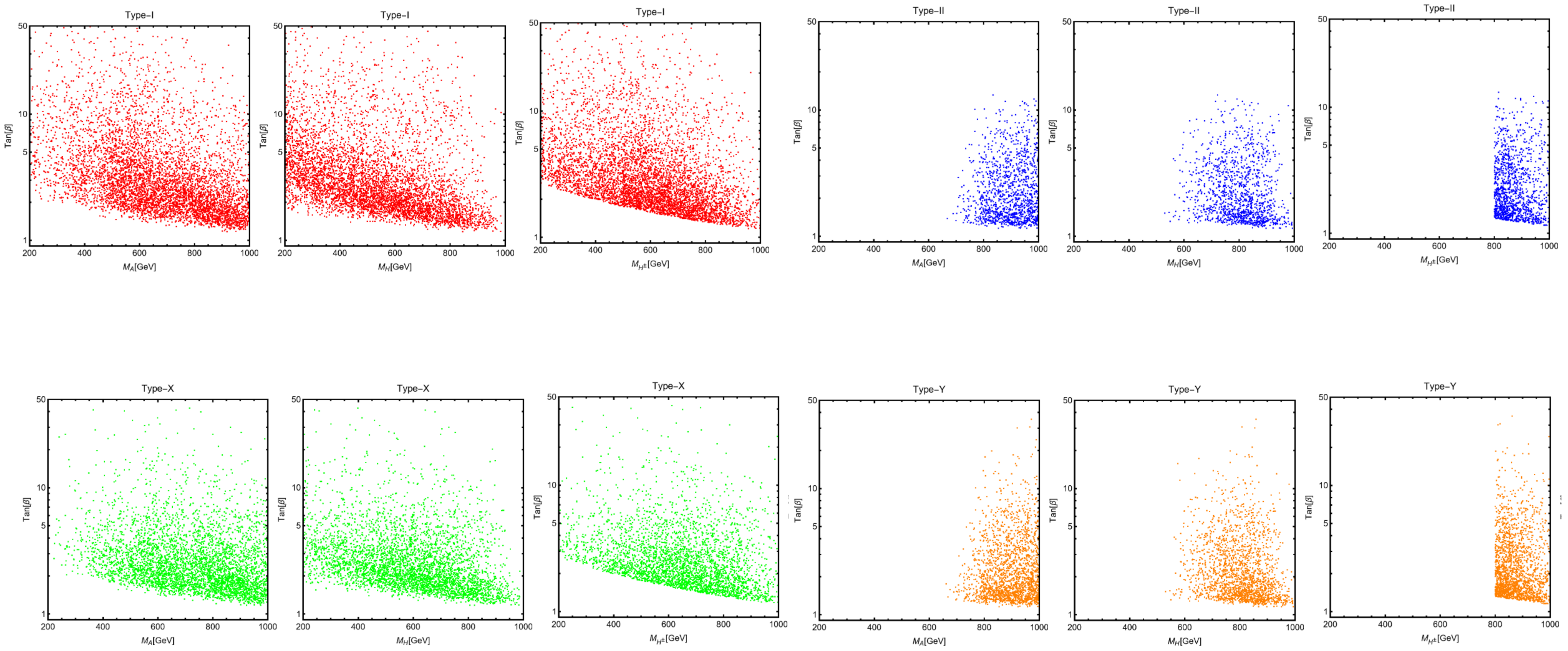
$pp \to A \to ZH, Zh$

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

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

$pp \to A \to ha\ (a \to \chi\chi)$

$pp \to h \to aa$


Type–I
Type–I
Type–I
Type–II
Type–II
Type–II
Type–X
Type–X
Type–X
Type–Y
Type–Y
Type–Y
Tan[β]
50
10
5
1
200
400
600
800
1000
M_A[GeV]
M_H[GeV]
$M_{H^\pm}$[GeV]

DM Phenomenology

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

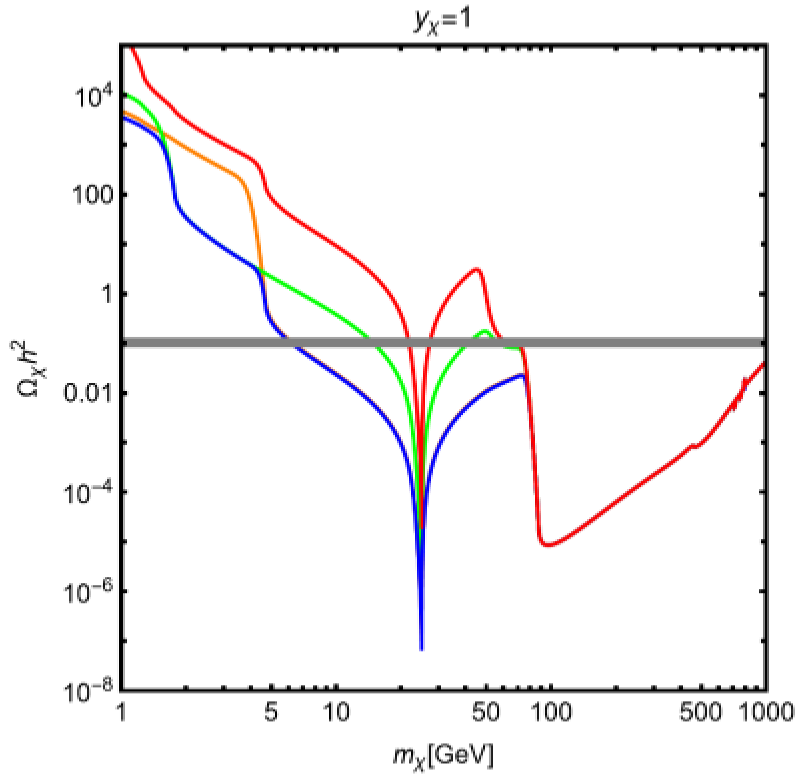
$$\langle\sigma v\rangle$$

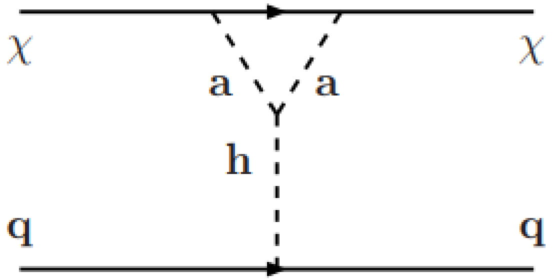
$$\bar{\chi}\chi \to a\,/A \to \bar{f}f$$

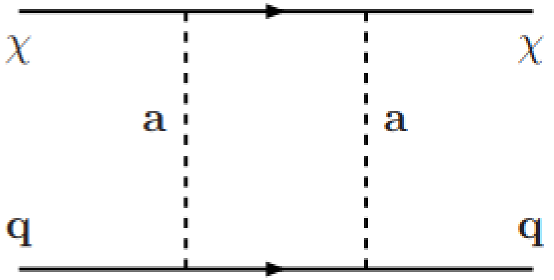
$$\bar{\chi}\chi \to a\,/A \to ha(A)$$

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

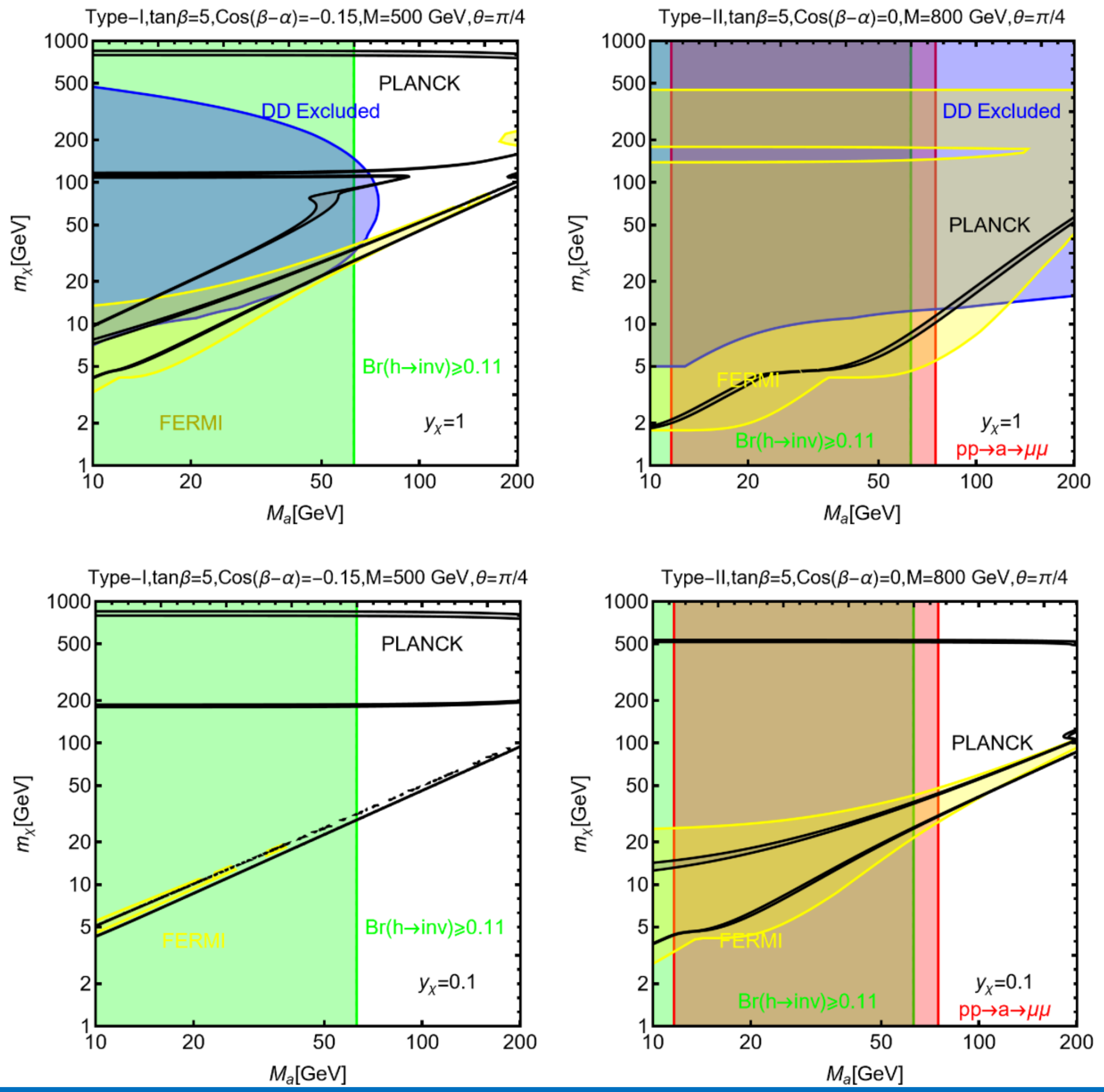
$$\Omega h^2 \propto \frac{1}{\langle\sigma v\rangle}$$

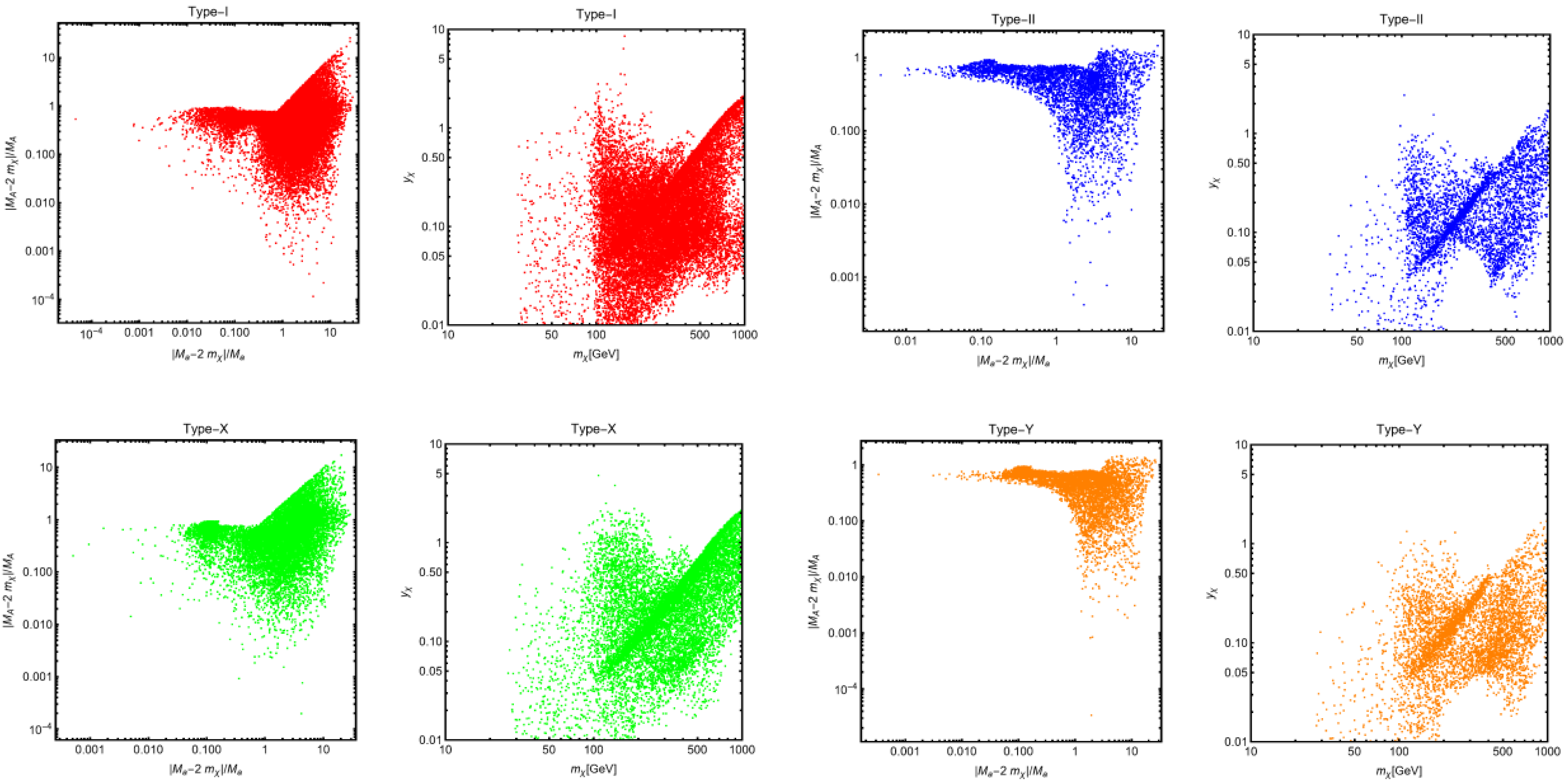






Induced at one-loop


Type−I,tanβ=5,Cos(β−α)=−0.15,M=500 GeV,θ=π/4
PLANCK
DD Excluded
Br(h→inv)≥0.11
FERMI
y_χ=1
m_χ[GeV]
M_a[GeV]
Type−II,tanβ=5,Cos(β−α)=0,M=800 GeV,θ=π/4
DD Excluded
PLANCK
FERMI
Br(h→inv)≥0.11
y_χ=1
pp→a→μμ
Type−I,tanβ=5,Cos(β−α)=−0.15,M=500 GeV,θ=π/4
PLANCK
Br(h→inv)≥0.11
FERMI
y_χ=0.1
Type−II,tanβ=5,Cos(β−α)=0,M=800 GeV,θ=π/4
PLANCK
FERMI
Br(h→inv)≥0.11
y_χ=0.1
pp→a→μμ



Type–I
|M_A–2 m_χ|/M_A
|M_a–2 m_χ|/M_a
Type–I
y_χ
m_χ[GeV]
Type–II
|M_A–2 m_χ|/M_A
|M_a–2 m_χ|/M_a
Type–II
y_χ
m_χ[GeV]
Type–X
|M_A–2 m_χ|/M_A
|M_a–2 m_χ|/M_a
Type–X
y_χ
m_χ[GeV]
Type–Y
|M_A–2 m_χ|/M_A
|M_a–2 m_χ|/M_a
Type–Y
y_χ
m_χ[GeV]

One-loop thermal effective potential

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

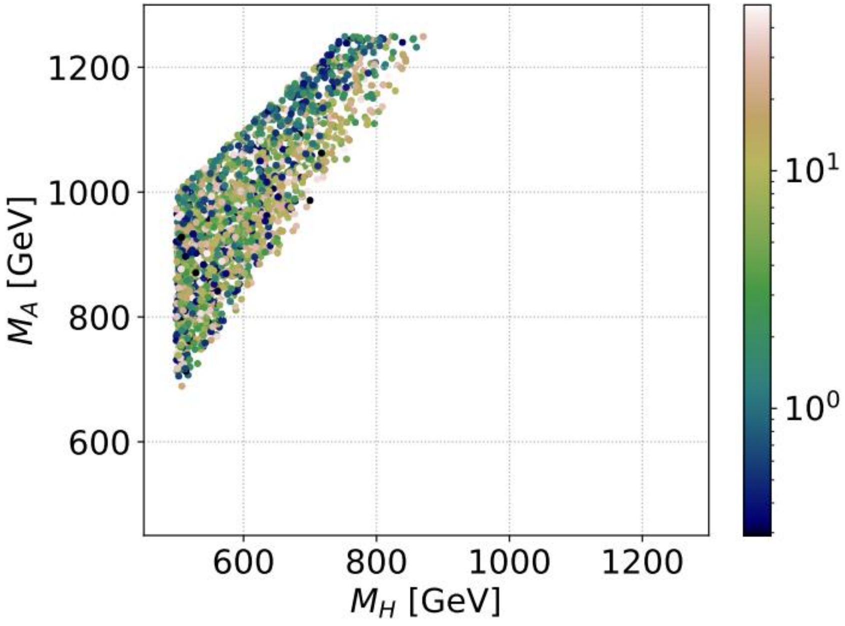
- V_{CW} → One loop quantum corrections
- V_T → Thermal corrections
- V_{CT} → Counterterms (to compensate the shift from V_{CW} to the vevs)
- V_0 → Tree-level potential

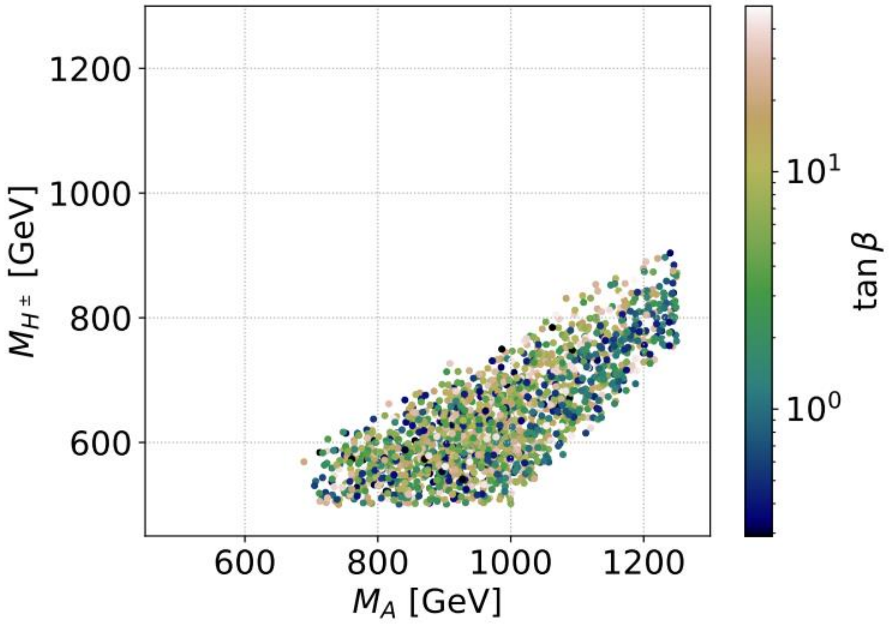
$$V_0 = \frac{m_{11}^2}{2}(h^0)^2 + \frac{m_{22}^2}{2}(H^0)^2 - m_{12}^2 h^0 H^0 + \frac{\lambda_1}{8}(h^0)^4 + \frac{\lambda_2}{8}(H^0)^4 + \frac{\lambda_3+\lambda_4+\lambda_5}{2}(h^0)^2(H^0)^2$$

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

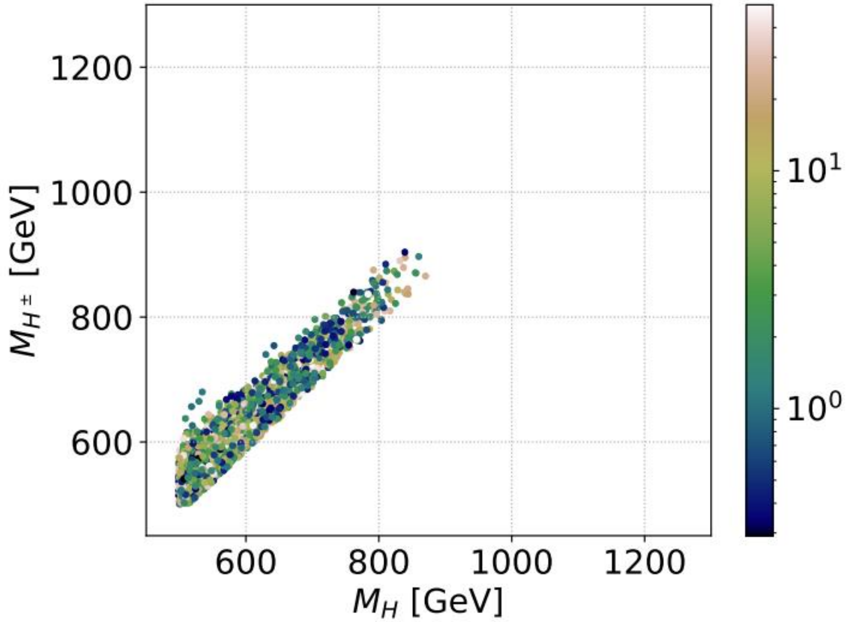
$$V_{CT} = \delta m_{11}^2(h^0)^2 + \delta m_{22}^2(H^0)^2 + \delta m_{12}^2 h^0 H^0 + \delta\lambda_1(h^0)^4 + \delta\lambda_2(H^0)^4$$

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





Parameter space leading to FOPT



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

GW Signal

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

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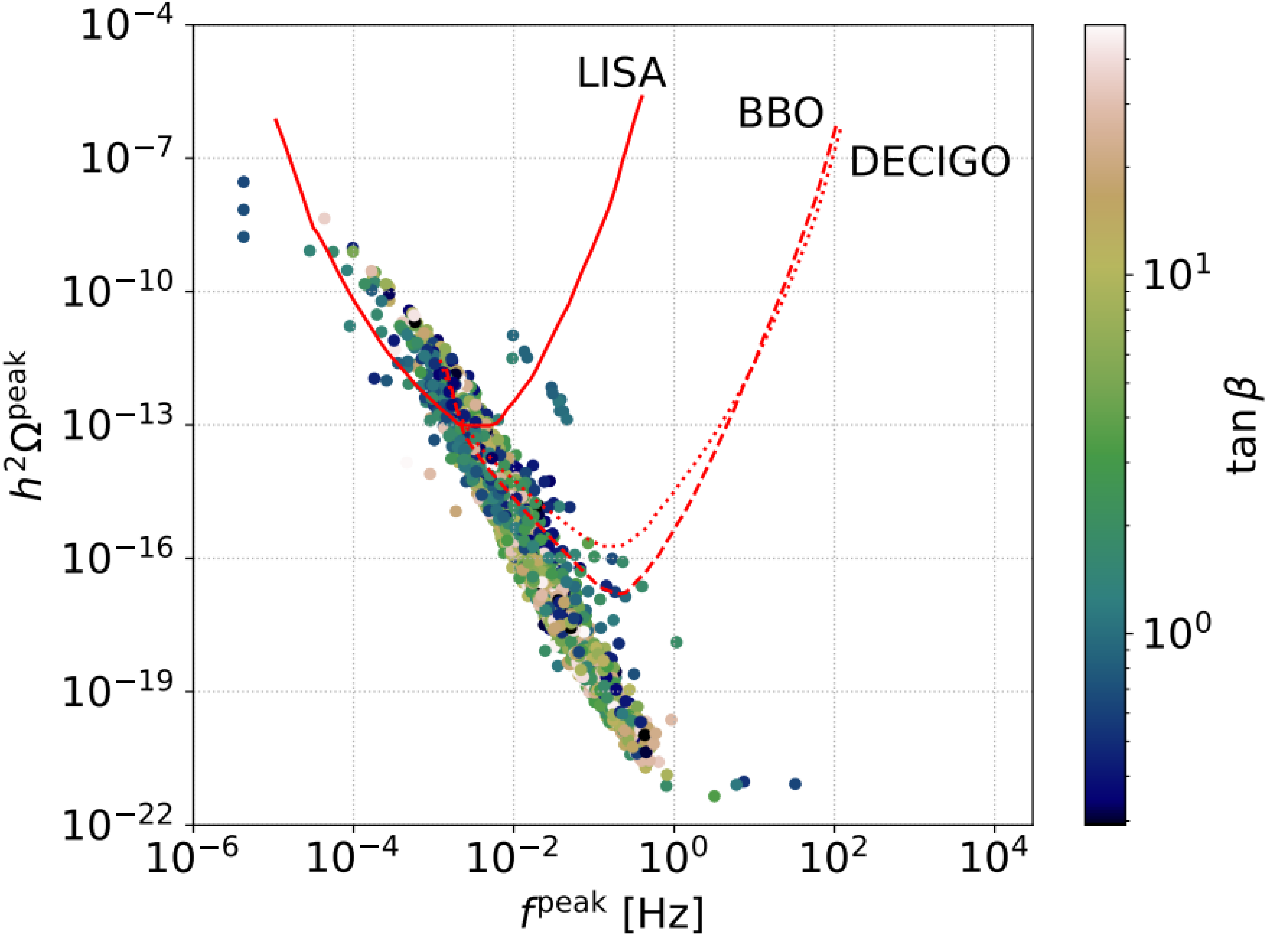
Contribution from sound wave overlap

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

Contribution from Magneto-Hydrodynamical (MHD) turbolence

Contribution from bubble collisions


LISA
BBO
DECIGO
10^{-4}
10^{-7}
10^{-10}
10^{-13}
10^{-16}
10^{-19}
10^{-22}
$h^2\Omega^{\rm peak}$
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
$f^{\rm peak}$ [Hz]
10^{1}
10^{0}
$\tan\beta$

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.