

# GRAVITATIONAL WAVES AND NEW PHYSICS SEARCHES: A MULTI-MESSENGER PHILOSOPHY

ANTÓNIO PESTANA MORAIS

DEPARTAMENTO DE FÍSICA DA UNIVERSIDADE DE AVEIRO AND CENTER FOR  
RESEARCH AND DEVELOPMENT IN MATHEMATICS AND APPLICATIONS (CIDMA)

CO-AUTHORS: R. PASECHNIK, J. VIANA, H. YANG, A. MARCIANO, F. FREITAS

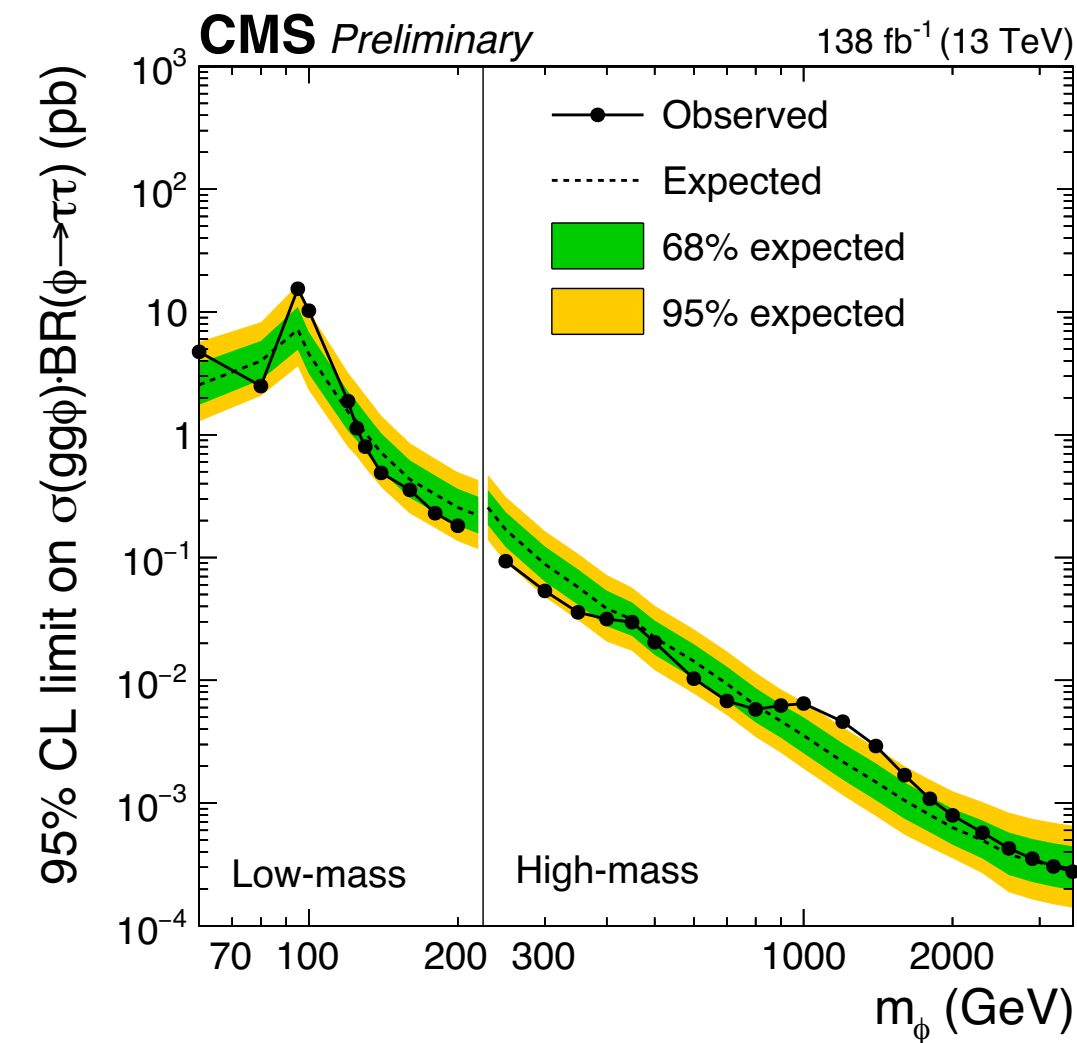


**The SM is a tremendously successful theory that explains  
“boringly” well all its predictions!**

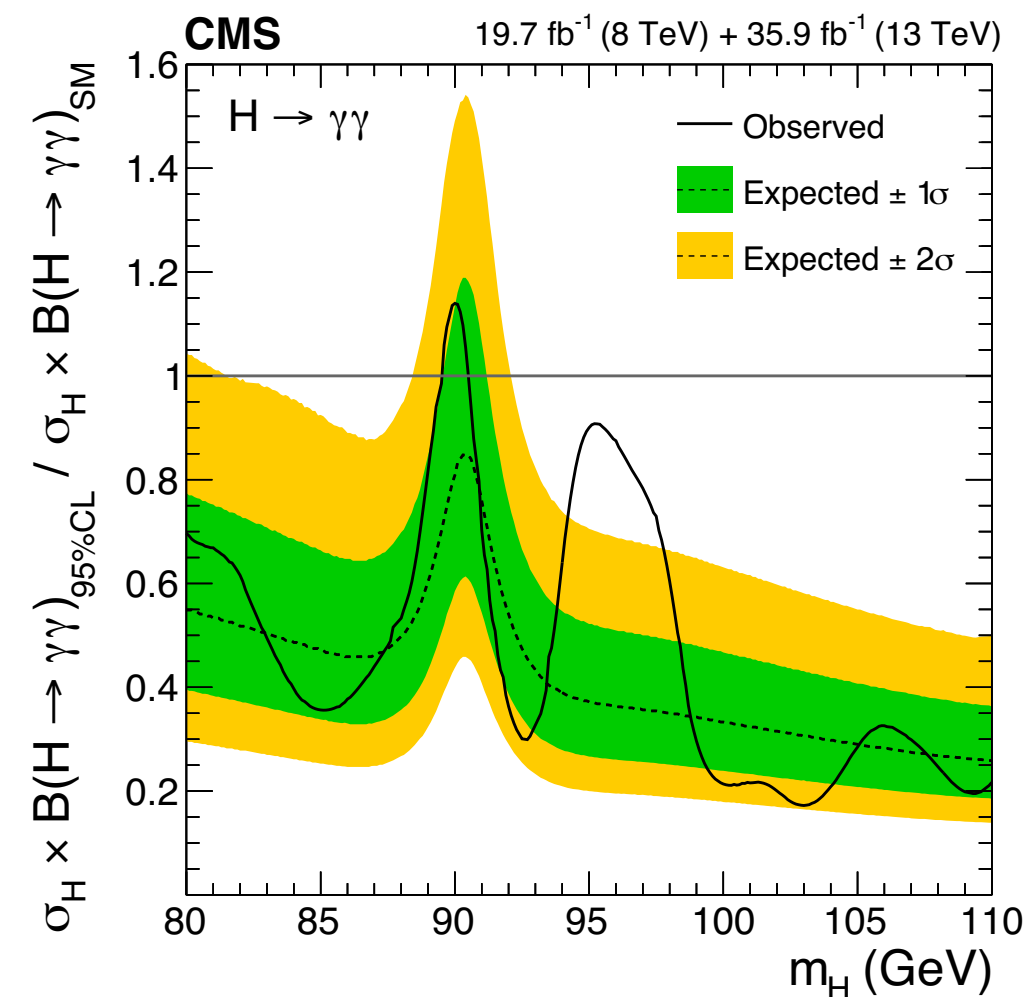
**However, it fails to...**

- **Explain neutrino masses**
- **Explain dark matter**
- **Explain CP violation and matter/anti-matter asymmetry**
- **Explain the observed flavour structure**

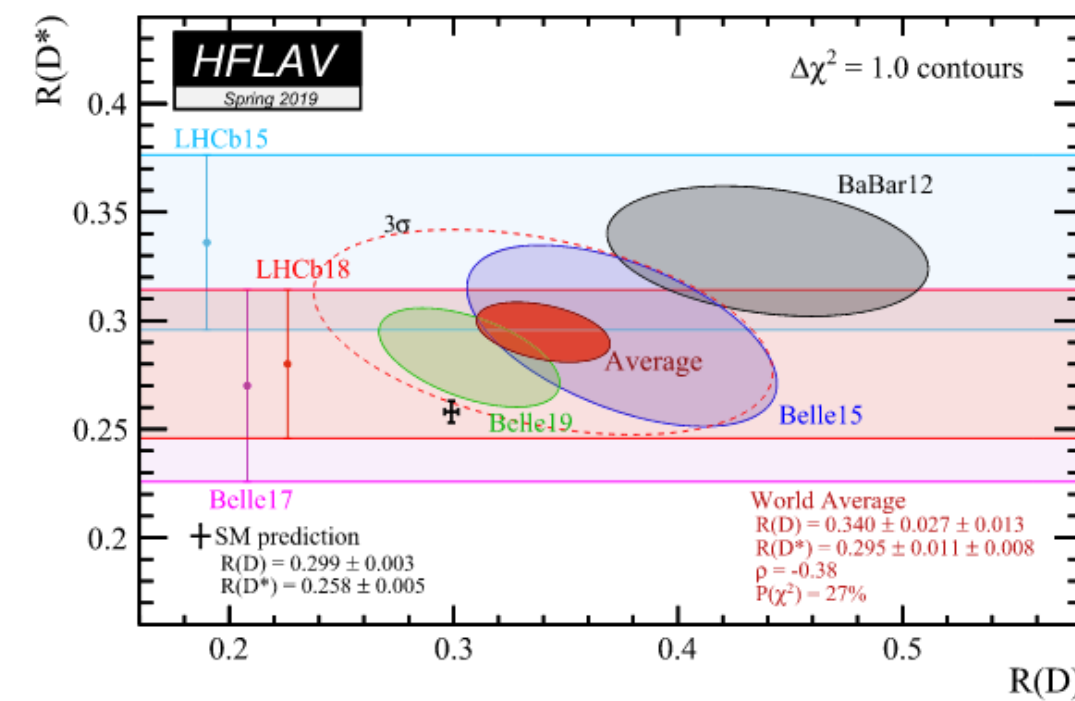
# And it is in tension with a number of emergent anomalies and excesses



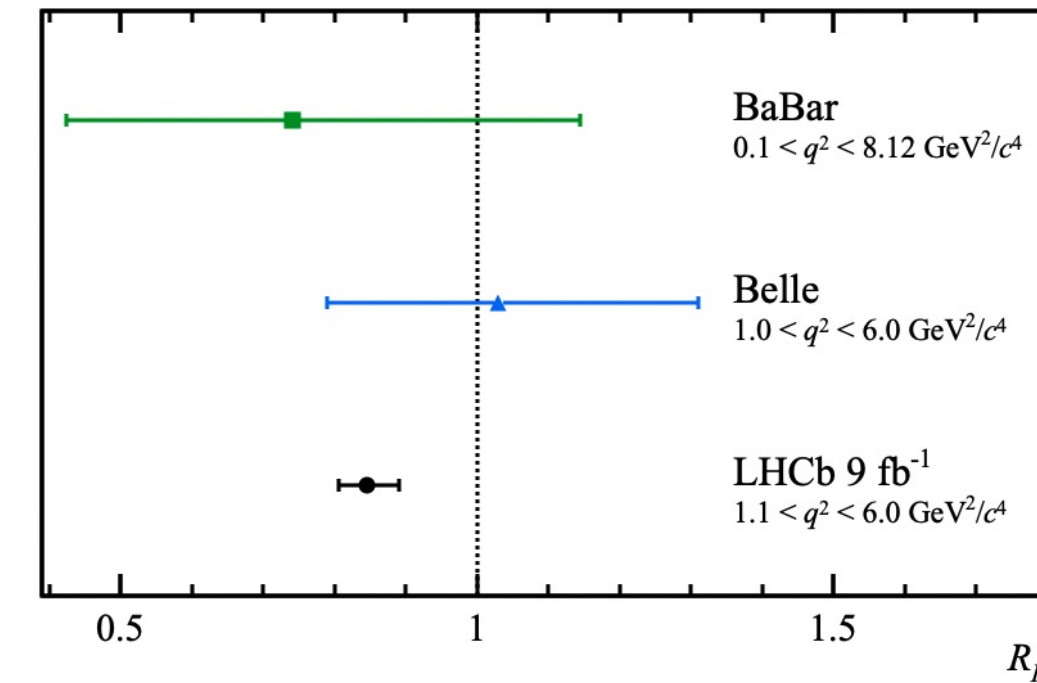
[CMS-PAS-HIG-21-001]



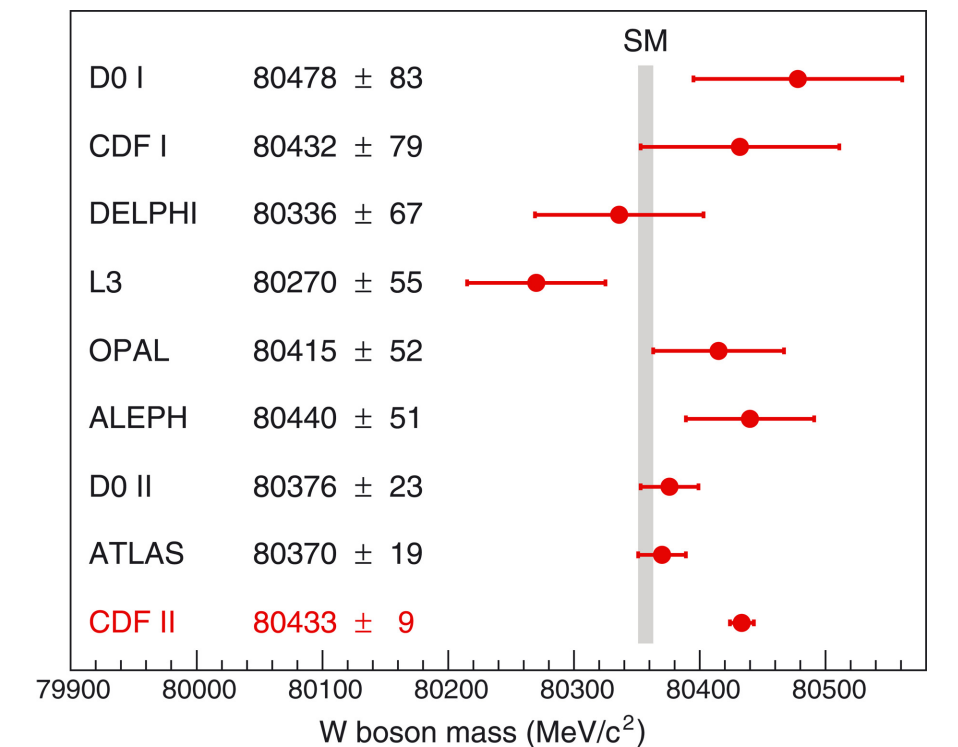
[Phys. Lett. B793 (2019) 320]



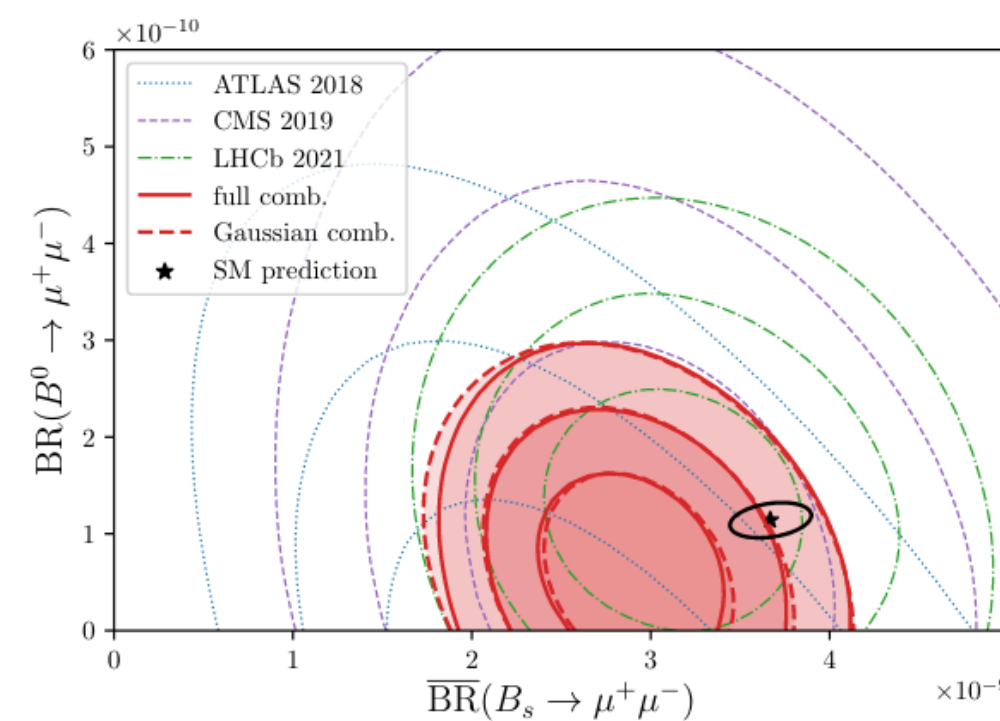
[Eur. Phys. J. C 81, 226 (2021)]



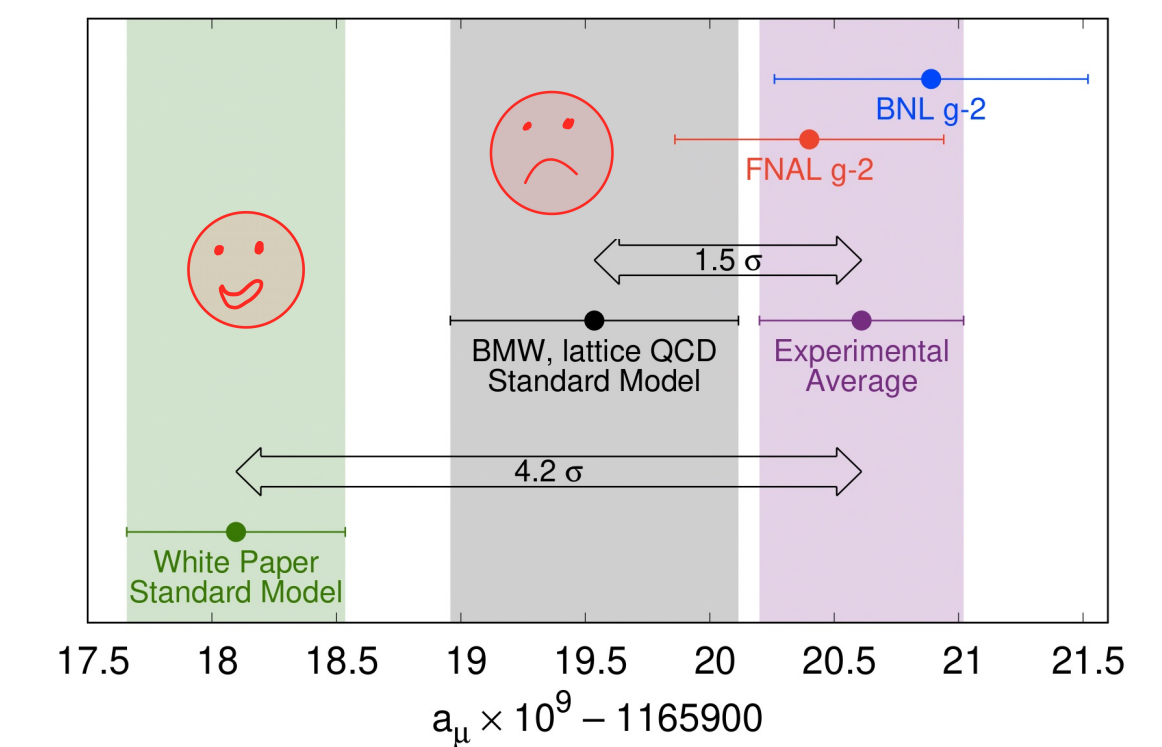
[Nature Phys. 18, 277 (2022)]



[Science 376, n6589, 170-176 (2022)]



[Eur. Phys. J. C 81, 952 (2021)]



[K. Szabo talk at Moriond 2022 on behalf of the BMW collaboration]

**Current and future experimental facilities will offer new multi-messenger channels to search for New Physics**

**LHC and future colliders**

**LISA and future GW observatories**

Accurate measurement of neutrino masses and light DM detection ( meV - eV)  $\longrightarrow$  **CNB experiments such as PTOLEMY**

# Why do Gravitational Waves matter?

**Quick answer:** GWs, in the form of a stochastic cosmological background, allow to probe physics not at the reach of collider experiments .

# Why do Gravitational Waves matter?

**Quick answer:** GWs, in the form of a stochastic cosmological background, allow to probe physics not at the reach of collider experiments .

- Cosmological events

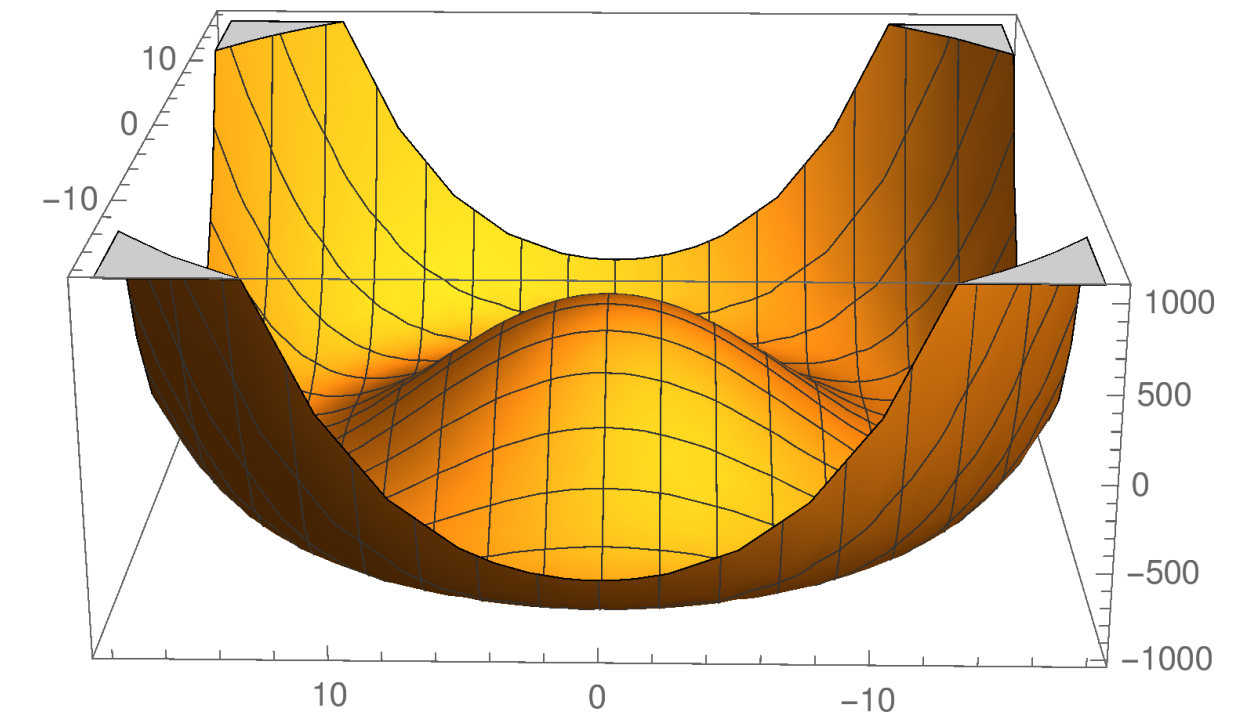
- (i) Inflation
- (ii) Cosmic strings
- (iii) **Strong cosmological phase transitions (PTs)** → by expanding vacuum bubbles of a broken phase in a universe filled with a symmetric phase

# Basics of Strong First Order PTs (SFOPTs)

Consider a the scalar potential:

$$V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2$$

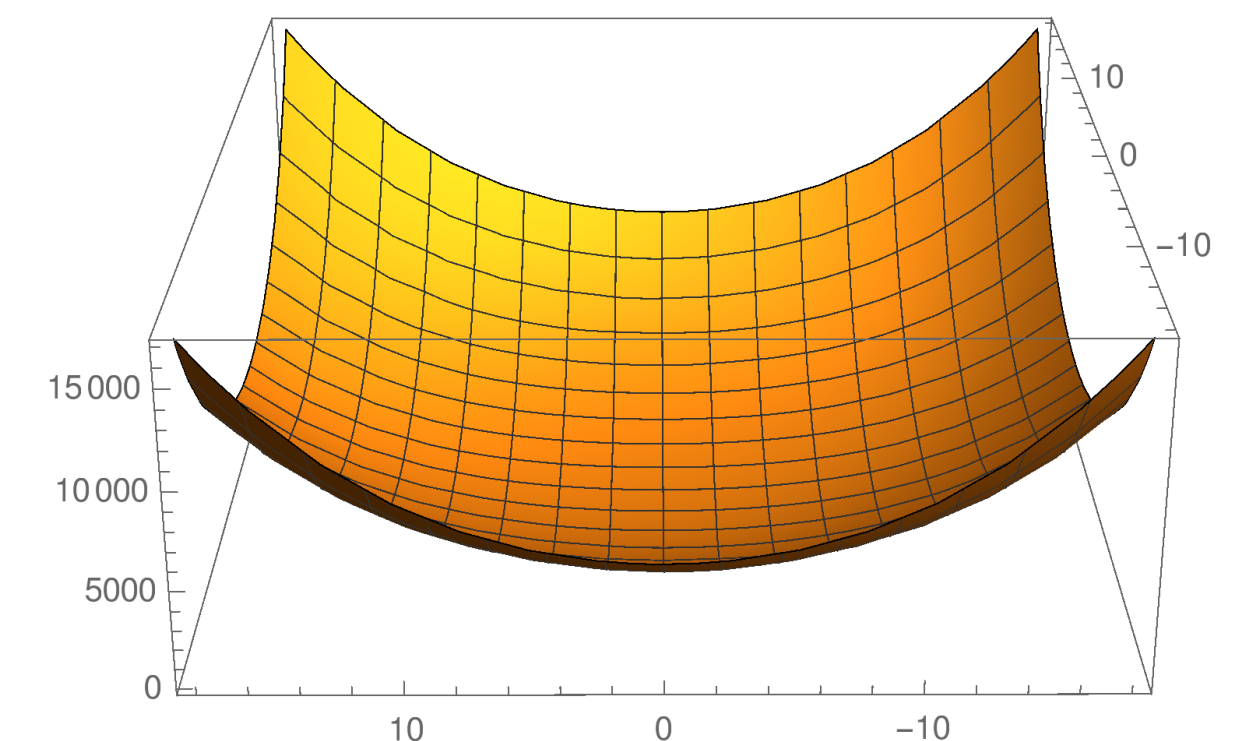
$$\mu^2 < 0 \text{ and } \lambda > 0$$



Add thermal corrections:

$$V(\phi, T) = (\mu^2 + C_\phi T^2) \phi^* \phi + \lambda (\phi^* \phi)^2$$

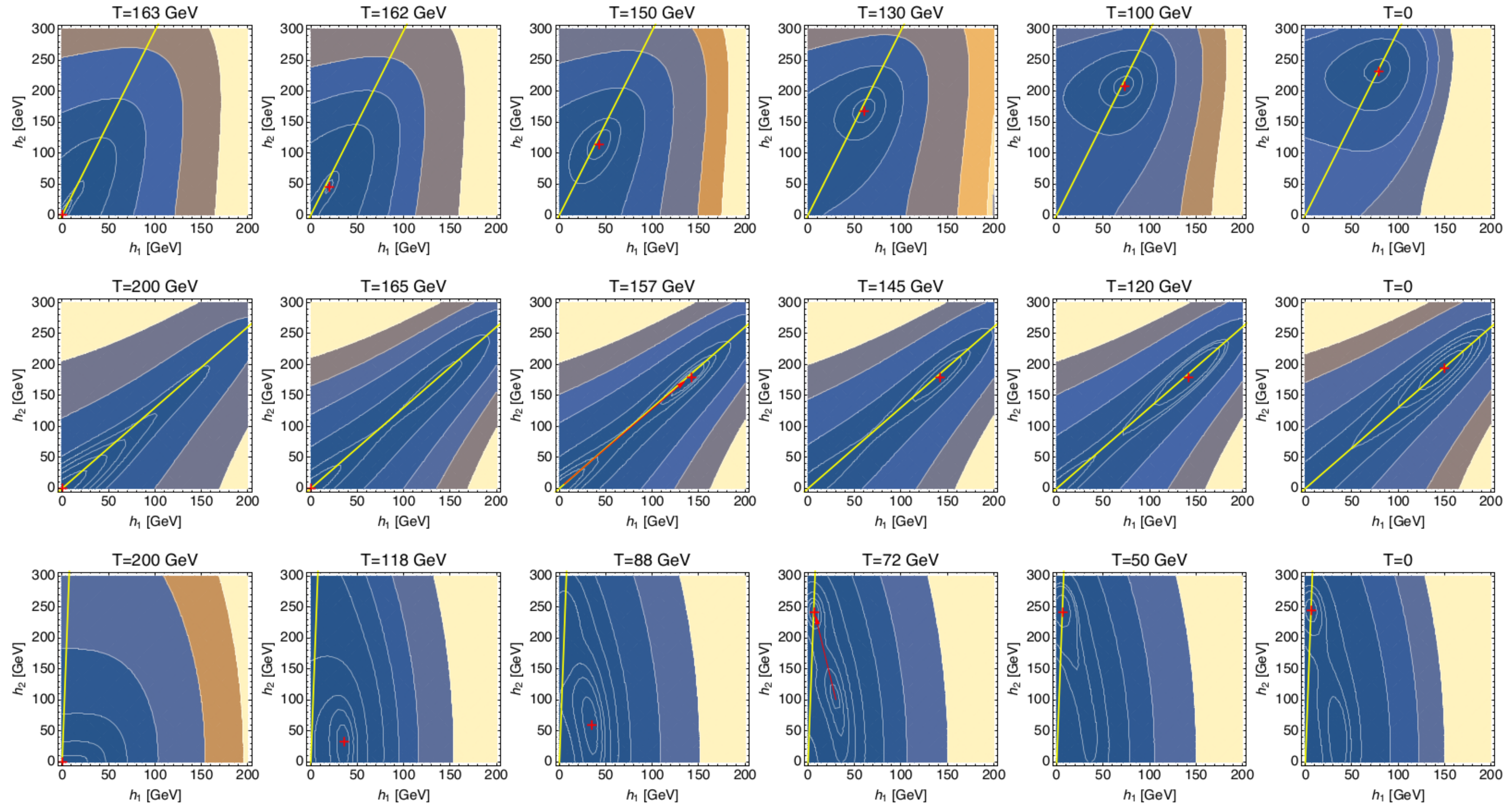
For  $C_\phi > 0$ , after a certain  $T > 0$ ,  $\mu_{eff} \equiv \mu^2 + C_\phi T^2 > 0$



**Restored symmetry**

If a **multi-Higgs** theory contains multiple vacua, phase transitions can take place:

$$V_{\text{BSM}}(h_1, h_2, T)$$





# 1st Order PTs



The larger the potential energy difference between the true and the false vacuum, the **stronger** the PT

Strength of the PT quantified as:

$$\alpha = \frac{1}{\rho_\gamma} \left[ V_i - V_f - \frac{T_*}{4} \left( \frac{\partial V_i}{\partial T} - \frac{\partial V_f}{\partial T} \right) \right]$$

$$\rho_\gamma = g_* \frac{\pi^2}{30} T_*^4$$

Duration of the PT quantified as:

$$\frac{\beta}{H} = T_* \left. \frac{\partial}{\partial T} \left( \frac{\hat{S}_3}{T} \right) \right|_{T_*}$$

Euclidean action:

$$\hat{S}_3(\hat{\phi}, T) = 4\pi \int_0^\infty dr r^2 \left\{ \frac{1}{2} \left( \frac{d\hat{\phi}}{dr} \right)^2 + V_{\text{eff}}(\hat{\phi}, T) \right\}$$

$$V_{\text{eff}}(T) = V_0 + V_{\text{CW}}^{(1)} + \Delta V(T) + V_{\text{ct}}$$

$\alpha, \beta/H, T_*$   $\longrightarrow$  calculated from a certain BSM theory, used as inputs to obtain the GW power spectrum

$$h^2\Omega_{\text{GW}} = h^2\Omega_{\text{GW}}^{\text{peak}} \left(\frac{4}{7}\right)^{-\frac{7}{2}} \left(\frac{f}{f_{\text{peak}}}\right)^3 \left[1 + \frac{3}{4} \left(\frac{f}{f_{\text{peak}}}\right)\right]^{-\frac{7}{2}}$$

Peak amplitude

Spectral function

$$h^2\Omega_{\text{GW}}^{\text{peak}} \propto T_*^2 K(\alpha) f_{\text{peak}}^{-2} \quad f_{\text{peak}} \propto (\beta/H) T_*$$

We use the formalism in [JCAP 2003, 024 (2020), JCAP 1906, 024 (2019)]

# The Model

	$SU(2)_W$	$U(1)_Y$	$\{U(1)_L\}$
$H$	<b>2</b>	1/2	0
$\sigma$	<b>1</b>	0	2
$\nu_{Ri}^c$	<b>1</b>	0	1
$S_i$	<b>1</b>	0	-1

- In [Phys.Lett.B 807 (2020) 135577] we have shown that observable GWs require a heavy **VISIBLE** Majoron  $O(100 \text{ GeV} - 1 \text{ TeV})$
- The needed size of the portal coupling to induce a false vacuum and SFOPTs too large for invisible Higgs decays
- How to make the Majoron lighter/darker?

$$V_0(H, \sigma) = V_{\text{SM}}(H) + V_{\text{BSM}}(H, \sigma) + V_{6\text{D}}(H, \sigma) + V_{\text{soft}}(\sigma),$$

$$V_{\text{SM}}(H) = \mu_h^2 H^\dagger H + \lambda_h (H^\dagger H)^2,$$

$$V_{\text{BSM}}(H, \sigma) = \mu_\sigma^2 \sigma^\dagger \sigma + \lambda_\sigma (\sigma^\dagger \sigma)^2 + \lambda_{\sigma h} H^\dagger H \sigma^\dagger \sigma,$$

$$V_{6\text{D}}(H, \sigma) = \frac{\delta_2}{\Lambda^2} (H^\dagger H)^2 \sigma^\dagger \sigma + \frac{\delta_4}{\Lambda^2} H^\dagger H (\sigma^\dagger \sigma)^2 + \frac{\delta_6}{\Lambda^2} (\sigma^\dagger \sigma)^3, \quad \frac{\delta_i}{\Lambda^2} v_\sigma^2 < 4\pi$$

$$V_{\text{soft}}(\sigma) = \frac{1}{2} \mu_b^2 (\sigma^2 + \sigma^{*2}).$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1 + i\omega_2 \\ \phi_h + h + i\eta \end{pmatrix}, \quad \sigma = \frac{1}{\sqrt{2}} (\phi_\sigma + h' + i\theta)$$

10 TeV <  $\Lambda$  < 1000 TeV  $\longrightarrow$  neutrino mass generation scale

$\delta_2$  and  $\delta_4$  allow co-existence of  $\Gamma_{\text{Higgs}}^{\text{invisible}}$  and a false vacuum

# Minimization

$$\left\langle \frac{\partial V_0}{\partial \phi_\alpha} \right\rangle_{\text{vac}} = 0, \quad \langle \phi_h \rangle_{\text{vac}} \equiv v_h \simeq 246 \text{ GeV}, \quad \langle \phi_\sigma \rangle_{\text{vac}} \equiv v_\sigma,$$

$$\mu_h^2 = -v_h^2 \lambda_h - \frac{1}{2} v_\sigma^2 \lambda_{\sigma h} - \frac{1}{2} \frac{v_h^2 v_\sigma^2 \delta_2}{\Lambda^2} - \frac{1}{4} \frac{v_\sigma^4 \delta_4}{\Lambda^2},$$

$$\mu_\sigma^2 = -v_\sigma^2 \lambda_\sigma - \mu_b^2 - \frac{1}{2} v_h^2 \lambda_{\sigma h} - \frac{1}{4} \frac{v_h^4 \delta_2}{\Lambda^2} - \frac{1}{2} \frac{v_h^2 v_\sigma^2 \delta_4}{\Lambda^2} - \frac{3}{4} \frac{v_\sigma^4 \delta_6}{\Lambda^2}.$$

# Scalar mass spectrum

$$M^2 = \begin{pmatrix} M_{hh}^2 & M_{\sigma h}^2 \\ M_{\sigma h}^2 & M_{\sigma\sigma}^2 \end{pmatrix}$$

$$M_{hh}^2 = 2v_h^2\lambda_h + \frac{v_h^2 v_\sigma^2 \delta_2}{\Lambda^2}, \quad M_{\sigma\sigma}^2 = 2v_\sigma^2\lambda_\sigma + \frac{v_h^2 v_\sigma^2 \delta_4}{\Lambda^2} + \frac{3v_\sigma^4 \delta_6}{\Lambda^2}, \quad M_{\sigma h}^2 = v_h v_\sigma \lambda_{\sigma h} + \frac{v_h^3 v_\sigma \delta_2}{\Lambda^2} + \frac{v_h v_\sigma^3 \delta_4}{\Lambda^2}.$$

$$\mathbf{m}^2 = O^\dagger_i{}^m M_{mn}^2 O^n{}_j = \begin{pmatrix} m_{h_1}^2 & 0 \\ 0 & m_{h_2}^2 \end{pmatrix}, \quad \text{with} \quad \mathbf{O} = \begin{pmatrix} \cos \alpha_h & \sin \alpha_h \\ -\sin \alpha_h & \cos \alpha_h \end{pmatrix}, \quad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \mathbf{O} \begin{pmatrix} h \\ h' \end{pmatrix}.$$

$$m_\theta^2 = -2\mu_b^2,$$

# Phenomenological inputs

**Invisible Higgs decays limit :**  $\text{Br}(h \rightarrow \theta\theta) < 0.19$  Used as input  
 [Phys. Lett. B 793 (2019) 520]

**Scalar mixing angle limit:**  $\cos \alpha_h > 0.85$  Used as input  
 [New J. Phys. 18(3), 033033 (2016)]

**Also used as inputs:**  $m_{h_1} = 125.09 \text{ GeV}, m_{h_2}, m_\theta, v_h, v_\sigma, \Lambda, \delta_2, \delta_6$

$$\text{Br}(h \rightarrow \theta\theta) = \frac{\Gamma(h \rightarrow \theta\theta)}{\Gamma(h \rightarrow \theta\theta) + \Gamma(h \rightarrow \text{SM})} \quad \Gamma(h \rightarrow \theta\theta) = \frac{1}{8\pi} \frac{\lambda_{h\theta\theta}^2}{m_h} \sqrt{1 - 4 \frac{m_\theta^2}{m_h^2}}$$

$$\lambda_{h_1\theta\theta} = \frac{v_h}{2\Lambda^2} \left[ (v_h^2 \delta_2 + v_\sigma^2 \delta_4 + \Lambda^2 \lambda_{\sigma h}) \cos \alpha_h + v_h v_\sigma \delta_4 \sin \alpha_h \right]$$

# Solve for $\lambda_{\sigma h}$ , $\lambda_{\sigma}$ , $\lambda_h$ , $\delta_4$

$$\lambda_{\sigma h} = \frac{1}{4v_h^2 v_\sigma \Lambda^2} \left\{ (M_{hh}^2 - M_{\sigma\sigma}^2) (2v_h \sin(2\alpha_h) + v_\sigma) \Lambda^2 \sec(2\alpha_h) - 4v_h^4 v_\sigma \delta_2 \right. \\ \left. + \left[ (M_{hh}^2 - M_{\sigma\sigma}^2) \Lambda^2 \sec(2\alpha_h) \sin(3\alpha_h) - 4v_h^3 v_\sigma A(\text{Br}) \right] v_\sigma \csc \alpha_h \right\},$$

$$\lambda_{\sigma} = - \frac{v_h + v_\sigma \cot \alpha_h}{4v_\sigma^2 \Lambda^2 (v_\sigma \cos \alpha_h + v_h \sin \alpha_h)} \left\{ 2v_h^3 v_\sigma A(\text{Br}) + \left[ 6v_\sigma^4 \delta_6 - (M_{hh}^2 + M_{\sigma\sigma}^2) \Lambda^2 \right. \right. \\ \left. \left. + (M_{\sigma\sigma}^2 - M_{hh}^2) \Lambda^2 \sec(2\alpha_h) \right] \sin \alpha_h \right\},$$

$$\lambda_h = \frac{1}{2} \left( \frac{M_{hh}^2}{v_h^2} - \frac{v_\sigma^2 \delta_2}{\Lambda^2} \right),$$

$$\delta_4 = \frac{A(\text{Br}) v_h^3 v_\sigma \csc \alpha_h + (M_{\sigma\sigma}^2 - M_{hh}^2) \Lambda^2 \cos(\alpha_h)^2 \sec(2\alpha_h)}{v_h^2 v_\sigma^2},$$

$$A(\text{Br}) = \pm 4\sqrt{2\pi} \left( 1 - 4\frac{m_\theta^2}{m_h^2} \right) m_h^{3/2} \frac{\Lambda^2}{v_h^3} \sqrt{\frac{\text{Br}(h \rightarrow \theta\theta) \Gamma(h \rightarrow \text{SM})}{[1 - \text{Br}(h \rightarrow \theta\theta)] (m_h^2 - 4m_\theta^2)}}.$$



# Neutrino masses — inverse seesaw

$$\mathcal{L}_\nu = y_\nu^{ij} \bar{L}_i \tilde{H} \nu_{Rj}^c + y_\sigma^{ij} S_i S_j \sigma + \Lambda^{ij} \nu_{Ri}^c S_j + \text{h.c.},$$

$$M_\nu = \begin{pmatrix} 0 & \frac{v_h}{\sqrt{2}} \mathbf{y}_\nu & 0 \\ \frac{v_h}{\sqrt{2}} \mathbf{y}_\nu & 0 & \Lambda \\ 0 & \Lambda & \frac{v_\sigma}{\sqrt{2}} \mathbf{y}_\sigma \end{pmatrix}$$

$$m_\nu \approx \frac{v_h^2 v_\sigma}{2\sqrt{2}} \mathbf{y}_\nu^\top \Lambda^{\top -1} \mathbf{y}_\sigma \Lambda^{-1} \mathbf{y}_\nu$$

**3 light active neutrinos**

$$m_{N\pm} \approx \Lambda \pm \frac{v_\sigma}{2\sqrt{2}} \mathbf{y}_\sigma$$

**6 heavy neutrinos**

Use normal ordering masses as input to obtain

$$y_\sigma^i = 2\sqrt{2} \frac{m_{\nu_i} \Lambda^2}{v_h^2 v_\sigma y_{\nu_i}^2}$$

# Thermal effective potential

$$V_{\text{eff}}(T) = V_0 + V_{\text{CW}}^{(1)} + \Delta V(T) + V_{\text{ct}}$$

$$V_{\text{CW}}^{(1)} = \sum_i (-1)^{F_i} n_i \frac{m_i^4(\phi_\alpha)}{64\pi^2} \left( \log \left[ \frac{m_i^2(\phi_\alpha)}{Q^2} \right] - c_i \right)$$

$$\Delta V(T) = \frac{T^4}{2\pi^2} \left\{ \sum_b n_b J_B \left[ \frac{m_b^2(\phi_\alpha)}{T^2} \right] - \sum_f n_f J_F \left[ \frac{m_f^2(\phi_\alpha)}{T^2} \right] \right\}$$

$$n_s = 6, \quad n_{A_L} = 1$$

$$n_W = 6, \quad n_Z = 3, \quad n_\gamma = 2$$

$$n_{u,d,c,s,t,b} = 12, \quad n_{e,\mu,\tau} = 4, \quad n_{\nu_{1,2,3}} = n_{N_{1,2,3}^\pm} = 2$$

$$J_{B/F}(y^2) = \int_0^\infty dx x^2 \log \left( 1 \mp \exp[-\sqrt{x^2 + y^2}] \right).$$

$$\left\langle \frac{\partial V_{\text{ct}}}{\partial \phi_\alpha} \right\rangle = \left\langle -\frac{\partial V_{\text{CW}}^{(1)}}{\partial \phi_\alpha} \right\rangle \quad \left\langle \frac{\partial^2 V_{\text{ct}}}{\partial \phi_\alpha \partial \phi_\beta} \right\rangle = \left\langle -\frac{\partial^2 V_{\text{CW}}^{(1)}}{\partial \phi_\alpha \partial \phi_\beta} \right\rangle$$

Counterterms are fixed such that the  
 → T=0 minimum conditions and physical masses are preserved at 1-loop

# Thermal mass resummation

At high-T thermal 1-loop effects overpower the tree-level T=0 potential

Breaks down fixed-order perturbation theory and large T/m ratios must be resummed

Done by introducing Daisy corrections in the effective potential

$$m_i^2 \rightarrow m_i^2 + c_i T^2$$

$$m_i^2 \rightarrow m_i^2 + c_i T^2$$

$$c_h = \frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{2}\lambda_h + \frac{1}{12}\lambda_{\sigma h} + \frac{1}{4}(y_t^2 + y_b^2 + y_c^2 + y_s^2 + y_u^2 + y_d^2) + \frac{1}{12}(y_\tau^2 + y_\mu^2 + y_e^2) + \frac{1}{24}K_\nu + K_\Lambda^h,$$

$$c_\sigma = \frac{1}{3}\lambda_\sigma + \frac{1}{6}\lambda_{\sigma h} + \frac{1}{24}K_\sigma + K_\Lambda^\sigma,$$

$$K_\nu = \sum_{i=1}^3 y_{\nu_i}^{\text{eff}} \quad \text{with} \quad y_{\nu_i}^{\text{eff}} = \frac{\phi_h \phi_\sigma}{2} \frac{y_{\nu_i}^2 y_{\sigma_i}}{\Lambda^2} \quad \text{and} \quad m_{\nu_i}(\phi_h) = \frac{\phi_h}{\sqrt{2}} y_{\nu_i}^{\text{eff}}$$

$$K_\sigma = \sum_{i=1}^3 y_{\sigma_i}^2 \quad K_\Lambda^h = \frac{\phi_h^2 + \phi_\sigma^2}{4\Lambda^2} \delta_2 + \frac{\phi_\sigma^2}{6\Lambda^2} \delta_4 \quad K_\Lambda^\sigma = \frac{\phi_h^2}{4\Lambda^2} \delta_2 + \frac{\phi_h^2}{6\Lambda^2} \delta_4 + \frac{\phi_\sigma^2}{2\Lambda^2} \delta_4 + \frac{9\phi_\sigma^2}{4\Lambda^2} \delta_6.$$

And for gauge bosons...

$$M_{\text{gauge}}^2(\phi_h; T) = M_{\text{gauge}}^2(\phi_h) + \frac{11}{6}T^2 \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & 0 \\ 0 & 0 & 0 & g'^2 \end{pmatrix}$$

$$m_{W_L}^2(\phi_h; T) = m_W^2(\phi_h) + \frac{11}{6}g^2T^2,$$

$$m_{Z_L, A_L}^2(\phi_h; T) = \frac{1}{2}m_Z^2(\phi_h) + \frac{11}{12}(g^2 + g'^2)T^2 \pm \mathcal{D},$$

$$\mathcal{D}^2 = \left( \frac{1}{2}m_Z^2(\phi_h) + \frac{11}{12}(g^2 + g'^2)T^2 \right)^2 - \frac{11}{12}g^2g'^2T^2 \left( \phi_h^2 + \frac{11}{3}T^2 \right)$$

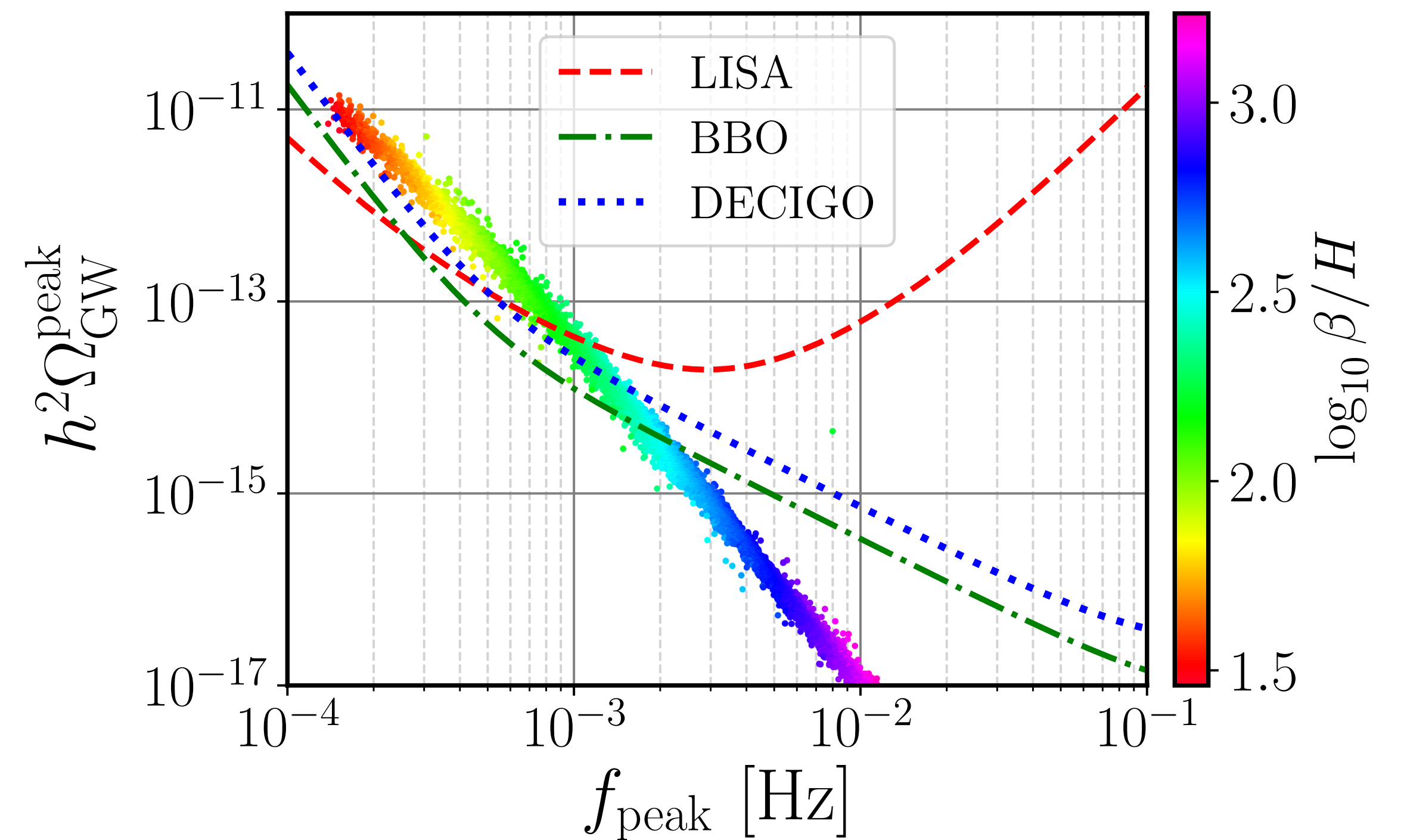
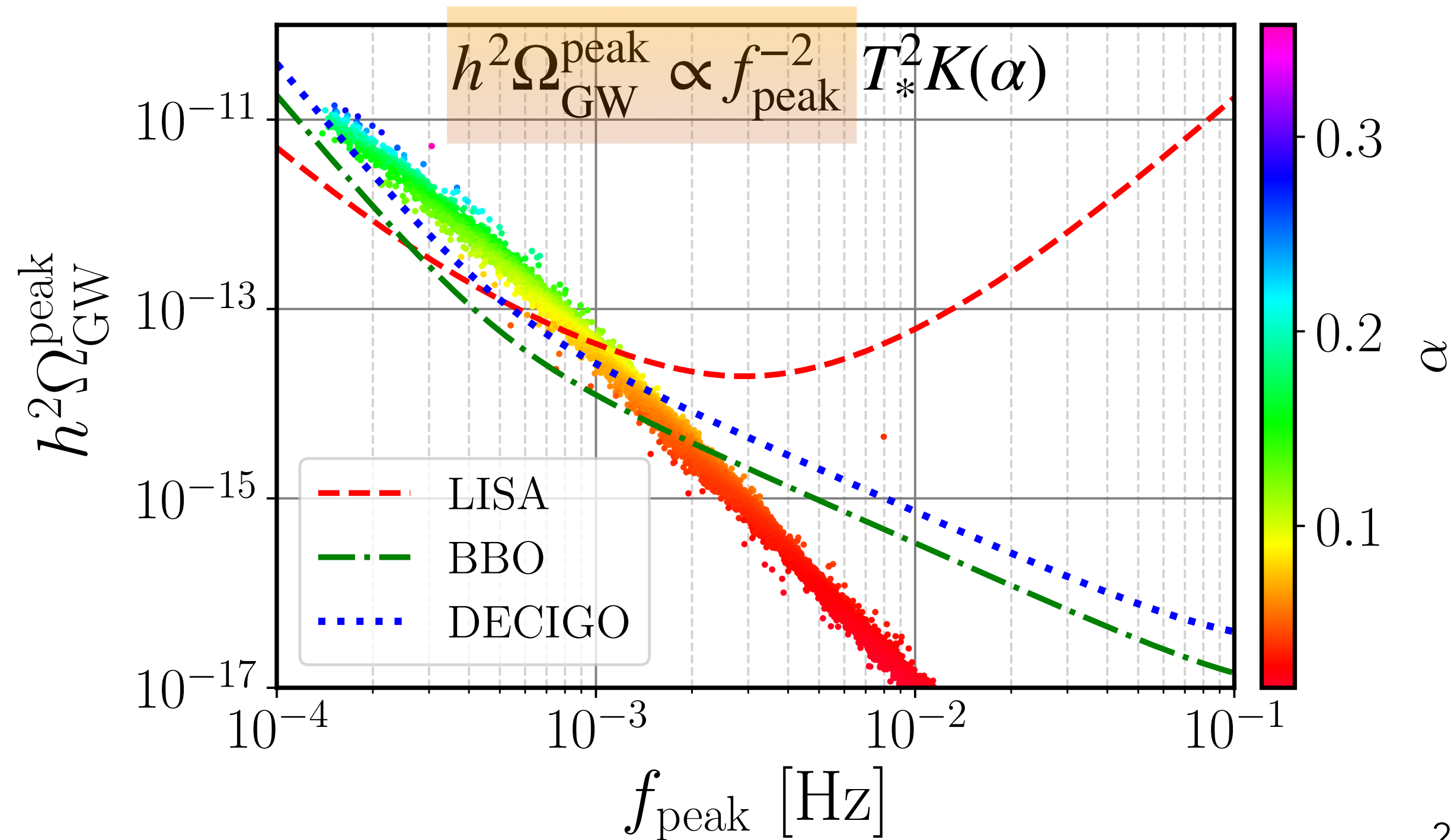
# Results

$$m_{h_2} : [60, 1000] \text{ GeV} \quad m_\theta : [10^{-10}, 10^6] \text{ eV} \quad \Lambda : [10, 1000] \text{ TeV} \quad v_\sigma : [100, 1000] \text{ GeV}$$

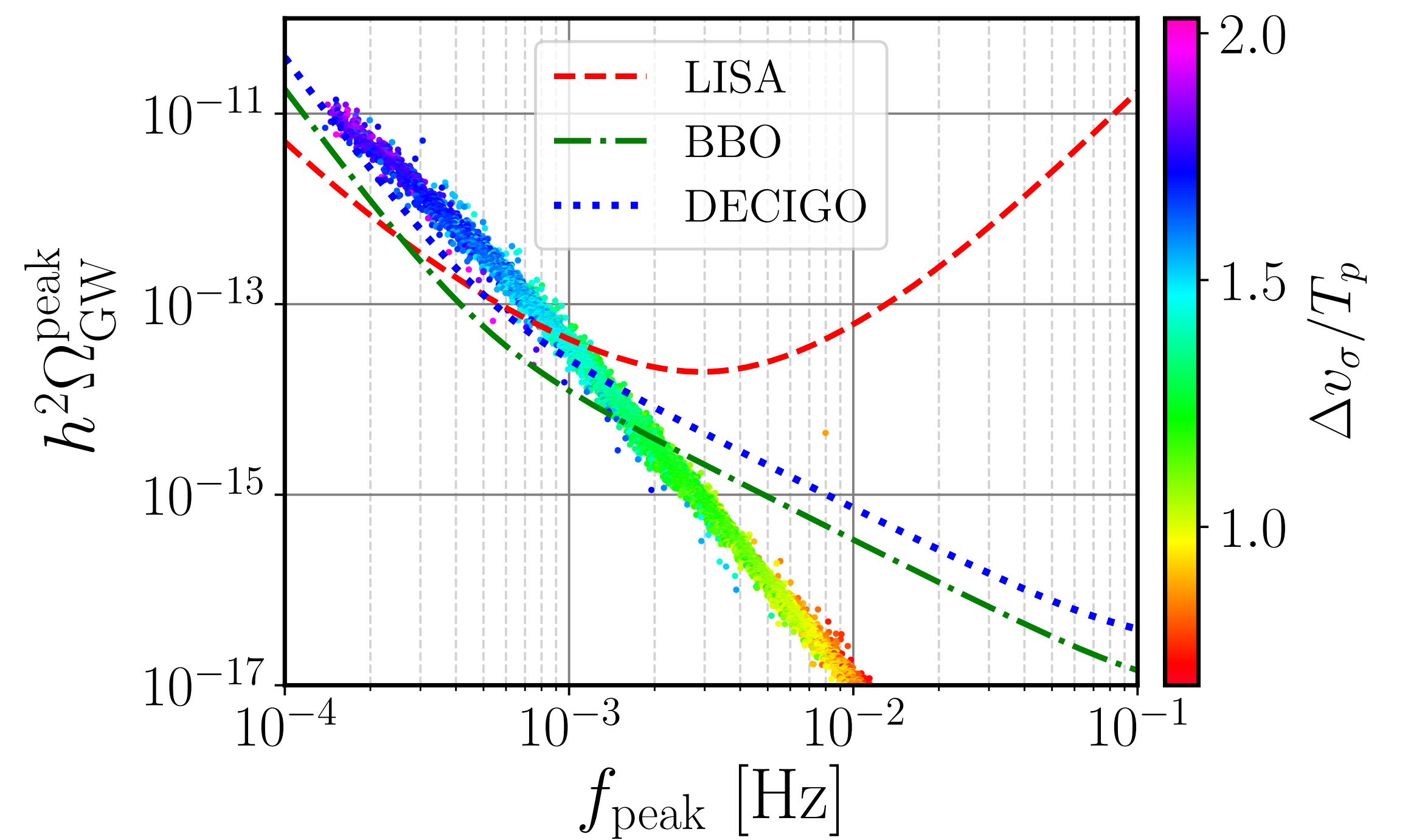
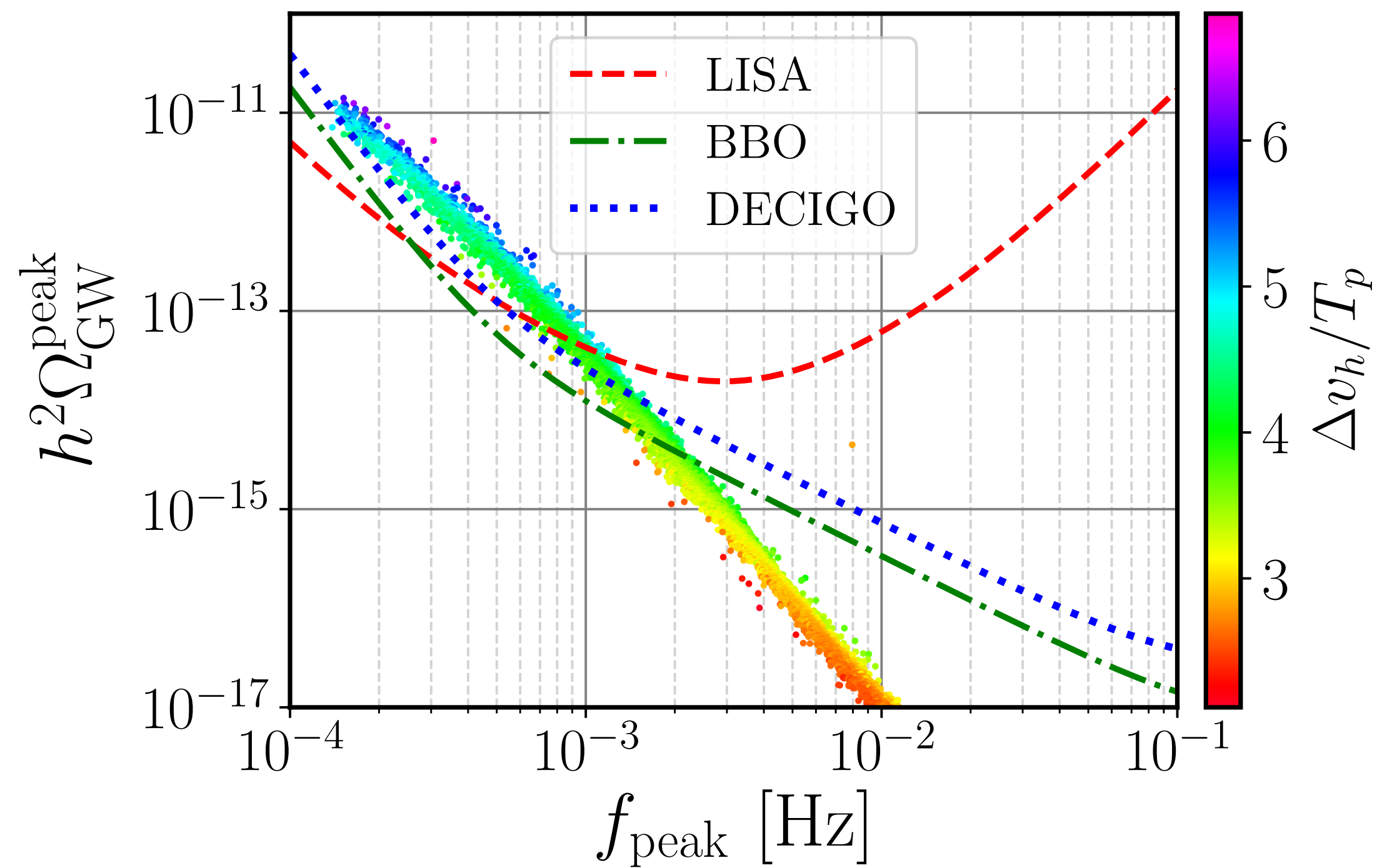
$$\cos \alpha_h : [0.85, 1] \quad \text{Br}(h_1 \rightarrow \theta\theta) : [10^{-15}, 0.19] \quad \delta_{2,6} : [10^{-2}, \Lambda^2/v_\sigma^2]$$

## Scan using *CosmoTransitions*

[Comp. Phys. Commun. 183, 2006 (2012)]



$$\Delta v_\phi = |v_\phi^f - v_\phi^i|, \quad \phi = h, \sigma$$



**Both order parameters must be large for observable signals**

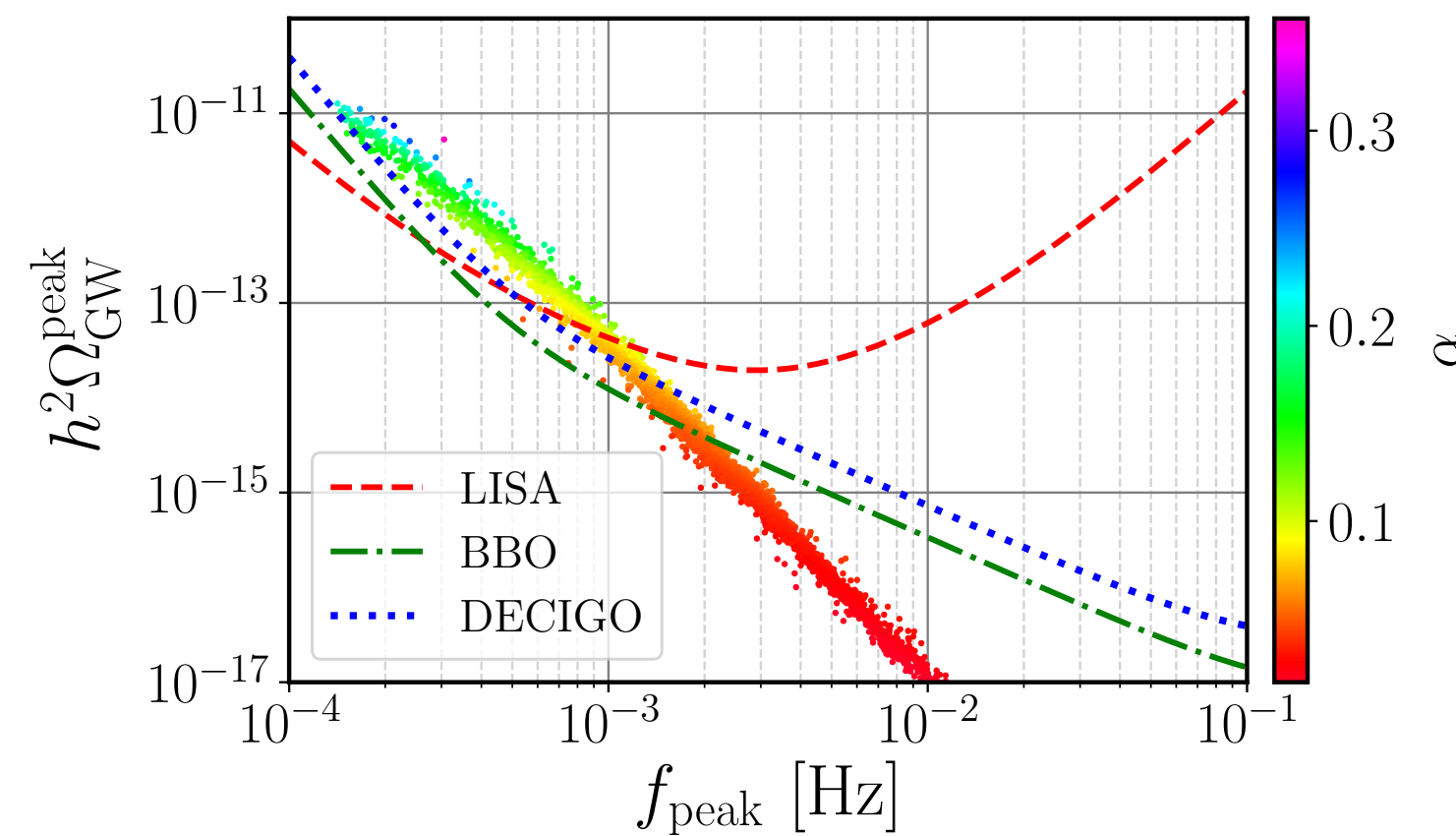
# When $m_\theta > 2 m_\nu$ the Majoron can decay $\theta \rightarrow \nu\nu$

[JCAP 09 (2019) 029; Phys.Rev.D 96 (2017) 3-035018; JCAP 04 (2018) 006; Phys.Rev.X 1 (2011) 021026; ... ]

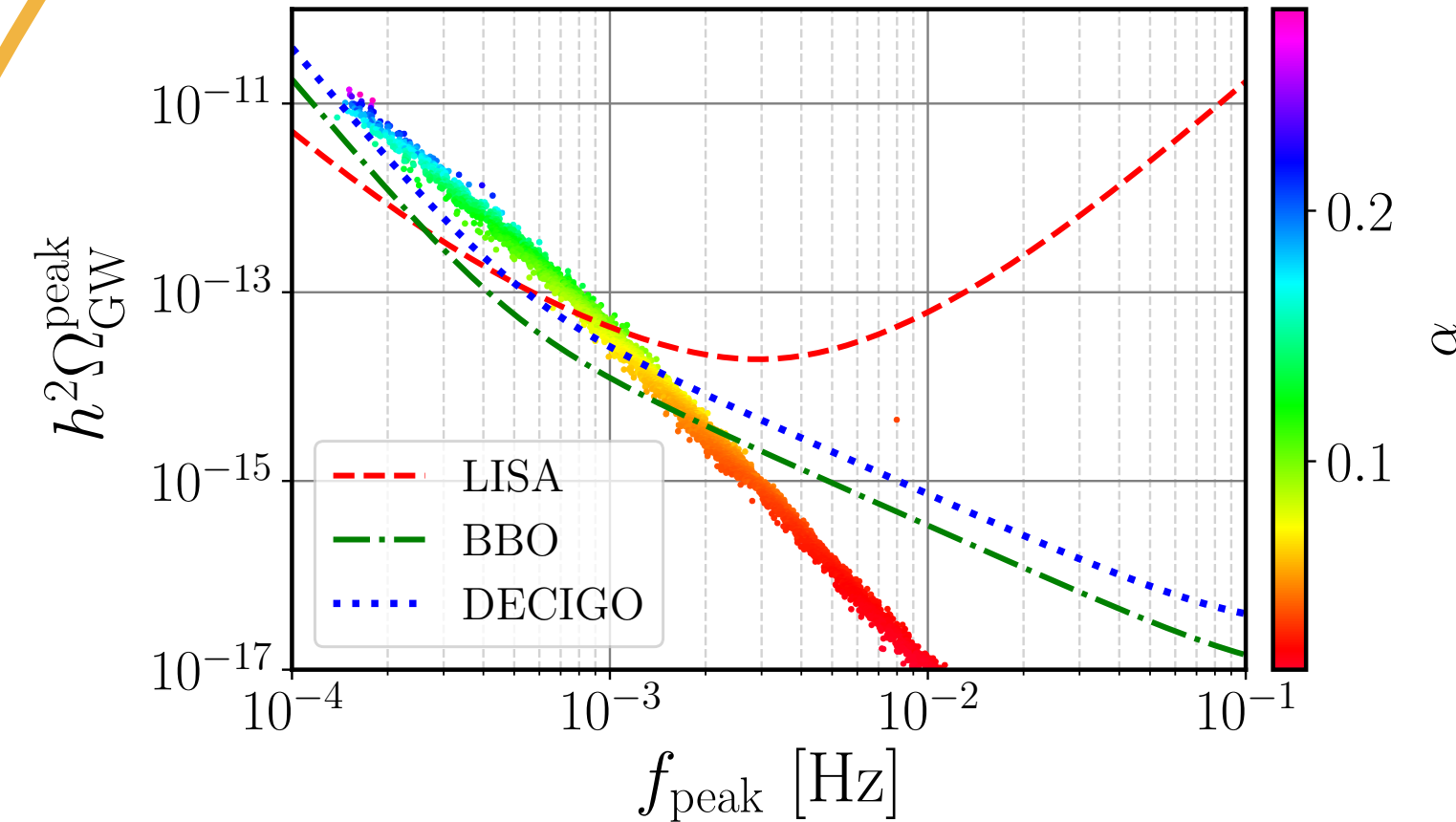
$$\Gamma(\theta \rightarrow \nu\nu) = \frac{m_\theta}{16\pi} \sum_i \frac{m_i^2}{v_\sigma^2} < 1.9 \times 10^{-19} s^{-1} @ 95 \% \text{ C.L.}$$

[New J.Phys. 16 (2014) 12, 125012 (Planck 2013, WMAP, WiggleZ, BOSS) ]

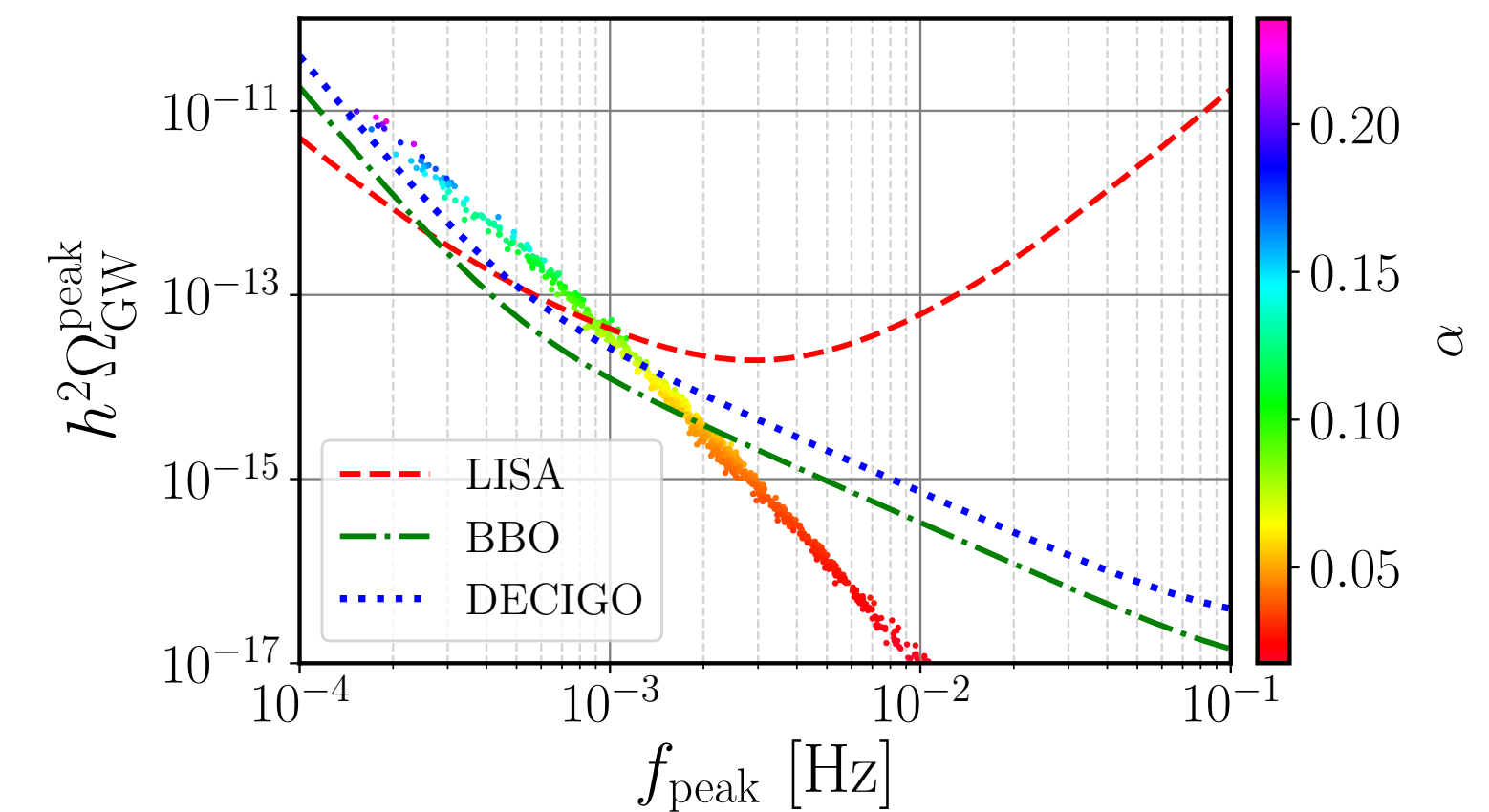
## Short-lived



## Long-lived (viable DM?)



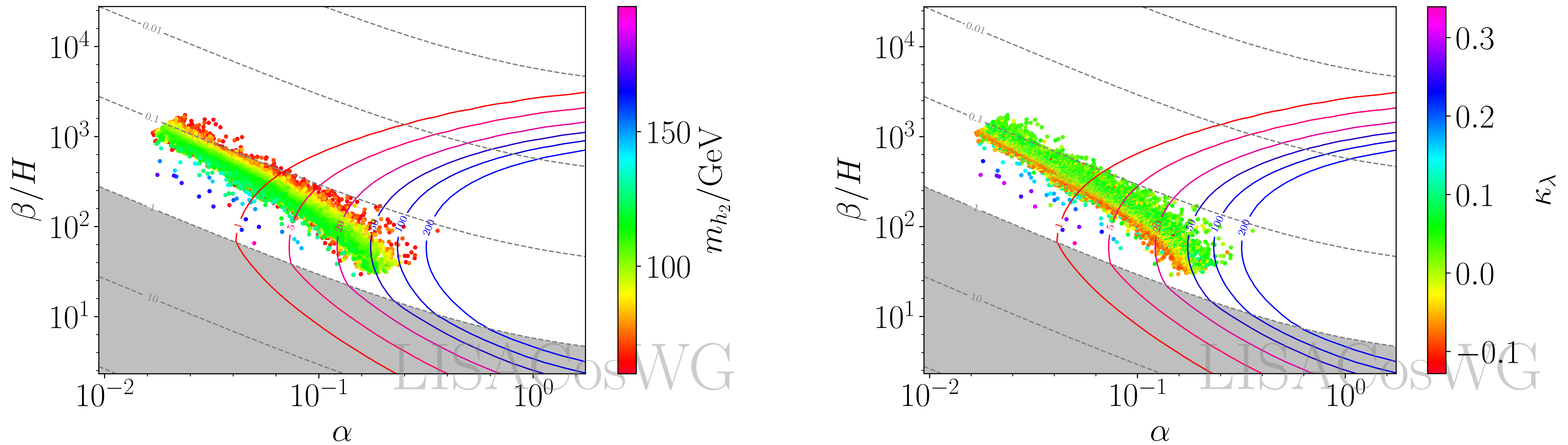
## Stable (viable DM?)



**Majorons decaying today can leave observable peaks in electron spectra induced by relic neutrinos capture: PTOLEMY [JCAP 03 (2021) 089 ]**

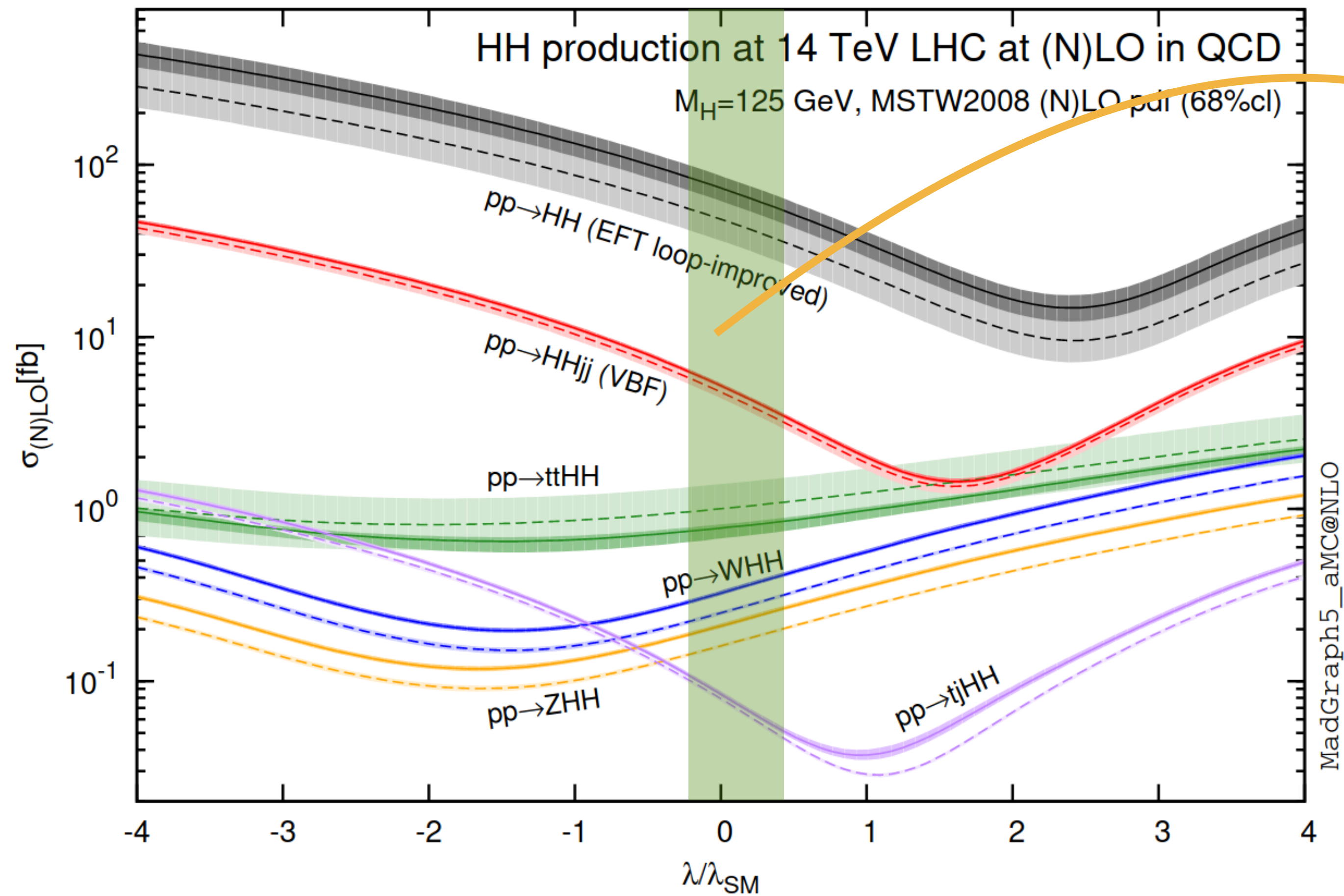


# New Higgs mass, triple Higgs coupling and GW SNR for LISA



Used PTPlot for SNR [JCAP 2003 (2020) 024 ]

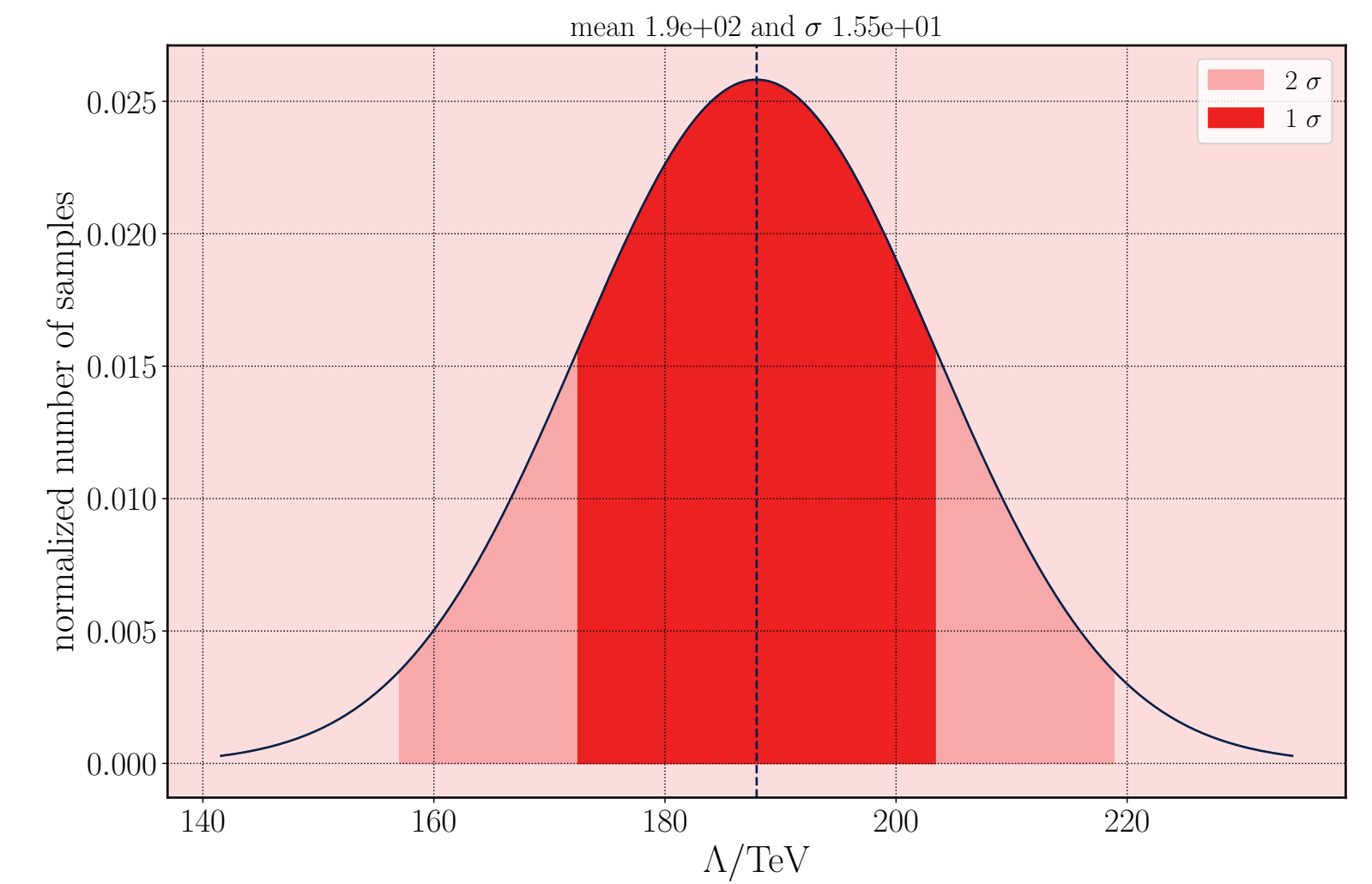
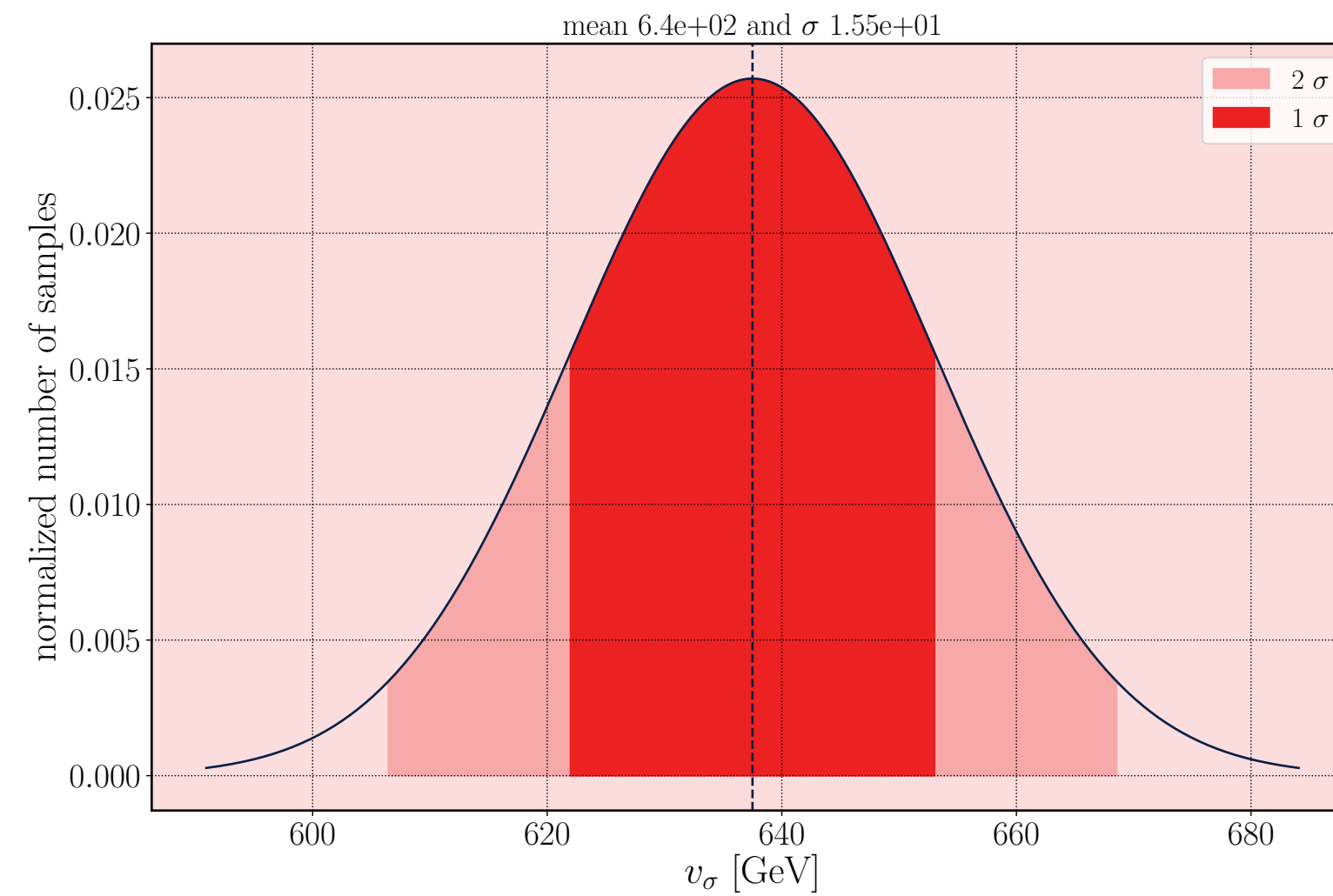
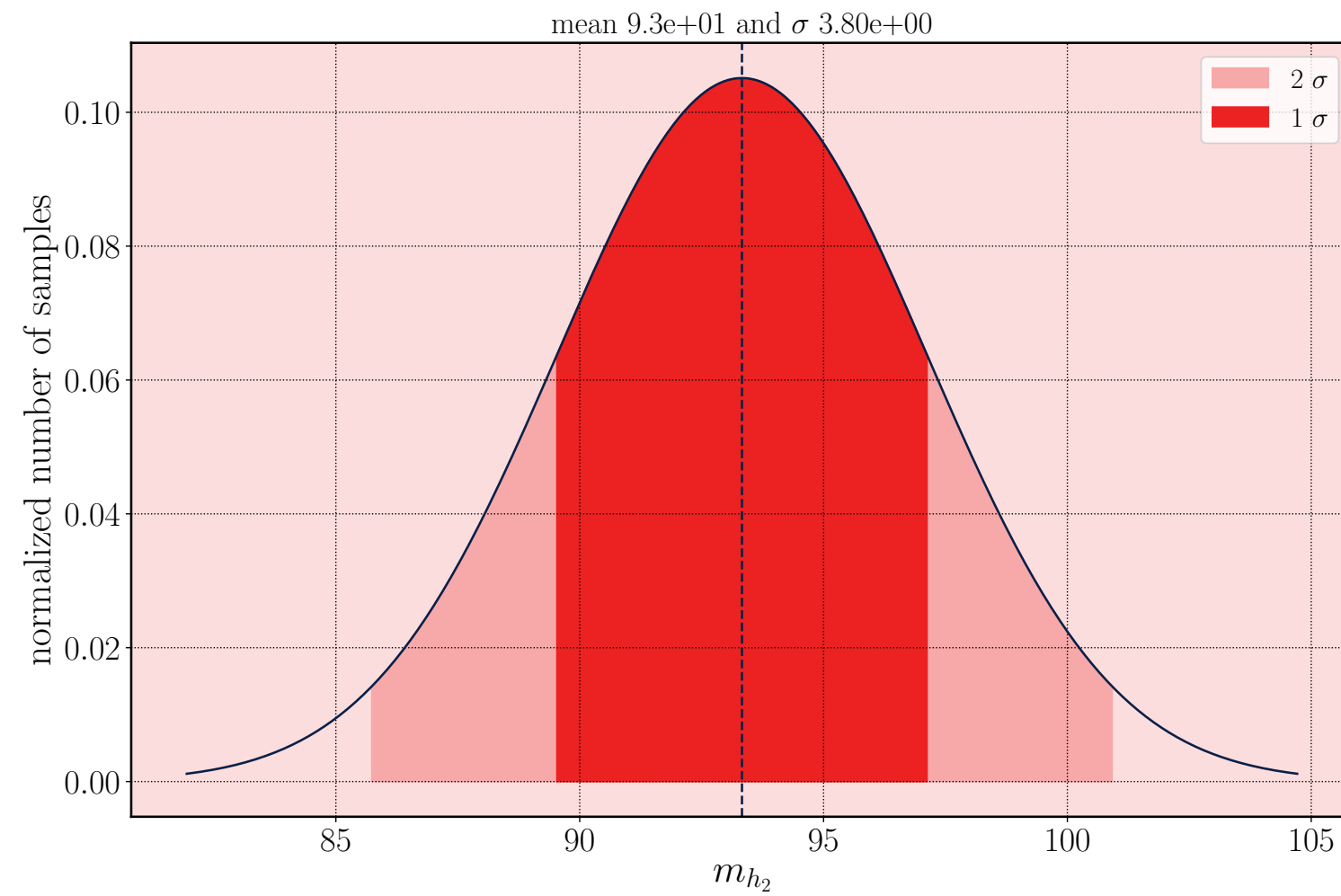
- Strongly favours light  $h_2$  with mass 80 - 120 GeV (CMS 95 GeV di-photon and di-tau excesses?)
- $\kappa_\lambda \equiv \lambda_{h_1 h_1 h_1} / \lambda_{\text{SM}} < 1$



Region compatible with observable SFOPTs in the 6D Majoron model with enhancement of Xsec

Phys.Lett.B 732 (2014) 142-149

# Gaussian fit to all generated data for observable SFOPTs



$$m_{h_2} = 93 \pm 3.8 \text{ GeV}$$

$$v_{\sigma} = 640 \pm 15.5 \text{ GeV}$$

$$\Lambda = 190 \pm 15.5 \text{ TeV}$$

**Hints for new physics (or model constraints) from an hypothetical observation of GWs at LISA**

# Conclusions

- SFOPTs and a light/dark(?) Majoron are compatible in the 6D model
- Several points with  $\text{SNR} > 10$  @ LISA
- Suppression of triple Higgs coupling with HH prod. Xsec enhancement
- New Higgs boson lighter than 100 GeV (CMS excess?)
- Heavy neutrinos at 100 TeV scale ( relevant for FCC physics?)
- For decaying Majorons potential physics case to PTOLEMY
- **Possibility to probe the model in multiple physics channels**



THANK YOU