GRAVITATIONAL RELICS OF A (DARK ?) MAJORON

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MULTI-HIGGS 2022 - IST

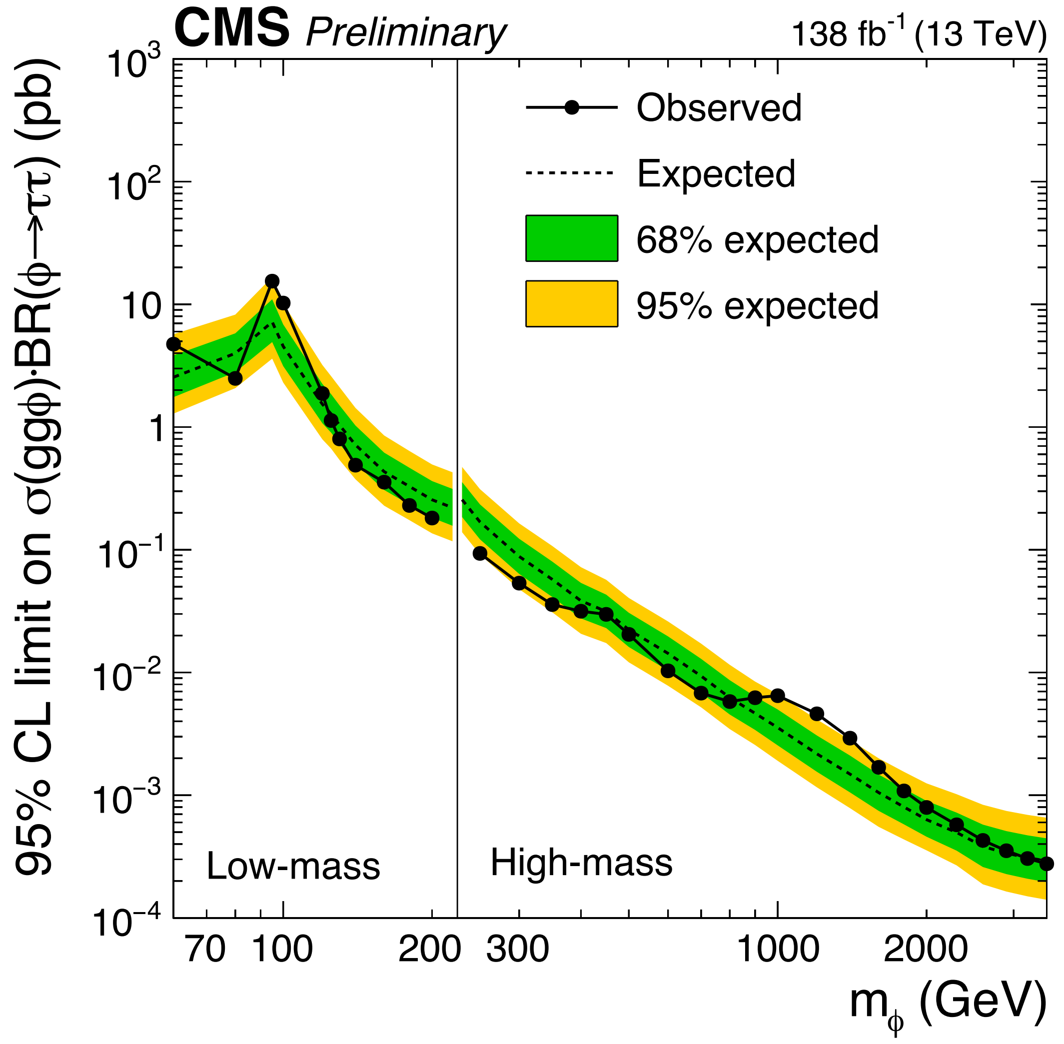
CENTRO 2020 PORTUGAL 2020 UNIÃO EUROPEIA Fundos Europeus Estruturais e de Investimento universidade de aveiro CIDMA CENTRO DE I&D EM MATEMÁTICA E APLICAÇÕES CENTER FOR R&D IN MATHEMATICS AND APPLICATIONS

The SM is a tremendously successful theory that explains "boringly" well all its predictions!

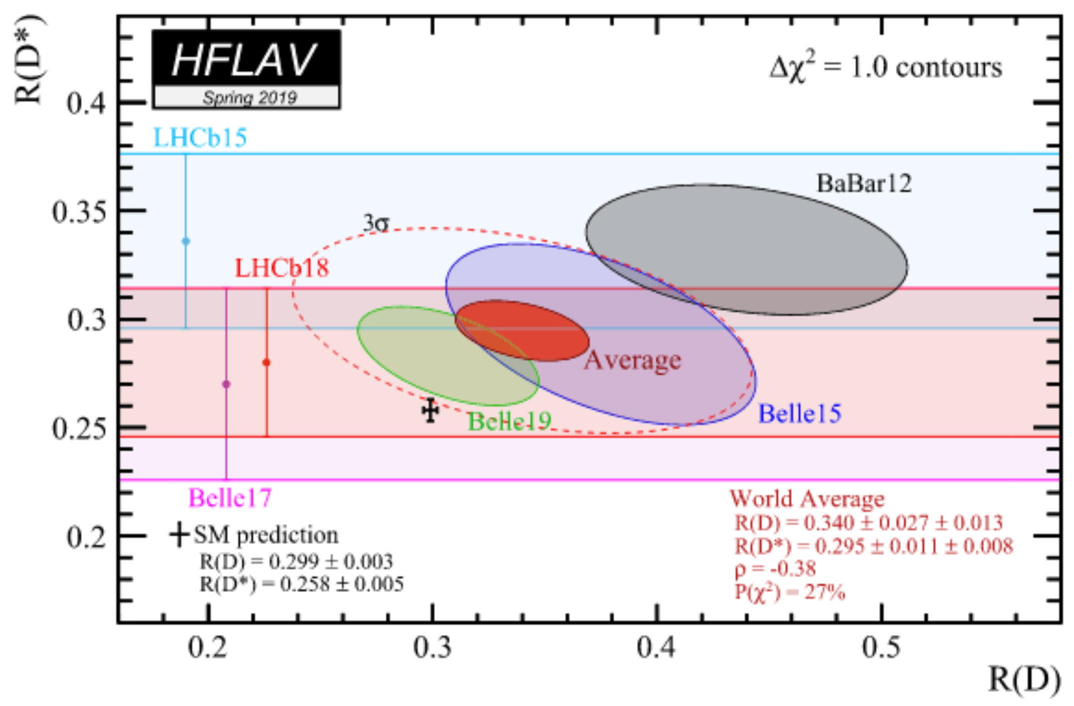
However, it fails to...

- Explain neutrino masses
- Explain dark matter
- Explain CP violino and matter/anti-matter assymetry
- Explain the observed flavour structure

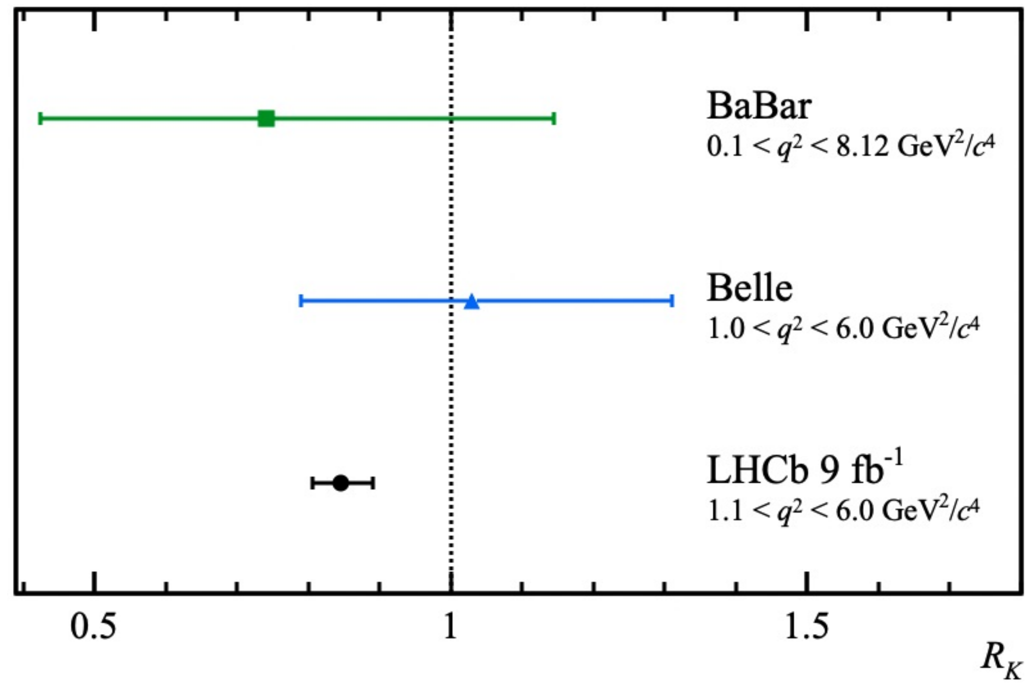
And it is in tension with a number of emergent anomalies and excesses



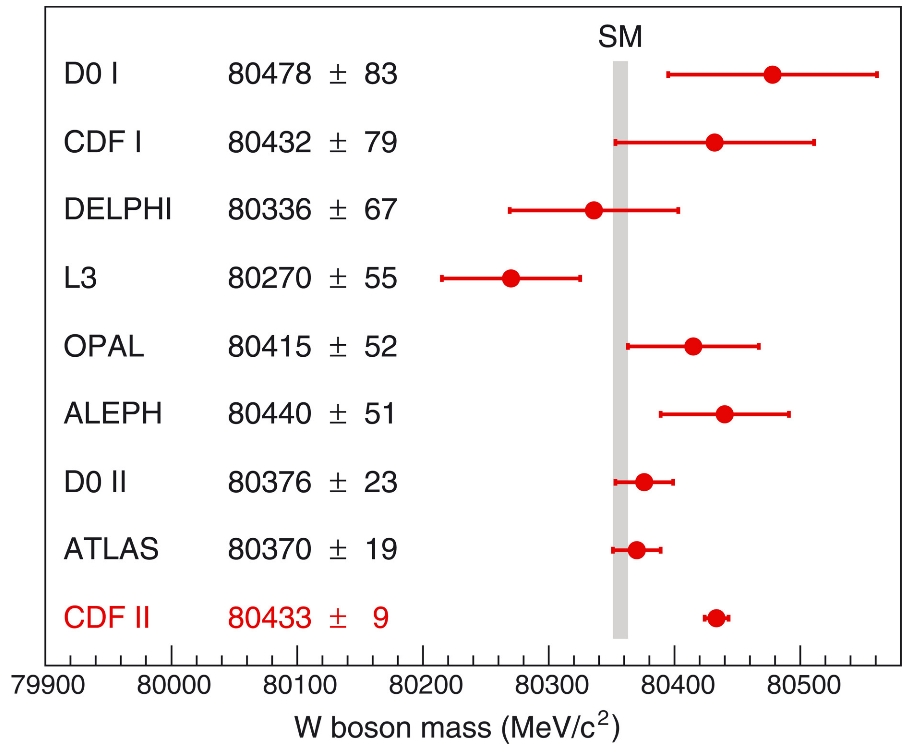
[CMS-PAS-HIG-21-001]



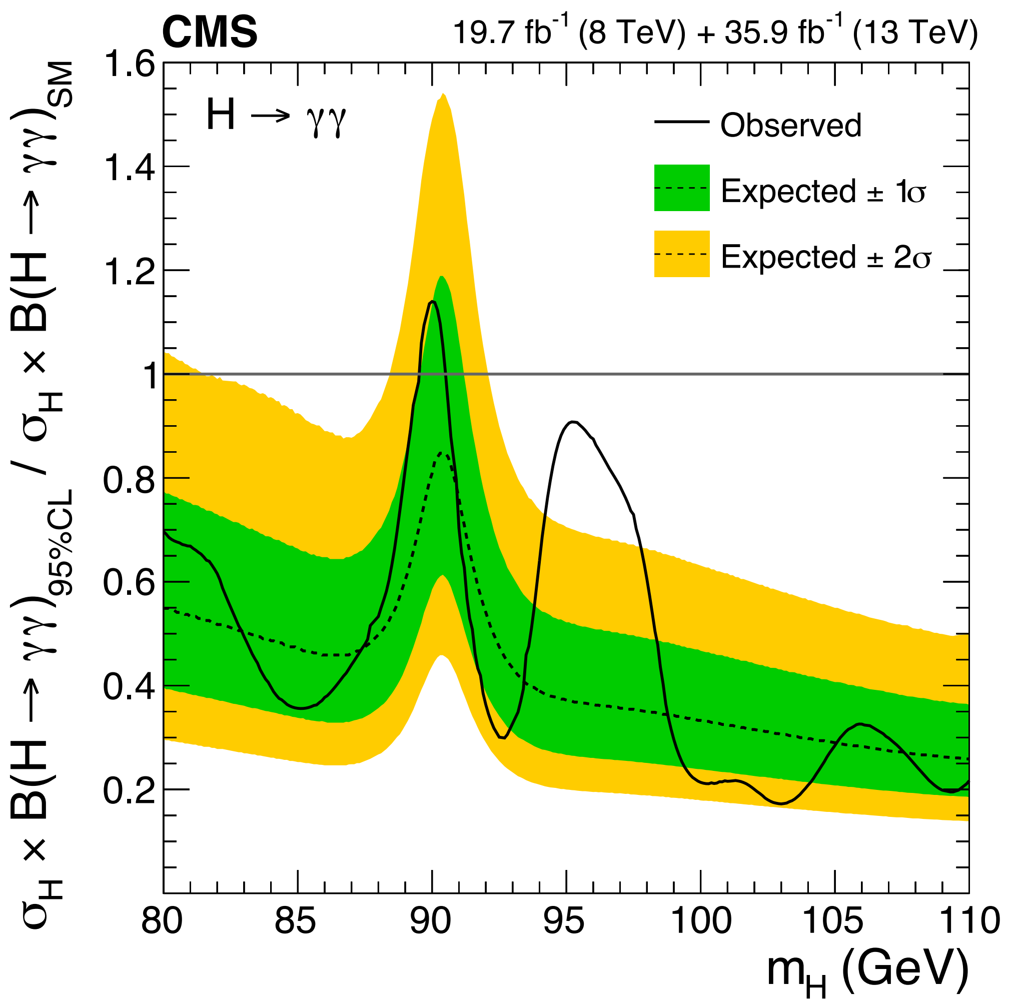
[Eur. Phys. J. C 81, 226 (2021)]



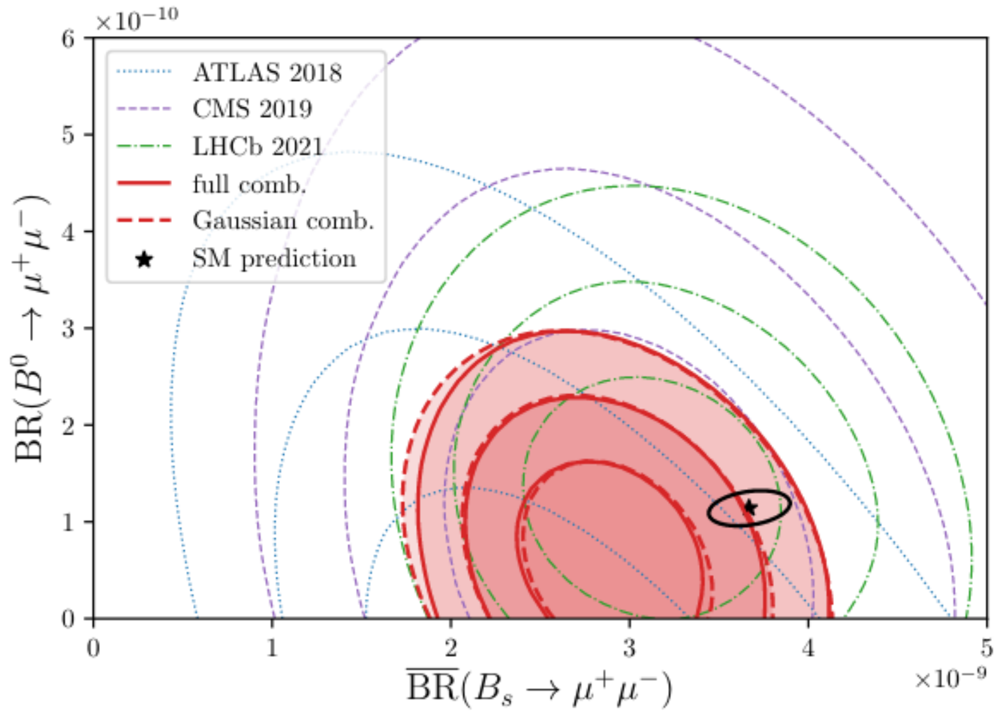
[Nature Phys. 18, 277 (2022)]



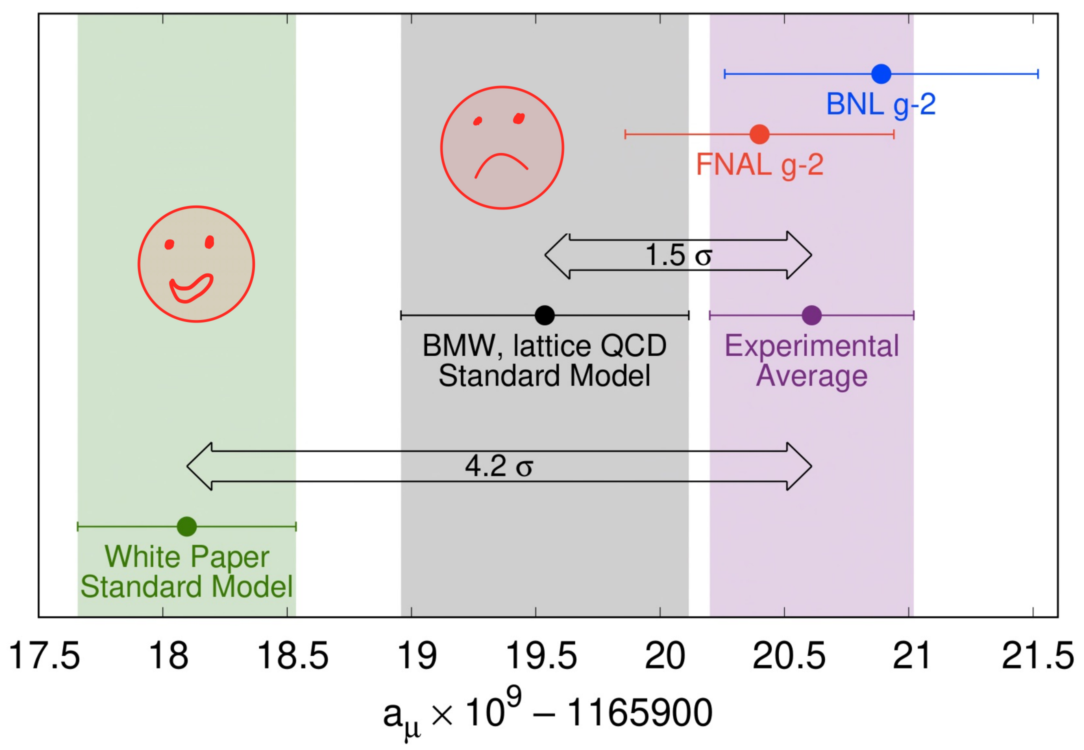
[Science 376, n6589, 170-176 (2022)]



[Phys. Lett. B793 (2019) 320]



[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 the vacuum structure.

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- Cosmological events

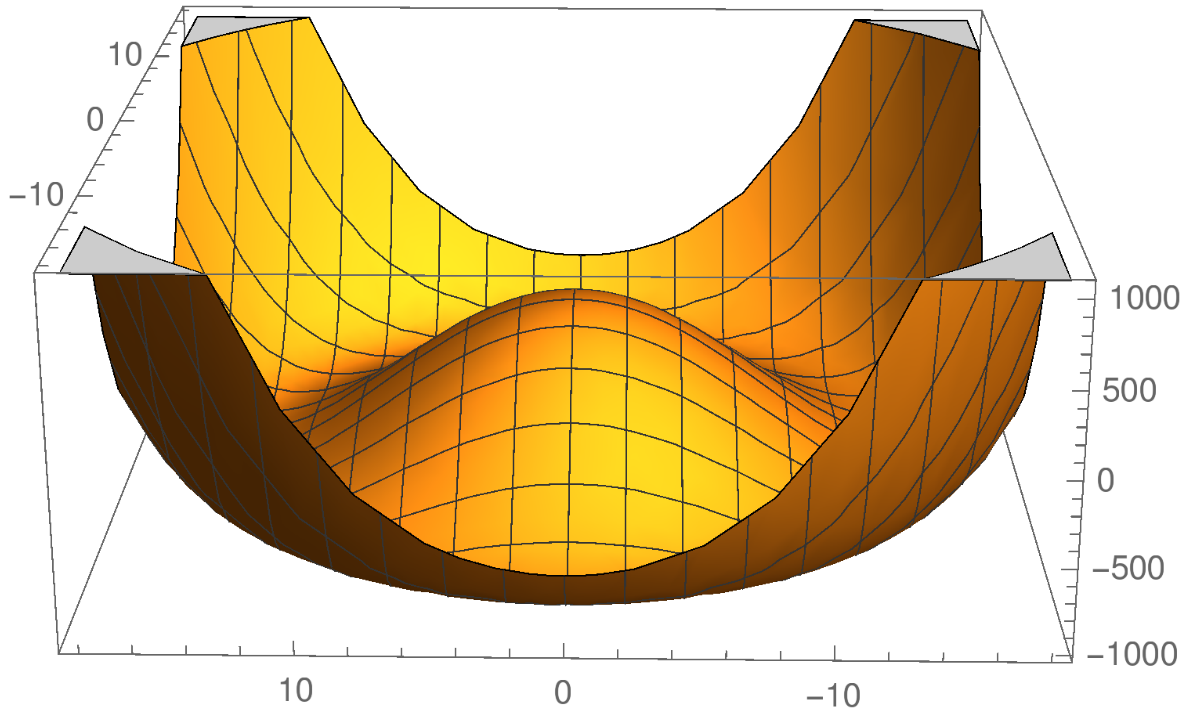
  (i) Inflation
  (ii) Cosmic strings
  (iii) **Strong cosmological phase transitions (PTs)** $\rightarrow$ by expanding vacuum bubbles of a broken phase in a universe filled with a symmetric phase

Basics of Strong First Order PTs (SFOPTs)

Consider a the scalar potential:

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

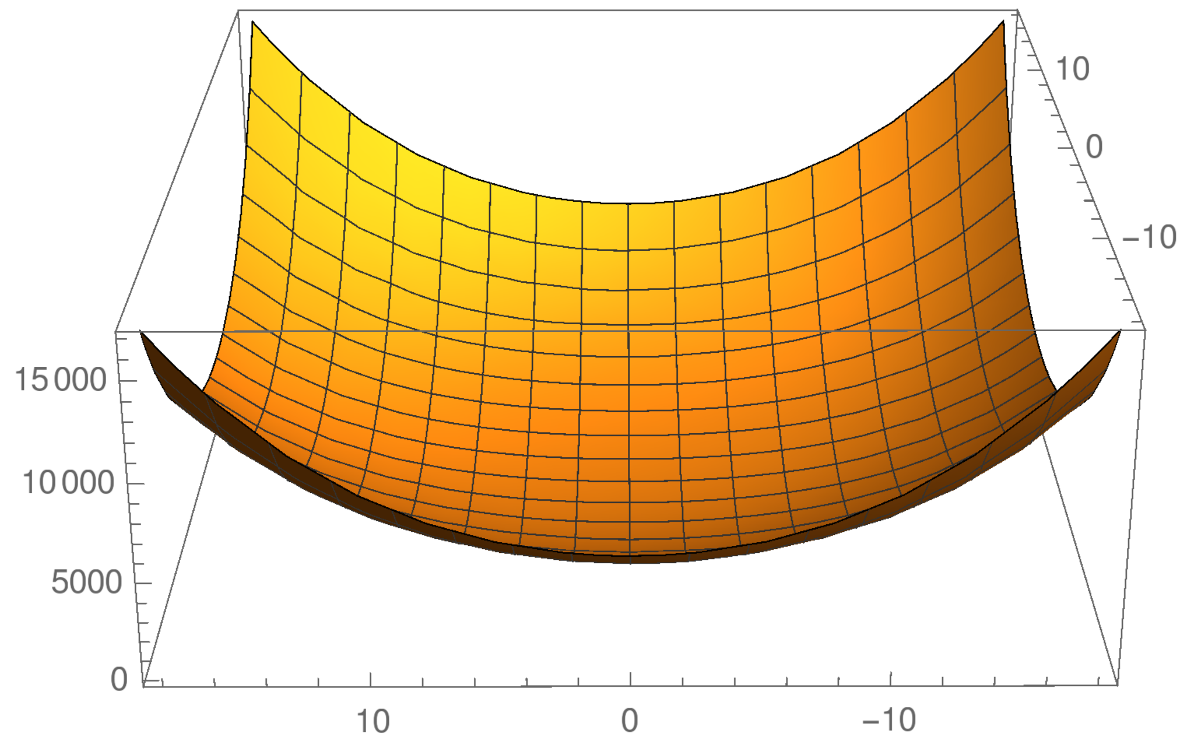
$$\mu^2 < 0 \text{ and } \lambda > 0$$



Add thermal corrections:

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

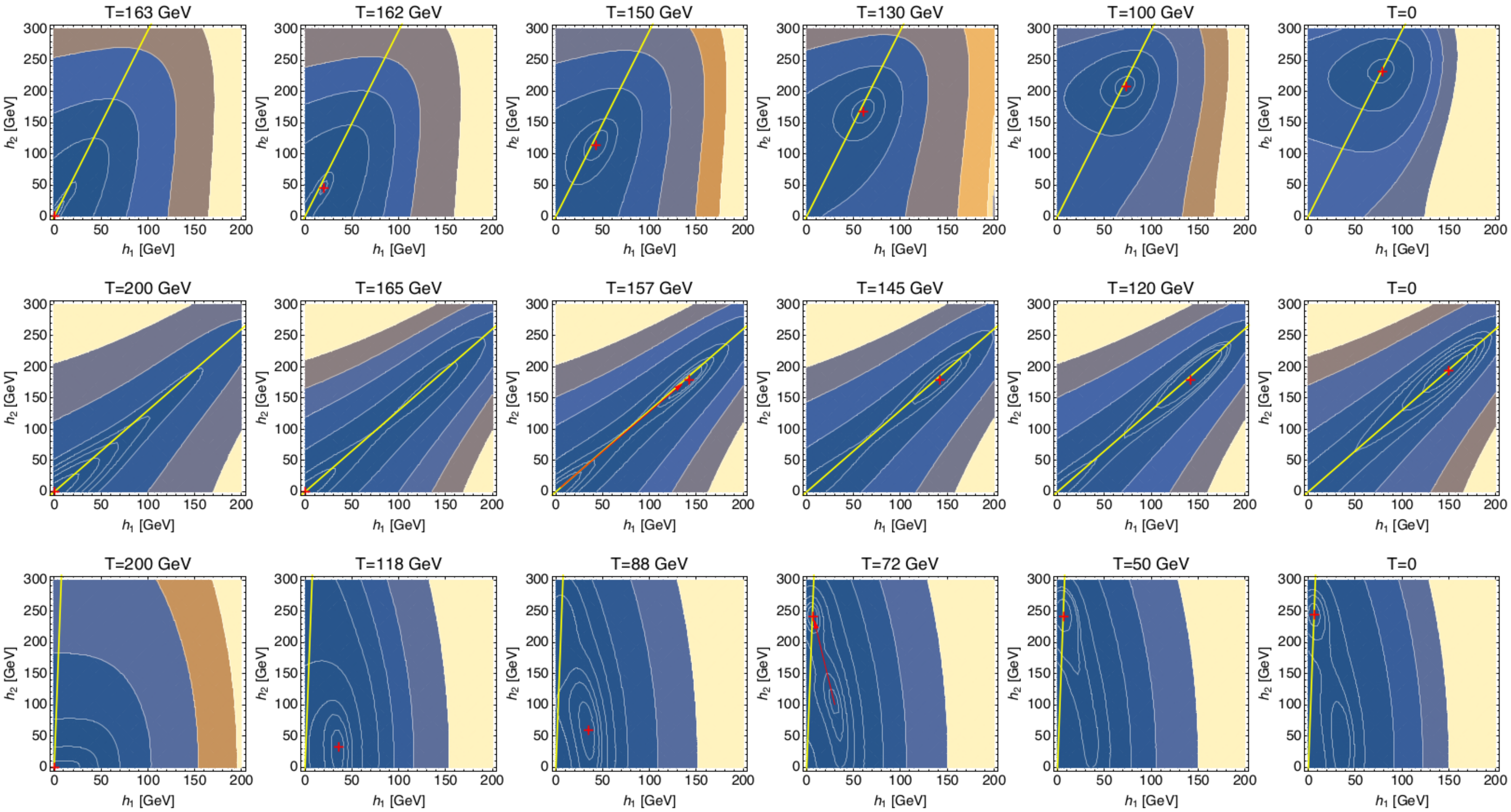
For $C_\phi > 0$, after a certain $T > 0$, $\mu_{eff} \equiv \mu^2 + C_\phi T^2 > 0$



Restored symmetry

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

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



JHEP 05 (2018) 151

1st Order PTs $\longrightarrow$ 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:

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

Euclidean action:

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

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

$$\alpha,\quad \beta/H,\quad T_* \longrightarrow$$

calculated from a certain BSM theory, used as inputs to obtain the GW power spectrum

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

Peak amplitude

Spectral function

$$h^2\Omega_{\rm GW}^{\rm peak}\left(\beta/H,\alpha\right)$$

$$f_{\rm peak}\left(\beta/H,T_*\right)$$

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	$\mathbf{2}$	$1/2$	0
σ	$\mathbf{1}$	0	2
$\nu^c_{\mathrm{R}\,i}$	$\mathbf{1}$	0	1
S_i	$\mathbf{1}$	0	-1

- In [Phys.Lett.B 807 (2020) 135577] we have shown that observable GWs require a heavy VISIBLE Majoron O(100 GeV - 1 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?

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

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

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

$$V_{\rm 6D}(H,\sigma) = \frac{\delta_2}{\Lambda^2}(H^\dagger H)^2\sigma^\dagger\sigma + \frac{\delta_4}{\Lambda^2}H^\dagger H(\sigma^\dagger\sigma)^2 + \frac{\delta_6}{\Lambda^2}(\sigma^\dagger\sigma)^3,$$

$$\frac{\delta_i}{\Lambda^2}v_\sigma^2 < 4\pi$$

$$V_{\rm soft}(\sigma) = \frac{1}{2}\mu_b^2\left(\sigma^2 + \sigma^{*2}\right)\,.$$

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

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

δ_2 and δ_4 allow co-existence of $\Gamma_{\rm Higgs}^{\rm invisible}$ and a false vacuum

Minimization

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

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

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

Scalar mass spectrum

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

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

$$\boldsymbol{m}^2 = {O^\dagger}_i{}^m M^2_{mn} {O^n}_j = \begin{pmatrix} m^2_{h_1} & 0 \\ 0 & m^2_{h_2} \end{pmatrix}, \quad \text{with} \quad \boldsymbol{O} = \begin{pmatrix} \cos\alpha_h & \sin\alpha_h \\ -\sin\alpha_h & \cos\alpha_h \end{pmatrix}, \quad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \boldsymbol{O} \begin{pmatrix} h \\ h' \end{pmatrix}.$$

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

Phenomenological inputs

Invisible Higgs decays limit : $\mathrm{Br}\left(h \to \theta\theta\right) < 0.19$ <u>Used as input</u>

[Phys. Lett. B 793 (2019) 520]

Scalar mixing angle limit: $\cos\alpha_h > 0.85$ <u>Used as input</u>

[New J. Phys. 18(3), 033033 (2016)]

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

$$\mathrm{Br}(h \to \theta\theta) = \frac{\Gamma\left(h \to \theta\theta\right)}{\Gamma\left(h \to \theta\theta\right) + \Gamma\left(h \to \mathrm{SM}\right)} \qquad \Gamma\left(h \to \theta\theta\right) = \frac{1}{8\pi}\frac{\lambda_{h\theta\theta}^2}{m_h}\sqrt{1 - 4\frac{m_\theta^2}{m_h^2}}\,.$$

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

Solve for $\lambda_{\sigma h}$, λ_σ, λ_h, δ_4

$$\lambda_{\sigma h} = \frac{1}{4v_h^2 v_\sigma \Lambda^2}\Big\{\left(M_{hh}^2 - M_{\sigma\sigma}^2\right)\left(2v_h \sin(2\alpha_h) + v_\sigma\right)\Lambda^2 \sec(2\alpha_h) - 4v_h^4 v_\sigma \delta_2$$
$$+ \left[\left(M_{hh}^2 - M_{\sigma\sigma}^2\right)\Lambda^2 \sec(2\alpha_h)\sin(3\alpha_h) - 4v_h^3 v_\sigma A(\mathrm{Br})\right] v_\sigma \csc\alpha_h\Big\}\ ,$$
$$\lambda_\sigma = -\frac{v_h + v_\sigma \cot\alpha_h}{4v_\sigma^2\Lambda^2(v_\sigma\cos\alpha_h + v_h \sin\alpha_h)}\Big\{2v_h^3 v_\sigma A(\mathrm{Br}) + \Big[6v_\sigma^4\delta_6 - \left(M_{hh}^2 + M_{\sigma\sigma}^2\right)\Lambda^2$$
$$+ \left(M_{\sigma\sigma}^2 - M_{hh}^2\right)\Lambda^2\sec(2\alpha_h)\Big]\sin\alpha_h\Big\}\ ,$$
$$\lambda_h = \frac{1}{2}\left(\frac{M_{hh}^2}{v_h^2} - \frac{v_\sigma^2\delta_2}{\Lambda^2}\right)\ ,$$
$$\delta_4 = \frac{A(\mathrm{Br})v_h^3 v_\sigma \csc\alpha_h + \left(M_{\sigma\sigma}^2 - M_{hh}^2\right)\Lambda^2\cos(\alpha_h)^2\sec(2\alpha_h)}{v_h^2 v_\sigma^2}\ ,$$

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

Neutrino masses — inverse seesaw

$$\mathcal{L}_\nu = y_\nu^{ij}\overline{L}_i\tilde{H}\nu^c_{\mathrm{R}j} + y_\sigma^{ij}S_iS_j\sigma + \Lambda^{ij}\nu^c_{\mathrm{R}i}S_j + \mathrm{h.c.}\,,$$

$$\boldsymbol{M_\nu} = \begin{pmatrix} 0 & \frac{v_h}{\sqrt{2}}\boldsymbol{y_\nu} & 0 \\ \frac{v_h}{\sqrt{2}}\boldsymbol{y_\nu} & 0 & \boldsymbol{\Lambda} \\ 0 & \boldsymbol{\Lambda} & \frac{v_\sigma}{\sqrt{2}}\boldsymbol{y_\sigma} \end{pmatrix}$$

$$\boldsymbol{m}_\nu \approx \frac{v_h^2 v_\sigma}{2\sqrt{2}}\boldsymbol{y_\nu}^\top\boldsymbol{\Lambda}^{\top-1}\boldsymbol{y_\sigma}\boldsymbol{\Lambda}^{-1}\boldsymbol{y_\nu}$$

3 light active neutrinos

$$\boldsymbol{m}_{N^\pm} \approx \boldsymbol{\Lambda} \pm \frac{v_\sigma}{2\sqrt{2}}\boldsymbol{y_\sigma}$$

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

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

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

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

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

$$n_{u,d,c,s,t,b} = 12, \qquad n_{e,\mu,\tau} = 4\,, \qquad n_{\nu_{1,2,3}} = n_{N^\pm_{1,2,3}} = 2$$

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

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

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

$\longrightarrow$ **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

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

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

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

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

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

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

And for gauge bosons...

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

$$m^2_{W_L}(\phi_h;T) = m^2_W(\phi_h) + \frac{11}{6}g^2T^2\,,$$

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

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

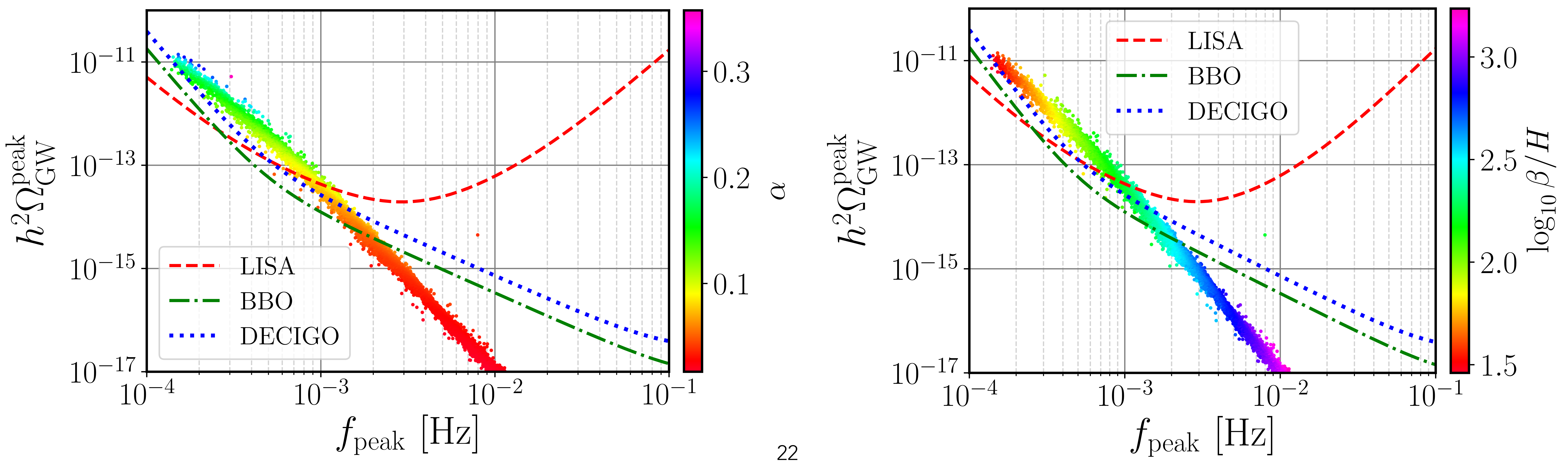
Results

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

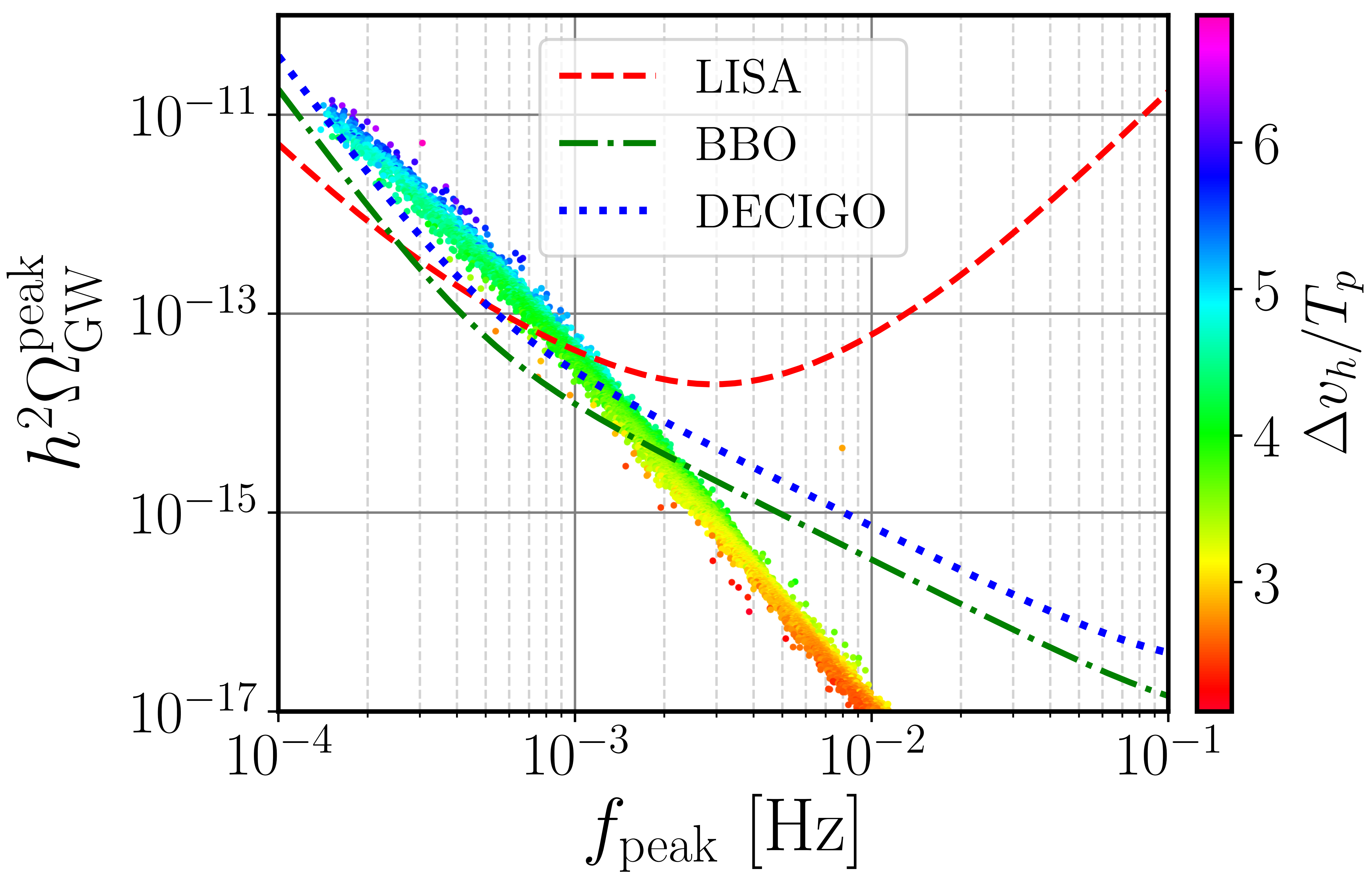
$\cos\alpha_h$: [0.85, 1] $\quad \mathrm{Br}(h_1 \to \theta\theta)$: $[10^{-15}, 0.19]$ $\quad \delta_{2,6}$: $[10^{-2}, \Lambda^2/v_\sigma^2]$

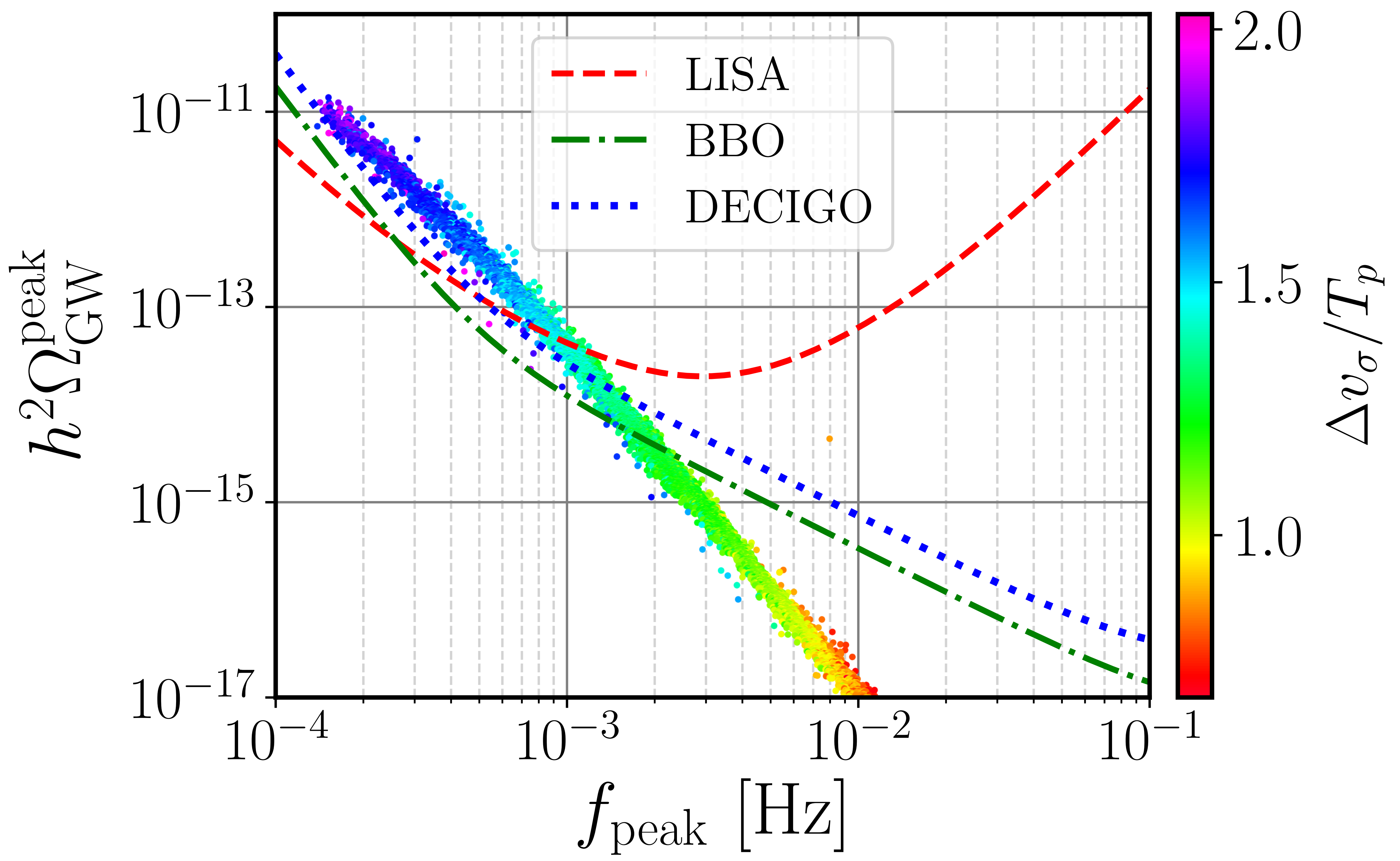
Scan using *CosmoTransitions*

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



$$\Delta v_\phi = \left| v_\phi^f - v_\phi^i \right| , \qquad \phi = h, \sigma$$





Both order parameters must be large for observable signals (c.f. João Viana talk)

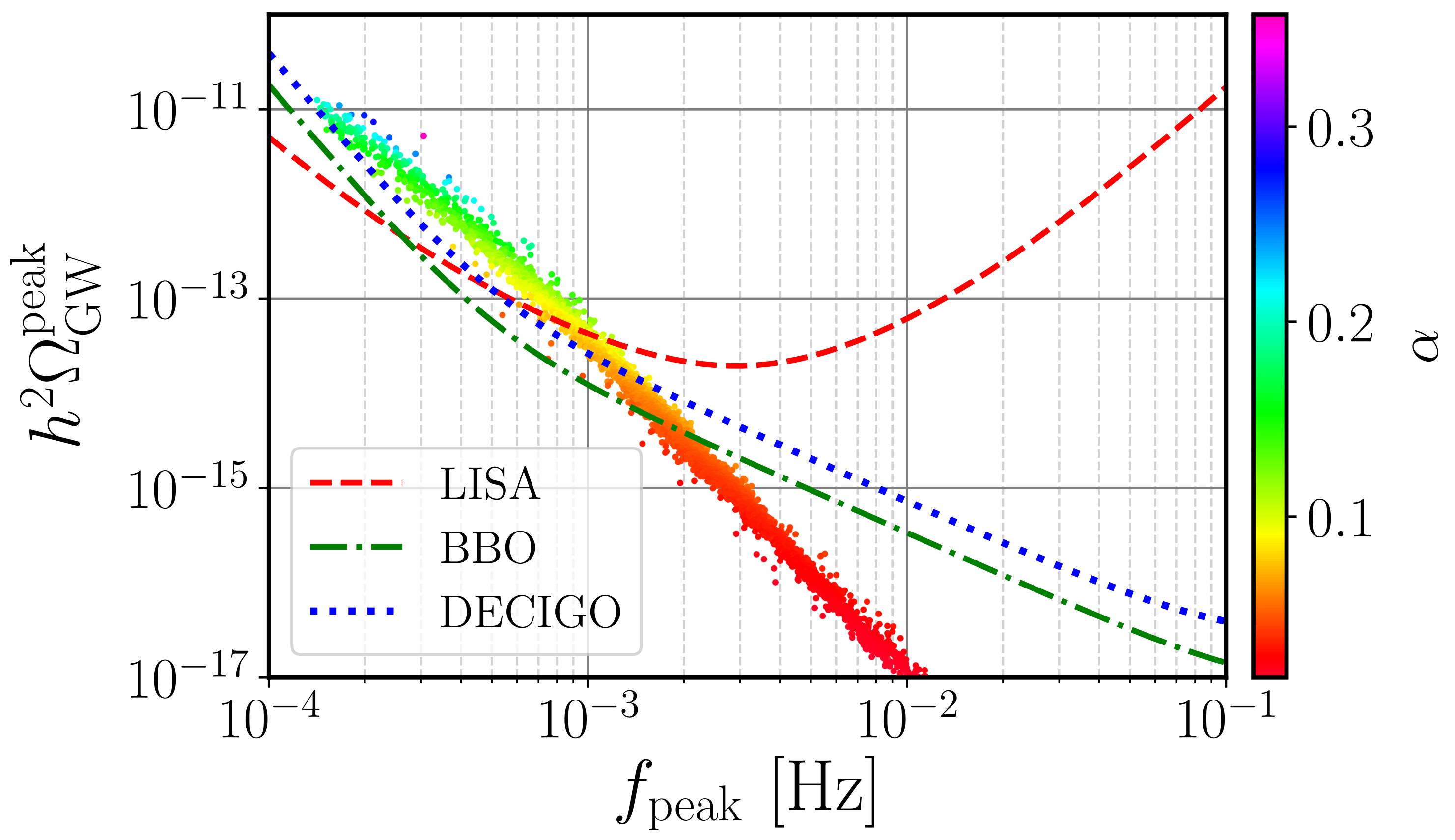
When $m_\theta > 2\, m_\nu$ the Majoron can decay $\theta \to \nu\nu$

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

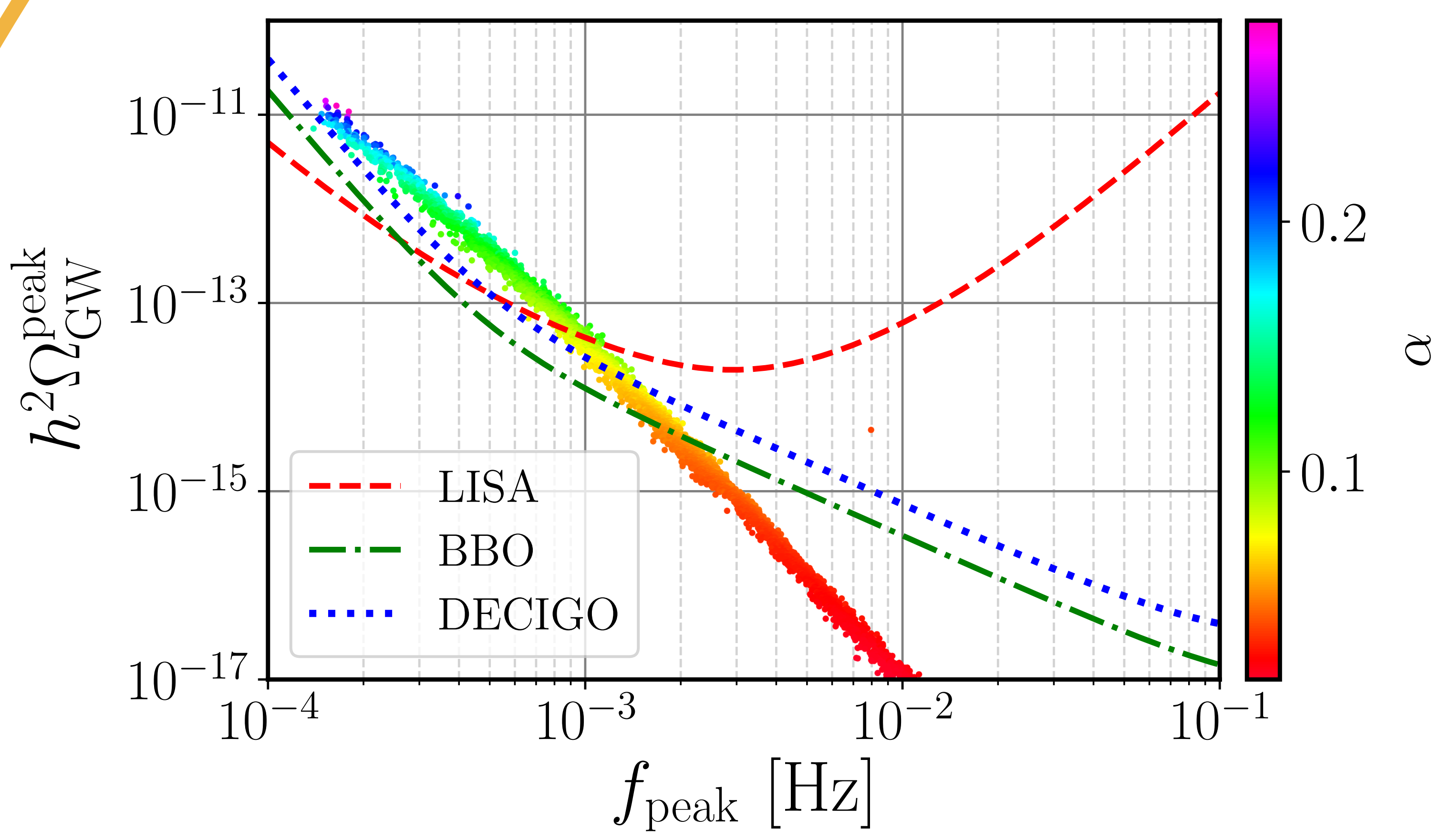
$$\Gamma(\theta \to \nu\nu) = \frac{m_\theta}{16\pi} \sum_i \frac{m_i^2}{v_\sigma^2} < 1.9 \times 10^{-19} s^{-1} @ 95\,\%\ \text{C.L.}$$

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

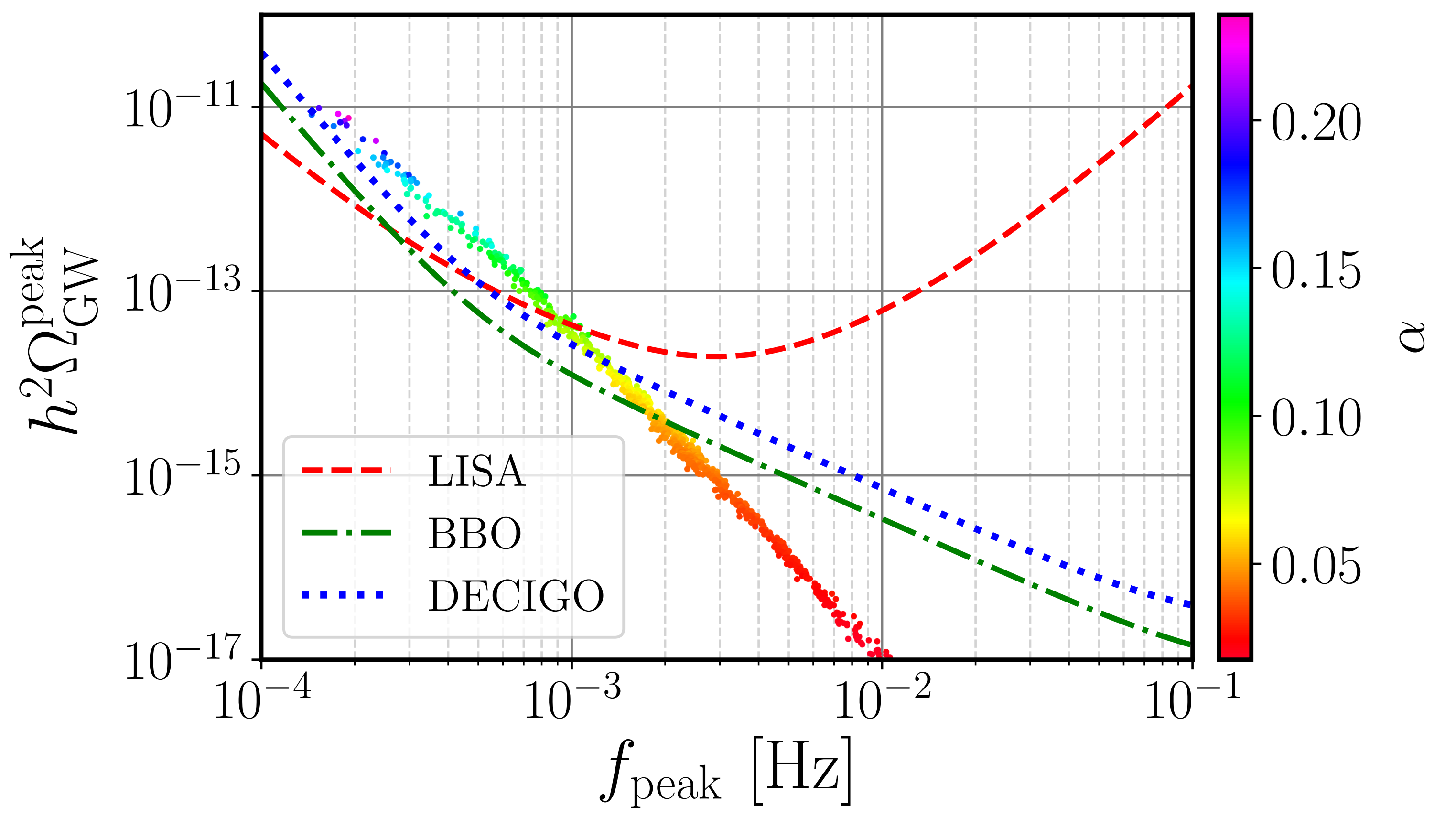
Short-lived



Long-lived (viable DM?)

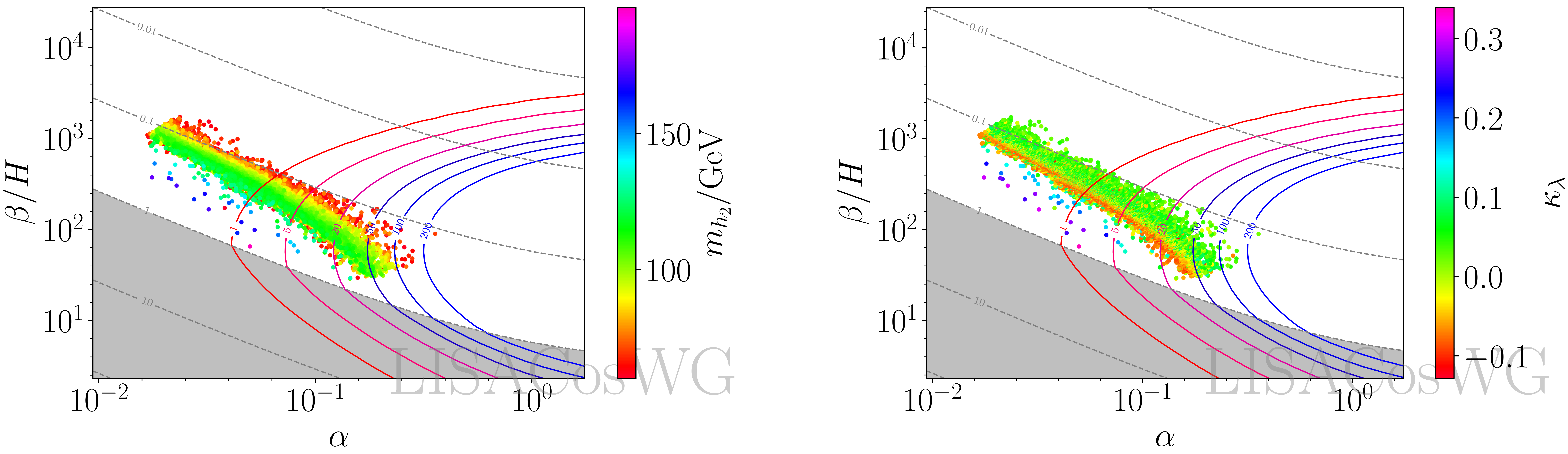


Stable (viable DM?)



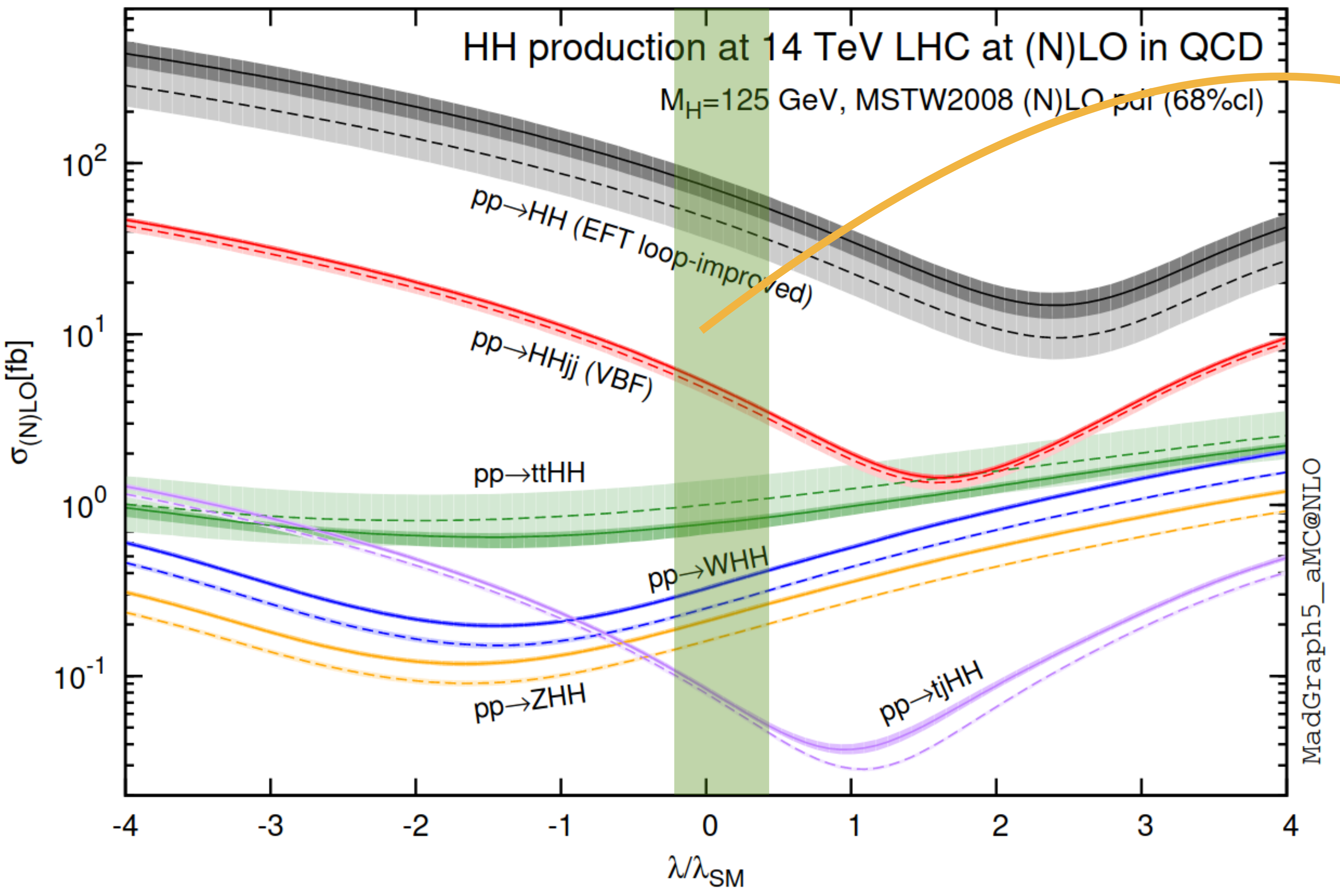
Majorons decaying today can leave observable peaks in electron spectra induced by relic neutrinos capture: PTOLEMY [JCAP 03 (2021) 089]

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



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

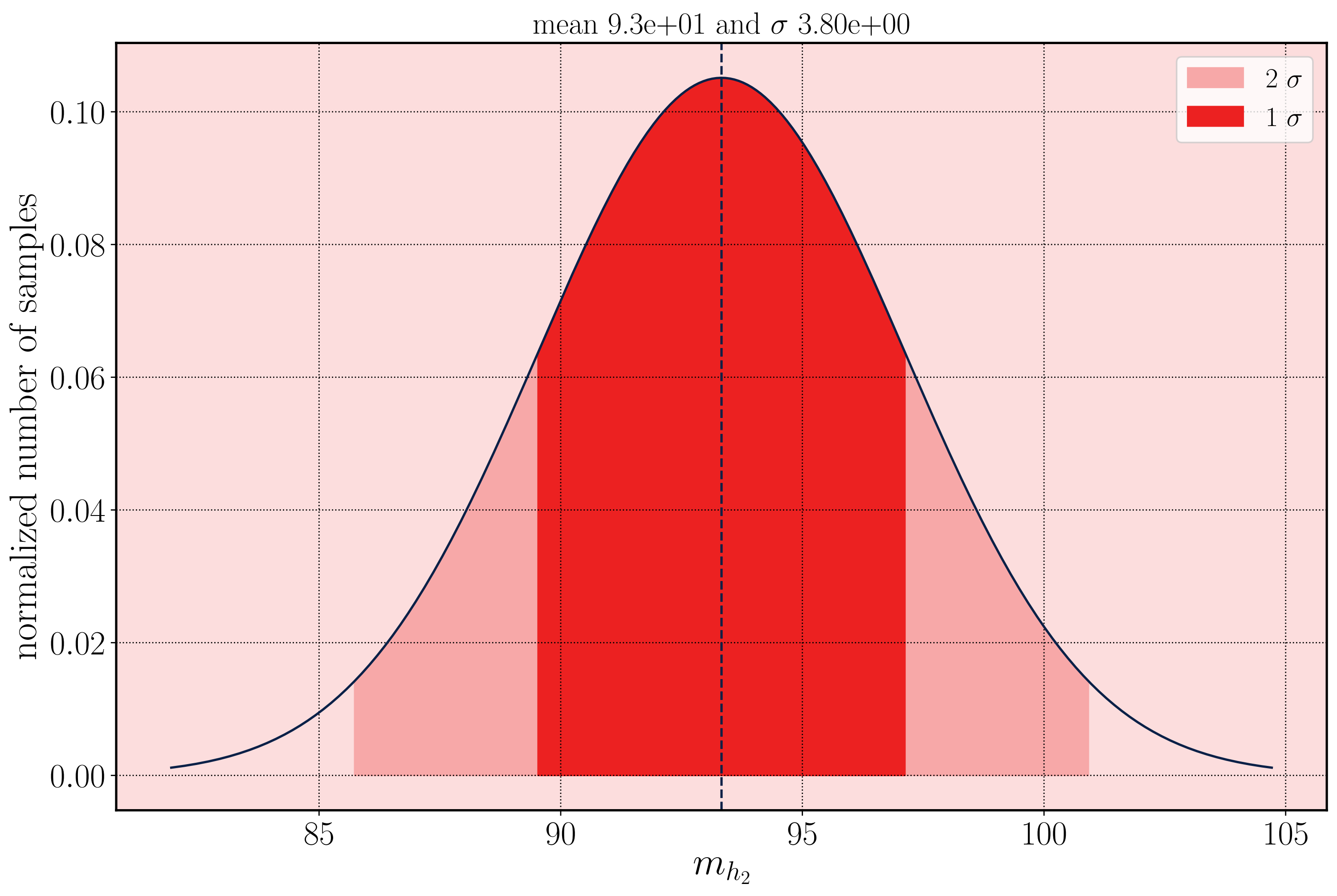
- **Strongly favours light h_2 with mass 80 - 120 GeV (CMS 95 GeV di-photon and di-tau excesses?)**
- $\kappa_\lambda \equiv \lambda_{h_1 h_1 h_1}/\lambda_{\mathrm{SM}} < 1$

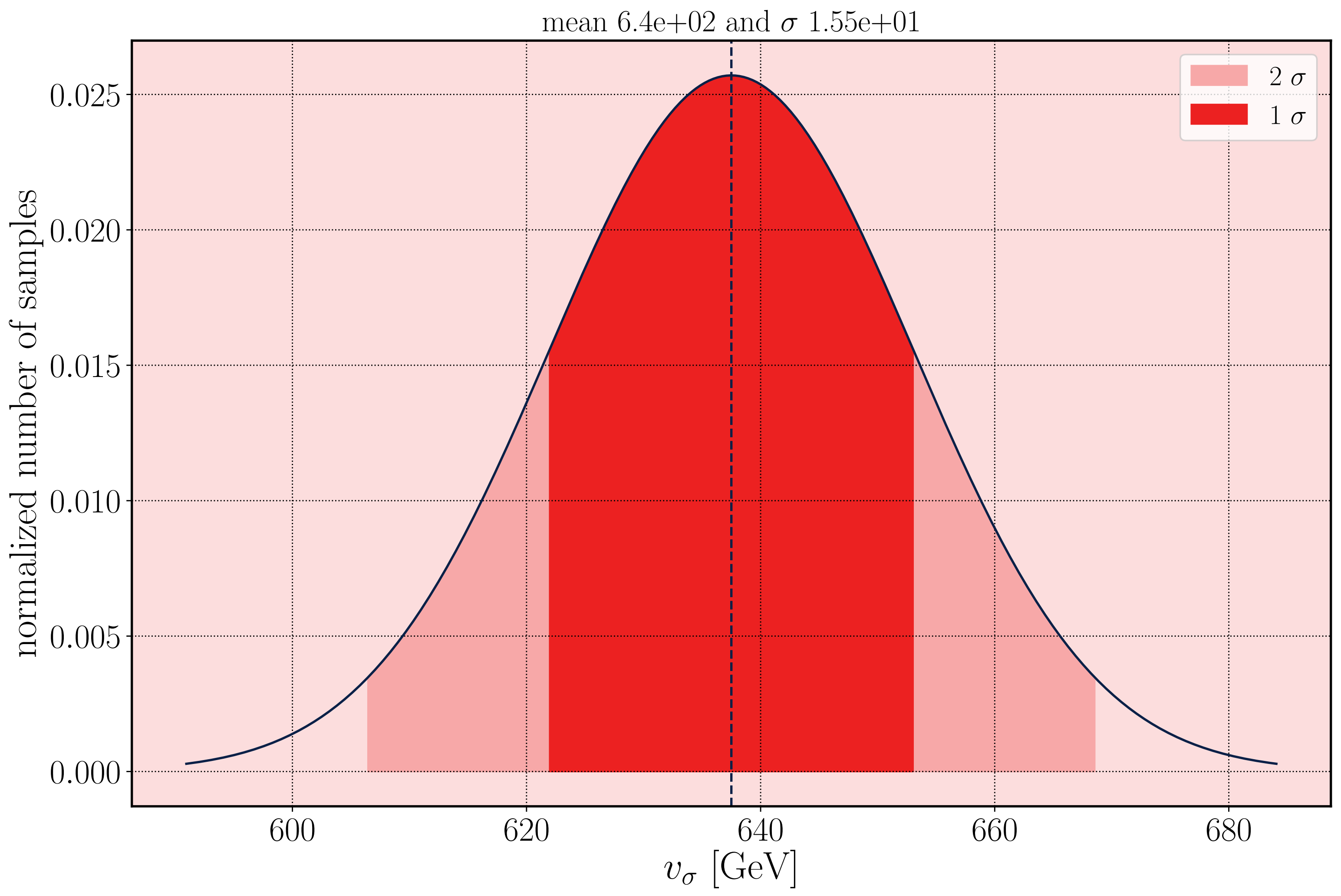


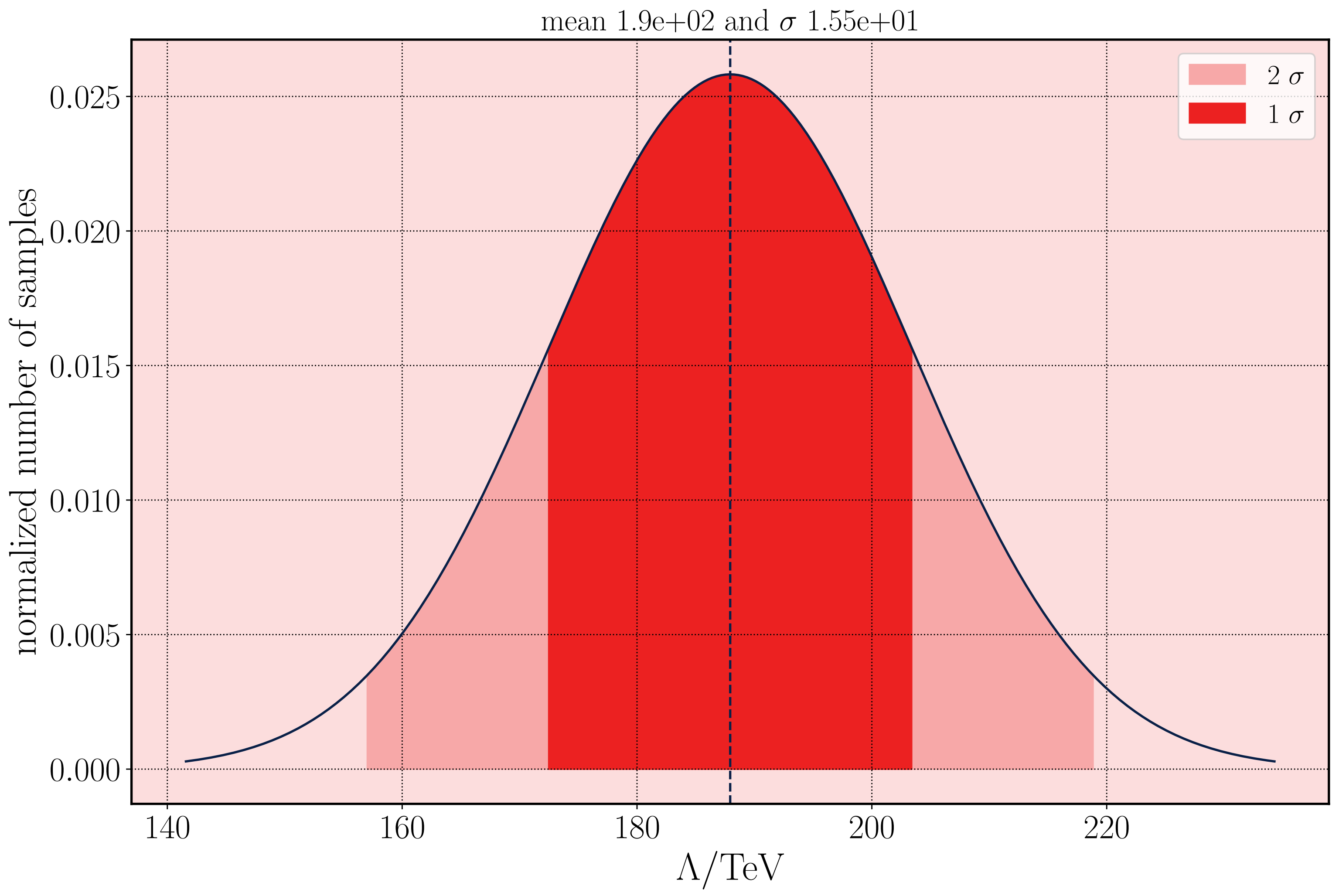
Region compatible with observable SFOPTs in the 6D Majoron model with enhancement of Xsec

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

Gaussian fit to all generated data for observable SFOPTs







$$m_{h_2} = 93 \pm 3.8 \text{ GeV} \qquad v_\sigma = 640 \pm 15.5 \text{ GeV} \qquad \Lambda = 190 \pm 15.5 \text{ TeV}$$

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 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