Probing new physics through gravitational wave measurements: W mass anomaly, dynamical electroweak symmetry breaking and neutrino mass models

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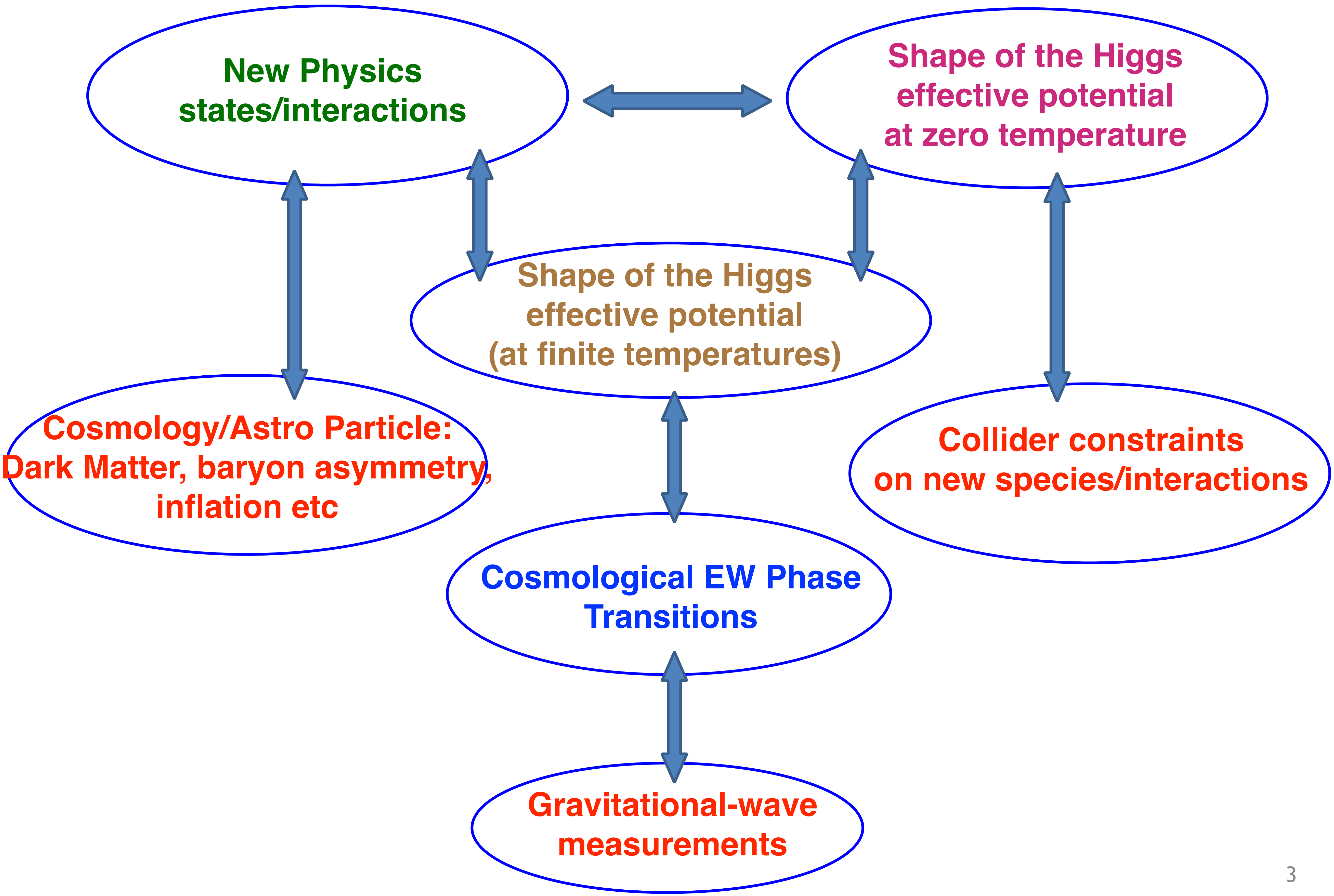
Why do Gravitational Waves matter?

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

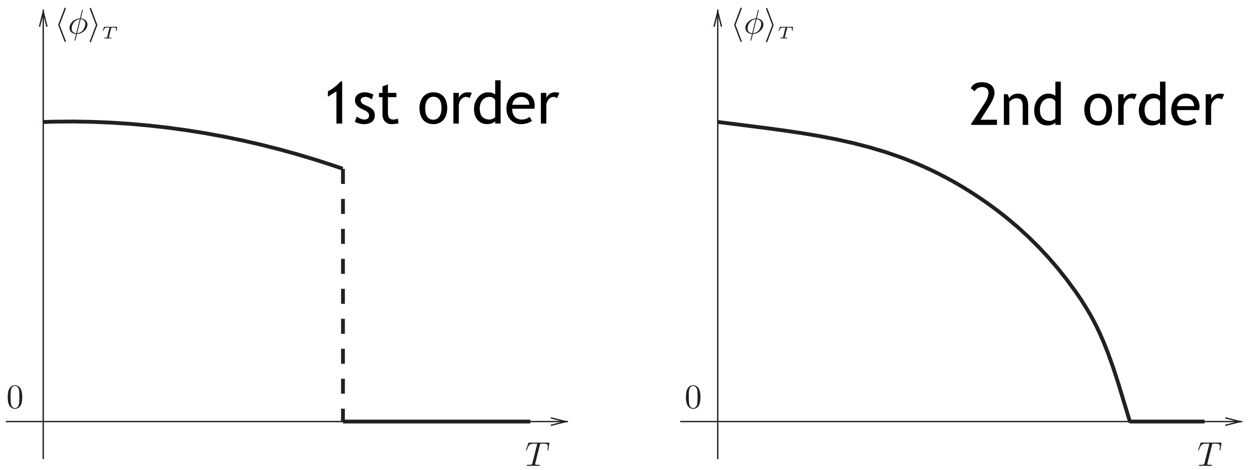
- Cosmological events
  - (i) Inflation
  - (ii) Cosmic strings
  - (iii) **Strong cosmological phase transitions (PTs)** $\rightarrow$ by expanding vacuum bubbles of a broken phase in a universe filled with a symmetric phase

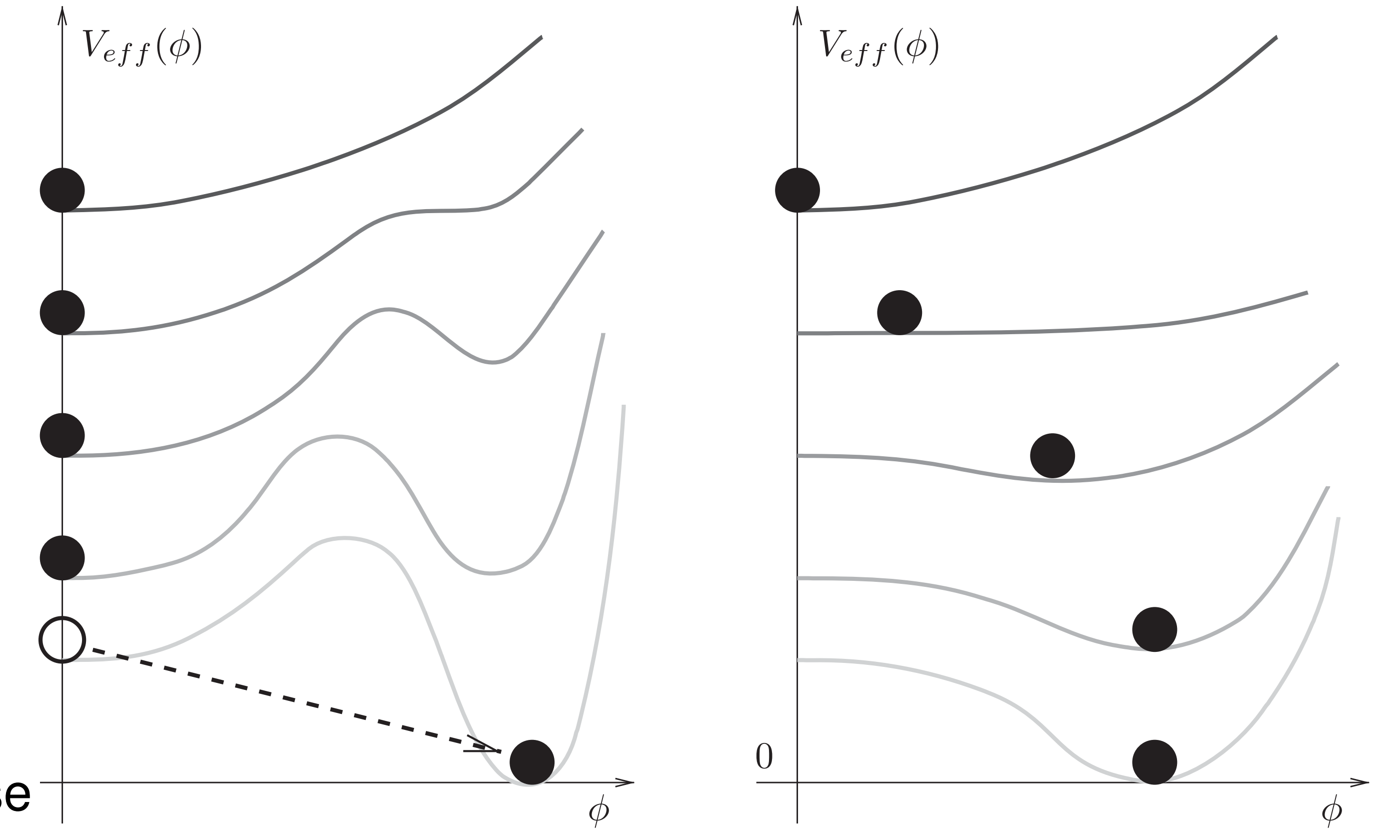
Decoding the structure of the Higgs effective potential…



Cosmological Phase Transitions

EW phase transitions





Strong cosmological phase transitions (PTs) $\rightarrow$
by expanding and colliding vacuum bubbles of new phase

Stochastic Gravitational Wave (GW) background
as a gravitational probe for New Physics

$$\frac{n_B - n_{\overline{B}}}{s} \sim 10^{-11}$$

Why strong FOPTs?

Sakharov'67

(i) B violation

(ii) C and CP violation

(iii) Departure from thermal equilibrium $\rightarrow$ **strong 1st-order PT**

Nucleation of expanding broken-phase vacuum bubbles $\rightarrow$ sphaleron suppression

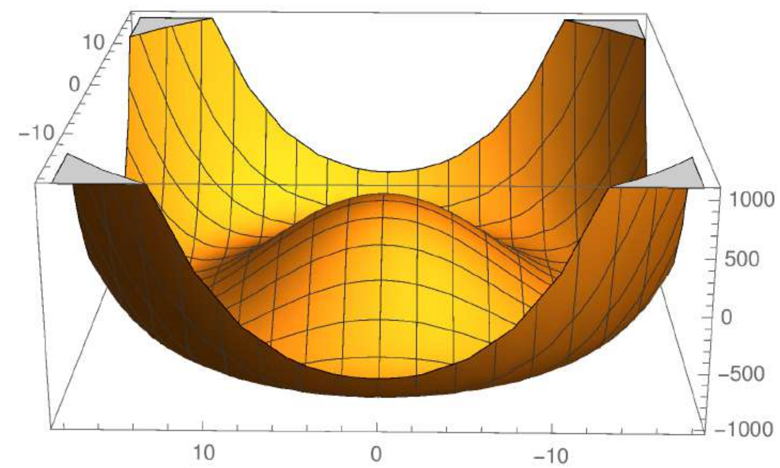
$$\frac{\phi(T_c)}{T_c} \gtrsim 1.1 \quad \rightarrow \quad 1^{\mathrm{st}} \text{ order PT}$$

Standard Model (SM) does not explain the BA $\rightarrow$ **the need to go beyond the SM**

Basics of Strong First Order PTs (SFOPTs)

Consider a the scalar potential: $V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2$

$\mu^2 < 0$ and $\lambda > 0$

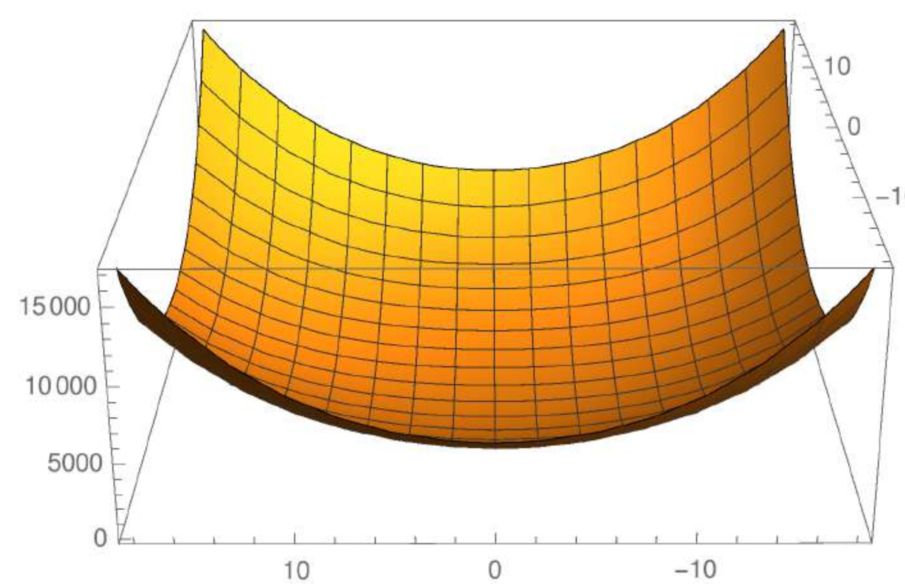


Add thermal corrections:

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

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

Restored symmetry



EW PTs in multi-scalar SM extensions

- The more scalar d.o.f.'s, the more complicated vacuum structure $\rightarrow$ new possibilities for **strong 1st-order EWPT at tree-level**
- Multi-Higgs SM extensions are very common and originate as e.g. low-energy limits of **Grand-Unified theories**
- Tree-level (strong) EWPT $\rightarrow$ free energy release is largely amplified $\rightarrow$ **stronger GW signals**
- Tree-level weak (2nd-order) transitions can become 1st-order ones due to **quantum corrections**
- Certain scenarios exhibit multi-step **successive 1st-order PTs**
- Multi-step transition $\rightarrow$ multi-peak structures in the induced GW spectrum $\rightarrow$ potential access by the next generation of **space-based GW interferometers**
- GW signature of multiple EW symmetry breaking steps $\rightarrow$ a **gravitational probe for New Physics**, yet unreachable at colliders

Dynamics of EWPTs

- High $T \to$ classical motion in Euclidean space described by action $\hat{S}_3$

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

- Effective potential: loop and thermal corrections

$$\begin{aligned} V_{\text{eff}}^{(1)}(\hat{\phi}) &= V_{\text{tree}} + V_{\text{CW}} + \Delta V^{(1)}(T) \\ V_{\text{CW}} &= \sum_i (-1)^F n_i \frac{m_i^4}{64\pi^2} \left(\log \left[\frac{m_i^2(\hat{\phi}_\alpha)}{\Lambda^2} \right] - c_i \right) \\ \Delta V^{(1)}(T) &= \frac{T^4}{2\pi^2} \left\{ \sum_b n_b J_B \left[\frac{m_b^2(\hat{\phi}_\alpha)}{T^2} \right] - \sum_f n_f J_F \left[\frac{m_f^2(\hat{\phi}_\alpha)}{T^2} \right] \right\} , \end{aligned}$$

- $\hat{\phi} \to$ solution of the e.o.m. found by the path that minimizes the energy.

$$\Delta V^{(1)}(T)|_{\text{L.O.}} = \frac{T^2}{24} \left\{ \mathrm{Tr}\left[M_{\alpha\beta}^2(\phi_\alpha) \right] + \sum_{i=W,Z,\gamma} n_i m_i^2(\phi_\alpha) + \sum_{i=t,b,\tau} \frac{n_i}{2} m_i^2(\phi_\alpha) \right\}$$

Characteristics of phase transitions

- Nucleation temperature $T_n \to$ the PT does effectively occur $\to$ vacuum bubble nucleation processes
- Satisfies $T_n < T_c$, where T_c is the critical temperature $\to$ degenerate minima
- Corresponds to probability to realize one transition per cosmological horizon volume equal one

- The phase transition rate

$$\Gamma \sim T^4 \left(\frac{\hat{S}_3}{2\pi T} \right)^{3/2} \exp\left(-\hat{S}_3/T\right)$$

$$\frac{\Gamma}{H^4} \sim 1 \qquad \Rightarrow \qquad \frac{\hat{S}_3}{T_n} \sim 140$$

Inverse time-scale of the PTs:

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

Relative latent heat (PT strength):

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

$$\rho_\gamma = g_* \frac{\pi^2}{30} T_n^4 \,, \qquad g_* \simeq 106.75$$

Probability to find a point in the false vacuum:

$$P(T) = e^{-I(T)},$$

$$I(T) = \frac{4\pi v_b^3}{3} \int_T^{T_c} \frac{\Gamma(T')dT'}{T'^4 H(T')} \left(\int_T^{T'} \frac{d\tilde{T}}{H(\tilde{T})} \right)^3$$

Percolation temperature

(temperature at which at least 34% of the false vacuum has tunnelled into the true vacuum)

$$I(T_*) = 0.34$$

- This formalism is implemented in CosmoTransitions package (Wainwright'12)

Gravitational-wave power spectrum

- GW energy density per logarithmic frequency

$$h^2\Omega_{\mathrm{GW}} \equiv \frac{h^2}{\rho_c}\frac{d\rho_{\mathrm{GW}}}{d\log f} \simeq h^2\Omega_{\mathrm{col}} + h^2\Omega_{\mathrm{sw}} + h^2\Omega_{\mathrm{MHD}}$$

C. Caprini *et al.*, JCAP **2003**, 024 (2020), 1910.13125

$$\boxed{\text{signal} \sim \text{amplitude} \times \text{spectral shape } (f/f_{\mathrm{peak}})}$$

Primordial GWs power spectrum:

$$h^2\Omega_{\mathrm{GW}} = \underbrace{h^2\Omega_{\mathrm{GW}}^{\mathrm{peak}}}_{\text{Peak amplitude}} \underbrace{\left(\frac{4}{7}\right)^{-\frac{7}{2}}\left(\frac{f}{f_{\mathrm{peak}}}\right)^3\left[1+\frac{3}{4}\left(\frac{f}{f_{\mathrm{peak}}}\right)\right]^{-\frac{7}{2}}}_{\text{Spectral function}}$$

peak frequency $f_{\mathrm{peak}} \propto (\beta/H)T_*$

$$h^2\Omega_{\mathrm{GW}}^{\mathrm{peak}} \propto T_*^2 K(\alpha) f_{\mathrm{peak}}^{-2}$$

Gravitational-wave probes:

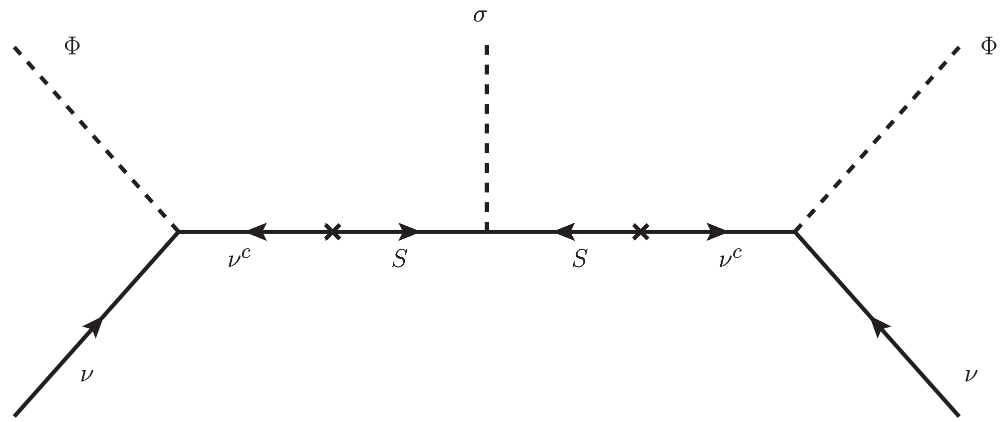
Example I: neutrino mass generation

Inverse Majoron See-Saw model

six species of singlet neutrinos

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

$$(\nu_i^c, S_i)$$



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

3 light active neutrinos

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

Using normal hierarchy:

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

6 heavy neutrinos

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

$$V_0(\Phi,\sigma) = \mu_\Phi^2\Phi^\dagger\Phi + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \mu_\sigma^2\sigma^\dagger\sigma + \lambda_\sigma(\sigma^\dagger\sigma)^2 + \lambda_{\Phi\sigma}\Phi^\dagger\Phi\sigma^\dagger\sigma + \left(\frac{1}{2}\mu_b^2\sigma^2 + \mathrm{h.c.}\right)$$

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} G + iG' \\ \phi_h + h + i\eta \end{pmatrix}, \qquad \sigma = \frac{1}{\sqrt{2}}(\phi_\sigma + \sigma_R + i\sigma_I)$$

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?

The role of D6 operators

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

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

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

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

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

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

$10\ \mathrm{TeV} < \Lambda < 1000\ \mathrm{TeV} \longrightarrow$ 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

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

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

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

$$m^2_\theta = -2\mu_b^2$$

Phenomenological inputs

Invisible Higgs decays limit : $\mathrm{Br}\left(h \to \theta\theta\right) < 0.19$ 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: $m_{h_1} = 125.09$ GeV, $m_{h_2}, m_\theta, v_h, v_\sigma, \Lambda, \delta_2, \delta_6$

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

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

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

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

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

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

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

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

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

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

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

And for gauge bosons…

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

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

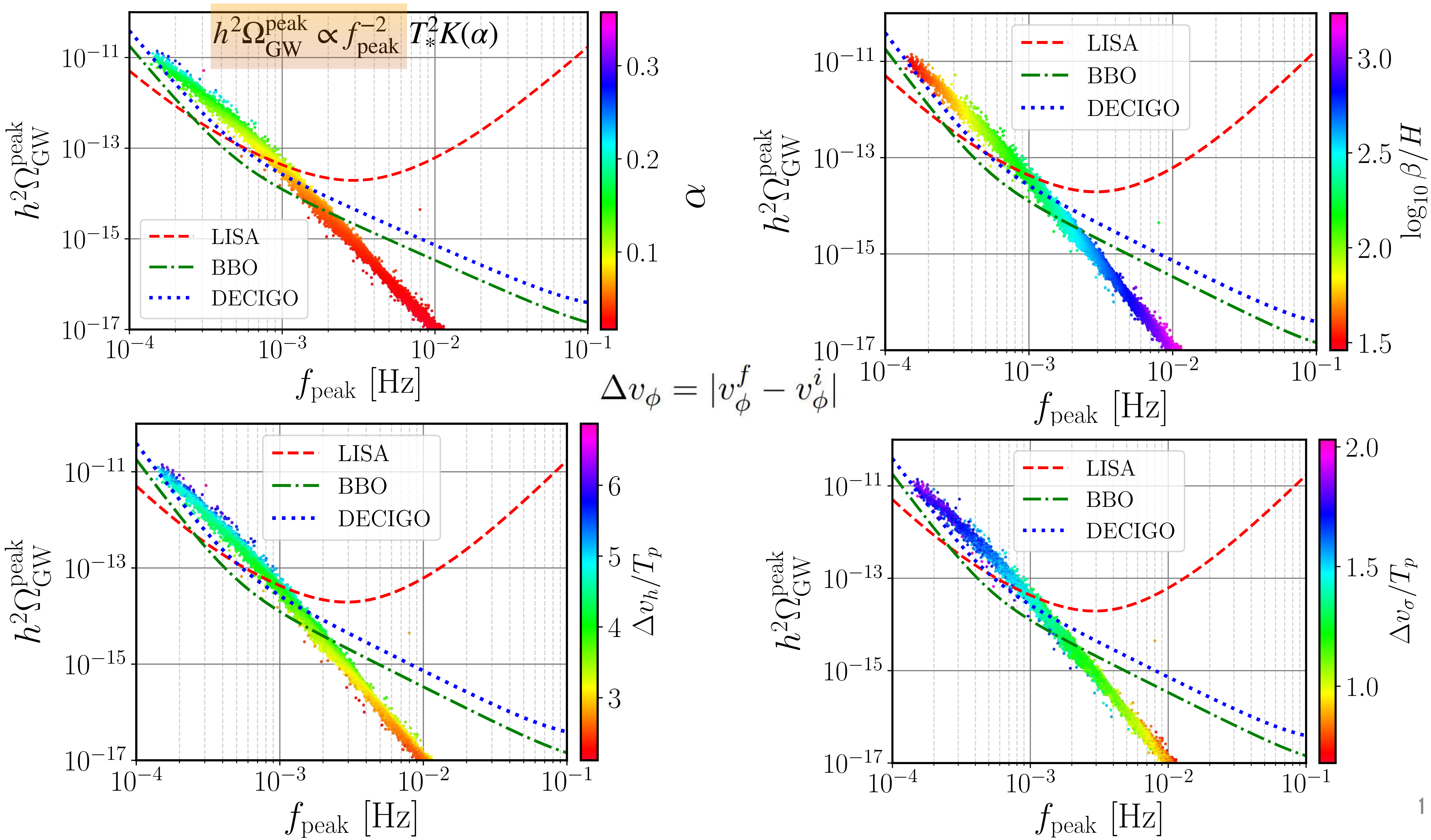
$$m^2_{Z_L,A_L}(\phi_h;T) = \frac{1}{2}m^2_Z(\phi_h) + \frac{11}{12}(g^2+{g'}^2)T^2 \pm \mathcal{D}\,,$$

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

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}, Λ^2/v_σ^2]



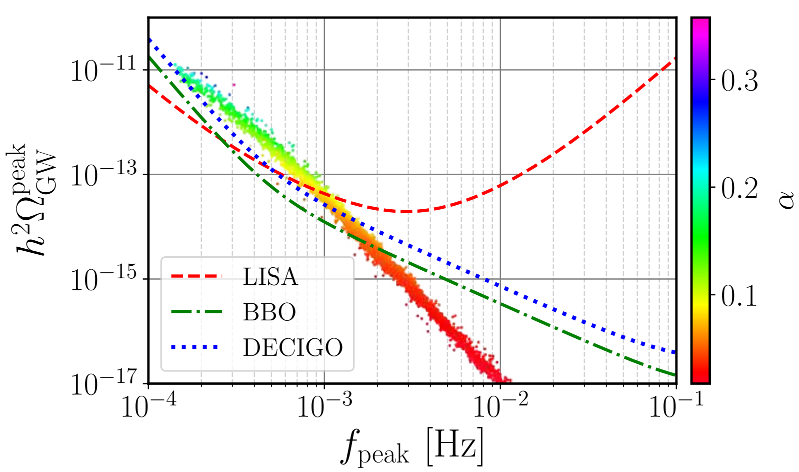
When $m_\theta > 2\ m_\nu$ the Majoron can decay $\theta \to \nu\nu$

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

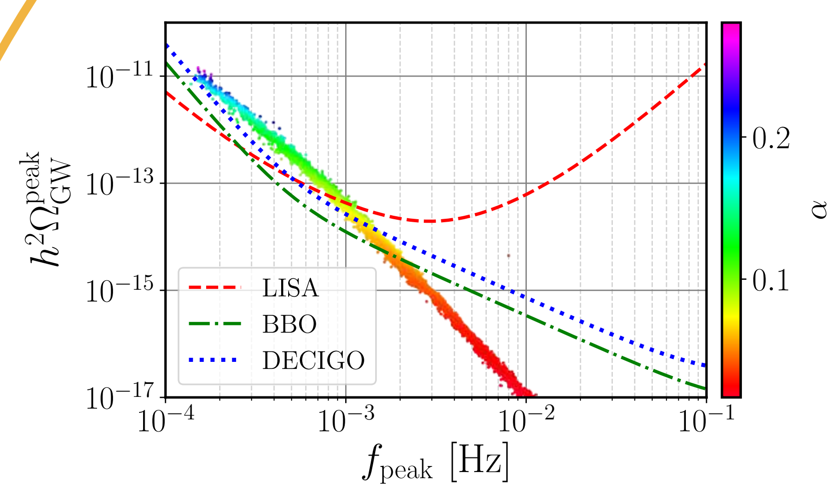
$$\Gamma(\theta \to \nu\nu) = \frac{m_\theta}{16\pi} \sum_i \frac{m_i^2}{v_\sigma^2} < 1.9 \times 10^{-19} s^{-1} @ 95\,\%\ \text{C.L.}$$

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

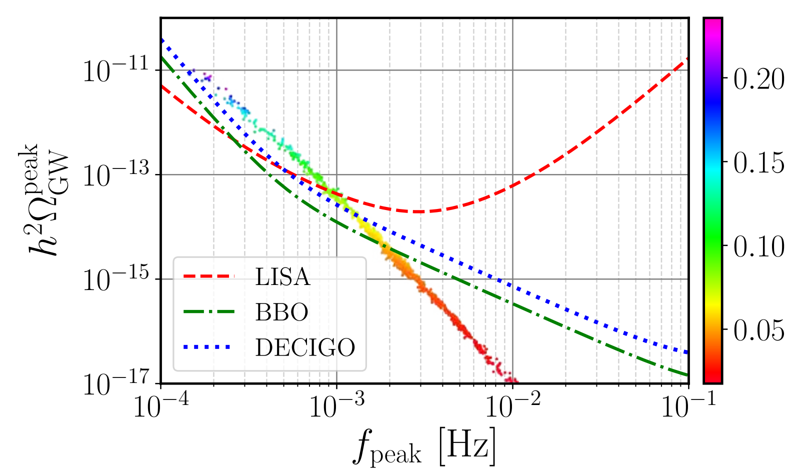
Short-lived



Long-lived (viable DM?)

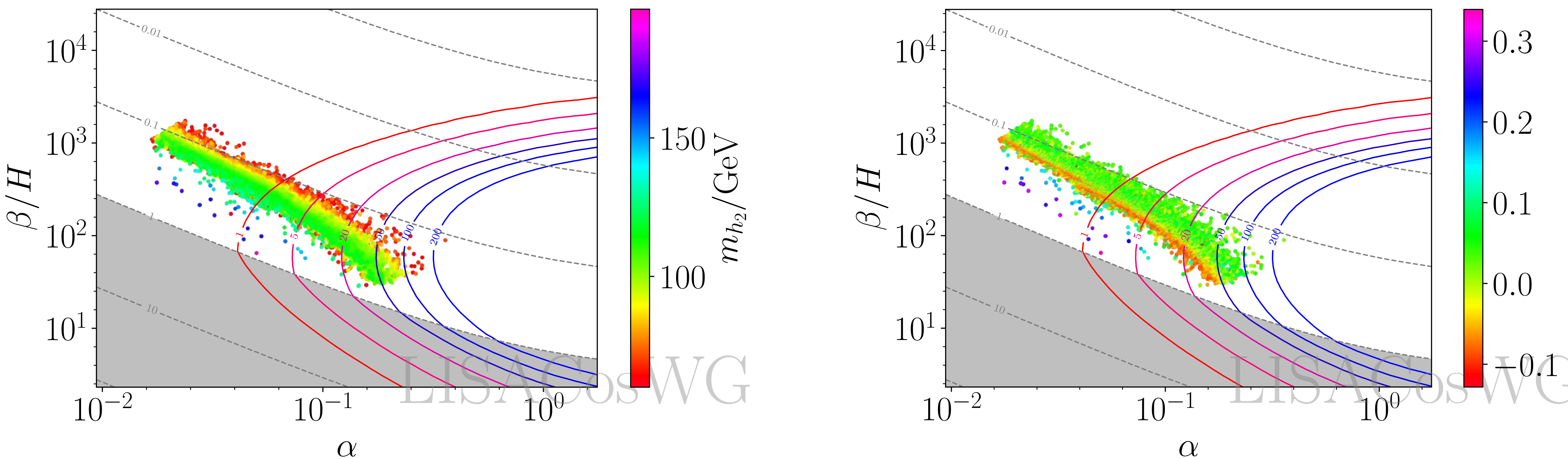


Stable (viable DM?)



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]

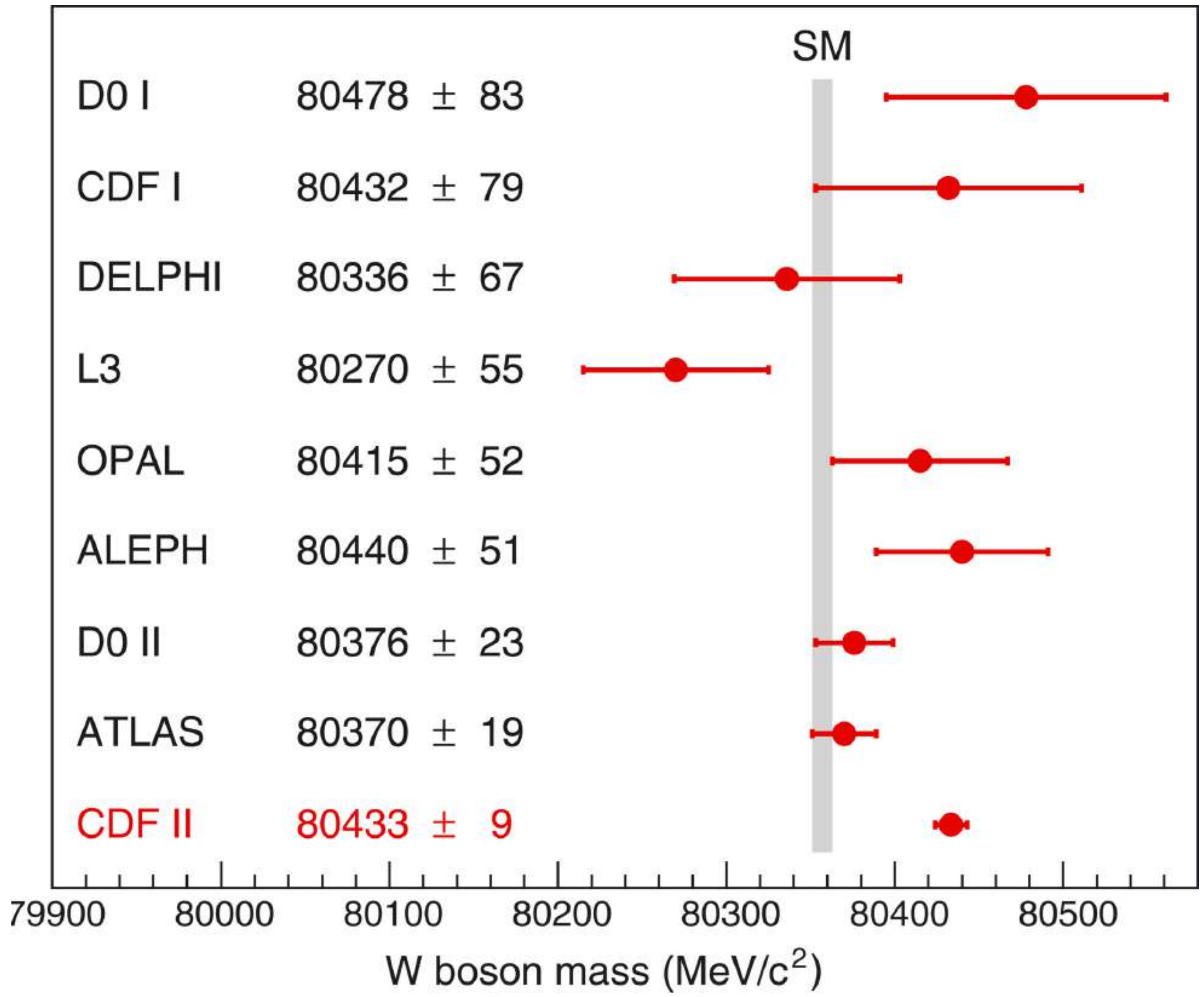
- **Strongly favours light h_2 with mass 80 - 120 GeV (CMS 95 GeV di-photon and di-tau excesses?)**
- $\kappa_\lambda \equiv \lambda_{h_1h_1h_1}/\lambda_{\rm SM} < 1$

Gravitational-wave probes:

Example II: W mass anomaly

W mass anomaly

**CDF II Collaboration,
Science 376, 170 (2022)**



- Surprising CDF II measurement of W mass lies 7.6σ away from the Standard Model

- Many scenarios beyond the SM have been deployed in the literature to explain this measurement (over 100 publications so far!)

- A large class of BSM scenarios offering such an explanation features the existence of a new SU(2) adjoint (triplet) scalar which provides a tree-level corrections to the SM W mass value

- Existence of such scalars may impact the Electro Weak phase transition in early Universe, possibly rendering such models testable in future gravitational-wave detectors

A minimal scalar SU(2) triplet extension

Let us focus on a simplified framework that relates the characteristics of EW phase transitions to a possible explanation of the W mass anomaly

The model by: L. Di Luzio, R. Gröber and P. Paradisi, "Higgs physics confronts the m_W anomaly" [arXiv:2204.05284 [hep-ph]]

W mass anomaly ⟷ **Anomaly in T-parameter (assuming U=0)**

$$\hat{T} \simeq (0.84 \pm 0.14) \times 10^{-3}$$

A. Strumia, [arXiv:2204.04191 [hep-ph]]

Effective Field Theory d=6 operator generates this anomaly

$$c_{\mathrm{HD}} \mathcal{O}_{\mathrm{HD}} = c_{\mathrm{HD}} (H^\dagger D_\mu H)((D_\mu H)^\dagger H)$$

$$\hat{T} = -\frac{v^2}{2} c_{\mathrm{HD}}$$

A new heavy state that generates this operator

$$\Delta = (1, 3, 0) \qquad \mathcal{L}_{\mathrm{T}} = -k_\Delta H^\dagger \Delta \cdot \sigma H + \mathrm{h.c.}$$

$$c_{\mathrm{HD}} = -2 \frac{k_\Delta^2}{M_\Delta^4}$$

negative effective coupling!

Scale of New Physics

Integrating out heavy new scalar triplet state yields both:
a positive contribution to the T-parameter and a modification of the Higgs potential

$$\hat{T} = \frac{k_\Delta^2 v^2}{M_\Delta^4} = 0.84 \times 10^{-3} \left(\frac{|k_\Delta|}{M_\Delta}\right)^2 \left(\frac{8.5\,\mathrm{TeV}}{M_\Delta}\right)^2$$

consistent with the observed shift in W mass for a TeV-scale scalar triplet state!

Saturating the perturbativity bound $|k_\Delta|/M_\Delta \leq 4\pi$ the mass scale cannot exceed 100 TeV

Higgs quartic couplings receives a tree-level correction

$$\lambda = \lambda_{\text{bare}} + (k_\Delta/m_\Delta)^2$$

$$\lambda = m^2/2v^2$$

m^2 Higgs mass parameter

$v \simeq 246\ \mathrm{GeV}$ Higgs VEV

$$\frac{\mu_\Delta}{3}\Delta^3 + \text{h.c.} \qquad \Delta^3 \equiv (\Delta\cdot\sigma)(\Delta\cdot\sigma)(\Delta\cdot\sigma)$$

d=6 Higgs self-interaction term is induced as well

crucial contribution to the Higgs potential that determines the nature and the strength of the EW phase transition

$$\frac{\kappa}{\Lambda^2}(H^\dagger H)^3 + \text{h.c.}$$

cutoff scale

$$\frac{\Lambda}{\sqrt{\kappa}} = \frac{\sqrt{3}M_\Delta^3}{\sqrt{\mu_\Delta}k_\Delta^{3/2}}$$

$$\kappa \lesssim 4\pi$$

Finite-T effective potential & EW FOPTs

In unitary gauge, one-loop effective Higgs potential:

$$V_{\rm eff}(T,h) = V_{\rm tree}(h) + V^{(1)}_{T=0}(h) + \Delta V_T(h,T)$$

$$V_{\rm tree}(h) = \frac{1}{2}m^2h^2 + \frac{\lambda}{4}h^4 + \frac{\kappa}{8\Lambda^2}h^6$$

The dominant thermal correction to the Higgs mass:

$$CT^2/2$$

$$C \simeq \frac{1}{16}\left(g'^2 + 3g^2 + 4y_{\rm t}^2 + 4\frac{m_{\rm h}^2}{v^2} + 36\frac{\kappa v^2}{\Lambda^2}\right)$$

$$m_{\rm h}^2 = 2\lambda v^2 + 3v^4\kappa/\Lambda^2$$

zero-T Higgs mass

$$m_{\rm h} = 125\,{\rm GeV}$$

Limit on the cutoff scale imposed by the strongly 1st order EW phase transition requirement yields:

F. Huang et al, Phys. Rev. D94 (2016) 041702 [arXiv:1601.01640 [hep-ph]]

$$480\,{\rm GeV} \lesssim \frac{\sqrt{3}M_\Delta^3}{\sqrt{\mu_\Delta}k_\Delta^{3/2}} \lesssim 840\,{\rm GeV}$$

$$v(T_{\rm c})/T_{\rm c} > 1$$

For saturated perturbativity

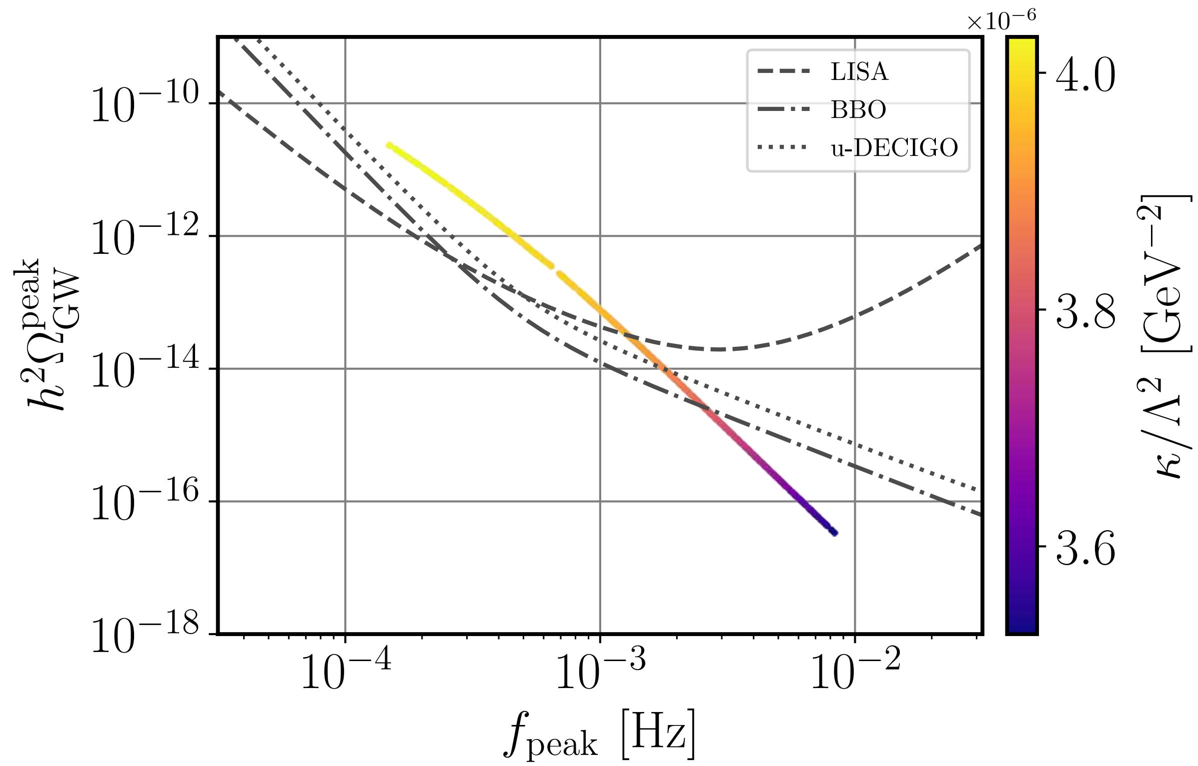
$$|k_\Delta|/M_\Delta \simeq 4\pi \text{ and } |\mu_\Delta|/M_\Delta \simeq 4\pi$$

The EW FOPT bound:

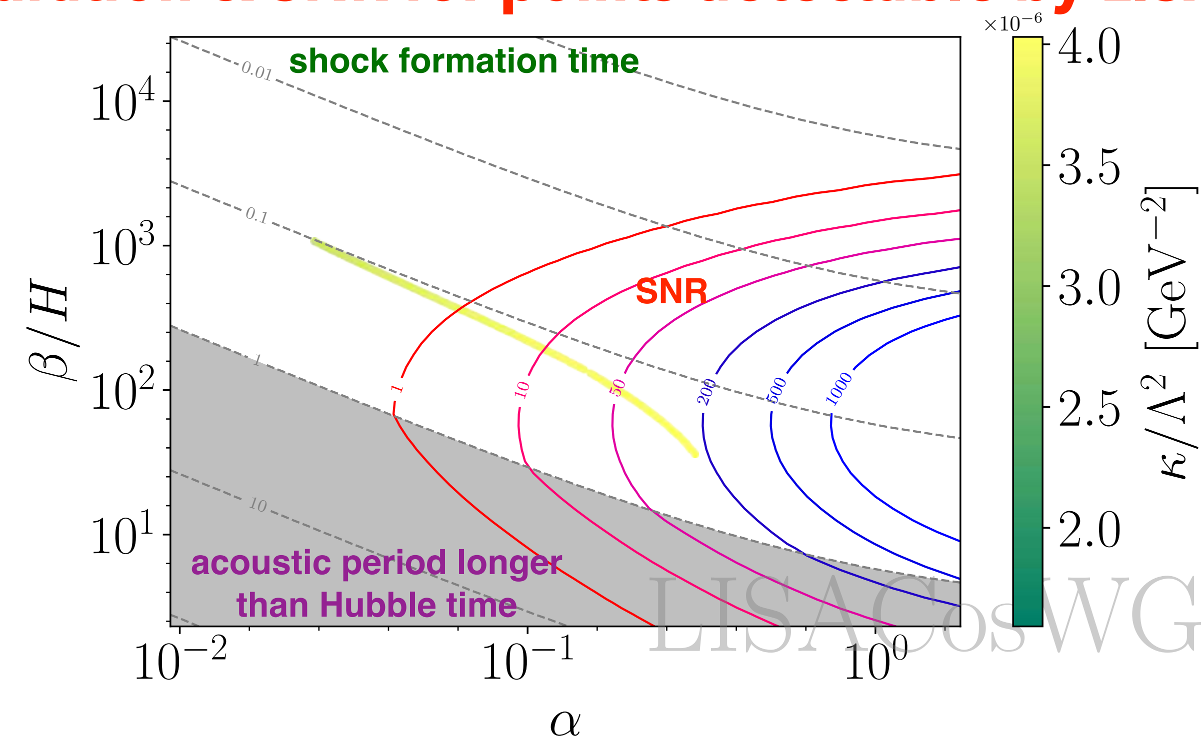
$$M_\Delta \simeq 5 \div 10\,{\rm TeV}$$

Primordial GWs in a minimal triplet model

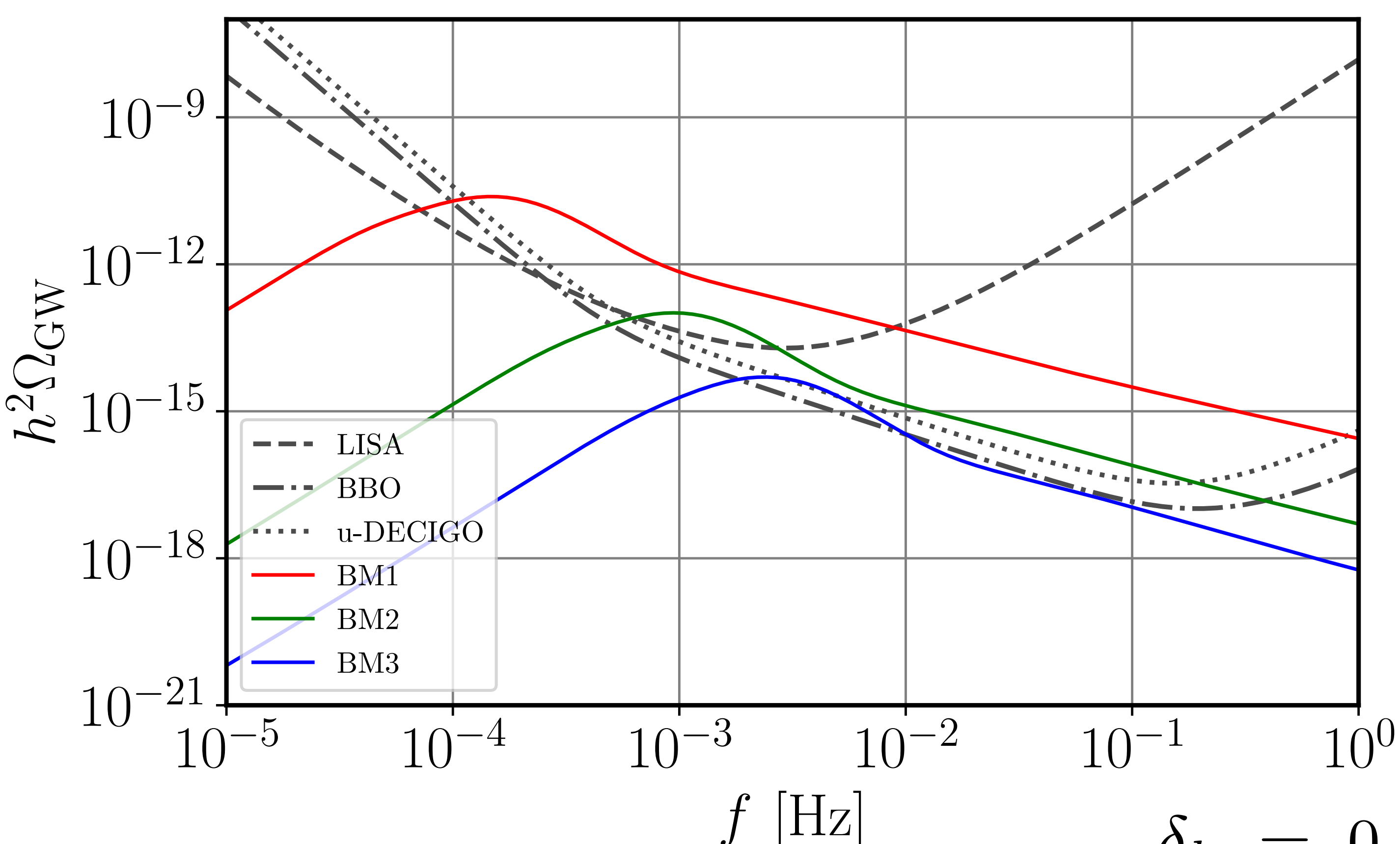
peak-amplitude vs energy scale



duration & SNR for points detectable by LISA



GWs power spectrum



Benchmarks:

T_*(GeV)	α	β/H_*	$\kappa^{-1/2}\Lambda$(GeV)	$\delta_{\sigma_{hz}}$(%)
43.8	0.30	36.37	498.12	1.8
55.6	0.12	180.94	502.40	2.1
64.2	0.07	394.14	508.38	2.2

- Consistent with LHC bounds
- Can be probed in future measurements of trilinear Higgs coupling:

$$\lambda_{3h} = -(1+\delta_h)\frac{Ah^3}{6} \qquad A = 3m_h^2/v$$

$$\delta_h = 0.66 \div 2 \qquad \Longleftrightarrow \qquad \delta_{\sigma_{hZ}} = \delta\sigma_{hZ}/\sigma_{hZ}$$

Gravitational-wave probes:

Example III: Dynamical EWSB

Dynamical EWSB

Many attractive features….

- ✓ **EWSB is triggered by a new strongly-coupled dynamics (more than one confinement scale in Nature?)**
- ✓ **No fundamental scalars (composite Higgs?)**
- ✓ **No hierarchy problem, no fine-tuning (best alternative to SUSY?)**
- ✓ **A plenty of new hadron-like objects, difficult to find/treat though (composite Dark Matter? LHC phenomenology?)**

Evolutions of DEWSB ideas/realizations….

Technicolor

Extended TC

Walking TC

Bosonic TC

Composite Higgs…

???

Hill & Simmons, Phys. Rept. 381, 235 (2003)
Sannino, Acta Phys. Polon. B40, 3533 (2009), etc

No reliable UV completion consistent with EW precision tests yet….

Toy-model of DEWSB: SU(2)LxSU(2)R LσM

Techniquark weak-SU(2) doublet: $$\tilde{Q} = \begin{pmatrix} \tilde{U} \\ \tilde{D} \end{pmatrix}$$

the source term

$$-g_{\rm TC}\bar{Q}(S + i\gamma_5 P^a)Q \quad \to \quad -g_{\rm TC}\Big(\langle\bar{Q}Q\rangle S + \bar{Q}(S + i\gamma_5 P^a\tau^a)Q\Big)$$

scalar T-sigma (singlet rep.) — **lightest T-glueball**

pseudoscalar T-pions (adjoint rep.) — **collective excitation of T-quark condensate**

QGC formation

$$\bar{Q}Q \to \langle\bar{Q}Q\rangle + \bar{Q}Q$$

$$S = u + \sigma$$

T-pion mass

$$m_Q \ll m_\pi = -\frac{g_{\rm TC}\langle\bar{\tilde{Q}}\tilde{Q}\rangle}{u}$$

global chiral SSB

$$SU(2)_{\rm L}\otimes SU(2)_{\rm R} \to SU(2)_{\rm V\equiv L+R}$$

$$\mu_{\rm S,H} \ll m_{\tilde{\pi}}$$

Potential

$$\frac{1}{2}\mu_{\rm S}^2(S^2+P^2) + \mu_{\rm H}^2\mathcal{H}^2 - \frac{1}{4}\lambda_{\rm TC}(S^2+P^2)^2 - \lambda_{\rm H}\mathcal{H}^4 + \lambda\mathcal{H}^2(S^2+P^2)$$

$$\langle\mathcal{H}\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad u = \left(\frac{\lambda_{\rm H}}{\delta}\right)^{1/3} g_{\rm TC}^{-1/3}\,, \qquad v = \left(\frac{\xi\lambda}{\lambda_{\rm H}}\right)^{1/2}\left(\frac{\lambda_{\rm H}}{\delta}\right)^{1/3} g_{\rm TC}^{-1/3}$$

Spontaneous EWSB

- *Both chiral and EW SSB are dynamically linked to T-quark condensate*
- *T-pion gets mass via T-sigma interaction with T-quark condensate*
- *T-pions remain physical, the Higgs-like mechanism becomes effective*

Thermal masses and renormalisation conditions

Thermal corrections

$$\mu_\alpha^2(T) = \mu_\alpha^2 + c_\alpha T^2$$

In analogy to QCD:

$$\left\langle \bar{\tilde{Q}}\tilde{Q} \right\rangle_T = \left\langle \bar{\tilde{Q}}\tilde{Q} \right\rangle \left[1 - \frac{1}{4 f_{\tilde{\pi}}^2} T^2 - \frac{1}{96 f_{\tilde{\pi}}^4} T^4 \right]$$

$$f_{\tilde{\pi}}^2 = -\frac{(m_{\tilde{U}} + m_{\tilde{D}}) \left\langle \bar{\tilde{Q}}\tilde{Q} \right\rangle}{m_{\tilde{\pi}}^2}$$

Counterterm potential:

$$\begin{aligned} V_{\rm ct} =& \frac{1}{2}\delta\mu_S^2 \phi_{\tilde{\sigma}}^2 + \frac{1}{2}\delta\mu_H^2 \phi_h^2 \\ &+ \frac{1}{4}\delta\lambda_{\rm TC}\phi_{\tilde{\sigma}}^4 + \frac{1}{4}\delta\lambda_H \phi_h^4 - \frac{1}{2}\delta\lambda \phi_h^2 \phi_{\tilde{\sigma}}^2 , \end{aligned}$$

$$\begin{aligned} \delta\mu_H^2 =& \frac{1}{2}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial \phi_h^2} \right\rangle_{\rm vac} - \frac{3}{2v}\left\langle \frac{\partial V_{\rm CW}^{(1)}}{\partial \phi_h} \right\rangle_{\rm vac} \\ &+ \frac{u}{2v}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial \phi_h \partial \phi_{\tilde{\sigma}}} \right\rangle_{\rm vac} , \\ \delta\mu_S^2 =& \frac{1}{2}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial \phi_{\tilde{\sigma}}^2} \right\rangle_{\rm vac} - \frac{3}{2u}\left\langle \frac{\partial V_{\rm CW}^{(1)}}{\partial \phi_{\tilde{\sigma}}} \right\rangle_{\rm vac} \\ &+ \frac{v}{2u}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial \phi_h \partial \phi_{\tilde{\sigma}}} \right\rangle_{\rm vac} , \end{aligned}$$

$$\begin{aligned} c_H =& \frac{1}{2}\lambda_H - \frac{1}{3}\lambda + \frac{3}{16}g^2 + \frac{1}{16}g'^2 \\ &+ \frac{1}{4}(y_t^2 + y_b^2 + y_c^2 + y_s^2 + y_u^2 + y_d^2) \\ &+ \frac{1}{12}(y_\tau^2 + y_e^2 + y_\mu^2) , \\ c_S =& \frac{1}{2}\lambda_{\rm TC} - \frac{1}{3}\lambda + \frac{2}{3}\mathcal{Y}_{\rm TC}^2 , \end{aligned}$$

$$\left\langle \frac{\partial V_{\rm eff}}{\partial \phi_\alpha} \right\rangle_{\rm vac} = \left\langle \frac{\partial V_0}{\partial \phi_\alpha} \right\rangle_{\rm vac} , \left\langle \frac{\partial^2 V_{\rm eff}}{\partial \phi_\alpha^2} \right\rangle_{\rm vac} = \left\langle \frac{\partial^2 V_0}{\partial \phi_\alpha^2} \right\rangle_{\rm vac}$$

$$\left\langle \frac{\partial^2 V_{\rm eff}}{\partial \phi_h \partial \phi_{\tilde{\sigma}}} \right\rangle_{\rm vac} = \left\langle \frac{\partial^2 V_0}{\partial \phi_h \partial \phi_{\tilde{\sigma}}} \right\rangle_{\rm vac}$$

$$\delta\lambda_H = -\frac{1}{2v^2}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial \phi_h^2} \right\rangle_{\rm vac} + \frac{1}{2v^3}\left\langle \frac{\partial V_{\rm CW}^{(1)}}{\partial \phi_h} \right\rangle_{\rm vac}$$

$$\delta\lambda_{\rm TC} = -\frac{1}{2u^2}\left\langle \frac{\partial^2 V_{\rm CW}^{(1)}}{\partial \phi_{\tilde{\sigma}}^2} \right\rangle_{\rm vac} + \frac{1}{2u^3}\left\langle \frac{\partial V_{\rm CW}^{(1)}}{\partial \phi_{\tilde{\sigma}}} \right\rangle_{\rm vac}$$

GWs from dynamical EWSB

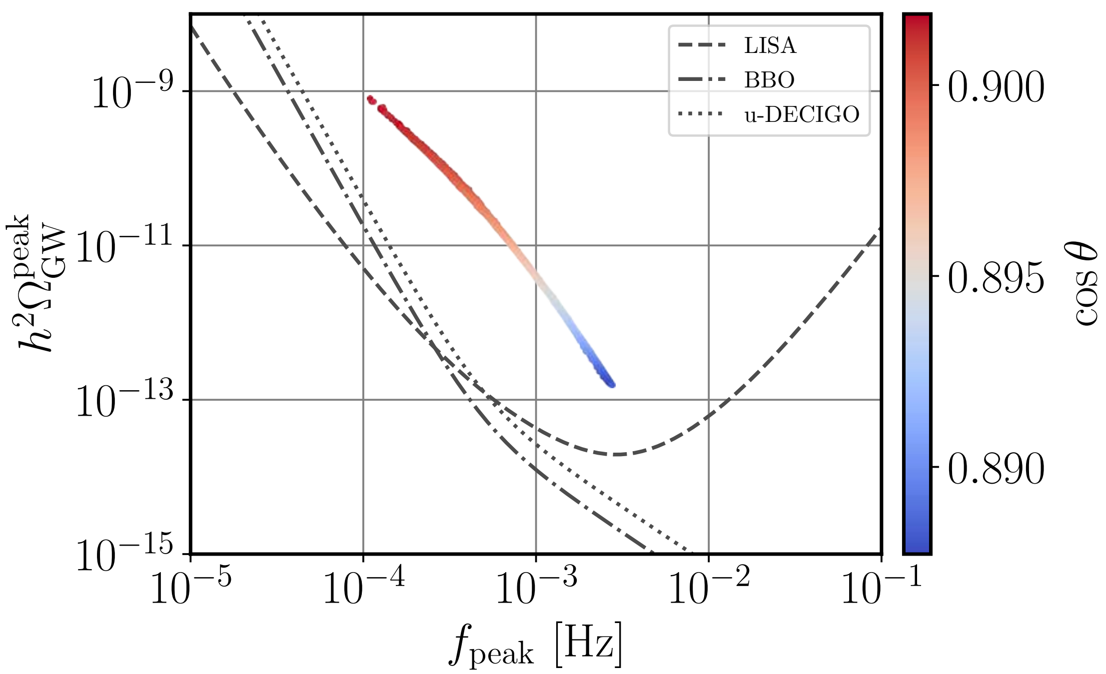
Scan parameters

$$m_{\tilde\sigma}\,,\qquad m_{\tilde\pi}\,,\qquad m_{\tilde Q}\,,\qquad \mathcal{Y}_{\rm TC}\,,\qquad \theta$$

Limits on physical parameters:

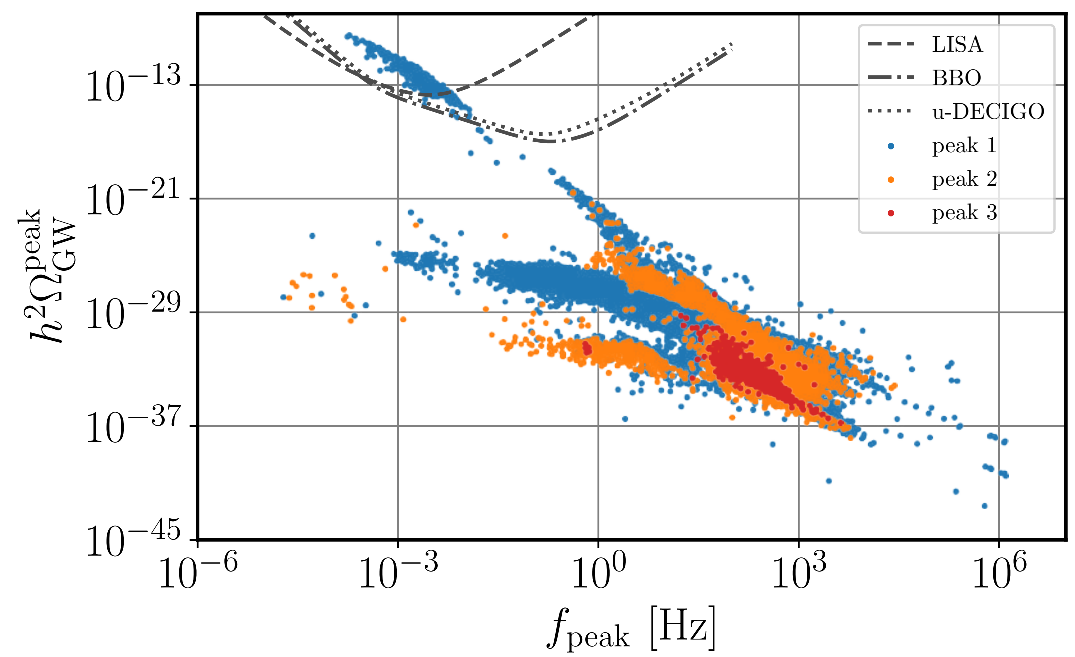
$$m_{\tilde\pi}\gtrsim 140\,{\rm GeV}\,,\ m_{\tilde\sigma}\gtrsim 500\,{\rm GeV}\,,\ m_{\tilde Q}\gtrsim 300\,{\rm GeV}$$

Example of a one-parametric scan:



$$m_{\tilde\sigma} = 702.0\,{\rm GeV},\ m_{\tilde\pi} = 347.1\,{\rm GeV},$$
$$m_{\tilde Q} = 466.6\,{\rm GeV},\ \mathcal{Y}_{\rm TC} = 2.86.$$

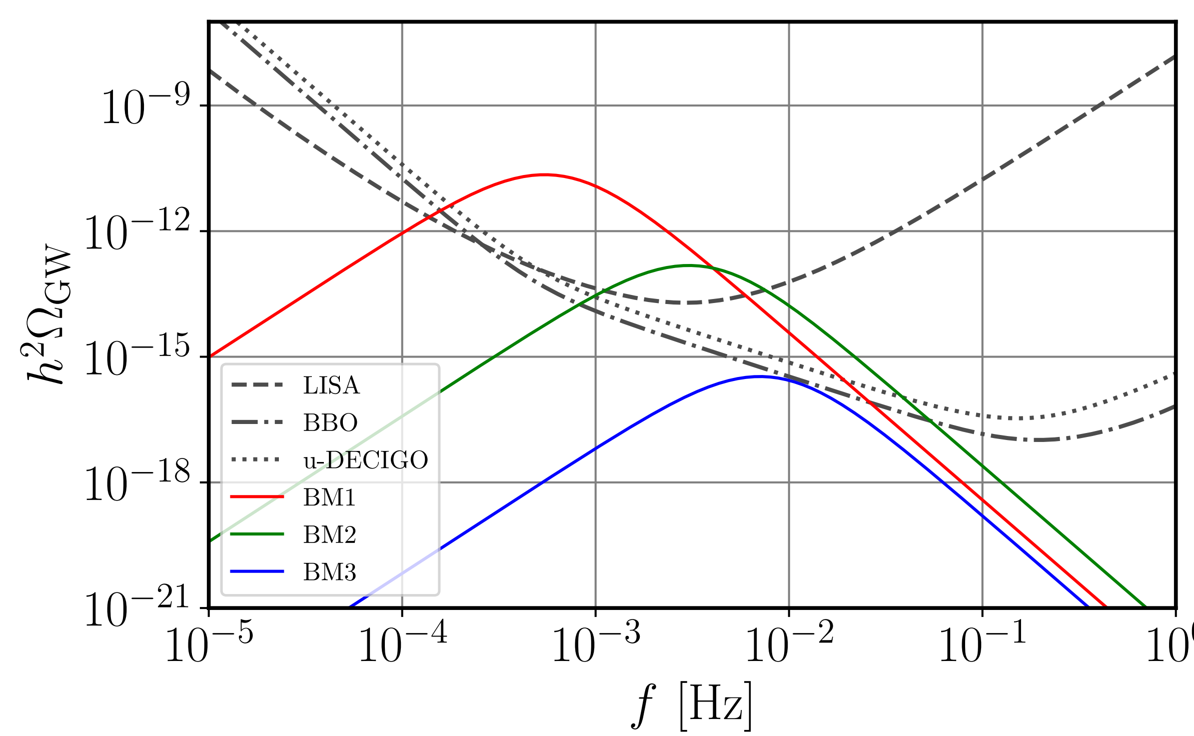
Multi-peak structure of the spectrum:



Benchmark points:

	Color	T_p	α	β/H	$\Delta v/T_p$	$\Delta u/T_p$
BM1	Red	46.36	1.23	124.50	5.47	1.86
BM2	Green	73.15	0.30	439.10	3.54	1.37
BM3	Blue	107.10	0.04	698.24	2.36	0.98

	Color	$m_{\tilde\sigma}$	$m_{\tilde\pi}$	$m_{\tilde Q}$	$\mathcal{Y}_{\rm TC}$	$\cos\theta$	u
BM1	Red	785.4	239.9	591.8	2.85	0.884	207.9
BM2	Green	744.3	303.7	470.3	2.85	0.859	165.0
BM3	Blue	626.2	291.1	490.5	2.38	0.859	206.4



Summary

- We considered three distinct examples for New Physics scenarios and performed an analysis of primordial GWs spectra originating from FOPTs in early Universe

- Primordial gravitational waves represent a complimentary source of information to the collider (such as HE-LHC and Circular e+e- Collider etc) and astroparticle (Dark Matter searches, cosmic rays etc) measurements

- Combining such future measurements as those of triple Higgs coupling, Higgs partners searches, precision W mass measurements, Dark Matter searches, neutrino sector properties with possible primordial GWs detection would provide strong case of probing many different classes of BSM scenarios