AUDIBLE GRAVITATIONAL ECHOES OF NEW PHYSICS

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10th LISA Cosmology Working Group Workshop - UiS

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

However, it fails to…

- Explain neutrino masses ⟵ Today's focus
- Explain dark matter
- Explain CP violation and matter/anti-matter assymetry
- Explain the observed flavour structure - Flavour Problem

SGWB

✓ Superposition of unresolved astrophysical sources

✓ Cosmological origin

- ◉ Inflation
- ◉ Topological defects
- ◉ Phase transitions

SGWB as a gravitational probe to New Physics, in combination with, or beyond colliders' reach

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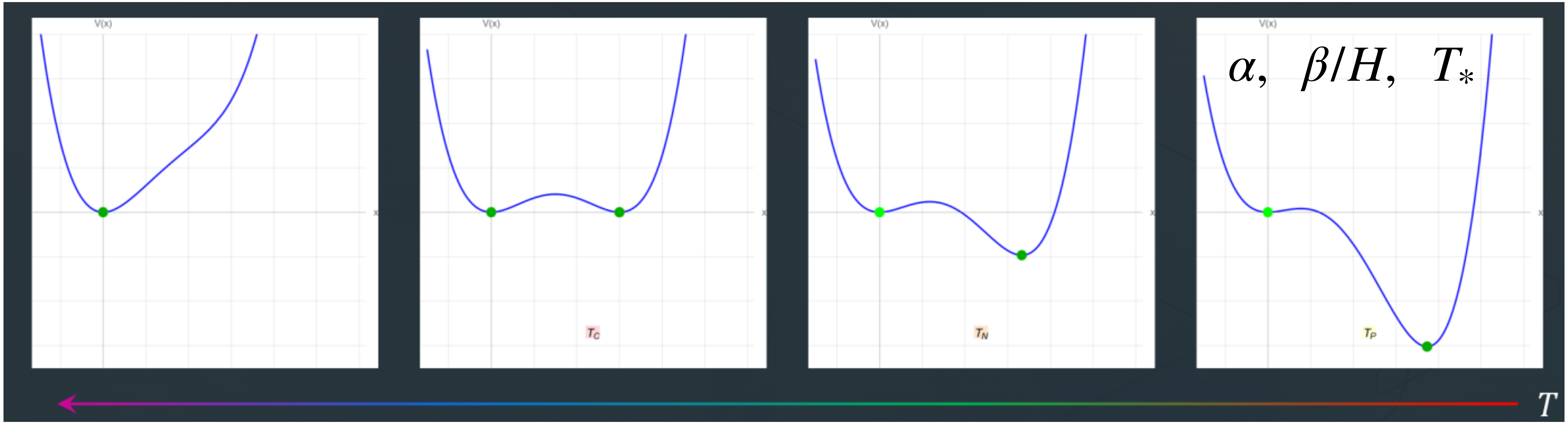
First order phase transition (FOPT)

(Illustration)



Credit: Marco Finetti

We use the templates for SW peak in [Caprini et al. JCAP 03 (2020) 024]

See Marek's talk for details on phase transitions

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Scenario 1: Neutrino masses from lepton number symmetry breaking

[2304.02399] ADDAZI, MARCIANÒ, APM, PASECHNIK, VIANA, YANG

Which seesaw model?

	L^i	ν_R^i	S^i	σ	H	Model
$U(1)_L$	1	1	$\times$	-2	0	T1S
	1	1	0	-1	0	IS
	1	1	-1	2	0	EIS

- $v_\sigma \gg v_h$ for the T1S; **beyond LISA**
- $v_\sigma \gg v_h$ and/or $\Lambda \ll v_h$ for the IS; **beyond LISA**
- $v_\sigma \sim v_h$ and $\Lambda \gg v_h$ for the EIS. **Well motivated for LISA range**

$$\boldsymbol{m}_\nu^{\mathrm{T1S}} \approx \frac{1}{\sqrt{2}} \frac{\boldsymbol{y}_\nu^2}{\boldsymbol{y}_\sigma} \frac{v_h^2}{v_\sigma}, \qquad \boldsymbol{m}_\nu^{\mathrm{IS}} \approx \frac{\boldsymbol{y}_\nu^2}{\boldsymbol{y}_\sigma^2} \frac{\boldsymbol{\Lambda} v_h^2}{v_\sigma^2}, \qquad \boldsymbol{m}_\nu^{\mathrm{EIS}} \approx \frac{\boldsymbol{y}_\nu^2 \boldsymbol{y}_\sigma}{2\sqrt{2}} \frac{v_h^2 v_\sigma}{\boldsymbol{\Lambda}^2}$$

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Neutrino sector revisited

$$\mathcal{L}_\nu^{\rm EIS} = y_\nu^{ij} \overline{L}_i \tilde{H} \nu_{{\rm R}j} + y_\sigma^{ij} \bar{S}_i^c S_j \sigma + y_\sigma^{\prime ij} \bar{\nu}_{{\rm R}i}^c \nu_{{\rm R}j} \sigma^* + \Lambda^{ij} \bar{\nu}_{{\rm R}i}^c S_j + {\rm h.c.}$$

$$\boldsymbol{M}_{\boldsymbol{\nu}}^{\rm EIS} = \begin{pmatrix} 0 & \frac{v_h}{\sqrt{2}} \boldsymbol{y_\nu} & 0 \\ \frac{v_h}{\sqrt{2}} \boldsymbol{y_\nu} & \frac{v_\sigma}{\sqrt{2}} \boldsymbol{y'_\sigma} & \boldsymbol{\Lambda} \\ 0 & \boldsymbol{\Lambda} & \frac{v_\sigma}{\sqrt{2}} \boldsymbol{y_\sigma} \end{pmatrix}$$

✓ EFT approach

$$\boldsymbol{m}_\nu^{\rm EIS} \approx \frac{\boldsymbol{y}_{\boldsymbol{\nu}}^2 \boldsymbol{y_\sigma}}{2\sqrt{2}} \frac{v_h^2 v_\sigma}{\boldsymbol{\Lambda}^2}$$

3 light active neutrinos

$$\boldsymbol{m}_{N^\pm} \approx \boldsymbol{\Lambda} \pm \frac{v_\sigma}{2\sqrt{2}} (\boldsymbol{y_\sigma} + \boldsymbol{y'_\sigma})$$

6 heavy neutrinos

Use normal ordering masses as input to obtain $y_\sigma^i = 2\sqrt{2} \frac{m_{\nu_i} \Lambda^2}{v_h^2 v_\sigma y_{\nu_i}^2}$

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$$V_0(H,\sigma) = V_{\rm SM}(H) + V_{\rm 4D}(H,\sigma) + V_{\rm 6D}(H,\sigma) + V_{\rm soft}(\sigma)$$

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

$$V_{\rm 4D}(H,\sigma) = \mu_\sigma^2 \sigma^\dagger \sigma + \lambda_\sigma (\sigma^\dagger \sigma)^2 + \lambda_{\sigma h} H^\dagger H \sigma^\dagger \sigma \,,$$

$$V_{\rm 6D}(H,\sigma) = \frac{\delta_0}{\Lambda^2}(H^\dagger H)^3 + \frac{\delta_2}{\Lambda^2}(H^\dagger H)^2 \sigma^\dagger \sigma + \frac{\delta_4}{\Lambda^2} H^\dagger H (\sigma^\dagger \sigma)^2 + \frac{\delta_6}{\Lambda^2}(\sigma^\dagger \sigma)^3 \,,$$

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

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

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

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

Results

Parameter	Range	Distribution
m_{h_2}	$[60,\ 1000]$ GeV	linear
m_J	$[10^{-10}$ eV, 100 keV$]$	exponential
m_{ν_1}	$[10^{-6},\ 10^{-1}]$ eV	exponential
$\mathrm{Br}(h_1 \to JJ)$	$[10^{-15},\ 0.18]$	exponential
$\sin(\alpha_h)$	$\pm[0,\ 0.24]$	linear
v_σ	$[100,\ 1000]$ GeV	linear
Λ	$[10,\ 1000]$ TeV	exponential
$\frac{\delta_0 v_h^2}{2\Lambda^2}$	$\pm[10^{-10},\ 4\pi]$	exponential
$\frac{\delta_2 \max(v_h^2, v_\sigma^2)}{2\Lambda^2}$	$\pm[10^{-10},\ 4\pi]$	exponential
$\frac{\delta_4 v_\sigma^2}{2\Lambda^2}$	$\pm[10^{-10},\ 4\pi]$	exponential

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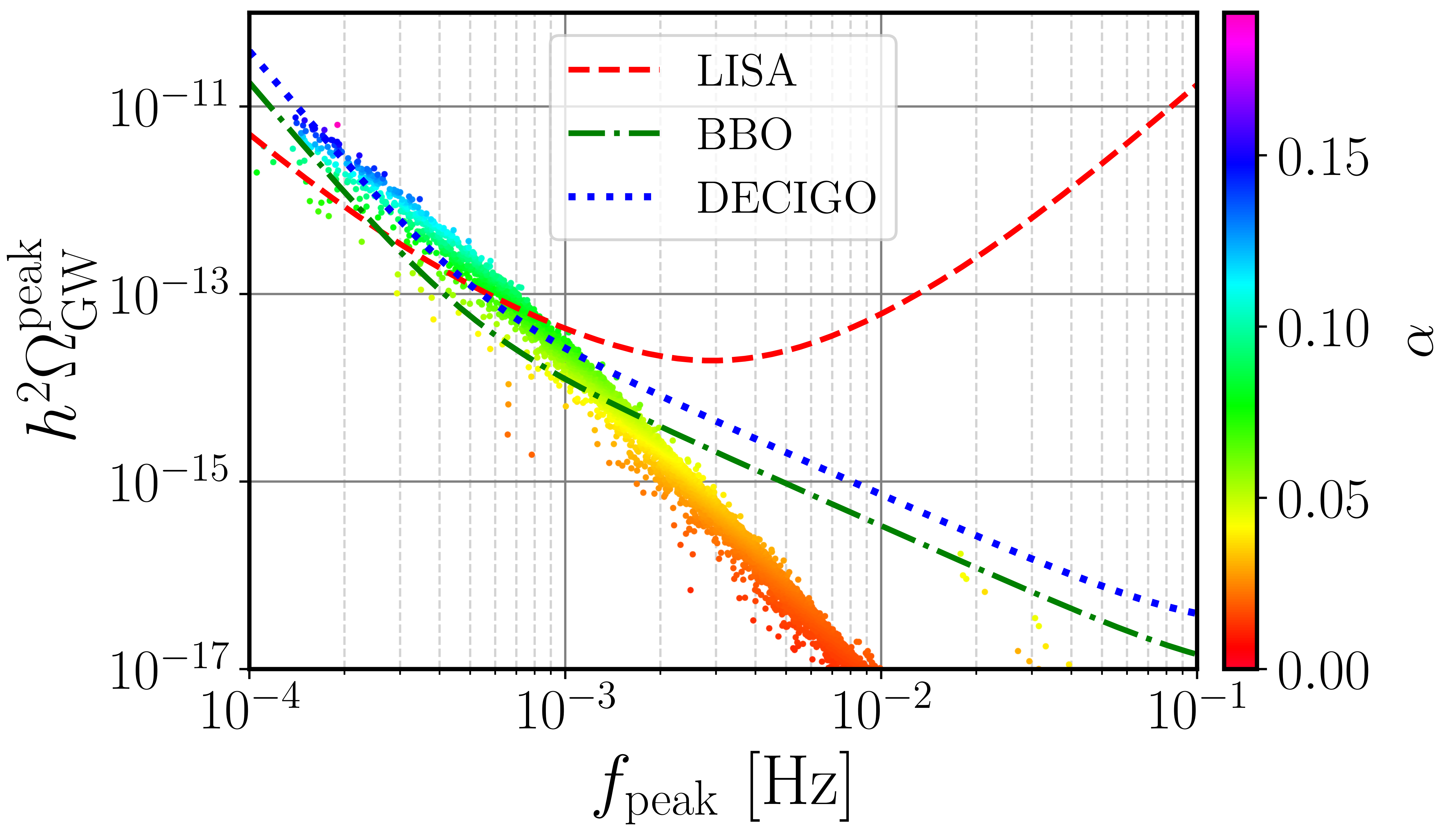
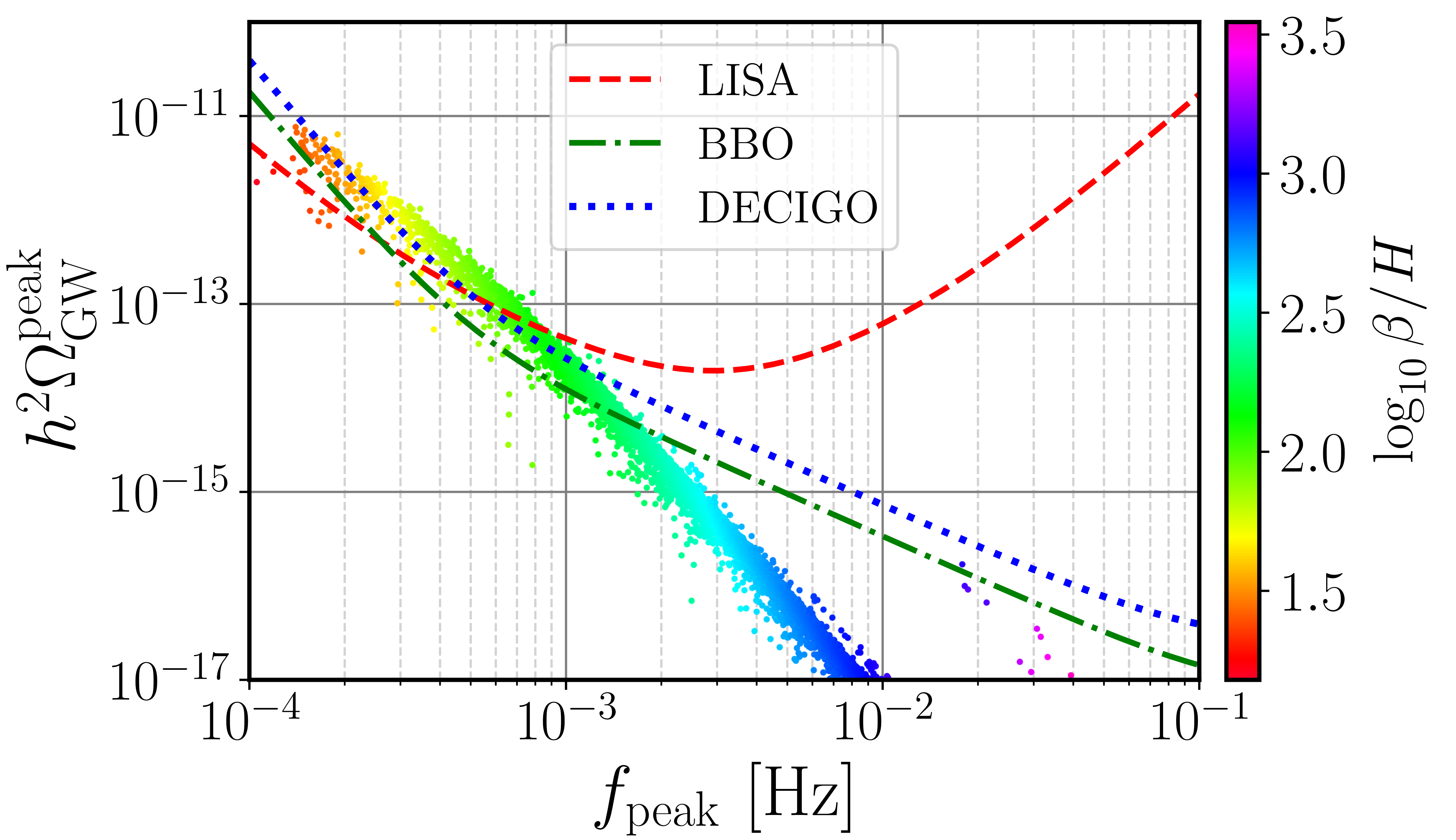
Results

$$\log_{10}(h^2\Omega_{\rm GW}^{\rm peak}) \propto -2\log_{10} f_{\rm peak} + \log_{10} F(\alpha, T_*)$$





Scan using *CosmoTransitions*

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

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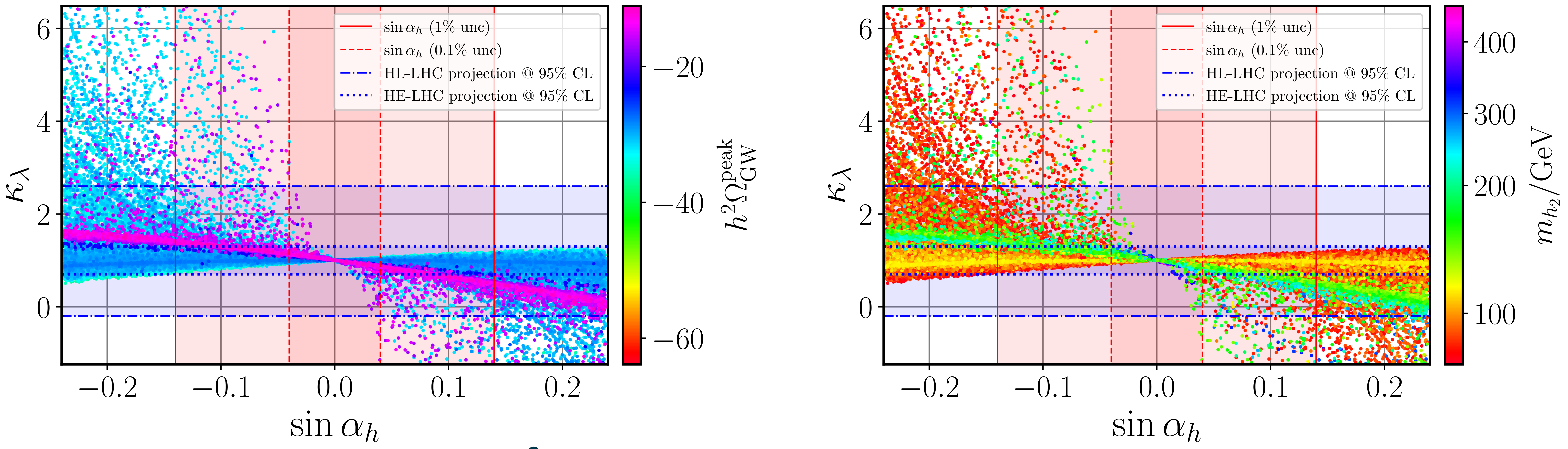
Trilinear Higgs coupling, scalar mixing angle and CP-even scalar mass



$$\kappa_\lambda \equiv \lambda_{h_1h_1h_1}/\lambda_{\rm SM}\,, \quad \lambda_{\rm SM} = 3m_{h_1}^2/v_h$$

- **Magenta band (LISA) / green band favour** $0 < \kappa_\lambda < 2$ and $m_{h_2} \approx (200 \pm 50)$ GeV
- **Illustrates the potential interplay between collider and SGWB interplay**

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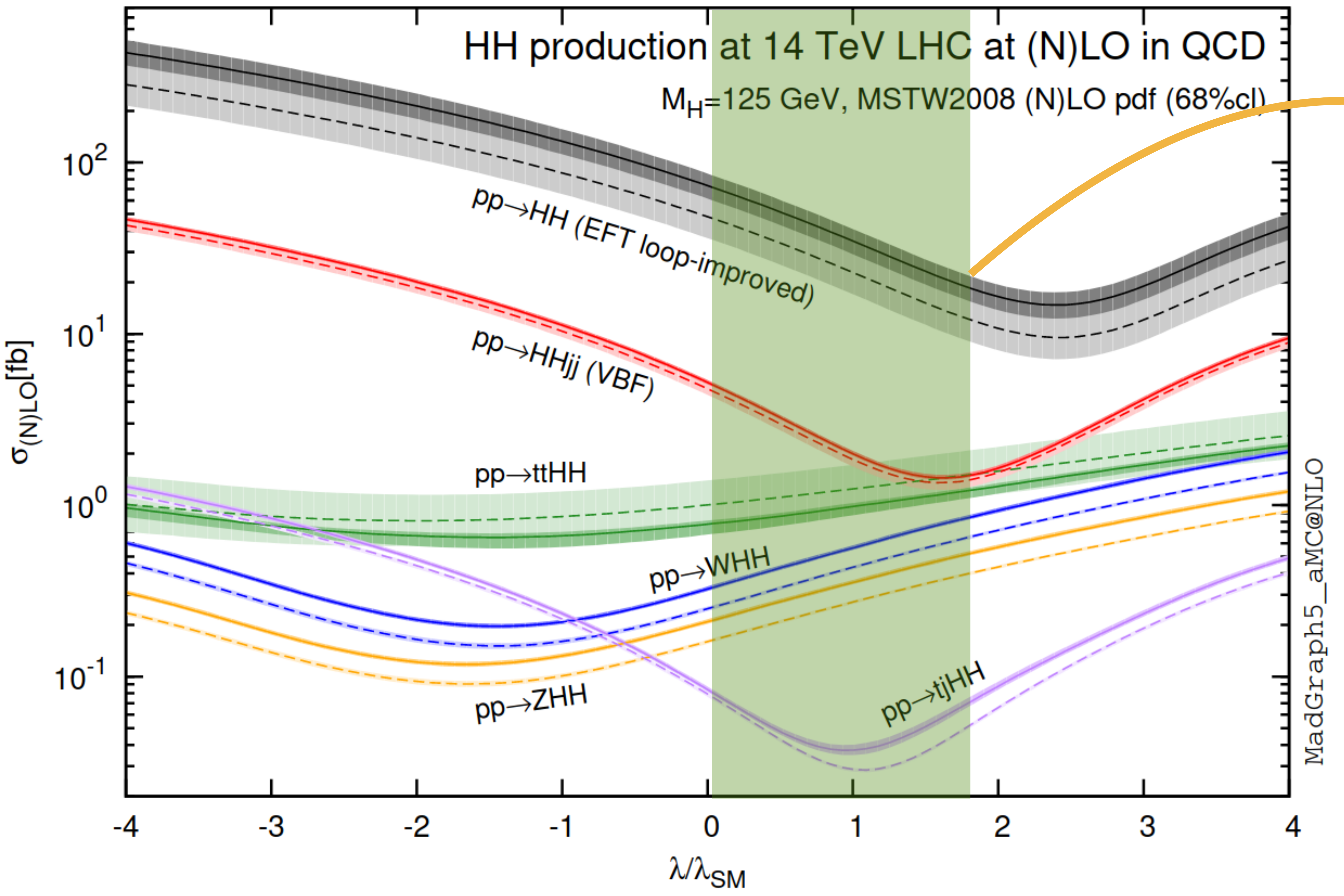
Di-Higgs production



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

Region compatible with observable SFOPTs in the 6D Majoron model

Scenario 2: Neutrino masses with colour restoration at low temperature

[WORK IN PROGRESS] BERTENSTAM, EKSTEDT, FINETTI, APM, PASECHNIK, VATELLIS

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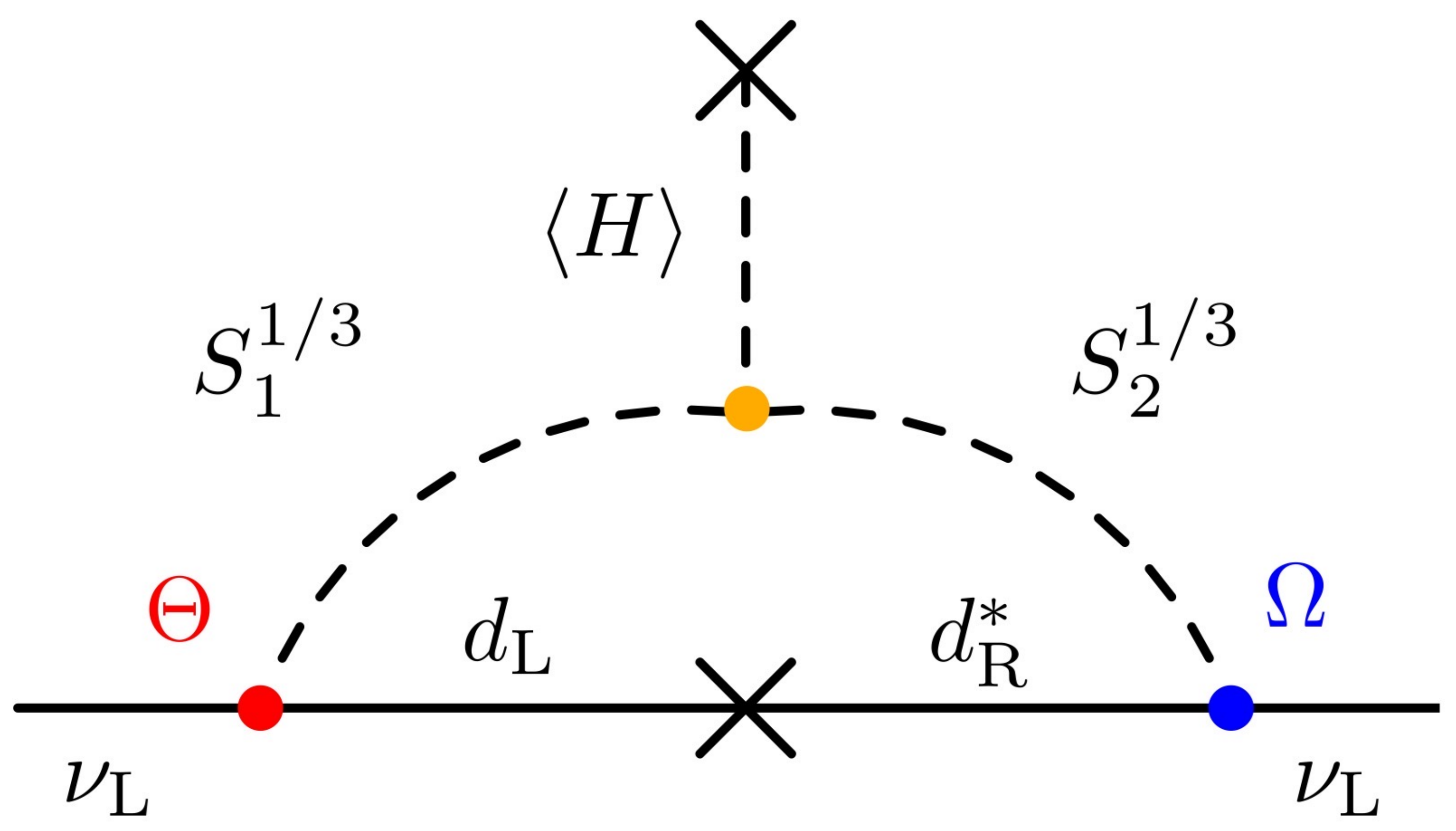
Another possibility for neurtrino masses

$$\mathcal{L}_{\rm Y} = \Theta_{ij}\bar{Q}^c_j L_i S + \Omega_{ij}\bar{L}_i d_j R^\dagger + \Upsilon_{ij}\bar{u}_j e_i S^\dagger + \text{h.c.}$$



$$S \sim (\bar{\mathbf{3}}, \mathbf{1})_{1/3} \qquad R \sim (\bar{\mathbf{3}}, \mathbf{2})_{1/6}$$

- **And an exhaustive flavour analysis**

  [Gonçalves, APM, Pasechnik, Porod, 2206.01674]

$$(M_\nu)_{ij} = \frac{3}{16\pi^2(m^2_{S_2^{1/3}} - m^2_{S_1^{1/3}})} \frac{v a_1}{\sqrt{2}} \ln\left(\frac{m^2_{S_2^{1/3}}}{m^2_{S_1^{1/3}}}\right) \sum_{m,a} (m_d)_a V_{am} (\Theta_{im}\Omega_{ja} + \Theta_{jm}\Omega_{ia}) \,,$$

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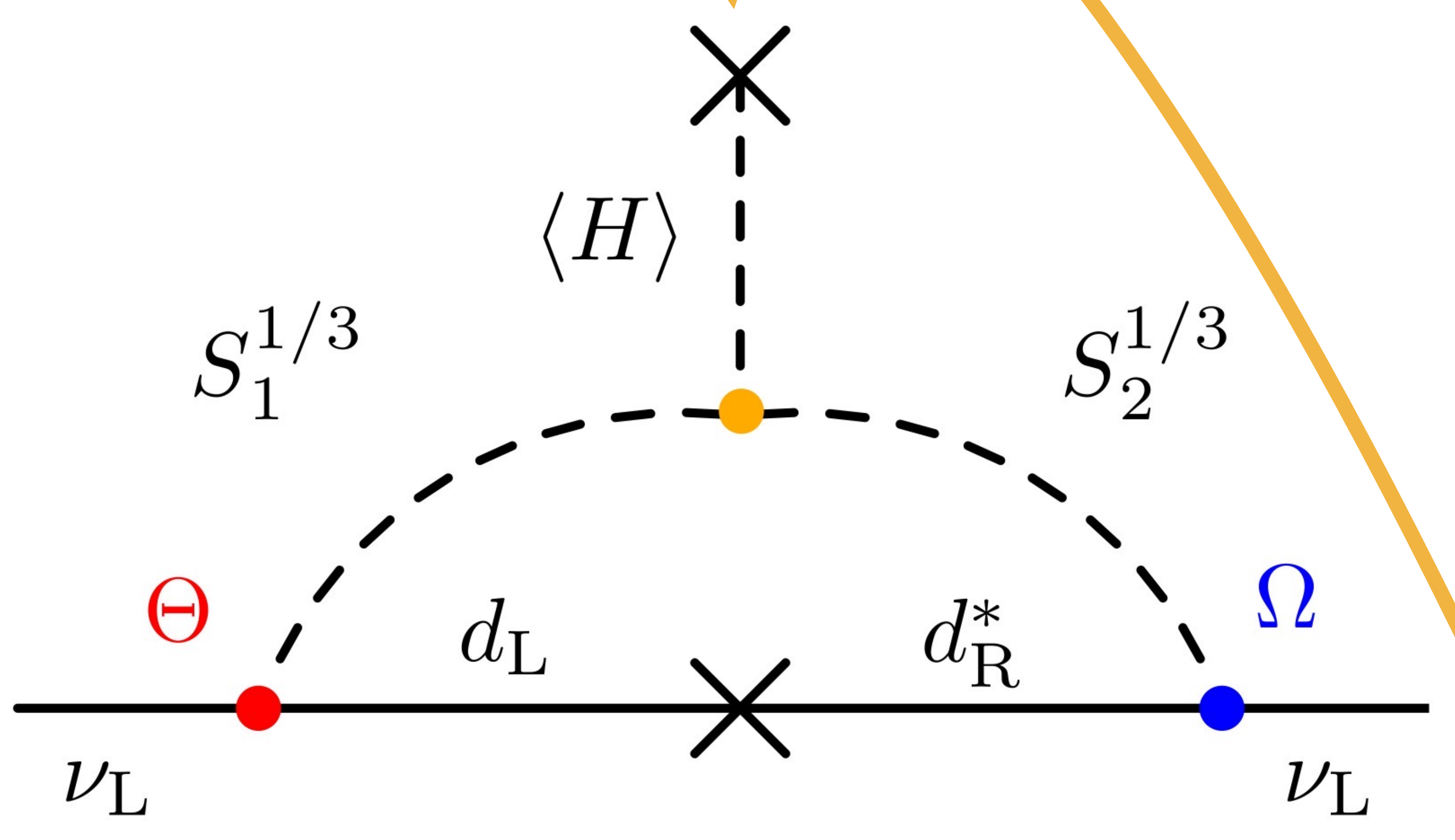
Another possibility for neurtrino masses

$$V \supset -\mu^2|H|^2 + \mu_S^2|S|^2 + \mu_R^2|R|^2 + \lambda(H^\dagger H)^2 + g_{HR}(H^\dagger H)(R^\dagger R) + g'_{HR}(H^\dagger R)(R^\dagger H) + g_{HS}(H^\dagger H)(S^\dagger S) + \left(a_1 RSH^\dagger + \text{h.c.}\right) .$$



✓ Consider the possibility of LQ VEVs at finite T

✓ Classify all possible FOPTs and determine SGWB

$$(M_\nu)_{ij} = \frac{3}{16\pi^2(m^2_{S_2^{1/3}} - m^2_{S_1^{1/3}})} \frac{v a_1}{\sqrt{2}} \ln\left(\frac{m^2_{S_2^{1/3}}}{m^2_{S_1^{1/3}}}\right) \sum_{m,a} (m_d)_a V_{am} (\Theta_{im}\Omega_{ja} + \Theta_{jm}\Omega_{ia}) ,$$

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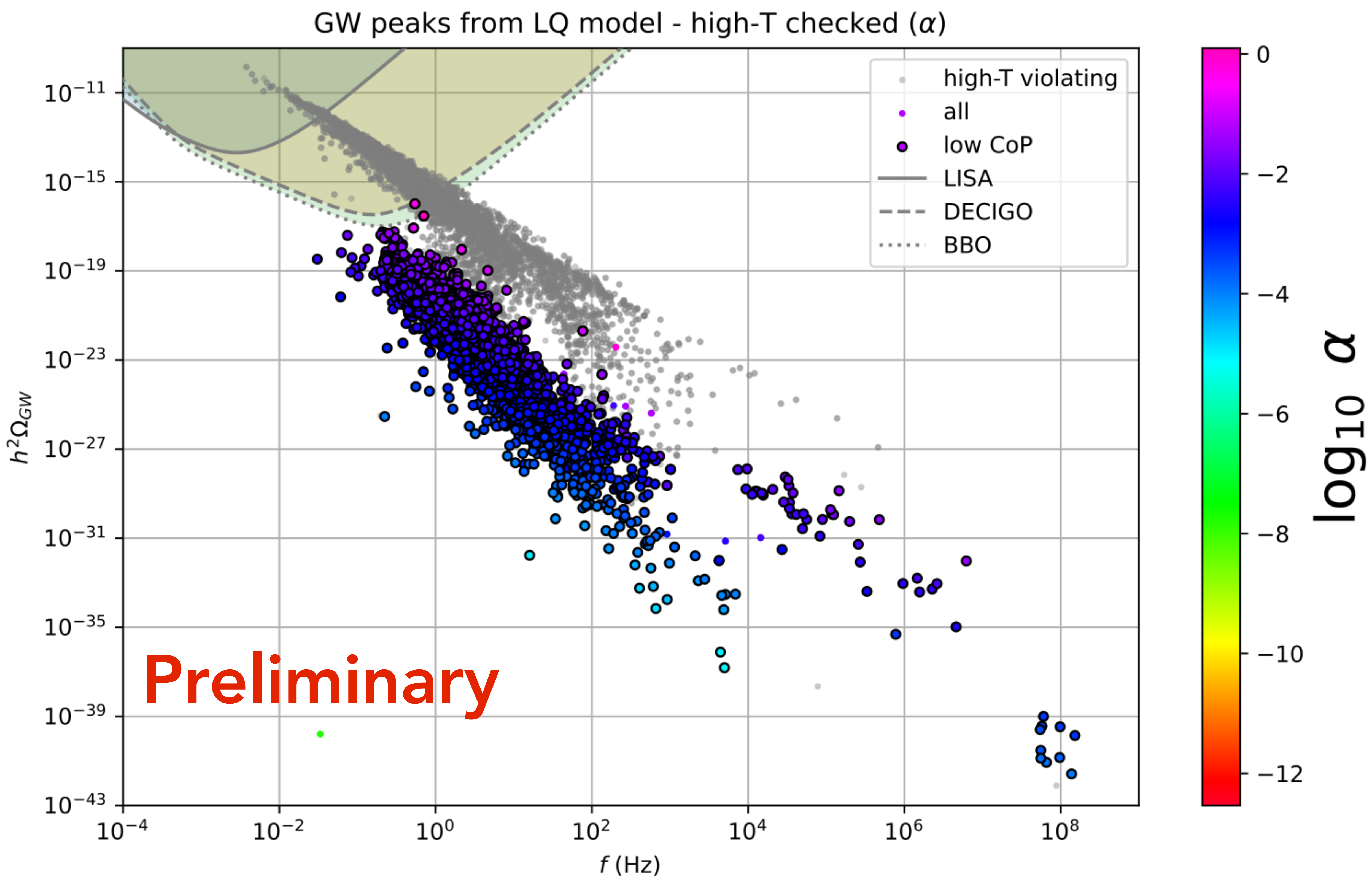

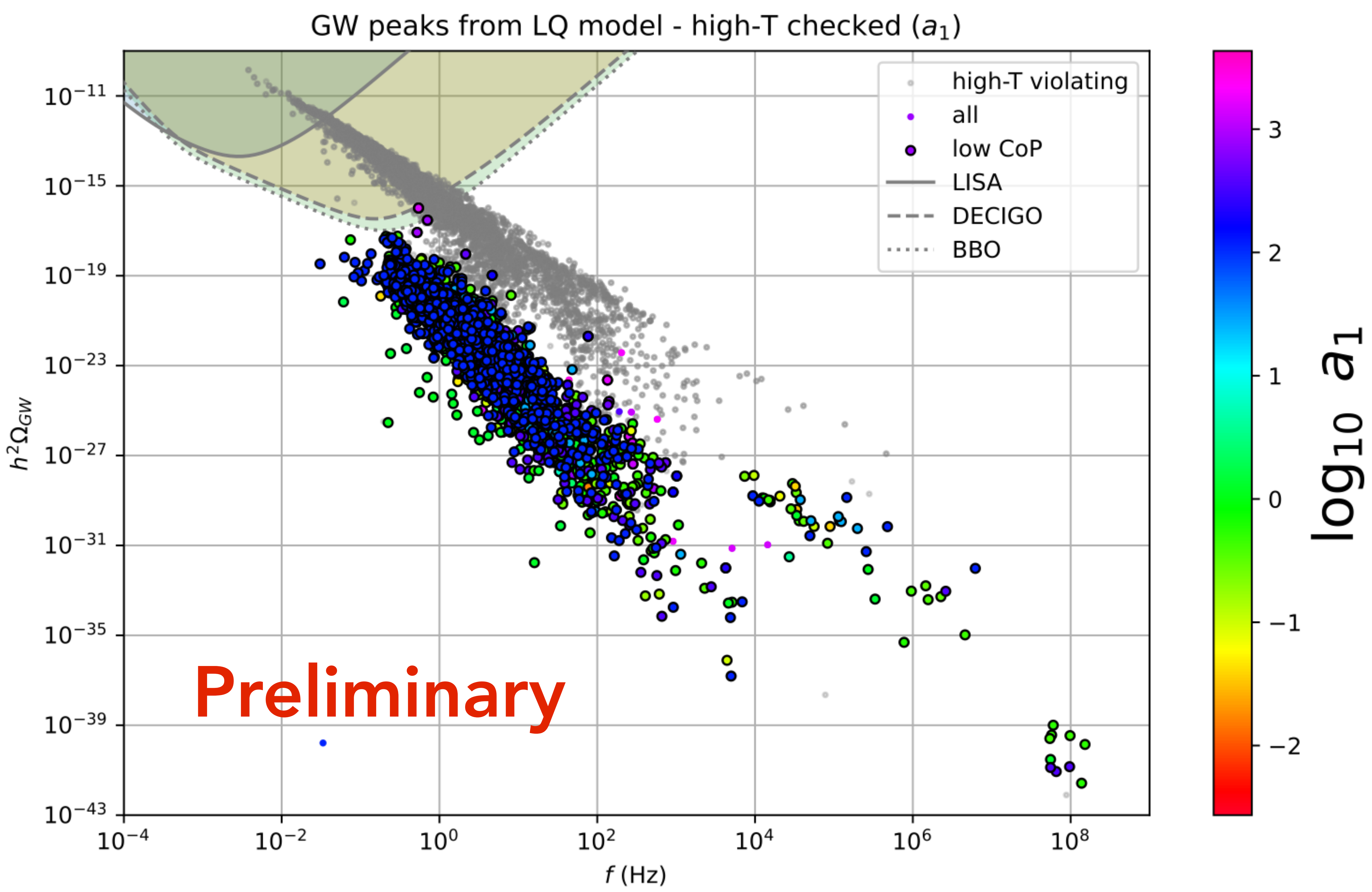

DRalgo + hacked *CosmoTransitions*

[Ekstedt, Schicho, Tenkanen, 2205.08815]

Needs 2 LQs $\longleftarrow 1 \lesssim a_1/GeV \lesssim 1000$

BBO?

- Viable FOPTs (CoP)

$(0,\phi_s,0) \to (\phi_h,0,0): \quad 3872$

$(\phi_h,\phi_s,\phi_r) \to (\phi_h',0,0): \quad 13$

- Low T phase

Colour restoration + EW broken

Colour restoration

Take home message

- Neutrino mass models require BSM physics
- LISA + future GW detectors can help uncovering its nature
- Combination with collider observables for further insights: new scalars (singlet, coloured,…) trilinear couplings, mixing angles

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THANK YOU
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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 ⟶ SGWB

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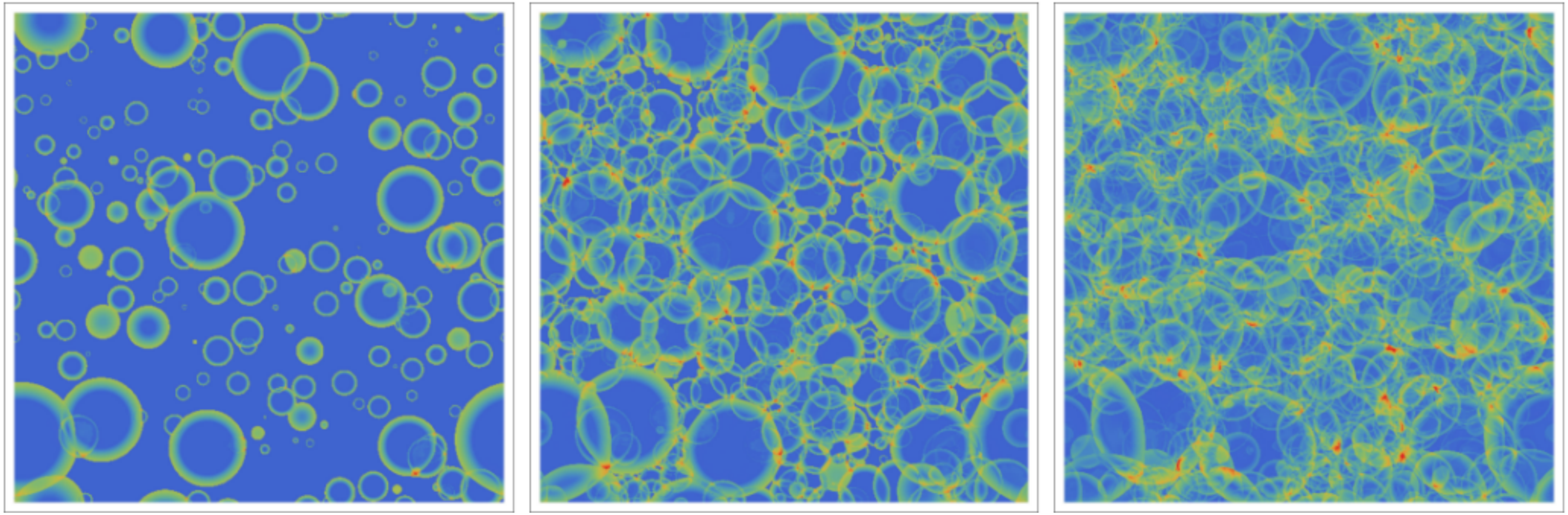
Basics of Phase Transitions

(Illustration)

✓ First order phase transition (FOPT) example



Credit: JCAP04(2021)014, Jinno, Konstantin, Rubira

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FOPTs $\longrightarrow$ 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

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

Peak amplitude

Spectral function

$$h^2\Omega_{\rm GW}^{\rm peak}(f_{\rm peak}) = 7.835 \times 10^{-17} f_{\rm peak}^{-2} \left(\frac{100}{g_*}\right)^{2/3} \left(\frac{T_*}{100}\right)^2 \frac{K^{\frac{3}{2}}}{c_s} \quad \text{for} \quad \mathrm{H}\tau_{\rm sh} = \frac{2}{\sqrt{3}}\frac{\mathrm{HR}}{\mathrm{K}^{1/2}} < 1$$

$$h^2\Omega_{\rm GW}^{\rm peak}(f_{\rm peak}) = 7.835 \times 10^{-17} f_{\rm peak}^{-2} \left(\frac{100}{g_*}\right)^{2/3} \left(\frac{T_*}{100}\right)^2 \frac{K^2}{c_s^2} \quad \text{for} \quad \mathrm{H}\tau_{\rm sh} = \frac{2}{\sqrt{3}}\frac{\mathrm{HR}}{\mathrm{K}^{1/2}} \simeq 1\,,$$

$$f_{\rm peak} = 26 \times 10^{-6} \left(\frac{1}{HR}\right)\left(\frac{T_*}{100}\right)\left(\frac{g_*}{100\ \mathrm{GeV}}\right)^{\frac{1}{6}} \mathrm{Hz} \qquad HR = \frac{H}{\beta}(8\pi)^{\frac{1}{3}} \max(v_b, c_s) \qquad K = \frac{\kappa\alpha}{1+\alpha}$$

We use the templates for SW peak in [Caprini et al. JCAP 03 (2020) 024]

Inverted equations

$$\lambda_{\sigma h} = \frac{\tan(2\alpha_h)\left(M_{hh}^2 - M_{\sigma\sigma}^2\right)}{2 v_h v_\sigma} - \frac{\delta_2 v_h^2 + \delta_4 v_\sigma^2}{\Lambda^2},$$

$$\lambda_\sigma = -\frac{2A(\mathrm{Br}) v_h^3 v_\sigma \csc(\alpha_h) + \Lambda^2 \sec(2\alpha_h)\left(M_{\sigma\sigma}^2 - M_{hh}^2\right) + \Lambda^2\left(-M_{hh}^2 + M_{\sigma\sigma}^2 - 2M_{\sigma\sigma}^2 v_\sigma\right)}{4\Lambda^2 (v_\sigma - 1) v_\sigma^2}$$

$$+ \frac{\delta_4 v_h^2}{2\Lambda^2},$$

$$\lambda_h = \frac{1}{2}\left(\frac{M_{hh}^2}{v_h^2} - \frac{3\delta_0 v_h^2 + \delta_2 v_\sigma^2}{\Lambda^2}\right),$$

$$\delta_6 = \frac{2A(\mathrm{Br}) v_h^3 v_\sigma \csc(\alpha_h) - \Lambda^2\left(\sec(2\alpha_h)\left(M_{hh}^2 - M_{\sigma\sigma}^2\right) + M_{hh}^2 + M_{\sigma\sigma}^2\right)}{6(v_\sigma - 1) v_\sigma^4},$$

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

$$M_{hh,\sigma\sigma}^2 = \frac{1}{2}\left[m_{h_1}^2 + m_{h_2}^2 \pm \left(m_{h_1}^2 - m_{h_2}^2\right)\cos(2\alpha_h)\right] \quad \text{and} \quad M_{\sigma h}^2 = \frac{1}{2}\left(m_{h_1}^2 - m_{h_2}^2\right)\sin(2\alpha_h)$$

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Phenomenological inputs

Invisible Higgs decays limit : $\mathrm{Br}\left(h \to JJ\right) < 0.18$ <u>Used as input</u>

[Phys. Rev. D 105 (2022) 9 092007]

Scalar mixing angle limit: $|\sin\alpha_h| < 0.23$ <u>Used as input</u>

[Papaefstathiou, Robens, White, 2207.00043]

Also used as inputs: $m_{h_1} = 125.09\ \mathrm{GeV},\ m_{h_2}, m_J,\ v_h,\ v_\sigma, \Lambda,\ \delta_2,\ \delta_4$

$$\lambda^{(0)}_{JJh_1} = \frac{v_h}{\Lambda^2}\left[\left(v_h^2\delta_2 + v_\sigma^2\delta_4 + \Lambda^2\lambda_{\sigma h}\right)\cos\alpha_h + v_\sigma\left(v_h^2\delta_4 + 3v_\sigma^2\delta_6 + 2\Lambda^2\lambda_\sigma\right)\sin\alpha_h\right]$$

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Which seesaw model?

	L^i	ν_R^i	S^i	σ	H	Model
	1	1	$\times$	-2	0	T1S
$U(1)_L$	1	1	0	-1	0	IS
	1	1	-1	2	0	EIS

$$M_{\boldsymbol{\nu}}^{\rm T1S} = \begin{pmatrix} 0 & \frac{v_h}{\sqrt{2}}\boldsymbol{y_\nu} \\ \frac{v_h}{\sqrt{2}}\boldsymbol{y_\nu} & \frac{v_\sigma}{\sqrt{2}}\boldsymbol{y_\sigma} \end{pmatrix}, \quad M_{\boldsymbol{\nu}}^{\rm IS} = \begin{pmatrix} 0 & \frac{v_h}{\sqrt{2}}\boldsymbol{y_\nu} & 0 \\ \frac{v_h}{\sqrt{2}}\boldsymbol{y_\nu} & 0 & \frac{v_\sigma}{\sqrt{2}}\boldsymbol{y_\sigma} \\ 0 & \frac{v_\sigma}{\sqrt{2}}\boldsymbol{y_\sigma} & \boldsymbol{\Lambda} \end{pmatrix}, \quad M_{\boldsymbol{\nu}}^{\rm EIS} = \begin{pmatrix} 0 & \frac{v_h}{\sqrt{2}}\boldsymbol{y_\nu} & 0 \\ \frac{v_h}{\sqrt{2}}\boldsymbol{y_\nu} & \frac{v_\sigma}{\sqrt{2}}\boldsymbol{y'_\sigma} & \boldsymbol{\Lambda} \\ 0 & \boldsymbol{\Lambda} & \frac{v_\sigma}{\sqrt{2}}\boldsymbol{y_\sigma} \end{pmatrix}$$

$$\boldsymbol{m}_\nu^{\rm T1S} \approx \frac{1}{\sqrt{2}}\frac{\boldsymbol{y_\nu^2}}{\boldsymbol{y_\sigma}}\frac{v_h^2}{v_\sigma}, \qquad \boldsymbol{m}_\nu^{\rm IS} \approx \frac{\boldsymbol{y_\nu^2}}{\boldsymbol{y_\sigma^2}}\frac{\boldsymbol{\Lambda} v_h^2}{v_\sigma^2}, \qquad \boldsymbol{m}_\nu^{\rm EIS} \approx \frac{\boldsymbol{y_\nu^2 y_\sigma}}{2\sqrt{2}}\frac{v_h^2 v_\sigma}{\boldsymbol{\Lambda}^2}$$

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Thermal effective potential

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

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

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

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

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

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

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

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

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

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

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Minimal scalar sector

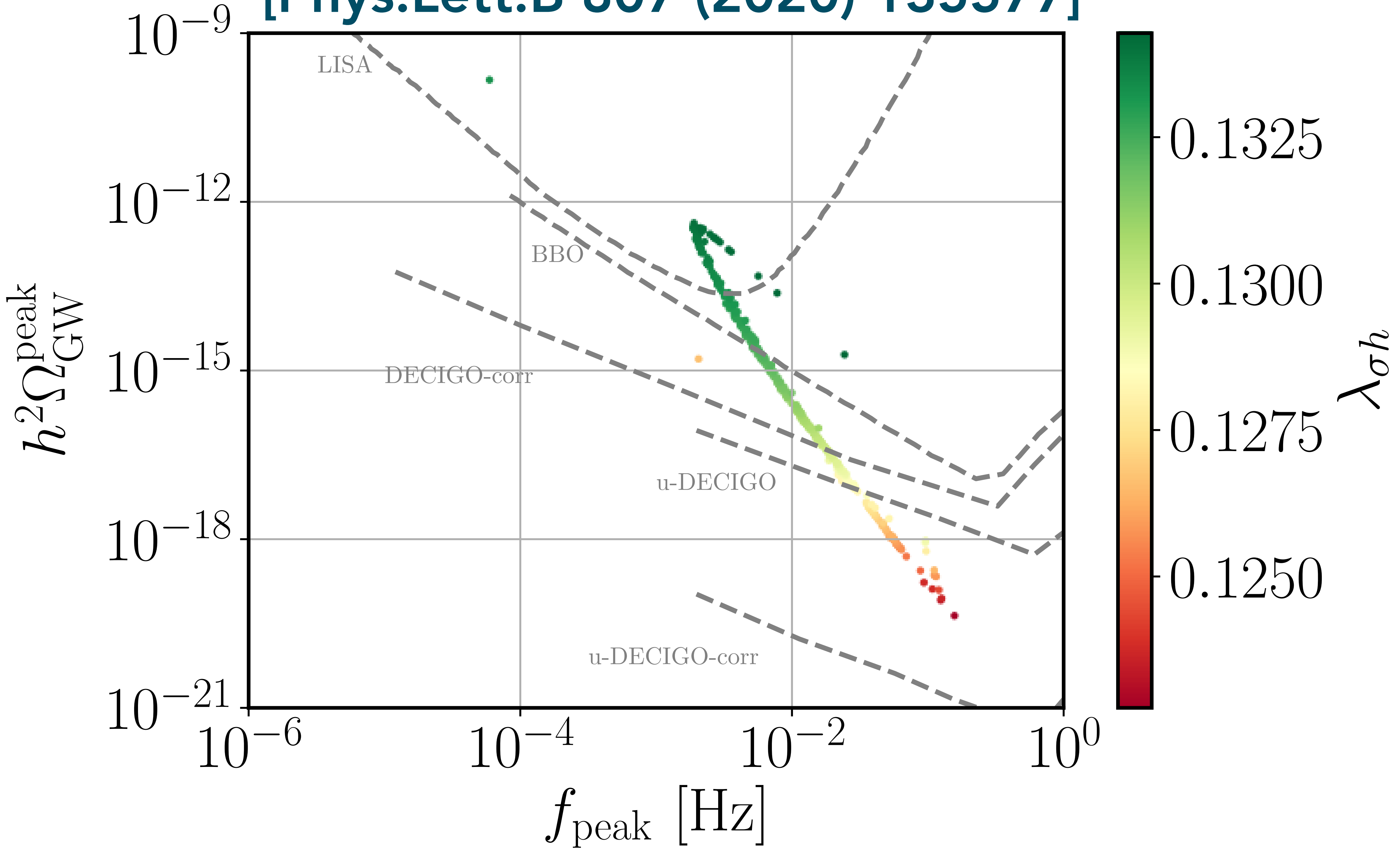
$$V_{\rm SM}(H) = \mu_h^2 H^\dagger H + \lambda_h (H^\dagger H)^2\,,$$

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

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

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

[Phys.Lett.B 807 (2020) 135577]



✓ The portal coupling size that induces SFOPTs is too large for invisible Higgs decays

✓ Only viable for Majoron O(100 GeV - 1 TeV)

Minimal scalar sector

$$\mathrm{Br}(h_1 \to JJ) = \frac{\Gamma(h_1 \to JJ)}{\Gamma(h_1 \to JJ) + \Gamma(h_1 \to \mathrm{SM})} < 0.18$$

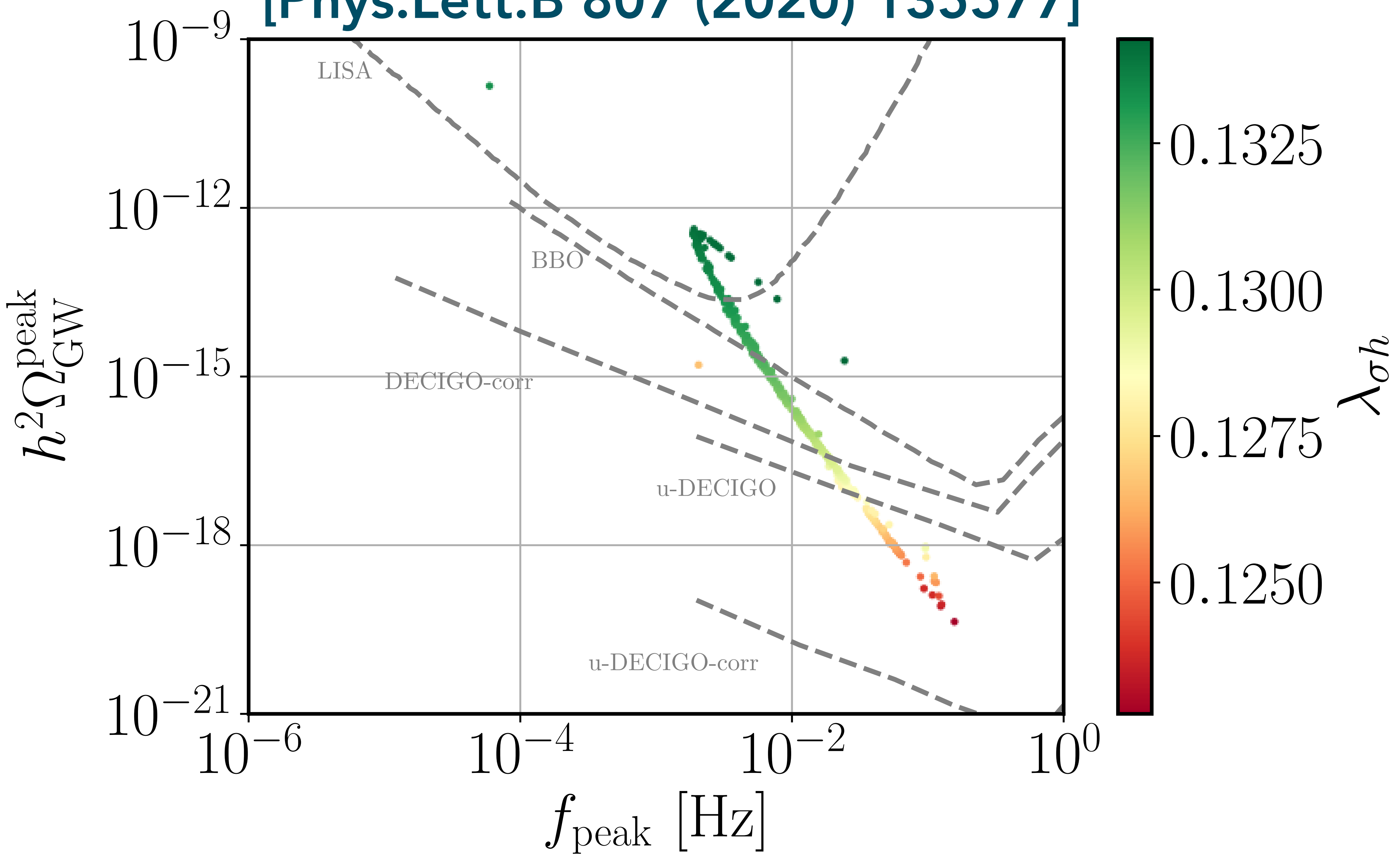
[CMS - Phys. Rev. D 105 (2022) 9 092007]

$$\Gamma(h_1 \to JJ) = \frac{1}{32\pi} \frac{\left(\lambda^{(0)}_{JJh_1}\right)^2}{m_{h_1}} \sqrt{1 - 4\frac{m_J^2}{m_{h_1}^2}}$$

$$\lambda^{(0)}_{JJh_1} = \tfrac{1}{2} v_h \lambda_{\sigma h} \cos\alpha_h$$

$$\lambda_{\sigma h} \lesssim \mathcal{O}(0.01)$$

[Phys.Lett.B 807 (2020) 135577]



✓ The portal coupling size that induces SFOPTs is too large for invisible Higgs decays

✓ Only viable for Majoron O(100 GeV - 1 TeV)

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Neutrino sector revisited

$$\mathcal{L}_\nu^{\rm EIS} = y_\nu^{ij} \overline{L}_i \tilde{H} \nu_{{\rm R}j} + y_\sigma^{ij} \bar{S}_i^c S_j \sigma + y_\sigma^{\prime ij} \bar{\nu}_{{\rm R}i}^c \nu_{{\rm R}j} \sigma^* + \Lambda^{ij} \bar{\nu}_{{\rm R}i}^c S_j + {\rm h.c.}$$

$$\boldsymbol{M}_{\boldsymbol{\nu}}^{\rm EIS} = \begin{pmatrix} 0 & \frac{v_h}{\sqrt{2}} \boldsymbol{y_\nu} & 0 \\ \frac{v_h}{\sqrt{2}} \boldsymbol{y_\nu} & \frac{v_\sigma}{\sqrt{2}} \boldsymbol{y'_\sigma} & \boldsymbol{\Lambda} \\ 0 & \boldsymbol{\Lambda} & \frac{v_\sigma}{\sqrt{2}} \boldsymbol{y_\sigma} \end{pmatrix}$$

$$\boldsymbol{m}_\nu^{\rm EIS} \approx \frac{\boldsymbol{y_\nu^2 y_\sigma}}{2\sqrt{2}} \frac{v_h^2 v_\sigma}{\boldsymbol{\Lambda}^2}$$

3 light active neutrinos

$$\boldsymbol{m}_{N^\pm} \approx \boldsymbol{\Lambda} \pm \frac{v_\sigma}{2\sqrt{2}} (\boldsymbol{y_\sigma} + \boldsymbol{y'_\sigma})$$

6 heavy neutrinos

Use normal ordering masses as input to obtain

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

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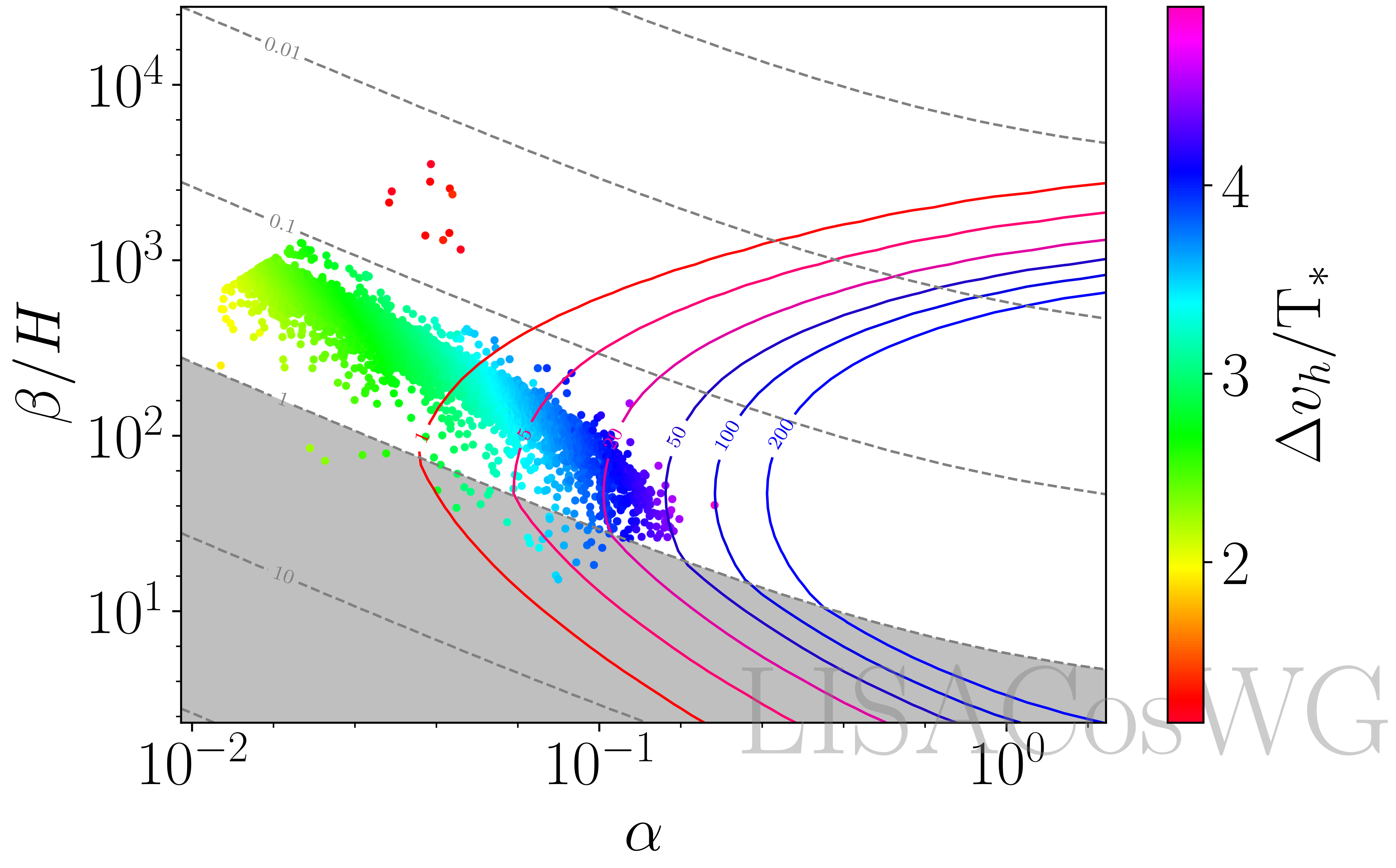
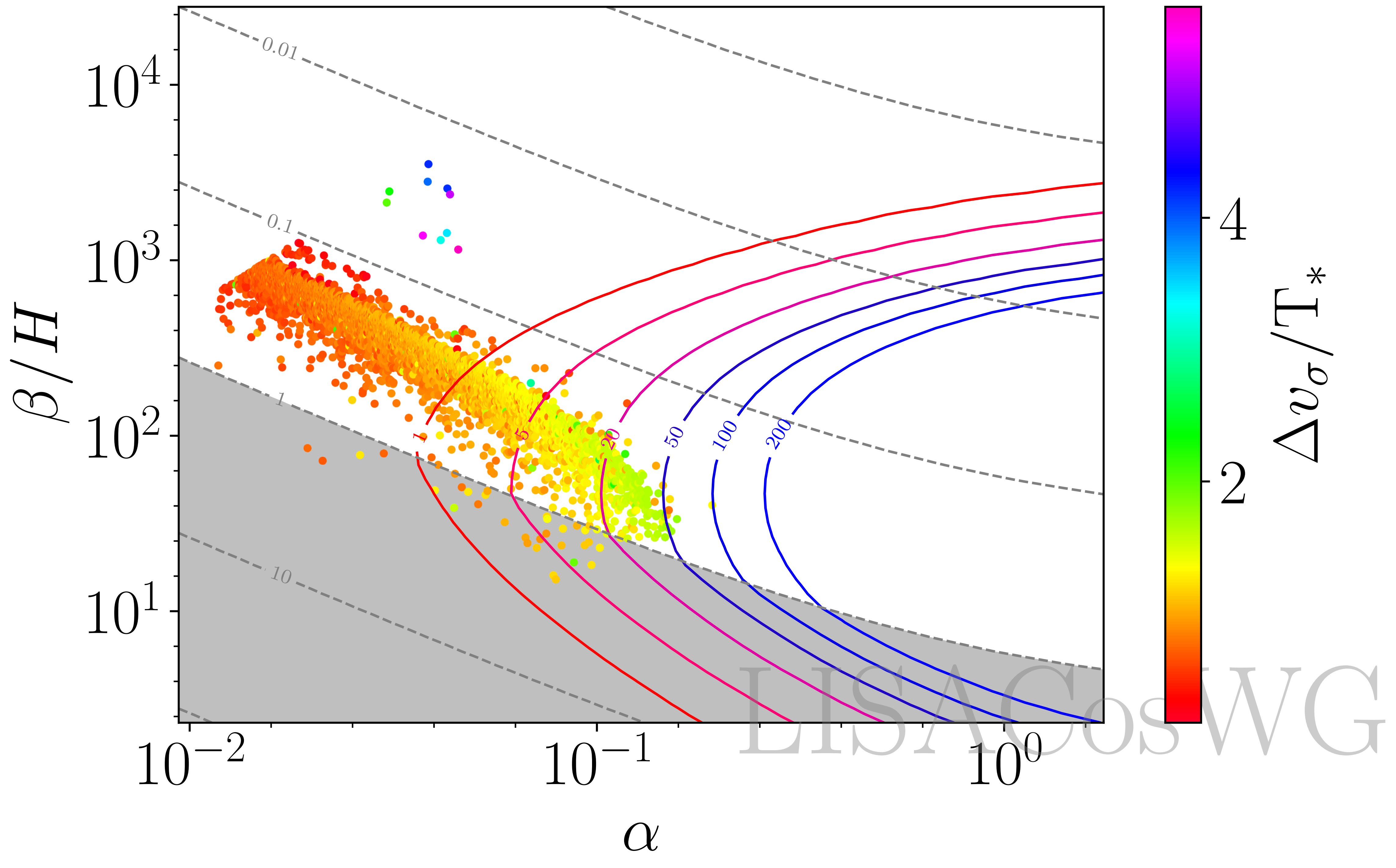
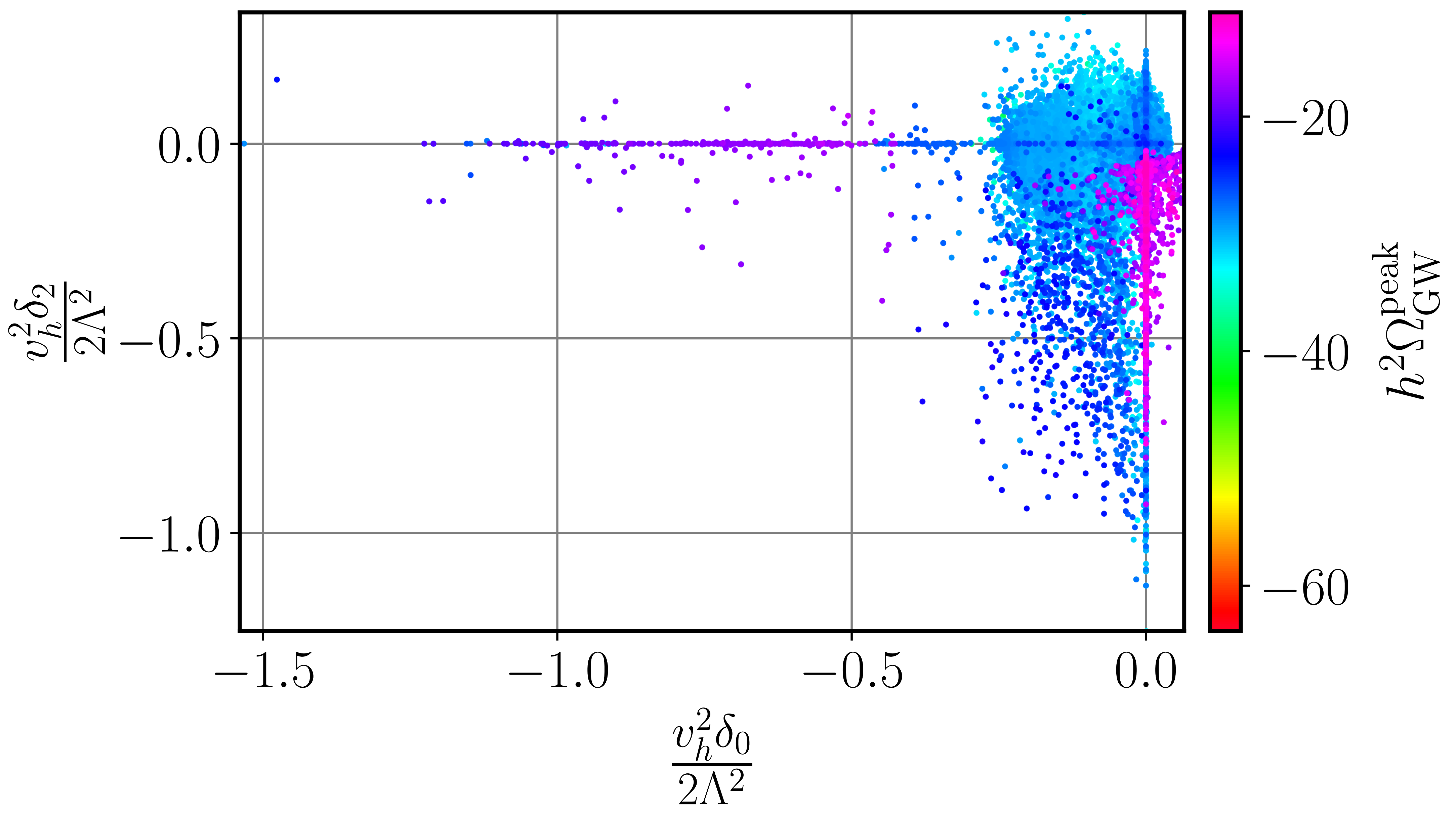
$$\Delta v_\phi = |v_\phi^f - v_\phi^i| , \qquad \phi = h, \sigma$$

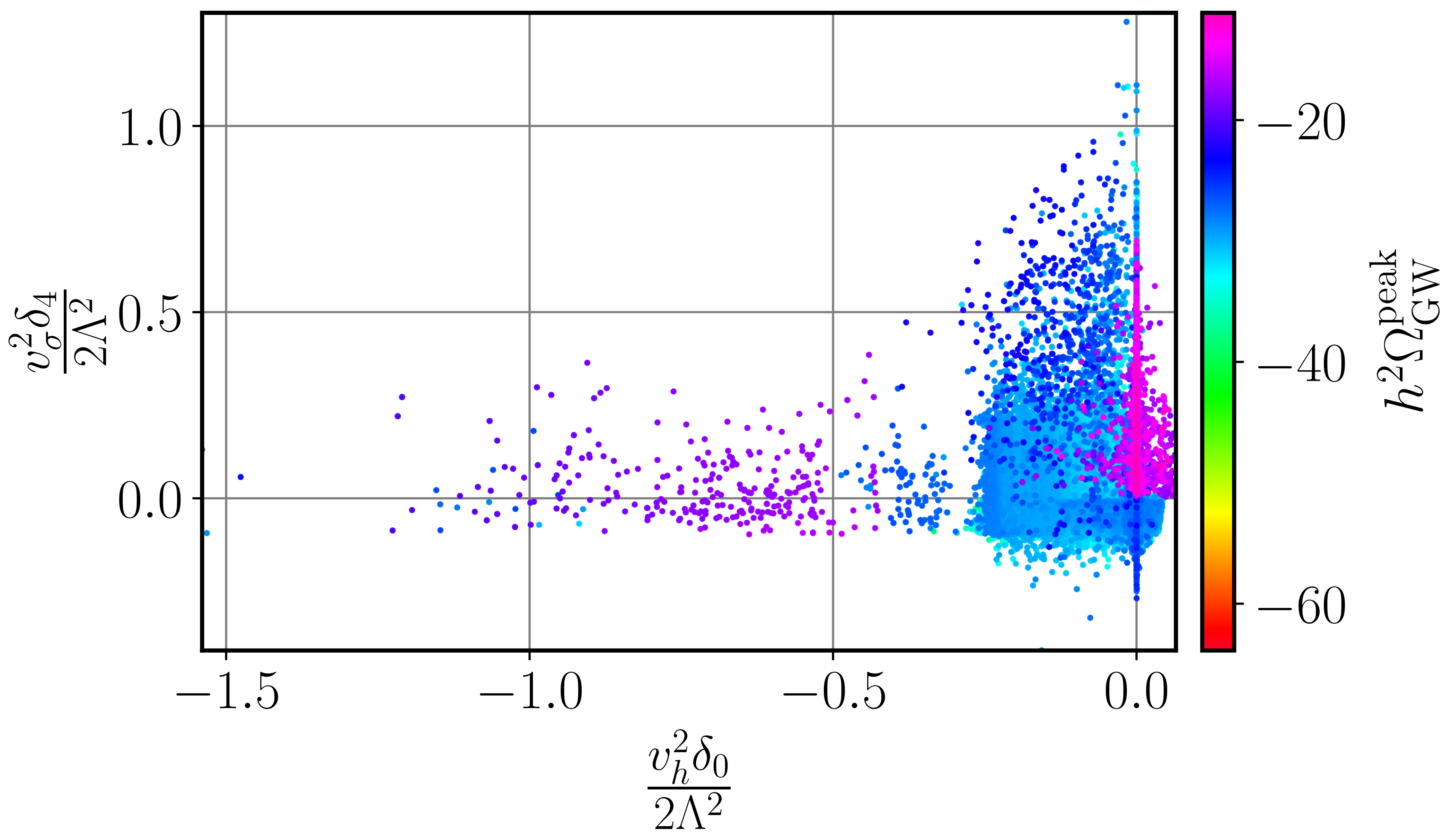
Used PTPlot for SNR [JCAP 2003 (2020) 024]

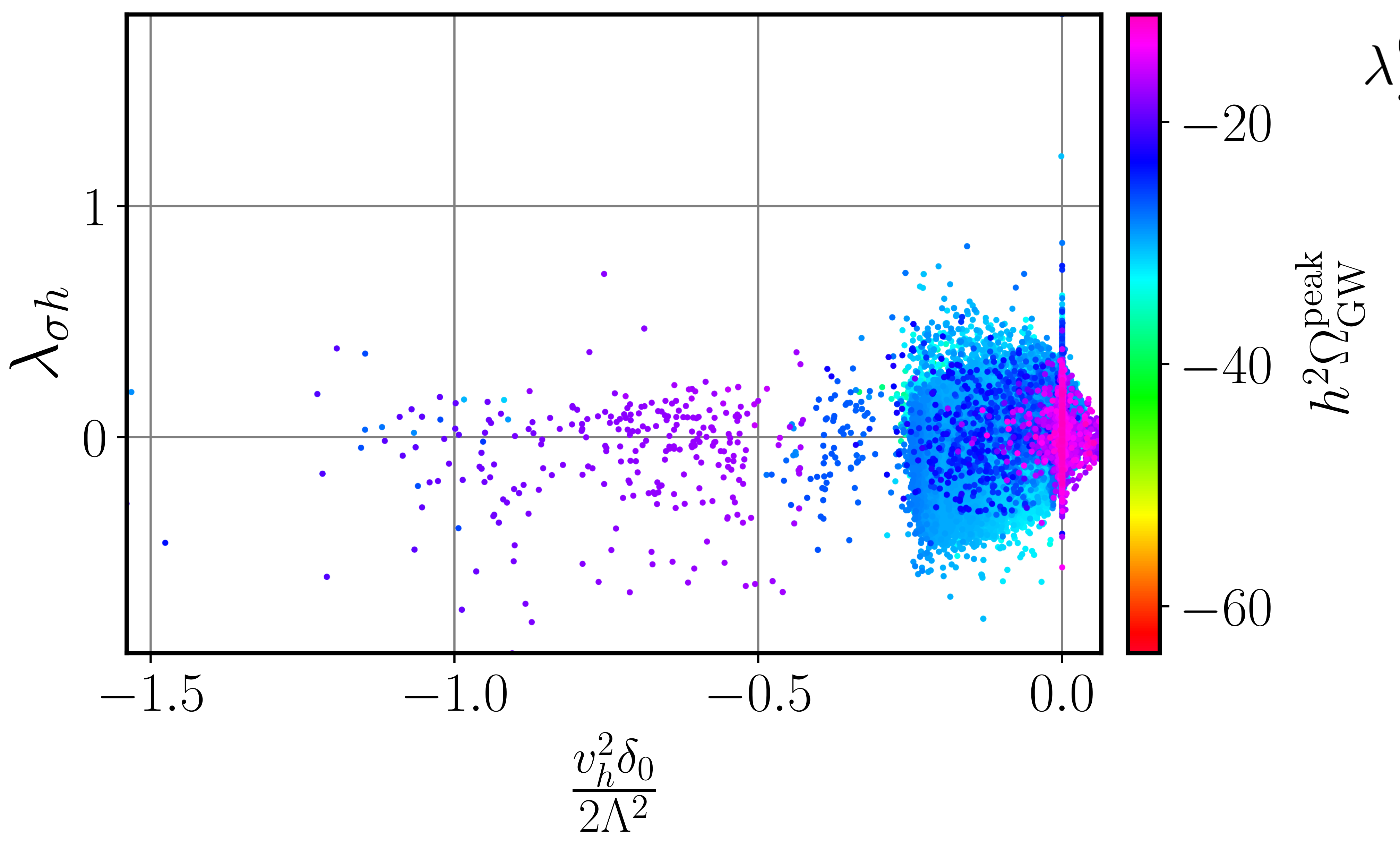




Both order parameters must be large for observable SGWB







$$\lambda^{(0)}_{JJh_1} = \frac{v_h}{\Lambda^2}\left[(v_h^2\delta_2 + v_\sigma^2\delta_4 + \Lambda^2\lambda_{\sigma h})\cos\alpha_h + v_\sigma(v_h^2\delta_4 + 3v_\sigma^2\delta_6 + 2\Lambda^2\lambda_\sigma)\sin\alpha_h\right]$$

$< \mathcal{O}(0.01)$

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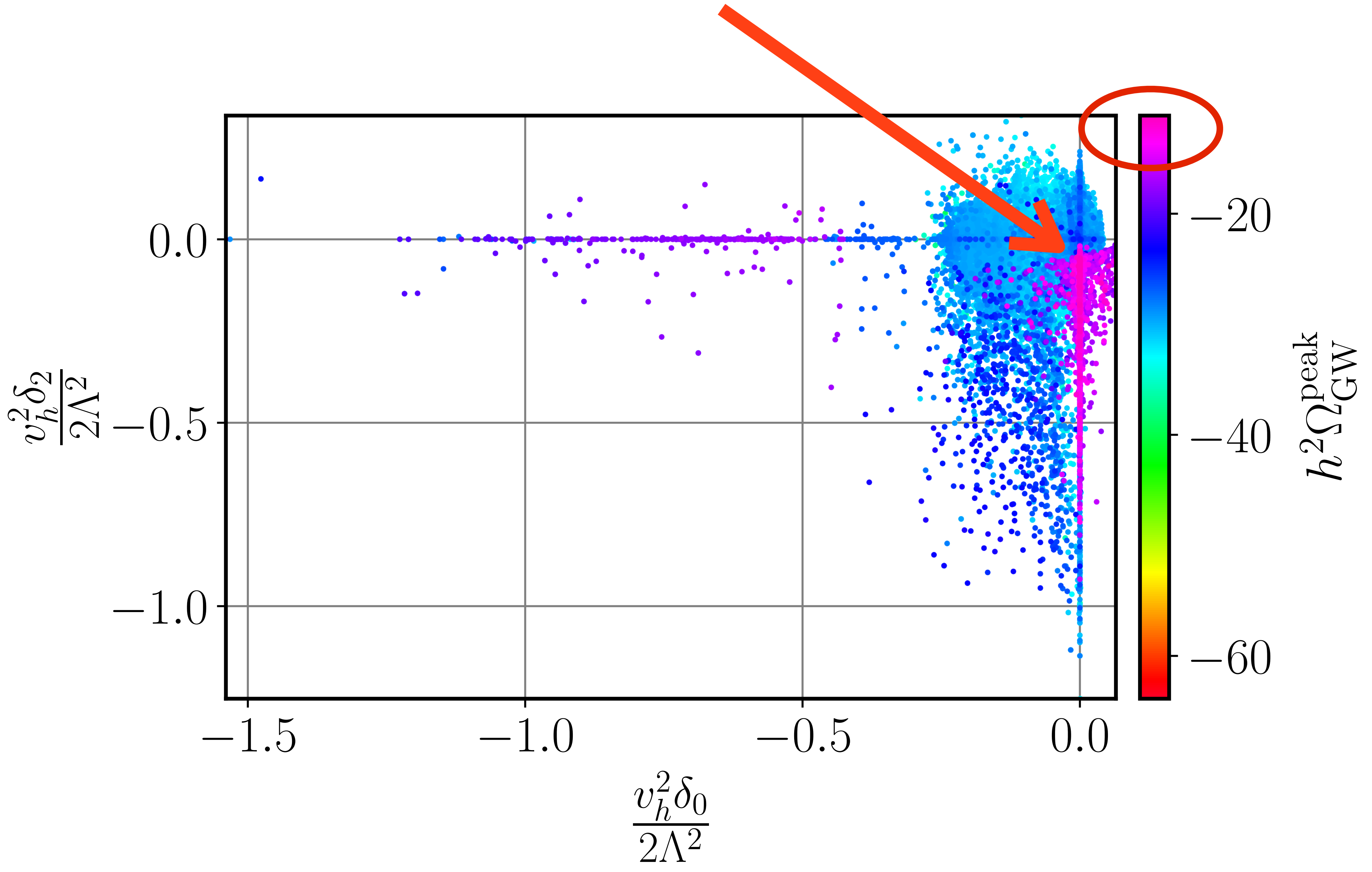
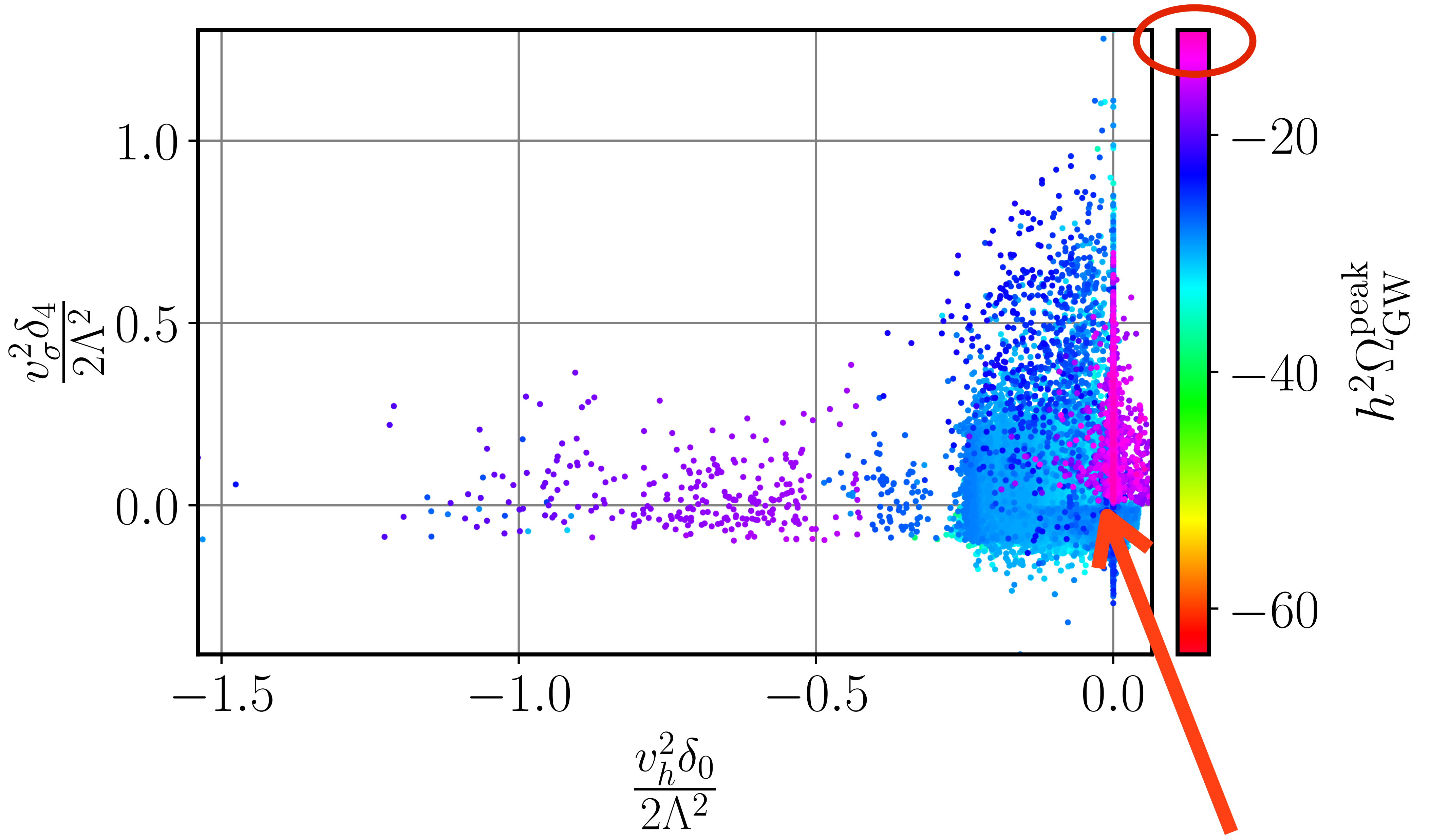
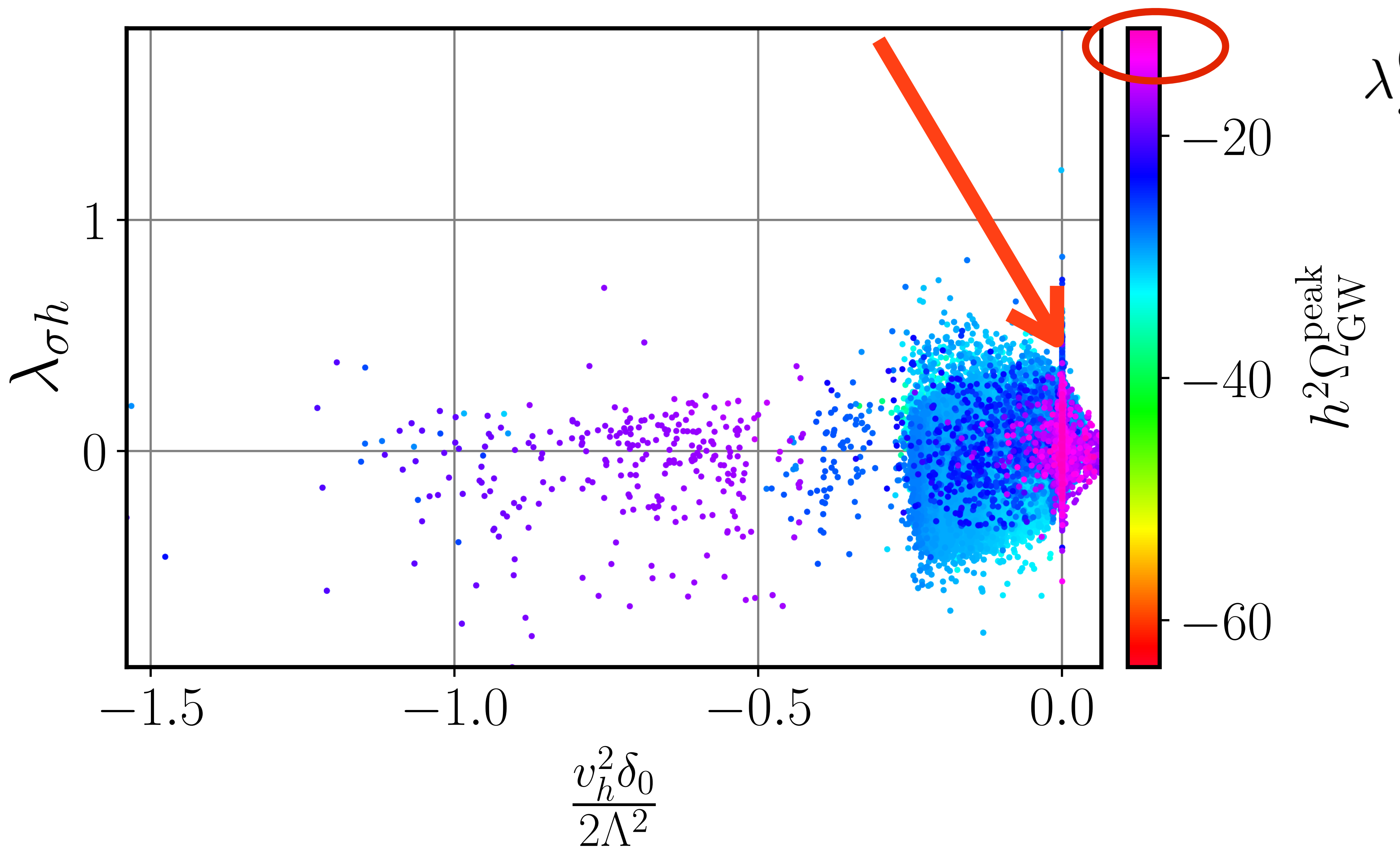






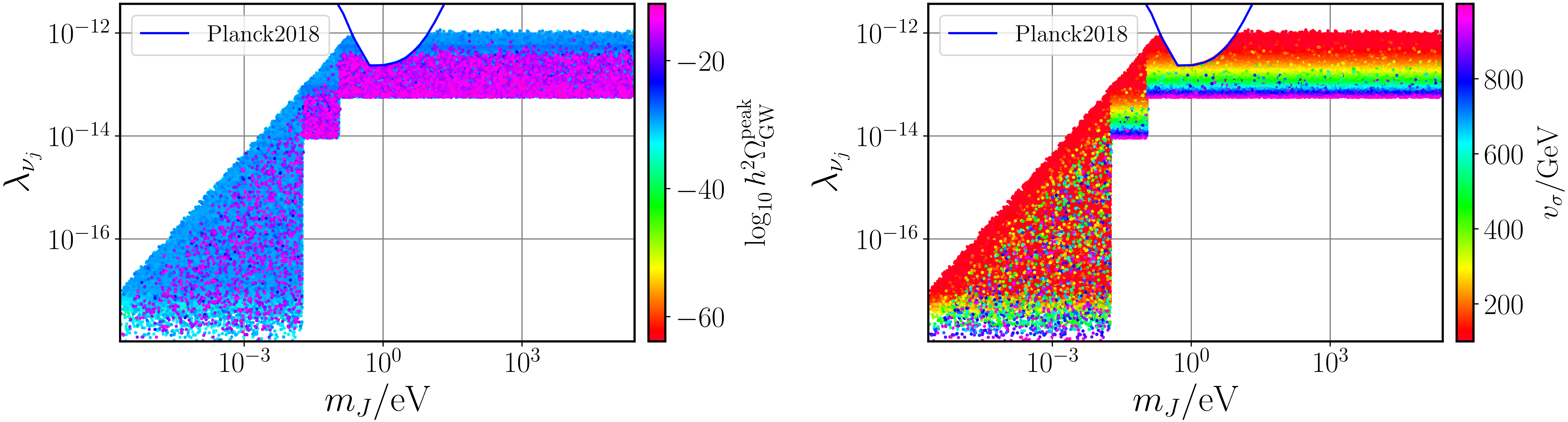
$$\lambda^{(0)}_{JJh_1} = \frac{v_h}{\Lambda^2}\left[(v_h^2\delta_2 + v_\sigma^2\delta_4 + \Lambda^2\lambda_{\sigma h})\cos\alpha_h + v_\sigma(v_h^2\delta_4 + 3v_\sigma^2\delta_6 + 2\Lambda^2\lambda_\sigma)\sin\alpha_h\right]$$

$< \mathcal{O}(0.01)$

✓ **LISA region favours small δ_0**

CMB constraints

[Planck Collaboration, 1807.06209, 1907.12875]



✓ **Planck2018 marginally constrains magenta band (LISA)**

[Escudero, White, EPJC 80 (2020) 4 294]

$$\mathcal{L} = \frac{i}{2}\lambda_{\nu_j} J \overline{\nu}_j \gamma_5 \nu_j$$

$$\lambda_{\nu_j} \equiv m_j / v_\sigma$$

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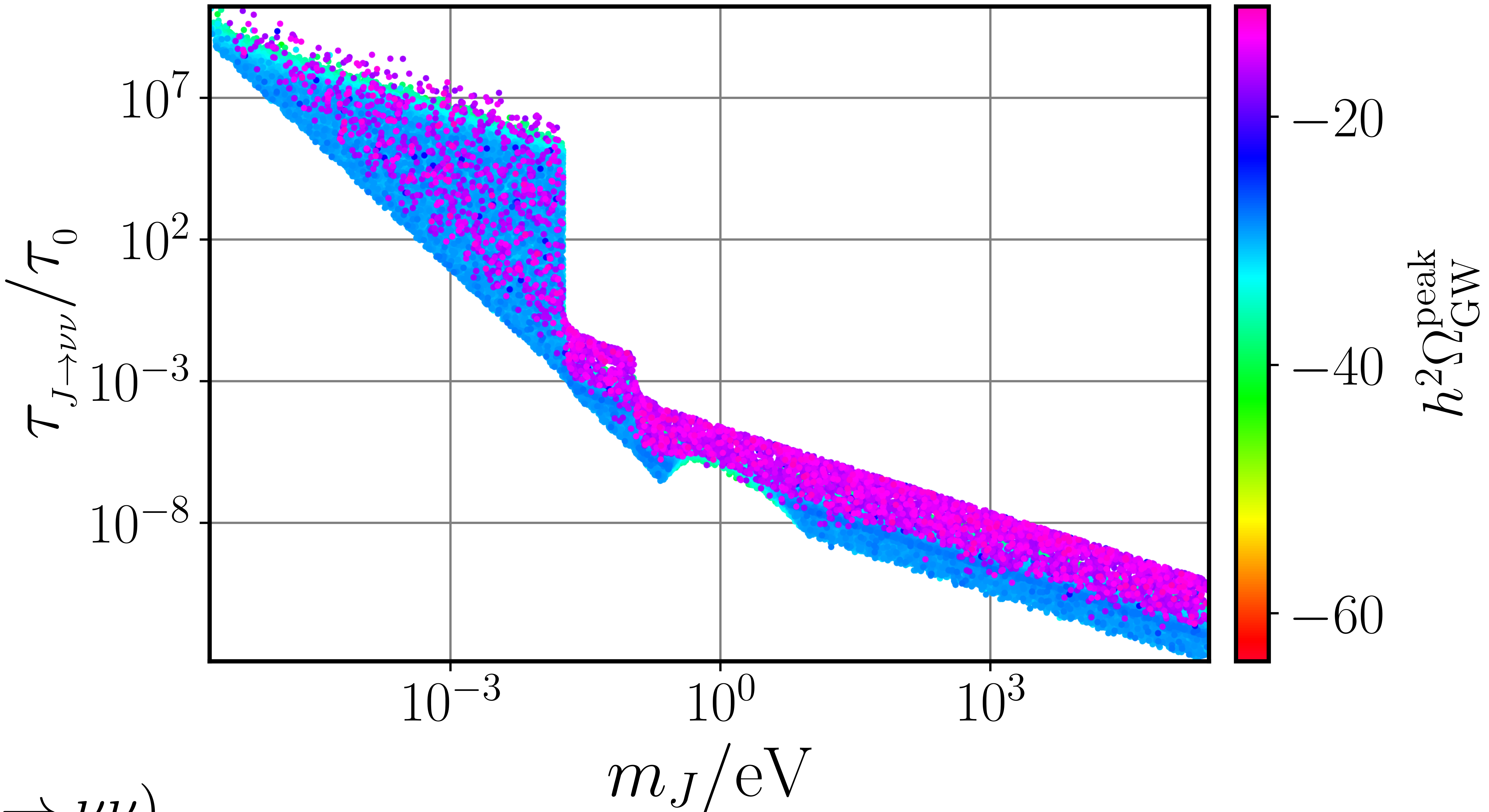
Decaying Majorons



$$\tau_{J\to\nu\nu} = \Gamma^{-1}(J \to \nu\nu)$$

$$\Gamma\left(J \to \nu\nu\right) = \frac{m_J}{16\pi v_\sigma^2}\sum_i\left(m_{\nu_i}^2\sqrt{1-\frac{4m_{\nu_i}^2}{m_J^2}}\right)$$

$$\tau_0 = 13.787\ \mathrm{Gyr}$$

[Nikolic, Kulkani, Pradler, EPJC 82 (2022) 7 650]

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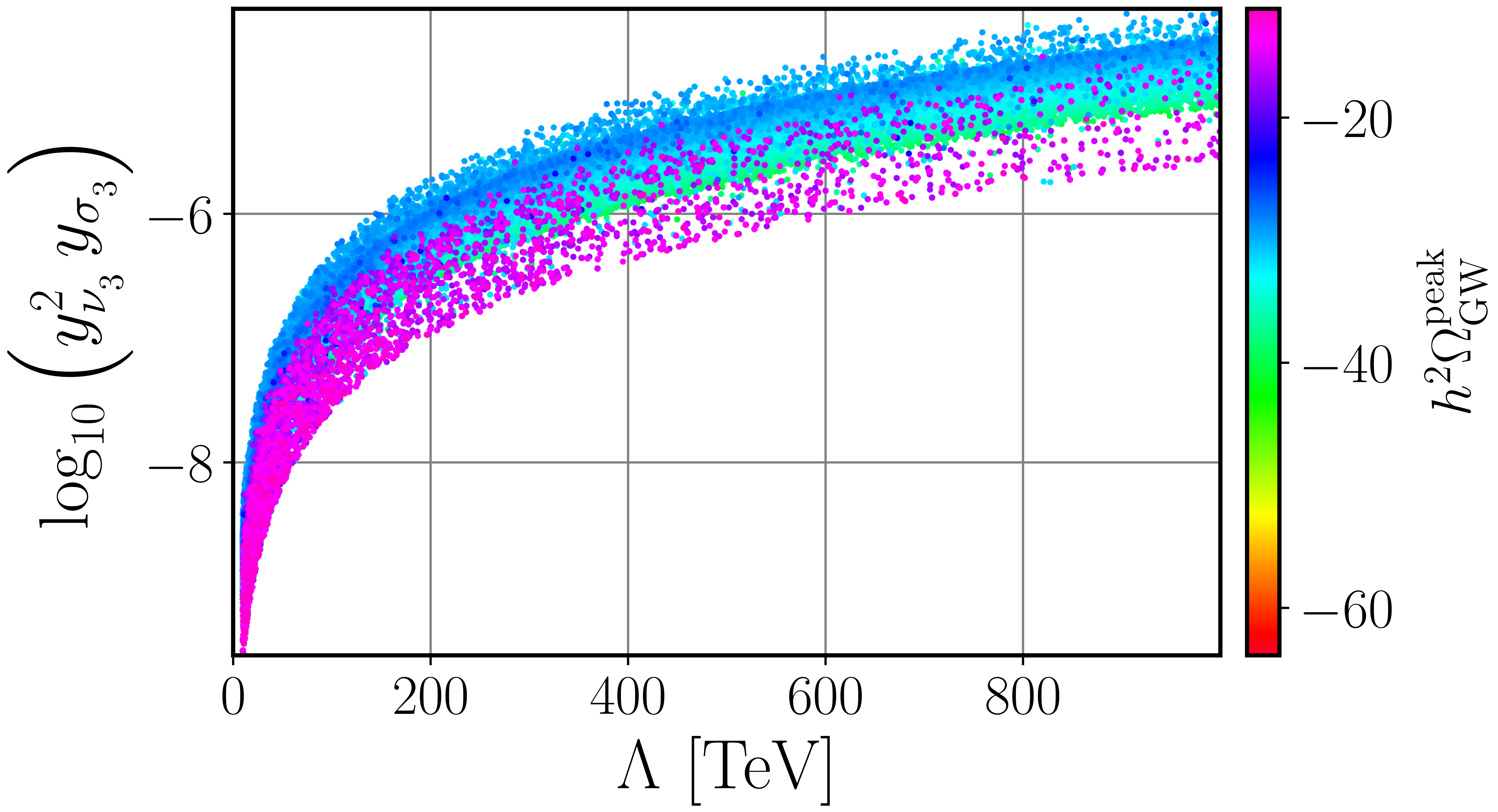
Seesaw effect vs FOPTs



$$m_\nu^{\rm EIS} \approx \frac{y_\nu^2 y_\sigma}{2\sqrt{2}}\,\frac{v_h^2 v_\sigma}{\Lambda^2}$$

$$m_{N^\pm} \approx \Lambda \pm \frac{v_\sigma}{2\sqrt{2}}\left(y_\sigma + y'_\sigma\right)$$

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Two LQ model

SM $+$ Singlet leptoquark $+$ Doublet leptoquark

$$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1})_{1/3} \qquad \tilde{R}_2 \sim (\mathbf{3}, \mathbf{2})_{1/6}$$

This field content has an UV inspiration…

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$[\mathrm{SU}(3)]^3 \times \mathrm{SU}(2)_\mathrm{F} \times \mathrm{U}(1)_\mathrm{F} \longrightarrow$ Flavoured Trinification

[APM, Pasechnik, Porod, Eur. Phys. J. C 80, (2020) 12, 1162]

$$L = \begin{pmatrix} H & \ell_\mathrm{L} \\ \ell_\mathrm{R} & \phi \end{pmatrix} \qquad Q_\mathrm{L} = \begin{pmatrix} q_\mathrm{L} & D_\mathrm{L} \end{pmatrix} \qquad Q_\mathrm{R} = \begin{pmatrix} q^c_\mathrm{R} & D^c_\mathrm{R} \end{pmatrix}^\mathsf{T}$$

$\tilde{R}_2$ $\qquad$ S_1

This FT contains an emergent $\mathbb{Z}_2$ B-parity

$$\mathbb{P}_B = (-1)^{3B+2S}$$

	L	$\tilde{L}$	Q_L	$\tilde{Q}_L$	Q_R	$\tilde{Q}_R$
$\mathbb{P}_B$	−	+	+	−	+	−
				$\tilde{R}_2$		S_1

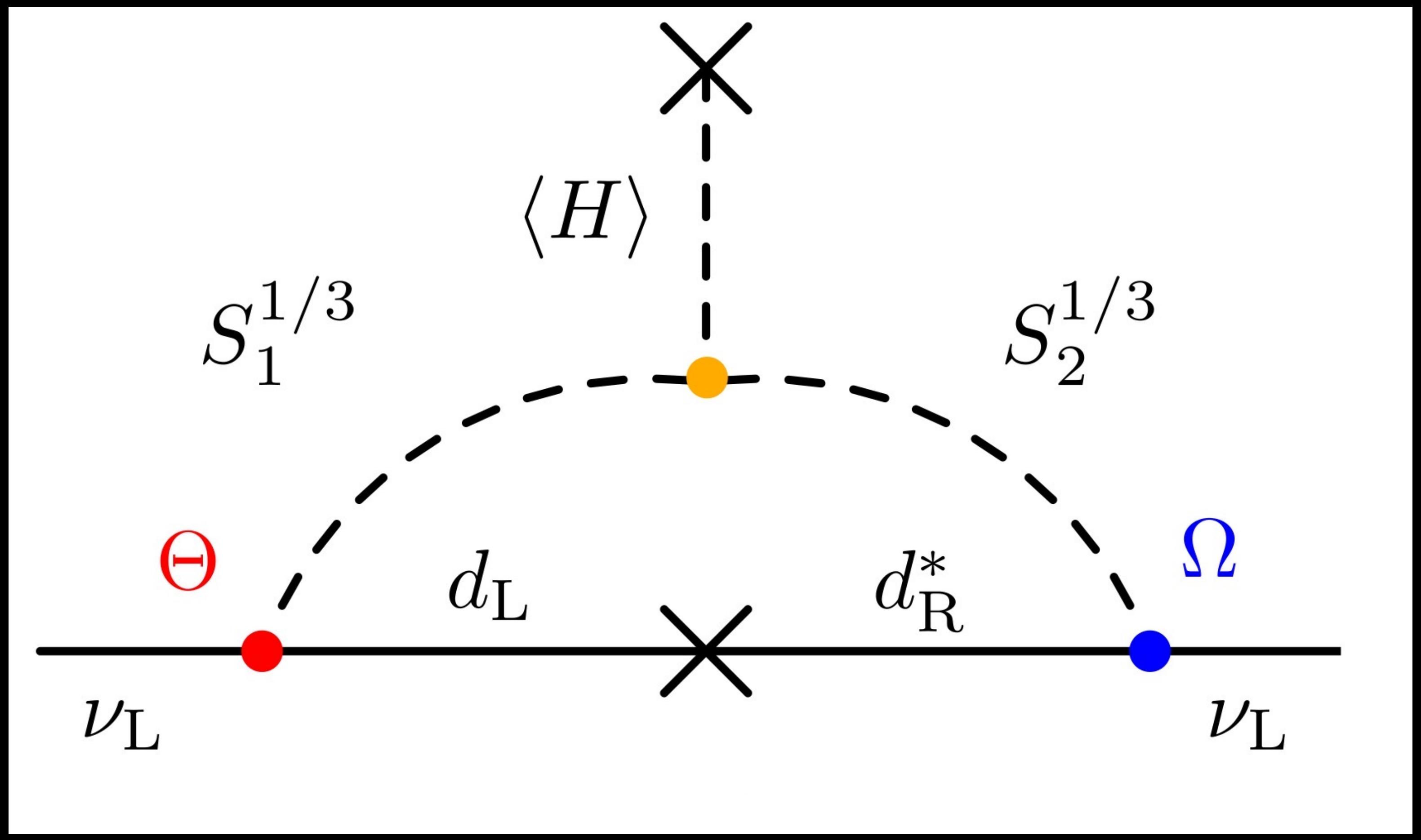
- **Forbids di-quark interactions**
- **Only allows leptoquark interactions**

$$\overset{-}{L}\,\overset{+}{Q_\mathrm{L}}\,\overset{-}{\tilde{Q}_\mathrm{R}} + \overset{-}{L}\,\overset{-}{\tilde{Q}_\mathrm{L}}\,\overset{+}{Q_\mathrm{R}}$$

- **Proton is stable**

Neutrino Masses

$$\mathcal{L}_{\mathrm{Y}} = \Theta_{ij}\bar{Q}^c_j L_i S + \Omega_{ij}\bar{L}_i d_j R^\dagger + \Upsilon_{ij}\bar{u}_j e_i S^\dagger + \mathrm{h.c.}$$



- **And an exhaustive flavour analysis**

[Gonçalves, APM, Pasechnik, Porod, 2206.01674]

[40] I. Doršner, S. Fajfer, and N. Košnik, Eur. Phys. J. C **77**, 417 (2017), 1701.08322.
[41] D. Aristizabal Sierra, M. Hirsch, and S. G. Kovalenko, Phys. Rev. D **77**, 055011 (2008), 0710.5699.
[42] D. Zhang, JHEP **07**, 069 (2021), 2105.08670.
[43] H. Päs and E. Schumacher, Phys. Rev. D **92**, 114025 (2015), 1510.08757.
[44] Y. Cai, J. Herrero-García, M. A. Schmidt, A. Vicente, and R. R. Volkas, Front. in Phys. **5**, 63 (2017), 1706.08524

$$(M_\nu)_{ij} = \frac{3}{16\pi^2\left(m^2_{S_2^{1/3}} - m^2_{S_1^{1/3}}\right)} \frac{v a_1}{\sqrt{2}} \ln\left(\frac{m^2_{S_2^{1/3}}}{m^2_{S_1^{1/3}}}\right) \sum_{m,a} (m_d)_a V_{am} \left(\Theta_{im}\Omega_{ja} + \Theta_{jm}\Omega_{ia}\right),$$

Scalar sector

- LQ scalar potential

$$V_{LQ} = \frac{1}{2}\left(\mu_H H^\dagger H + \mu_S S^\dagger S + \mu_R R^\dagger R\right) + \frac{1}{4}\left(\lambda_H \left(H^\dagger H\right)^2 + \lambda_S \left(S^\dagger S\right)^2 + \lambda_R \left(R^\dagger R\right)^2\right) + \frac{1}{4}\left(g_{HS}(H^\dagger H)(S^\dagger S) + g_{HR}(H^\dagger H)(R^\dagger R) + g'_{HR}(H^\dagger R)(R^\dagger H) + g_{RS}(R^\dagger R)(S^\dagger S)\right) + c_3\, R^\dagger S H$$

✓ Consider the possibility of LQ VEVs at finite T

✓ Classify all possible FOPTs and determine SGWB

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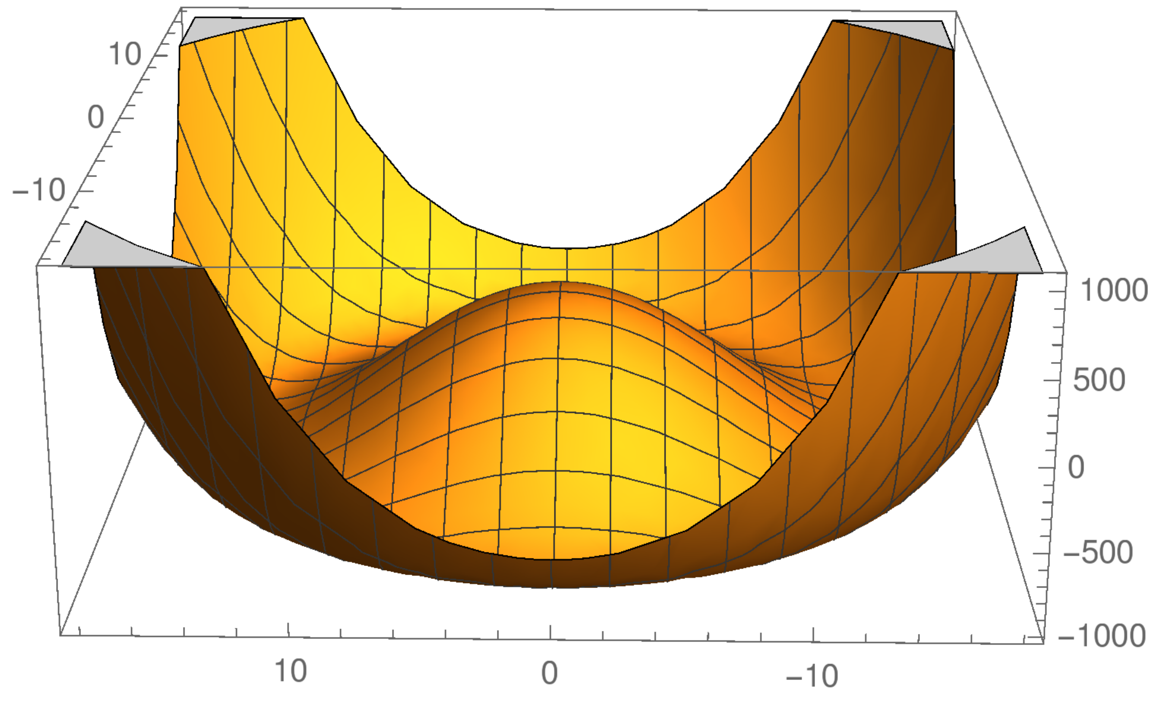
Basics of Phase Transitions

(Illustration)

Consider the scalar potential:

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

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

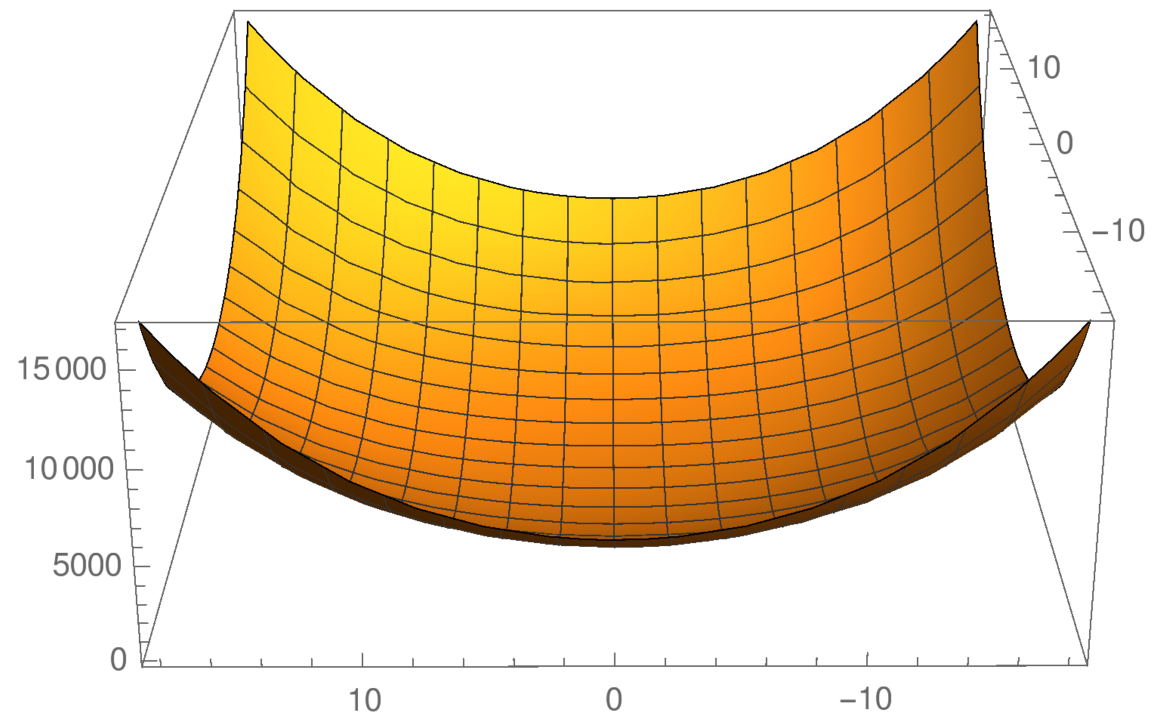


Add thermal corrections:

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

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

Restored symmetry at high T



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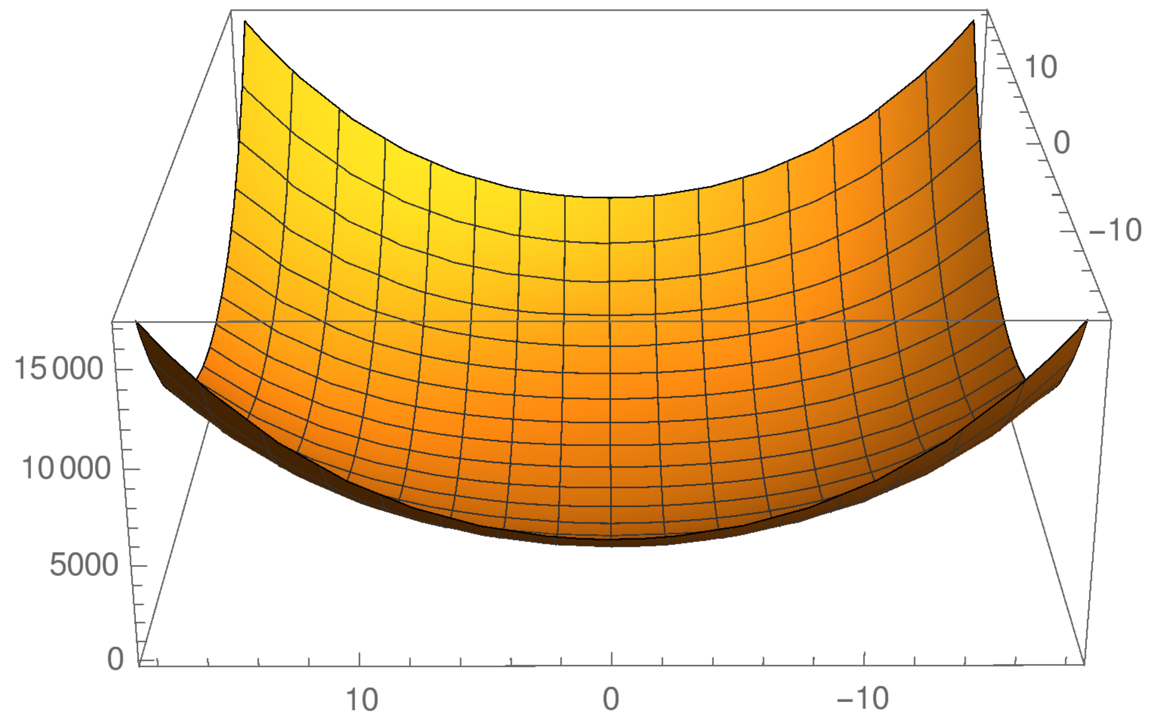
Basics of Phase Transitions

(Illustration)

Consider the scalar potential:

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

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

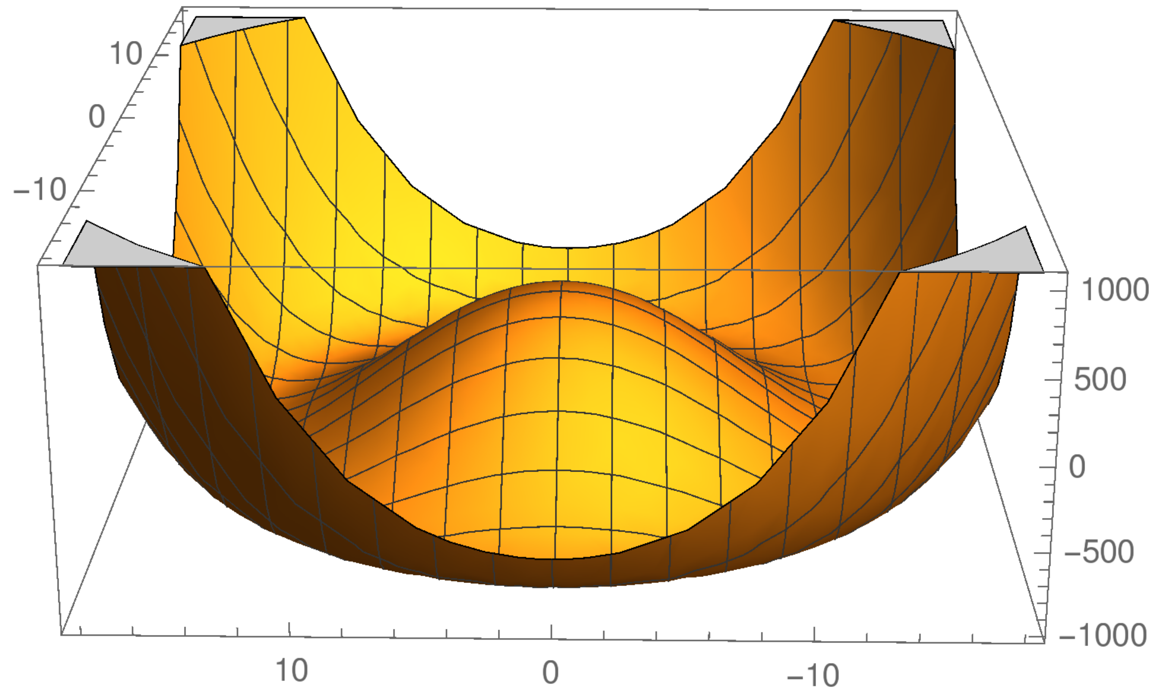


Add thermal corrections:

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

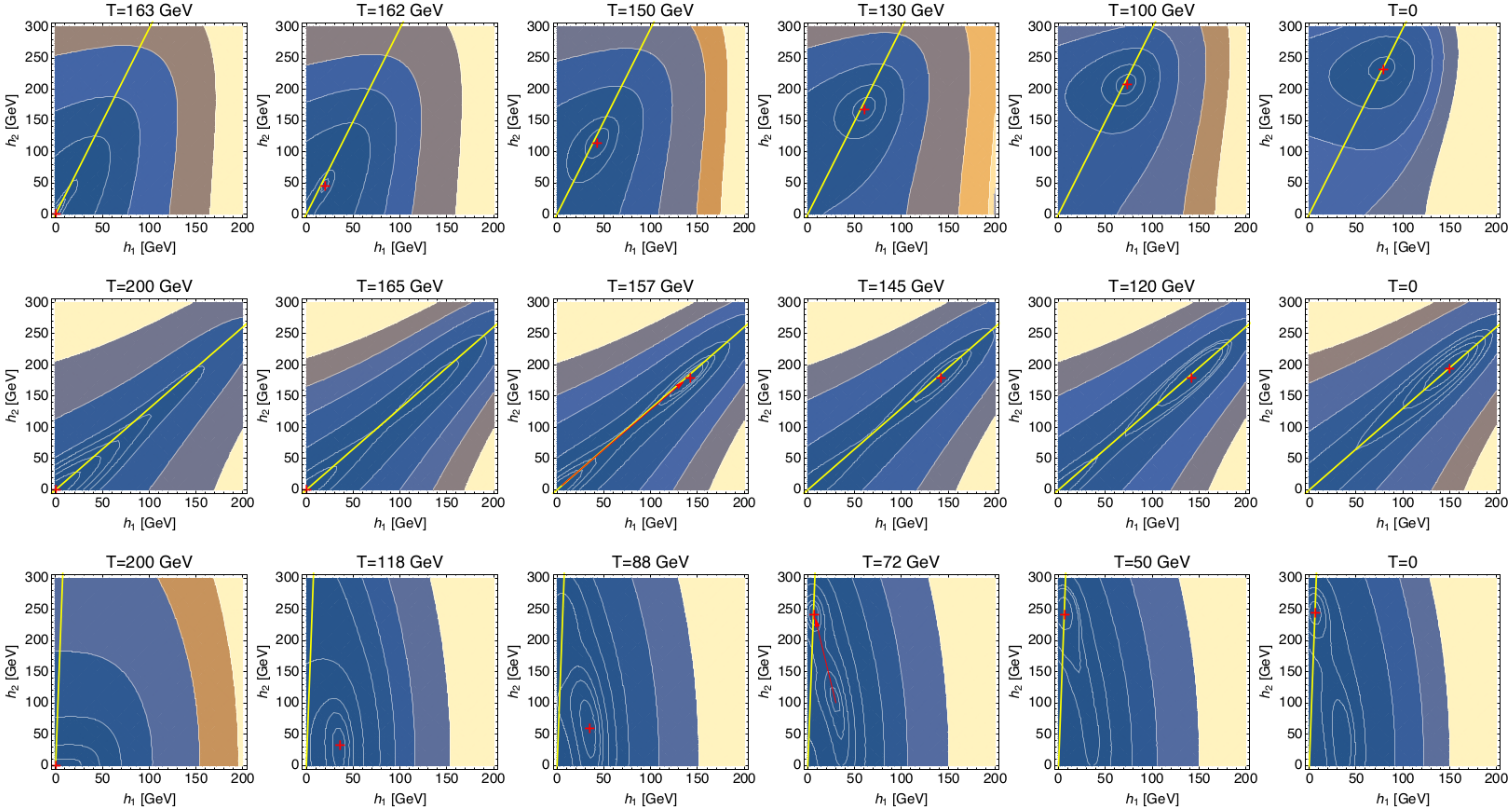
For $C_\phi < 0$, after a certain $T > 0$, $\mu_{eff} \equiv \mu^2 + C_\phi T^2 < 0$

Broken symmetry at high T



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

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



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Minimization

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

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

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

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Scalar mass spectrum

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

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

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

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

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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

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

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

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

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

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

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

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And for gauge bosons...

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

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

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

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

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