AUDIBLE GRAVITATIONAL ECHOES OF NEW PHYSICS

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CENTRO 2020
PORTUGAL 2020
UNIÃO EUROPEIA
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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 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 puzzles

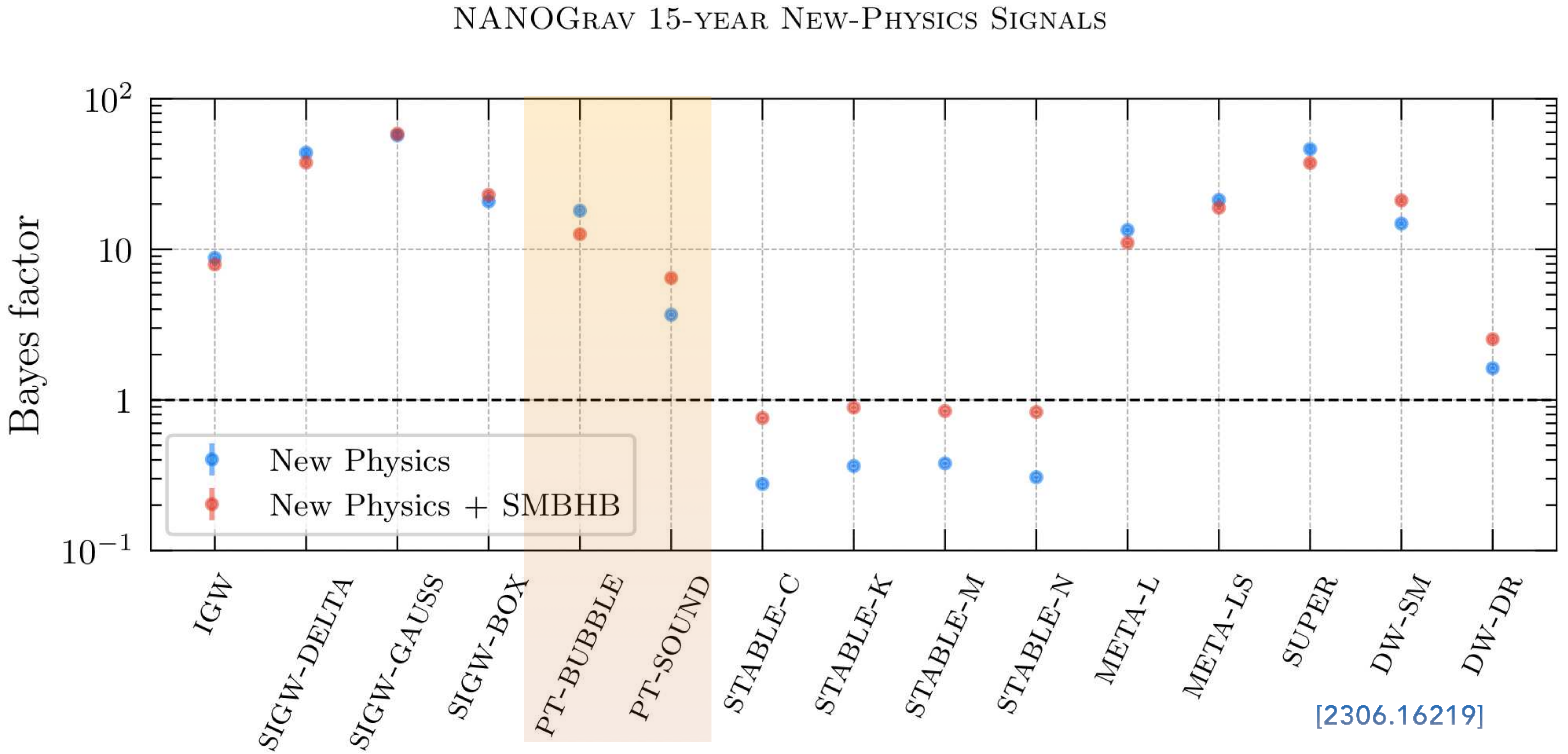
SGWB

- ✓ 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

SGWB

[2306.16213]

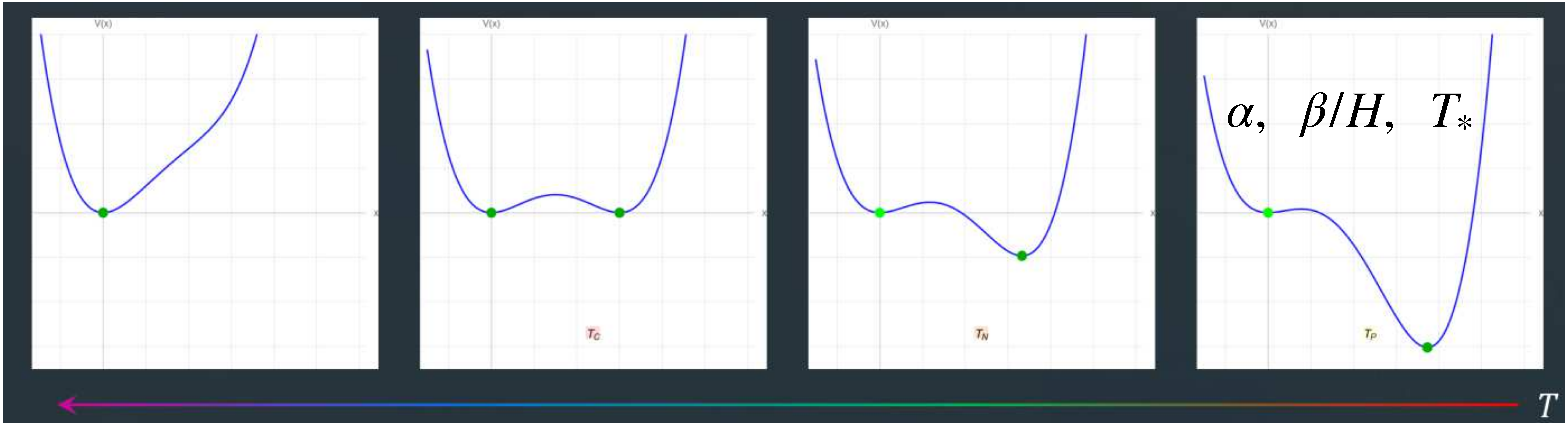


[2306.16219]

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

First order phase transition (FOPT)

(Illustration)



Credit: Marco Finetti

Strength and duration of the PT

$$\alpha = \frac{1}{\rho_\gamma}\left[V_i - V_f - \frac{T_*}{4}\left(\frac{\partial V_i}{\partial T} - \frac{\partial V_f}{\partial T}\right)\right] \qquad \frac{\beta}{H} = T_* \frac{\partial}{\partial T}\left(\frac{\hat{S}_3}{T}\right)\Bigg|_{T_*}$$

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

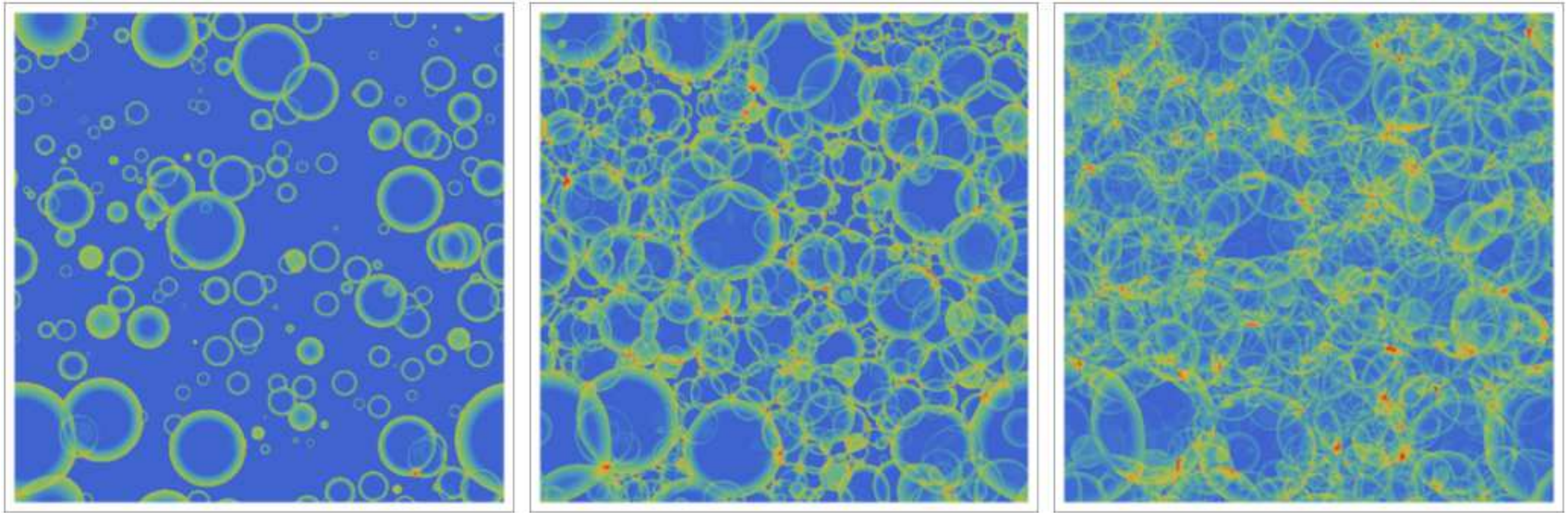
$$\hat{S}_3(\hat{\phi}, T) = 4\pi \int_0^\infty \mathrm{d}r\, r^2 \left\{ \frac{1}{2}\left(\frac{\mathrm{d}\hat{\phi}}{\mathrm{d}r}\right)^2 + V_{\rm eff}(\hat{\phi}, T) \right\}$$

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

First order phase transition (FOPT)

(Illustration)

✓ First order phase transition (FOPT) example



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

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

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

Peak amplitude

Spectral function

$$h^2\Omega^{\rm peak}_{\rm GW}(f_{\rm peak}) = 7.835\times 10^{-17} f_{\rm peak}^{-2}\left(\frac{100}{g_*}\right)^{2/3}\left(\frac{T_*}{100}\right)^2\frac{K^{\frac{3}{2}}}{c_s}$$

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

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

Scenario 1: Neutrino masses from lepton number symmetry breaking

ACCEPTED IN JCAP [2304.02399] ADDAZI, MARCIANÒ, APM, PASECHNIK, VIANA, YANG

Which seesaw model?

	L^i	ν_{R}^i	S^i	σ	H	Model
$\mathrm{U}(1)_{\mathrm{L}}$	1	1	$\times$	-2	0	T1S
	1	1	0	-1	0	IS
	1	1	-1	2	0	EIS

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

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

Which seesaw model?

	L^i	ν_R^i	S^i	σ	H	Model
	1	1	$\times$	-2	0	T1S
$\mathrm{U(1)_L}$	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**

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

Neutrino sector

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

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

✓ EFT approach

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

3 light active neutrinos

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

6 heavy neutrinos

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

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

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

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

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

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

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

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

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

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

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

Minimal scalar sector: why not suitable for SFOPT

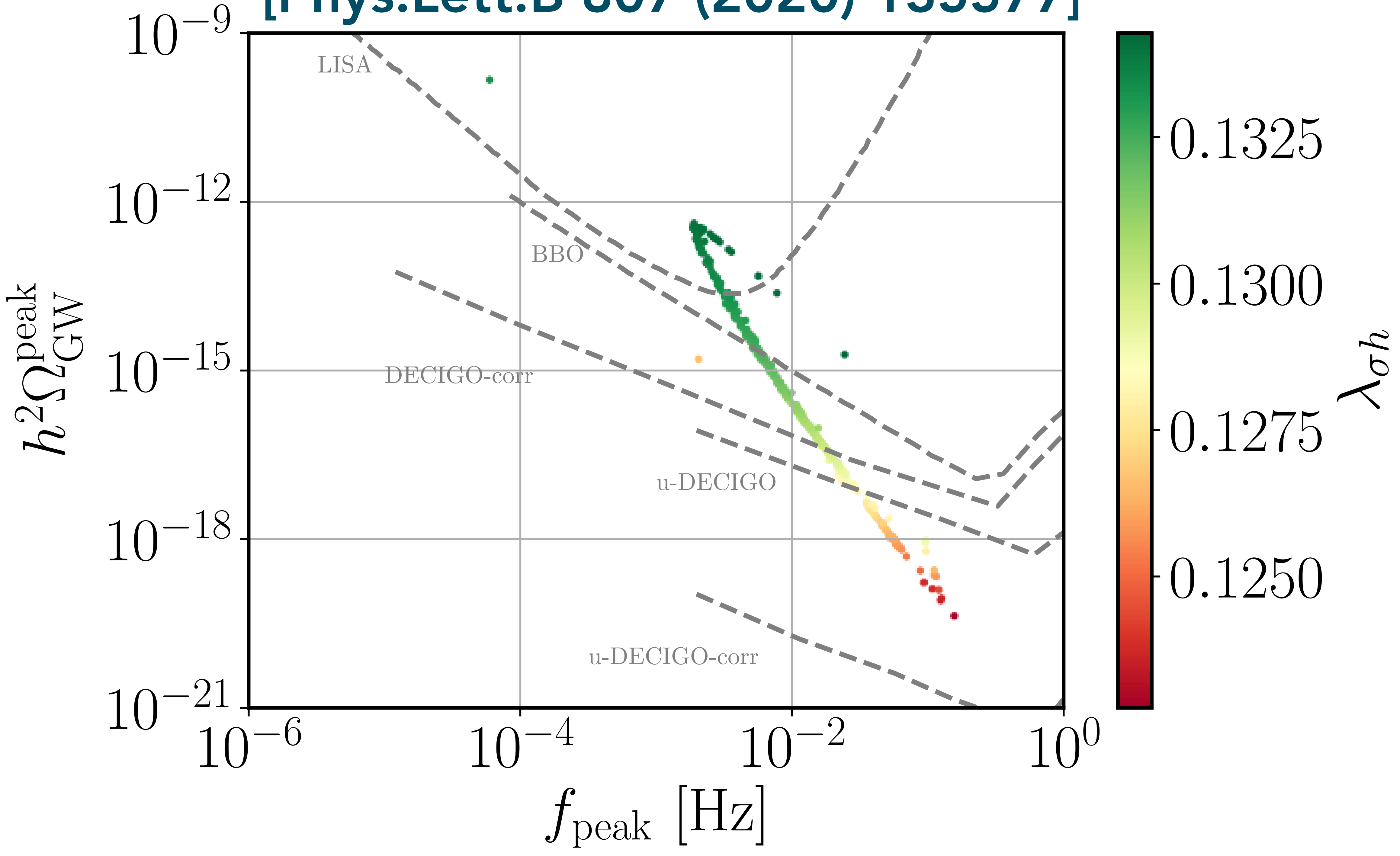
$$V_{\rm SM}(H) = \mu_h^2 H^\dagger H + \lambda_h (H^\dagger H)^2 \,,$$

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

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

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

[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: why not suitable for SFOPT

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

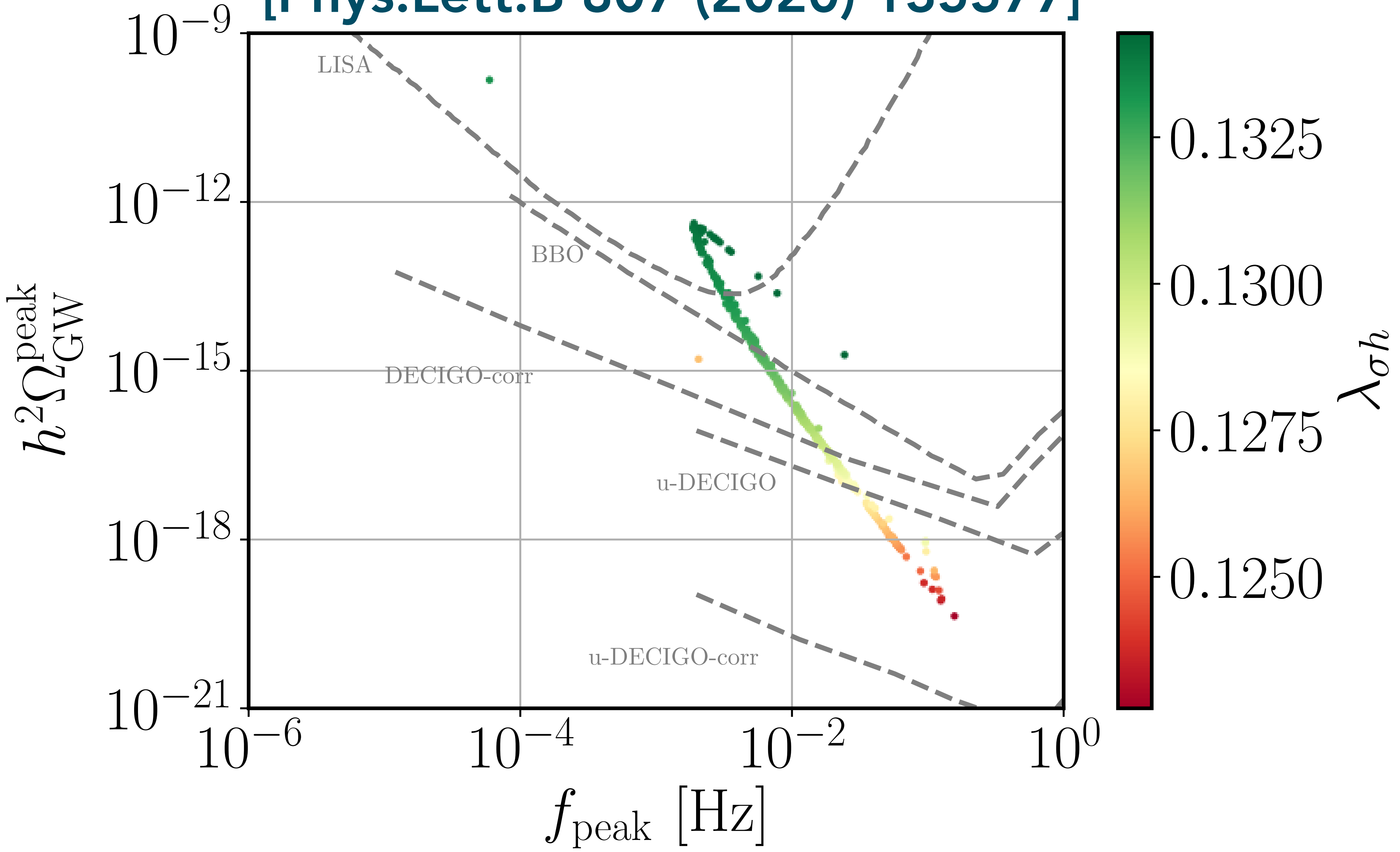
[CMS - Phys. Rev. D 105 (2022) 9 092007]

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

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

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

[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)

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

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

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

$|\sin \alpha_h| < 0.24$ [Papaefstathiou, Robens, White, 2207.00043]

Inverted equations

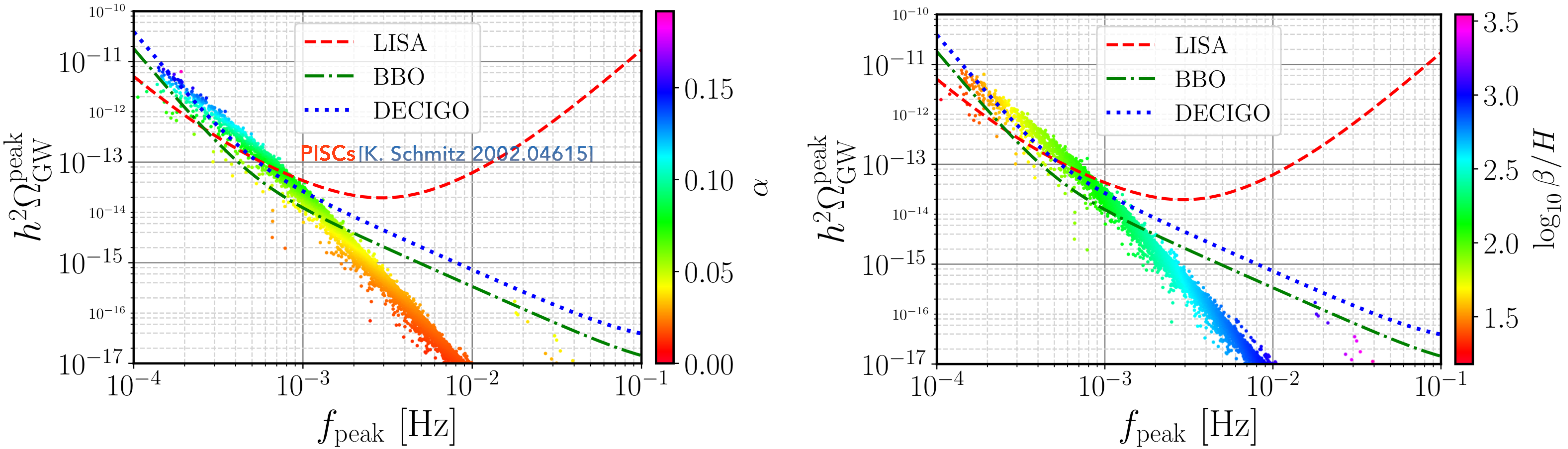
$$\begin{aligned}
\lambda_{\sigma h} &= \frac{\tan\left(2\alpha_h\right)\left(M_{hh}^2 - M_{\sigma\sigma}^2\right)}{2 v_h v_\sigma} - \frac{\delta_2 v_h^2 + \delta_4 v_\sigma^2}{\Lambda^2}\,, \\
\lambda_\sigma &= -\frac{2A(\mathrm{Br}) v_h^3 v_\sigma \csc\left(\alpha_h\right) + \Lambda^2 \sec\left(2\alpha_h\right)\left(M_{\sigma\sigma}^2 - M_{hh}^2\right) + \Lambda^2\left(-M_{hh}^2 + M_{\sigma\sigma}^2 - 2M_{\sigma\sigma}^2 v_\sigma\right)}{4\Lambda^2\left(v_\sigma - 1\right) v_\sigma^2} \\
&\quad + \frac{\delta_4 v_h^2}{2\Lambda^2}\,, \\
\lambda_h &= \frac{1}{2}\left(\frac{M_{hh}^2}{v_h^2} - \frac{3\delta_0 v_h^2 + \delta_2 v_\sigma^2}{\Lambda^2}\right)\,, \\
\delta_6 &= \frac{2A(\mathrm{Br}) v_h^3 v_\sigma \csc\left(\alpha_h\right) - \Lambda^2\left(\sec\left(2\alpha_h\right)\left(M_{hh}^2 - M_{\sigma\sigma}^2\right) + M_{hh}^2 + M_{\sigma\sigma}^2\right)}{6(v_\sigma - 1)v_\sigma^4}\,,
\end{aligned}$$

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

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

Results

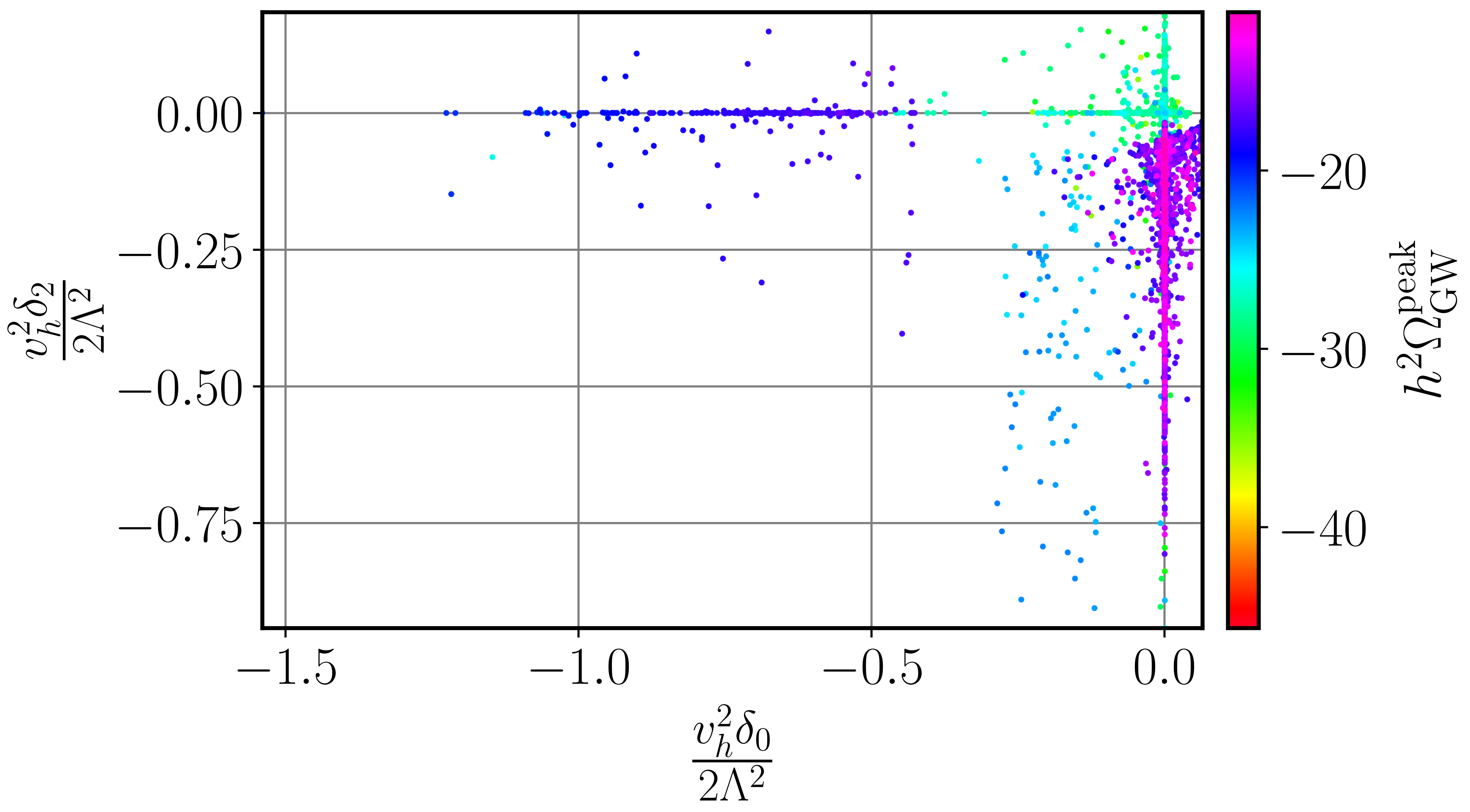
$$\log_{10}(h^2\Omega_{\mathrm{GW}}^{\mathrm{peak}}) \propto -2\log_{10} f_{\mathrm{peak}} + \log_{10} F(\alpha, T_*)$$

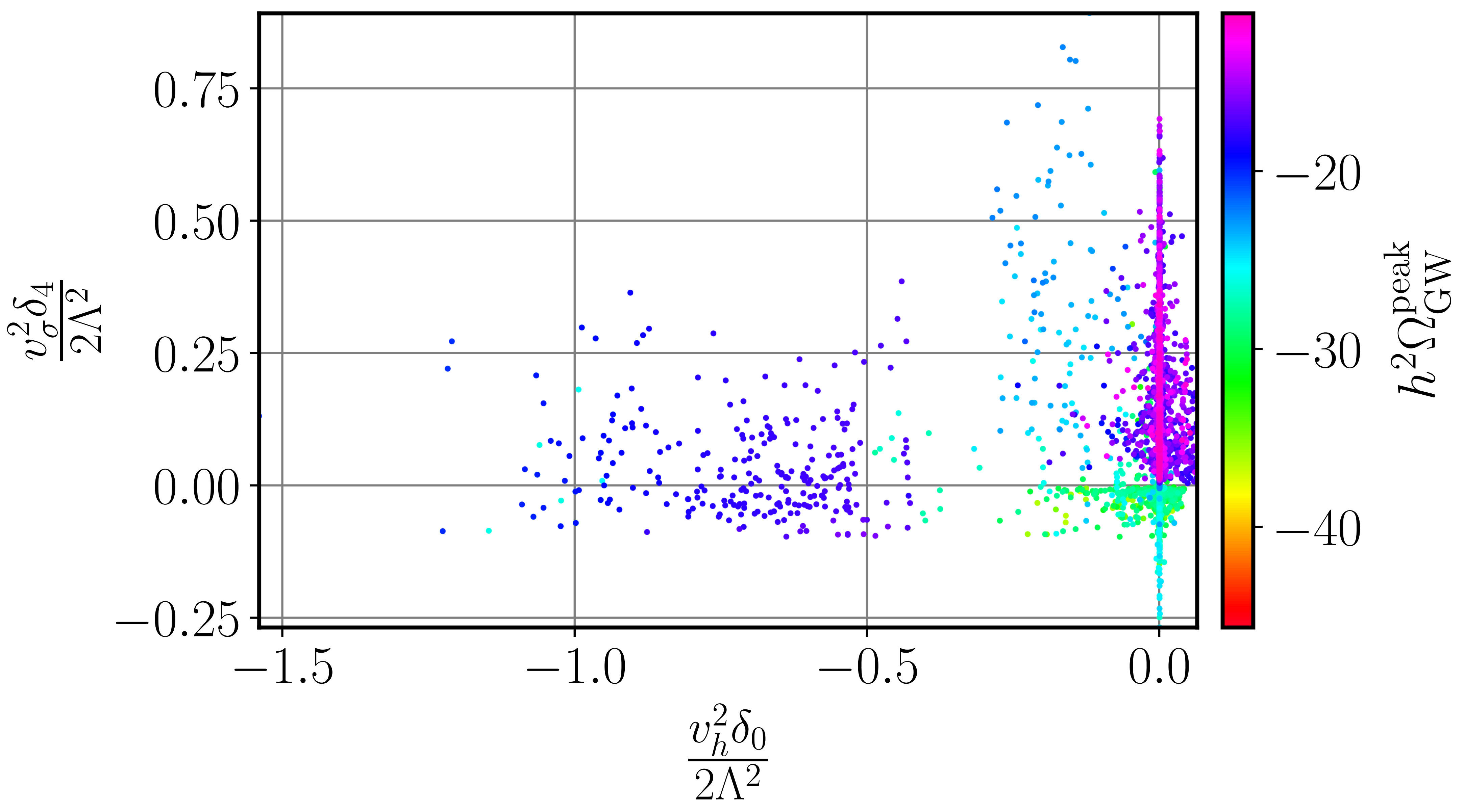


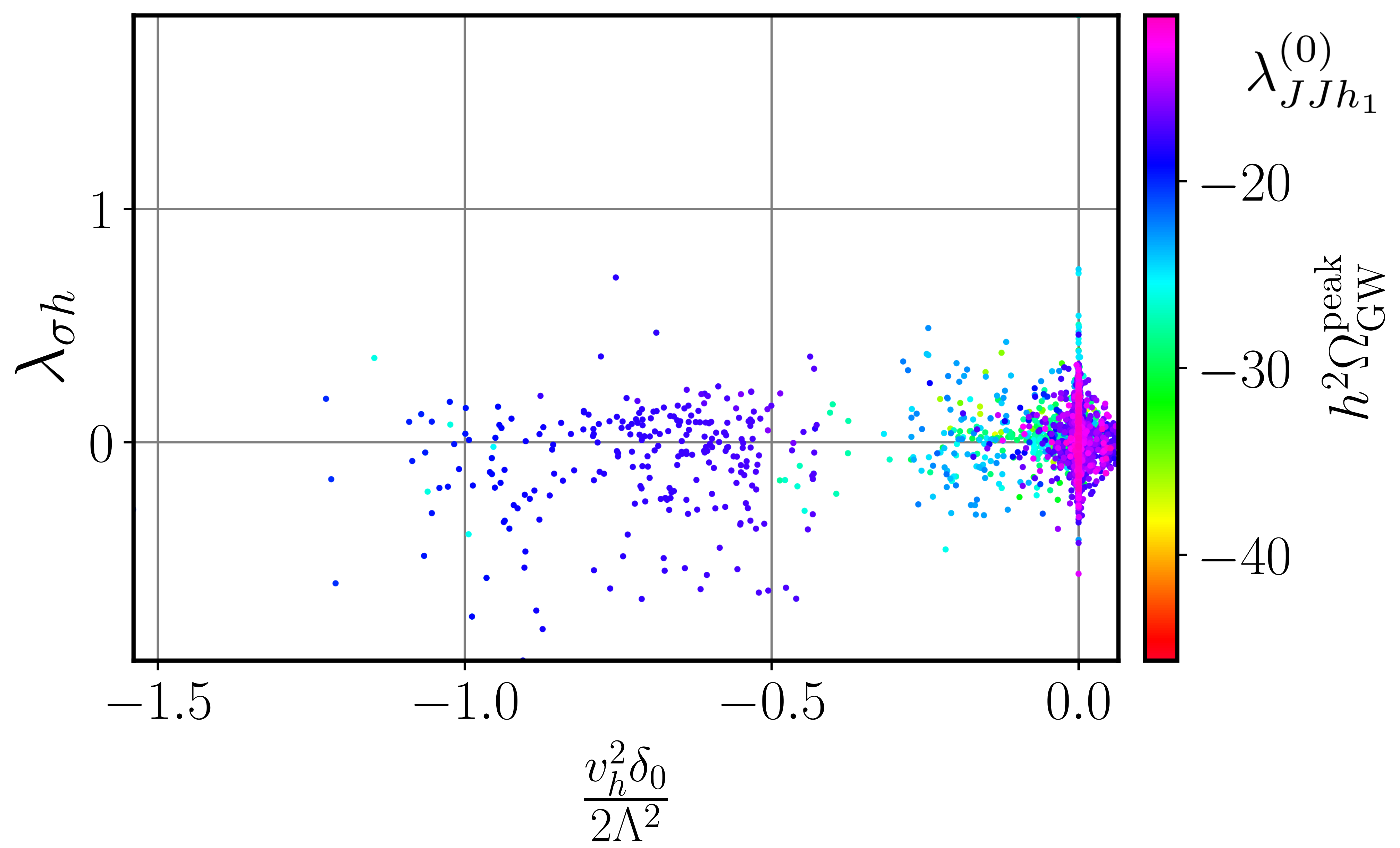
PISCs [K. Schmitz 2002.04615]

Scan using *CosmoTransitions*

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

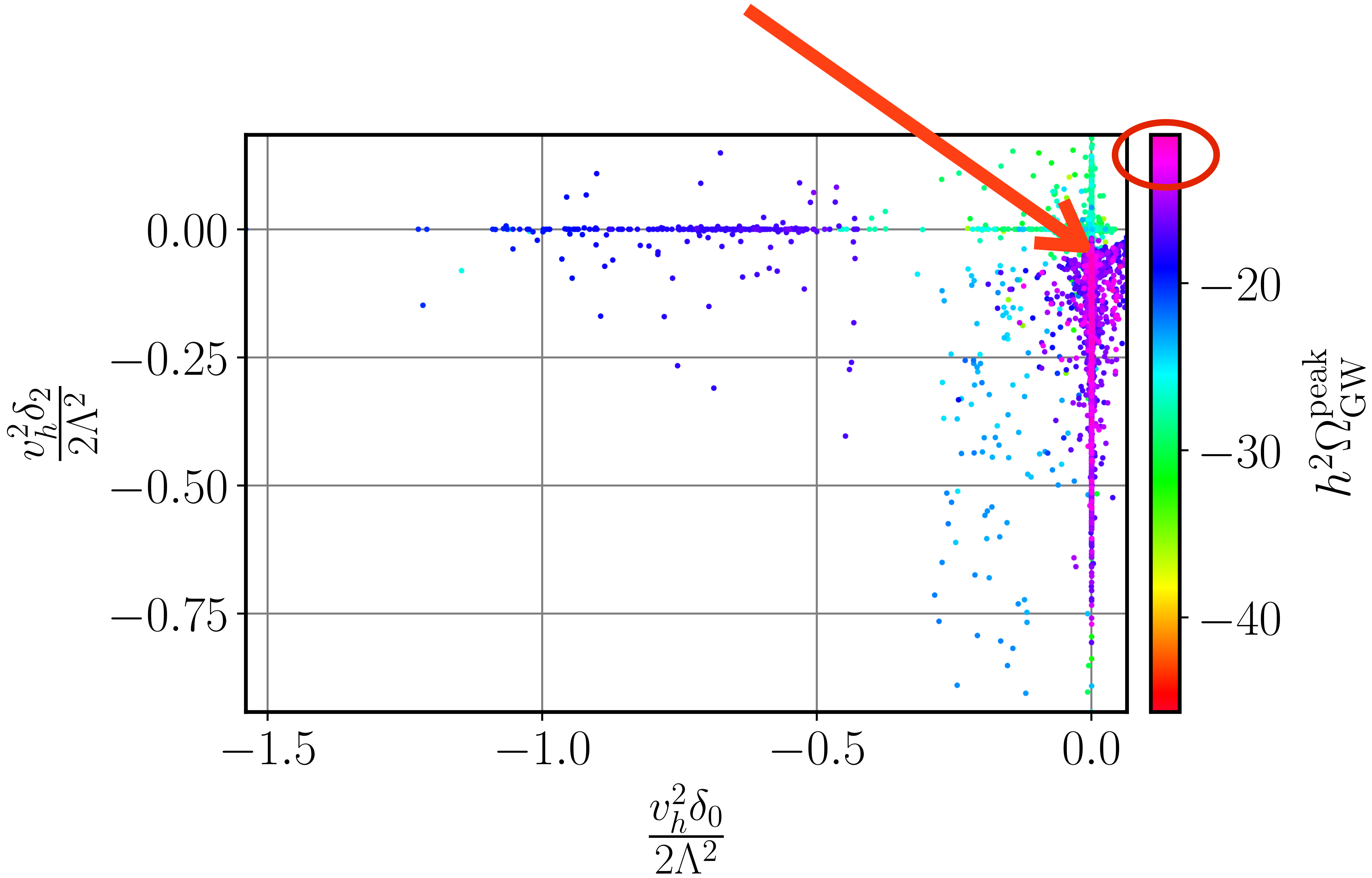


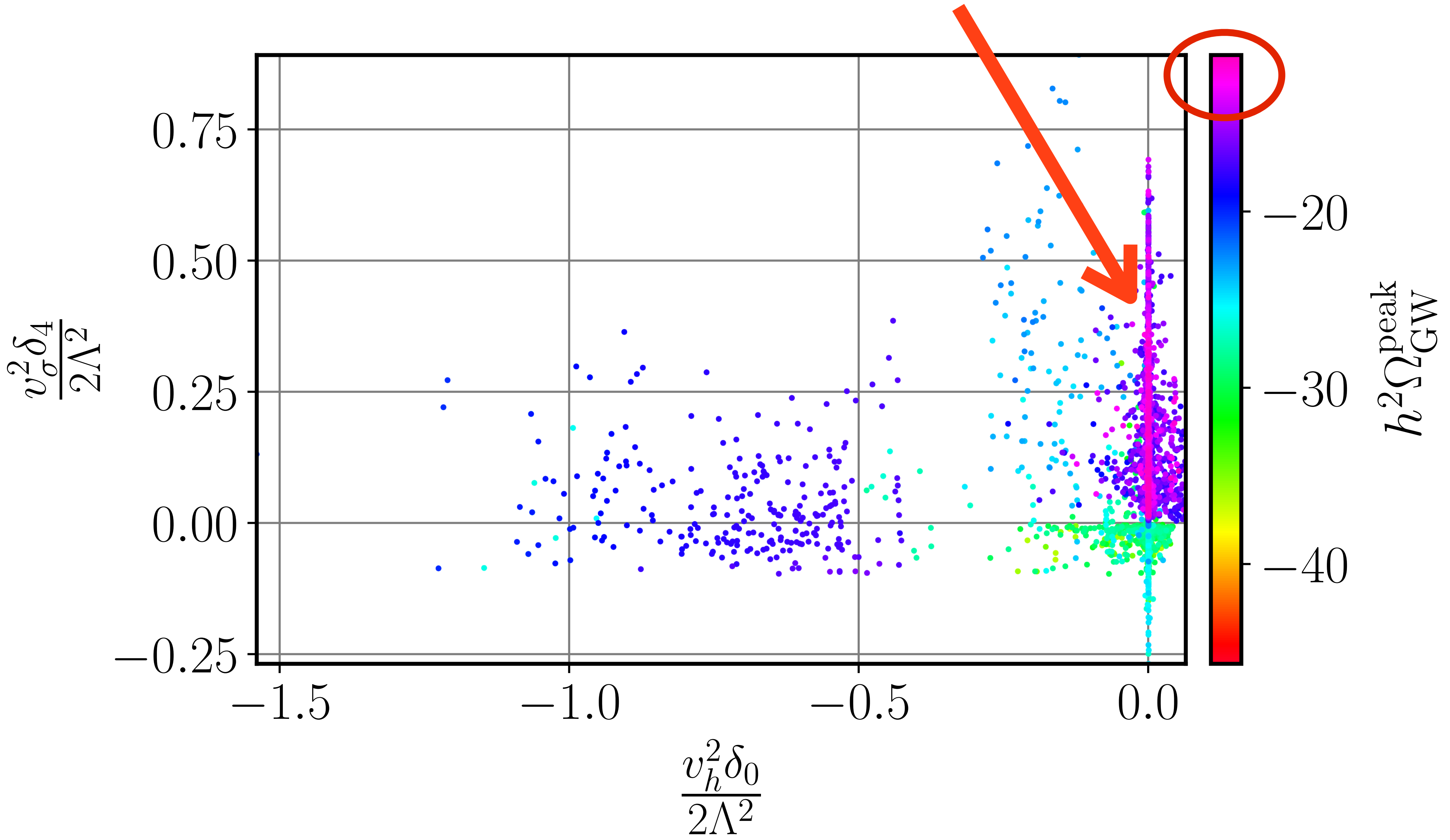


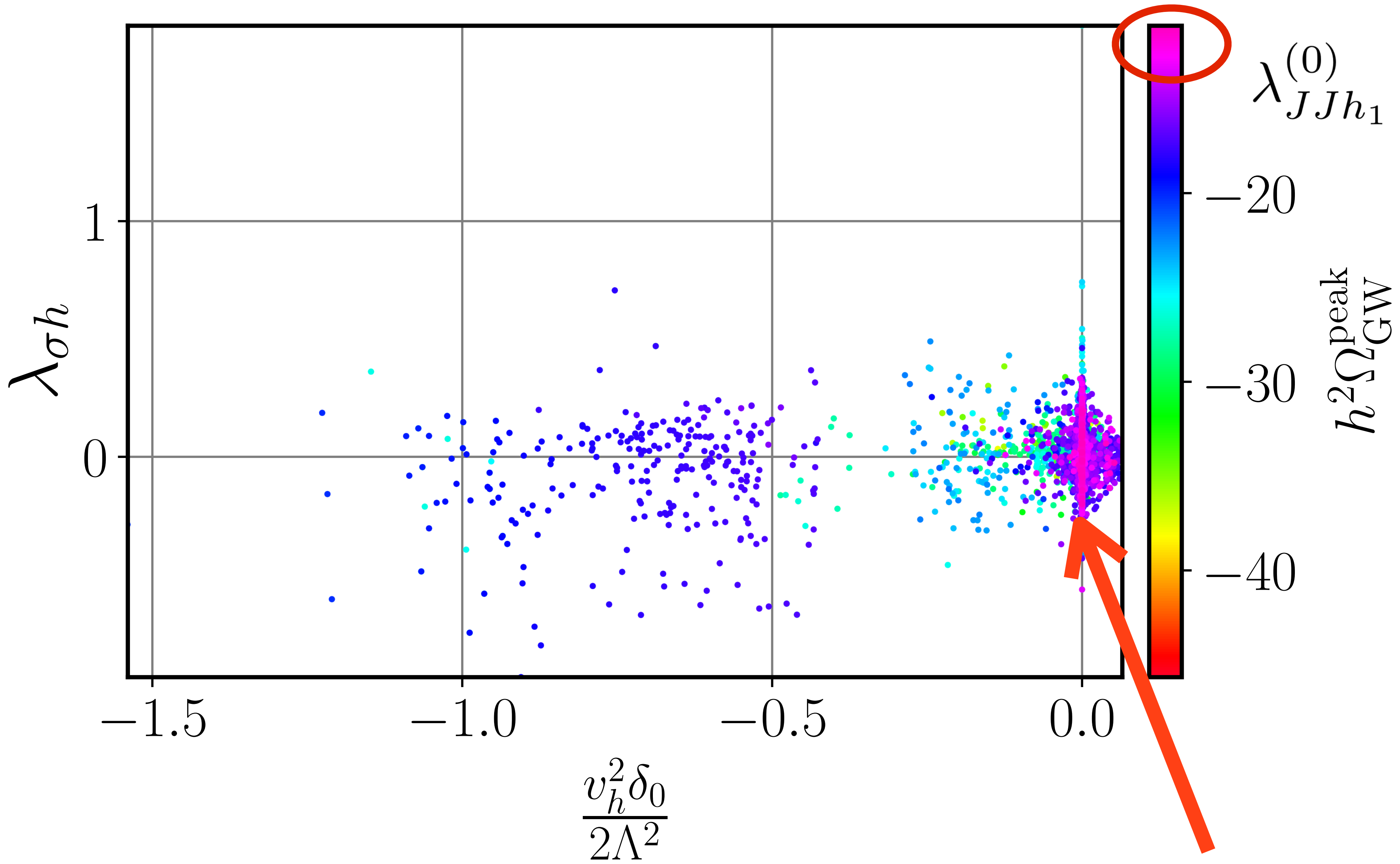


$$\lambda^{(0)}_{JJh_1} = \frac{v_h}{\Lambda^2}\left[(v_h^2\delta_2 + v_\sigma^2\delta_4 + \Lambda^2\lambda_{\sigma h})\cos\alpha_h + v_\sigma(v_h^2\delta_4 + 3v_\sigma^2\delta_6 + 2\Lambda^2\lambda_\sigma)\sin\alpha_h\right]$$

$< \mathcal{O}(0.01)$





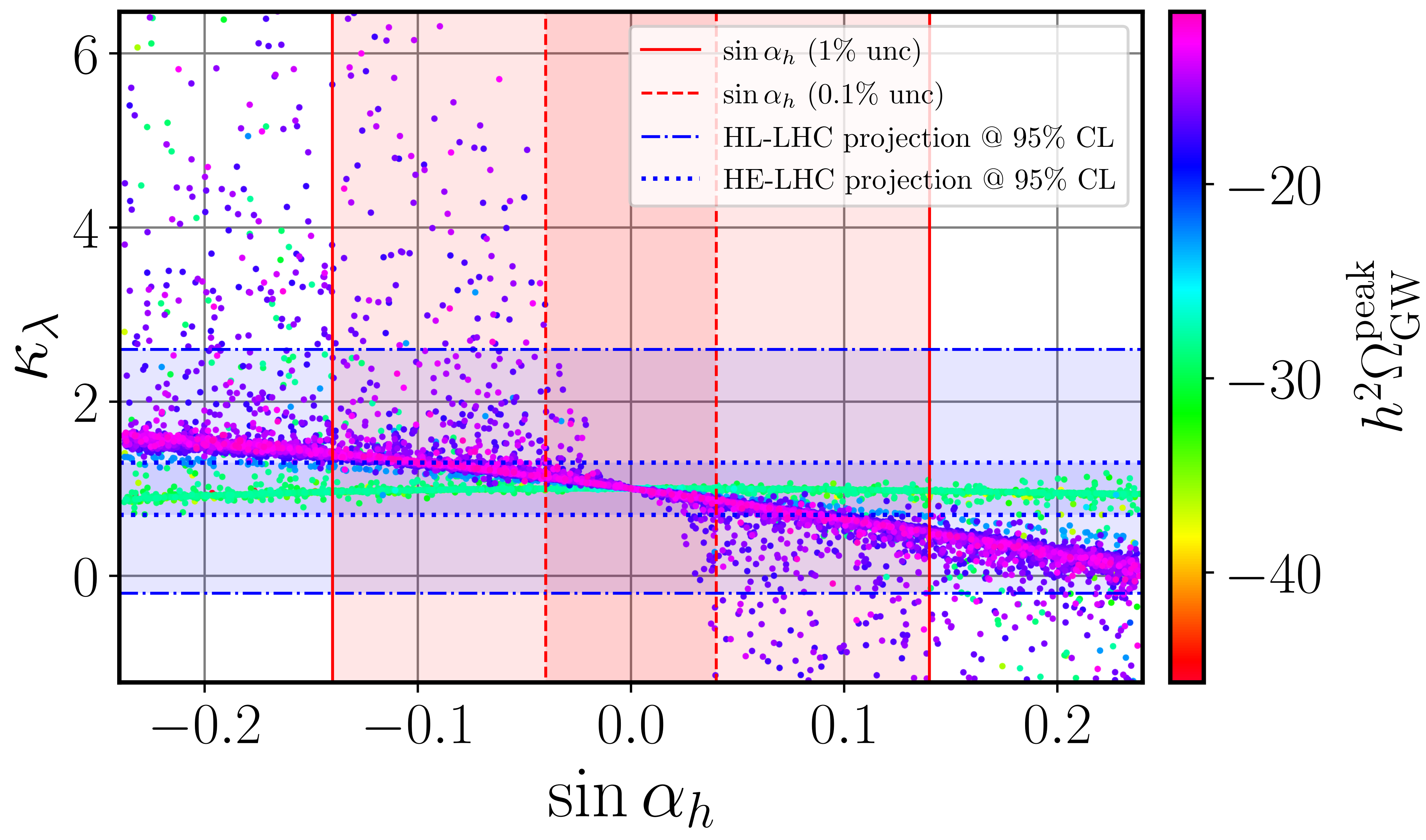


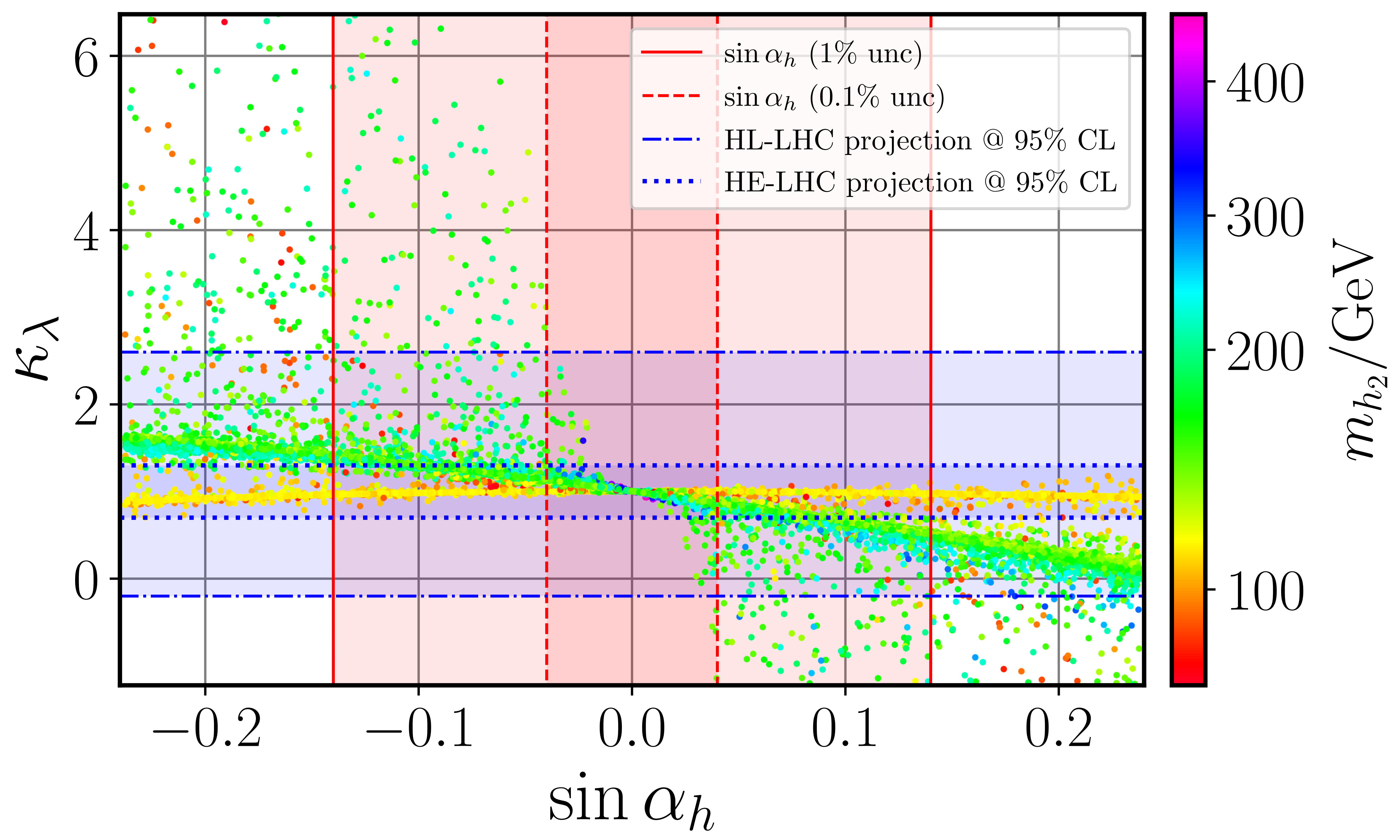
$$\lambda^{(0)}_{JJh_1} = \frac{v_h}{\Lambda^2}\left[(v_h^2\delta_2 + v_\sigma^2\delta_4 + \Lambda^2\lambda_{\sigma h})\cos\alpha_h + v_\sigma(v_h^2\delta_4 + 3v_\sigma^2\delta_6 + 2\Lambda^2\lambda_\sigma)\sin\alpha_h\right]$$

$< \mathcal{O}(0.01)$

✓ **LISA region favours small** δ_0

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

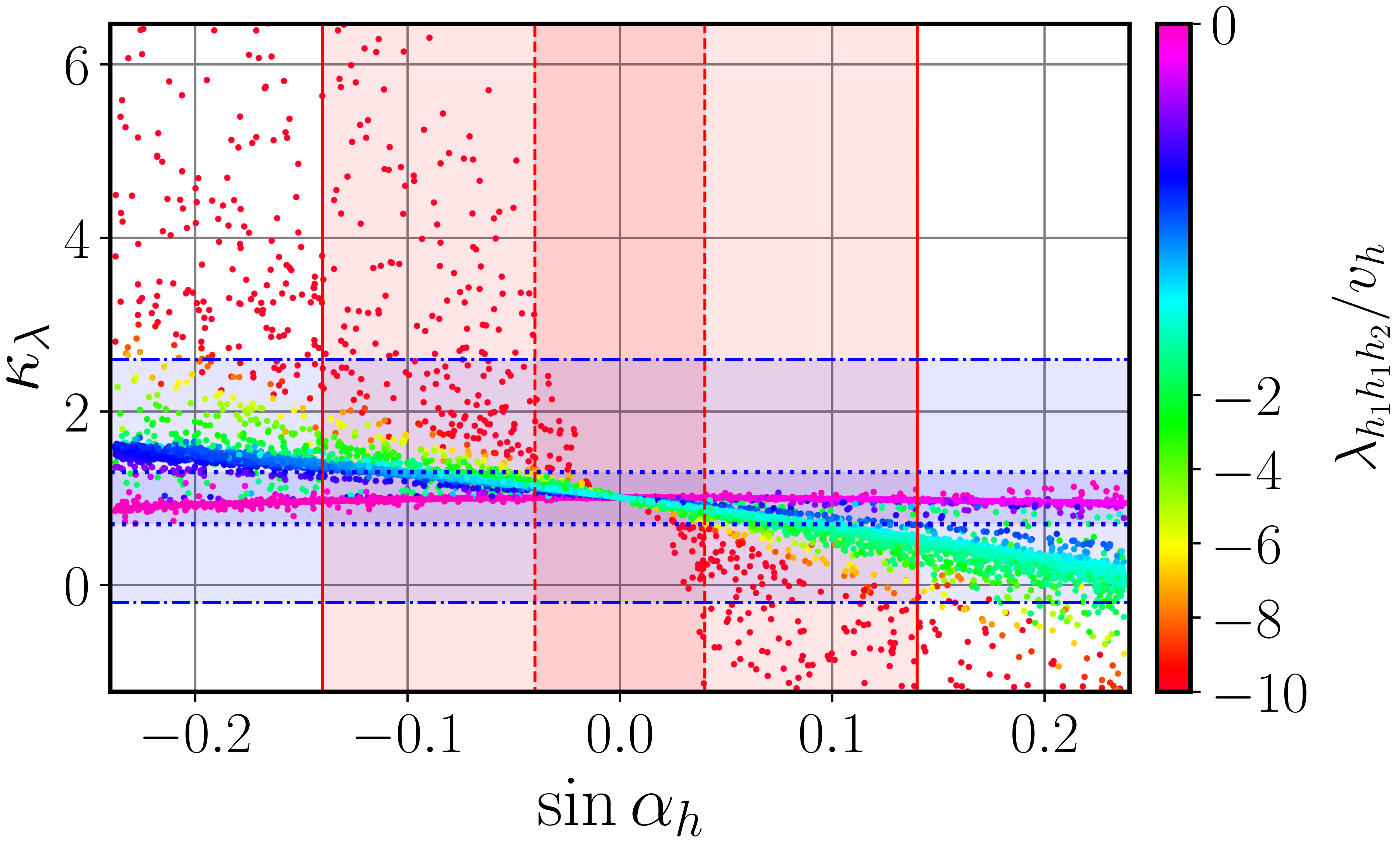


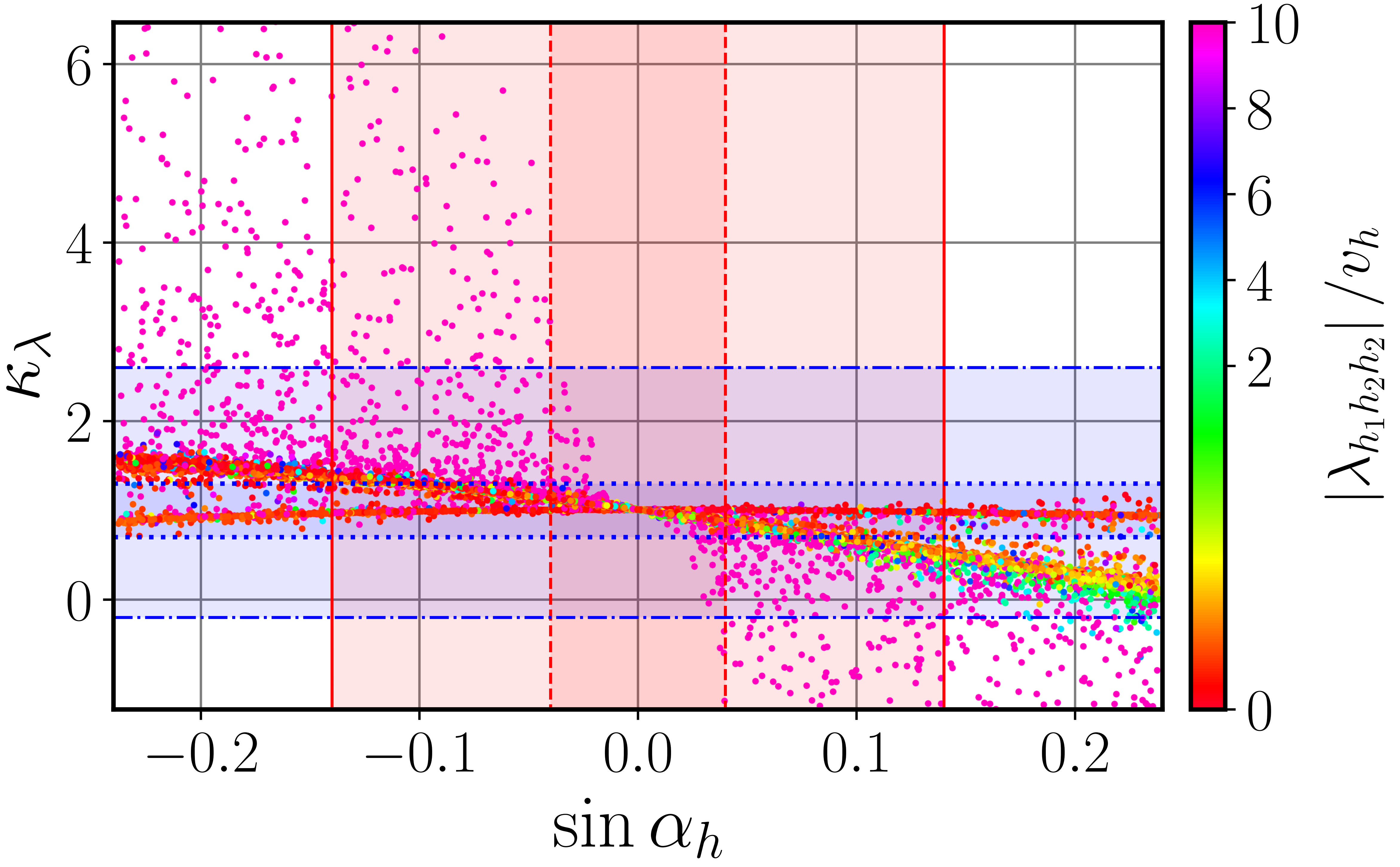


$$\kappa_\lambda \equiv \lambda_{h_1h_1h_1}/\lambda_{\rm SM}\,, \quad \lambda_{\rm SM} = 3m_{h_1}^2/v_h$$

- 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**

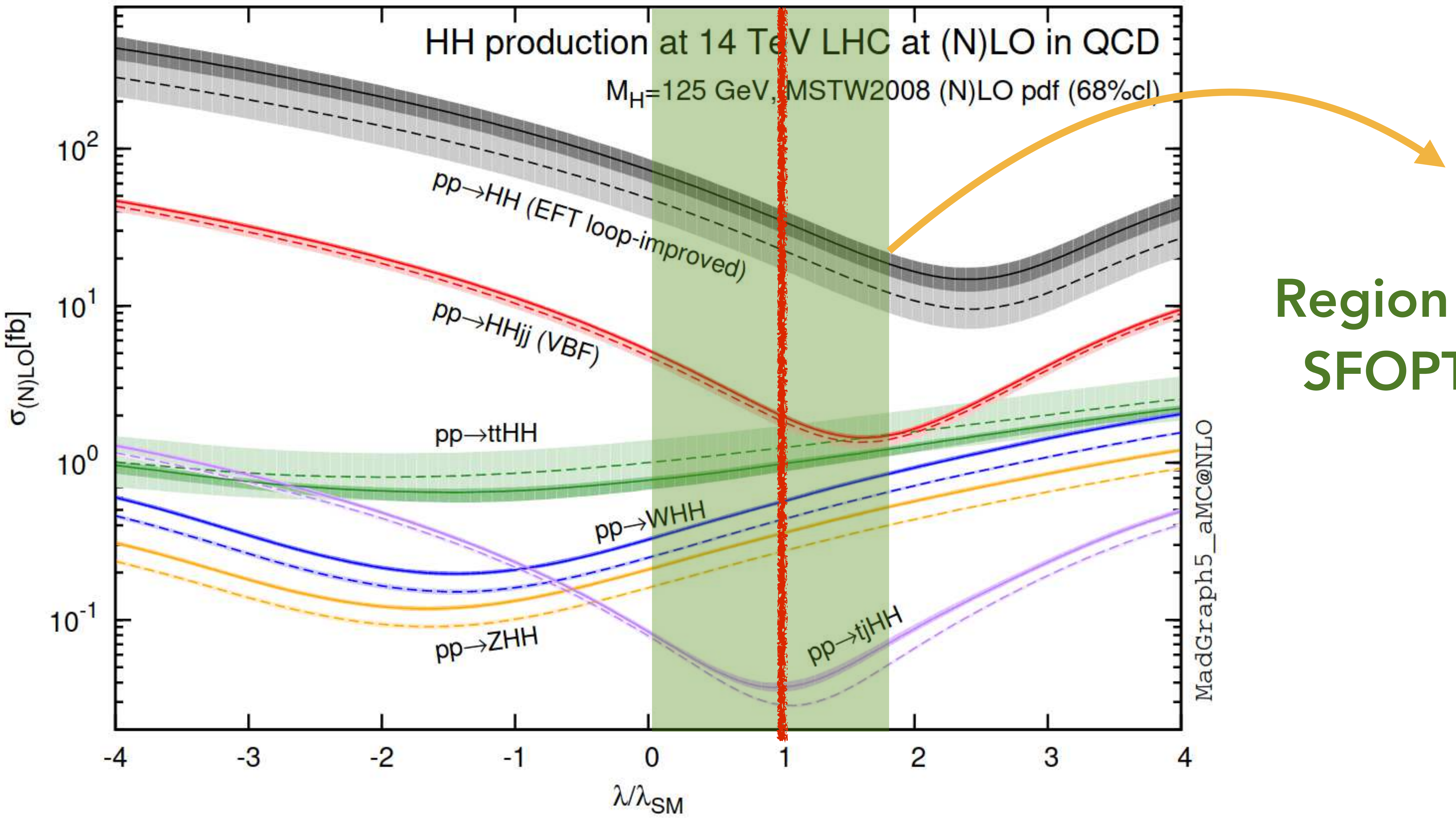
Trilinear BSM Higgs couplings





- When $\kappa_\lambda < 1$, $\lambda_{h_1h_1h_2}$ and $\lambda_{h_1h_2h_2}$ enhance the strength of the phase transion
- Illustrates the potential interplay between collider and SGWB

Di-Higgs production

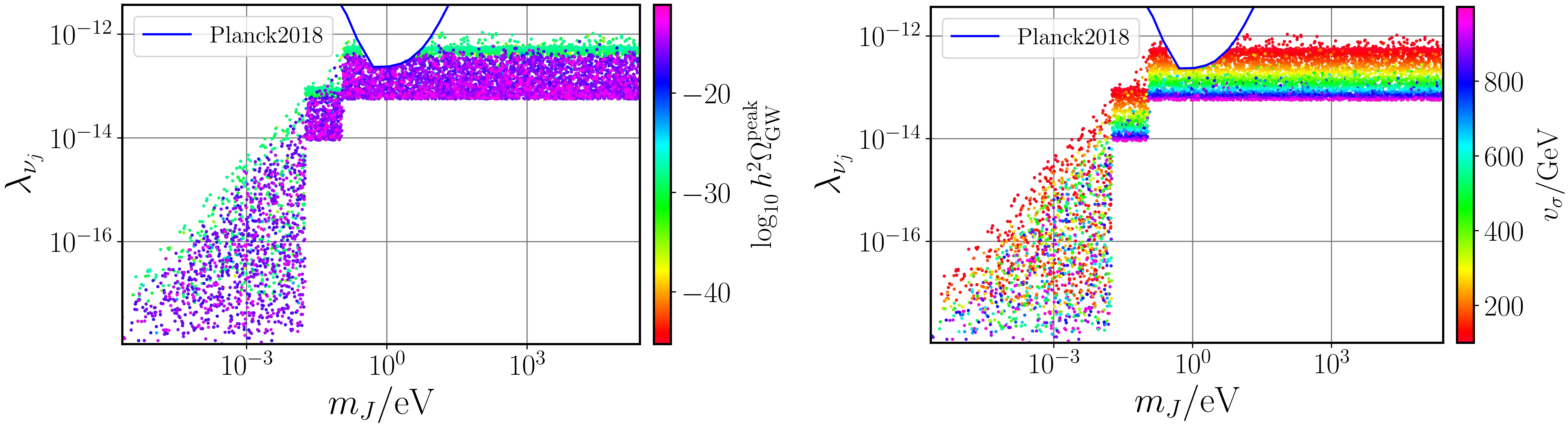


Phys.Lett.B 732 (2014) 142-149

Region compatible with observable SFOPTs in the 6D Majoron model

CMB constraints

[Planck Collaboration, 1807.06209, 1907.12875]



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

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

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

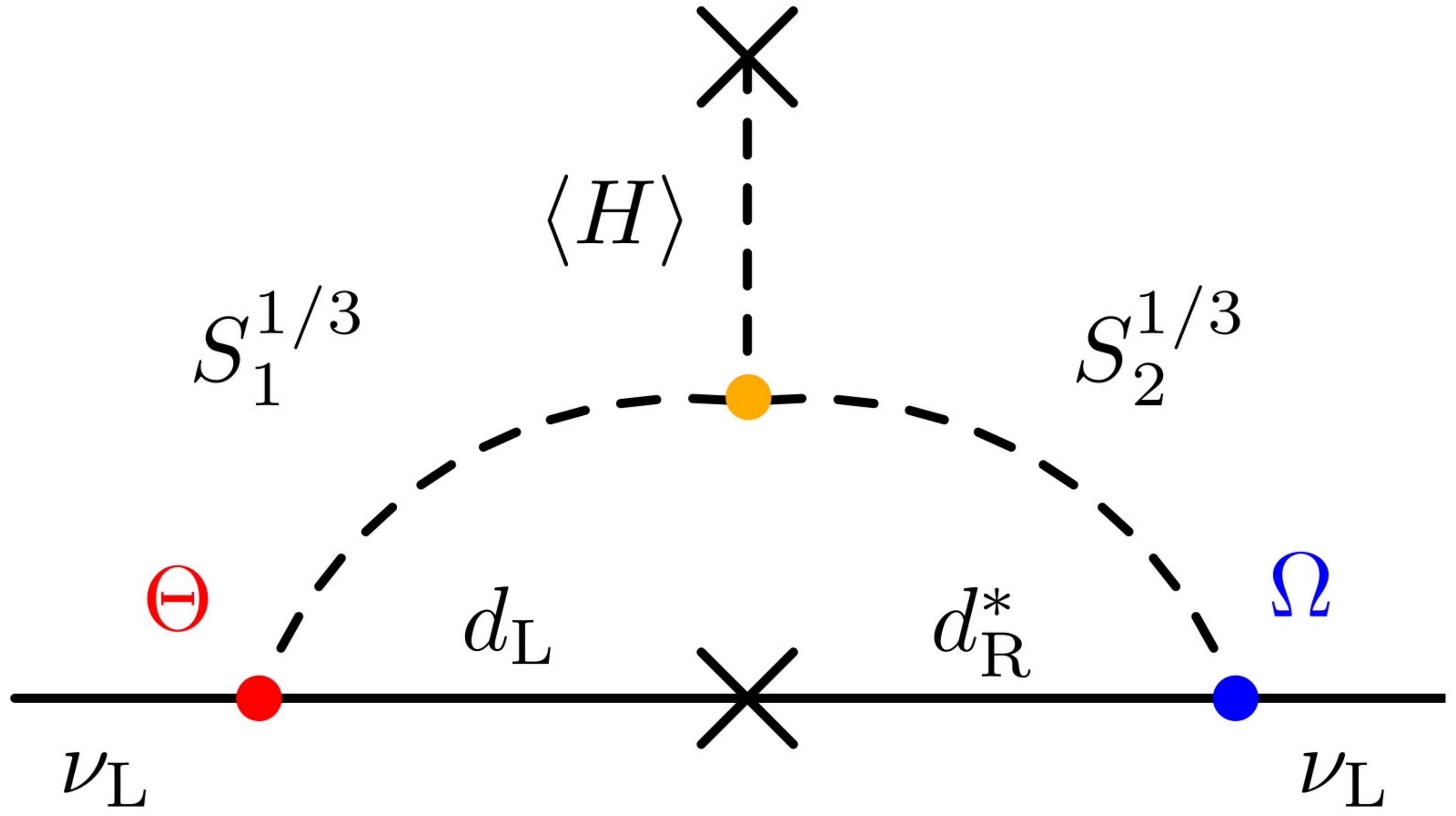
$$\lambda_{\nu_j} \equiv m_j/v_\sigma$$

Scenario 2: Neutrino masses with colour restoration at low temperature

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

Another possibility for neurtrino masses

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



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

- **And an exhaustive flavour analysis**

[Gonçalves, APM, Pasechnik, Porod, 2206.01674]

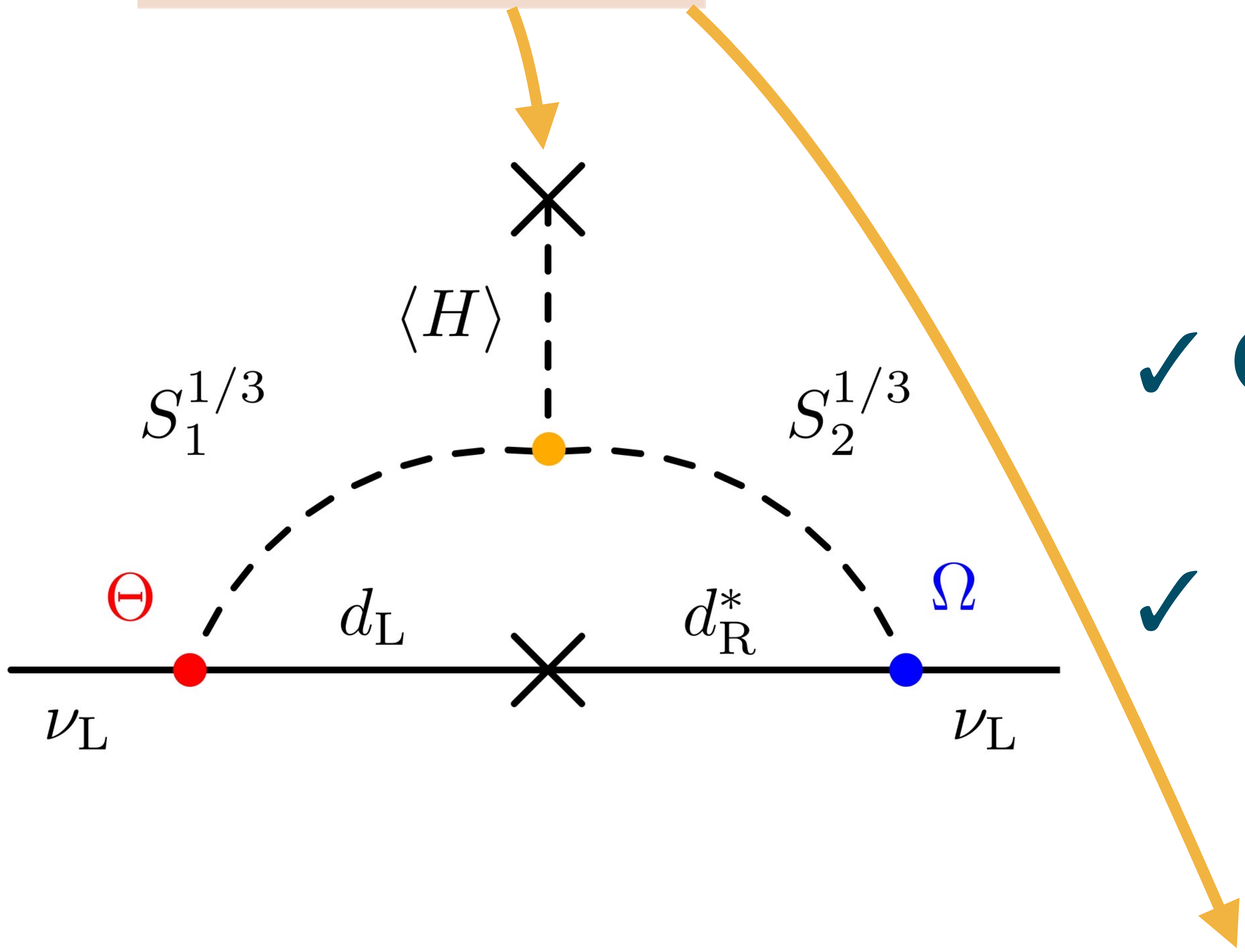
[Gonçalves, APM, Onofre, Pasechnik, 2306.15460]

See also João Gonçalves talk, Wednesday 30th

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

Another possibility for neurtrino masses

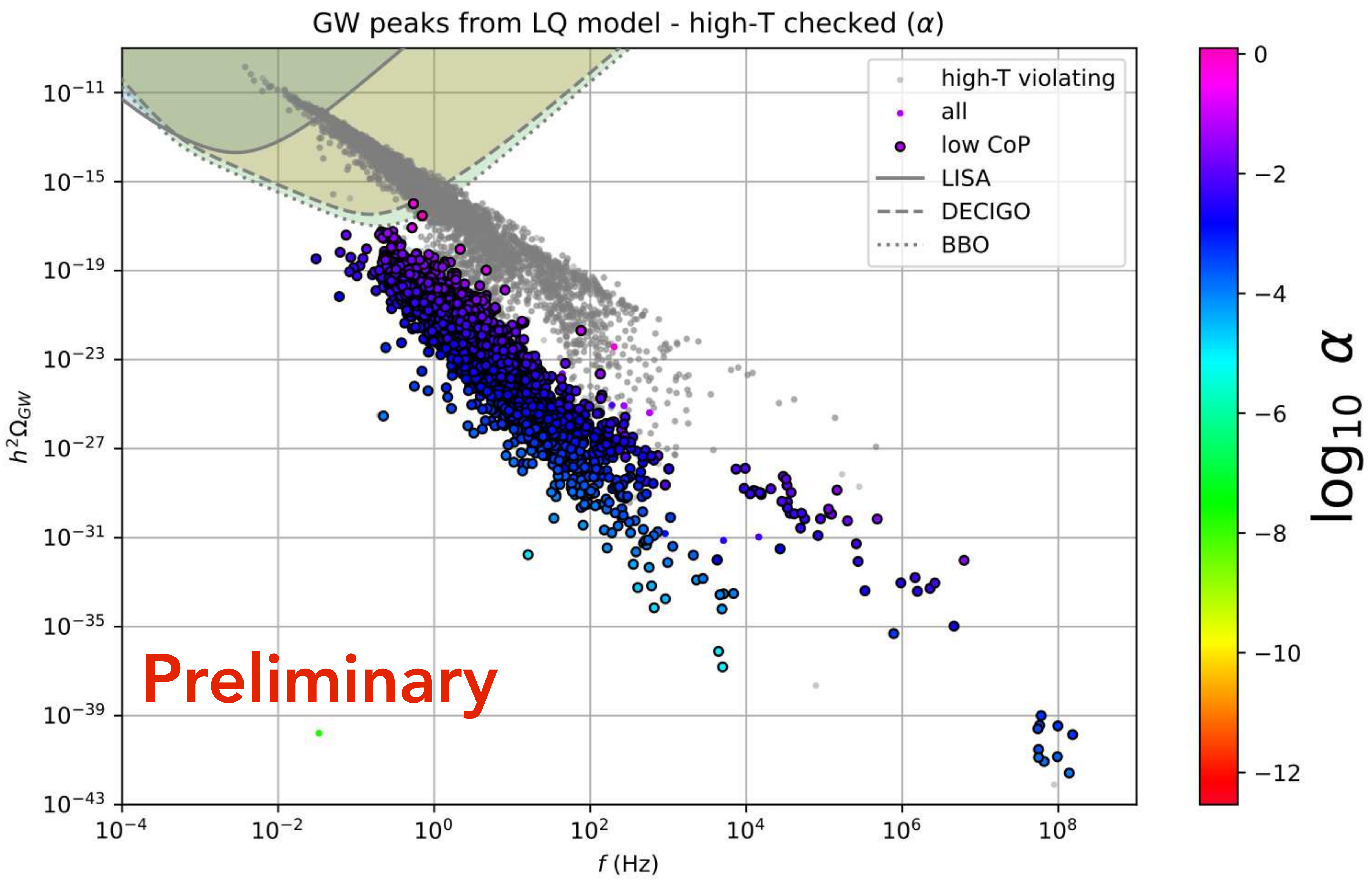
$$V \supset \; -\mu^2|H|^2 + \mu_S^2|S|^2 + \mu_R^2|R|^2 + \lambda(H^\dagger H)^2 + g_{HR}(H^\dagger H)(R^\dagger R) + g'_{HR}(H^\dagger R)(R^\dagger H) + g_{HS}(H^\dagger H)(S^\dagger S) + \left(a_1 RSH^\dagger + \text{h.c.}\right) .$$

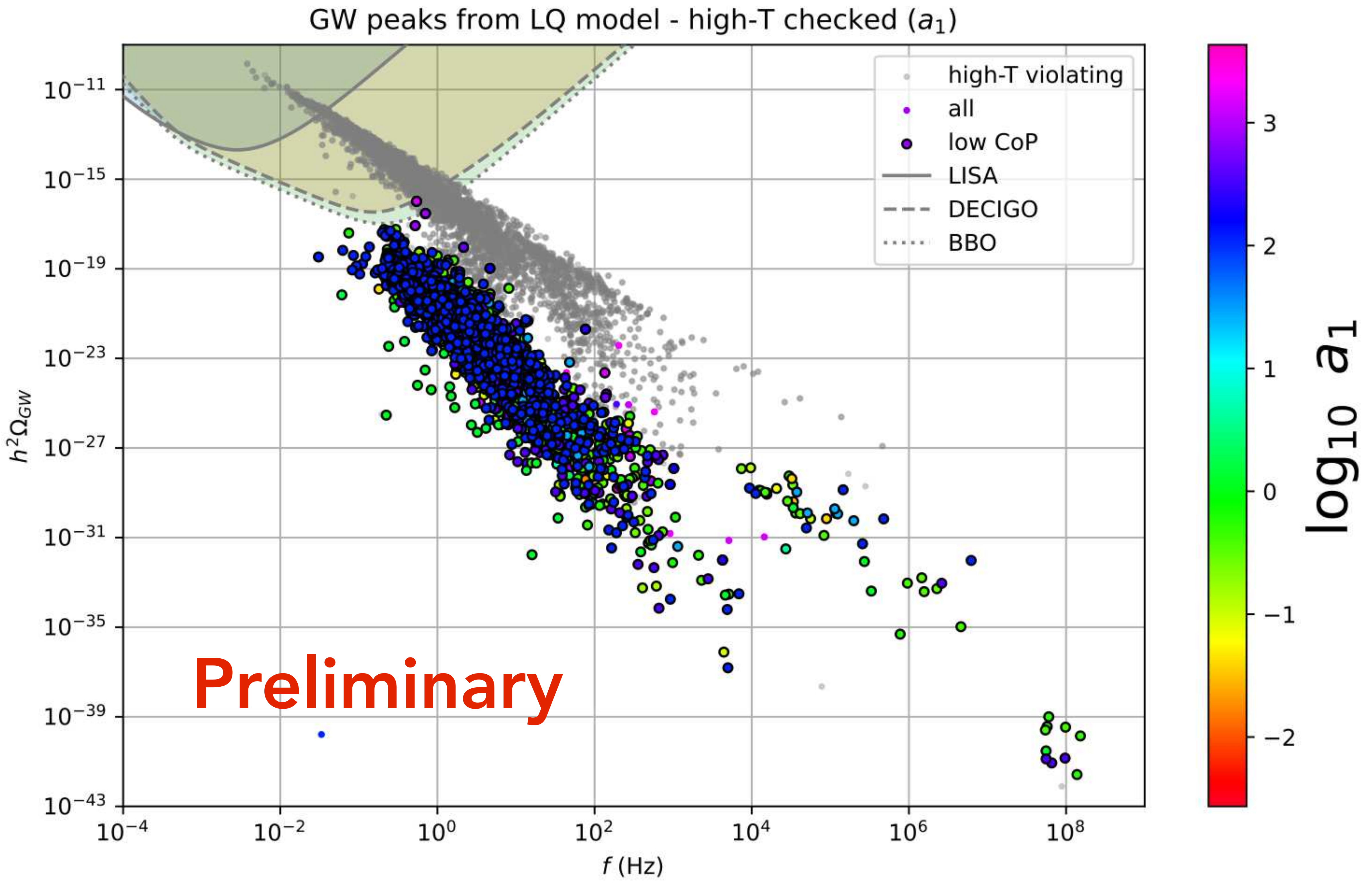


✓ Consider the possibility of LQ VEVs at finite T

✓ Classify all possible FOPTs and determine SGWB

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





DRalgo + hacked *CosmoTransitions*

[Ekstedt, Schicho, Tenkanen, 2205.08815]

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

BBO?

- **Viable FOPTs (CoP)**

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

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

- **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
- The nature of neutrino masses can have profound impact in the SGWB
- Combination with collider observables for further insights: new scalars (singlet, coloured,…) trilinear couplings, mixing angles

THANK YOU

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**

Phenomenological inputs

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

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

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

[Papaefstathiou, Robens, White, 2207.00043]

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

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

Thermal effective potential

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

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

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

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

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

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

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

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

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

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

Neutrino sector revisited

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

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

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

3 light active neutrinos

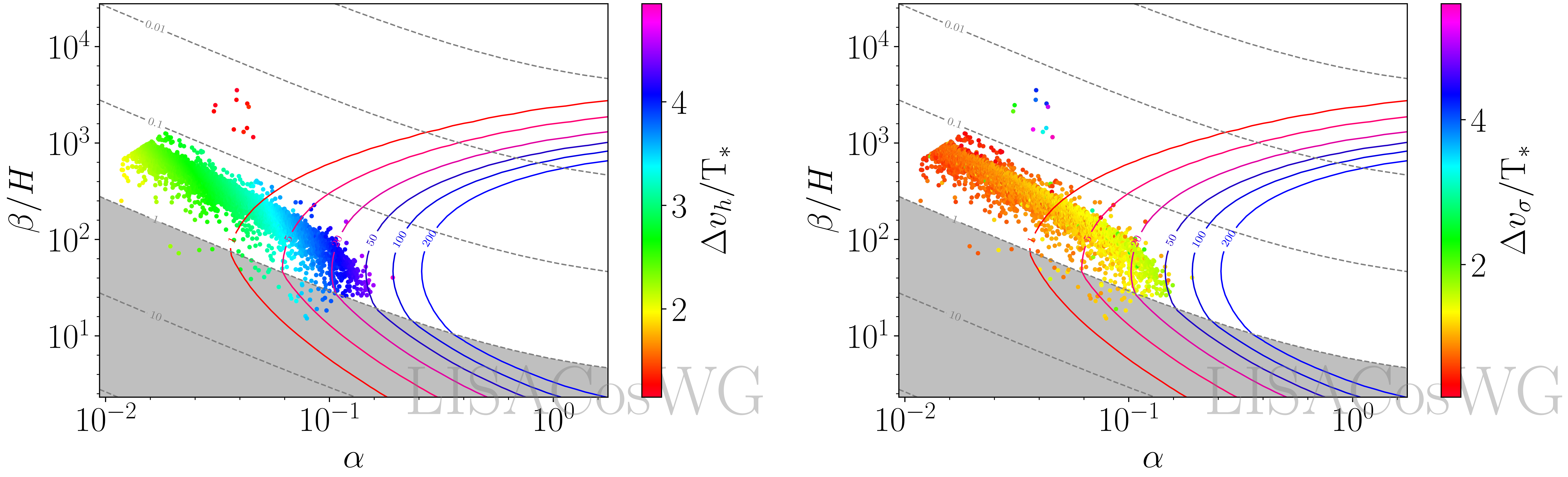
$$\boldsymbol{m}_{N^\pm} \approx \boldsymbol{\Lambda} \pm \frac{v_\sigma}{2\sqrt{2}}(\boldsymbol{y_\sigma} + \boldsymbol{y'_\sigma})$$

6 heavy neutrinos

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

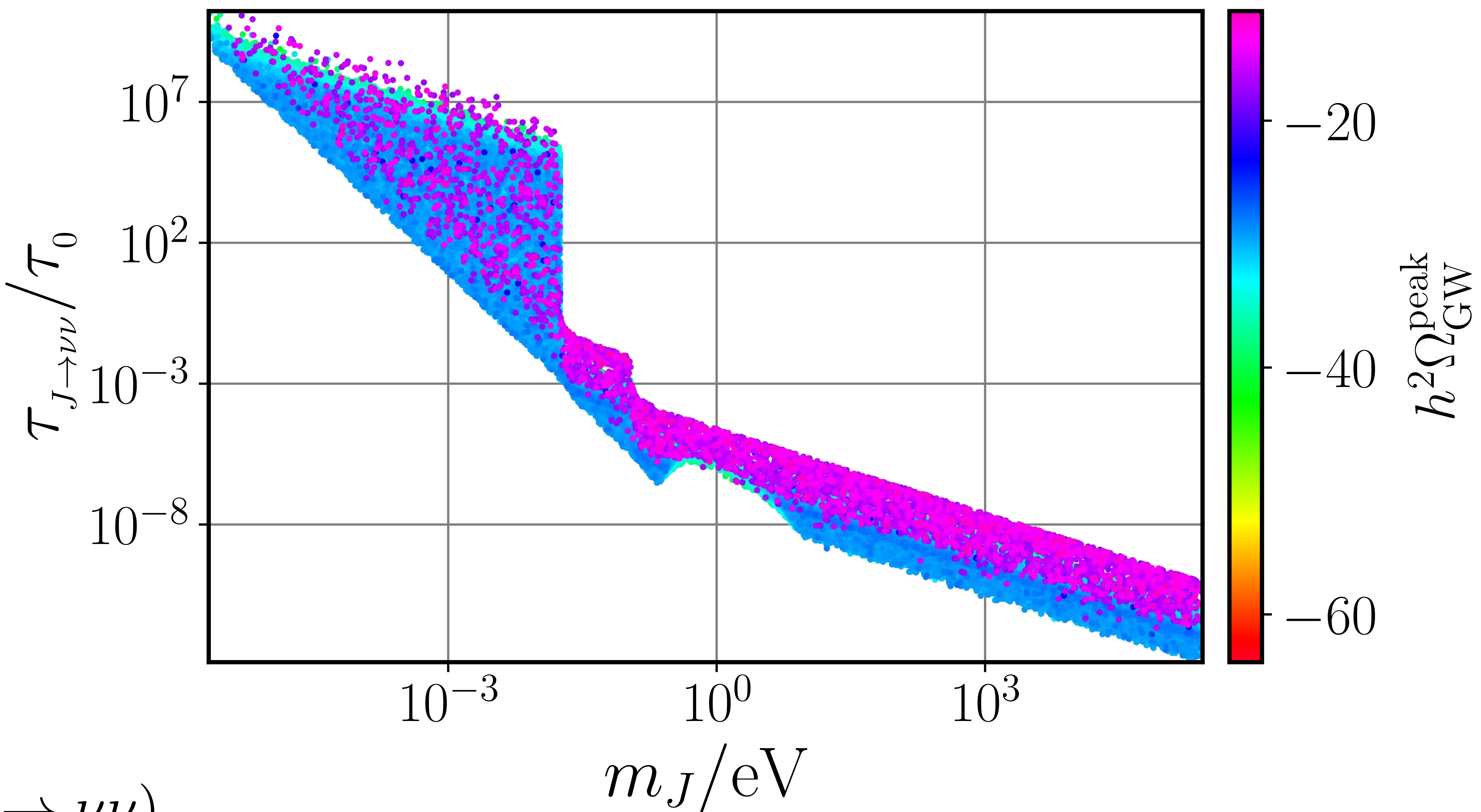
$$\Delta v_\phi = \left|v_\phi^f - v_\phi^i\right| , \qquad \phi = h, \sigma$$

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



Both order parameters must be large for observable SGWB

Decaying Majorons



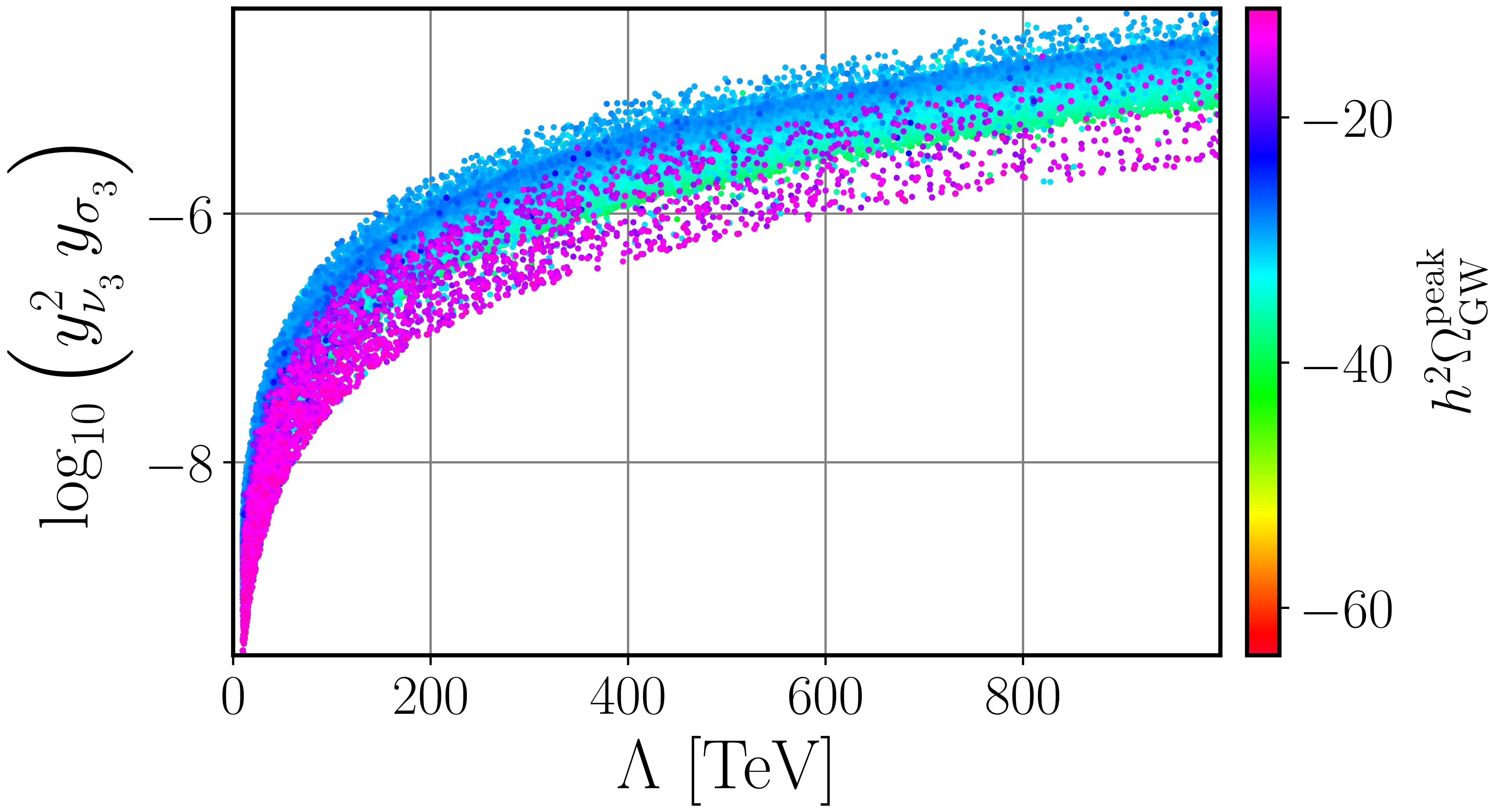
$$\tau_{J\to\nu\nu} = \Gamma^{-1}(J \to \nu\nu)$$

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

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

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

Seesaw effect vs FOPTs



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

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

Two LQ model

SM $+$ Singlet leptoquark $+$ Doublet leptoquark

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

This field content has an UV inspiration…

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

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

$$L = \begin{pmatrix} H & \ell_\mathrm{L} \\ \ell_\mathrm{R} & \phi \end{pmatrix} \qquad Q_\mathrm{L} = \begin{pmatrix} \underset{\tilde{R}_2}{q_\mathrm{L}} & D_\mathrm{L} \end{pmatrix} \qquad Q_\mathrm{R} = \begin{pmatrix} q_\mathrm{R}^c & \underset{S_1}{D_\mathrm{R}^c} \end{pmatrix}^\mathsf{T}$$

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**

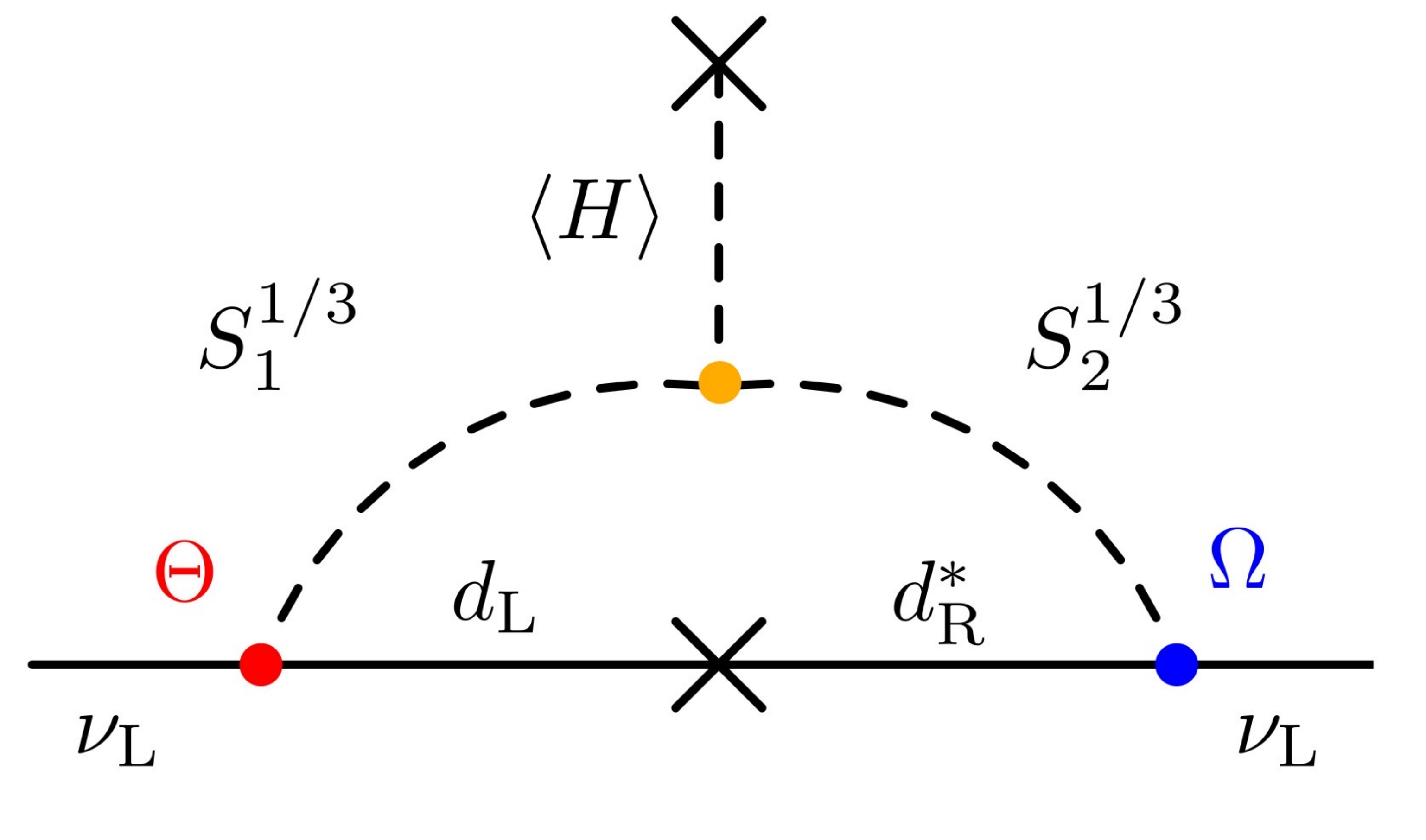
- **Only allows leptoquark interactions**

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

- **Proton is stable**

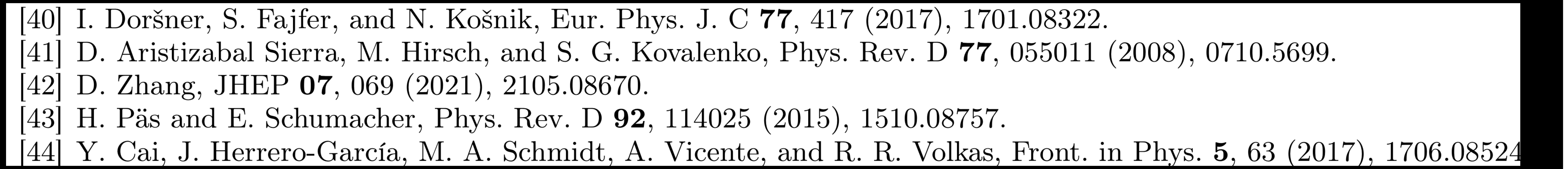
Neutrino Masses

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



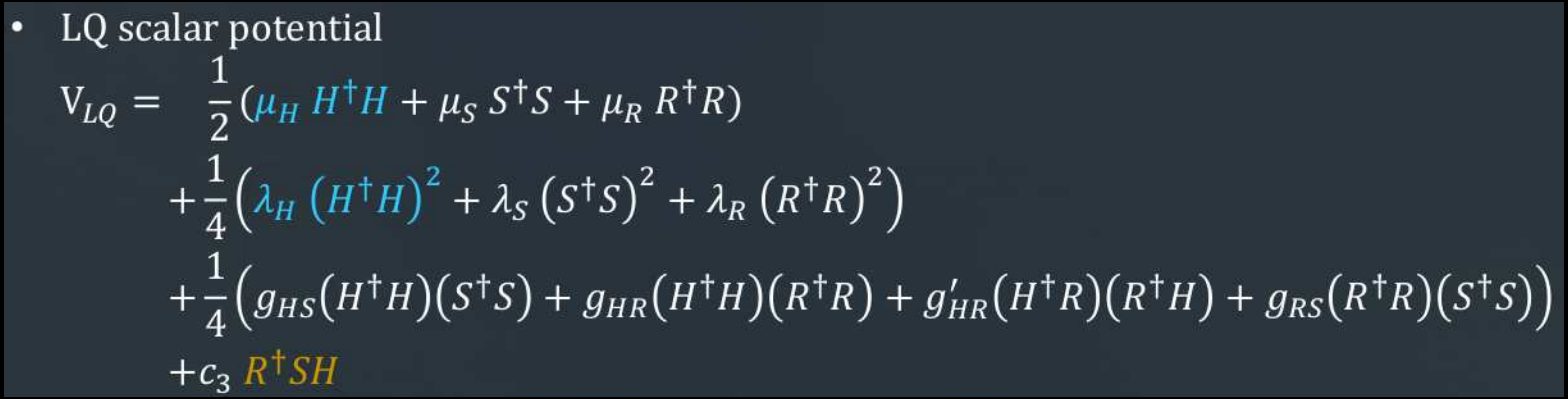
- **And an exhaustive flavour analysis**

[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

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

✓ Consider the possibility of LQ VEVs at finite T

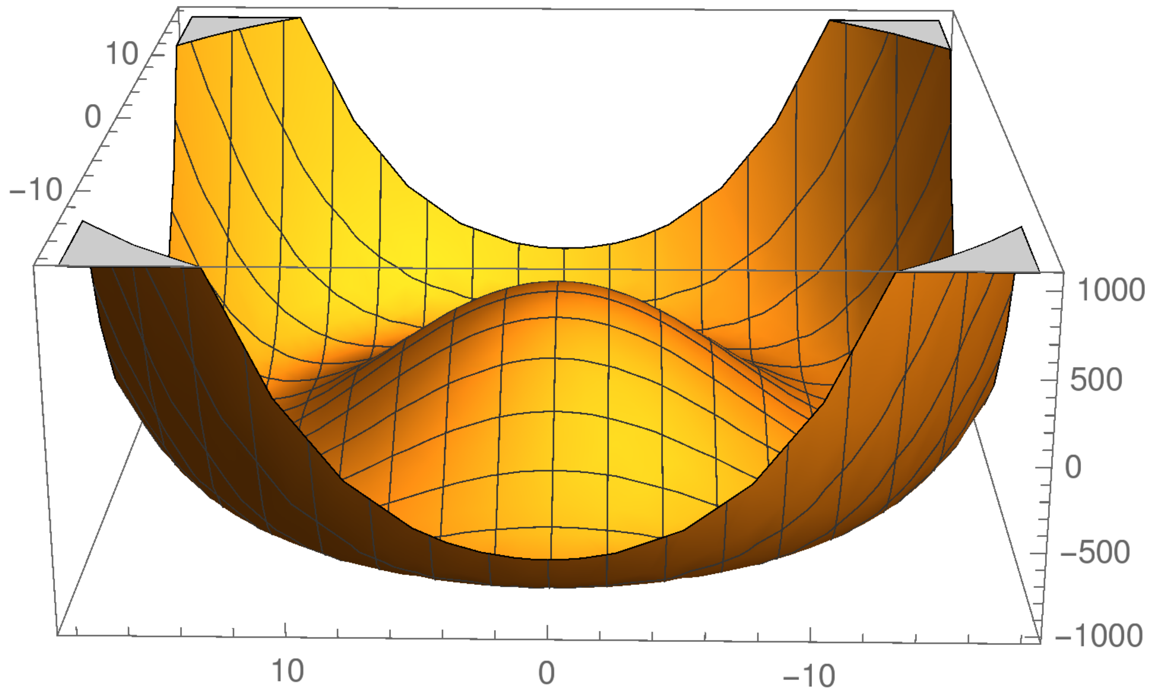
✓ Classify all possible FOPTs and determine SGWB

Basics of Phase Transitions

(Illustration)

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

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

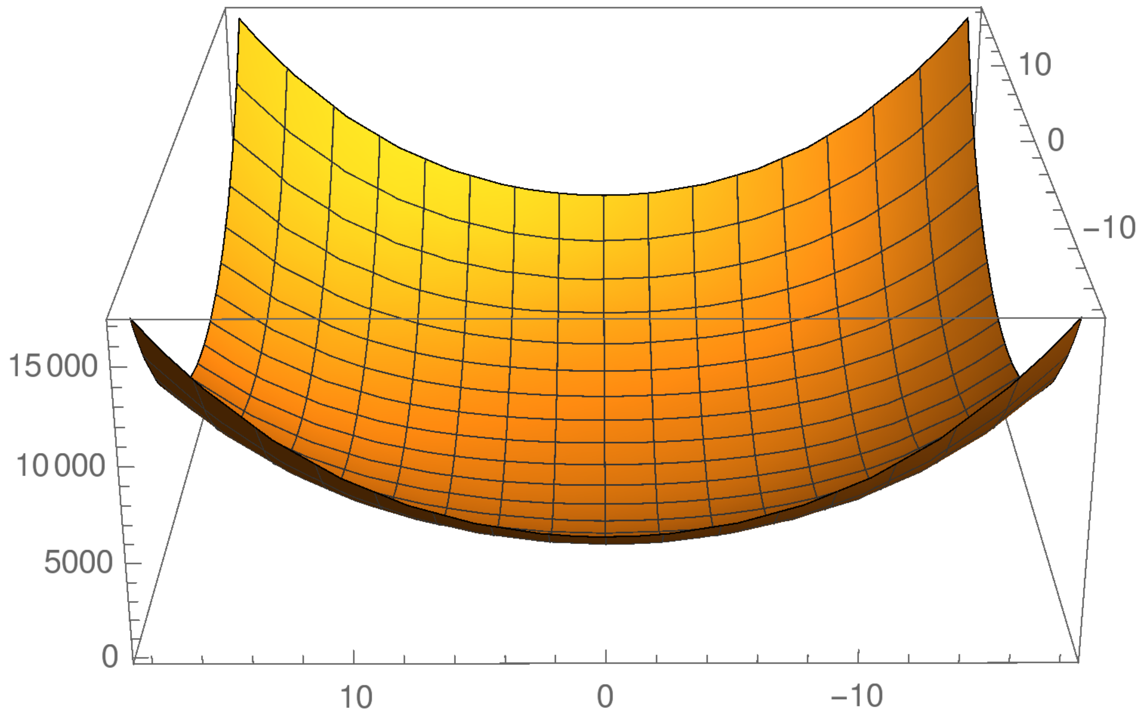


Add thermal corrections:

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

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

Restored symmetry at high T



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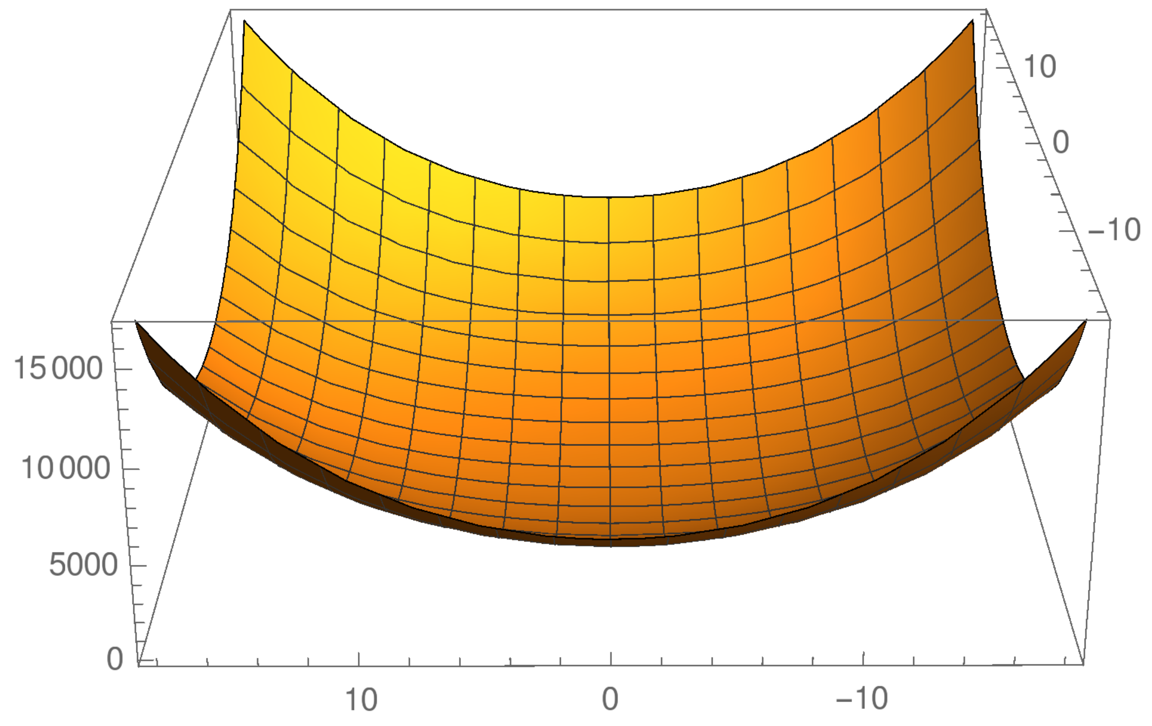
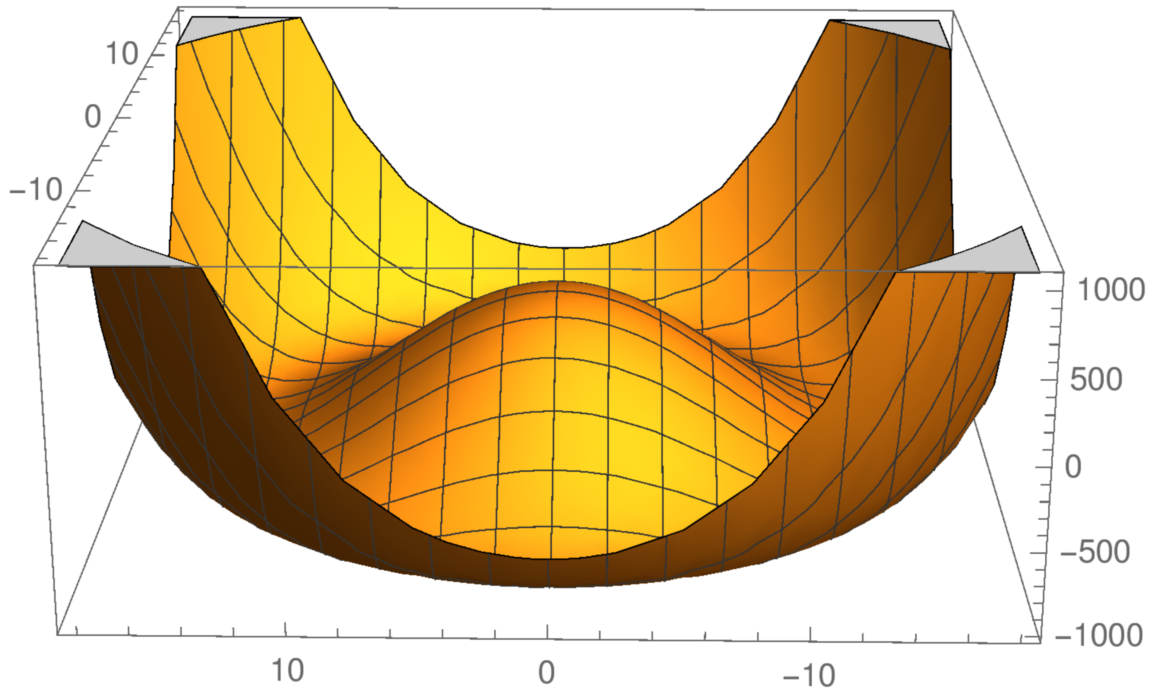


Add thermal corrections:

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

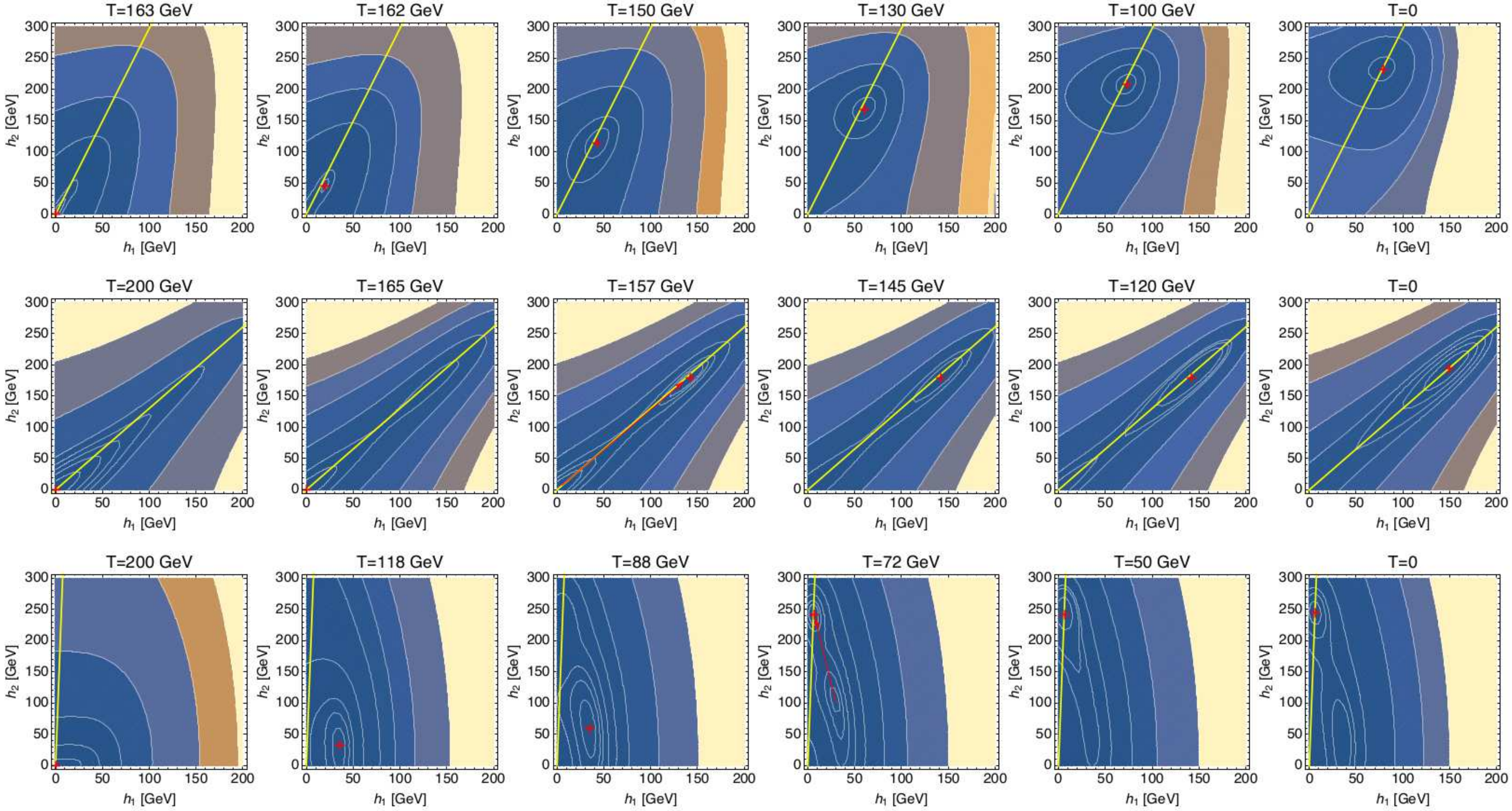
For $C_\phi < 0$, after a certain $T > 0$, $\mu_{eff} \equiv \mu^2 + C_\phi T^2 < 0$

Broken symmetry at high T



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

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



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FOPTs ⟶ 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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

And for gauge bosons…

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

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

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

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