Audible gravitational echoes of new physics

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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

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 $\longrightarrow$ SGWB

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

$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$

[JCAP 07(2019)047]

CMB experiments such as Planck

SGWB

✓ Superposition of unresolved astrophysical sources

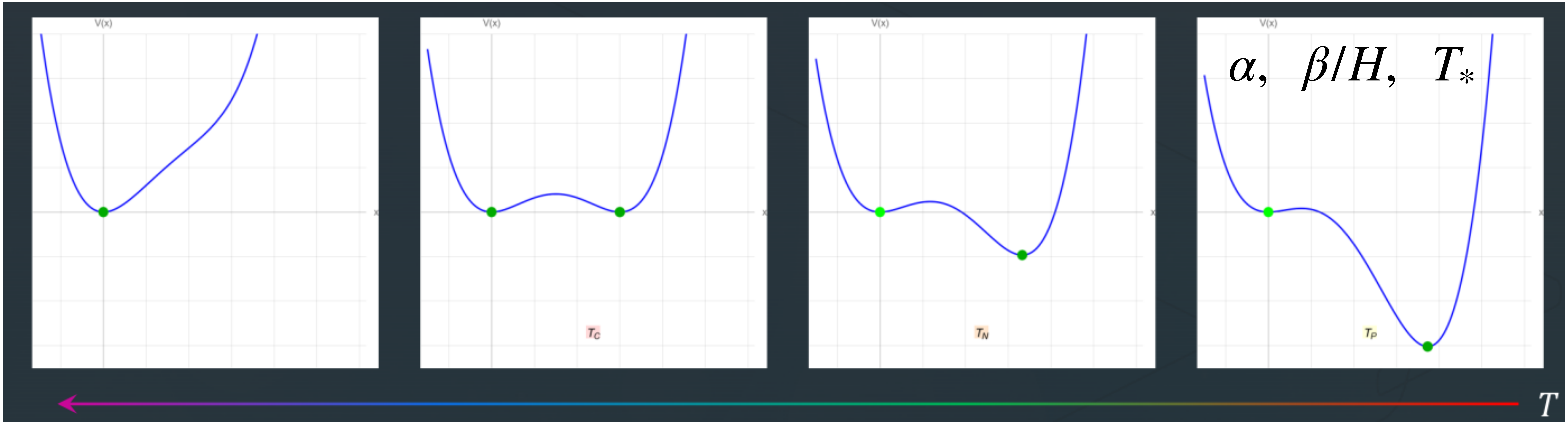
✓ Cosmological origin

- ◉ Inflation
- ◉ Topological defects
- ◉ Phase transitions

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

First order phase transition (FOPT)

(Illustration)



Credit: Marco Finetti

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

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
	1	1	$\times$	-2	0	T1S
$U(1)_L$	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**

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

Neutrino sector revisited

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

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

✓ 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

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

6 heavy neutrinos

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

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

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

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

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

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

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

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

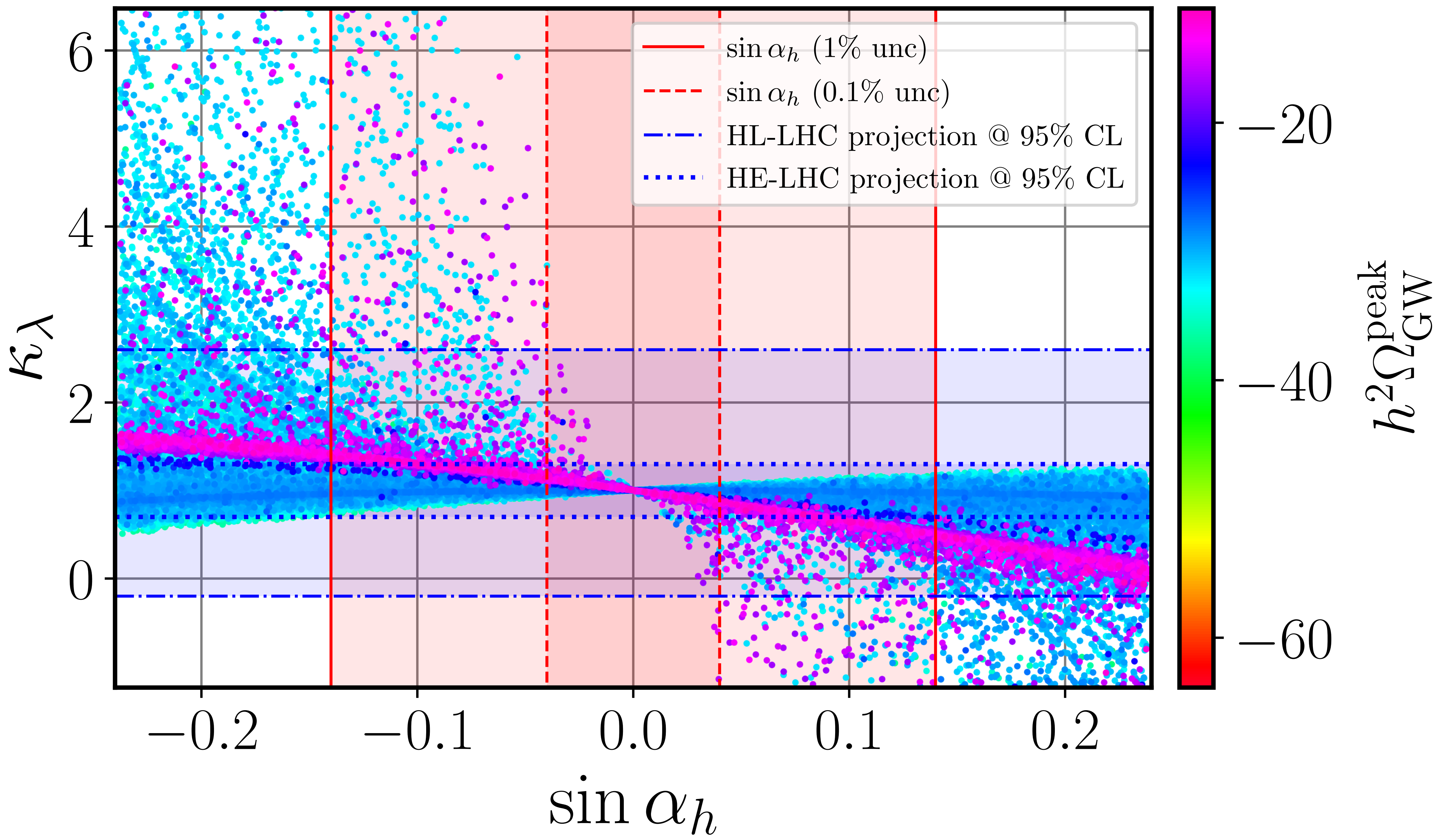
Results

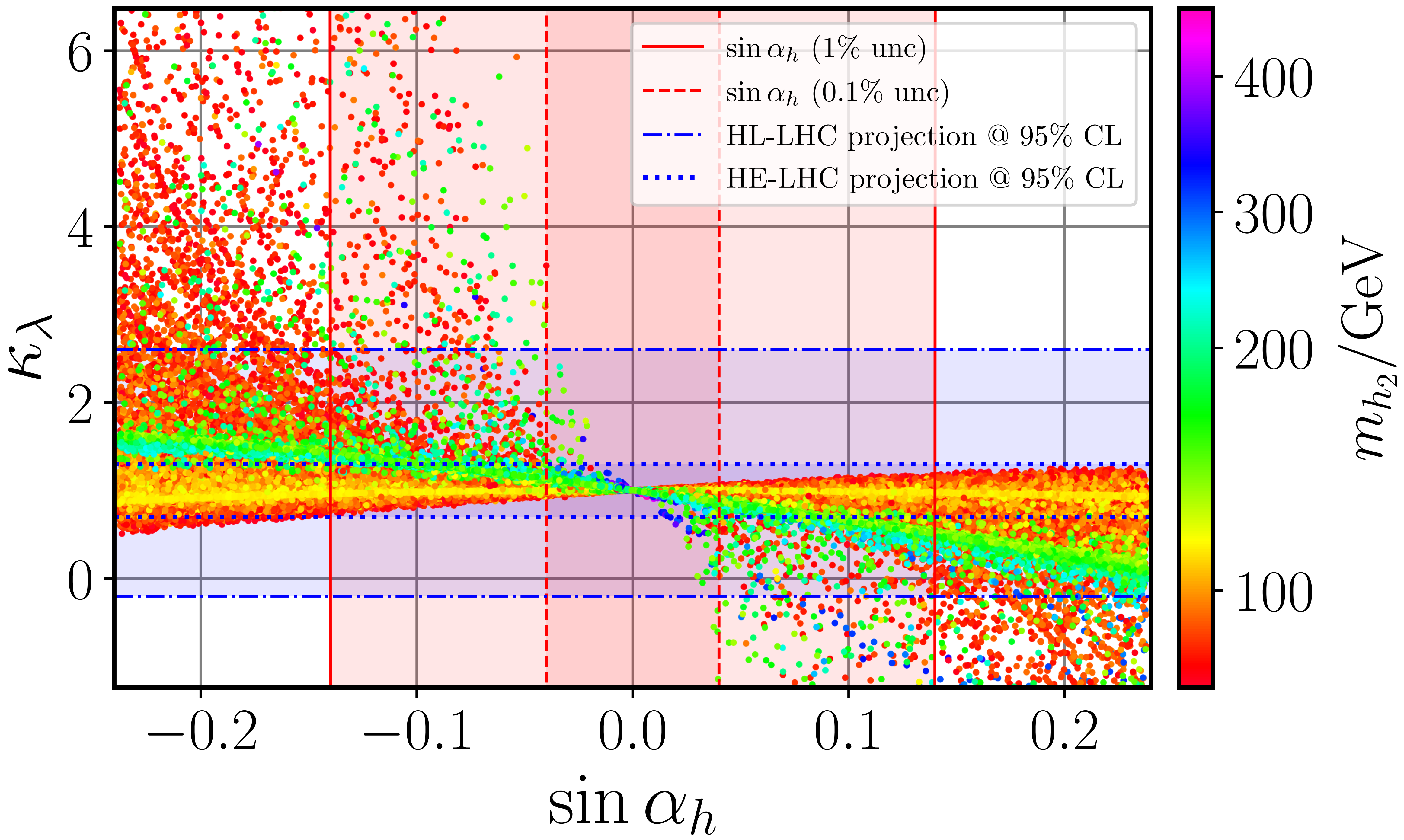
$$\log_{10}(h^2\Omega_{\rm GW}^{\rm peak}) \propto -2\log_{10} f_{\rm peak} + \log_{10} F(\alpha, T_*)$$

Scan using *CosmoTransitions*

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

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

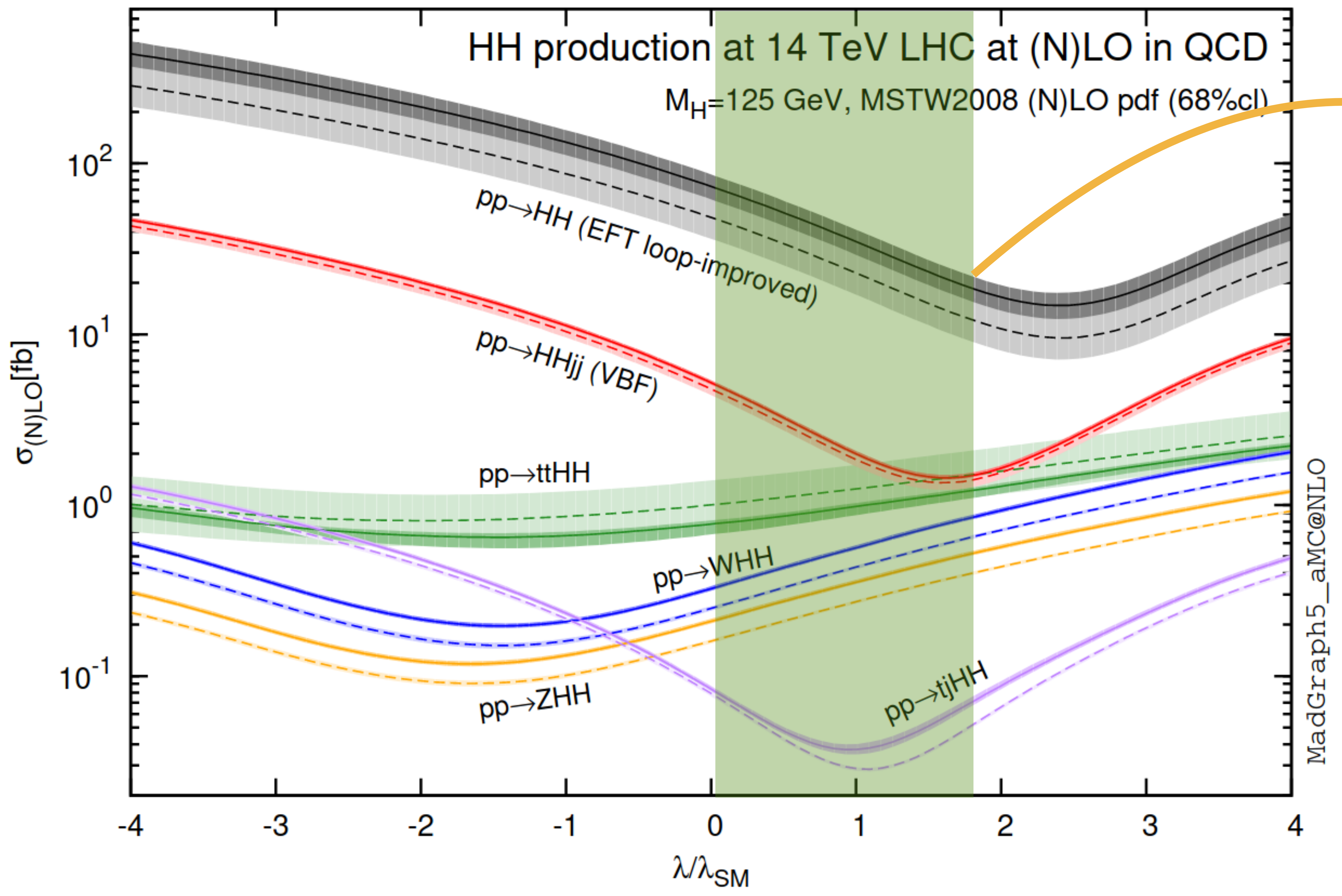




$$\kappa_\lambda \equiv \lambda_{h_1h_1h_1}/\lambda_{\rm SM}\,, \quad \lambda_{\rm SM} = 3m_{h_1}^2/v_h$$

- 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

Di-Higgs production



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

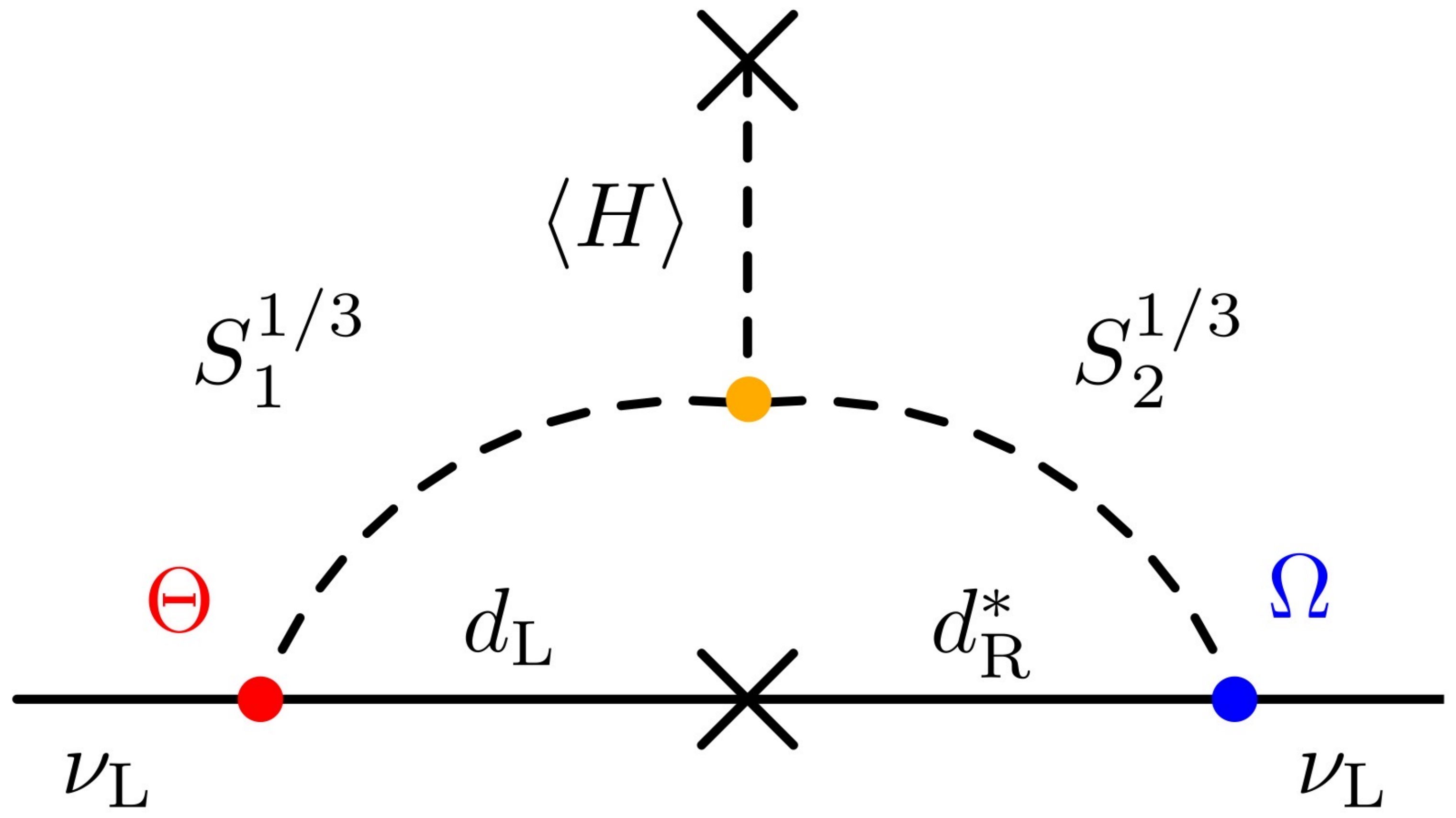
Region compatible with observable SFOPTs in the 6D Majoron model

Scenario 2: Neutrino masses with colour restoration at low temperature

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

Another possibility for neurtrino masses

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



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

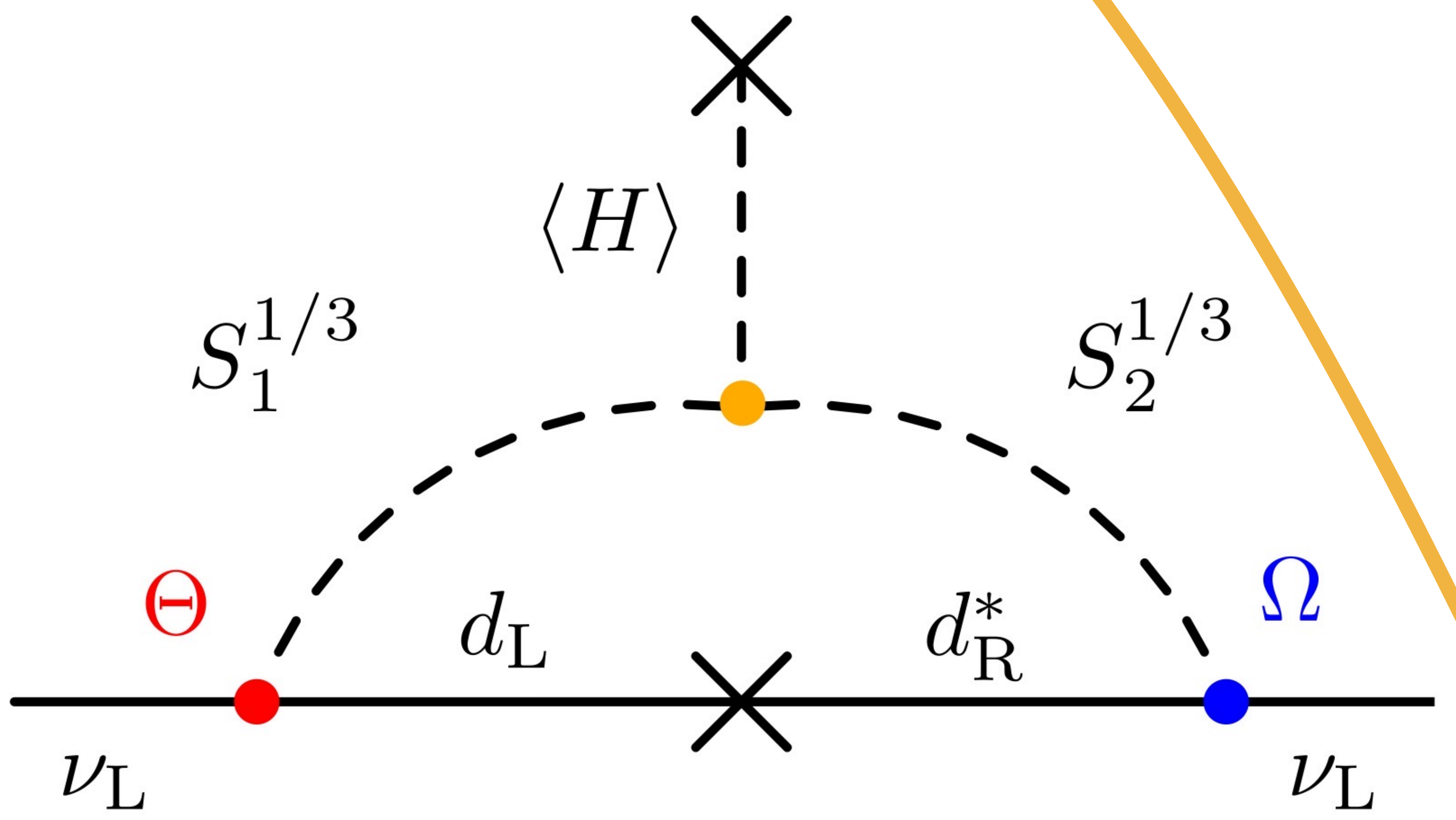
- **And an exhaustive flavour analysis**

  [Gonçalves, APM, Pasechnik, Porod, 2206.01674]

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

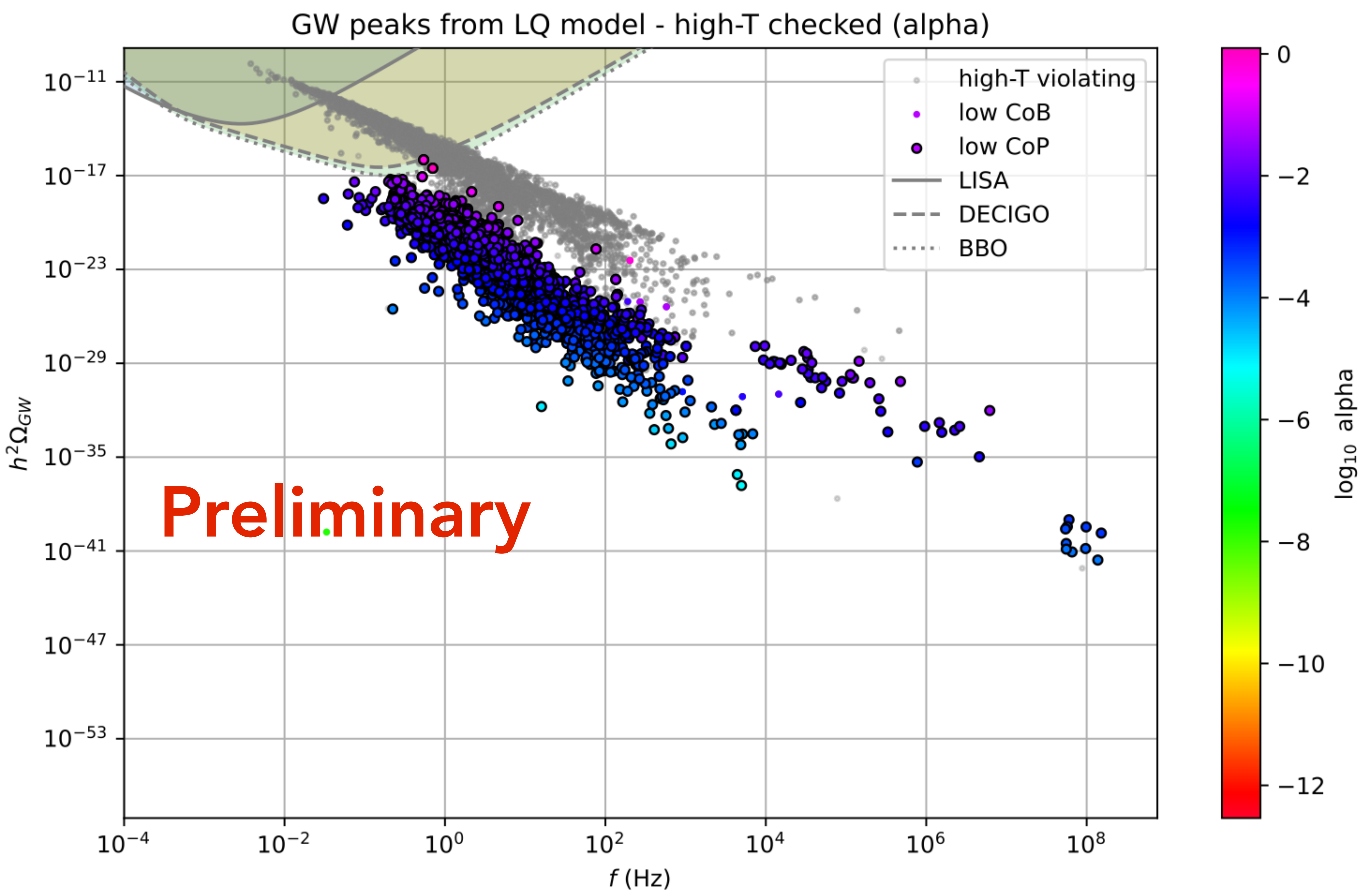
Another possibility for neurtrino masses

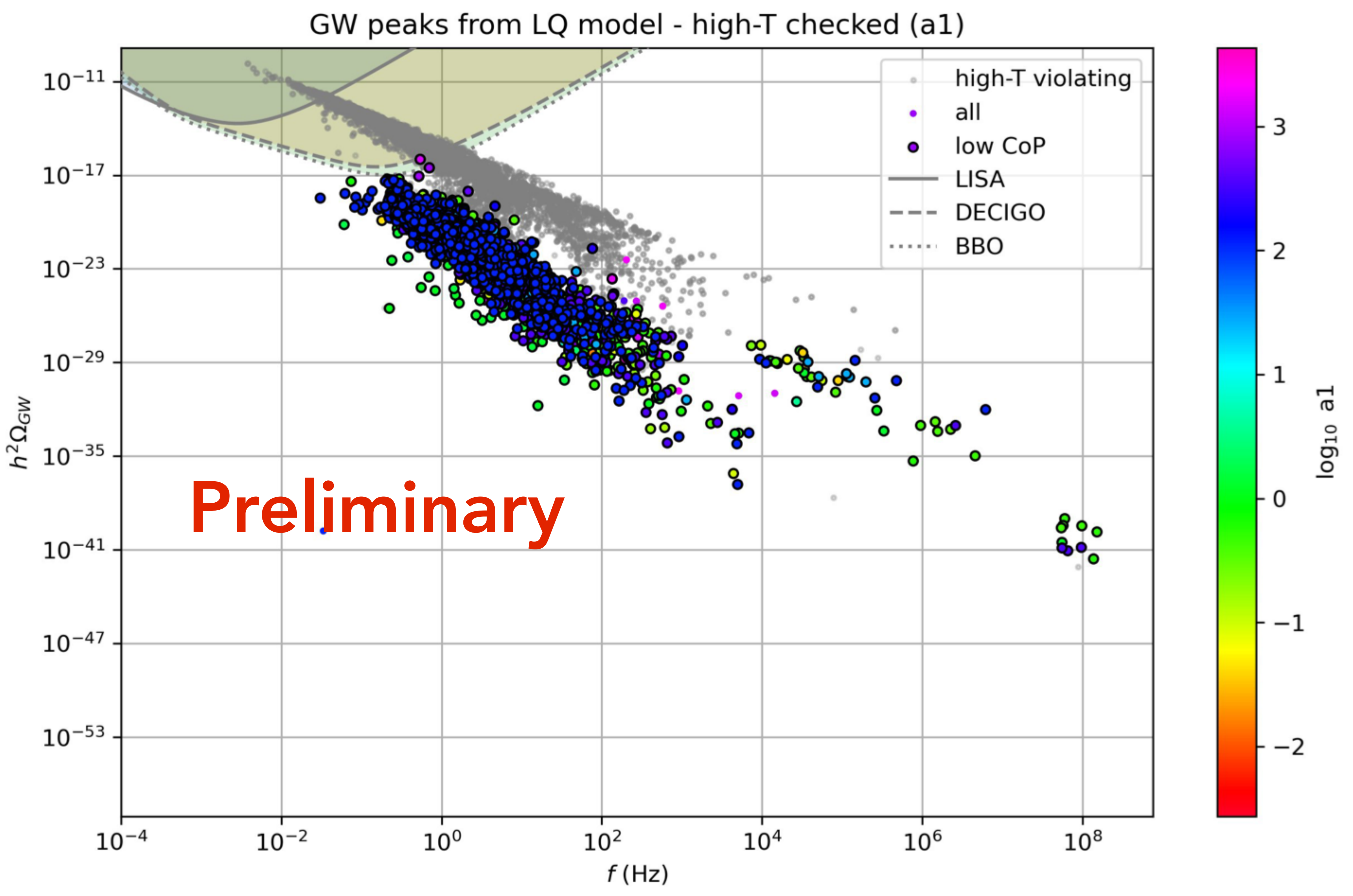
$$V \supset -\mu^2|H|^2 + \mu_S^2|S|^2 + \mu_R^2|R|^2 + \lambda(H^\dagger H)^2 + g_{HR}(H^\dagger H)(R^\dagger R) + g'_{HR}(H^\dagger R)(R^\dagger H) + g_{HS}(H^\dagger H)(S^\dagger S) + \left(a_1 RSH^\dagger + \text{h.c.}\right) .$$



- ✓ 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 $\longleftarrow 1 \lesssim a_1 \lesssim 1000$

BBO?

- Viable FOPTs (CoP)

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

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

- 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 (new scalars? trilinear couplings? mixing angles?)