

GRAVITATIONAL WAVES AND MAGNETOGENESIS IN MULTI-SCALAR EXTENSIONS OF THE STANDARD MODEL

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Based upon:

JHEP 02 (2025) 110, 2412.02645 [hep-ph] (Marfatia, Gonçalves, APM, Pasechnik)

JCAP 10 (2025) 064, 2505.08011 [hep-ph] (Balaji, Marfatia, Gonçalves, APM, Pasechnik)

Workshop on Multi-Higgs models 2026 - IST



ERC-PT A-Projects 'Unveiling'



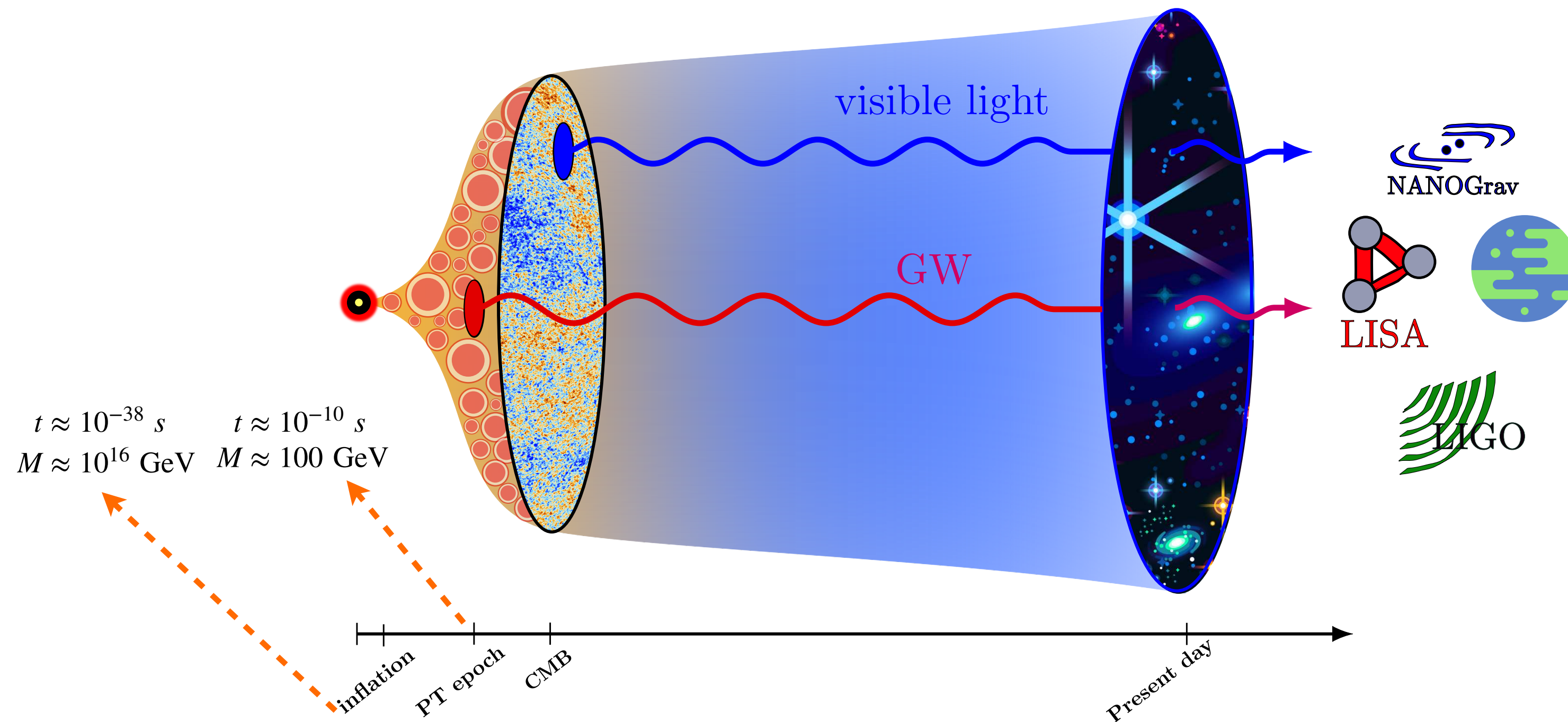
Universidade do Minho
Escola de Ciências



Topics of the talk

1. **First-Order Phase Transitions (FOPTs) in the Early Universe**
2. **Primordial Gravitational Waves as probes of BSM Physics**
3. **Primordial Magnetic fields from strongly supercooled FOPTs**

Relics of the early Universe



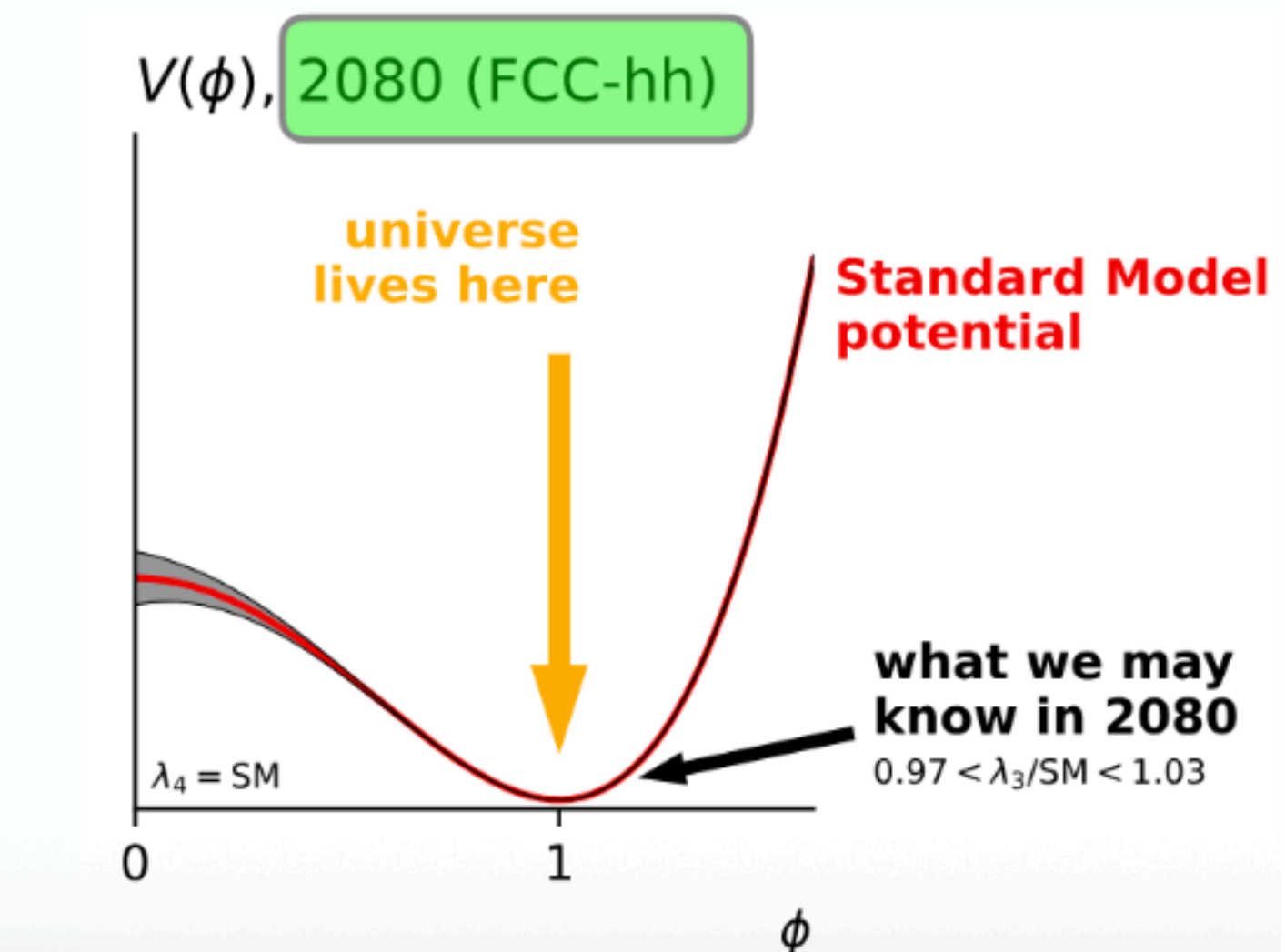
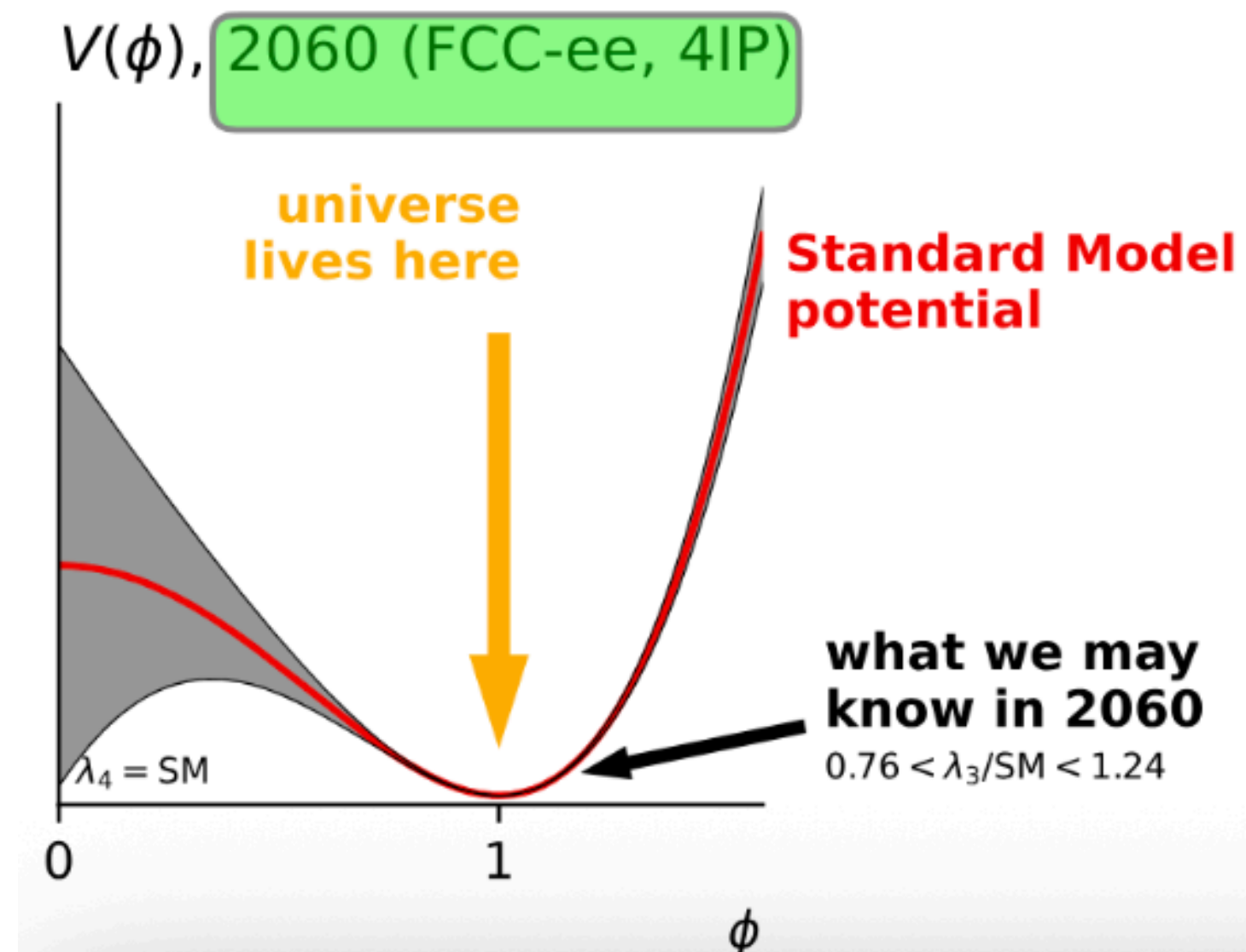
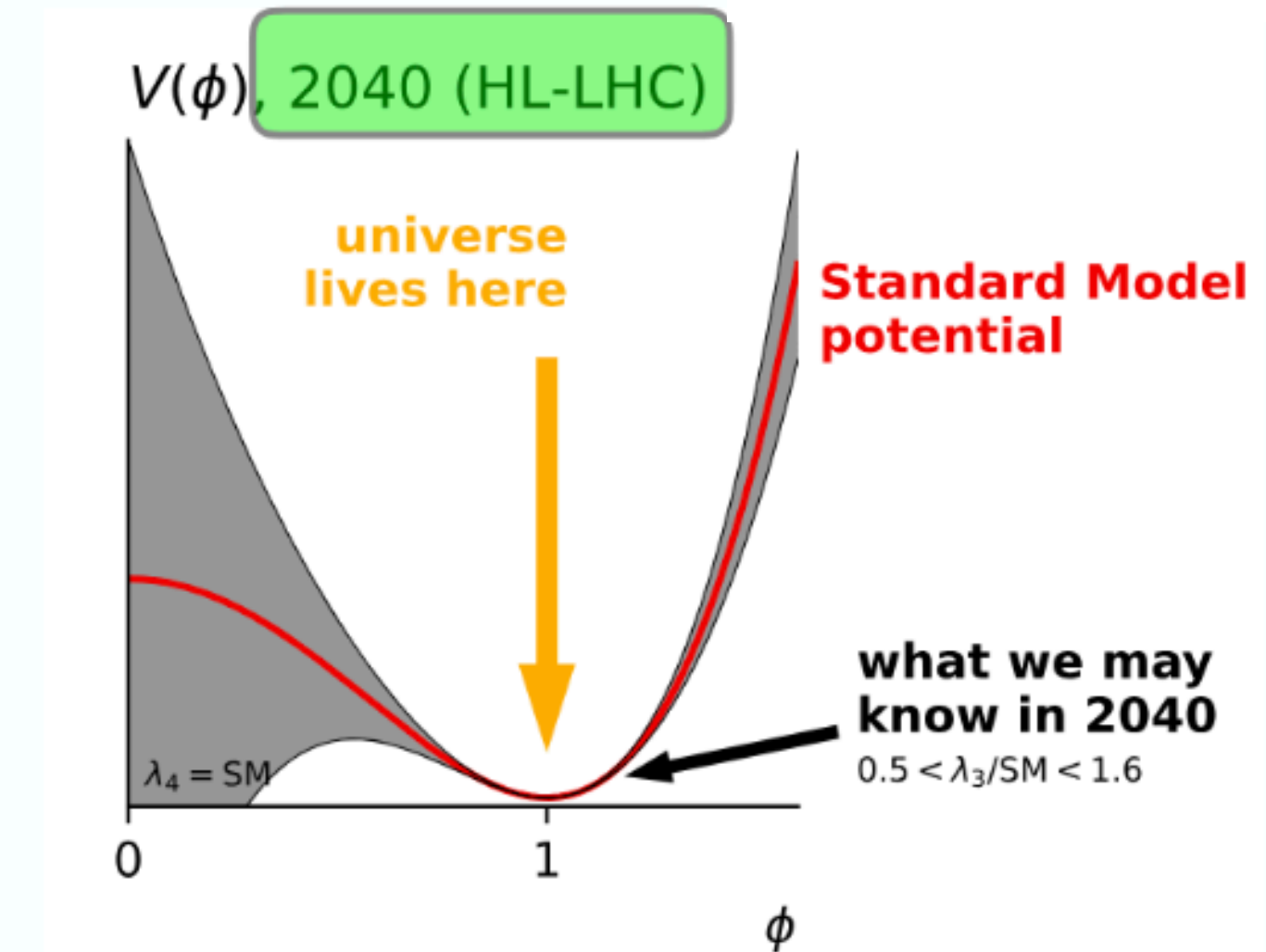
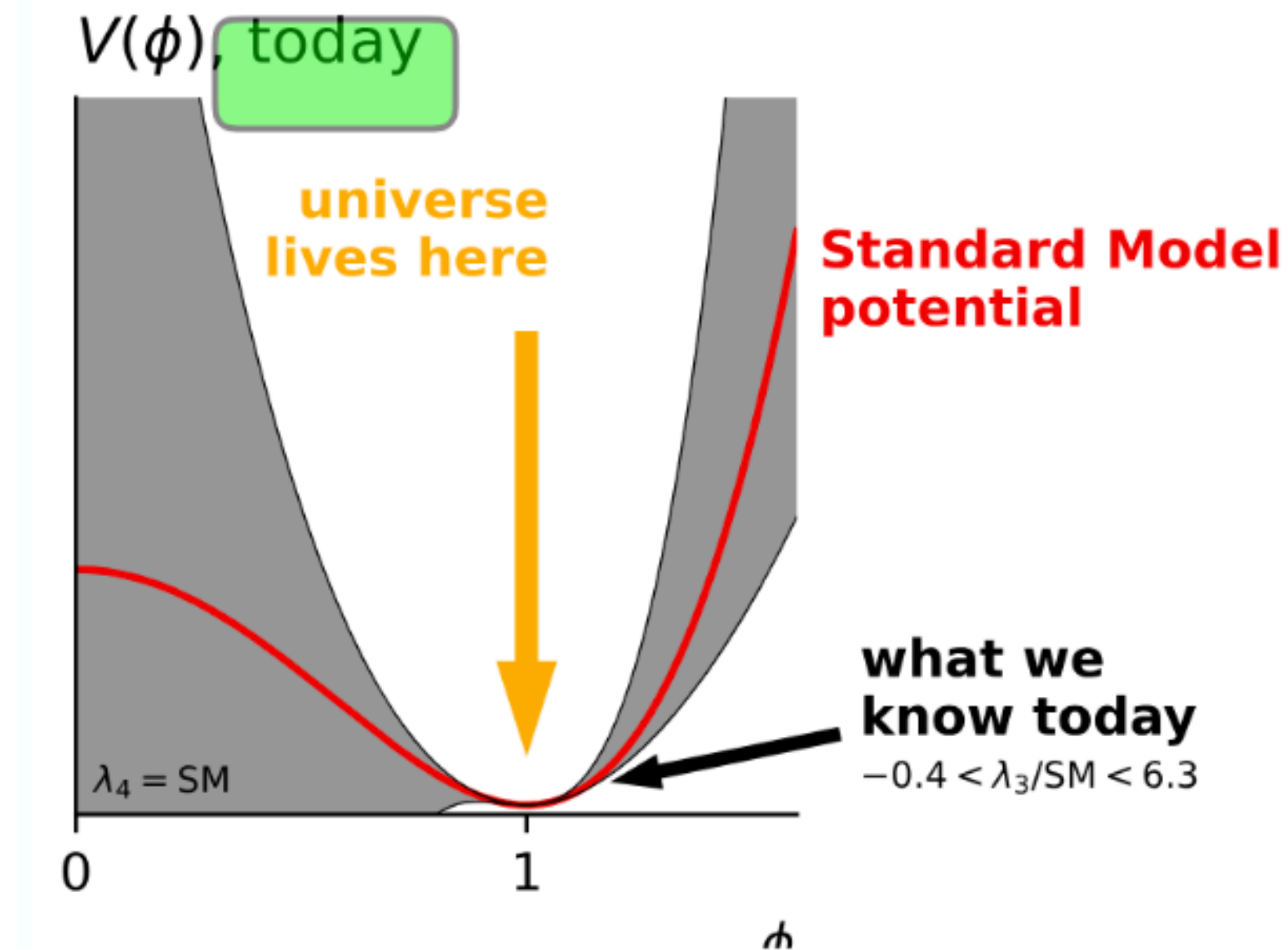
CMB provides a snapshot at the time of last photon scattering.

GWs carry information from much earlier epochs inaccessible to electromagnetic probes.

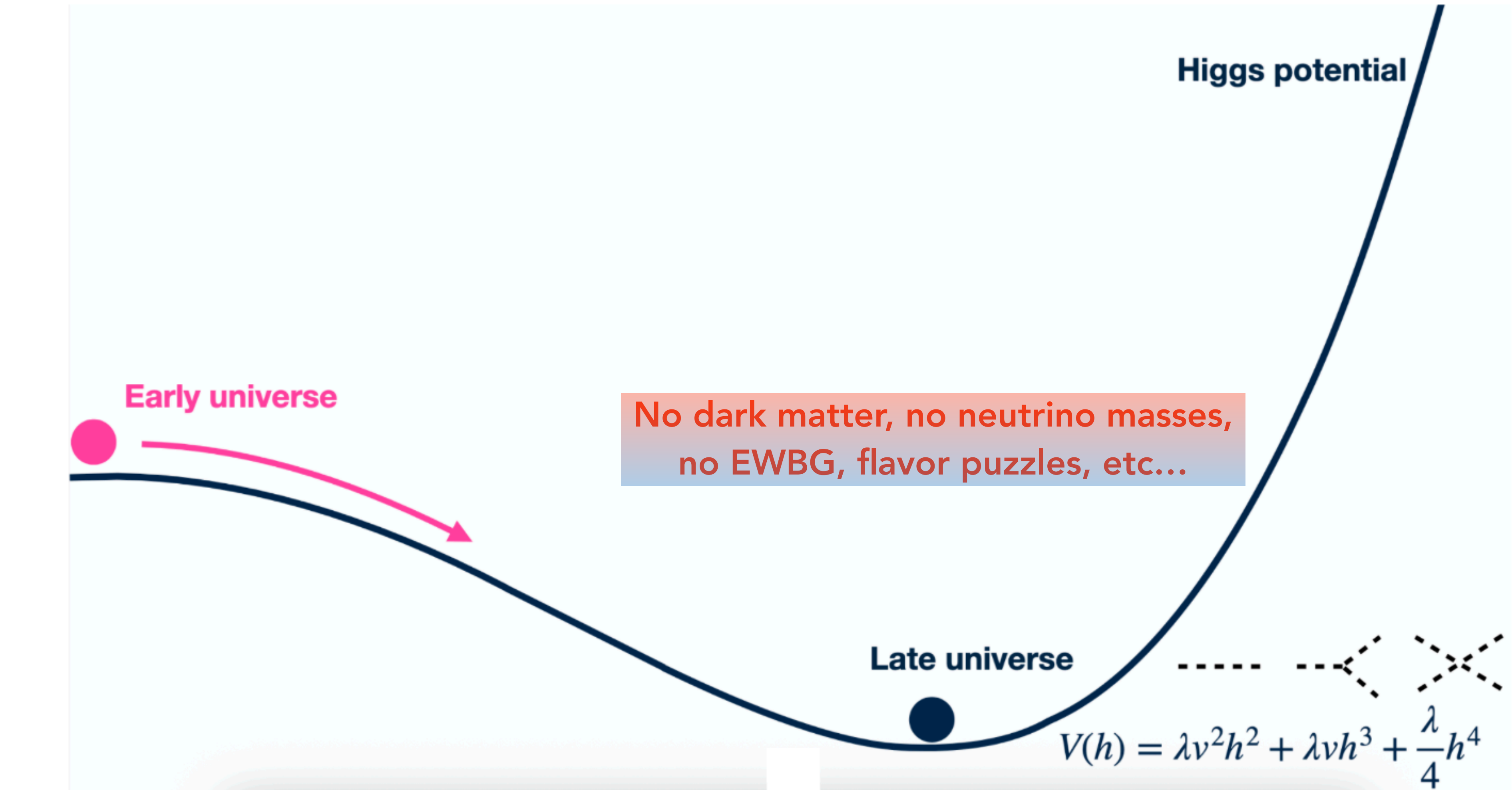
- The CMB is mapped by telescopes, while GWs require detectors like NANOGrav (pulsar timing arrays), LISA (space-based), or LIGO (ground-based),
- GWs are a complementary messenger to the CMB and **particle colliders**, opening a unique observational window to the physics of the universe's first instants.

The Higgs potential in the Standard Model

Credit: Gavin Salam



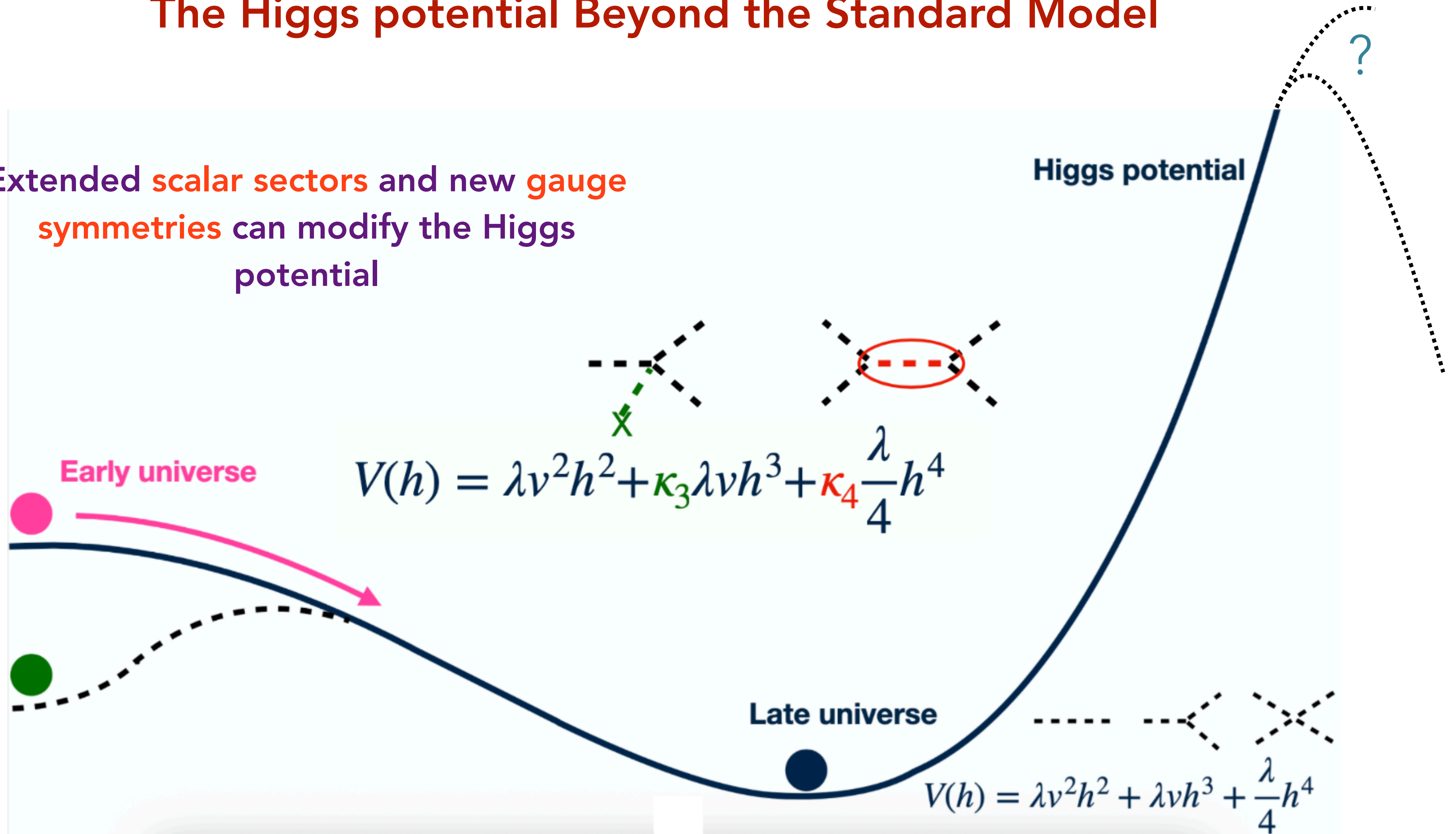
The Higgs potential in the Standard Model



Credit: Kevin Nelson

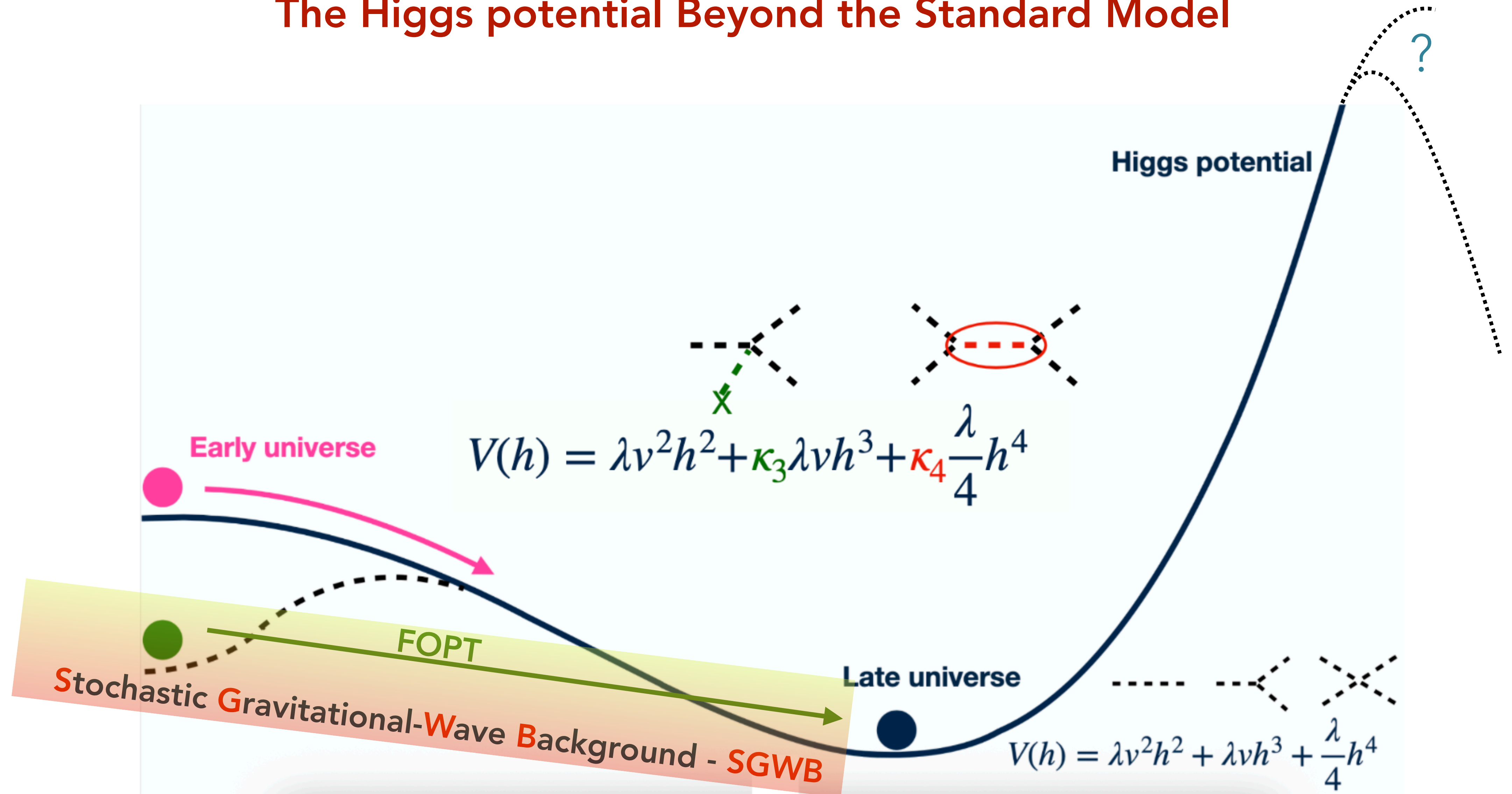
The Higgs potential Beyond the Standard Model

Extended **scalar sectors** and new **gauge symmetries** can modify the Higgs potential



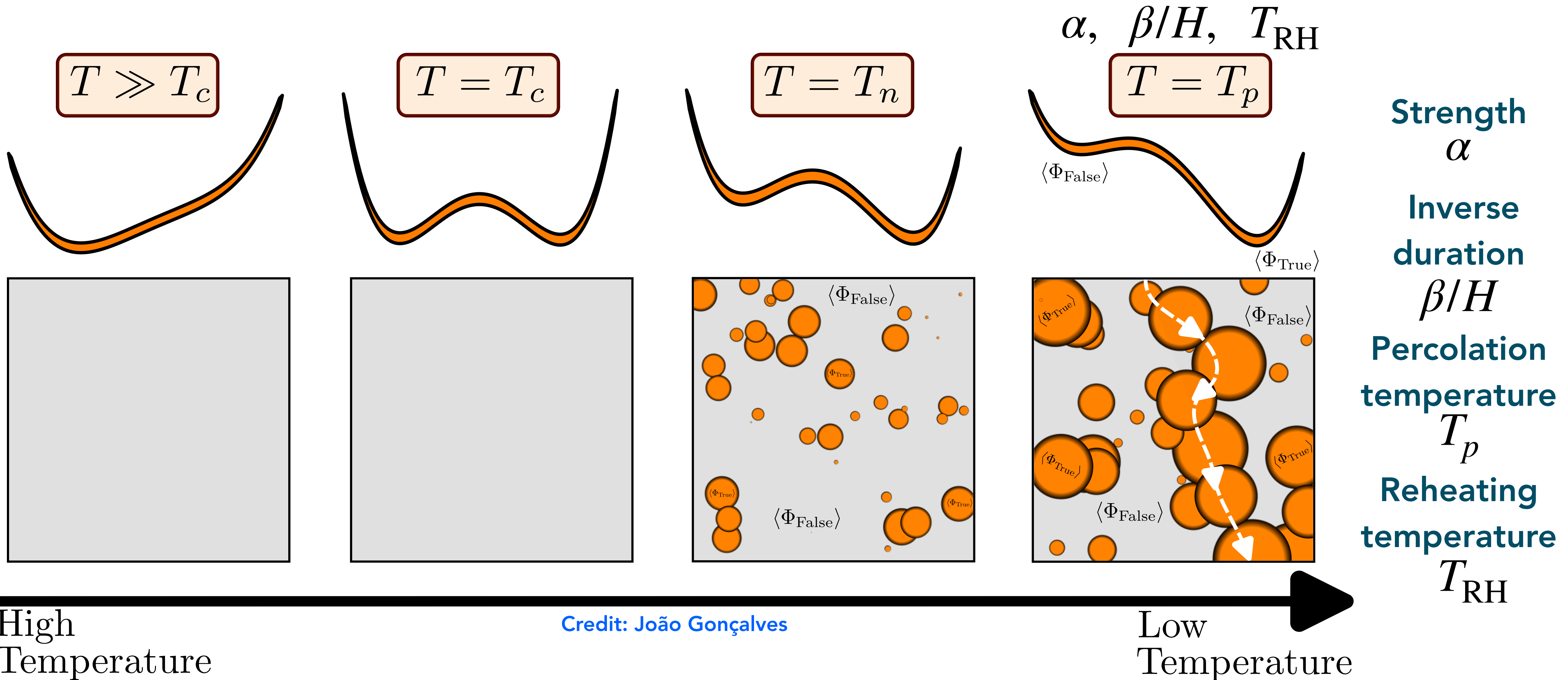
Credit: Kevin Nelson

The Higgs potential Beyond the Standard Model



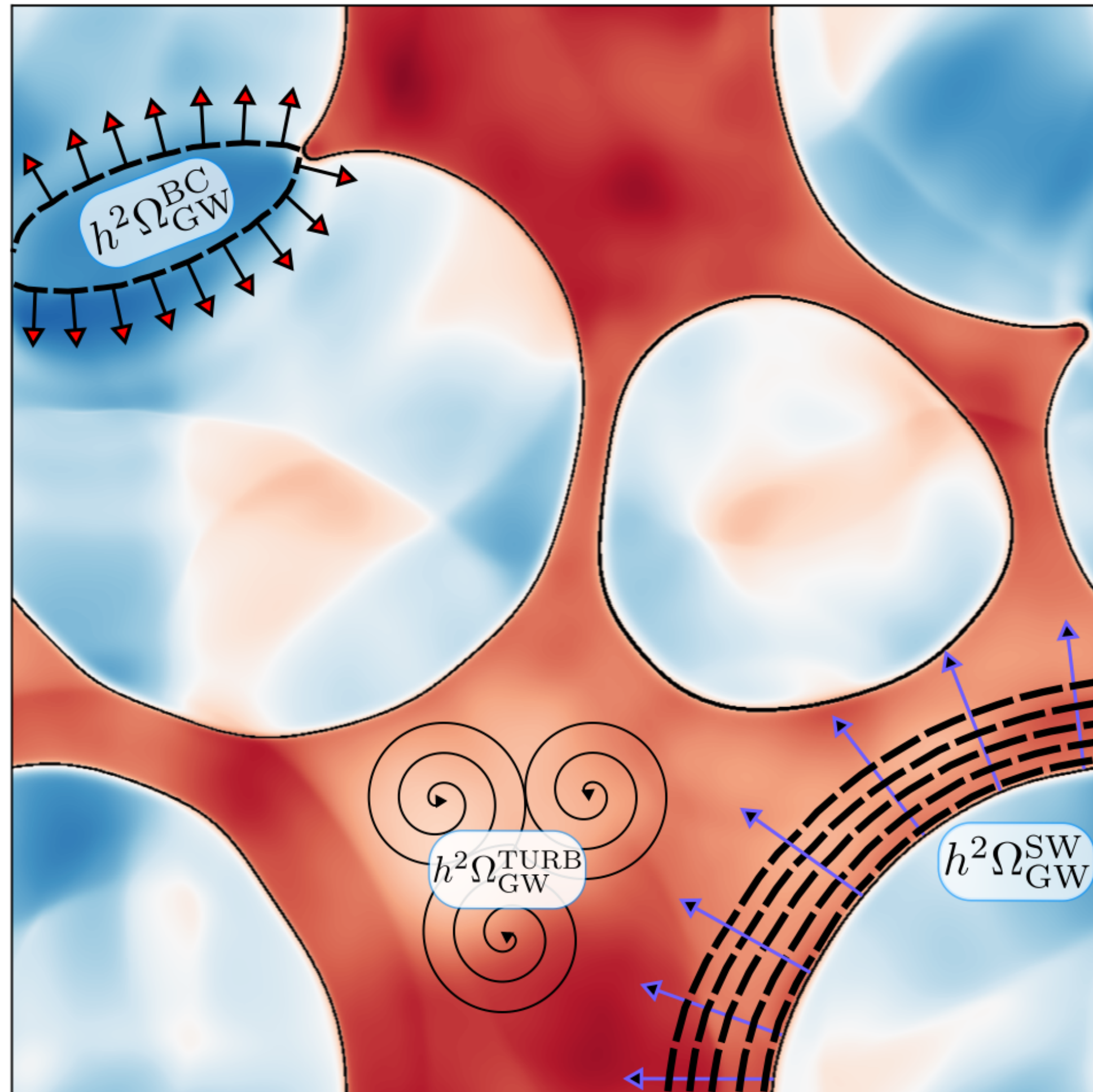
Credit: Kevin Nelson

First order phase transition (FOPT) (Illustration)



Credit: João Gonçalves

Sources of SGWB



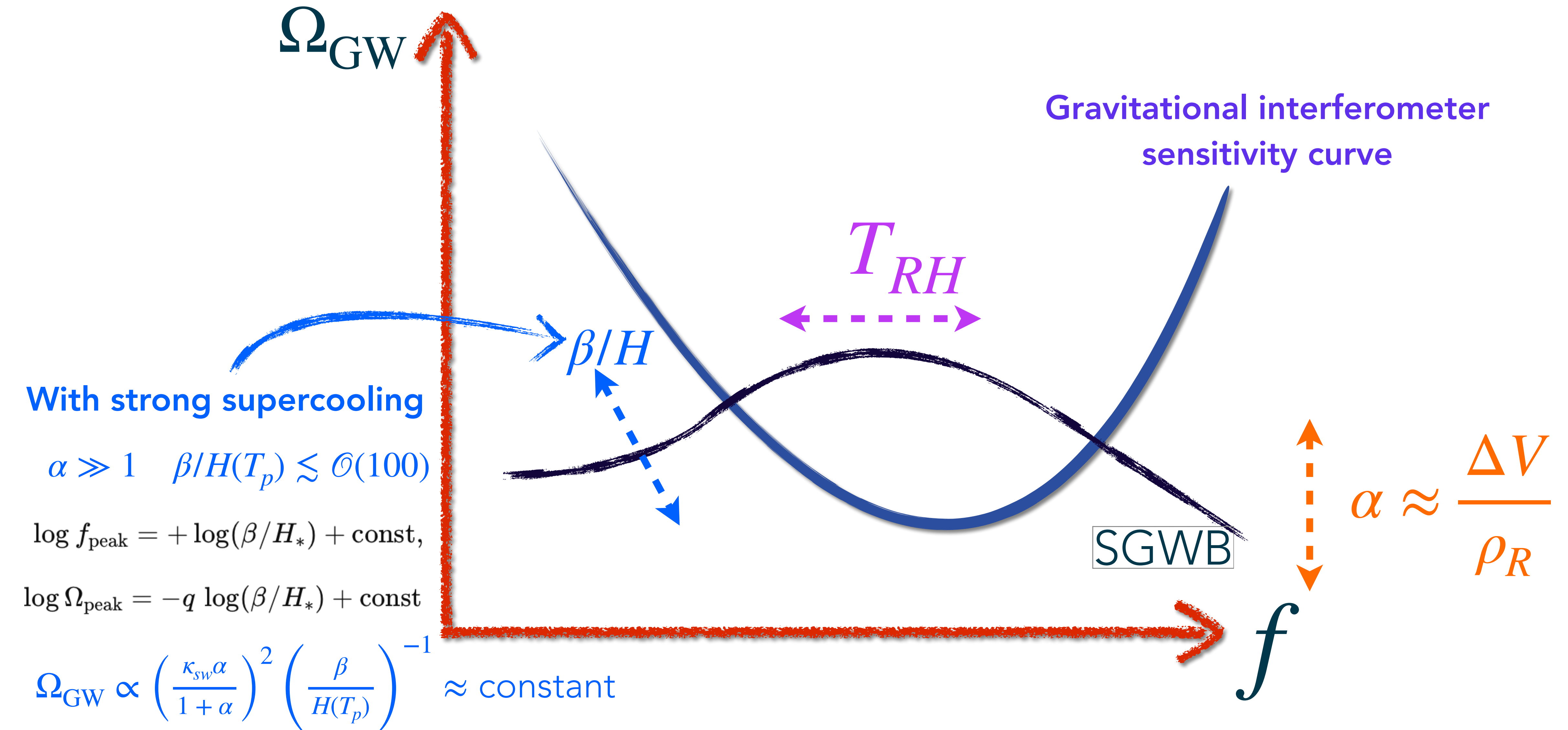
Adapted from *Phys.Rev.Lett.* 125 (2020) 2, 021302

1. **Bubble collisions:** Can become efficient with supercooling for extreme $\alpha \gg 1$
2. **Sound waves:** Dominant in most cases due to friction
3. **Magnetohydrodynamics turbulence:** highly uncertain and subdominant at the peak (according to current knowledge)

Use latest SGWB templates taken from LISA CosWG

[C. Caprini, et al., 2403.03723]

Effect of the thermodynamic parameters on the SGWB



Case I: Classical scale invariant $U(1)'$ models

Classical scale invariant U(1)' models that explain all neutrino oscillation data

Classical scale symmetry (CSS)

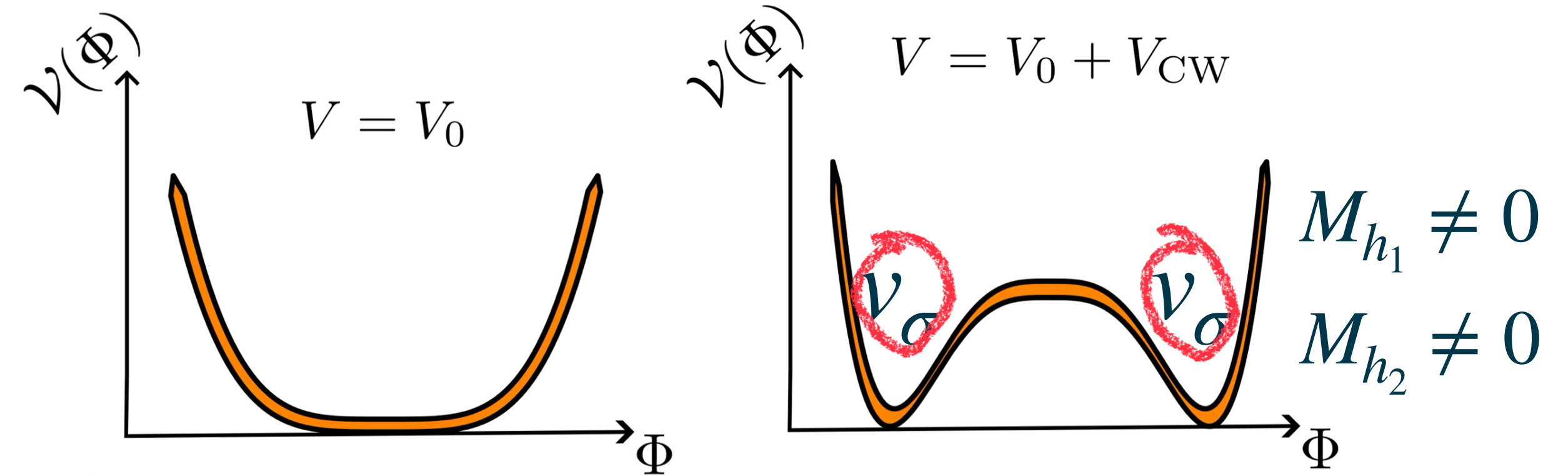
$$x \rightarrow x' = \rho x$$

$$\Phi \rightarrow \Phi' = \rho^a \Phi$$

$$a = -1 \quad \text{for bosons}$$

$$a = -3/2 \quad \text{for fermions}$$

Field	U(1)'
Q	$\frac{1}{3}x_{\mathcal{H}} + \frac{1}{6}x_{\sigma}$
u_R	$\frac{4}{3}x_{\mathcal{H}} + \frac{1}{6}x_{\sigma}$
d_R	$-\frac{2}{3}x_{\mathcal{H}} + \frac{1}{6}x_{\sigma}$
L	$-x_{\mathcal{H}} - \frac{1}{2}x_{\sigma}$
e_R	$-2x_{\mathcal{H}} - \frac{1}{2}x_{\sigma}$
$\mathcal{H}$	$x_{\mathcal{H}}$
N	$-\frac{1}{2}x_{\sigma}$
σ	x_{σ}



[S. R. Coleman, E. J. Weinberg, Physical.Rev. D7 (1973) 1888]

$$V_0(\mathcal{H}, \sigma) = \lambda_h(\mathcal{H}^\dagger \mathcal{H})^2 + \lambda_\sigma(\sigma^\dagger \sigma)^2 + \lambda_{\sigma h}(\mathcal{H}^\dagger \mathcal{H})(\sigma^\dagger \sigma)$$

SM Higgs sector

Dark sector

Portal interactions

$$V_{\text{CW}}(\phi) \propto \frac{1}{64\pi^2} \phi^4 \log \left(\frac{\phi^2}{\mu^2} + C \right)$$

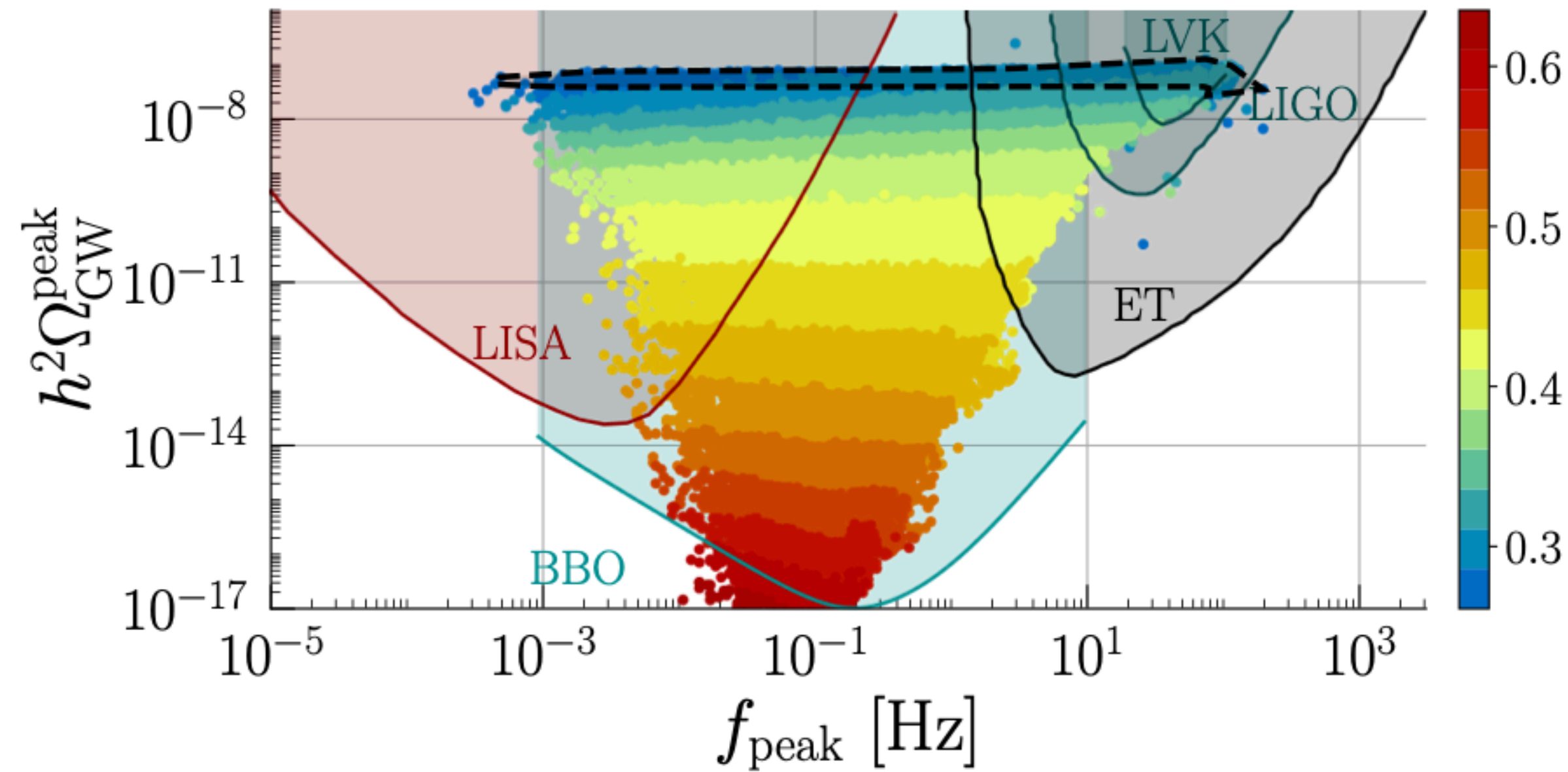
Neutrino masses and mixing via type-I seesaw with scalar singlet σ

$$\mathcal{L}_\nu = y_\nu^{ij} \bar{N}_i \mathcal{H} L_j + y_\sigma^{ij} \bar{N}_i^c N_j \sigma + \text{h.c.}$$

$$M_N \approx \frac{v_\sigma}{\sqrt{2}} y_\sigma \quad m_\nu \approx \frac{1}{\sqrt{2}} \frac{v^2}{v_\sigma} y_\nu^T y_\sigma^{-1} y_\nu$$

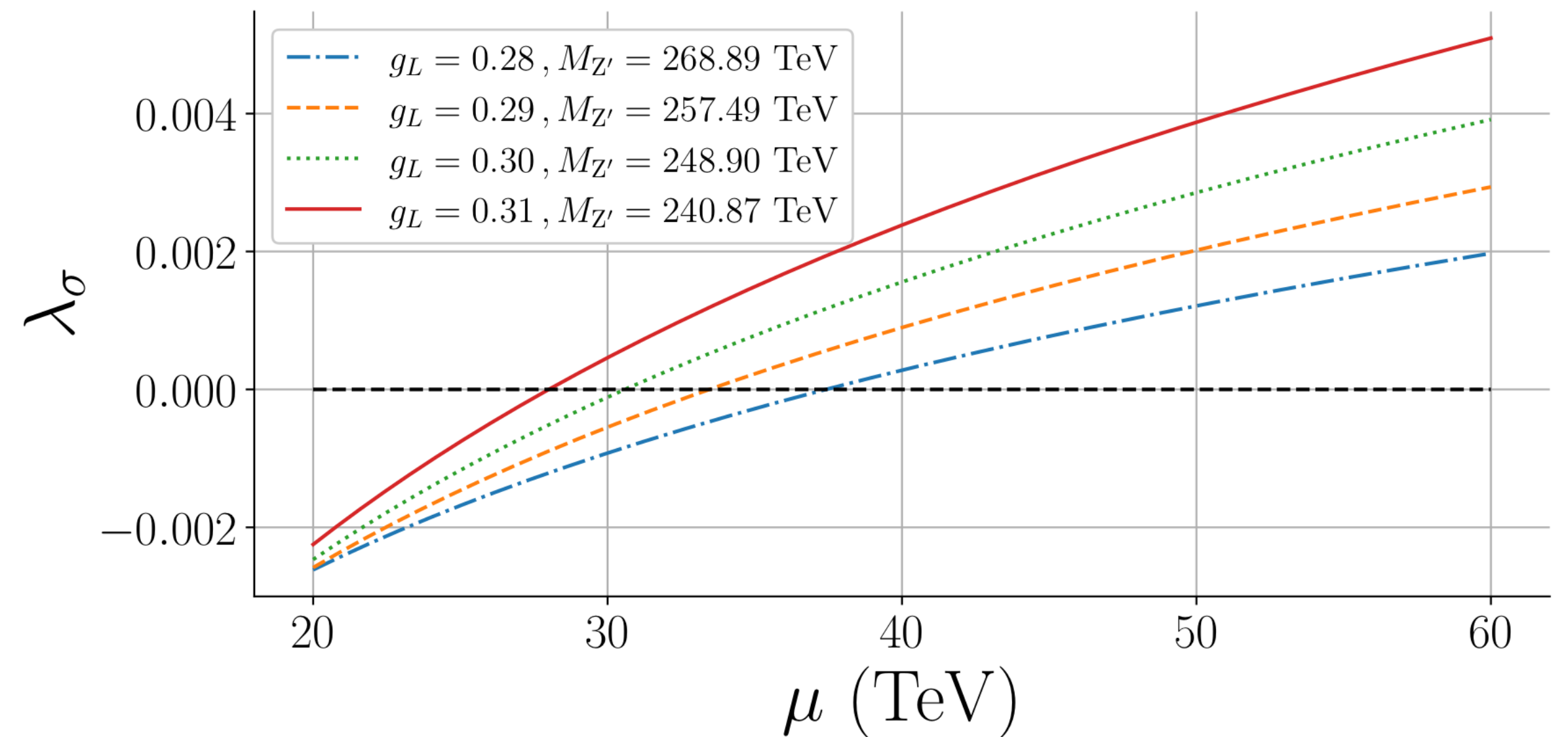
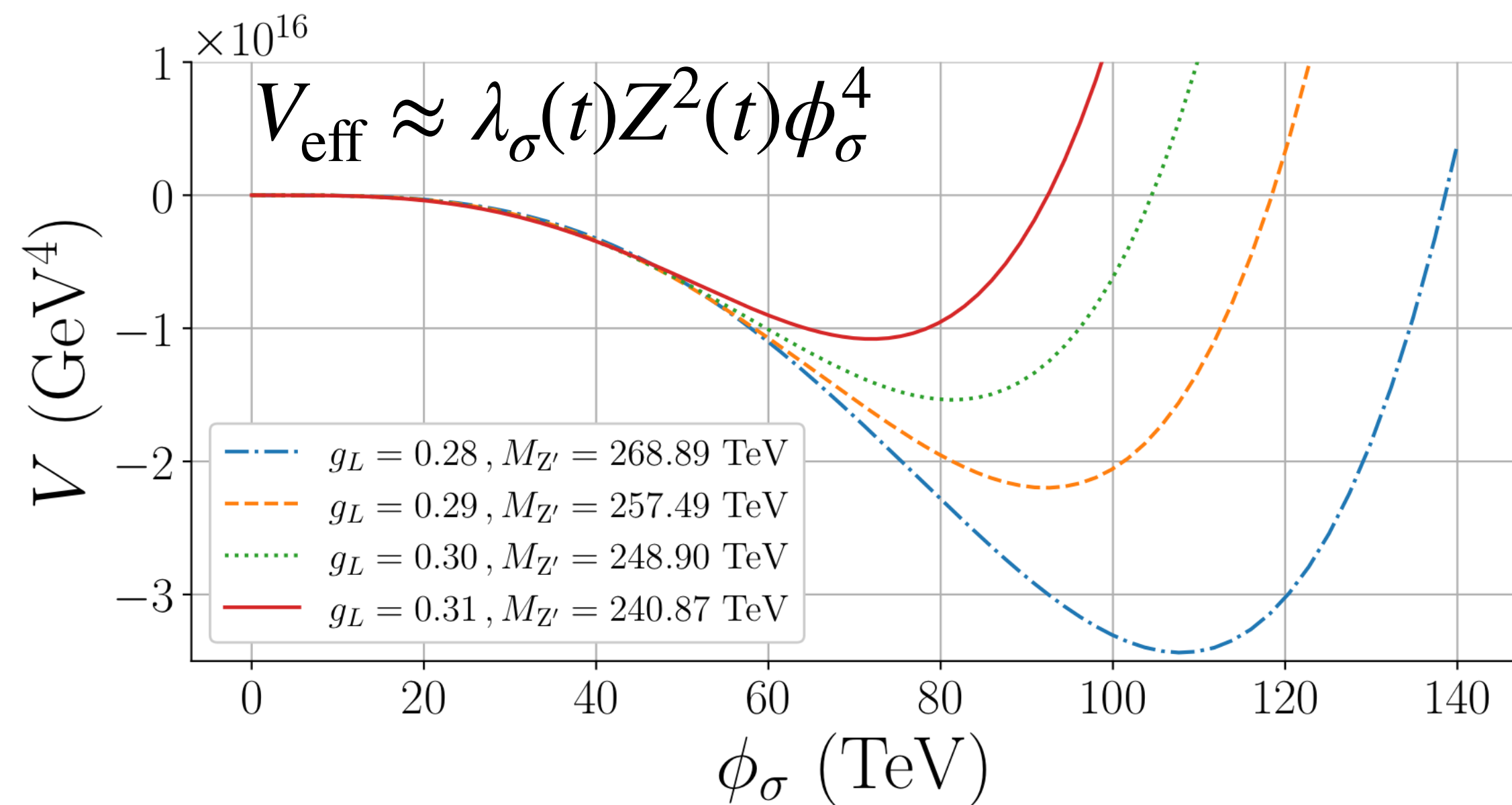
$$\sum_{i=1}^3 m_{\nu_i} < 0.12 \text{ eV}$$

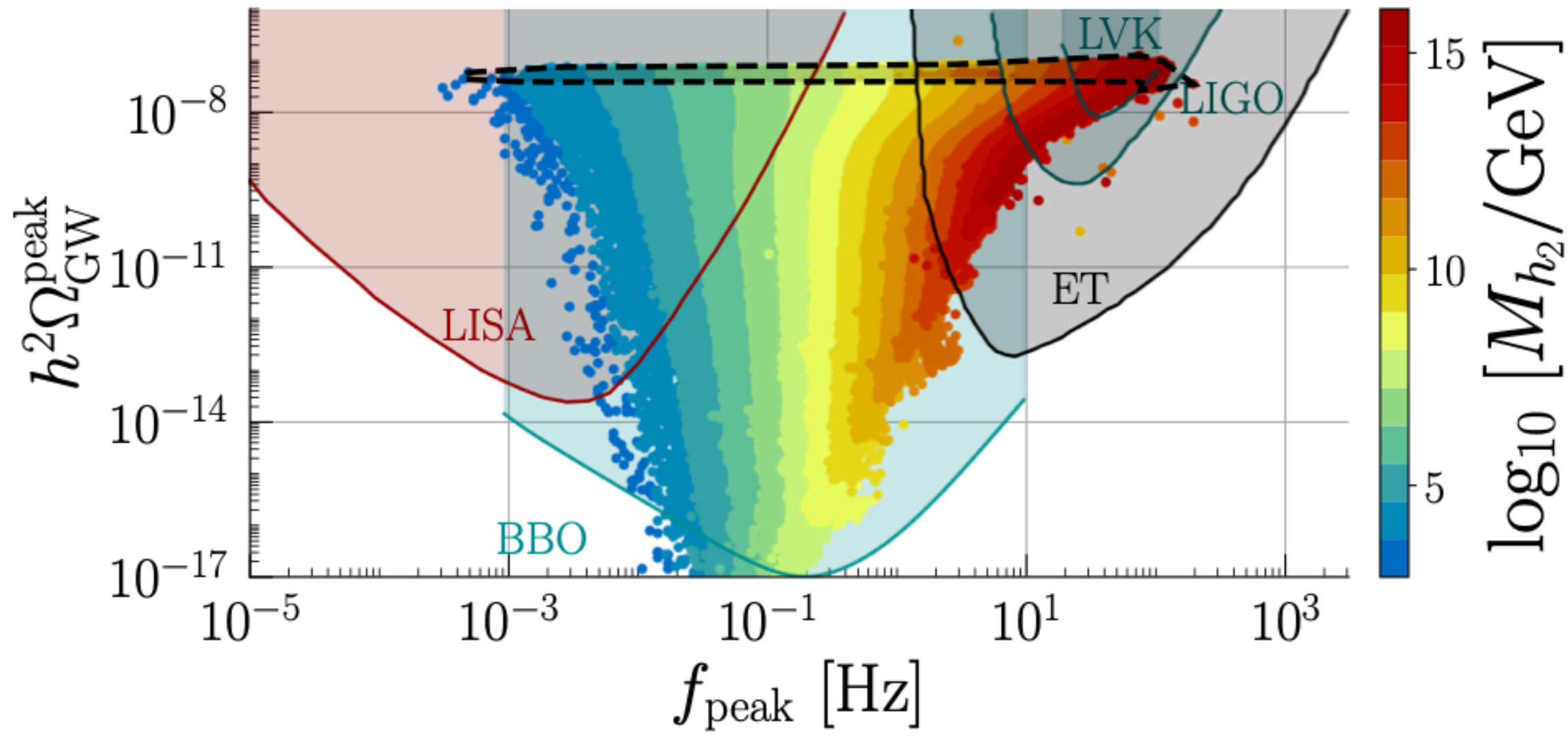
SGWB predictions: The $U(1)_{B-L}$ case $x_\sigma = 2$ and $x_H = 0$



Gauge coupling controls the peak amplitude

Larger $h^2 \Omega_{\text{GW}}^{\text{peak}}$ for smaller g_L due to slower running
 $16\pi^2 \beta_{\lambda_\sigma} = 3g_L^4 x_\sigma^4 + \dots$





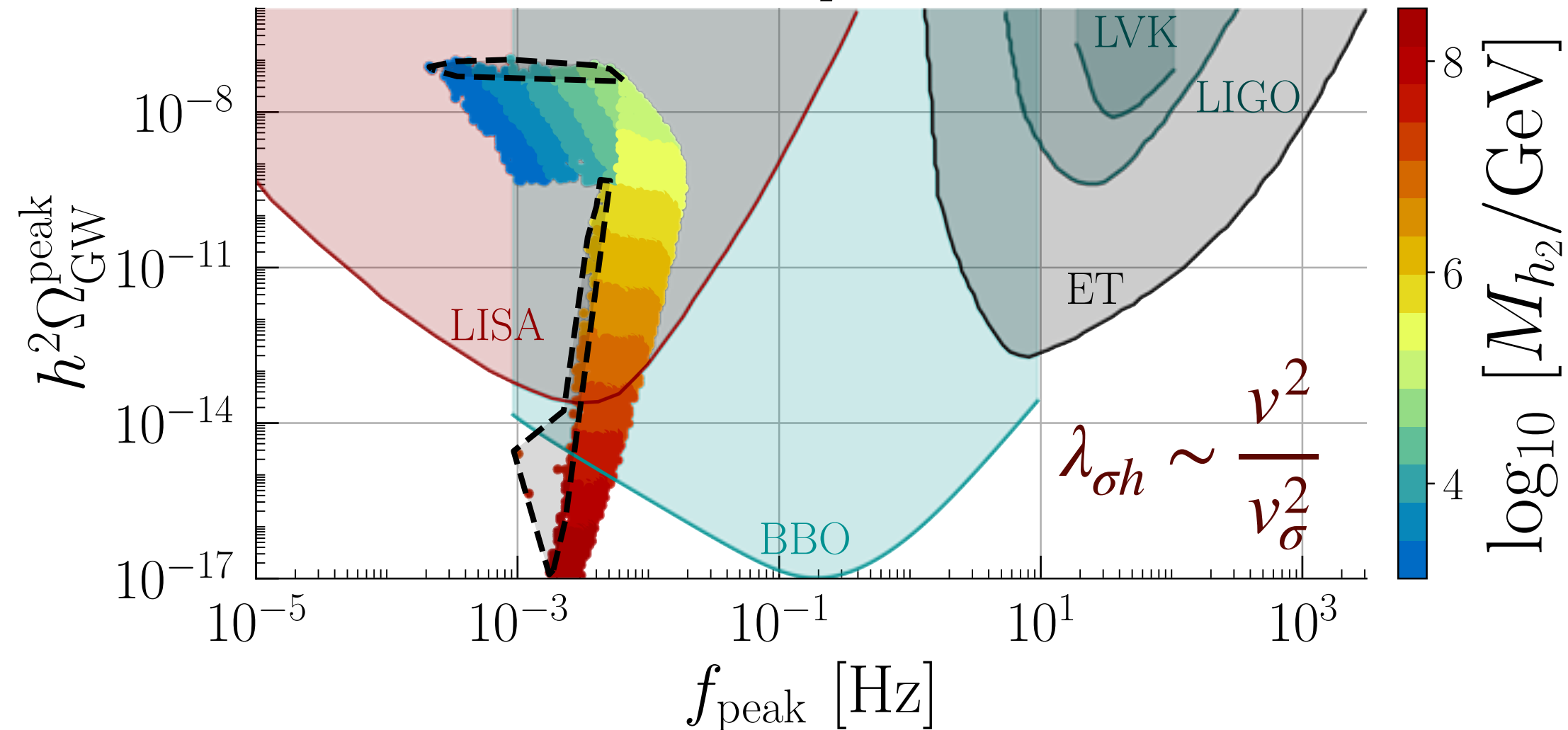
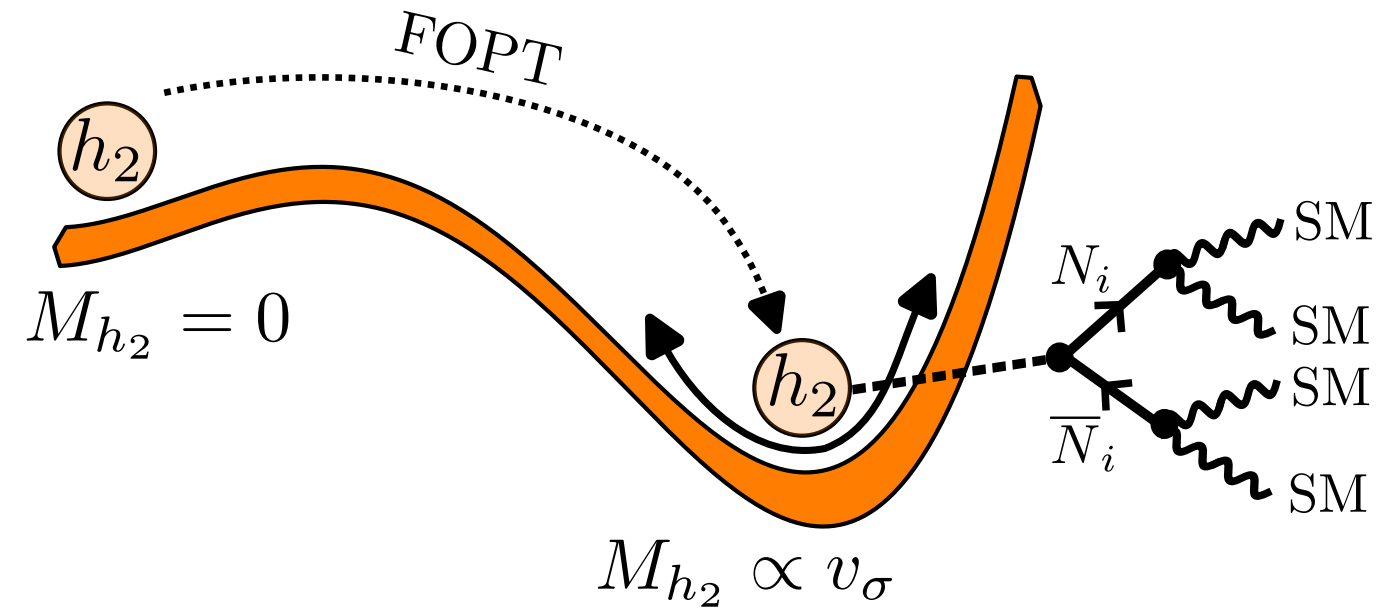
Peak frequency controlled by the mass scale

LVK can already constrain $M_{h_2} \sim 10^{15}$ GeV for $g_L \approx 0.3$ and in classical conformal $U(1)_{B-L}$ models

$$\Gamma_{h_2} = \Gamma_{h_2 \rightarrow p_{SM} p_{SM}^*} + \Gamma_{h_2 \rightarrow \bar{N}_i N_i} \Gamma_{N_i \rightarrow p_{SM} p_{SM}^*}$$

Checked using MadGraph

Without a neutrino sector...



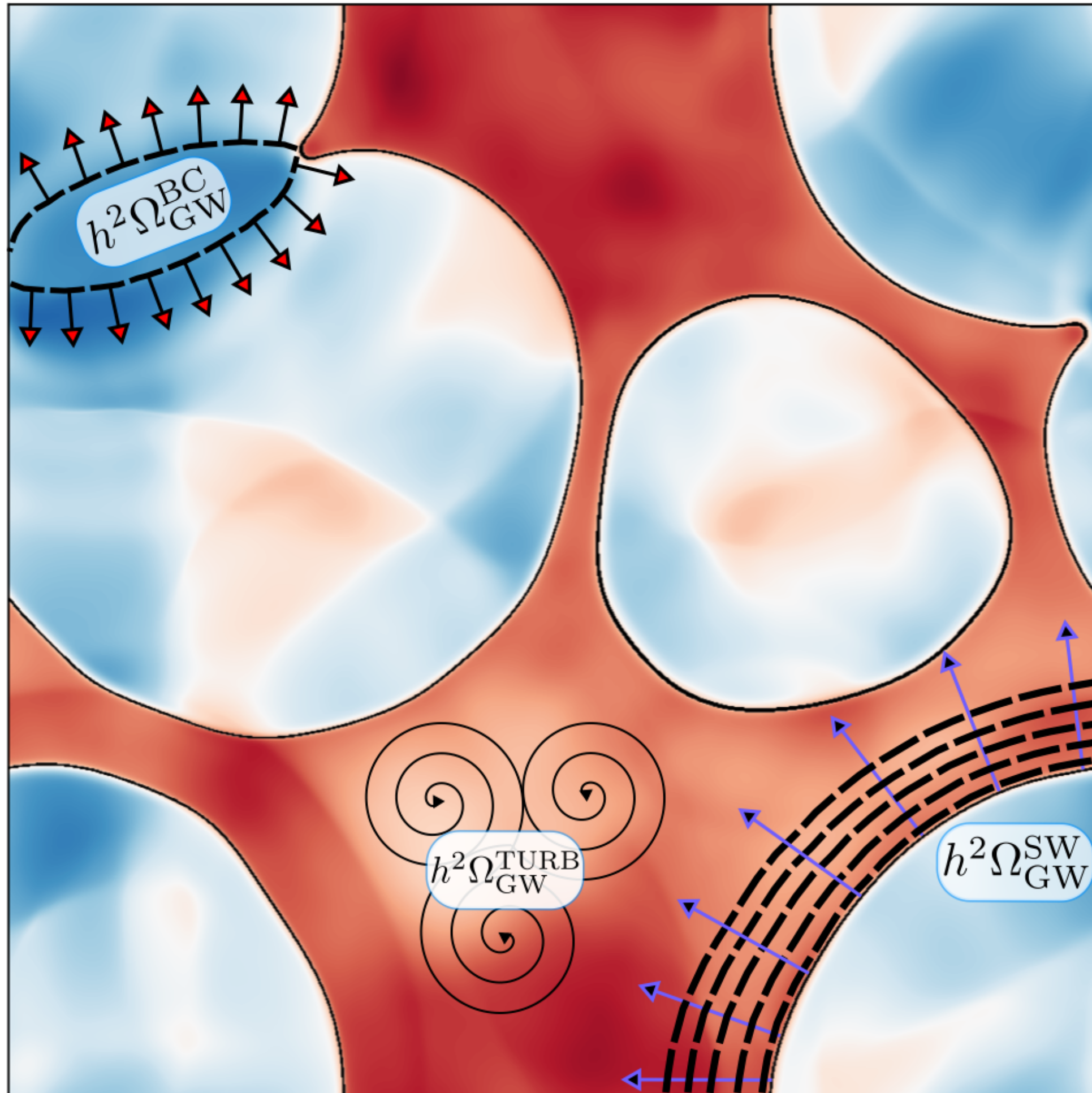
Early matter domination if
 $\Gamma_{h_2} < H(T_p) \implies$ SUPPRESSION of SGWB

$$h^2 \Omega_{SW}^{\text{peak}} \propto \left(\frac{\kappa_{sw} \alpha}{1 + \alpha} \right)^2 \left(\frac{\beta}{H(T_p)} \right)^{-1} \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{2/3}$$

$$f_{\text{peak}} \propto \left(\frac{\beta}{H(T_p)} \right) \left(\frac{T_{RH}}{\text{GeV}} \right) \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{-1/3}$$

$$T_{RH} \approx T_p (1 + \alpha)^{1/4} \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{1/2} \quad T_c > T_{RH} \gg T_n > T_p$$

Primordial Magnetic Fields in the Early Universe



- Primordial magnetic fields (PMFs) may arise during FOPTs due to plasma motion (MHD turbulence), potentially seeding present-day inter-galactic magnetic fields
- The initial topology (helicity) of the magnetic field determines how quickly its energy decays and how rapidly its coherence length grows.

[Banerjee, Jedamzik, *Phys.Rev.D* 70 (2004) 123003]

1. Helical PMFs ($b=0$) exhibit slow decay due to helicity conservation enhancing large-scale coherence and longevity to the present Universe
2. Non-helical PMFs ($b=1$) decay more rapidly; their energy is dissipated at smaller scales and is less likely to survive to the present era

Adapted from *Phys.Rev.Lett.* 125 (2020) 2, 021302

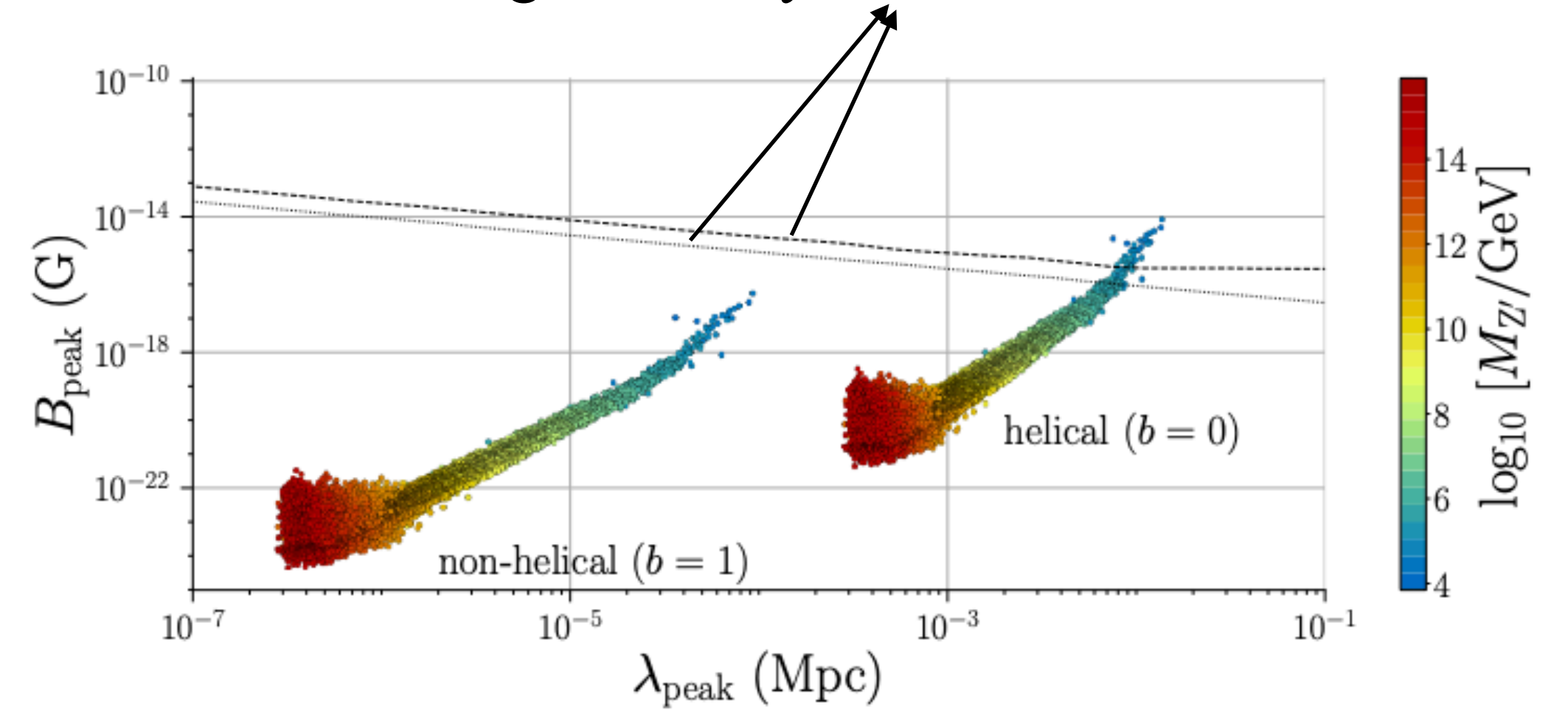
Present-day peak magnetic field spectrum

Blazar gamma-ray bounds [1804.08035, 2210.03321]

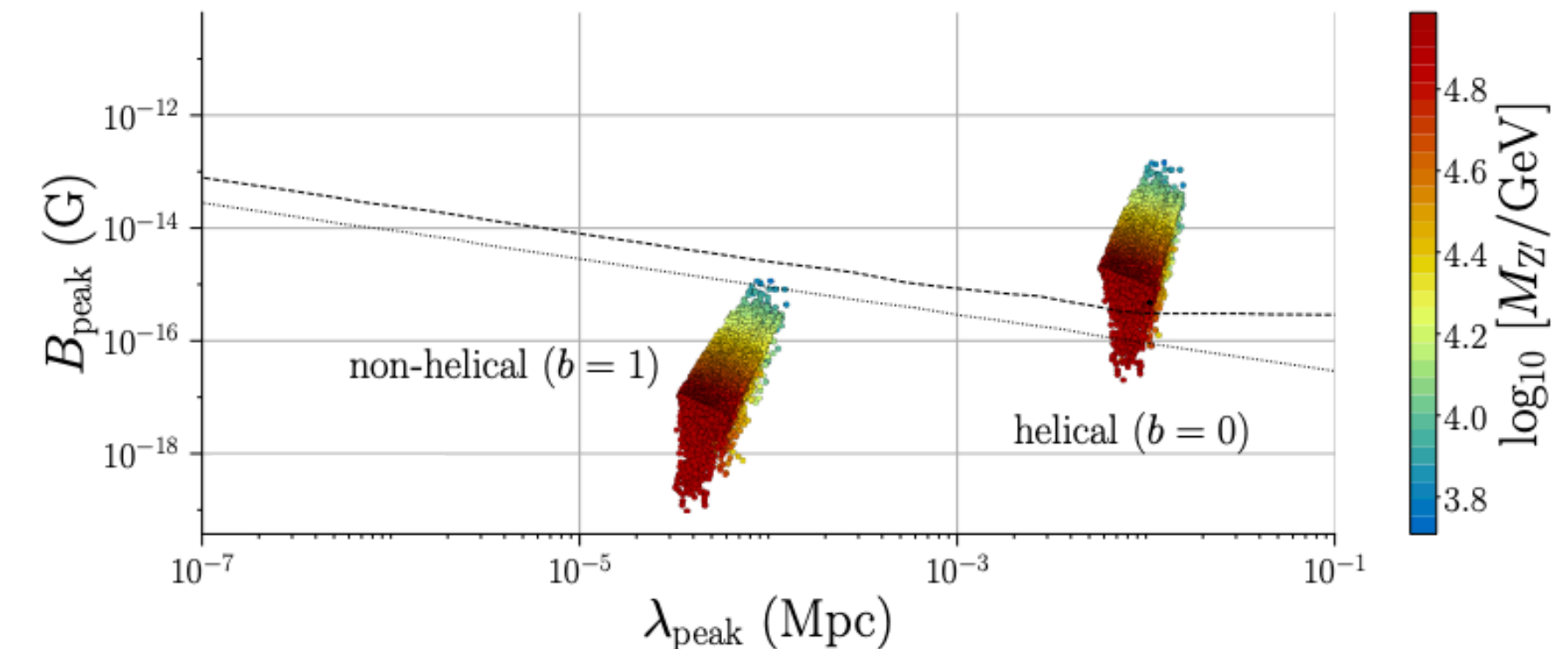
- Peak magnetic field and peak coherence length for:

- **helical fields:** $B_{\text{peak}}^0 \propto T_{\text{RH}}^{-7/3} \sqrt{\kappa_h}$ and $\lambda_{\text{peak}}^0 \propto T_{\text{RH}}^{-1/3}$
- **non-helical fields:** $B_{\text{peak}}^1 \propto T_{\text{RH}}^{-5/2} \sqrt{\kappa_h}$ and $\lambda_{\text{peak}}^1 \propto T_{\text{RH}}^{-1/2}$

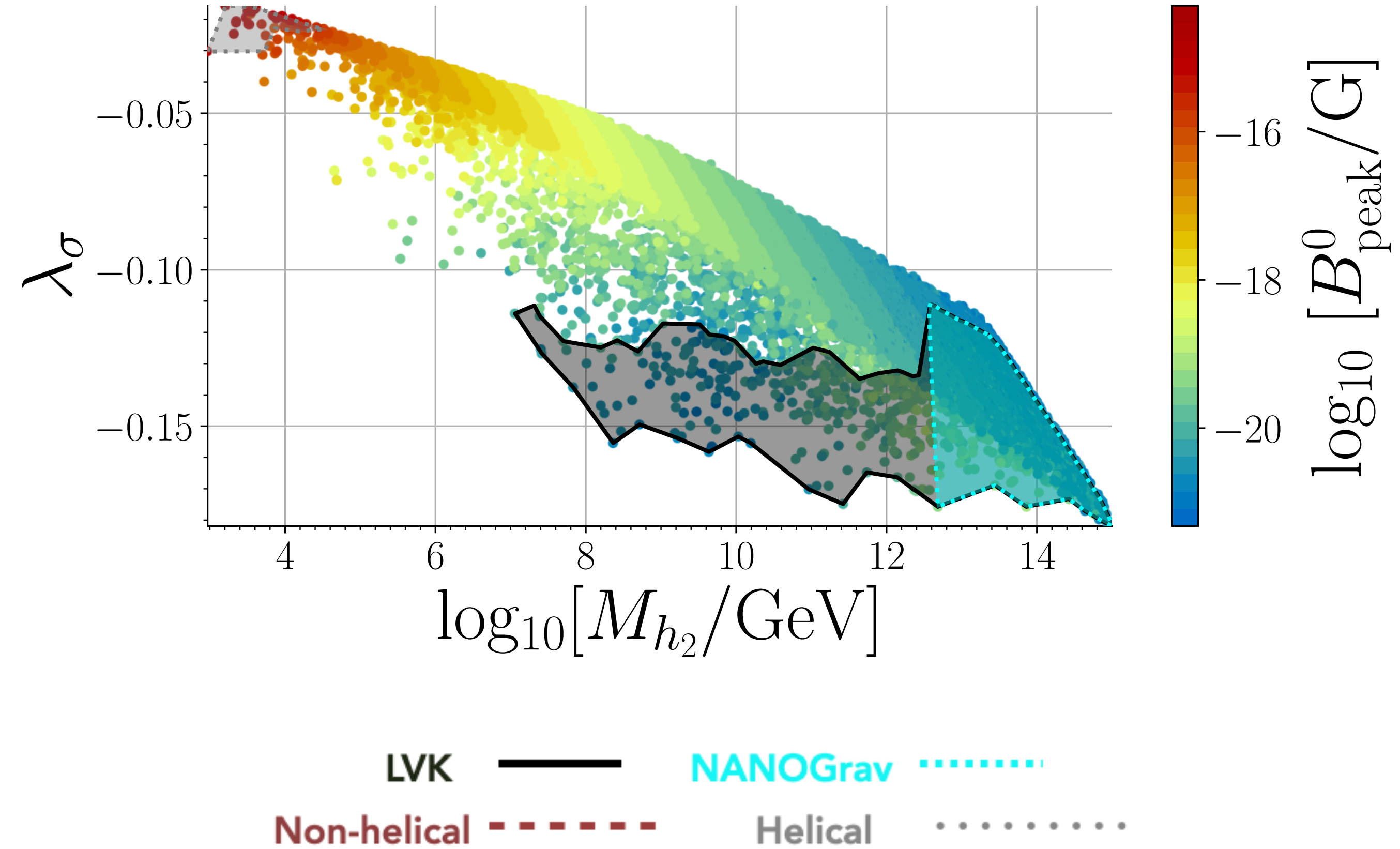
$$\kappa_h = 1 - \frac{\mathcal{V}_{\text{eff}}(v_\sigma(T_p), v)}{\mathcal{V}_{\text{eff}}(v_\sigma(T_p), 0)} \longrightarrow \text{Fraction of the bubble wall energy of the dark scalar transferred to the Higgs field via the Higgs portal coupling } \lambda_{\sigma h}$$



- **Blazar bounds mark the threshold for observable intergalactic magnetic fields that may have been sourced by FOPTs in the early Universe**
- **Strong correlation with Z' and h_2 masses** $\longrightarrow M_{h_2} \approx 0.1 M_{Z'}$



Global picture



Combined information from cosmological and astrophysical probes can provide us with information about the scalar sector

Case II: Classical scale invariant dark SU(3) models

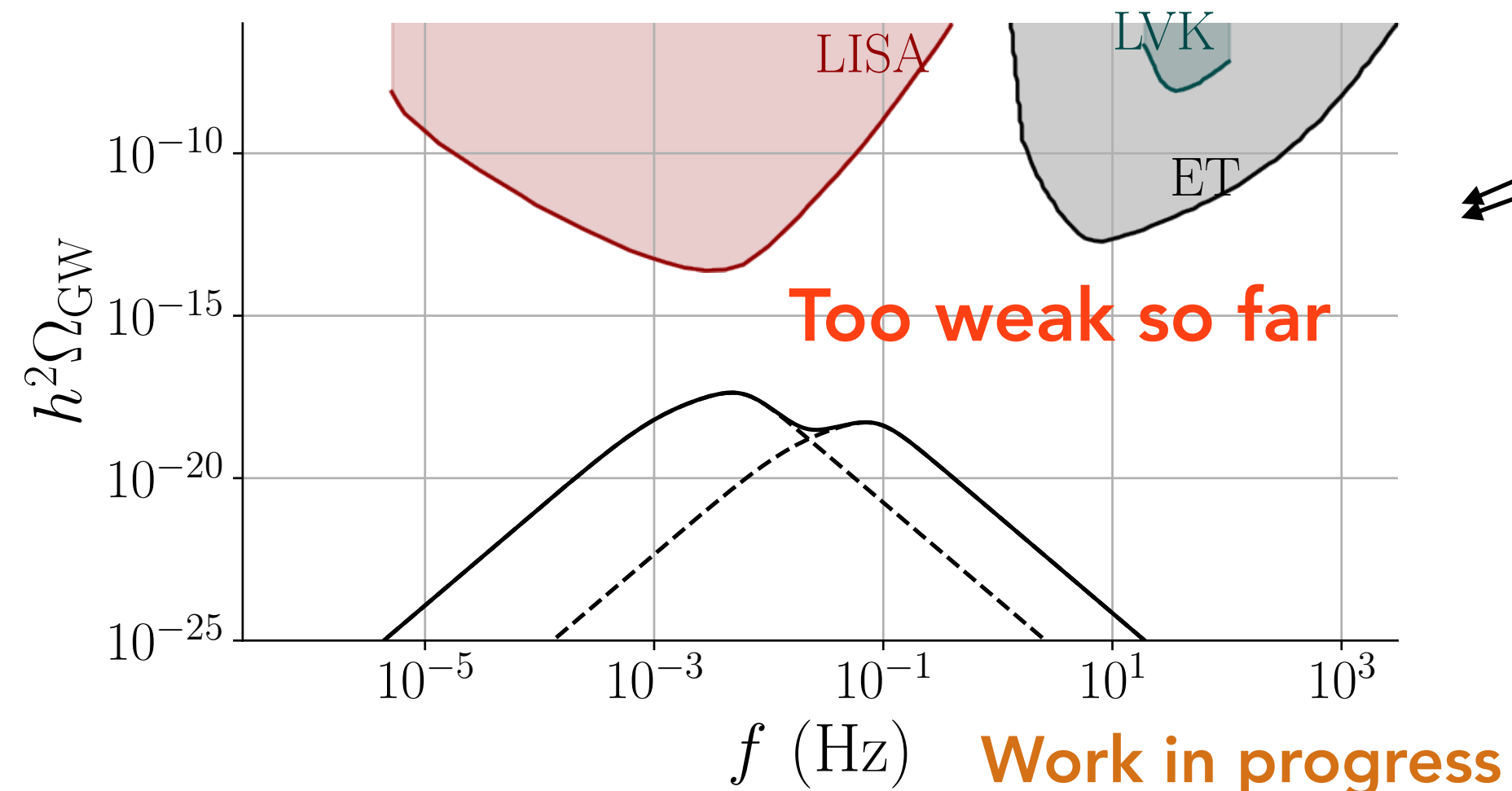
(**Work in progress**: credit to João Gonçalves and Daniel Araújo)

Classical scale invariant dark SU(3) models that explain all neutrino oscillation data

Need two scalar triplets to fully break SU(3)

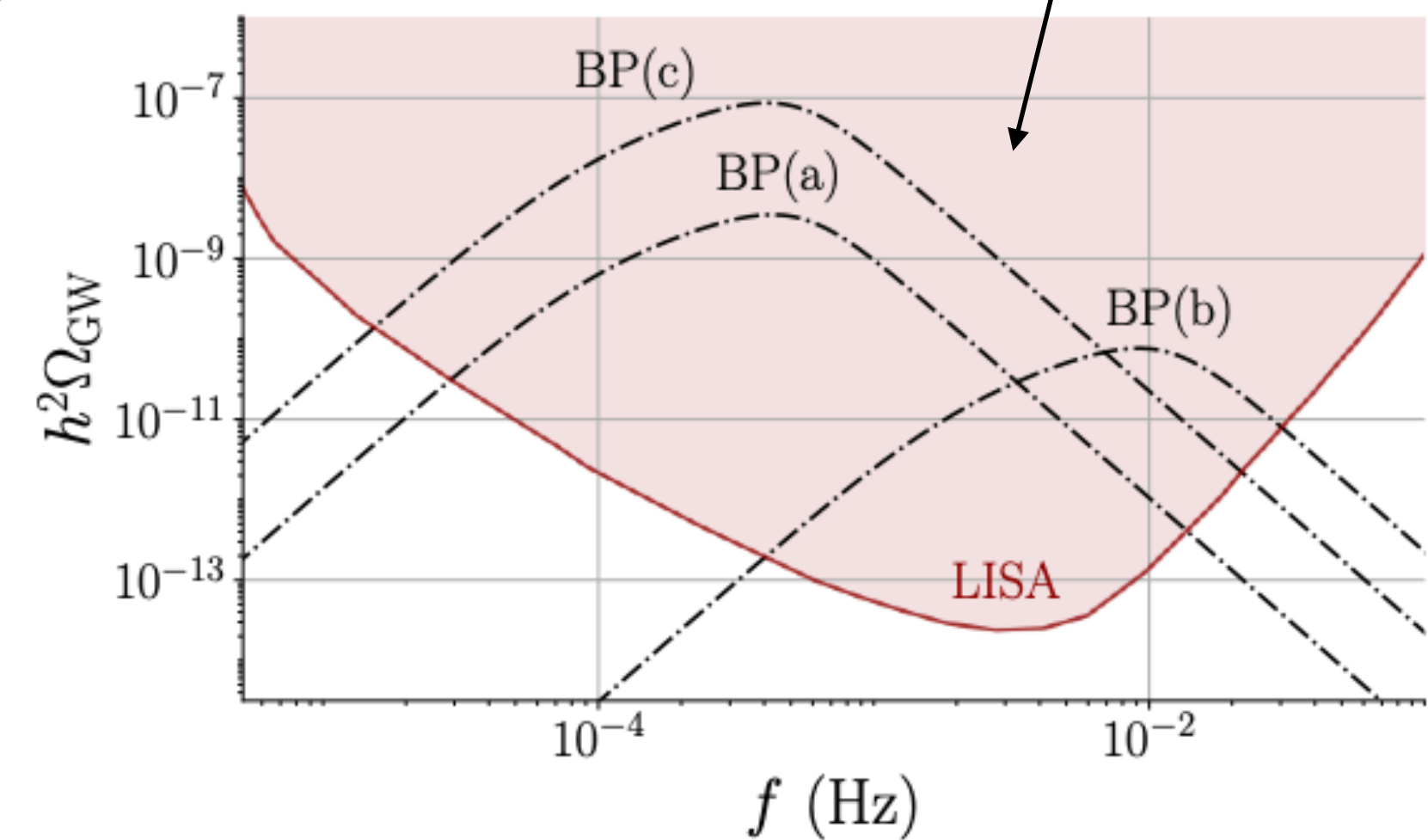
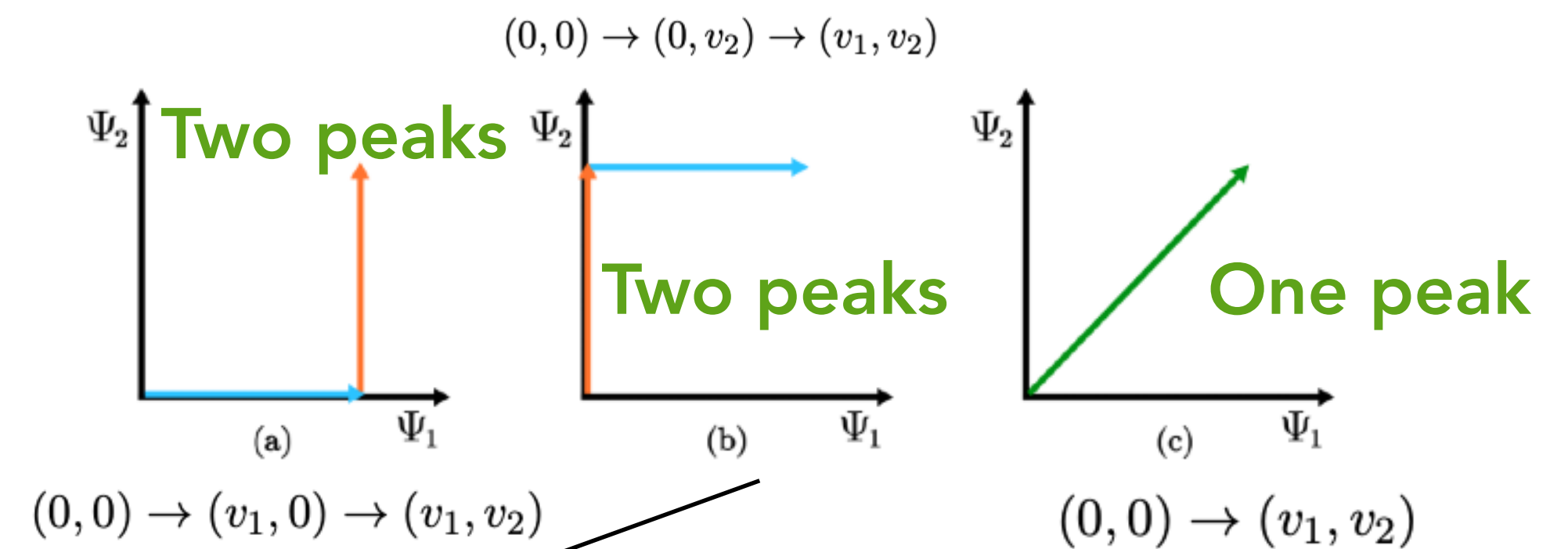
$$\mathbb{Z}_2 : \quad \Psi_2 \longrightarrow -\Psi_2$$

$$V_0 = \lambda_h (\mathcal{H}^\dagger \mathcal{H})^2 + \lambda_1 (\Psi_1^\dagger \Psi_1)^2 + \lambda_2 (\Psi_2^\dagger \Psi_2)^2 \\ - \lambda_3 (\Psi_1^\dagger \Psi_1) (\Psi_2^\dagger \Psi_2) + \lambda_4 (\Psi_1^\dagger \Psi_2) (\Psi_2^\dagger \Psi_1) \\ + \left[\frac{\lambda_5}{2} (\Psi_1^\dagger \Psi_2)^2 + \text{H.c.} \right] \\ - \lambda_{h1} (\mathcal{H}^\dagger \mathcal{H}) (\Psi_1^\dagger \Psi_1) + \lambda_{h2} (\mathcal{H}^\dagger \mathcal{H}) (\Psi_2^\dagger \Psi_2).$$



$$\langle \Psi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \\ v_1 \end{pmatrix} \quad \langle \Psi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \\ 0 \end{pmatrix}$$

Possibility for double-step FOPTs



Neutrino sector

Name	Generations	$U(1)_Y$	$SU(2)_L$	$SU(3)_X$
L	3	$-\frac{1}{2}$	2	1
ν_R	2	0	1	1
N	1	0	1	$\bar{3}$
N'	1	0	1	3


Anomaly cancellation

$$y_{N\Psi_i}^{(j)}\bar{N}_\alpha^c\nu_R^{(j)}\Psi_i^\alpha+y_{N'\Psi_i}^{(j)}\bar{N}'_\alpha^c\nu_R^{(j)}\Psi_i^\alpha+y_\nu^{(j,k)}\nu_R^{(j)}\mathcal{H}L^{(k)}+\text{h.c.}$$

$$\mu\bar{N}'^cN+\mu'_{jk}\bar{\nu}_R^{c,(j)}\nu_R^{(k)}\longrightarrow\text{Small deviation from conformality responsible for small neutrino masses}$$

Inverse-seesaw mechanism with conformal symmetry playing the usual role of U(1) lepton-number symmetry

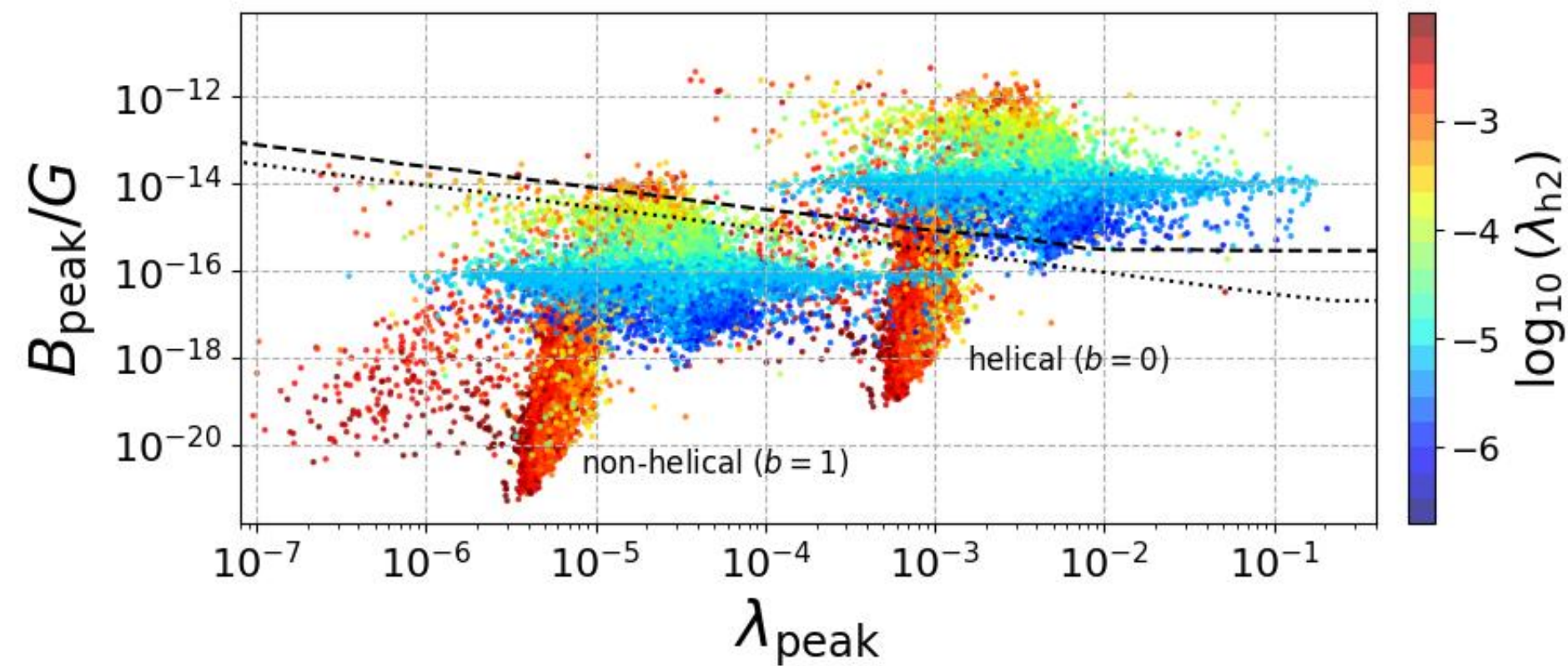
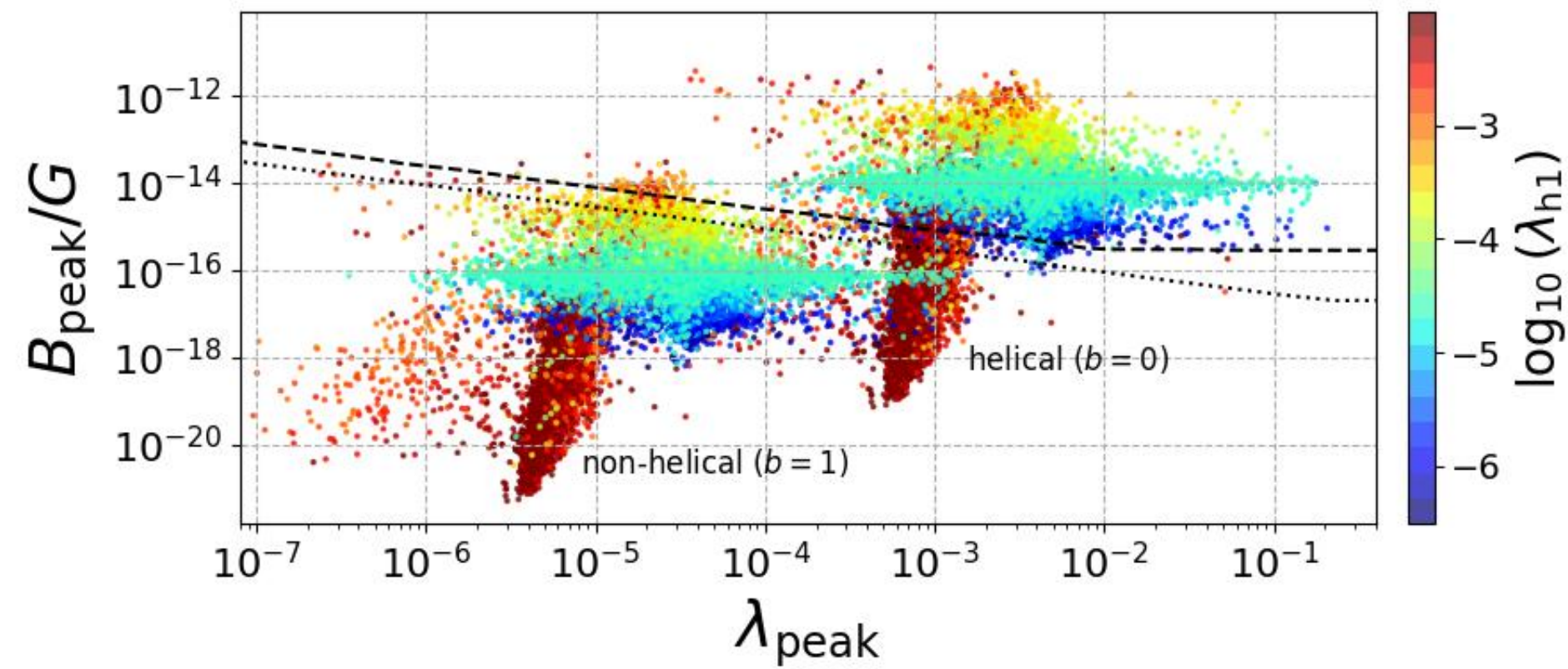
$$\mathcal{M}_\nu=\frac{1}{\sqrt{2}}\begin{pmatrix}0&Y_{\nu_L}v_h&0&0\\Y_{\nu_L}^Tv_h&\sqrt{2}\mu'&Y_NV&Y_{N'}V\\0&V^TY_N^T&0&\mu\mathbf{1}\\0&V^TY_{N'}^T&\mu\mathbf{1}&0\end{pmatrix}\qquad V=\begin{pmatrix}v_1\\v_2\end{pmatrix}$$

$$M_\nu^{\text{light}}\sim\mu'\qquad M_\nu^{\text{sterile}}\sim\mu\qquad M_\nu^{\text{heavy}}\sim v_{1,2}$$

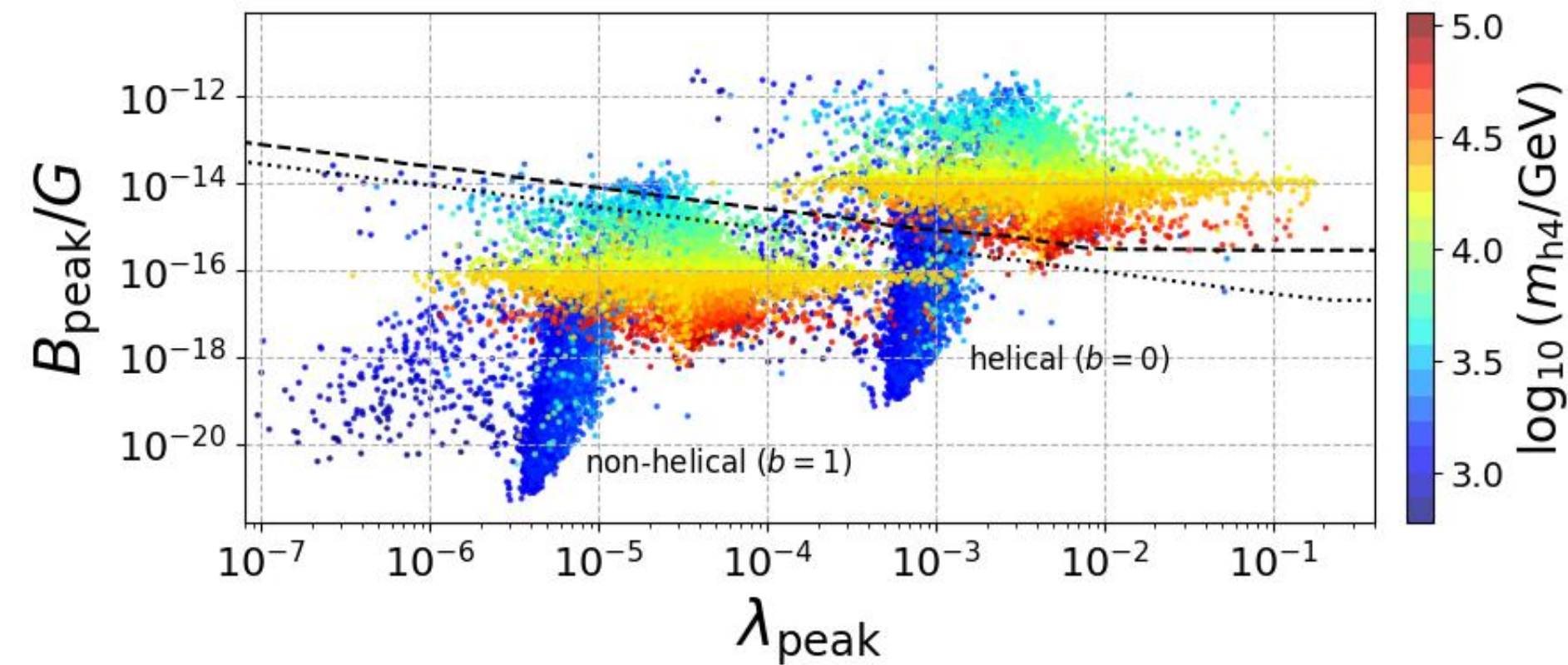
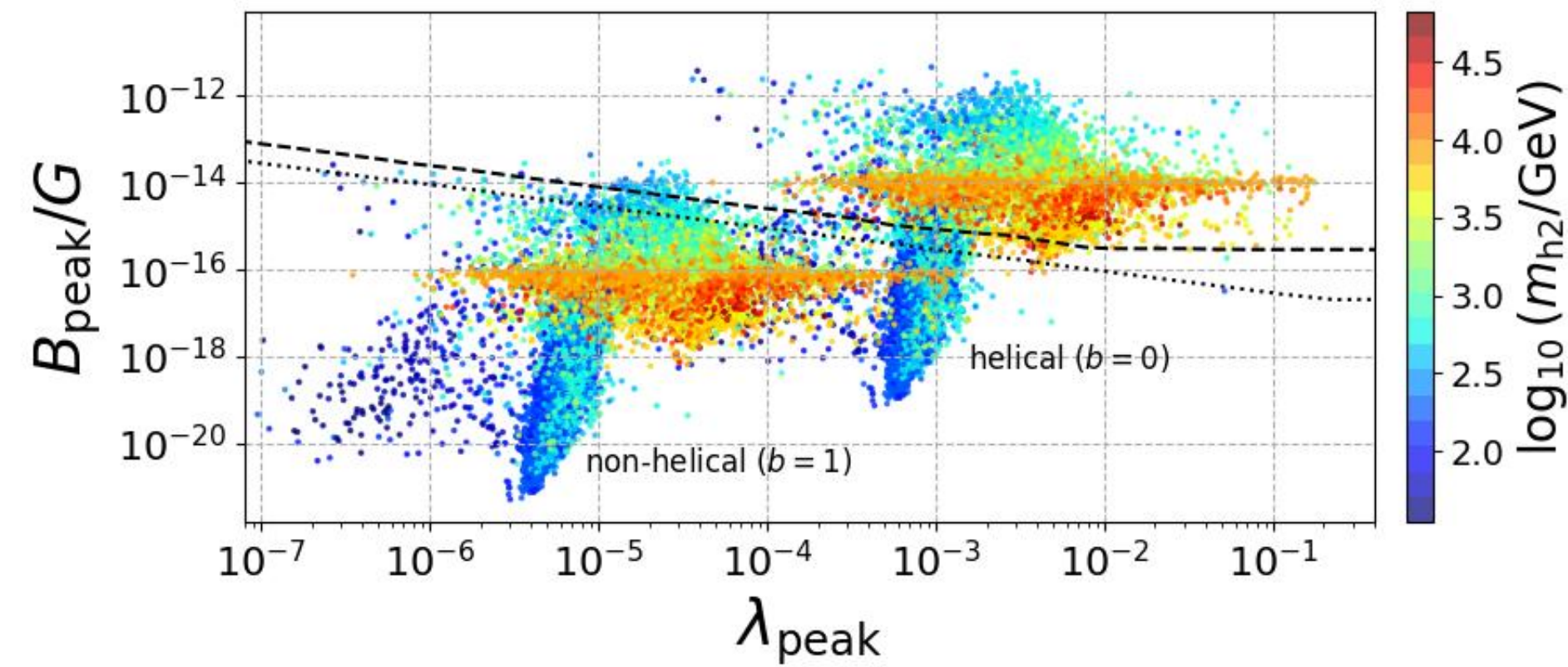

Connected with the SGWB peak frequency(ies)

PMFs for one-step FOPTs

Portal couplings



Scalar masses



- Possibility for magnetogenesis with TeV scale masses

- Possibility for new Higgs bosons at colliders

- Possibility for modified Higgs couplings at colliders

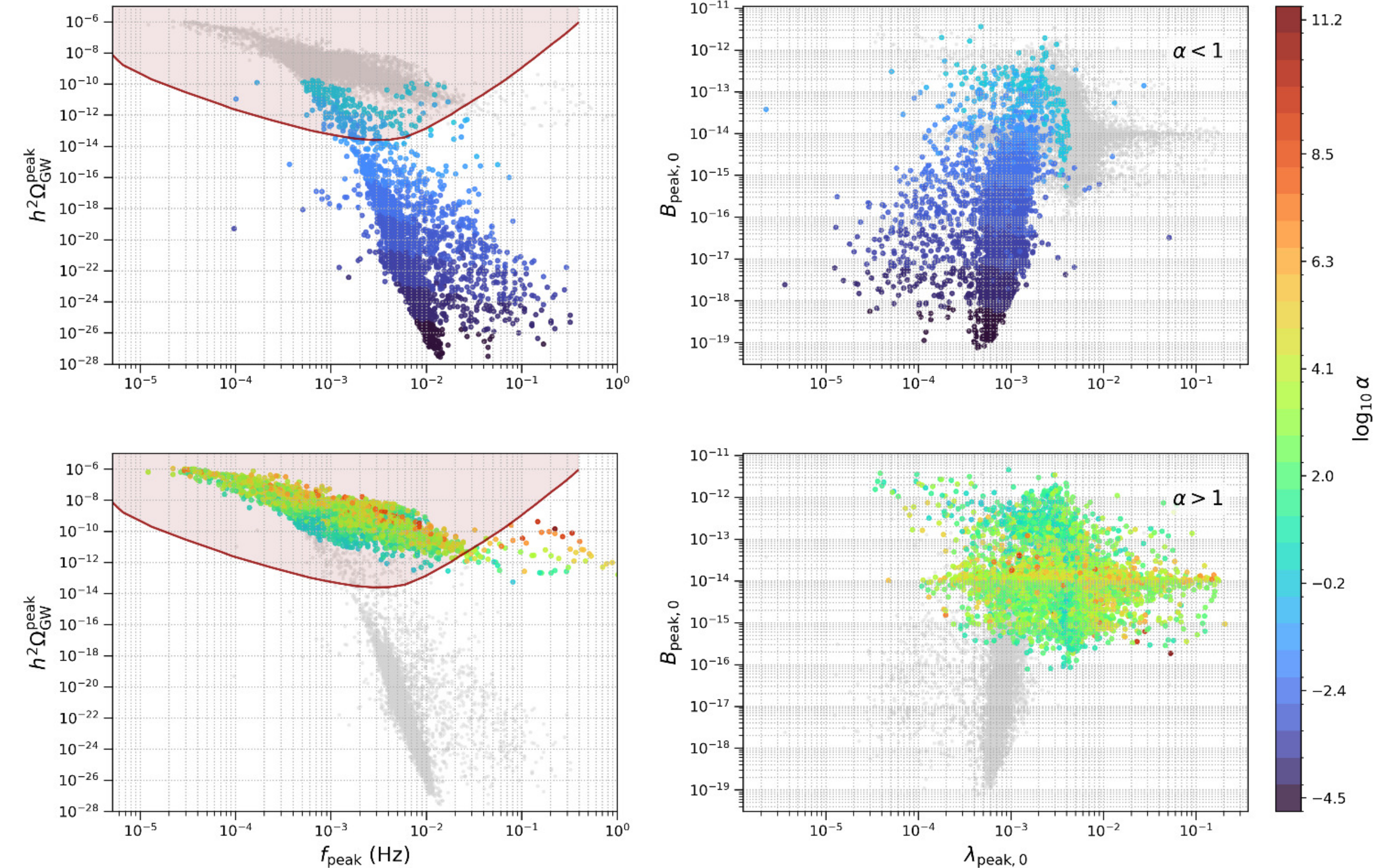
- Possibility for multi-component DM

[Arcadi et al, JHEP12(2016)081]

Similar behaviour to U(1) case but more dispersion caused by a greater freedom

(Work in progress)

Origin of the two branches



Possibility for SGWB at LISA

Great complementarity between
atrophysical, cosmological and
Higgs physics observables

Summary

1. Current and future GW experiments can be used to:
 - (i) Gather information about scalar and gauge sectors in HEP
 - (ii) Test the presence of strong supercooling with $\alpha \gtrsim 10$ in generic CSI models
2. Neutrino sector essential in preventing early matter domination
3. Strongly supercooled FOPTs can lead to the formation of PMF
4. LISA+ET+LIGO can either challenge the hypothesis of supercooled FOPTs, or lead to a groundbreaking discovery

A wide-angle photograph of a tropical beach. The foreground shows white sand with some footprints and small mounds of sand. The water is a vibrant turquoise color, with gentle waves lapping at the shore. Several people are swimming in the water, and a few yellow buoys are visible. The sky is a clear, pale blue with a few wispy clouds on the horizon.

THANK YOU

Rich SGWB predictions due to strongly supercooled FOPTs $\Rightarrow h^2\Omega_{\text{GW}}$ is large

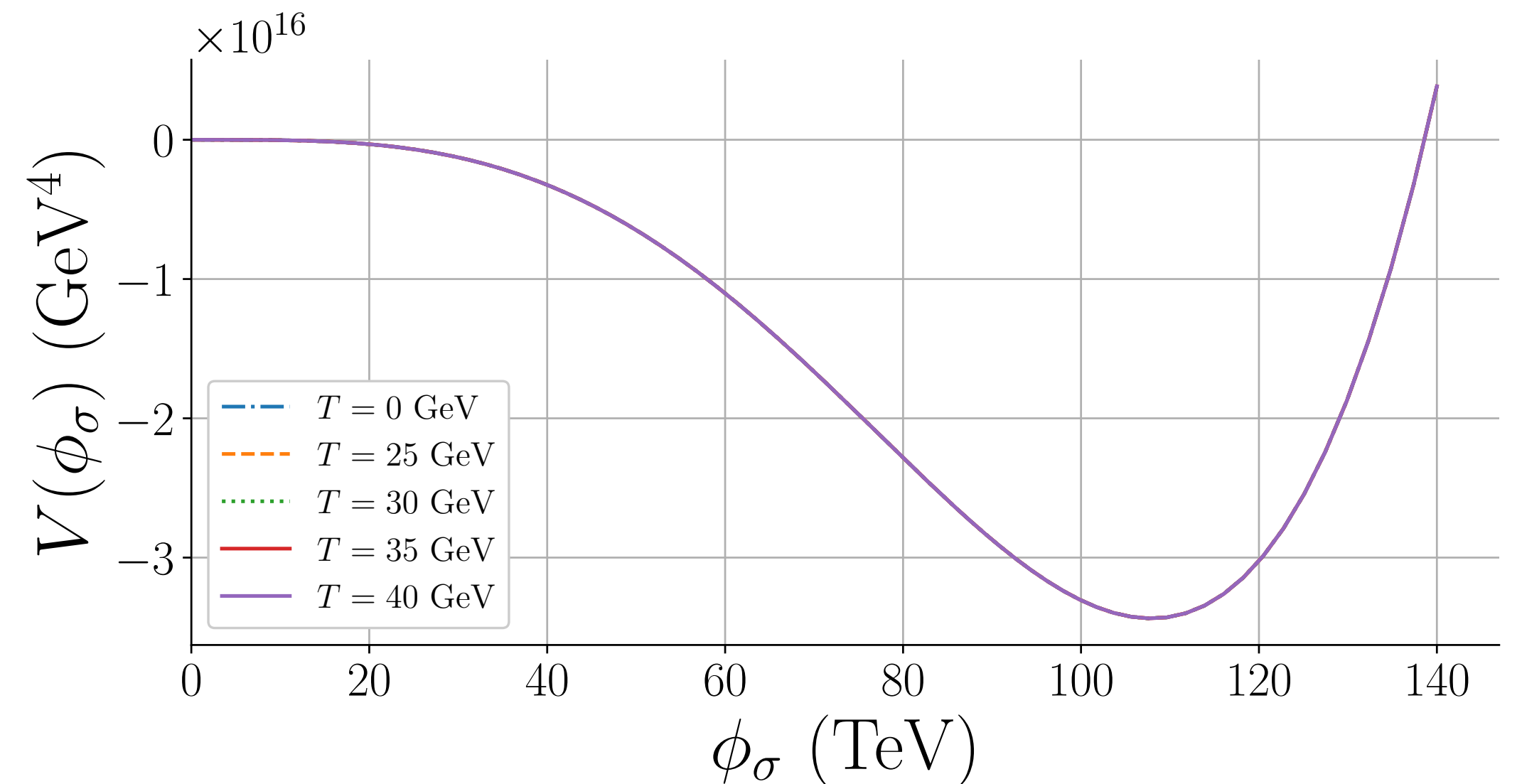
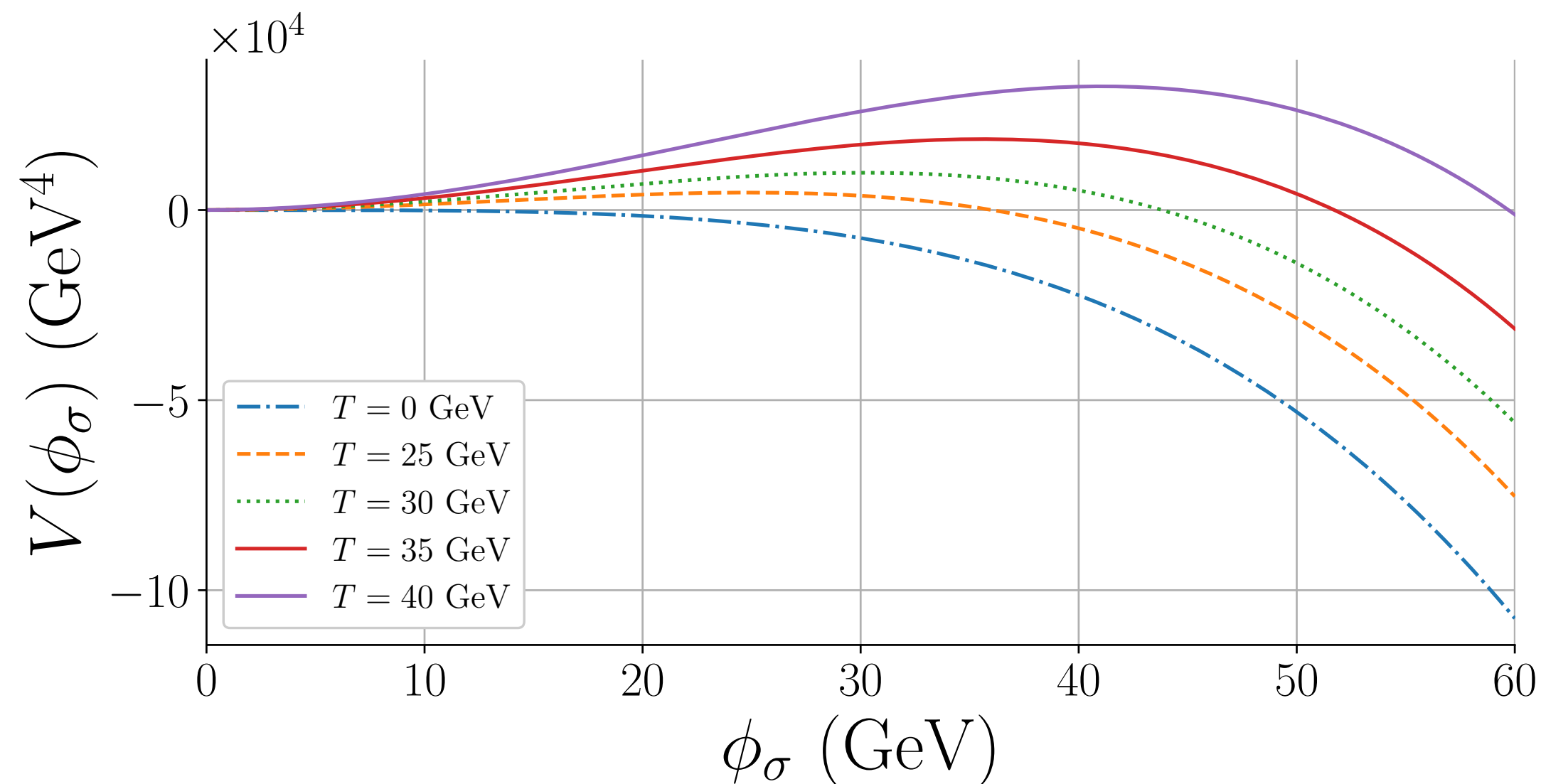
$$V_{\text{eff}}^{\text{HT}} = \phi_{\sigma}^4 \left(-\frac{g_L^4}{2\pi^2} - \frac{g_L^3}{2\sqrt{2}\pi} + \frac{\lambda_{\sigma}}{4} + \frac{\ln 2 \left(\left[\sum_{i=1}^3 [\mathbf{y}_{\sigma}^4]_{ii} \right) \right)}{32\pi^2} \right) - \phi_{\sigma}^3 \frac{4g_L^3 T}{3\pi} + \phi_{\sigma}^2 \left(\frac{g_L^2 T^2}{2} - \frac{g_L^3 T^2}{\sqrt{2}\pi} + \frac{T^2}{48} \sum_{i=1}^3 [\mathbf{y}_{\sigma}^2]_{ii} \right)$$

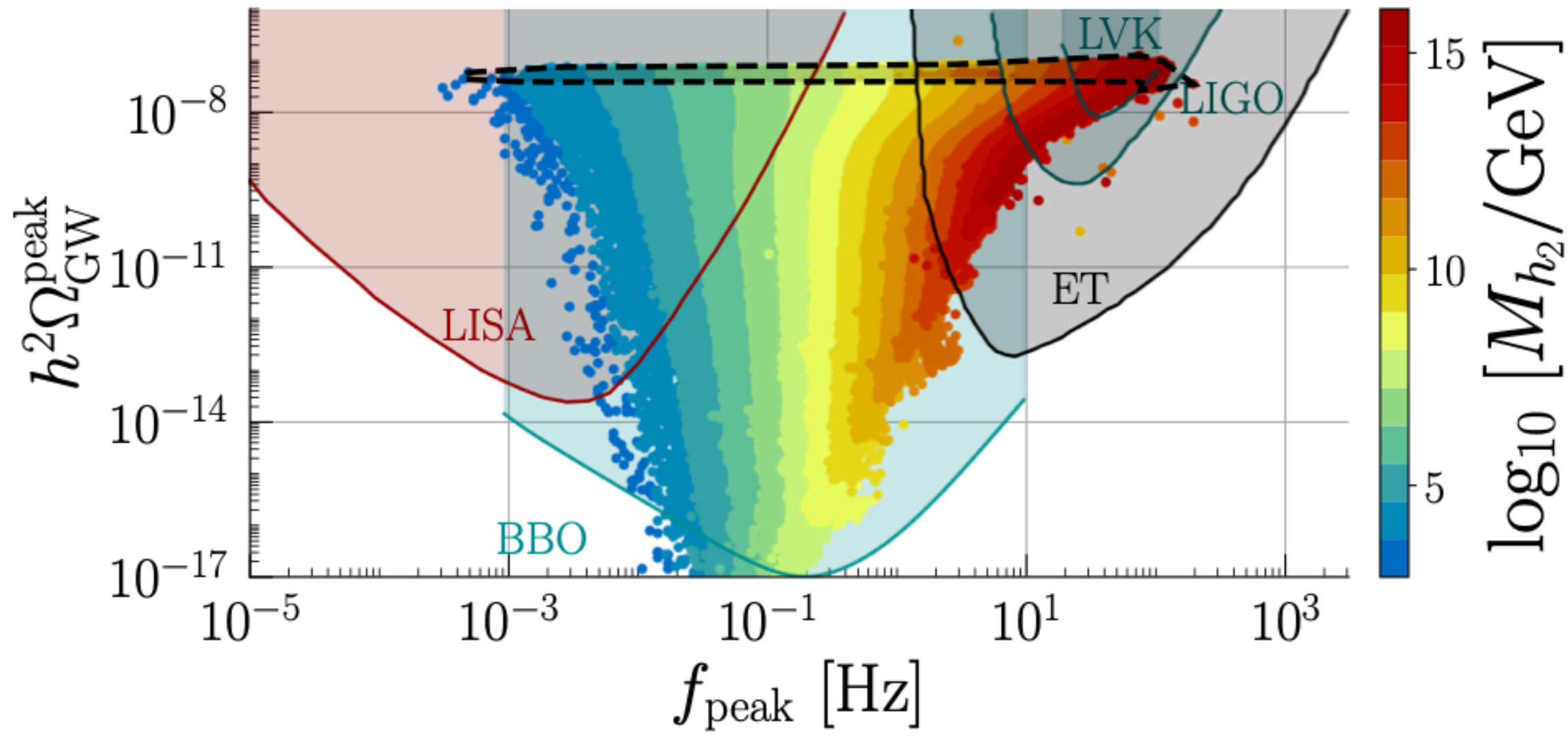
Negative cubic term generated at finite T

Potential barrier persists as the Universe **supercools** down to $T \rightarrow 0$

ΔV is maximized $\Rightarrow \alpha \approx \frac{\Delta V}{\rho_R} \gg 1$

Long lasting FOPT $\beta/H \sim \mathcal{O}(10 - 100)$





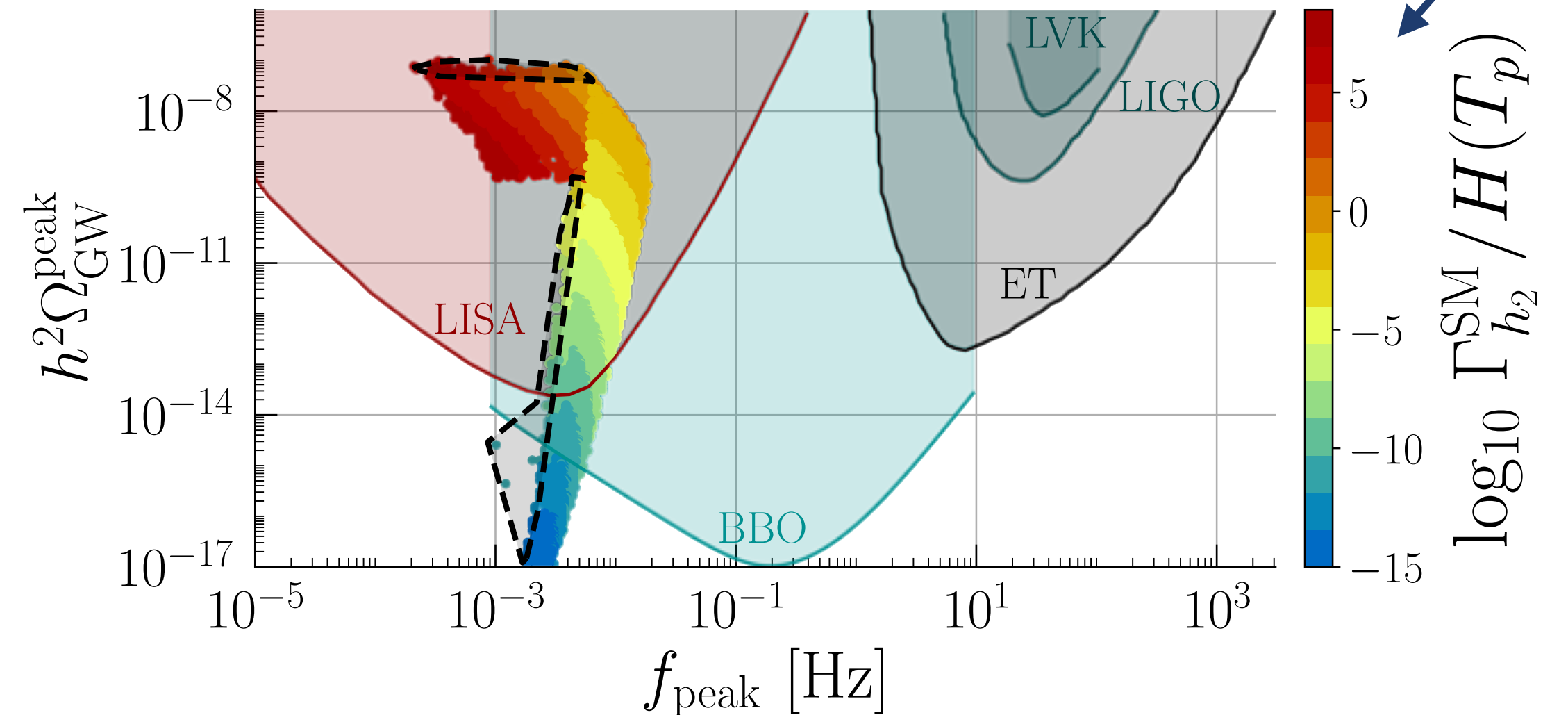
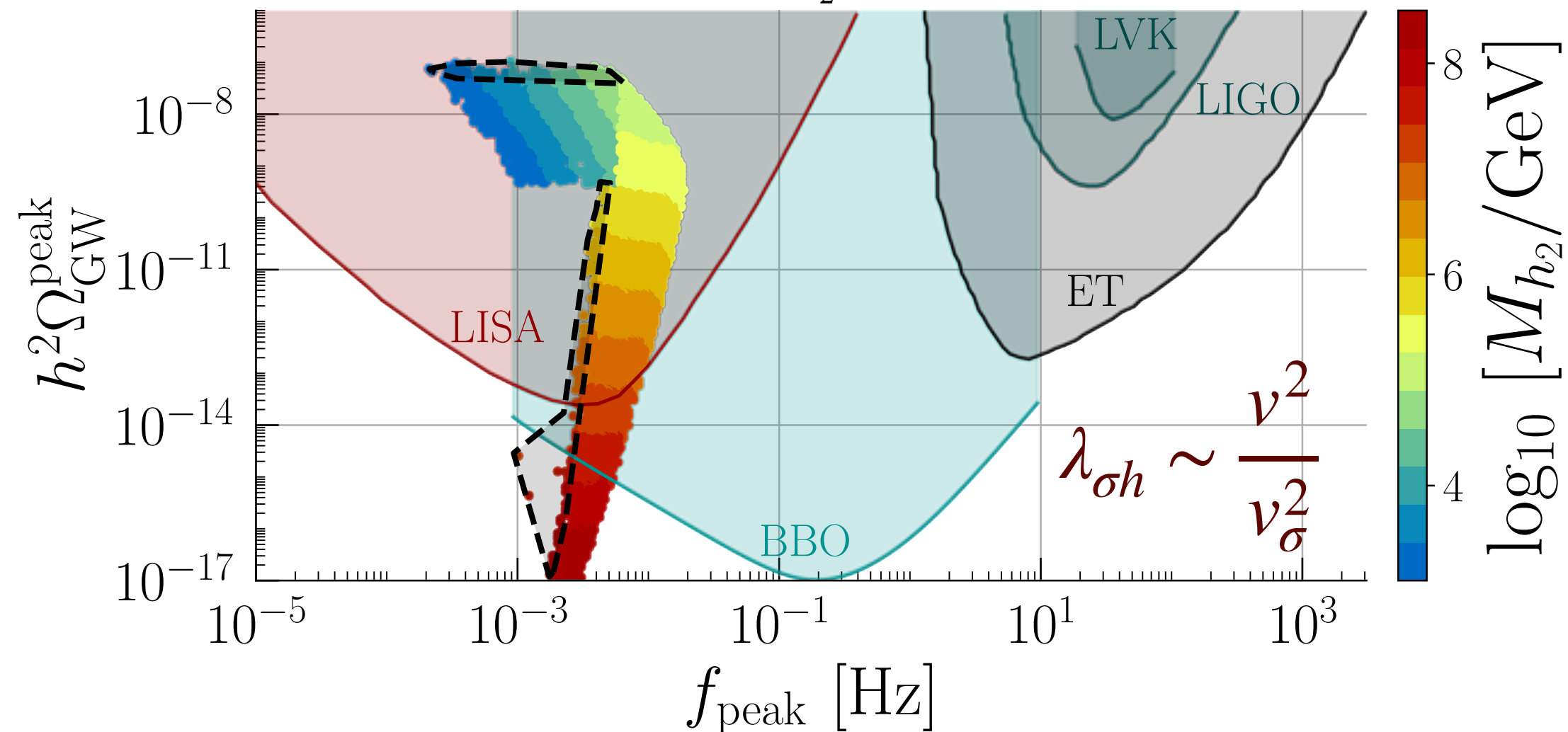
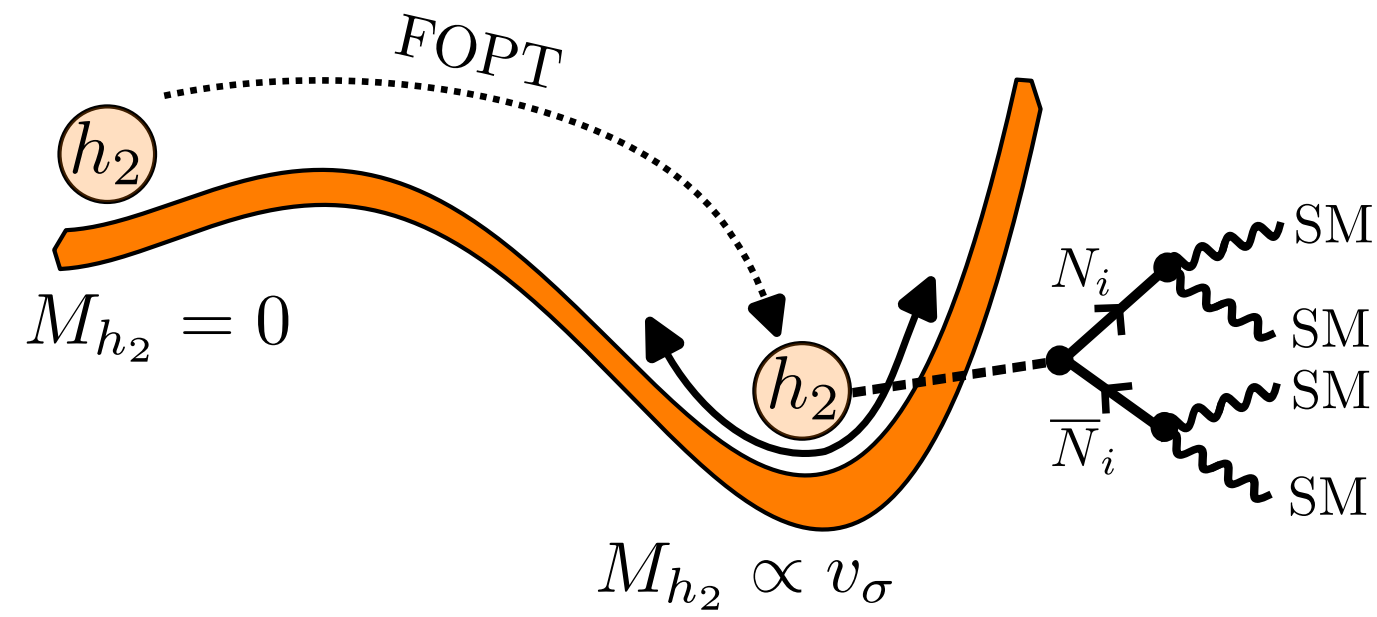
Peak frequency controlled by the mass scale

LVK can already constrain $M_{h_2} \sim 10^{15}$ GeV for $g_L \approx 0.3$ and in classical conformal $U(1)_{\text{B-L}}$ models

$$\Gamma_{h_2} = \Gamma_{h_2 \rightarrow p_{\text{SM}} p_{\text{SM}}^*} + \Gamma_{h_2 \rightarrow \bar{N}_i N_i} \Gamma_{N_i \rightarrow p_{\text{SM}} p_{\text{SM}}^*}$$

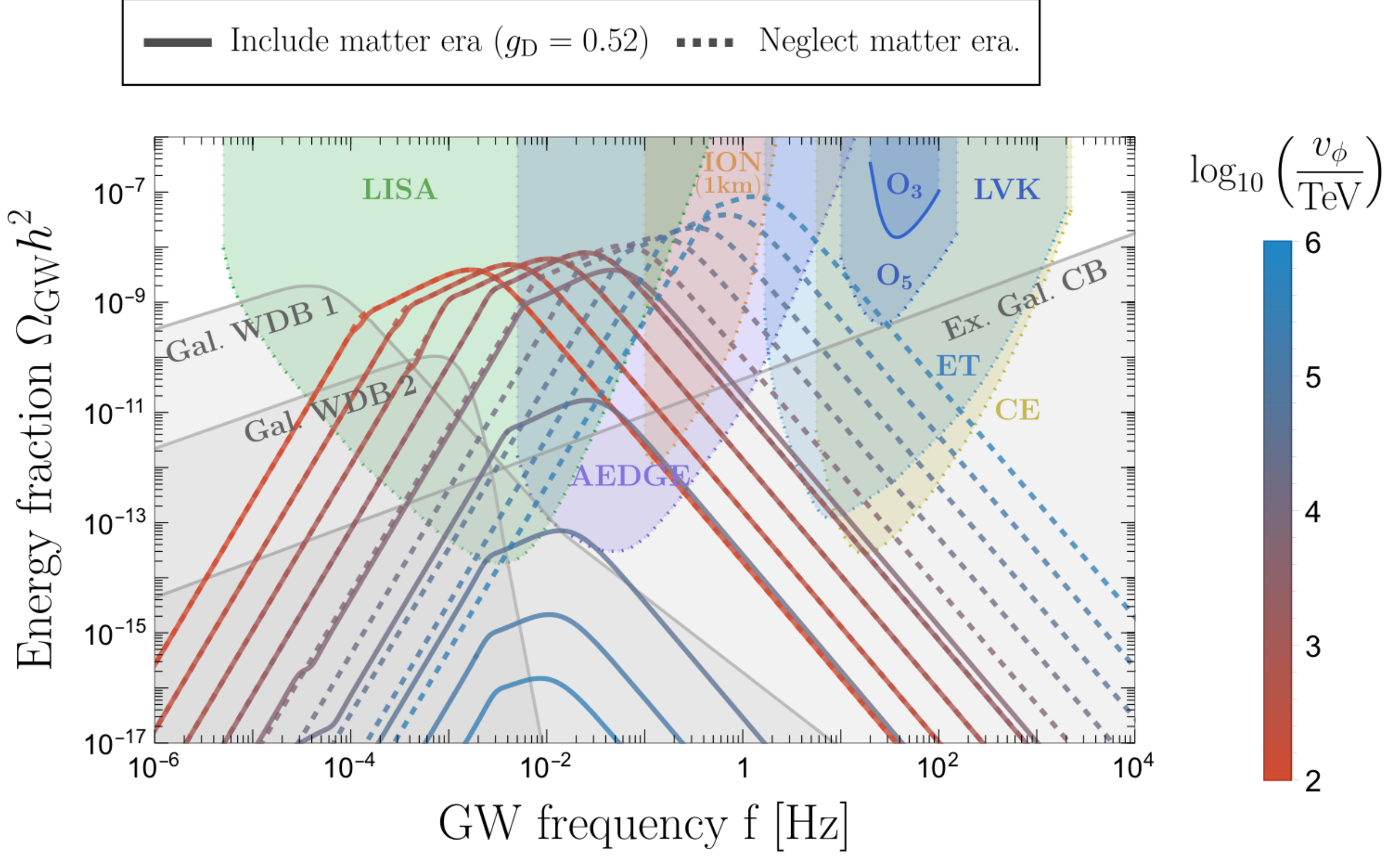
Checked using MadGraph

Without a neutrino sector...



Comparison with a conformal dark $U(1)_D$ model (without neutrino masses)

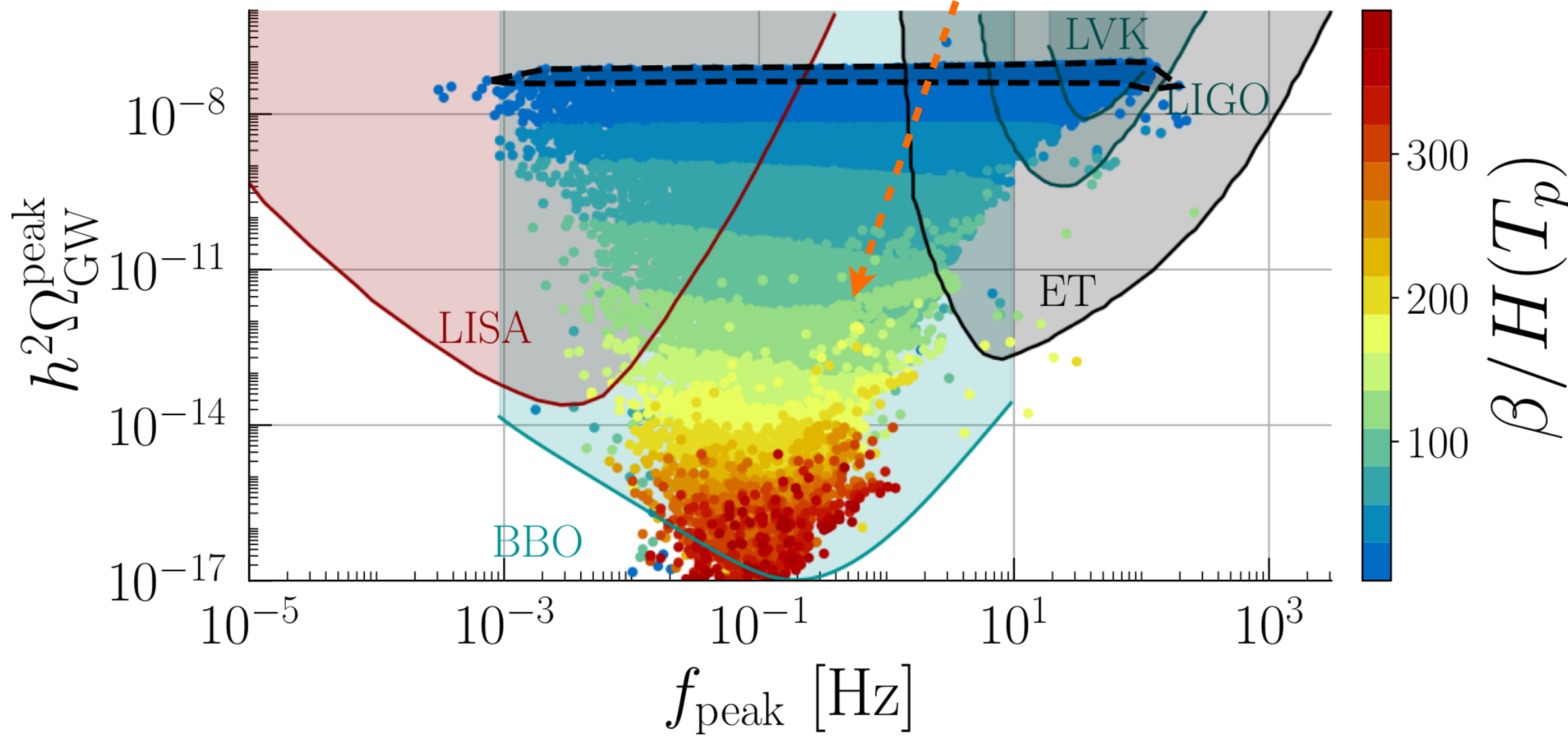
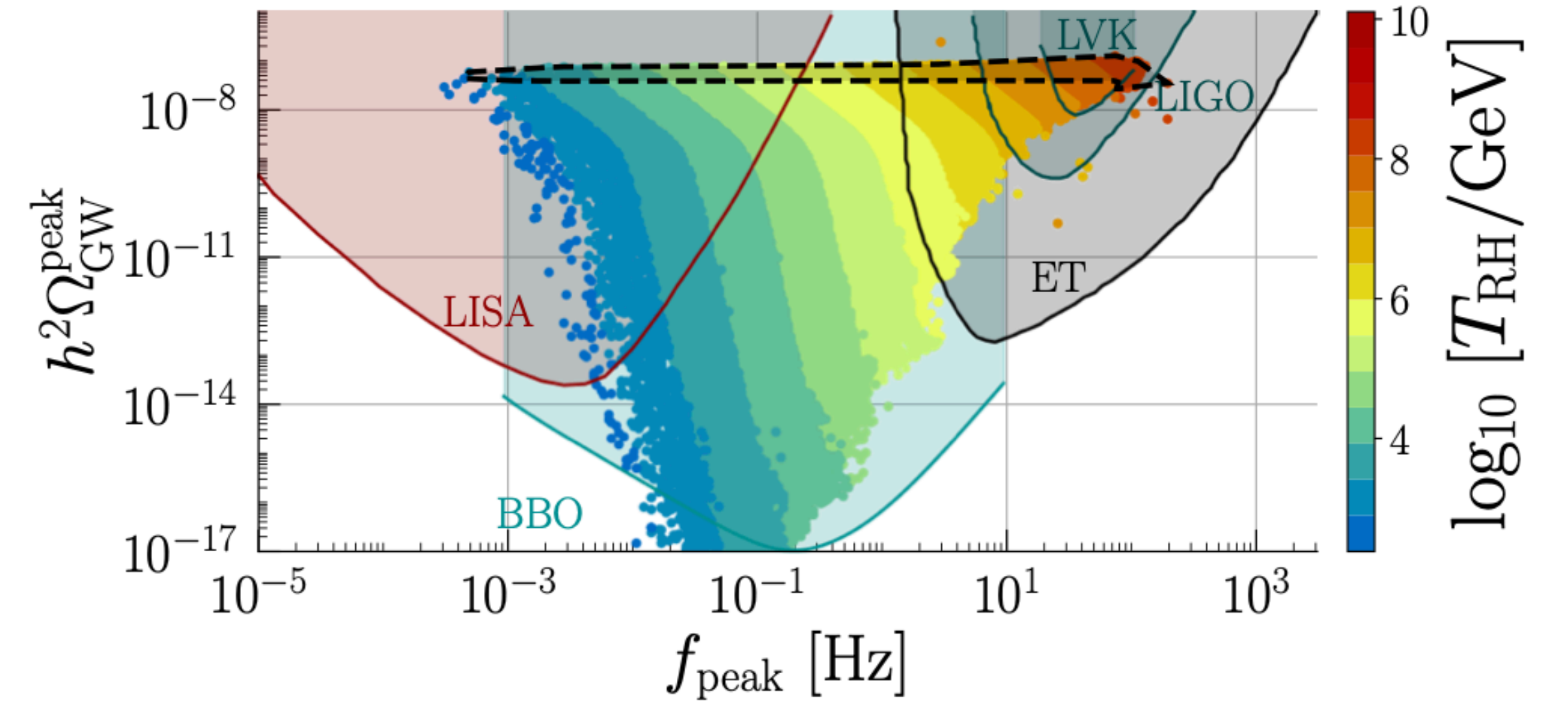
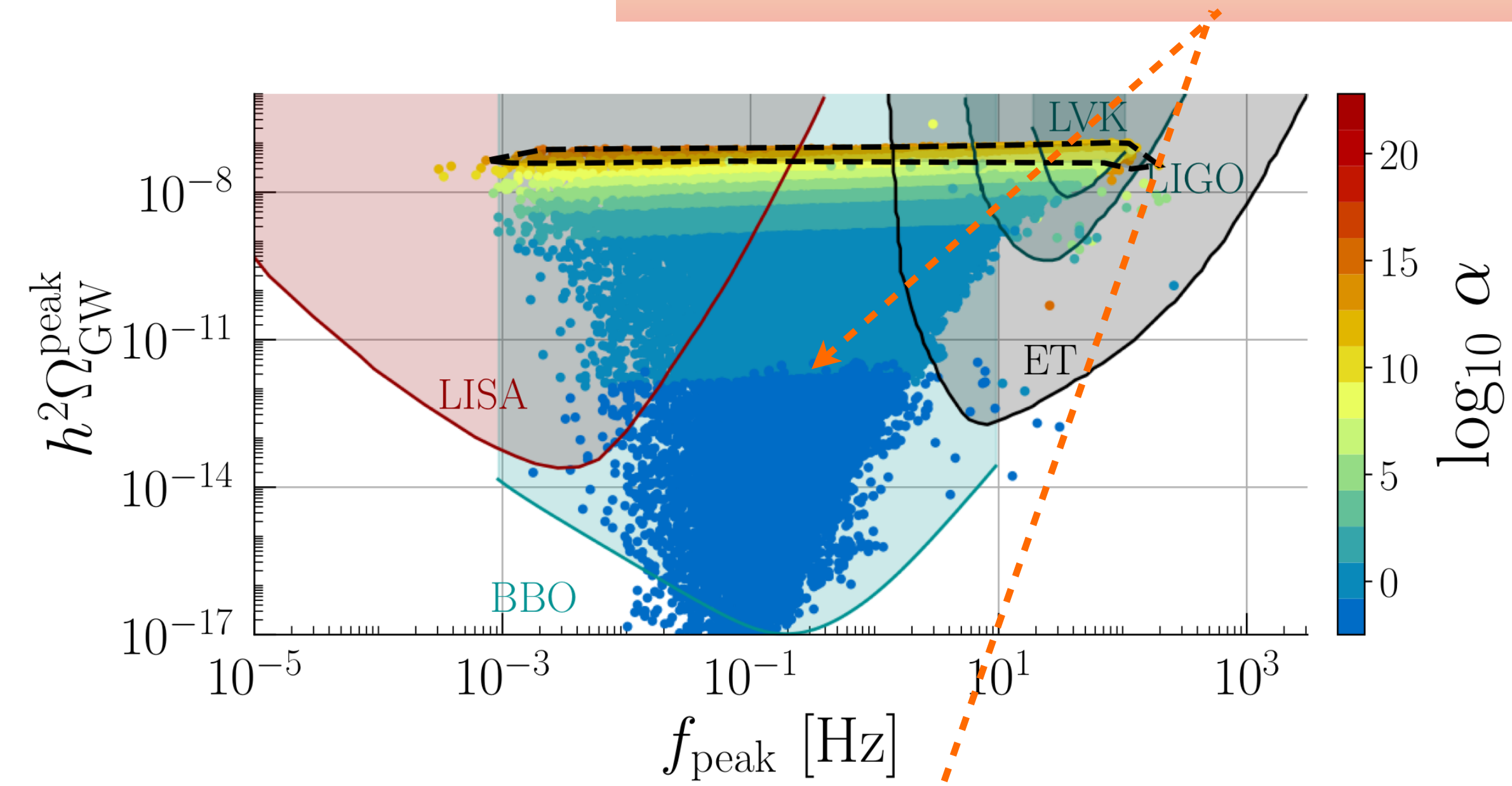
Field	$U(1)'$	$U(1)_D$
Q	$\frac{1}{3}x_u + \frac{1}{6}x_\sigma$	0
u_R	$\frac{4}{3}x_u + \frac{1}{6}x_\sigma$	0
d_R	$-\frac{2}{3}x_u + \frac{1}{6}x_\sigma$	0
L	$-x_\ell - \frac{1}{2}x_\sigma$	0
e_R	$-2x_\ell - \frac{1}{2}x_\sigma$	0
$\mathcal{H}$	$x_\mathcal{H}$	0
N	$-\frac{1}{2}x_\sigma$	X
σ	x_σ	✓



[Gouttenoire, 2311.13640]

Early matter domination forbids SGWB at LIGO and ET for a minimal dark $U(1)$ model

Strong supercooled FOPTs with $\alpha > 10$ and $\beta/H \sim \mathcal{O}(10 - 100)$

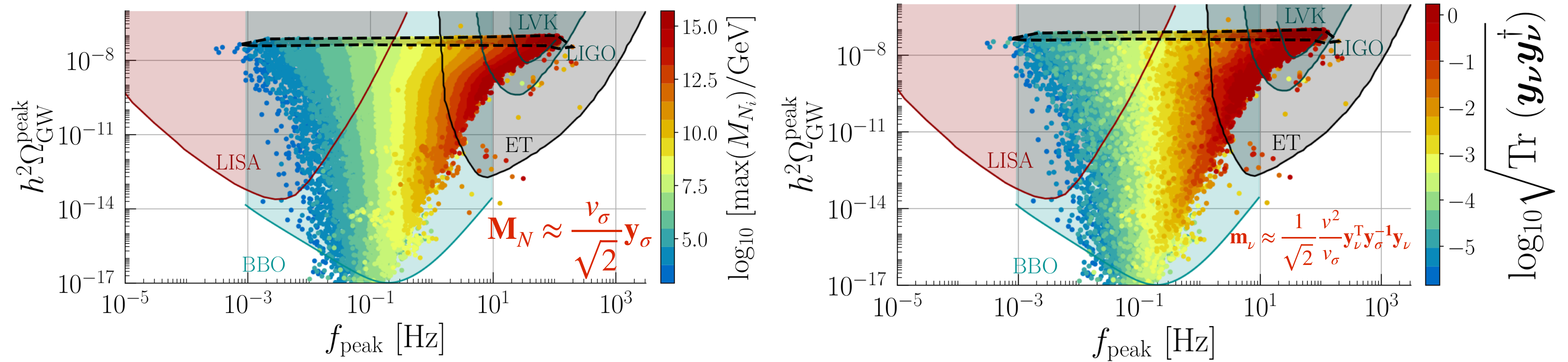


$$T_{\text{RH}} \approx \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{1/2} T_p [1 + \alpha(T_p)]^{1/4}, \quad \Gamma_{h_2} < H(T_p),$$

$$\approx T_p [1 + \alpha(T_p)]^{1/4}, \quad \Gamma_{h_2} > H(T_p).$$

Inside dashed contour the volume of false vacuum near T_p is not decreasing but only at $T < T_p$

Neutrino sector parameters



Require thermal equilibrium of N_i with SM before onset of the FOPT [Di Bari, Marfatia, Zhou, 2106.00025]

1. At LISA frequencies seesaw scale in $10^4 \lesssim M_N/\text{GeV} \lesssim 10^8$ with $10^{-6} \lesssim y_\nu \lesssim 10^{-3}$

2. At LIGO and ET frequencies seesaw scale in $10^9 \lesssim M_N/\text{GeV} \lesssim 10^{15}$ with $10^{-2} \lesssim y_\nu \lesssim 1$

LVK can already constrain $M_N \sim 10^{15}$ GeV for $y_\sigma \sim 0.1$ and $y_\nu \sim 1$ in classical conformal $U(1)_{B-L}$ models with type-I seesaw

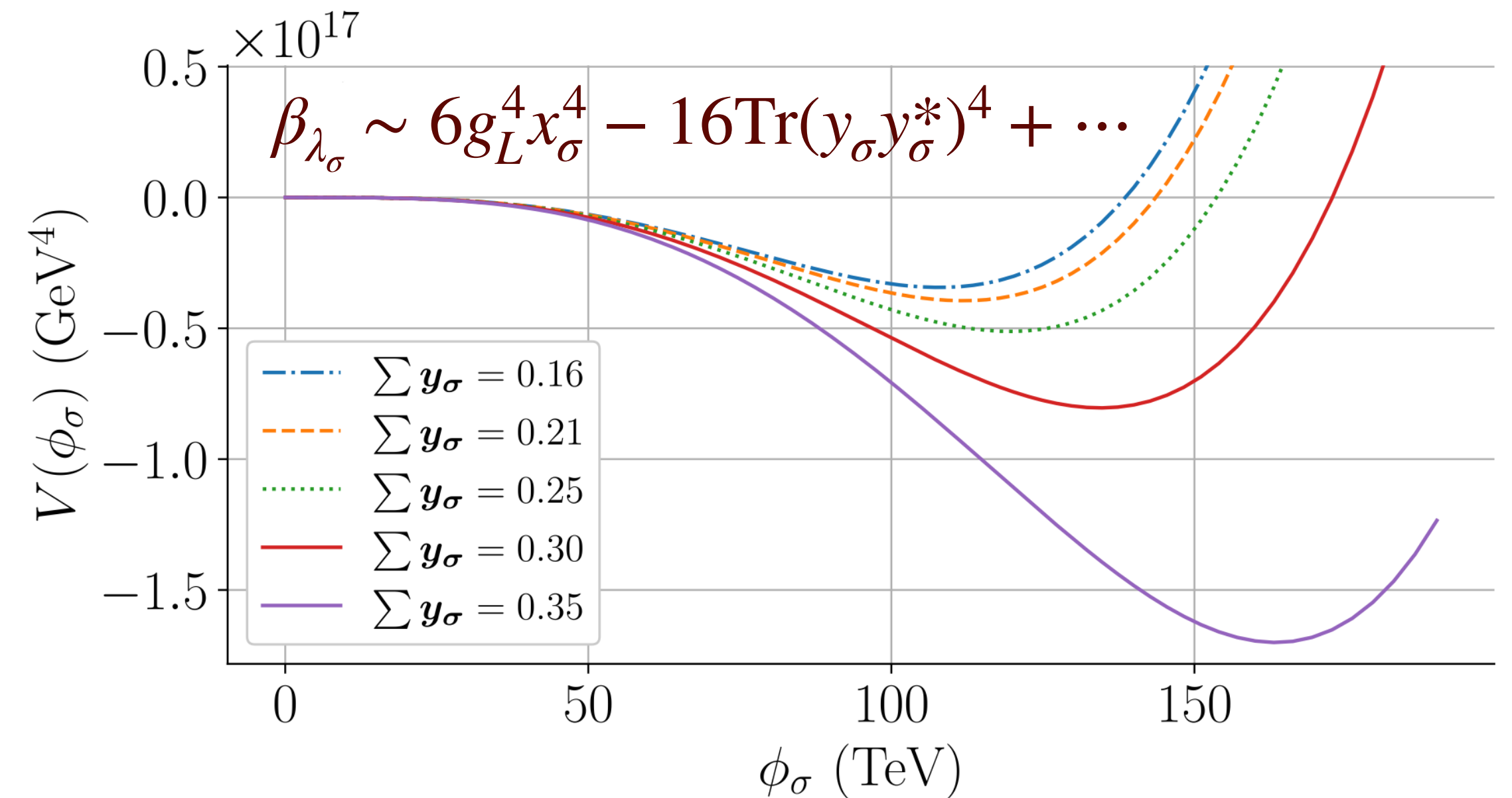
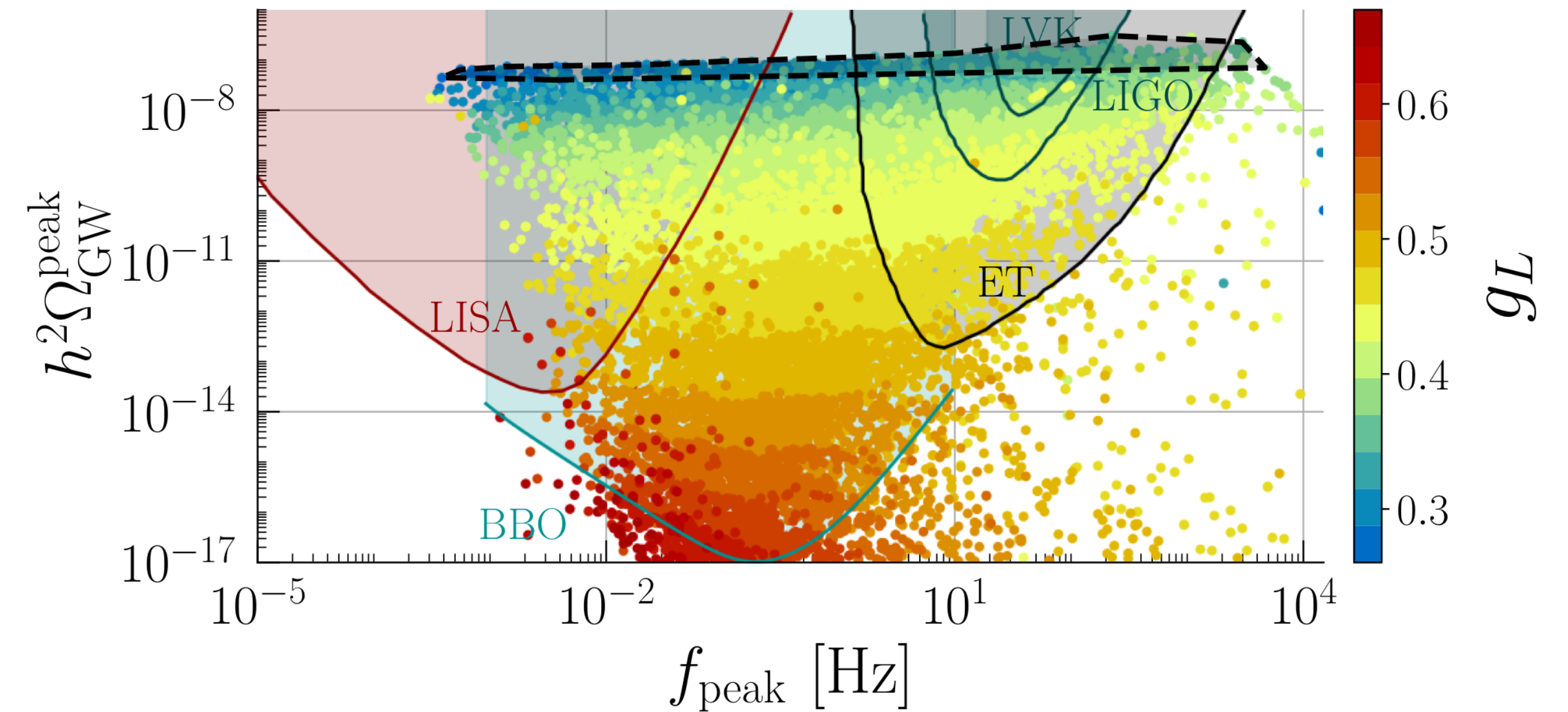
What if we “strongly” couple heavy neutrino sector $\text{Tr}(y_\sigma) > g_L$?

When $y_\sigma \gtrsim g_L$ they start to compete:

1. Can reach up to $f_{\text{peak}} \approx 10$ kHz

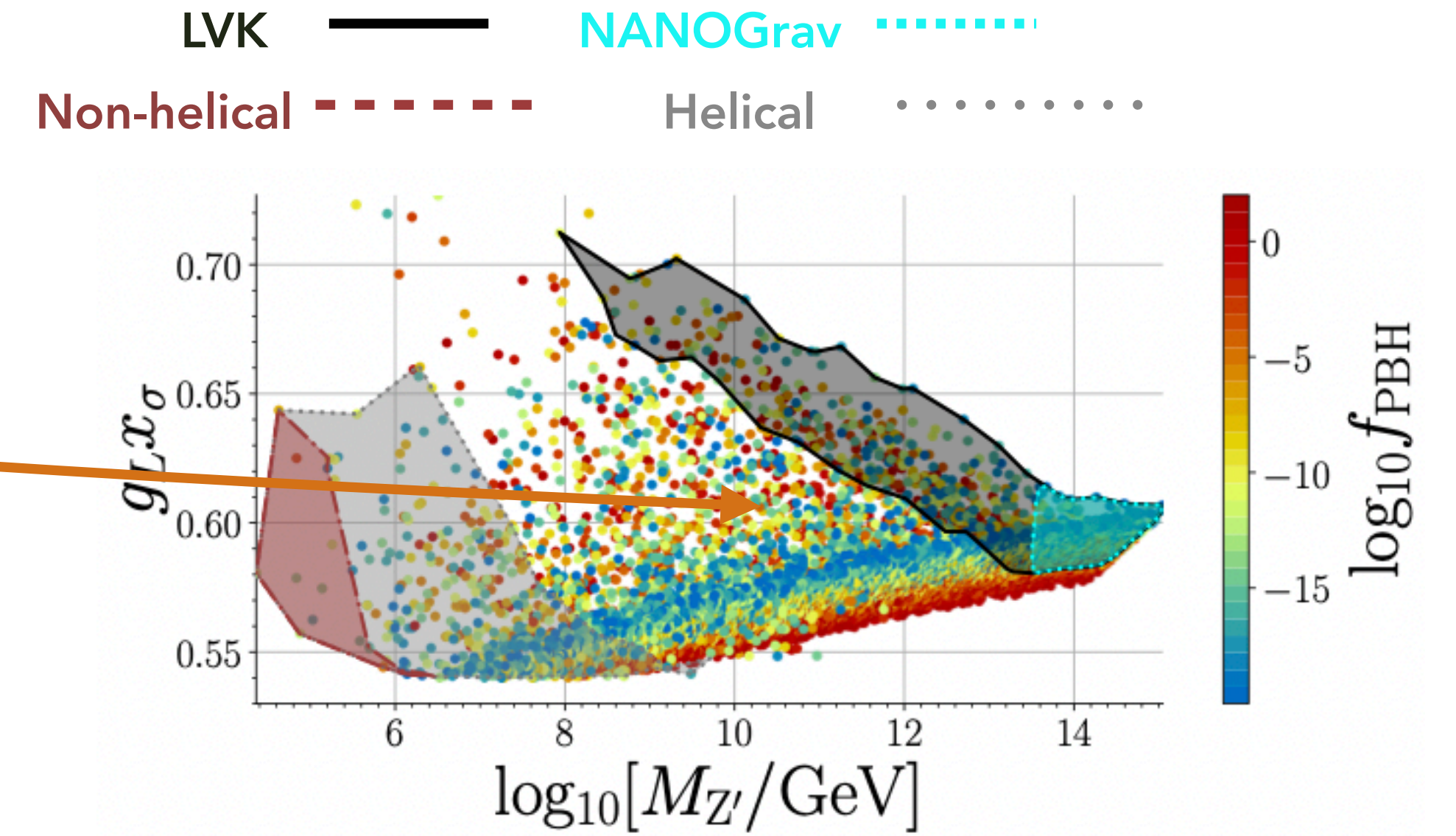
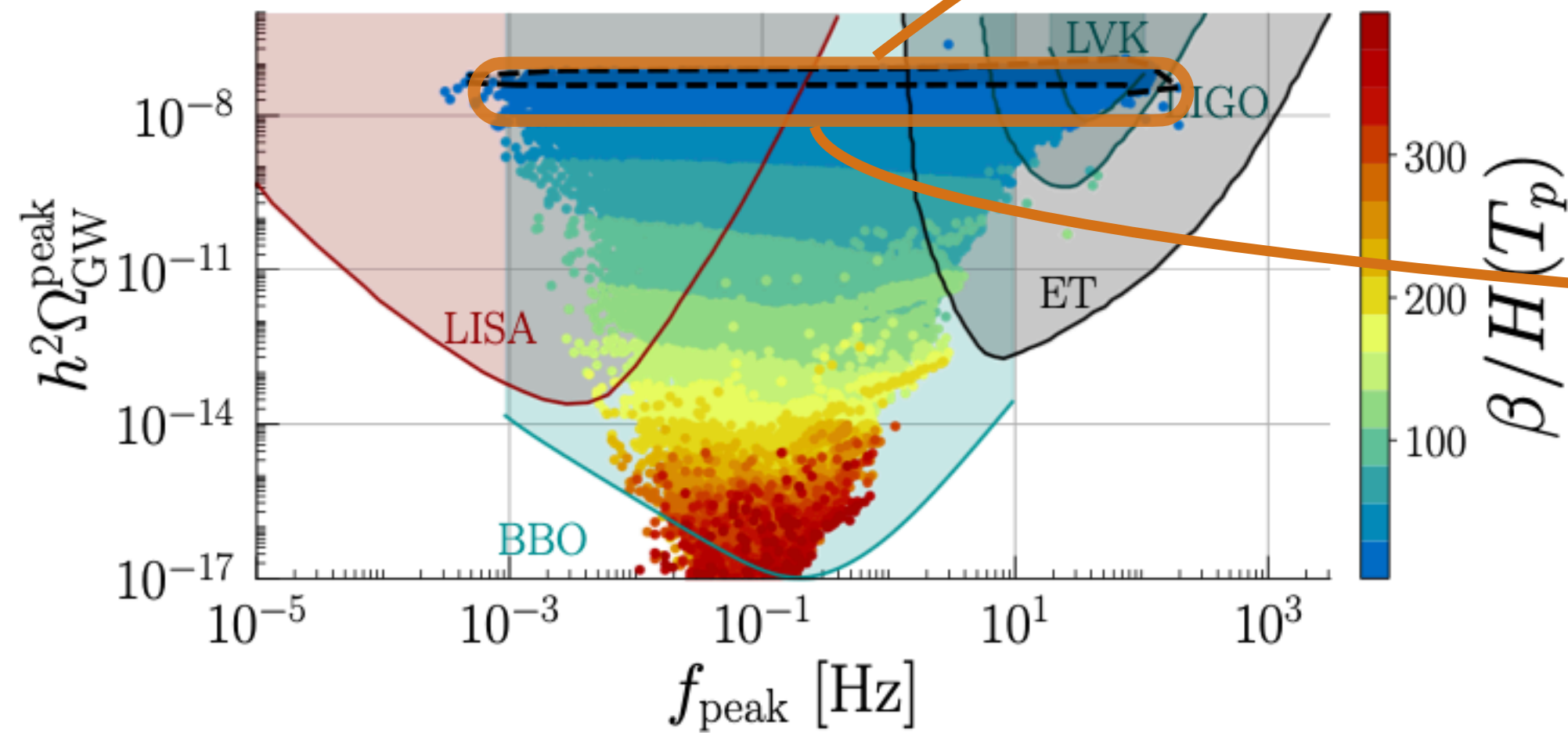
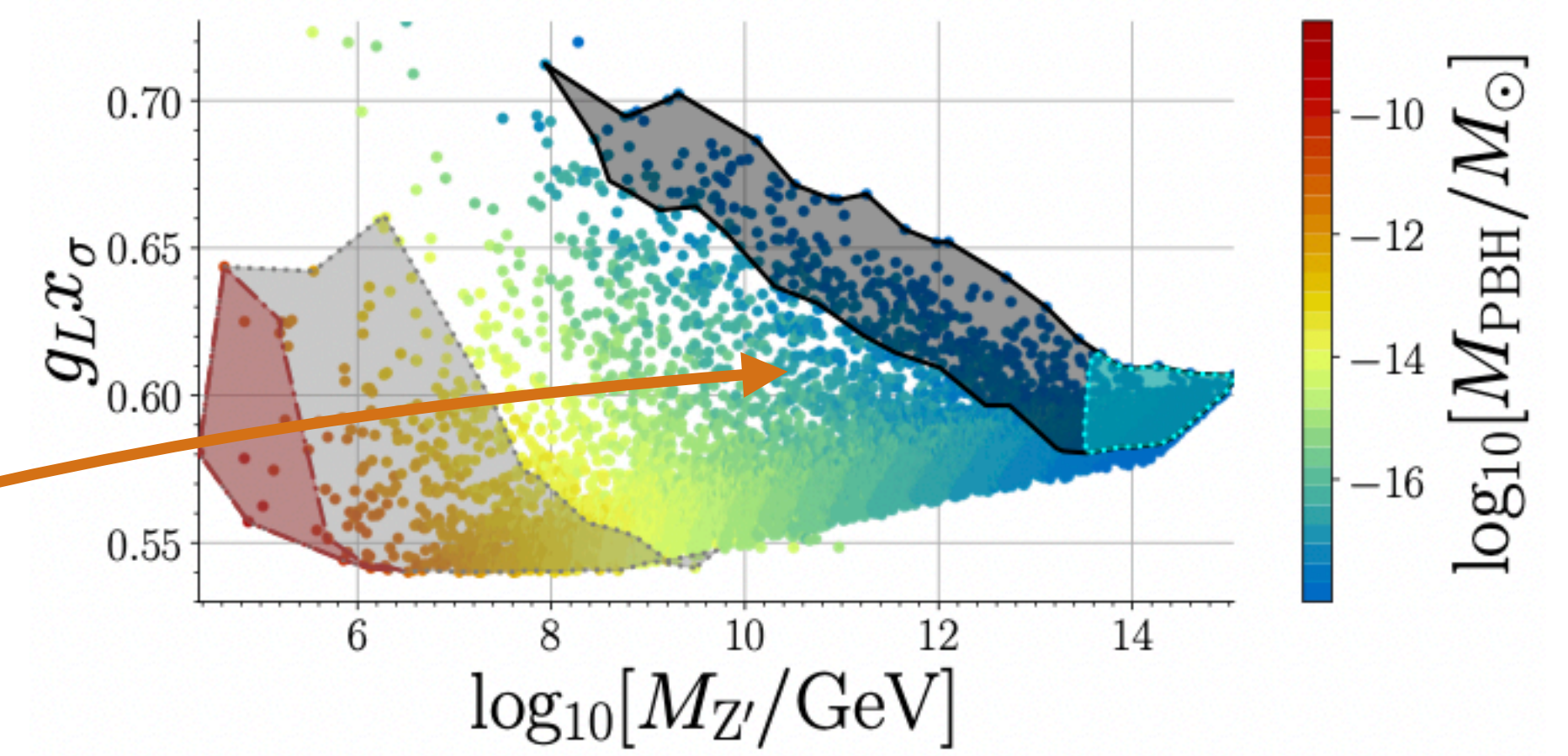
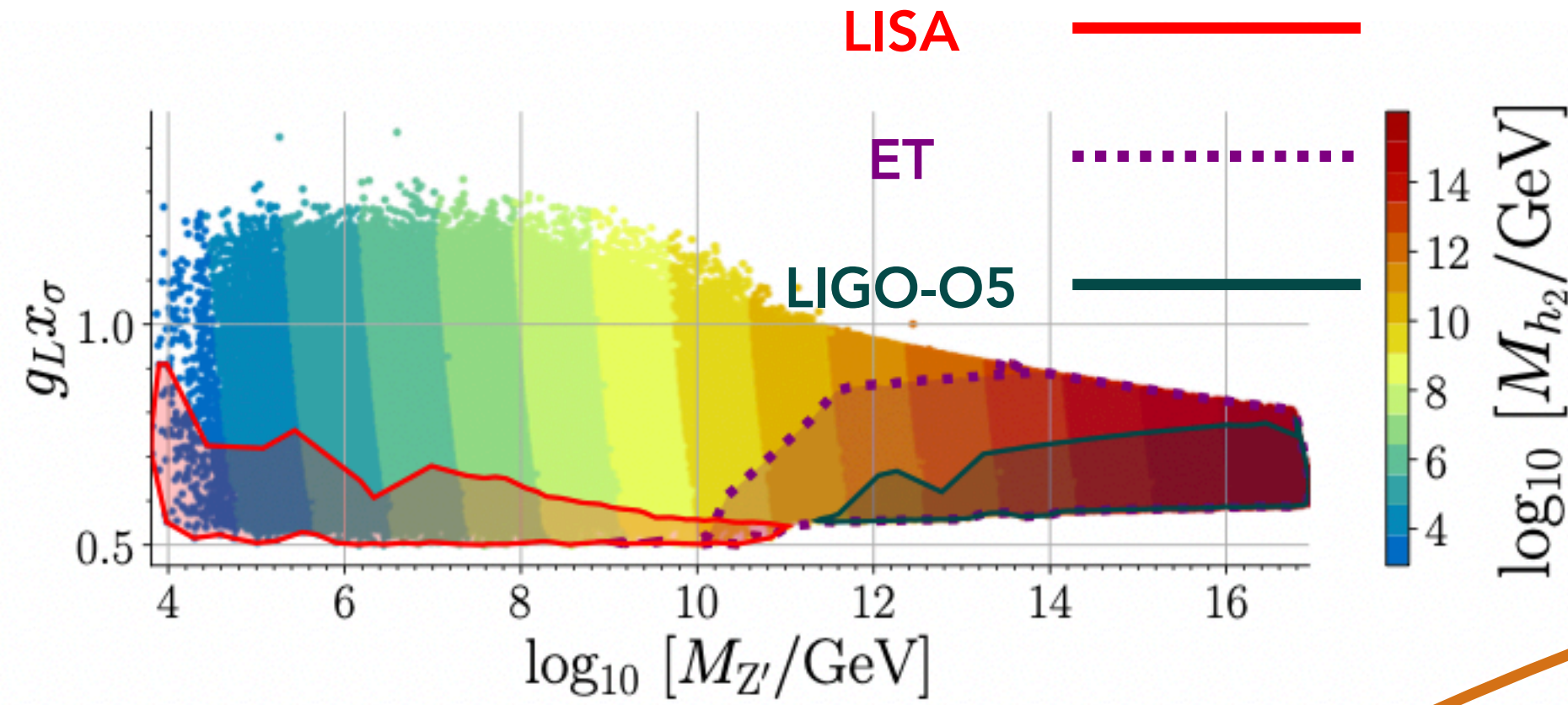
A. Opposite sign in β_{λ_σ} slows down RG running with sign flip at larger ϕ_σ

B. For fixed g_L minimum gets deeper, thus ΔV is larger $\Rightarrow$ larger $h^2\Omega_{\text{GW}}^{\text{peak}}$

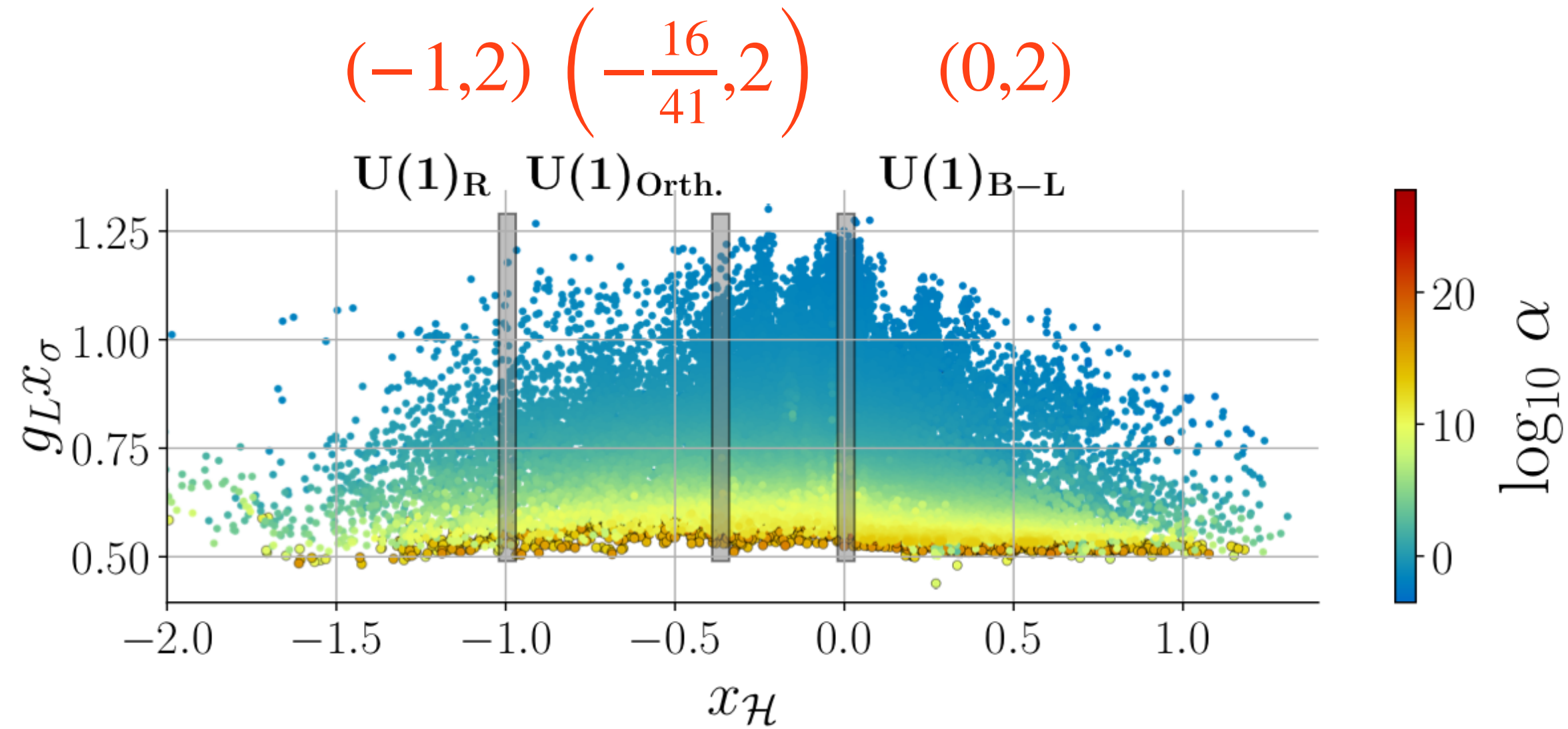


Global picture

Refined picture for $\beta/H(T_p) < 10$

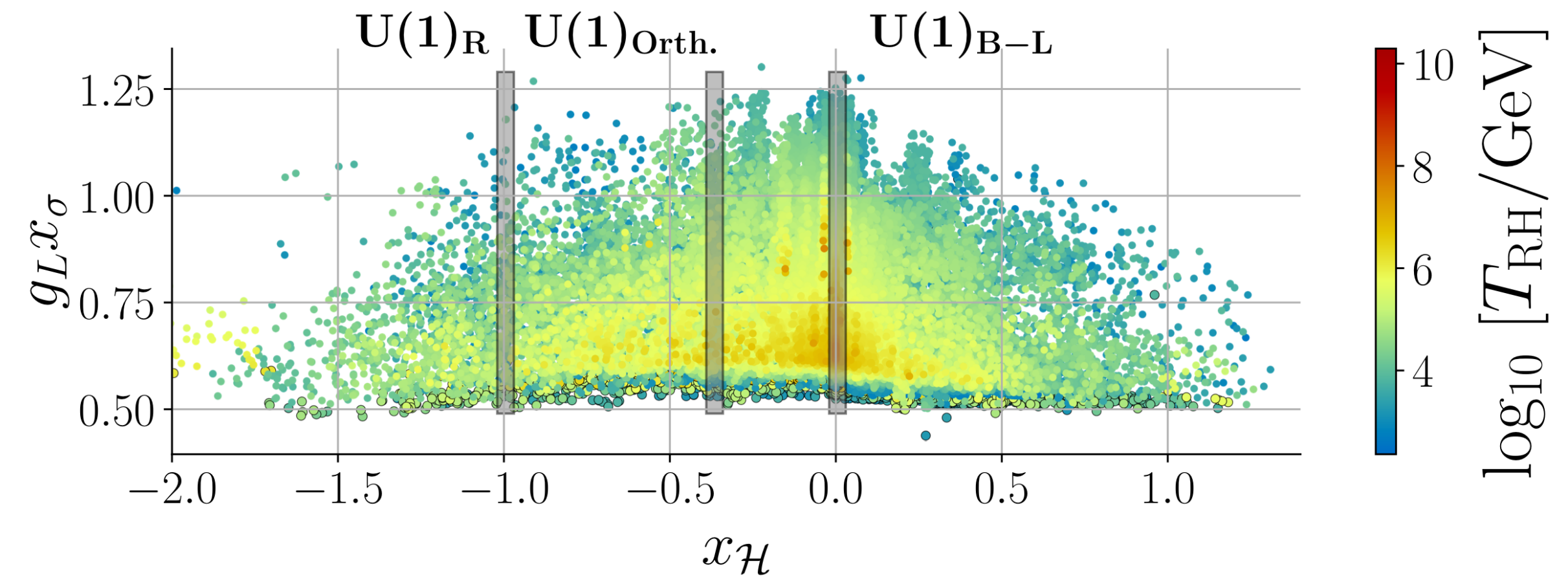
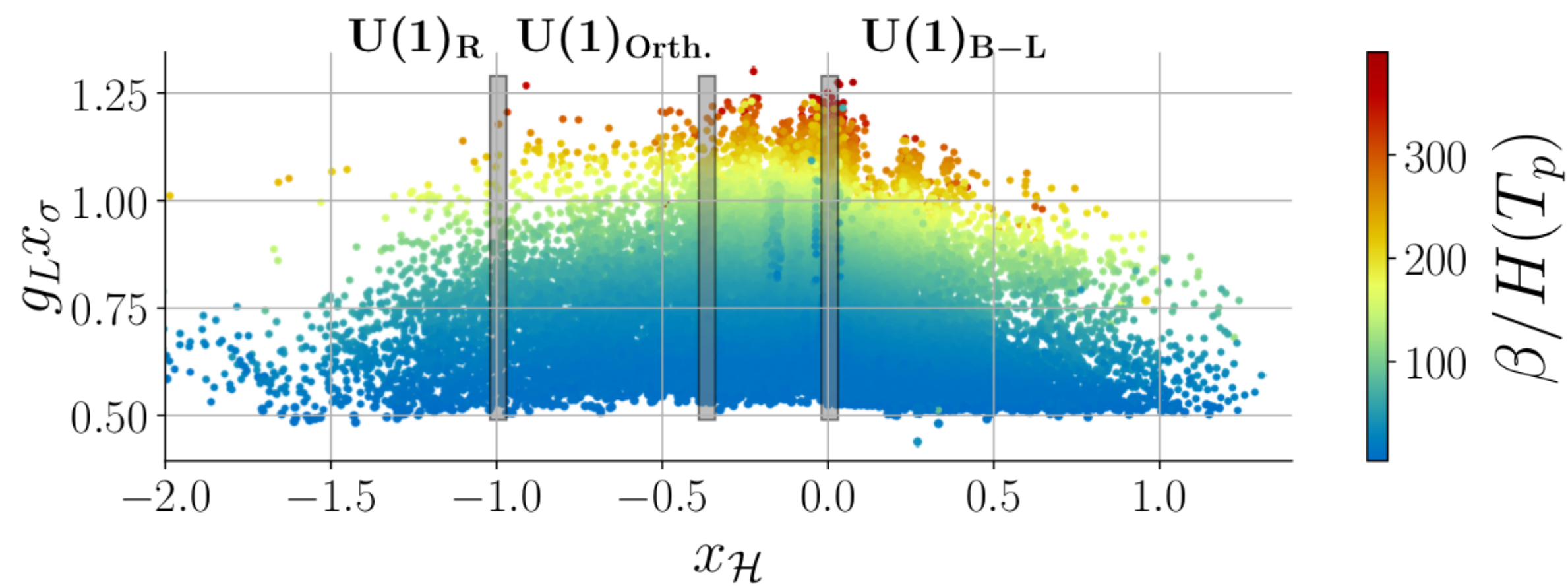


SGWB predictions for generic $U(1)'$ with charges (x_H, x_σ)



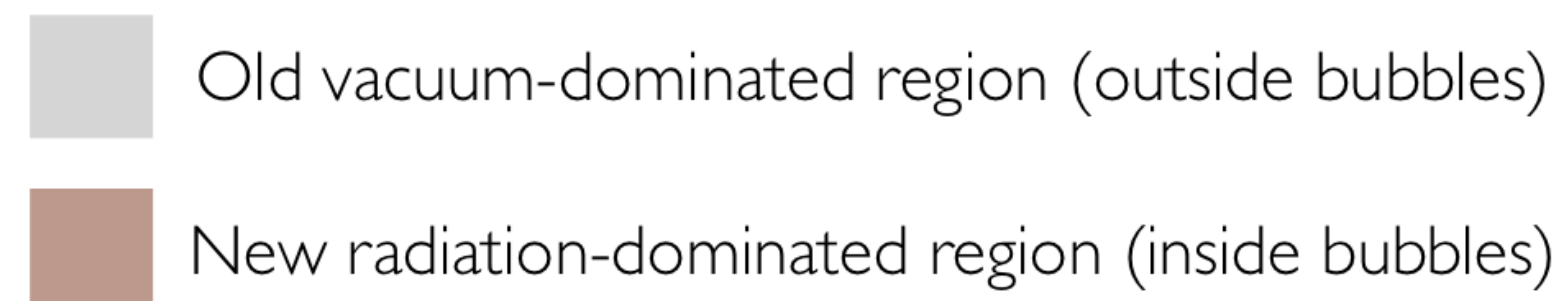
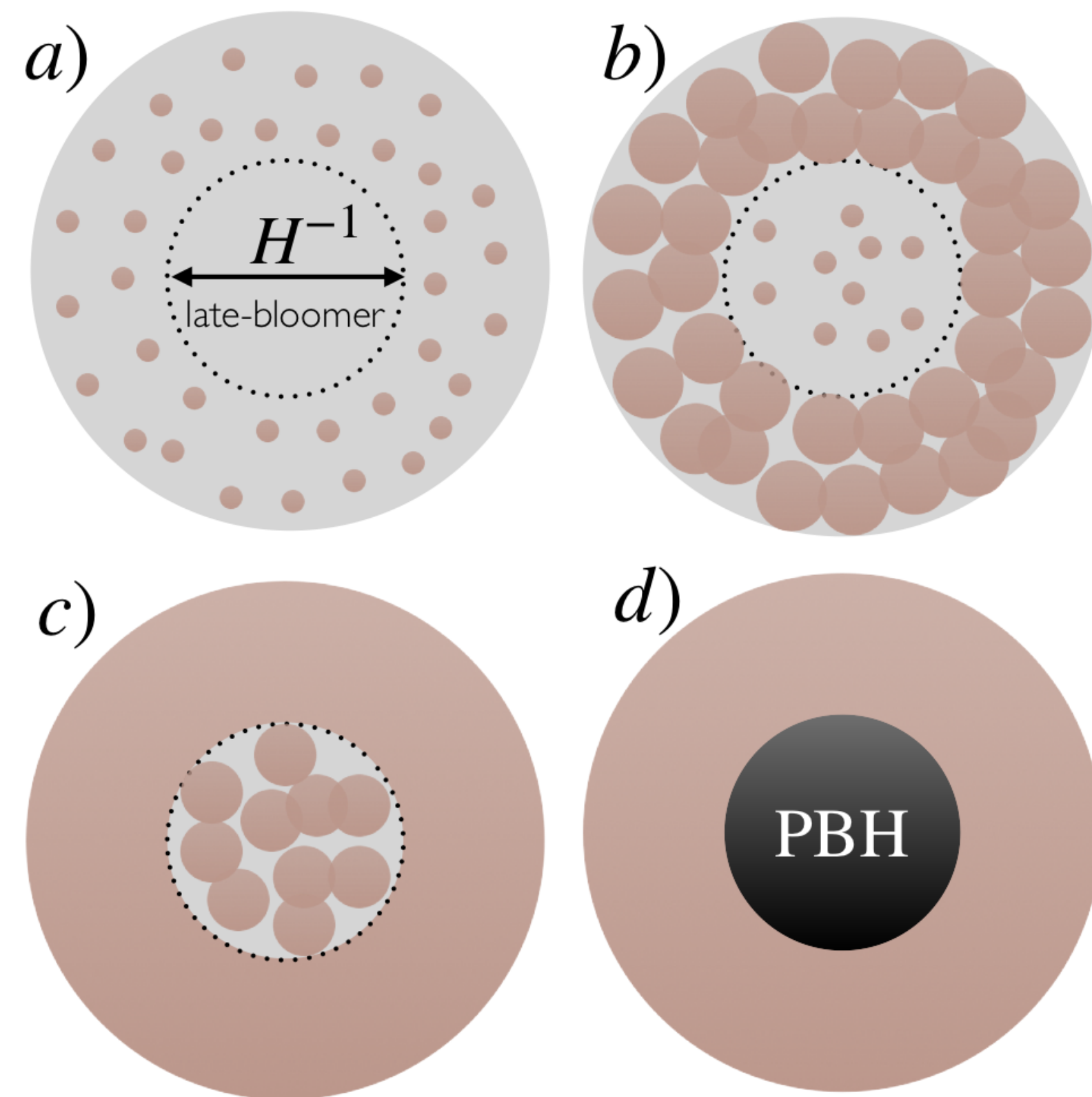
Thermodynamic parameters weakly dependent on x_H

Higher temperatures preferred near the B-L model $\Leftarrow$ larger charges imply Landau poles at lower scales



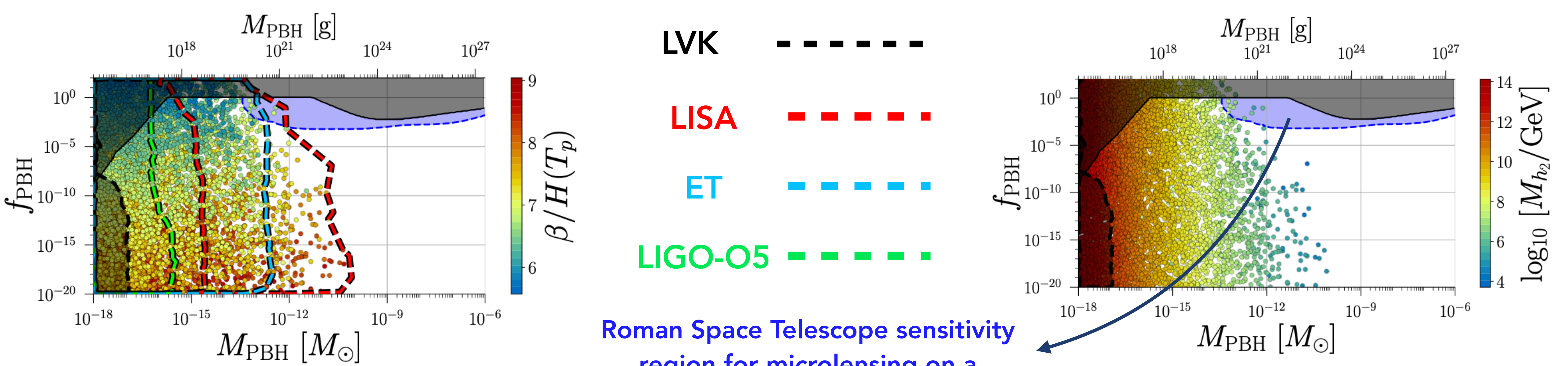
**Actually... no particle dark matter candidate in
this setting, but...**

PBH formation via collapse of delayed false vacuum patches



[Gouttenoire, Volansky, 2305.04942]

- In strongly supercooled FOPTs the energy density of the Universe is dominated by the latent heat $\alpha \approx \frac{\Delta V}{\rho_R} \gg 1$ that acts as a **cosmological constant**
- Universe undergoes a thermal inflation period until the new phase percolates
- Bubble nucleation is a stochastic process
 1. Regions outside bubbles expand faster (vacuum dominated)
 2. Delayed nucleation within a causal patch (late-bloomer) can develop high curvature and collapse into PBH



Roman Space Telescope sensitivity
region for microlensing on a
dedicated survey to M31
[A. Drlica-Wagner et al., 2209.08215]

PBH and h_2 masses are related

$$M_{\text{PBH}}(T_{\text{reh}}) = M_{\odot} \left(\frac{20}{g_r(T_{\text{reh}})} \right)^{1/2} \left(\frac{140 \text{ MeV}}{T_{\text{reh}}} \right)^2$$

[Gouttenoire, Volansky, 2305.04942]

• f_{PBH} is fraction of Dark Matter (DM) in the form of PBHs

$$f_{\text{PBH}}(\beta/H, T_{\text{reh}}) = \frac{e^{-a_1(\beta/H)_*^{a_2}(1+\delta_c)^{a_3(\beta/H)_*}} T_{\text{reh}}}{2.2 \times 10^{-8} \cdot 0.14}$$

• Shaded area is excluded due to evaporation (left), microlensing (right) and DM overproduction ($f_{\text{PBH}} > 1$)

• DM can be explained for $6 \lesssim \beta/H(T_p) \lesssim 7$ and $10^5 \lesssim M_{h_2}/\text{GeV} \lesssim 10^{10}$

• In [Franciolini, Gouttenoire, Jinno, 2503.01962] f_{PBH} is revised to be much lower, however the authors do not consider the energy density in bubble walls which may play an important role

Present-day peak magnetic field spectrum

- Peak magnetic field and peak coherence length for:

- helical fields: $B_{\text{peak}}^0 \propto T_{\text{RH}}^{-7/3} \sqrt{\kappa_h}$ and $\lambda_{\text{peak}}^0 \propto T_{\text{RH}}^{-1/3}$
- non-helical fields: $B_{\text{peak}}^1 \propto T_{\text{RH}}^{-5/2} \sqrt{\kappa_h}$ and $\lambda_{\text{peak}}^1 \propto T_{\text{RH}}^{-1/2}$

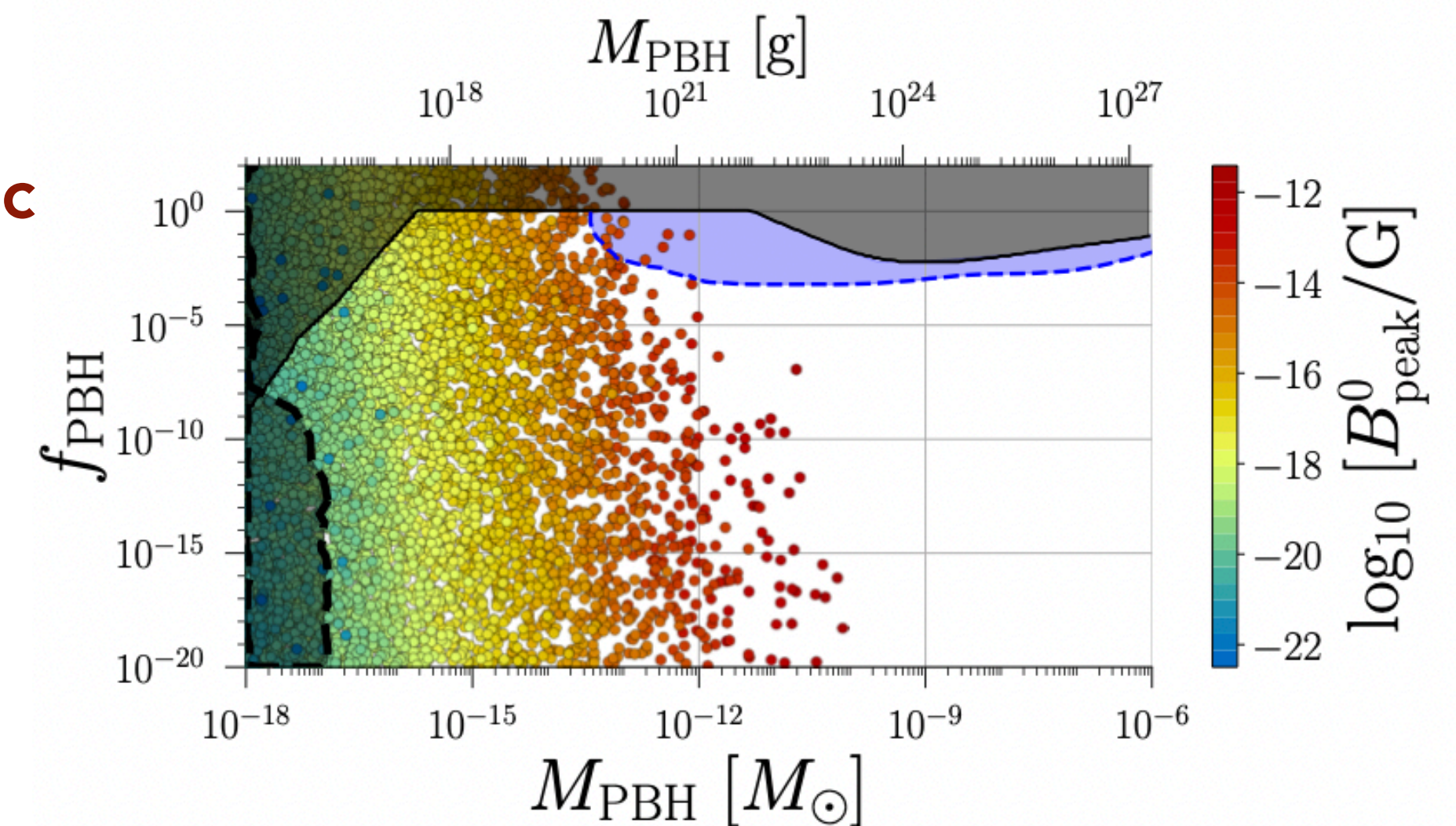
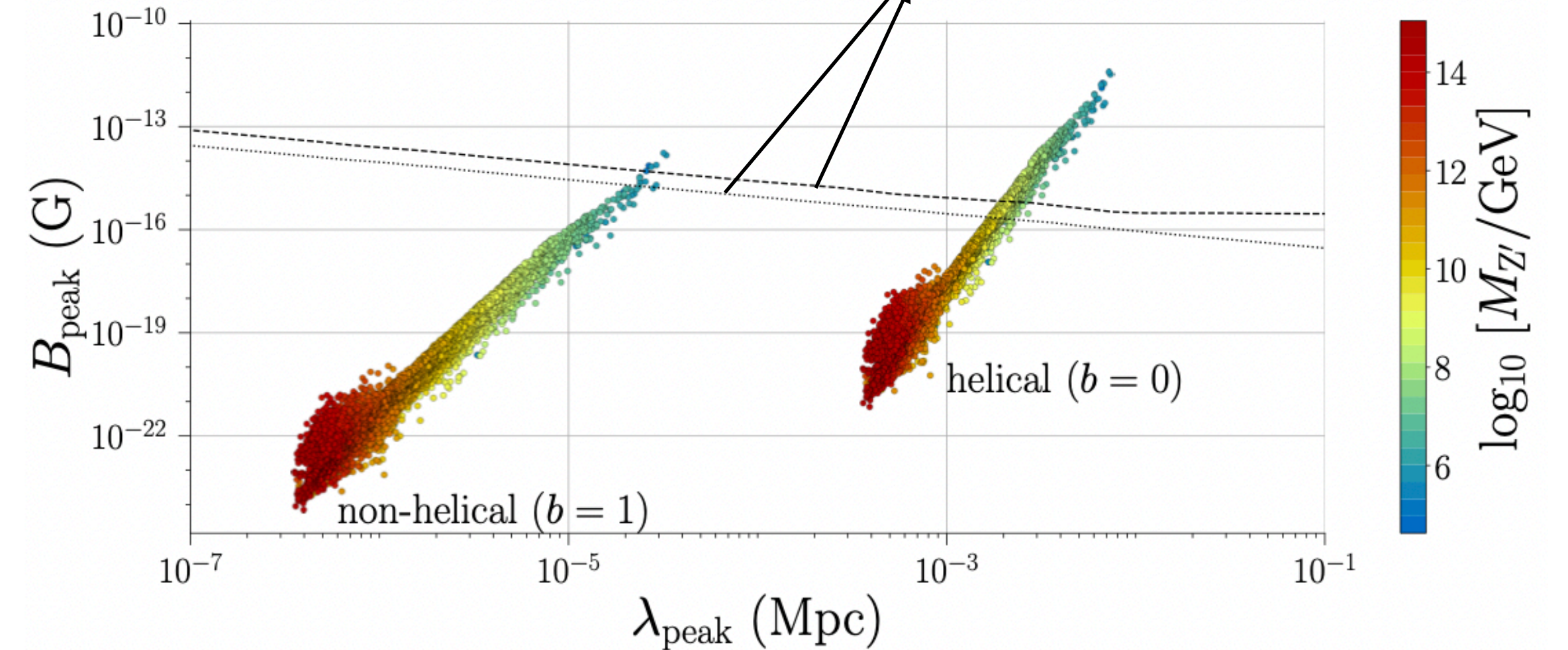
$$\kappa_h = 1 - \frac{\mathcal{V}_{\text{eff}}(v_\sigma(T_p), v)}{\mathcal{V}_{\text{eff}}(v_\sigma(T_p), 0)} \longrightarrow \text{Fraction of the bubble wall energy of the dark scalar transferred to the Higgs field via the Higgs portal coupling } \lambda_{\sigma h}$$

- Blazar bounds mark the threshold for observable intergalactic magnetic fields that may have been sourced by FOPTs in the early Universe

- Strong correlation with PBH mass

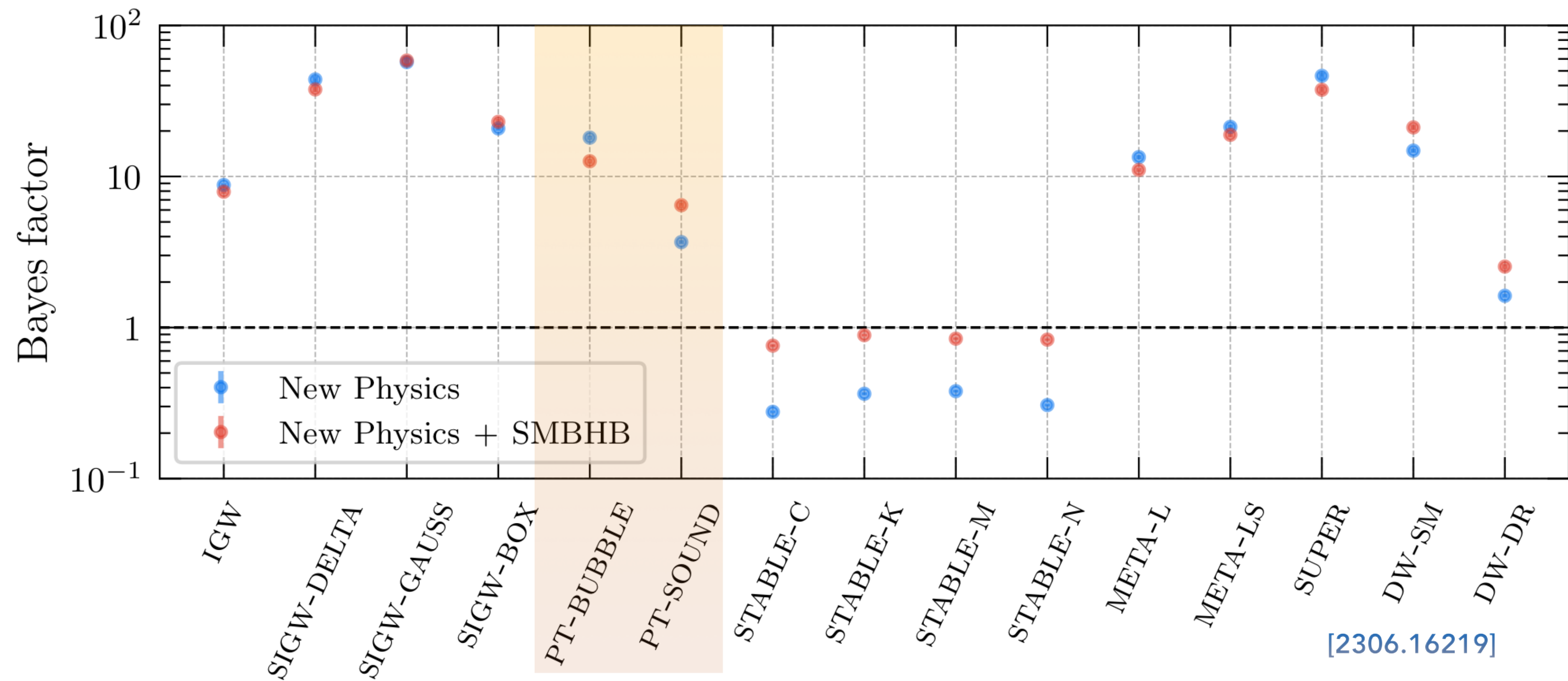
$$M_{\text{PBH}} \propto T_{\text{RH}}^{-2}$$

Blazar gamma-ray bounds [1804.08035, 2210.03321]



Mechanisms for PBH formation

- Collapse of cosmic strings, domain walls, scalar condensates,... and
- Cosmological first order phase transitions:
 - A. Bubble collisions
 - B. Matter squeezing by bubble walls
 - C. Transitions to a metastable vacuum during inflation
 - D. Collapse of delayed false vacuum patches



A SGWB detection can represent the first direct measurement of the Universe prior to the BBN era, a breakthrough comparable to the discovery of the CMB

Case study: Classical scale invariant U(1)' models that explain all neutrino oscillation data

Field	U(1)'
Q	$\frac{1}{3}x_{\mathcal{H}} + \frac{1}{6}x_{\sigma}$
u_R	$\frac{4}{3}x_{\mathcal{H}} + \frac{1}{6}x_{\sigma}$
d_R	$-\frac{2}{3}x_{\mathcal{H}} + \frac{1}{6}x_{\sigma}$
L	$-x_{\mathcal{H}} - \frac{1}{2}x_{\sigma}$
e_R	$-2x_{\mathcal{H}} - \frac{1}{2}x_{\sigma}$
$\mathcal{H}$	$x_{\mathcal{H}}$
N	$-\frac{1}{2}x_{\sigma}$
σ	x_{σ}

Classical scale symmetry (CSS)

$$x \rightarrow x' = \rho x$$

$$\Phi \rightarrow \Phi' = \rho^a \Phi$$

$$a = -1 \quad \text{for bosons}$$

$$a = -3/2 \quad \text{for fermions}$$

Neutrino masses and mixing via type-I seesaw with Majoron σ

$$\mathcal{L}_{\nu} = y_{\nu}^{ij} \overline{N}_i \mathcal{H} L_j + y_{\sigma}^{ij} \overline{N}_i^c N_j \sigma + \text{h.c.}$$

$$M_N \approx \frac{v_{\sigma}}{\sqrt{2}} y_{\sigma} \qquad m_{\nu} \approx \frac{1}{\sqrt{2}} \frac{v^2}{v_{\sigma}} y_{\nu}^T y_{\sigma}^{-1} y_{\nu} \qquad \sum_{i=1}^3 m_{\nu_i} < 0.12 \text{ eV}$$

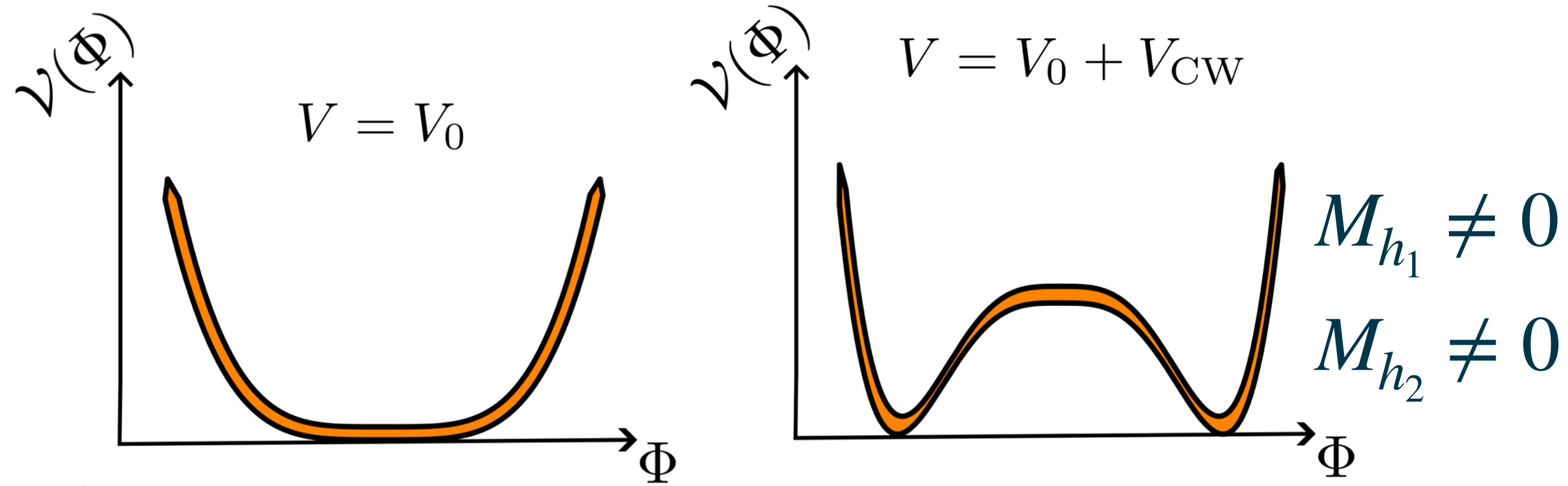
$$V_0(\mathcal{H}, \sigma) = \lambda_h (\mathcal{H}^{\dagger} \mathcal{H})^2 + \lambda_{\sigma} (\sigma^{\dagger} \sigma)^2 + \lambda_{\sigma h} (\mathcal{H}^{\dagger} \mathcal{H}) (\sigma^{\dagger} \sigma)$$

$$M_{h_1}^{(0)} \neq 0 \qquad M_{h_2}^{(0)} = 0$$



New CP-even Higgs as a **Pseudo-Goldstone of CSS** denoted as *scalon* in 1976 by Gildener and Weinberg

E. Gildener and S. Weinberg, *Symmetry Breaking and Scalar Bosons*, *Phys. Rev. D* **13** (1976) 3333.



$$0 = \lambda_h v^3 + \frac{1}{2} \lambda_{\sigma h} v v_\sigma^2 + \left. \frac{\partial V_{\text{CW}}}{\partial \phi_h} \right|_{\phi_h=v, \phi_\sigma=v_\sigma},$$

$$0 = \lambda_\sigma v_\sigma^3 + \frac{1}{2} \lambda_{\sigma h} v^2 v_\sigma + \left. \frac{\partial V_{\text{CW}}}{\partial \phi_\sigma} \right|_{\phi_h=v, \phi_\sigma=v_\sigma}$$

[S. R. Coleman, E. J. Weinberg, Physical.Rev. D7 (1973) 1888]

$$V_{\text{CW}}(\phi) \propto \frac{1}{64\pi^2} \phi^4 \log \left(\frac{\phi^2}{\mu^2} + C \right)$$

Advantages:

1. Dynamical symmetry breaking μ is the renormalization scale and C is a constant
2. Only 1 free parameter in the scalar sector M_{h_2}
3. Only 1+2 free parameters in the gauge sector g_L and the charges x_σ, x_H
4. Only 3 free parameter in neutrino sector $[y_\sigma]_{ii}$ taken as diagonal
5. Rich SGWB predictions due to strongly supercooled FOPTs $\implies h^2 \Omega_{\text{GW}}$ is large

Just a few technicalities

M_{h_2} (GeV)	g_L	$x_{\mathcal{H}}$	x_{σ}	$(\mathbf{y}_{\sigma})_{ii}$	$\lambda_{\sigma}, \lambda_{\sigma h}$	λ_h, v_{σ}	$M_{Z'}$
$[150, 10^{18}]$	$[0.20, 1.0]$	$[-2, 2]$	$[0, 5]$	$[10^{-10}, 1]$	Derived from inputs		



$$V(\phi_{\sigma}, T) = V_0(\phi_{\sigma}) + V_{\text{CW}}(\phi_{\sigma}) + V_T(\phi_{\sigma}, T) + V_{\text{Daisy}}(\phi_{\sigma}, T)$$

Thermal corrections

Rescale couplings and fields

$$\lambda \rightarrow \lambda(t)$$

$$\phi \rightarrow \frac{\phi^2}{2} \exp \left\{ \int_0^t dt \gamma(\lambda(t)) \right\}$$

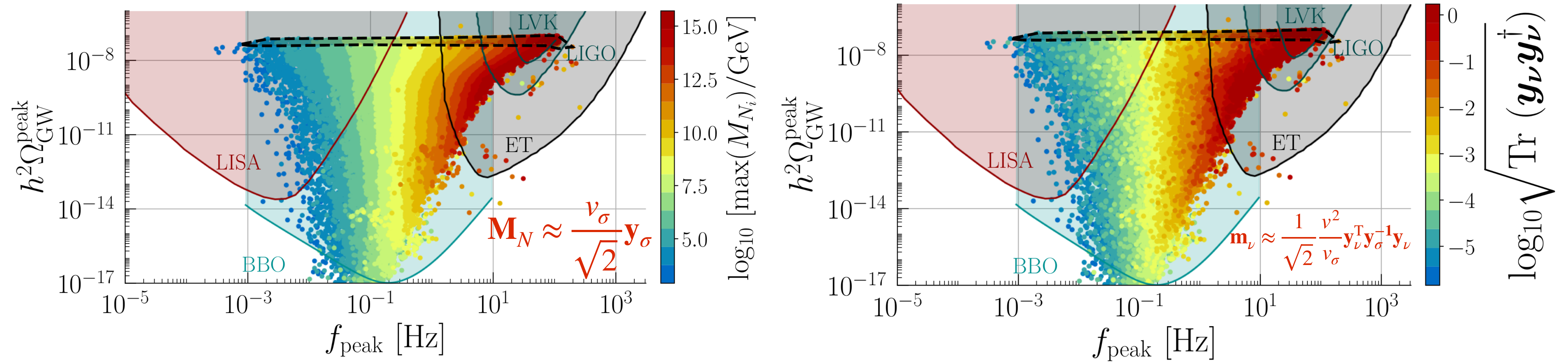
$$t = \log(\mu/M_Z)$$

$$V_T(\phi_{\sigma}, T) = \frac{T^4}{2\pi^2} \sum_i n_i J_i \left(\frac{M^2(\phi_{\sigma})}{T^2} \right) \quad J_{F,B}(y^2) = \int_0^{\infty} dx x^2 \log \left(1 \pm e^{-\sqrt{x^2 + y^2}} \right)$$

$$V_{\text{Daisy}}(\phi_{\sigma}, T) = -\frac{T}{2\pi} \sum_i n_i \left[(M(\phi_{\sigma}) + \Pi(T))^3 - M^3(\phi_{\sigma}) \right]$$

Use CosmoTransitions for phase tracing and bounce solution

Neutrino sector



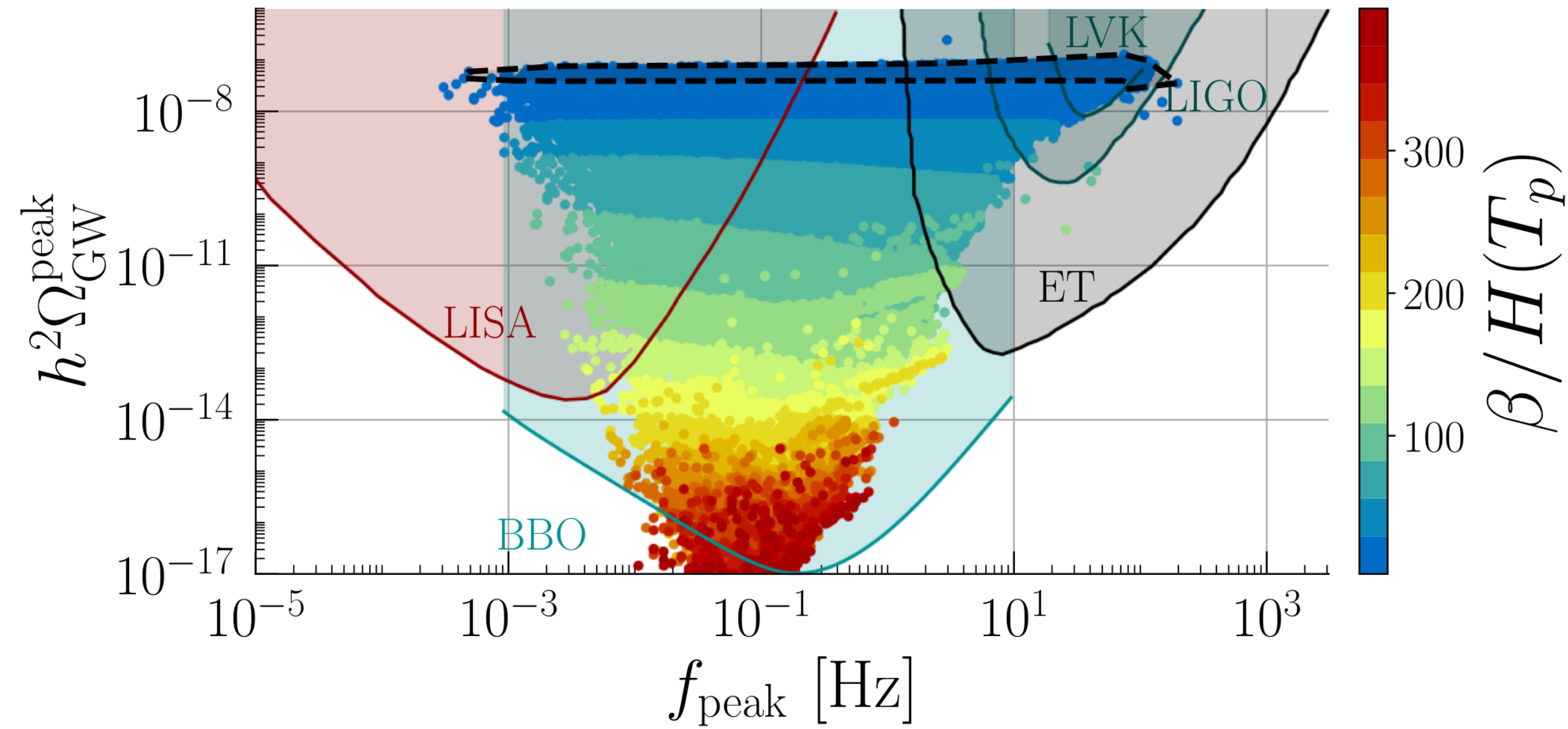
Require thermal equilibrium of N_i with SM before onset of the FOPT: $\frac{(\mathbf{y}_\nu \mathbf{y}_\nu^\dagger)_{ii} v^2}{5T_c m_{eq}} > 1$ with $m_{eq} \approx 1.1 \text{ meV} \sqrt{g_*/g_*^{\text{SM}}}$
 [Di Bari, Marfatia, Zhou, 2106.00025]

1. At LISA frequencies seesaw scale in $10^4 \lesssim M_N/\text{GeV} \lesssim 10^8$ with $10^{-6} \lesssim y_\nu \lesssim 10^{-3}$

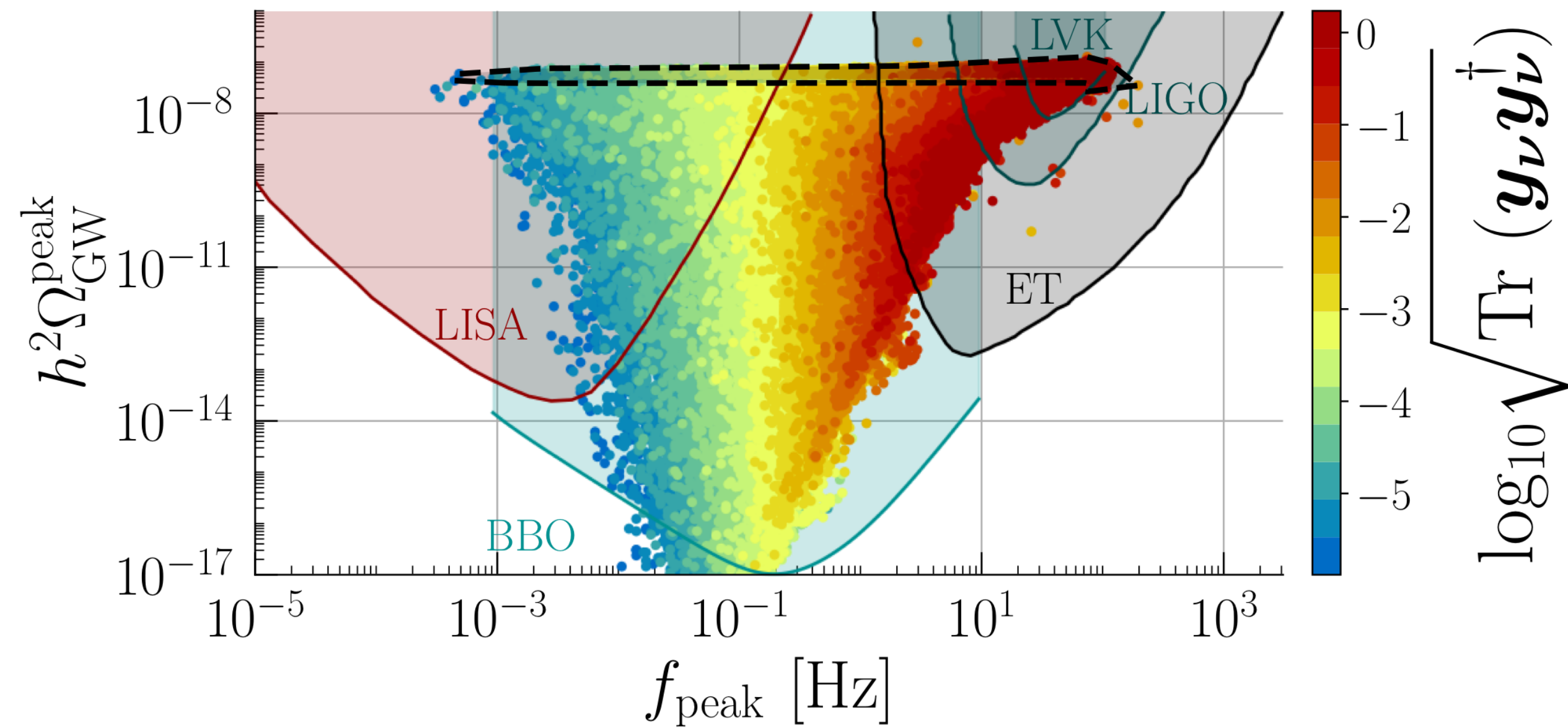
2. At LIGO and ET frequencies seesaw scale in $10^9 \lesssim M_N/\text{GeV} \lesssim 10^{15}$ with $10^{-2} \lesssim y_\nu \lesssim 1$

LVK can already constrain $M_N \sim 10^{15} \text{ GeV}$ for $y_\sigma \sim 0.1$ and $y_\nu \sim 1$ in classical conformal $U(1)_{B-L}$ models with type-I seesaw

SGWB predictions: The $U(1)_{B-L}$ case $x_\sigma = 2$ and $x_H = 0$



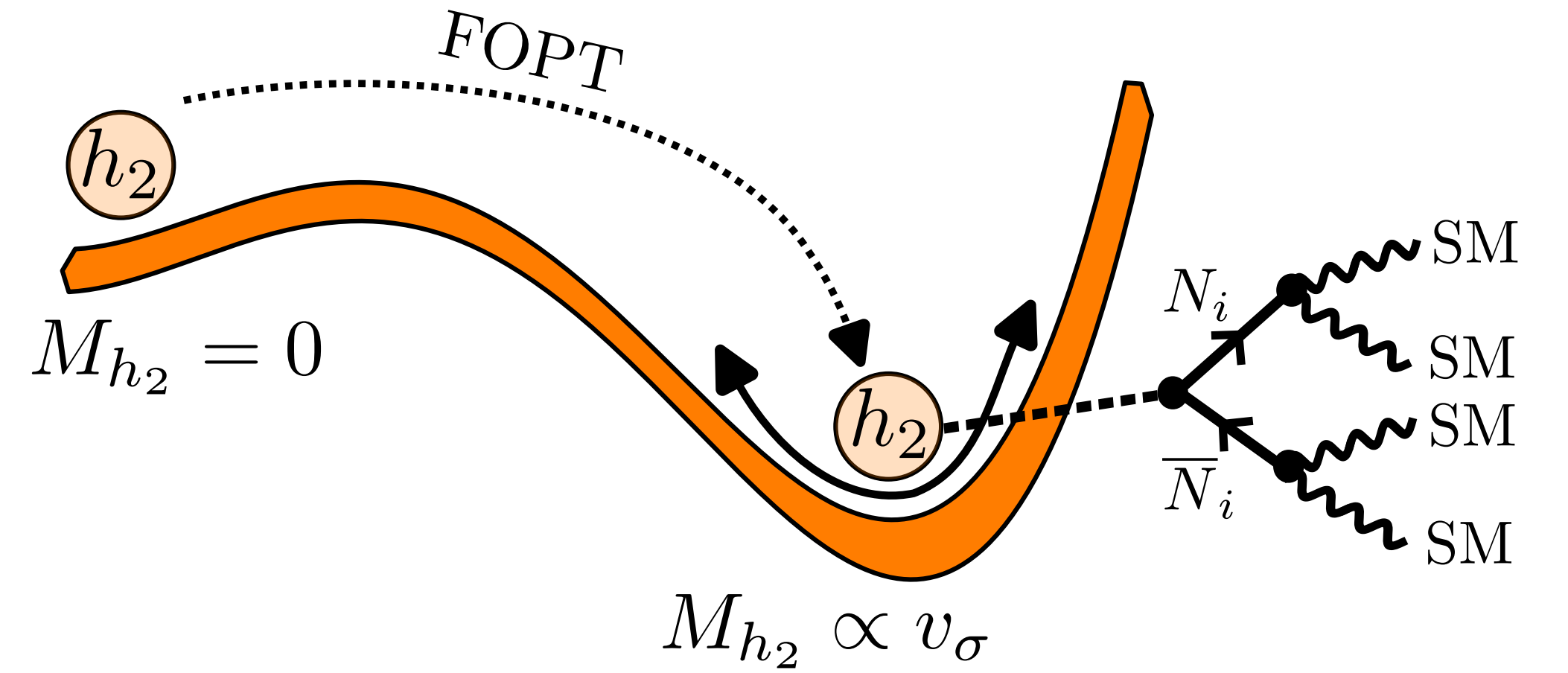
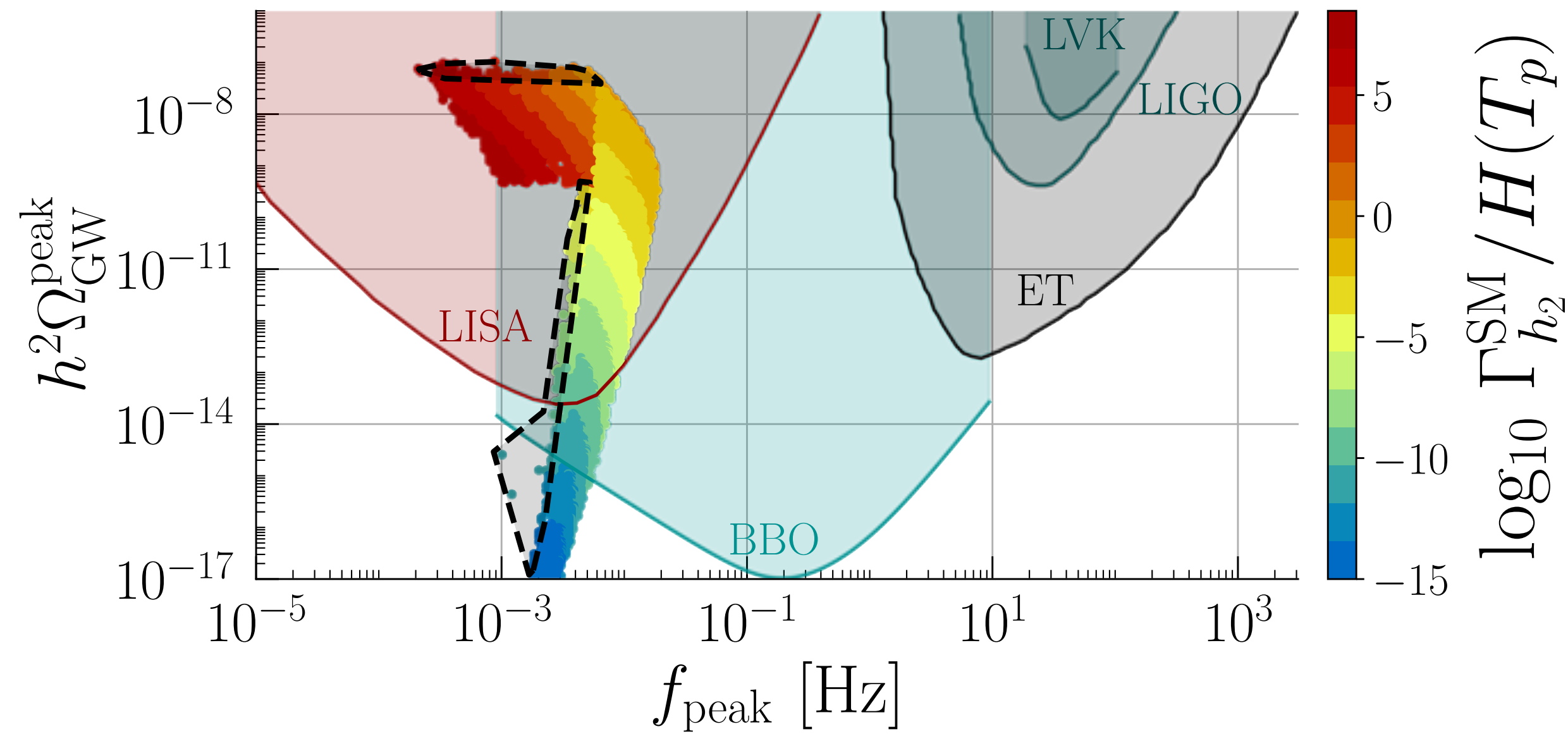
Long lasting FOPTs with $\beta/H(T_p) \lesssim \mathcal{O}(10)$
relevant for PBH formation



Active SM neutrinos Yukawa couplings
correlated with SGWB frequency

$$\mathbf{m}_\nu \approx \frac{1}{\sqrt{2}} \frac{v^2}{v_\sigma} \mathbf{y}_\nu^T \mathbf{y}_\sigma^{-1} \mathbf{y}_\nu$$

What if we decouple heavy neutrino sector $\text{Tr}(y_\sigma) \rightarrow 0$?



$$\Gamma_{h_2} = \Gamma_{h_2 \rightarrow p_{\text{SM}} p_{\text{SM}}^*} + \Gamma_{h_2 \rightarrow \bar{N}_i N_i} \Gamma_{N_i \rightarrow p_{\text{SM}} p_{\text{SM}}^*}$$

Checked using MadGraph

No SGWB predictions at high frequencies — LIGO, ET

Heavy Higgs decay to SM highly suppressed by portal

coupling $\lambda_{\sigma h} \sim \frac{v^2}{v_\sigma^2}$ for $M_{h_2} \gtrsim 100$ TeV

SGWB at LIGO/ET can be seen as a strong hint for the presence of the neutrino sector in this class of models

Early matter domination if

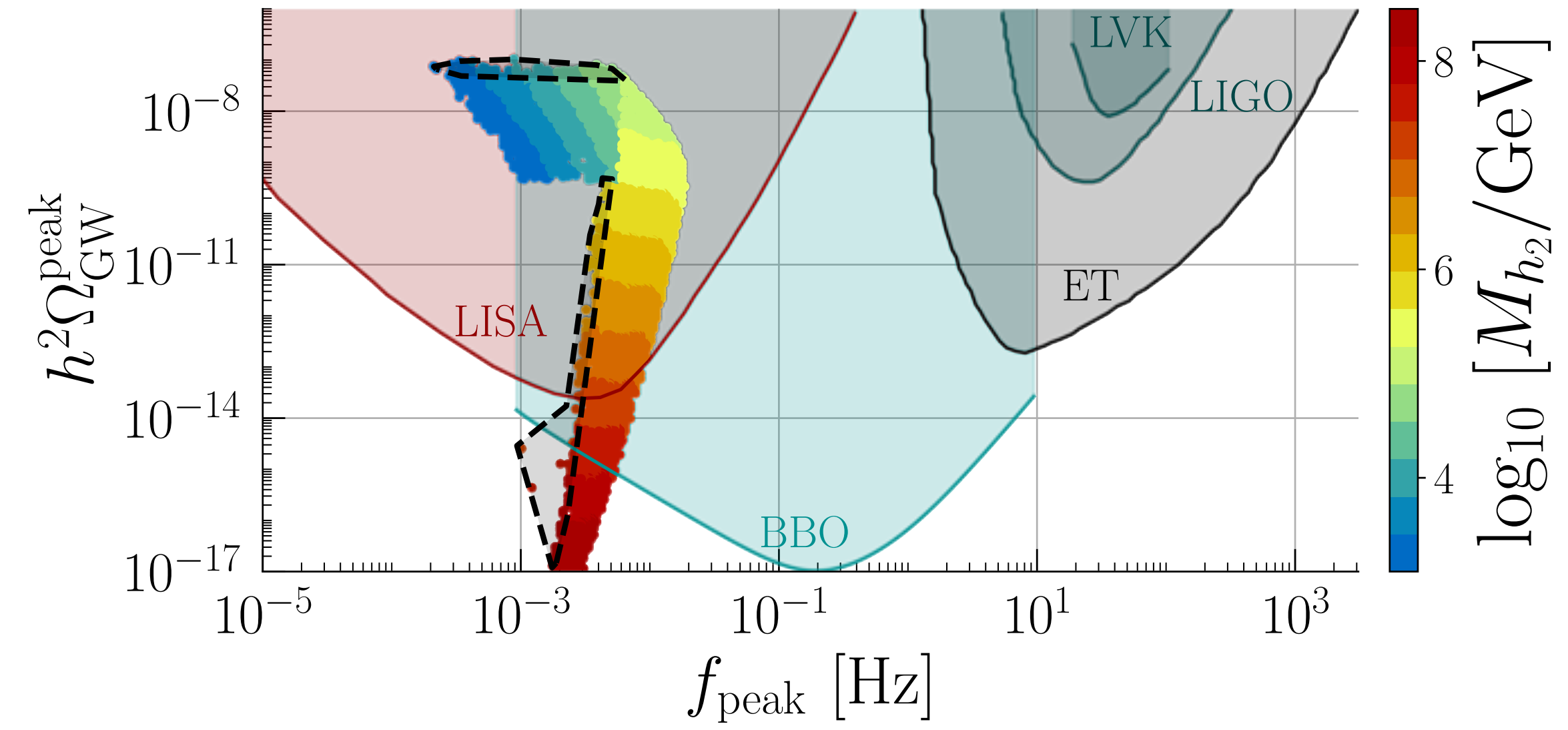
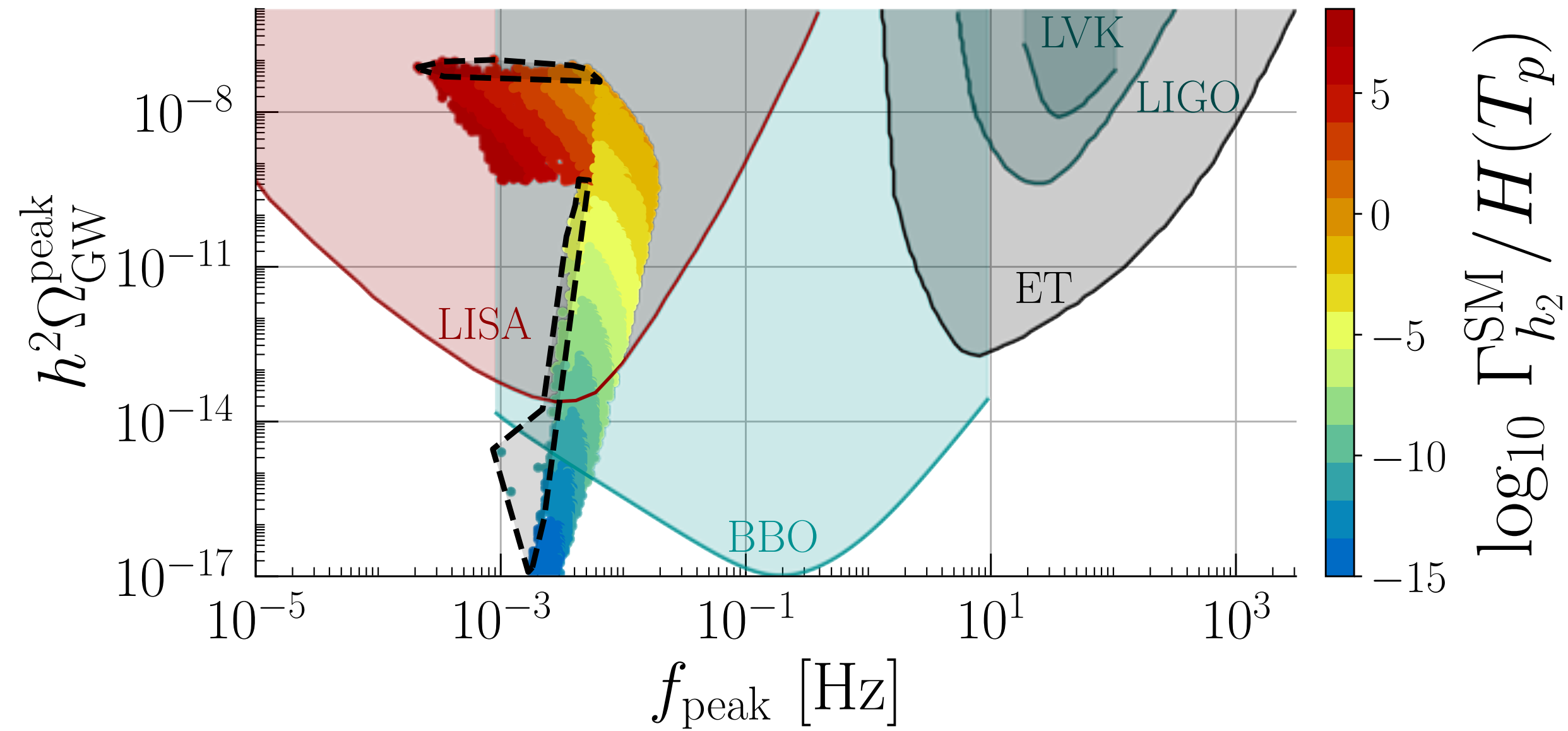
$\Gamma_{h_2} < H(T_p) \implies$ SUPPRESSION of SGWB

$$h^2 \Omega_{\text{SW}}^{\text{peak}} \propto \left(\frac{\kappa_{\text{sw}} \alpha}{1 + \alpha} \right)^2 \left(\frac{\beta}{H(T_p)} \right)^{-1} \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{2/3}$$

$$f_{\text{peak}} \propto \left(\frac{\beta}{H(T_p)} \right) \left(\frac{T_{\text{RH}}}{\text{GeV}} \right) \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{-1/3}$$

$$T_{\text{RH}} \approx T_p (1 + \alpha)^{1/4} \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{1/2} \quad T_c > T_{\text{RH}} \gg T_n > T_p$$

What if we decouple heavy neutrino sector $\text{Tr}(y_\sigma) \rightarrow 0$?



$\Gamma_{h_2}^{\text{SM}}/H(T_p) \approx [3.16 \times 10^{-20} \text{ GeV}^{3.85}] M_{h_2}^{-3.85} \Rightarrow$ **matter domination for masses $M_{h_2} \gtrsim 2.1 \times 10^5 \text{ GeV}$**

No SGWB predictions at high frequencies — LIGO, ET

SGWB at LIGO/ET can be seen as a strong hint for the presence of the neutrino sector in this class of models

Early matter domination if $\Gamma_{h_2} < H(T_p) \Rightarrow$ SUPPRESSION of SGWB

$$h^2 \Omega_{\text{SW}}^{\text{peak}} \propto \left(\frac{\kappa_{\text{sw}} \alpha}{1 + \alpha} \right)^2 \left(\frac{\beta}{H(T_p)} \right)^{-1} \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{2/3}$$

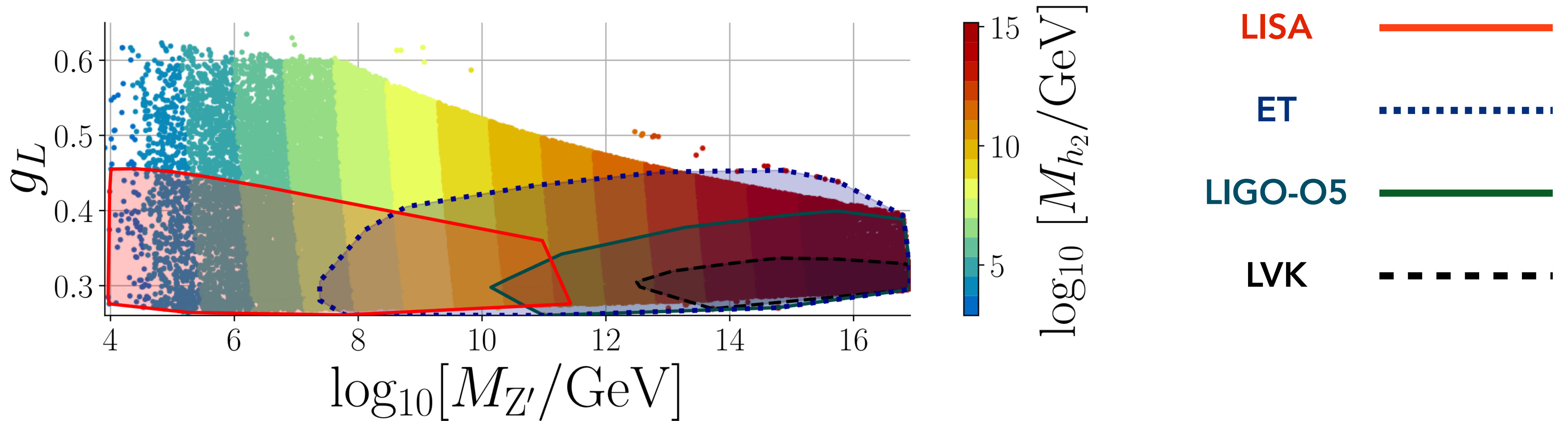
$$f_{\text{peak}} \propto \left(\frac{\beta}{H(T_p)} \right) \left(\frac{T_{\text{RH}}}{\text{GeV}} \right) \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{-1/3}$$

$$T_{\text{RH}} \approx T_p (1 + \alpha)^{1/4} \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{1/2} \quad T_c > T_{\text{RH}} \gg T_n > T_p$$

Testing supercooling with SGWB in the $U(1)_{B-L}$ model for $\text{Tr}(y_\sigma) < g_L$

$$\text{SNR} = \sqrt{\mathcal{T} \int df \frac{h^2 \Omega_{\text{GW}}(f)}{h^2 \Omega_{\text{Sens}}(f)}}$$

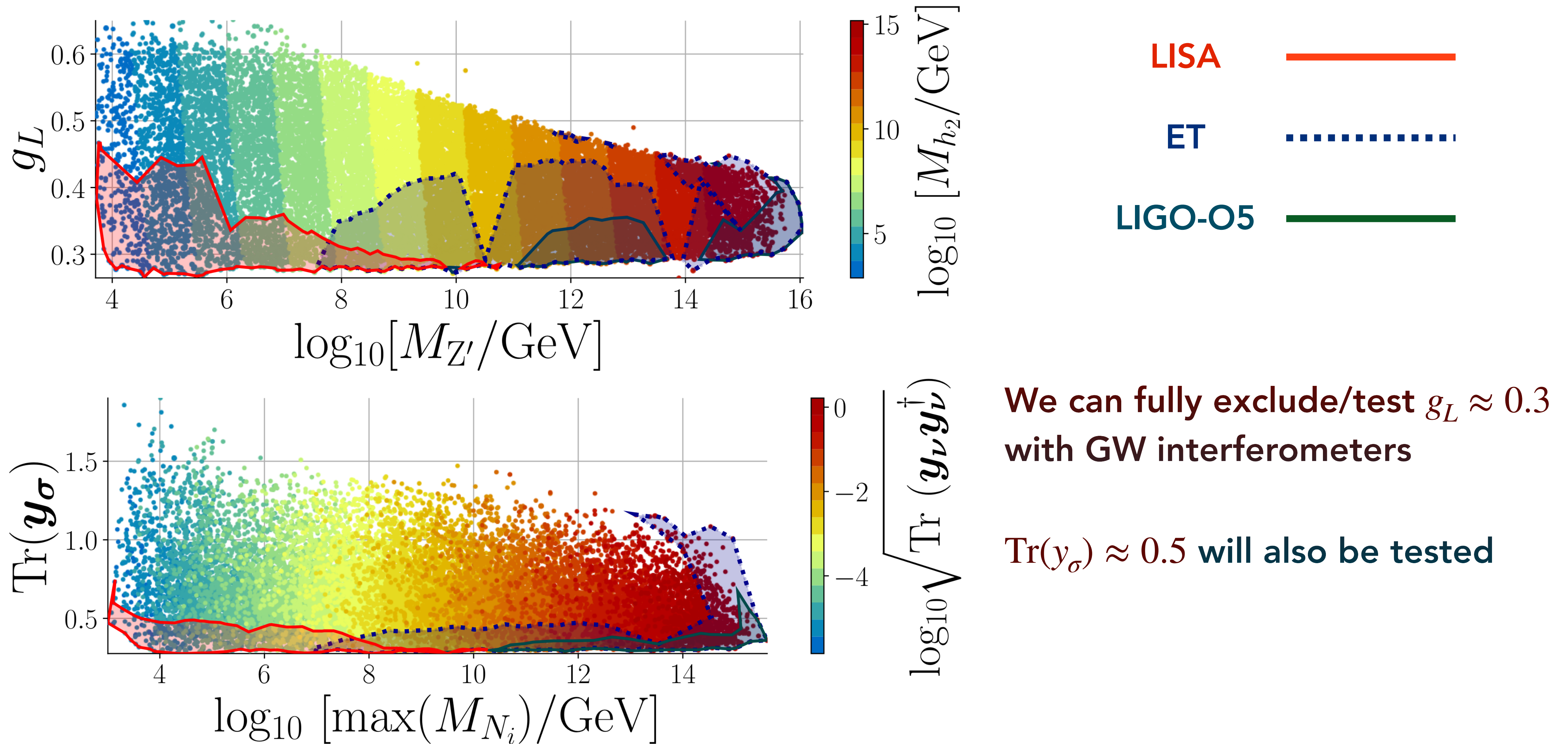
Used $\mathcal{T} = 4$ years exposure and required $\text{SNR} > 10$ for observable SGWB

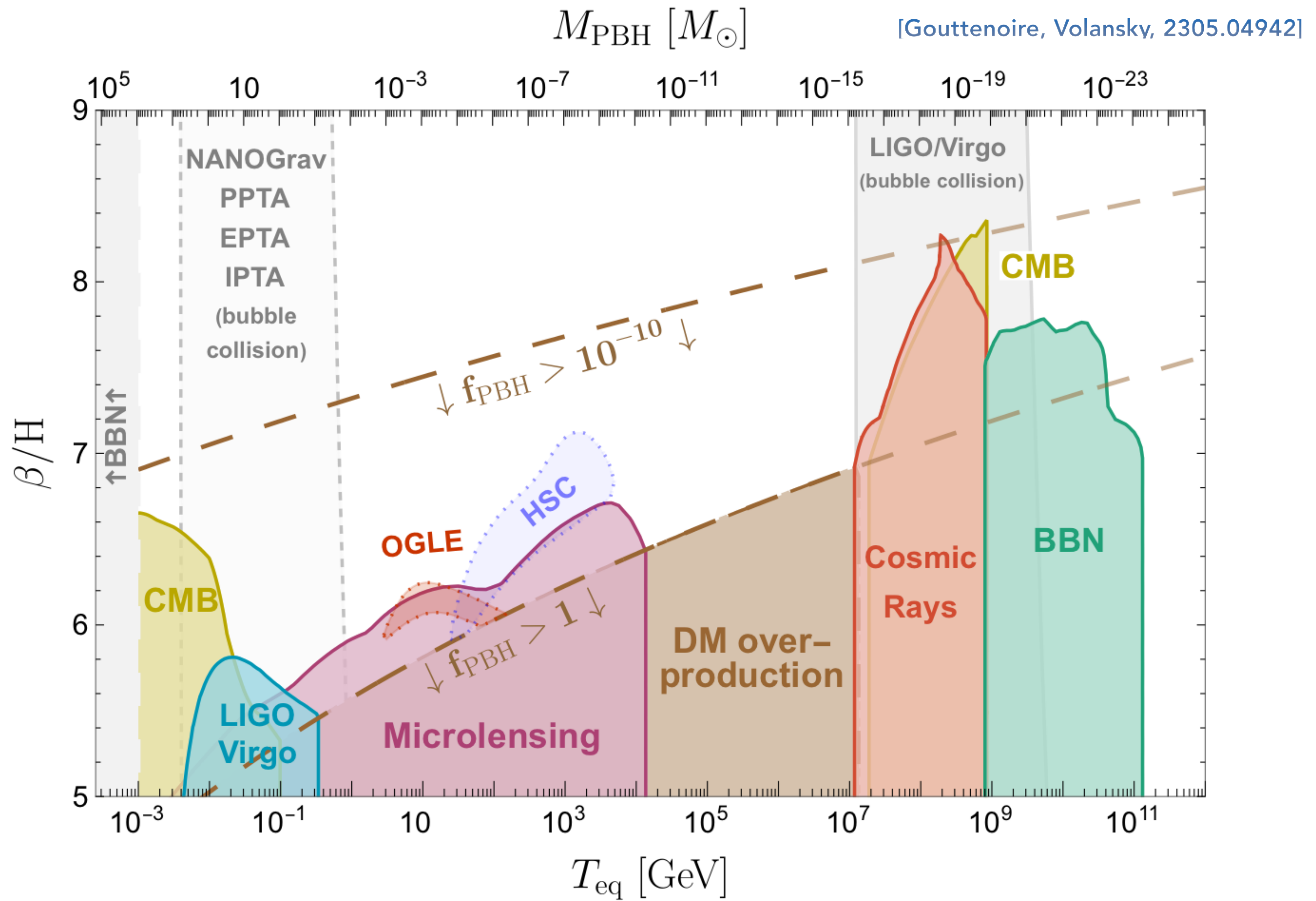


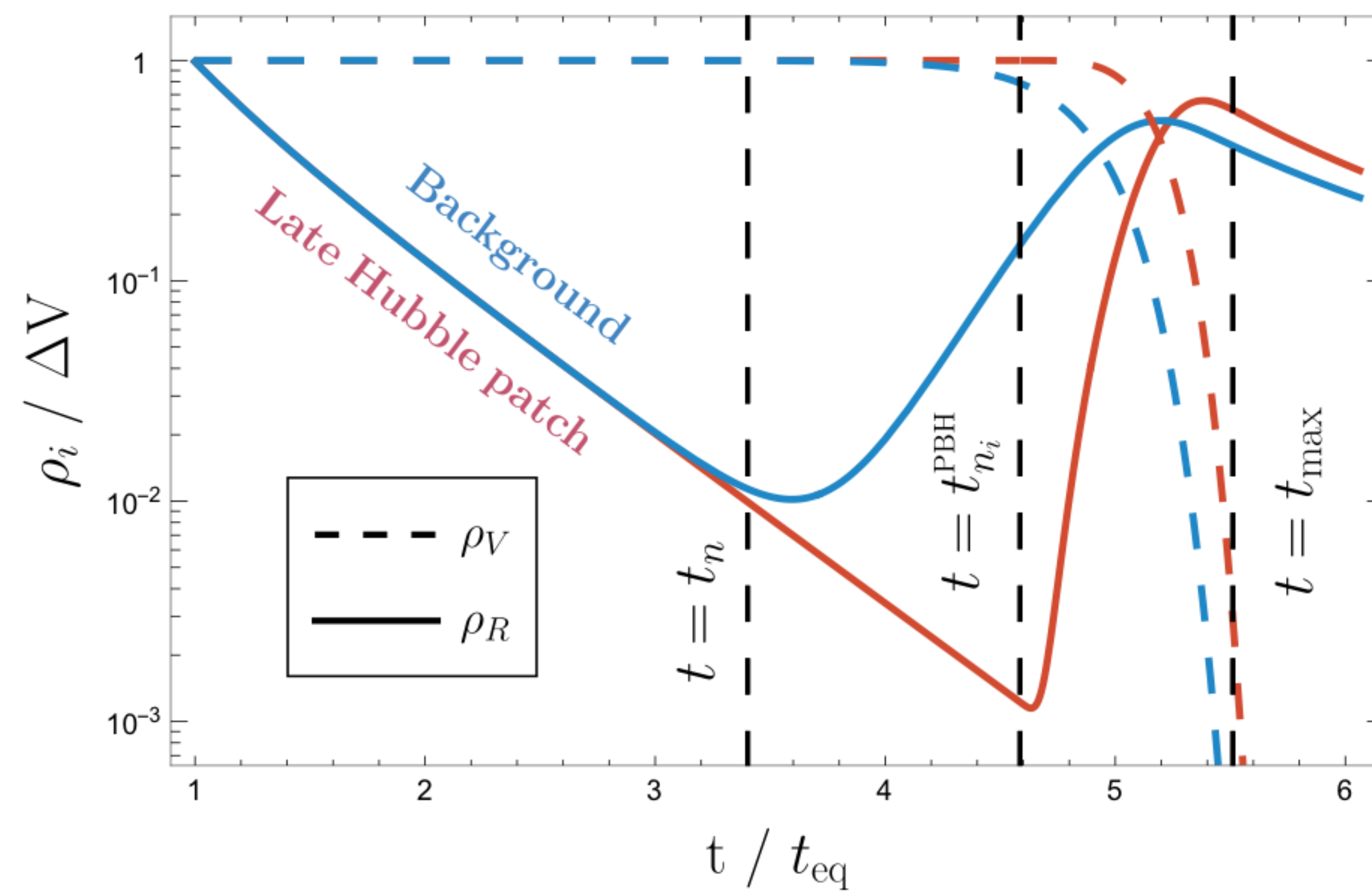
LVK excluded a region with $10^{11} \text{ GeV} \lesssim 10 M_{h_2} \sim M_{Z'} < 10^{16} \text{ GeV}$ with $g_L \sim 0.3$

LISA+ET+LIGO can cover the entire mass range $M_{h_2} > 1\text{TeV}, M_{Z'} > 10 \text{ TeV}$ with $0.25 \lesssim g_L \lesssim 0.45$

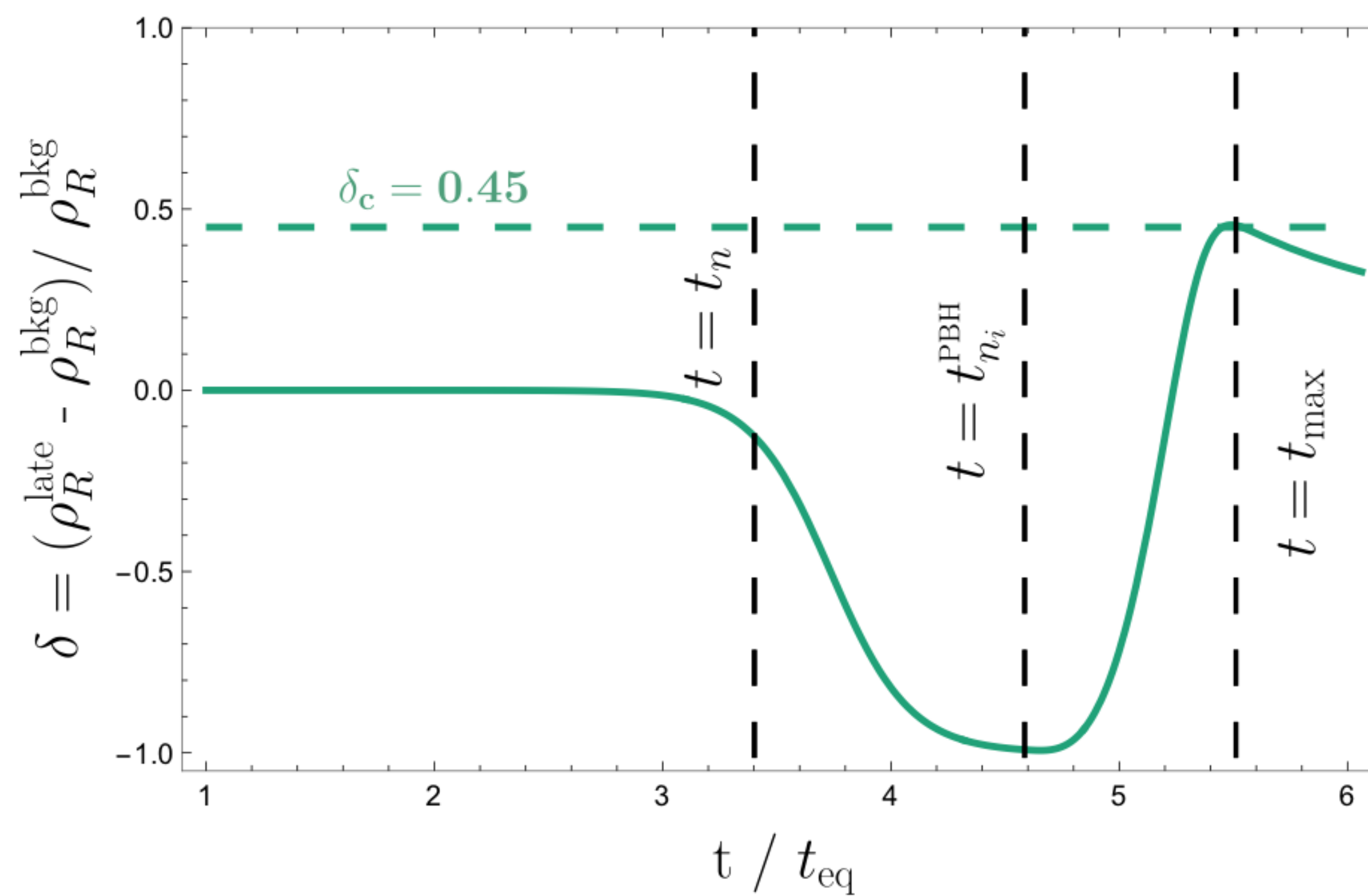
Testing supercooling with SGWB in the $U(1)_{B-L}$ model for $\text{Tr}(y_\sigma) > g_L$







[Gouttenoire, Volansky, 2305.04942]



From thermodynamic to SGWB geometric parameters

$$h^2 \Omega_{\text{SW}}^{\text{peak}} \propto \left(\frac{\kappa_{\text{sw}} \alpha}{1 + \alpha} \right)^2 \left(\frac{\beta}{H(T_p)} \right)^{-1} \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{2/3}$$

$$h^2 \Omega_{\text{BC}}^{\text{peak}} \propto \left(\frac{\kappa_{\text{bc}} \alpha}{1 + \alpha} \right)^2 \left(\frac{\beta}{H(T_p)} \right)^{-2} \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{2/3}$$

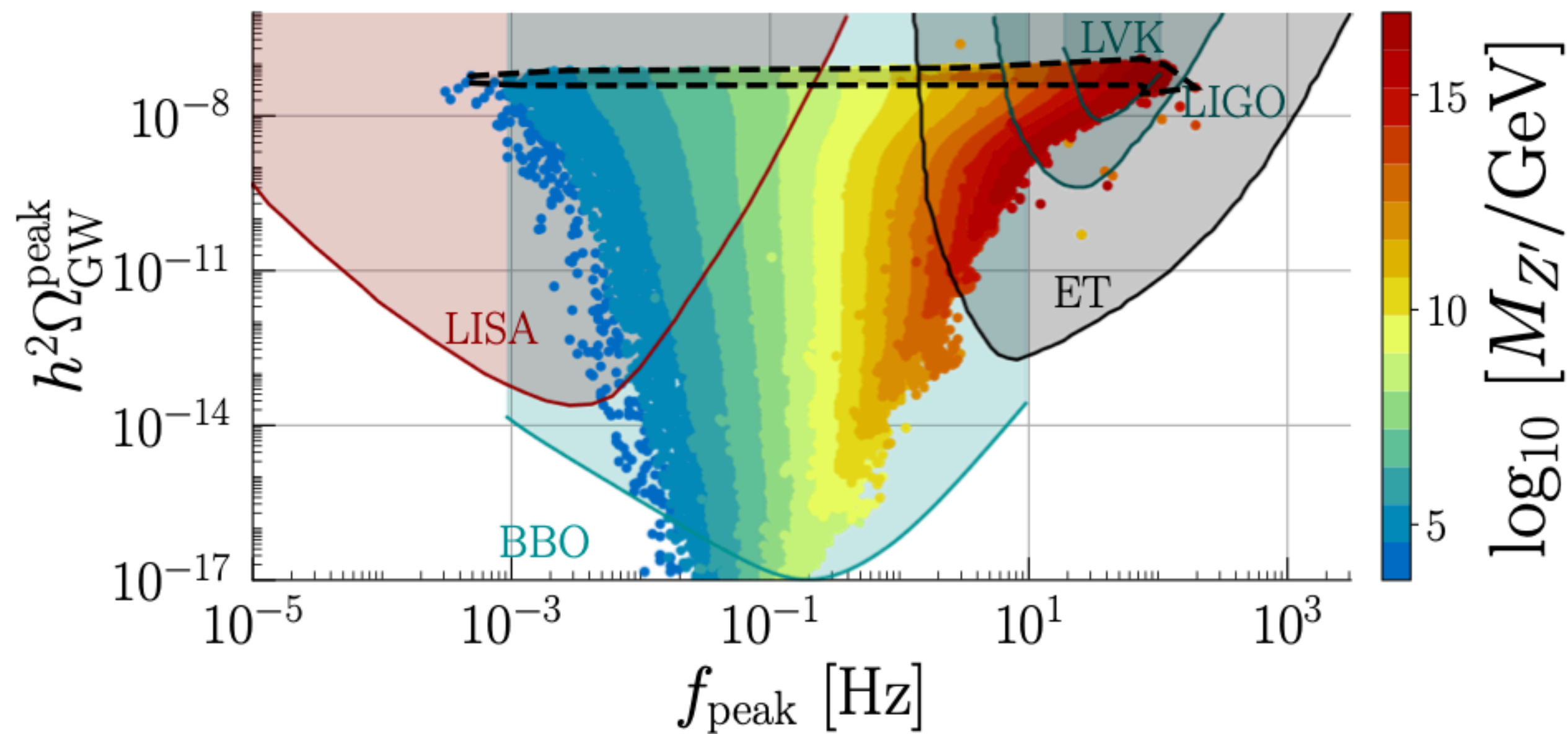
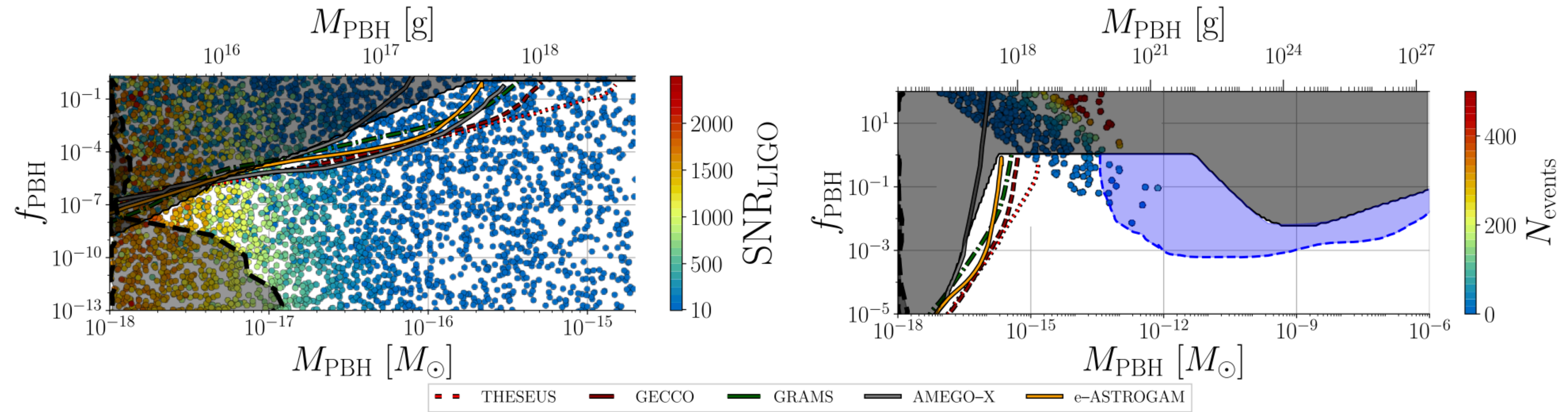
$$f_{\text{peak}} \propto \left(\frac{\beta}{H(T_p)} \right) \left(\frac{T_{\text{RH}}}{\text{GeV}} \right) \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{-1/3}$$

$$T_{\text{RH}} \approx T_p (1 + \alpha)^{1/4} \left(\frac{\Gamma_{h_2}}{H(T_p)} \right)^{1/2}$$

$$T_c > T_{\text{RH}} \gg T_n > T_p$$

Early matter domination if $\Gamma_{h_2} < H(T_p) \implies$ SUPPRESSION of SGWB

Take $\frac{\Gamma_{h_2}}{H(T_p)} = 1$ if radiation domination *i.e.* $\Gamma_{h_2} > H(T_p)$



Peak frequency controlled by the mass scale

Z' is always ≈ 1 order of magnitude heavier than $h_2 \rightarrow$ pseudo-Goldstone of CSS breaking

LVK can already constrain $M_{h_2} \sim 10^{15} \text{ GeV}$ and $M_{Z'} \sim 10^{16} \text{ GeV}$ for $g_L \approx 0.3$ and in classical conformal $U(1)_{\text{B-L}}$ models