GRAVITATIONAL WAVES FROM SUPERCOOLED PHASE TRANSITIONS IN CONFORMAL MAJORON MODELS

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Extended Scalar Sectors from All Angles- CERN - 22 October 2024

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CIDMA

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

However, it fails to…

- Explain neutrino masses
- Explain dark matter
- Explain CP violation and matter/anti-matter assymetry
- Explain the observed flavour structure - Flavour puzzles
- Suffers from the Higgs mass *hierarchy problem*

Check A. Trautner talk on Custodial Naturalness

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

However, it fails to…

Extended scalar sectors and new gauge symmetries can assist in solving these problems

First Order Phase Transitions - FOPTs

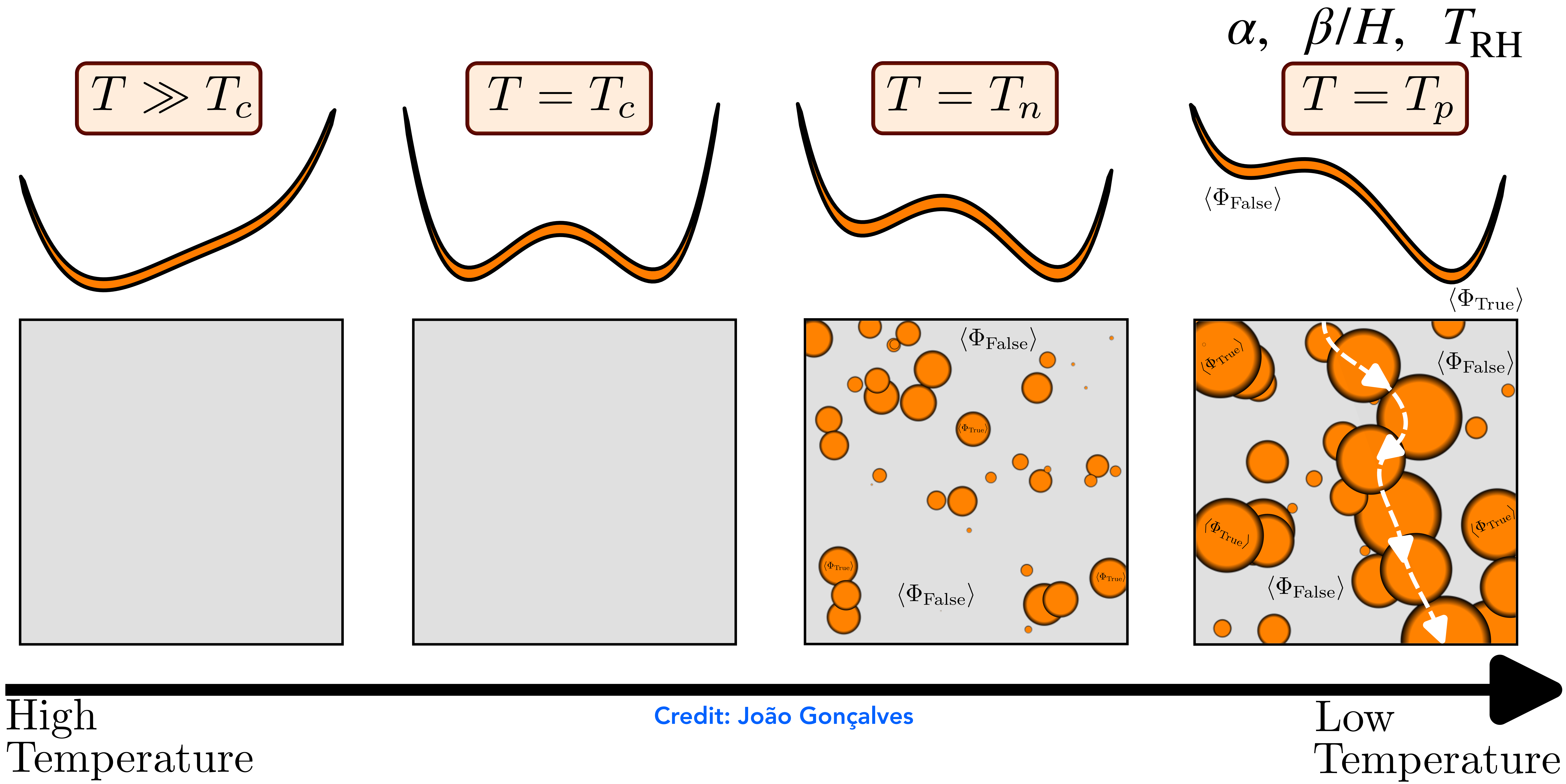
Stochastic Gravitational-Wave Background - SGWB

- Explain neutrino masses
- Explain dark matter
- Explain CP violation and matter/anti-matter assymetry
- Explain the observed flavour structure - Flavour puzzles
- Suffers from the Higgs mass *hierarchy problem*

Check A. Trautner talk on Custodial Naturalness

First order phase transition (FOPT)

(Illustration)



Credit: João Gonçalves

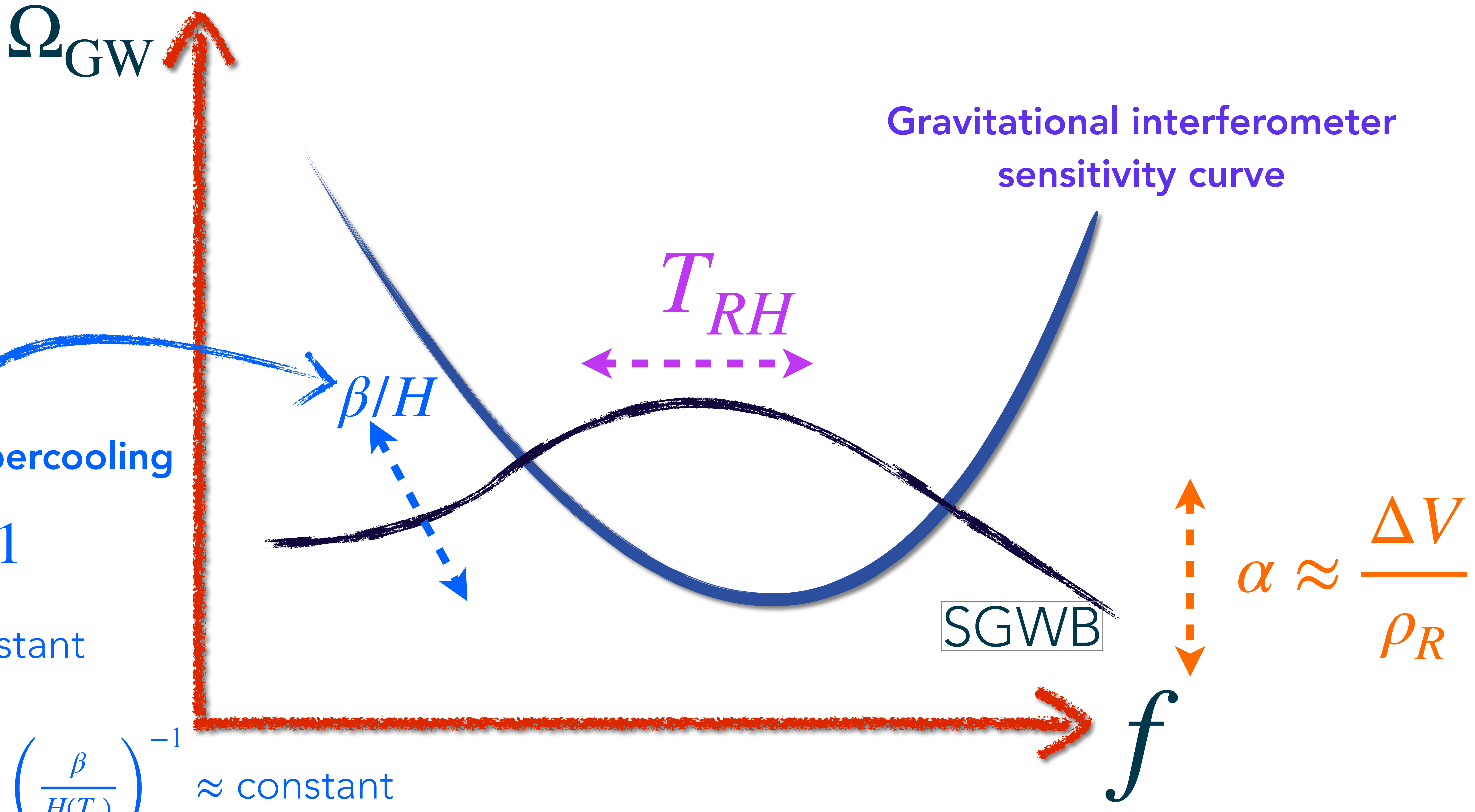
Strength
α

Inverse duration
β/H

Percolation temperature
T_p

Reheating temperature
$T_{\rm RH}$

Effect of the thermodynamic parameters on the SGWB



With strong supercooling

$$\alpha \gg 1$$

$$\frac{\beta}{H(T_p)} \approx \text{constant}$$

$$\Omega_{\rm GW} \propto \left(\frac{\kappa_{sw}\alpha}{1+\alpha}\right)^2 \left(\frac{\beta}{H(T_p)}\right)^{-1} \approx \text{constant}$$

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

Field	$\mathbf{U(1)'}$
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	$-2x_{\mathcal{H}} - \frac{1}{2}x_\sigma$
$\mathcal{H}$	$x_{\mathcal{H}}$
ν_R	$-\frac{1}{2}x_\sigma$
σ	x_σ

Classical scale symmetry (CSS)

$$x \to x' = \rho x$$

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

$a = -1$ for bosons

$a = -3/2$ for fermions

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

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

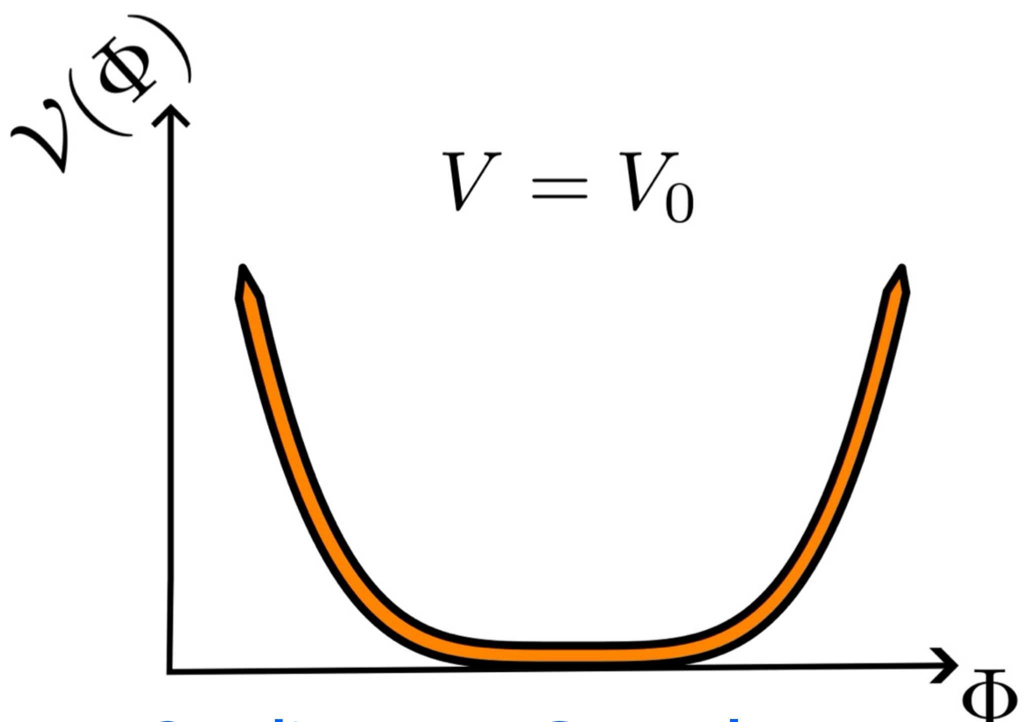
$$\boldsymbol{M_N} \approx \frac{v_\sigma}{\sqrt{2}}\boldsymbol{y_\sigma} \qquad \boldsymbol{m_\nu} \approx \frac{1}{\sqrt{2}}\frac{v^2}{v_\sigma}\boldsymbol{y_\nu^{\mathrm{T}} y_\sigma^{-1} y_\nu}$$

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

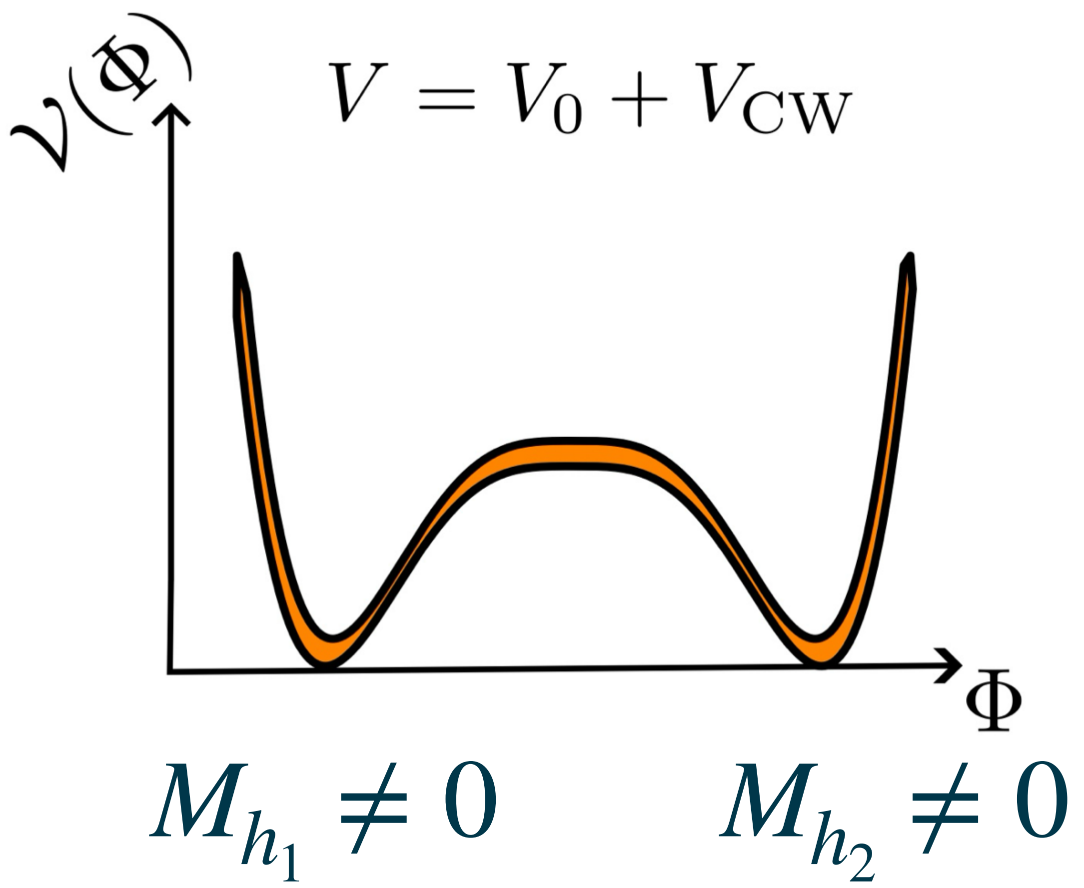
$$M_{h_1}^{(0)} \neq 0 \qquad M_{h_2}^{(0)} = 0$$

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.



Credit: João Gonçalves



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

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

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

Advantages:

1. Dynamical symmetry breaking
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 $\Longrightarrow h^2\Omega_{\rm GW}$ is large

Just a few technicalities

M_{h_2} (GeV)	g_L	$x_{\mathcal{H}}$	x_σ	$(\boldsymbol{y_\sigma})_{ii}$	$\lambda_\sigma, \lambda_{\sigma h}$	λ_h, v_σ	$M_{Z'}$
$[150, 10^{18}]$	$[0.20, 1.0]$	$[-2, 2]$	$[0, 5]$	$[10^{-16}, 1]$	Derived from inputs		

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

RG improved potential

$$\lambda \to \lambda(t)$$

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

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

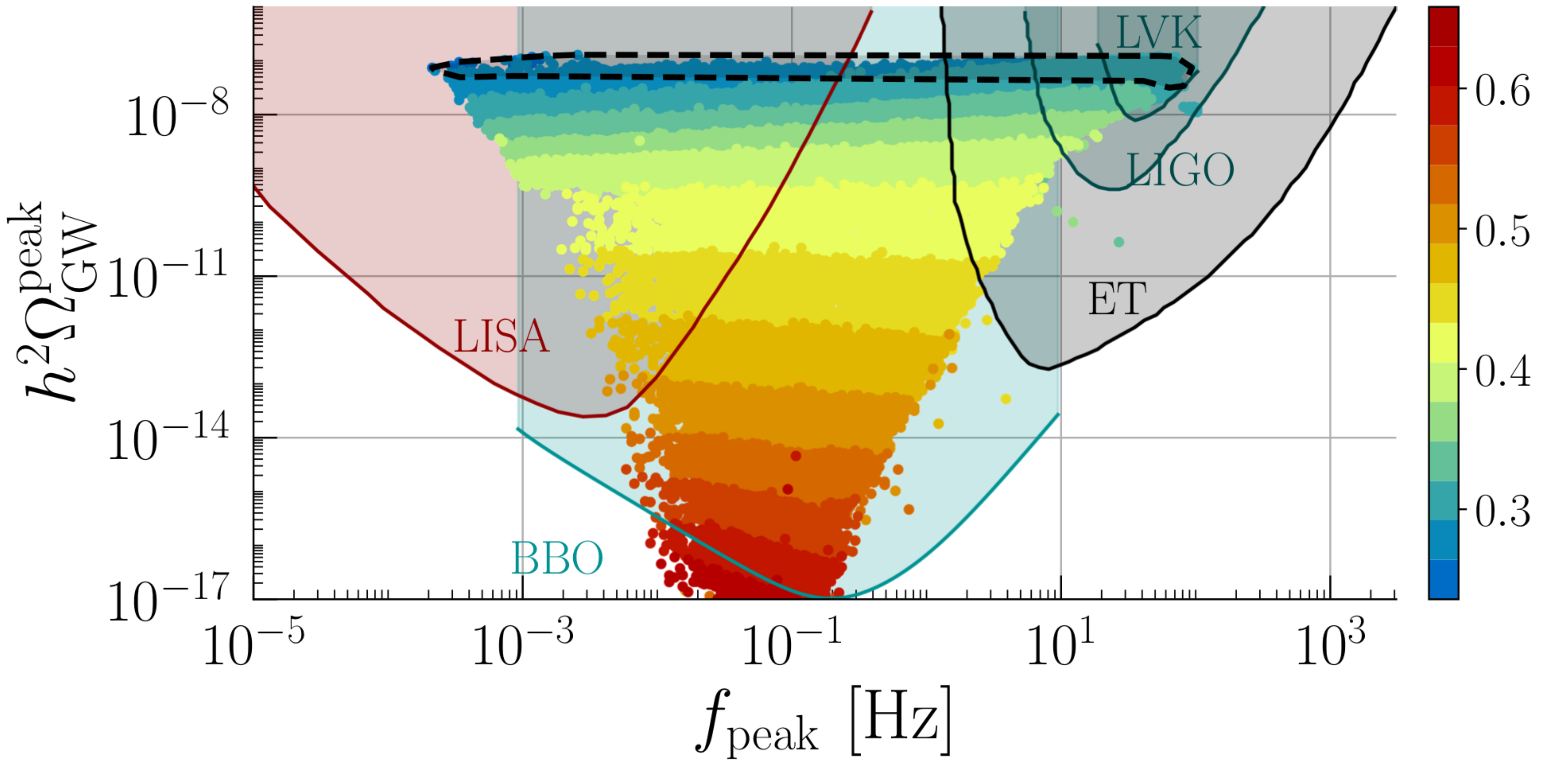
Thermal corrections

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

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

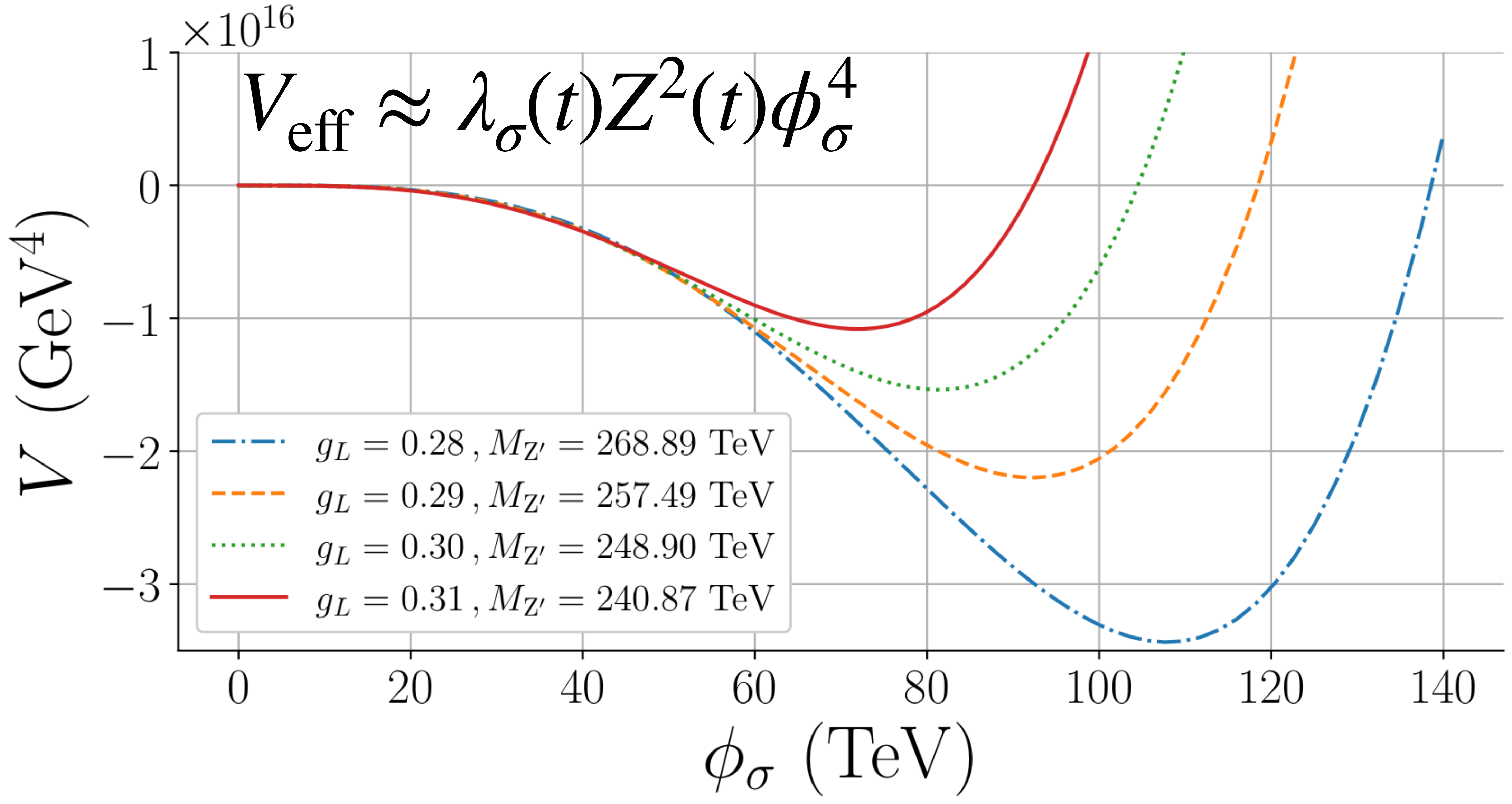
Use `CosmoTransitions` for phase tracing and bounce solution

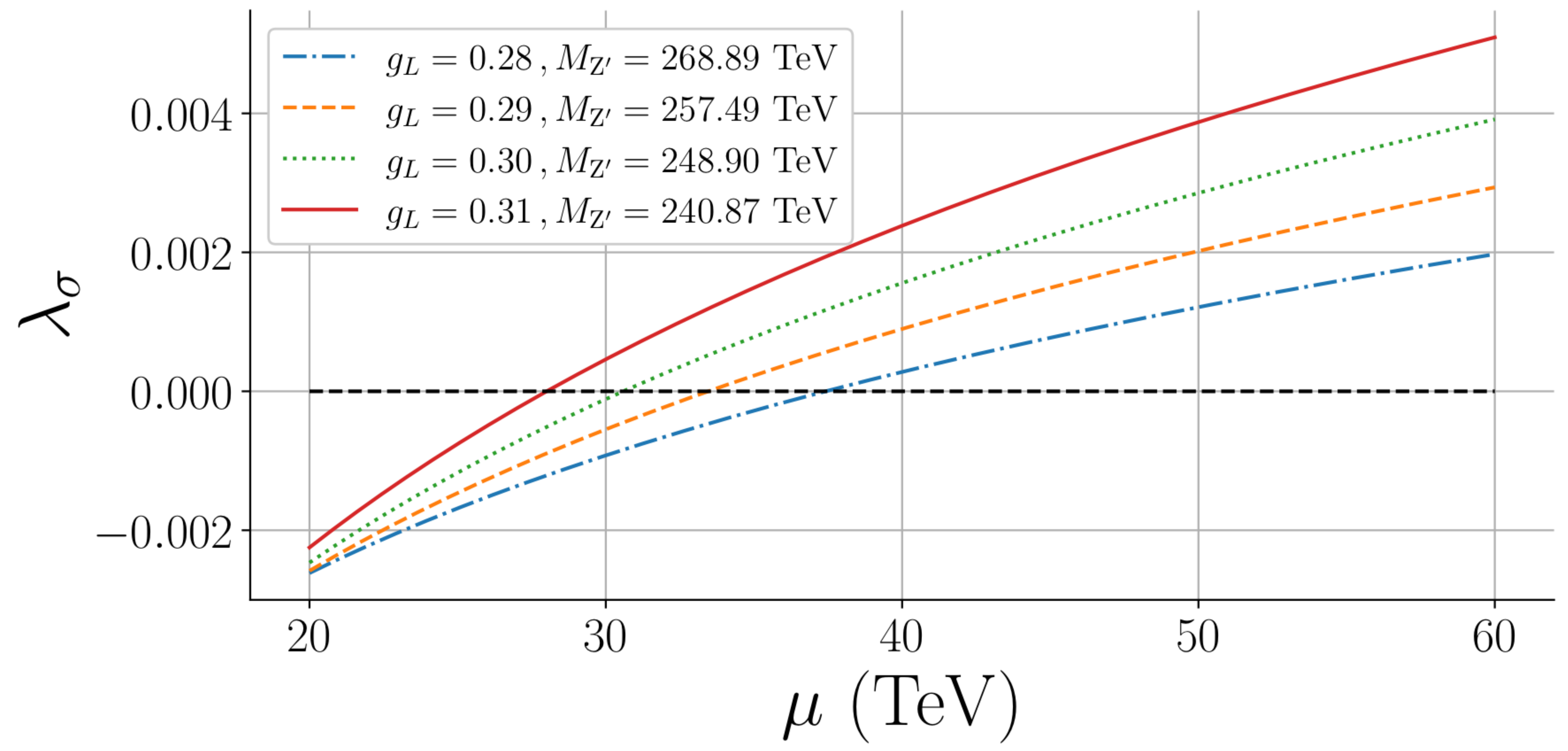
SGWB predictions: The $\mathrm{U(1)_{B-L}}$ case $x_\sigma = 2$ and $x_H = 0$



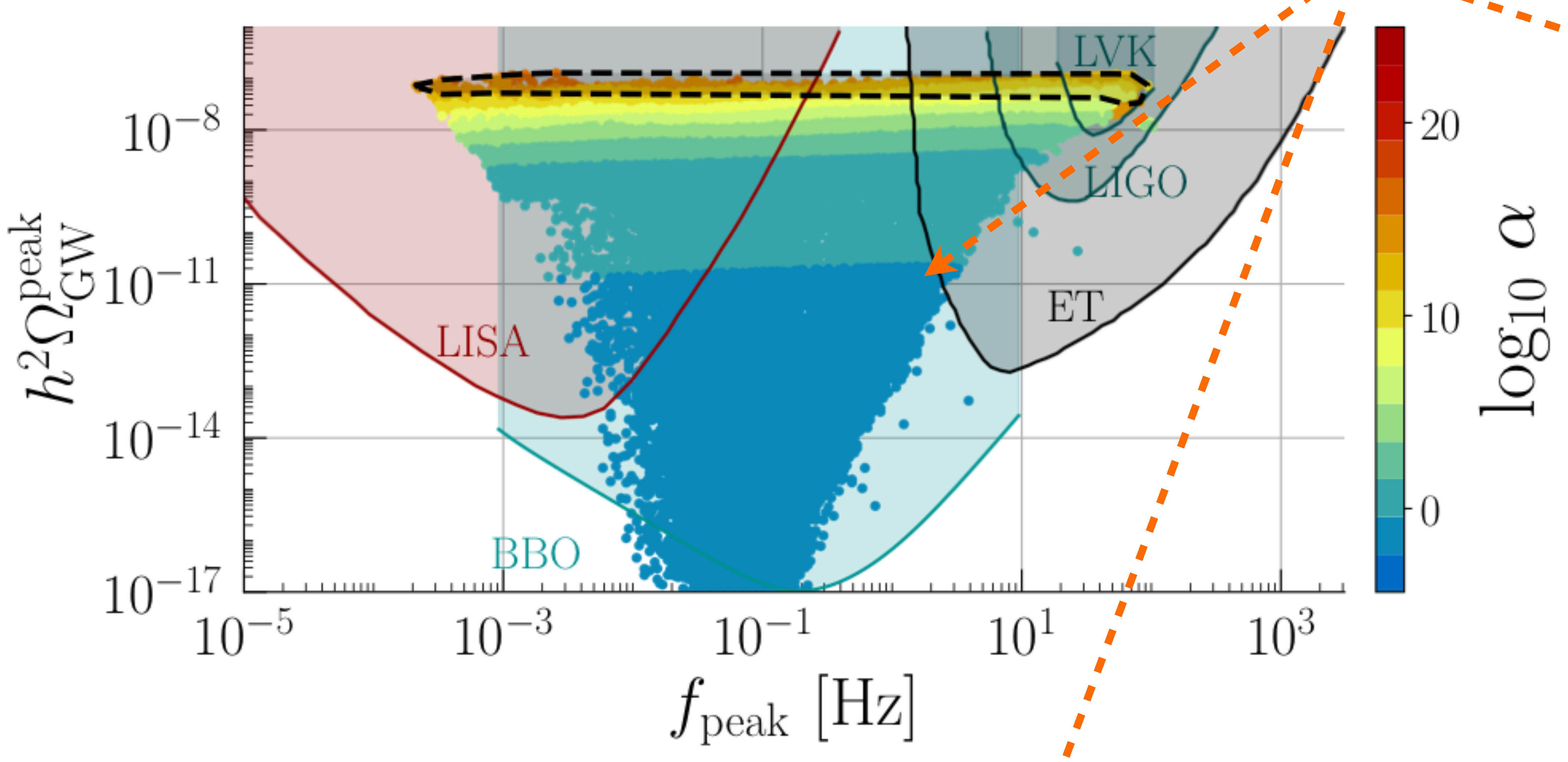
Gauge coupling controls the peak amplitude

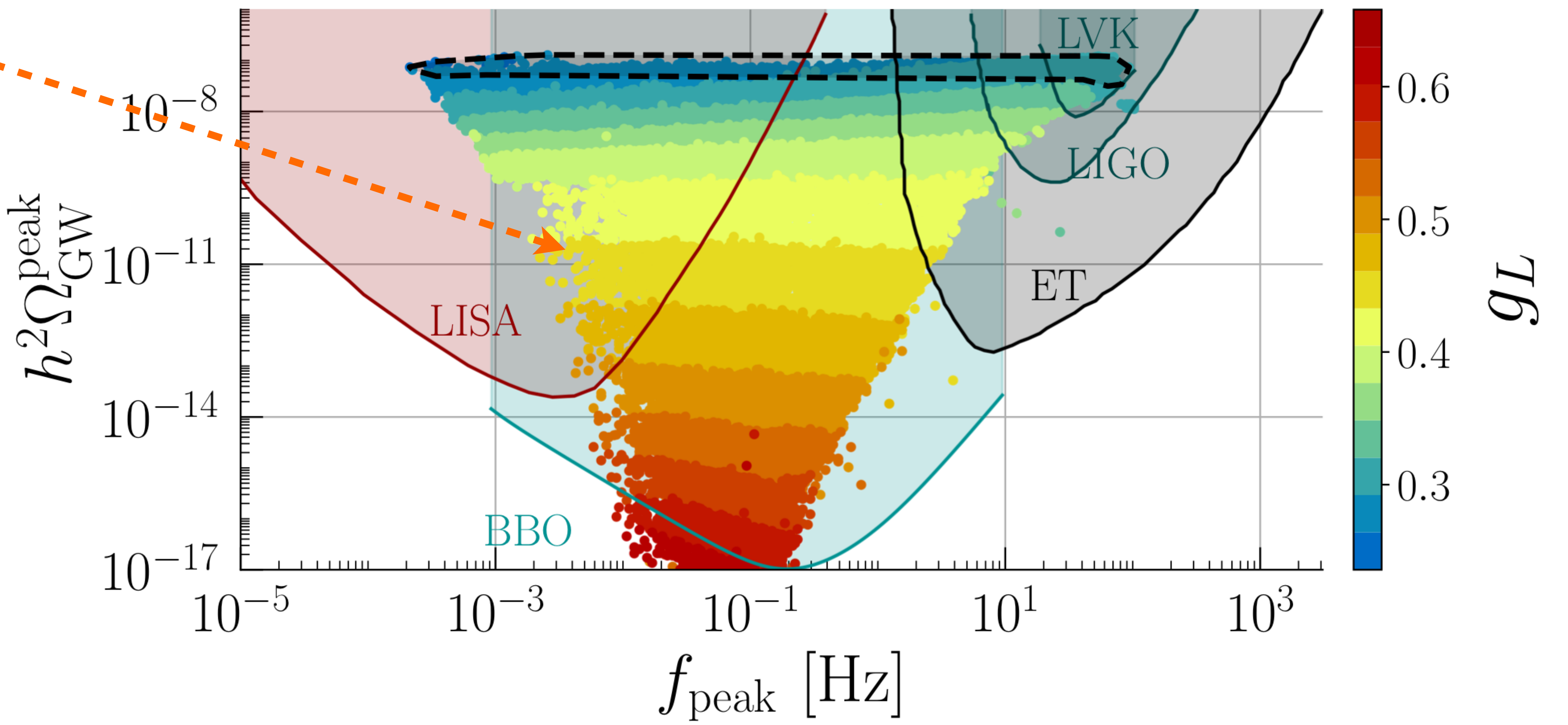
Larger $h^2\Omega_{\rm GW}^{\rm peak}$ for smaller g_L due to slower running $16\pi^2\beta_{\lambda_\sigma} = 3g_L^4 x_\sigma^4 + \cdots$

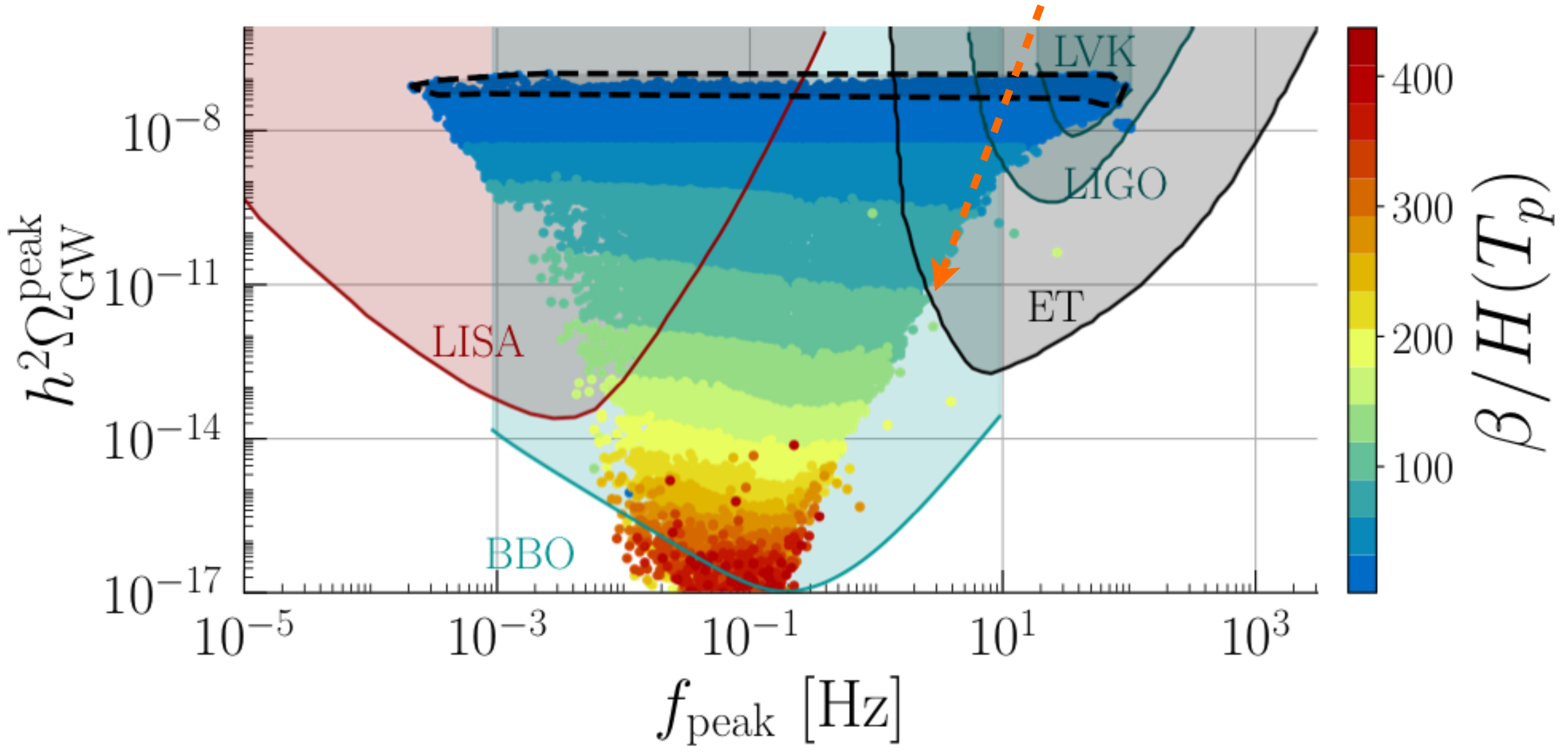




Strong supercooled FOPTs with $\alpha > 10$ and $\beta/H \sim \mathcal{O}(10-100)$ for $0.26 \lesssim g_L \lesssim 0.42$



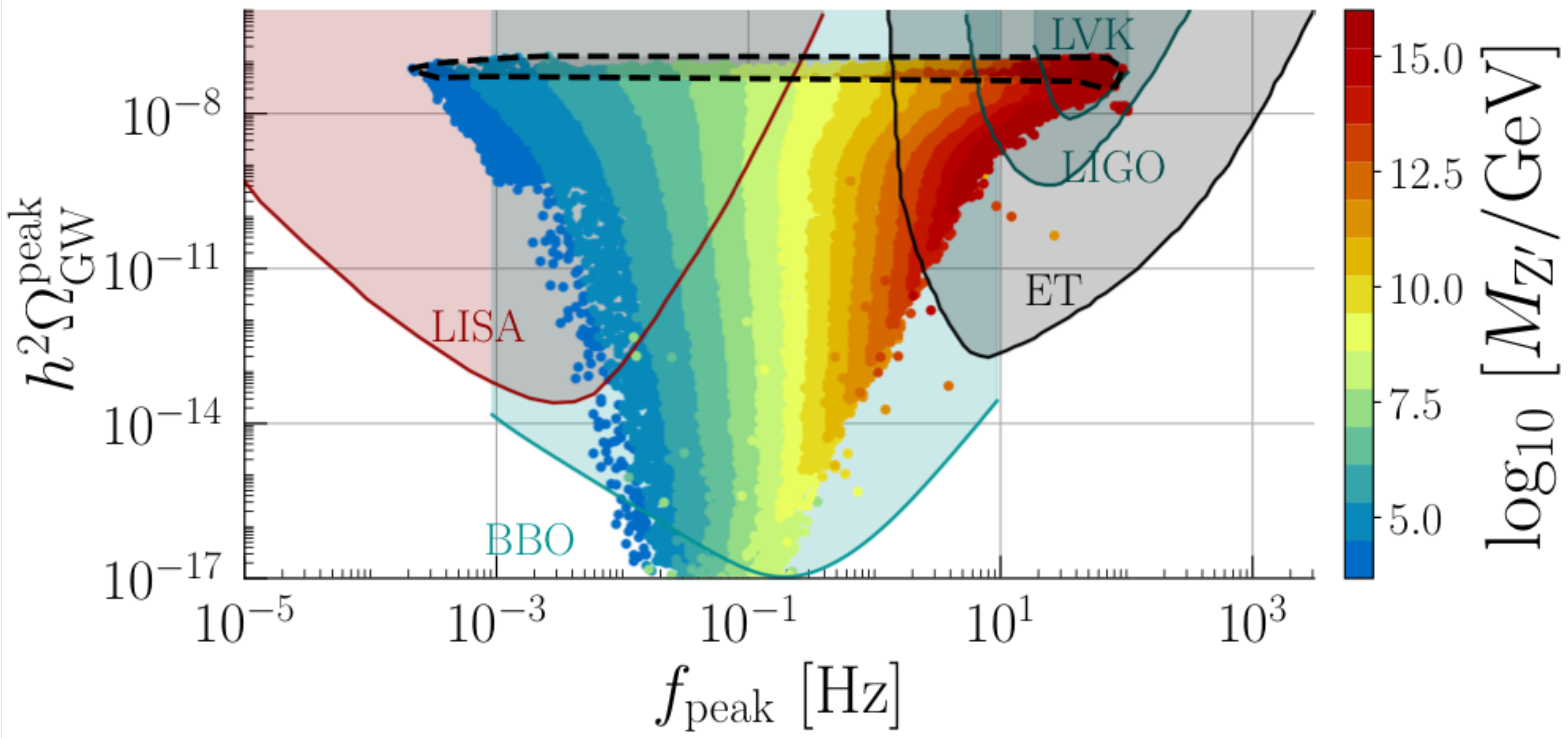


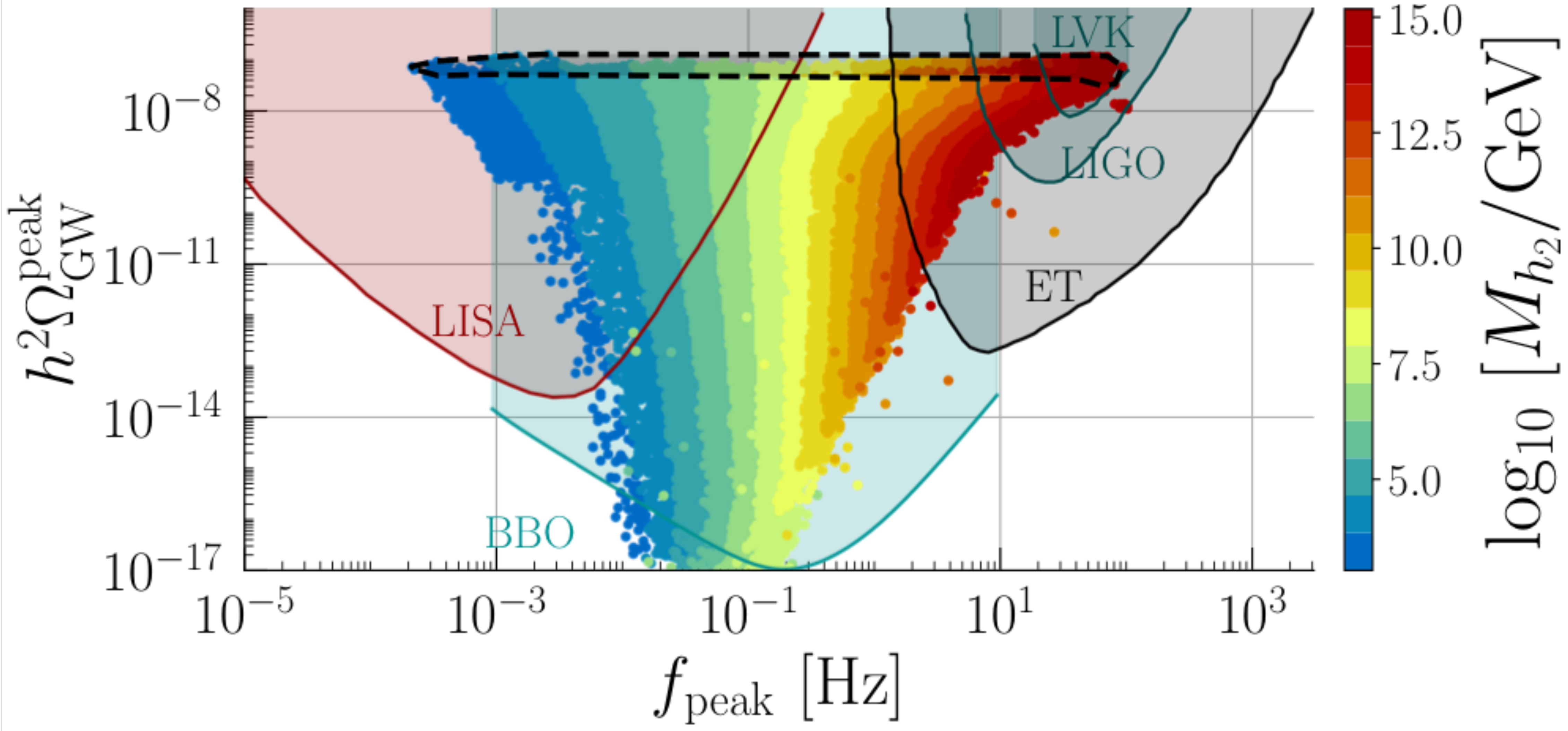


LVK data already setting constraints

β/H dependency flattens out with strong supercooling

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



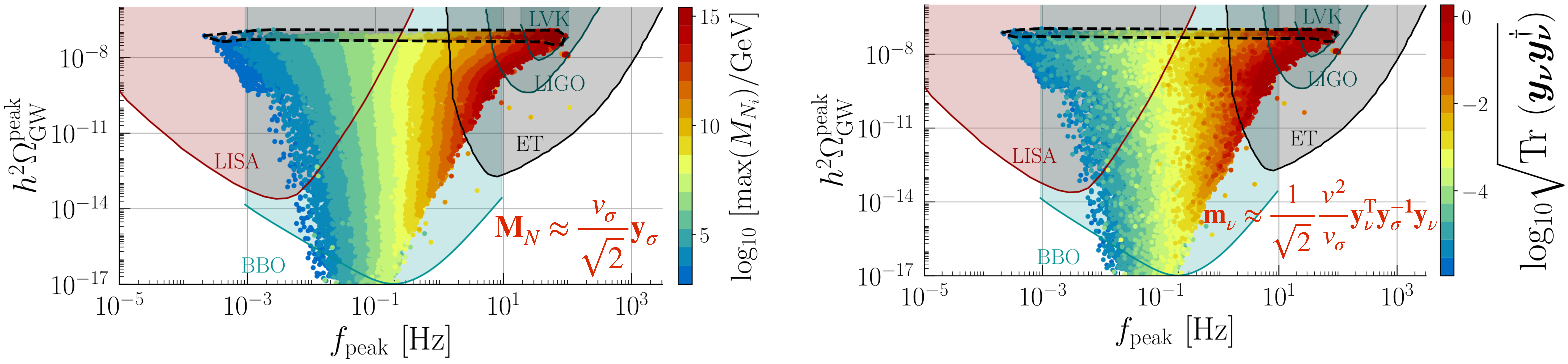


Peak frequency controlled by the mass scale

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

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

Neutrino sector



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

[Di Bari, Marfatia, Zhou, 2106.00025]

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

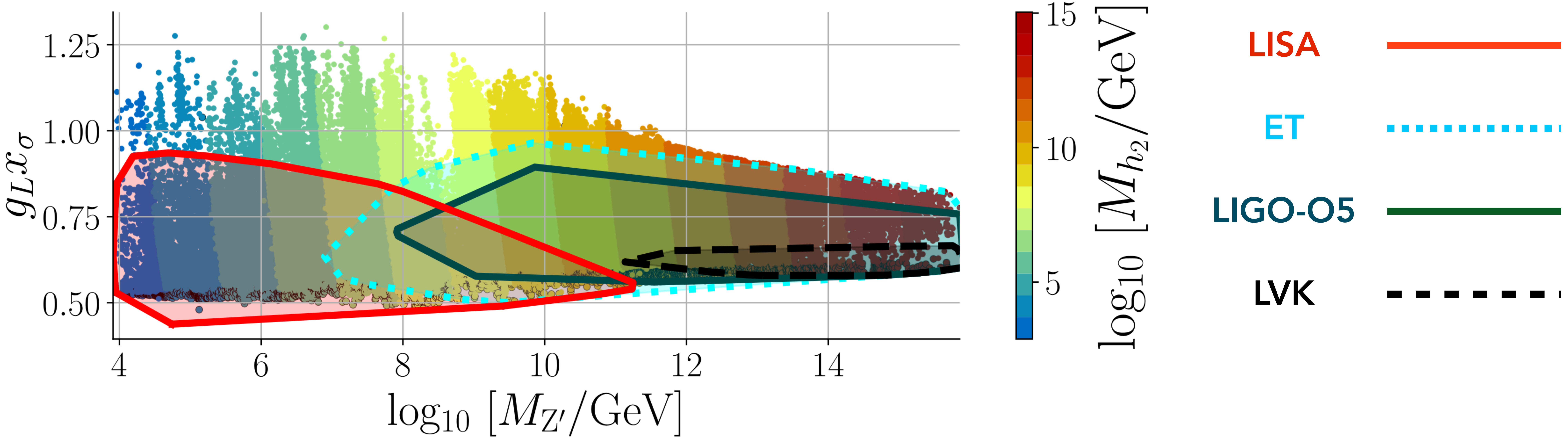
2. **At LIGO and ET frequencies seesaw scale in** $10^9 \lesssim M_N/\text{GeV} \lesssim 10^{15}$ **with** $10^{-2} \lesssim y_\nu \lesssim 1$

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

Testing supercooling with SGWB in generic $\mathrm{U}(1)'$ models

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

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



LVK excluded a region with $10^{11}\ \mathrm{GeV} \lesssim 10\ M_{h_2} \sim M_{Z'} < 10^{16}\ \mathrm{GeV}$ with $g_L x_\sigma \sim 0.6$

LISA+ET+LIGO can cover the entire mass range $M_{h_2} > 1\mathrm{TeV}\,, M_{Z'} > 10\ \mathrm{TeV}$ with $0.5 \lesssim g_L x_\sigma \lesssim 0.8$

Conclusions

1. Current and near future GW interferometers (LISA+ET+LIGO) can:

   (i) Test the presence of strong supercooling with $\alpha \gtrsim 10$ in generic CSS $\mathrm{U}(1)'$ models

   (ii) Put constraints on the seesaw scale as well as on gauge $g_L x_\sigma$ and Yukawa y_σ and y_ν couplings in the presence of supercooled FOPTs

   (iii) LVK data is already constraining this class of models for masses above 10^{11} GeV, $g_L x_\sigma \approx 0.6$, $y_\nu \sim 1$ and $y_\sigma \sim 0.1$

2. Presence of right-handed neutrinos is crucial for SGWB observables at high frequencies

3. Overall, LISA+ET+LIGO can either rule out most of the parameter space challenging the hypothesis of supercooled FOPTs and CSS, or lead to a groundbreaking discovery

MY FAVOURITE DARK MATTER MODEL

14–17 Apr 2025
Portugal
Europe/Lisbon timezone

Enter your search term

- Overview
- Timetable
- Registration
- Participant List

Rui Santos
rasantos@fc.ul.pt

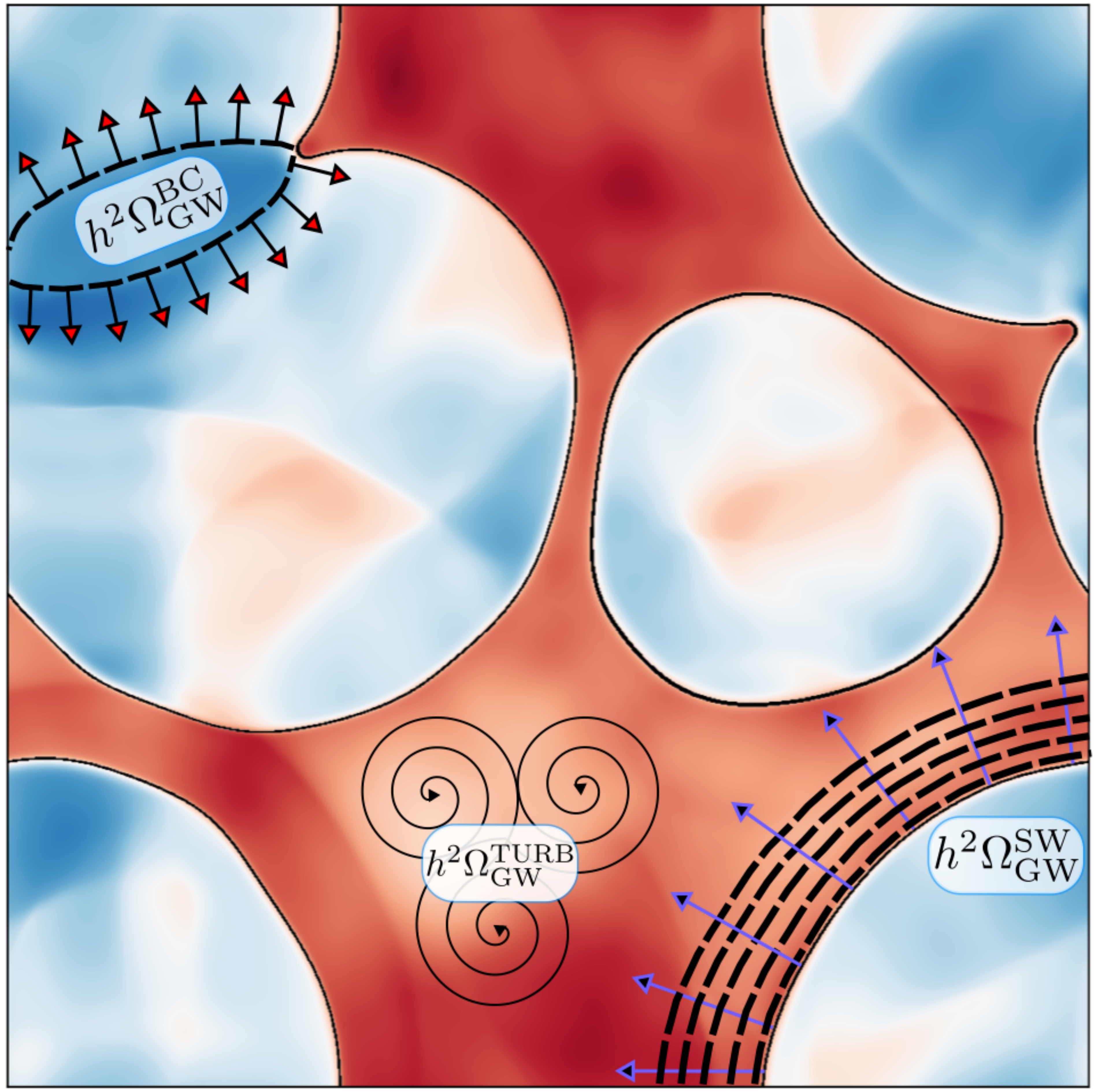
Goal of the meeting

Dark matter is a long outstanding problem in modern astrophysics and one of the biggest mysteries physicists are currently struggling to understand. Its presence throughout the Universe is inferred by its

https://indico.cern.ch/event/1346673/overview

THANK YOU

Sources of SGWB



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

1. **Bubble collisions: Can become efficient with supercooling for extreme $\alpha \ggg 1$**

2. **Sound waves: Dominant in most cases due to friction**

3. **Magnetohydrodynamics turbulence: highly uncertain and subdominant at the peak (at least for now…)**

Latest SGWB templates taken from LISA CosWG

[C. Caprini, et al., 2403.03723]

5. Rich SGWB predictions due to strongly supercooled FOPTs $\Longrightarrow h^2\Omega_{\rm GW}$ is large

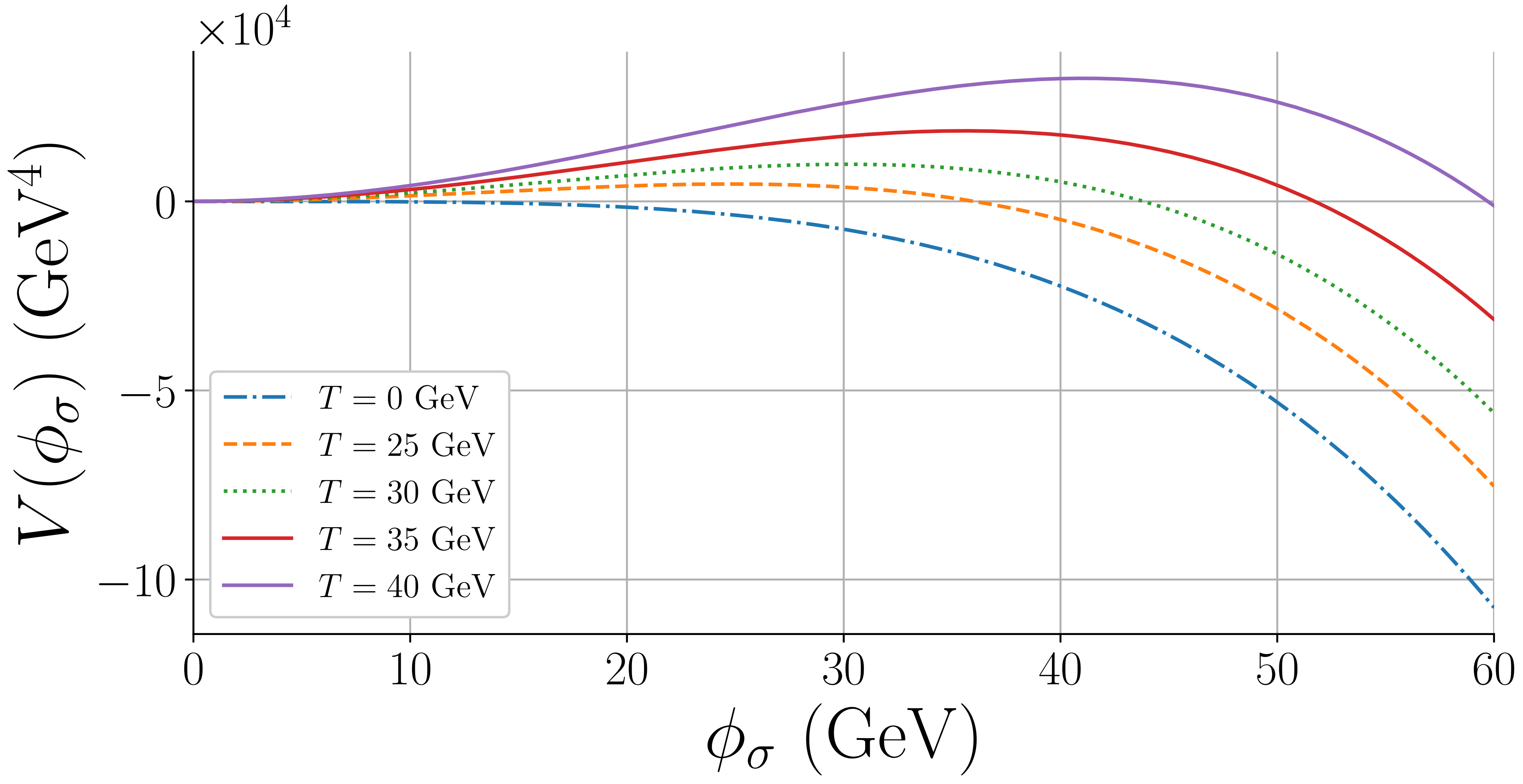
$$V_{\rm eff}^{\rm HT} = \phi_\sigma^4 \left(-\frac{g_L^4}{2\pi^2} - \frac{g_L^3}{2\sqrt{2}\pi} + \frac{\lambda_\sigma}{4} + \frac{\ln\, 2 \left([\sum_{i=1}^3 [\boldsymbol{y_\sigma^4}]_{ii} \right)}{32\pi^2} \right) - \phi_\sigma^3 \frac{4 g_L^3 T}{3\pi} + \phi_\sigma^2 \left(\frac{g_L^2 T^2}{2} - \frac{g_L^3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

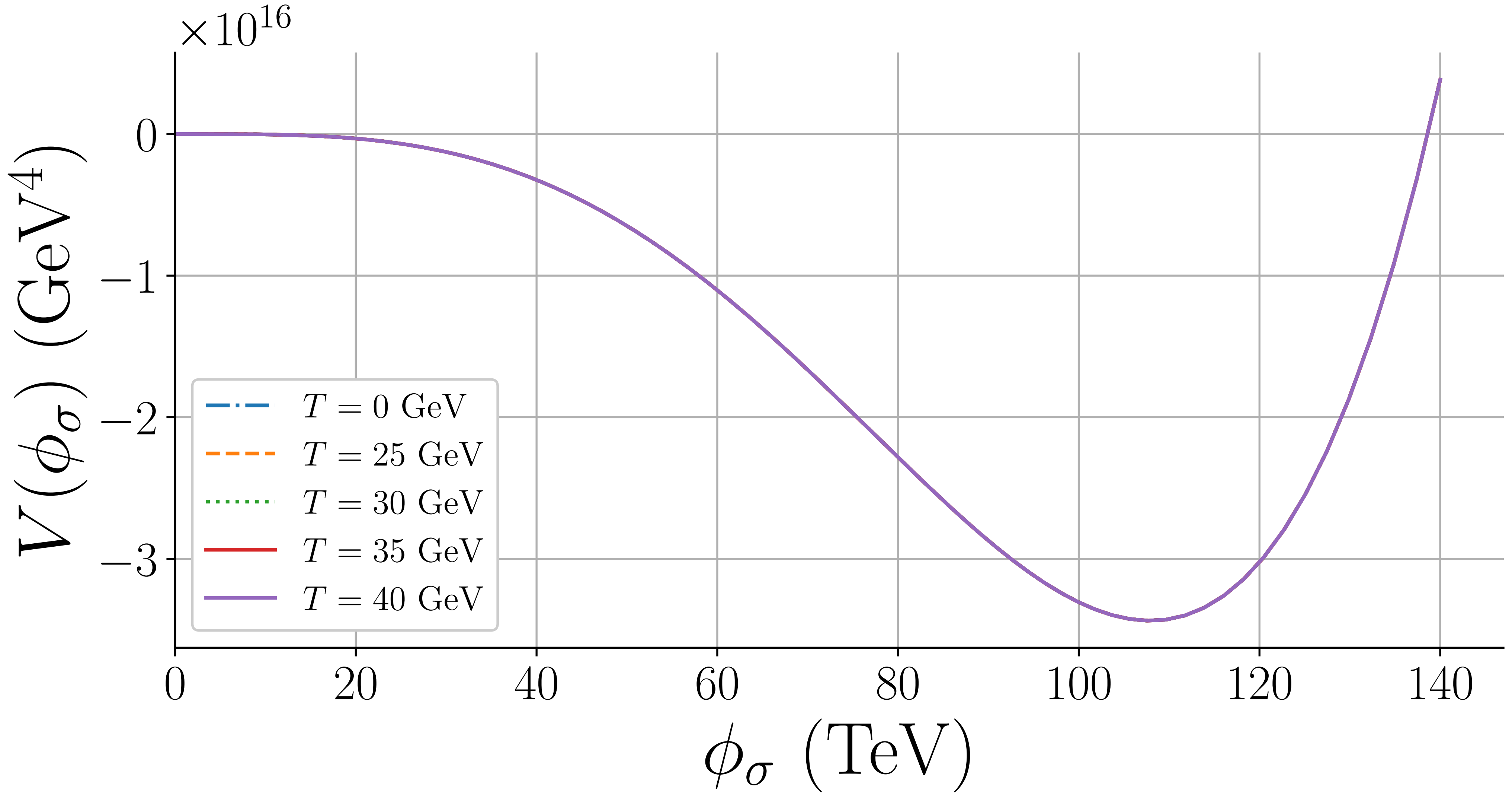
5.1) Negative cubic term generated at finite T

5.2) Potential barrier persists as the Universe supercools down to $T \to 0$

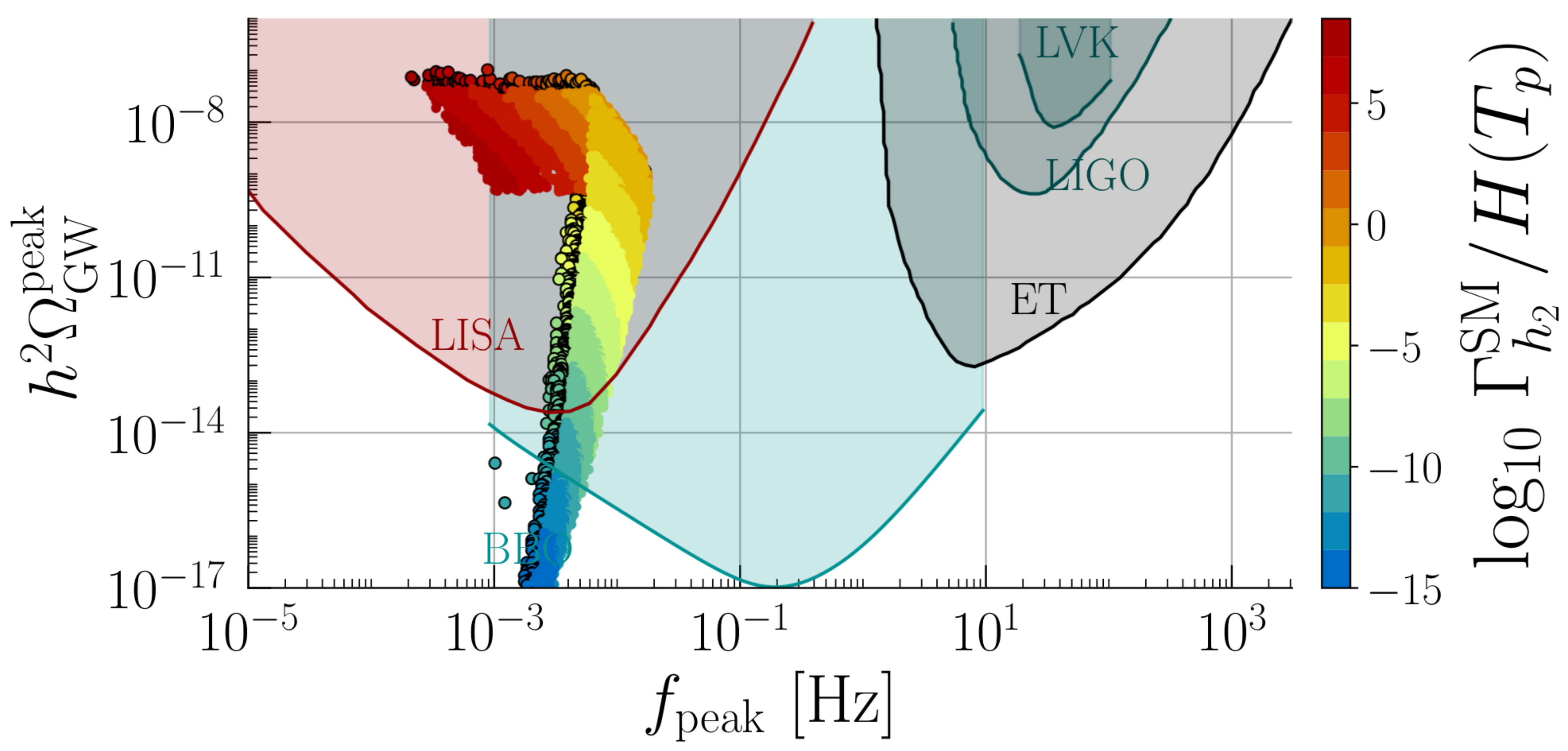
5.3) ΔV is maximized $\Longrightarrow \alpha \approx \frac{\Delta V}{\rho_R} \gg 1$

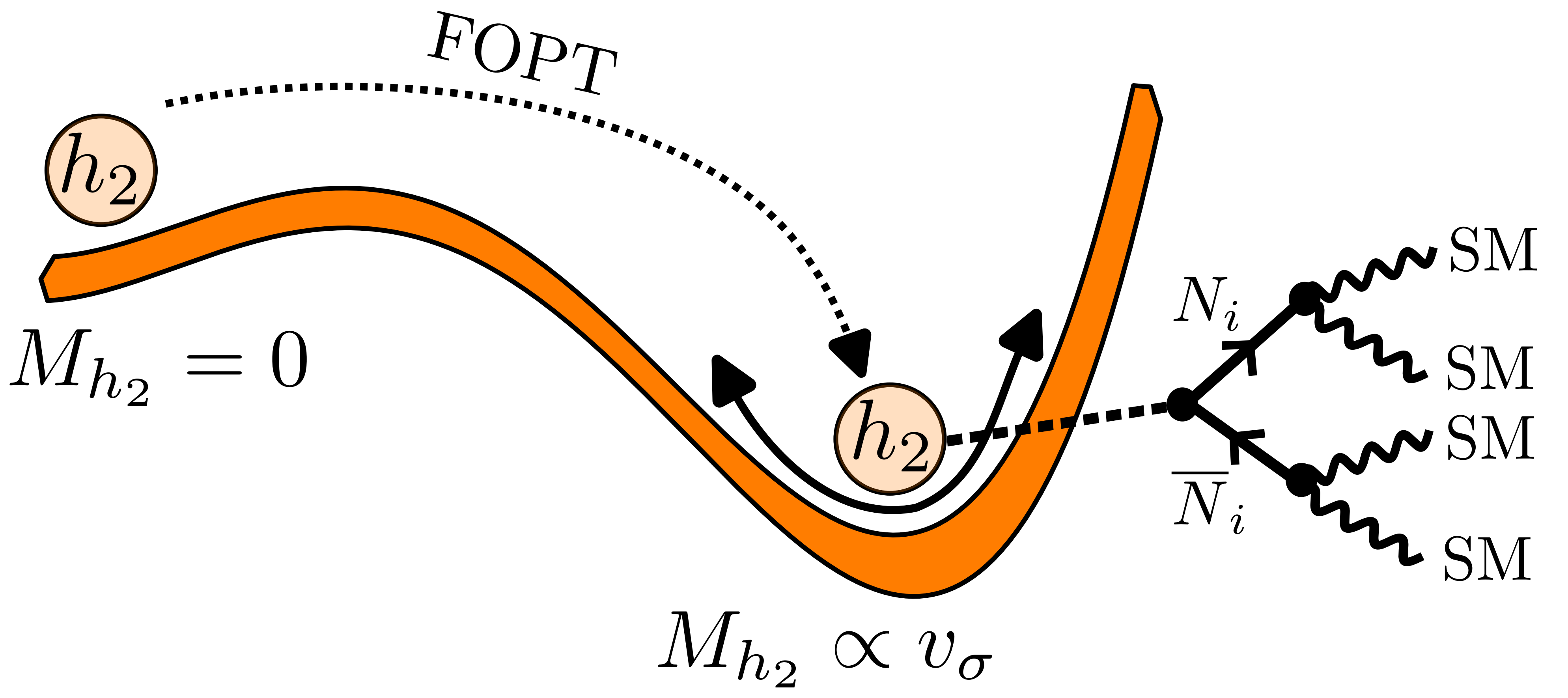
5.4) Long lasting FOPT $\beta/H \sim \mathcal{O}(10 - 100)$





What if we remove neutrino sector $[y_\sigma]_{ii} \to 0$





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

Checked using `MadGraph`

No SGWB predictions at high frequencies — LIGO, ET

Heavy Higgs decay to SM highly suppressed by portal coupling $\lambda_{\sigma h} \sim \dfrac{v^2}{v_\sigma^2}$ 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

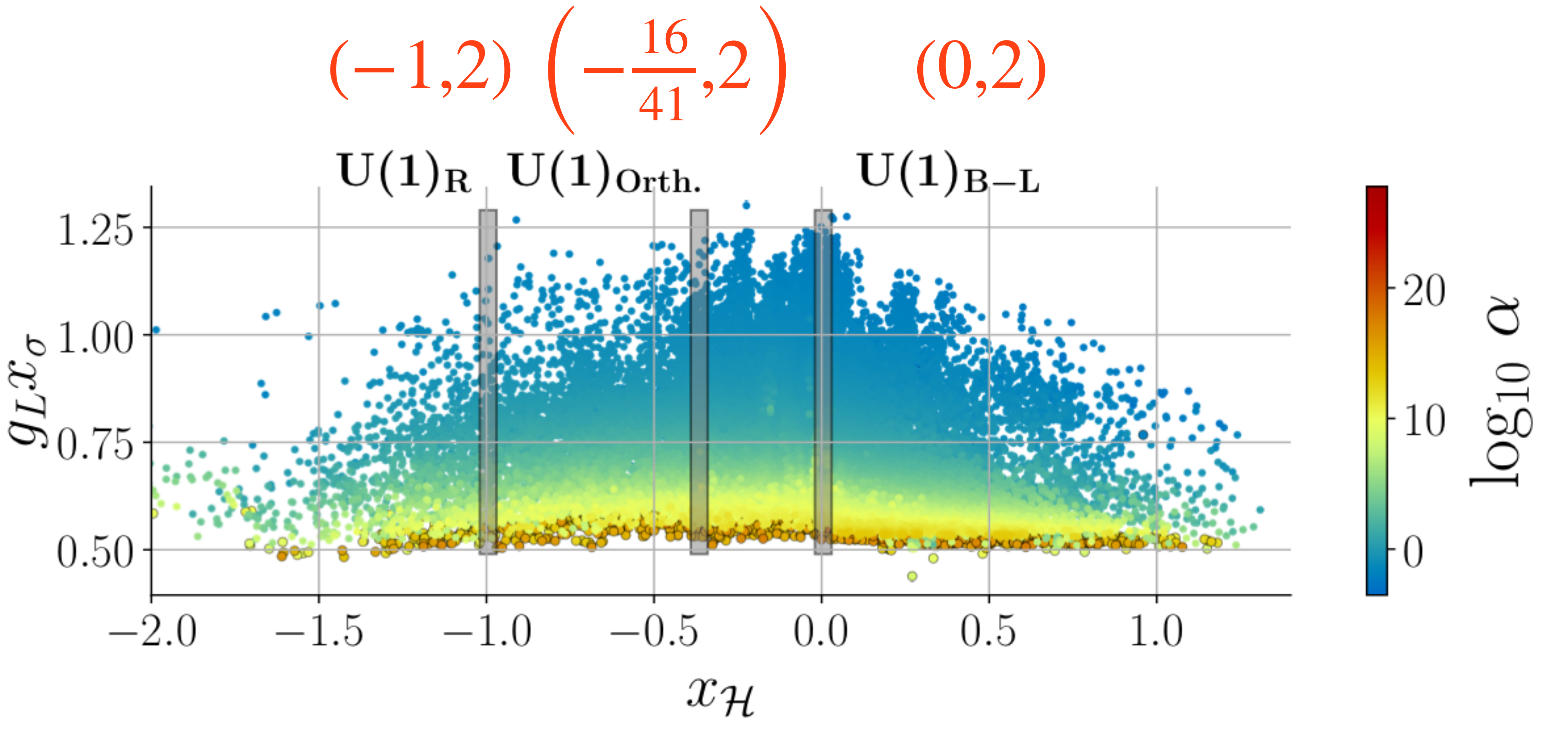
$\Gamma_{h_2} < H(T_p) \implies$ SUPRESSION of SGWB

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

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

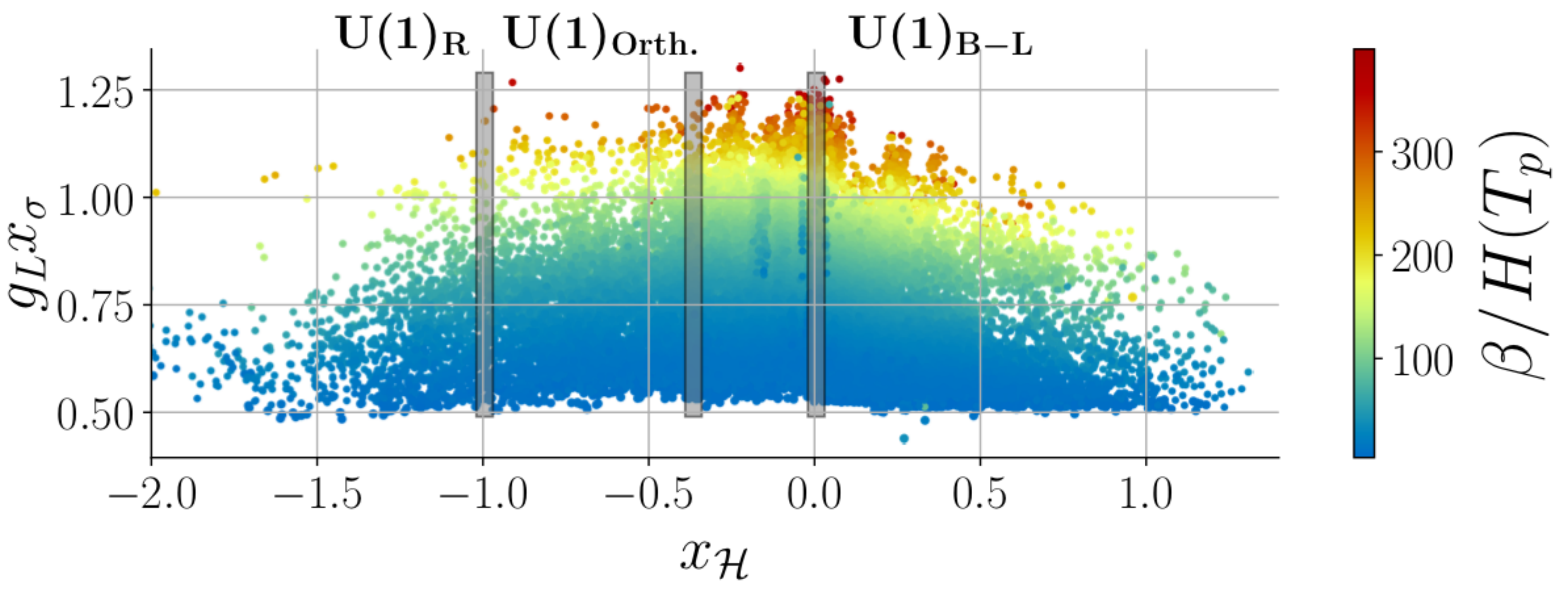
$$T_{RH} \approx T_p(1+\alpha)^{1/4}\left(\frac{\Gamma_{h_2}}{H(T_p)}\right)^{1/2} \qquad T_c > T_{RH} \gg T_n > T_p$$

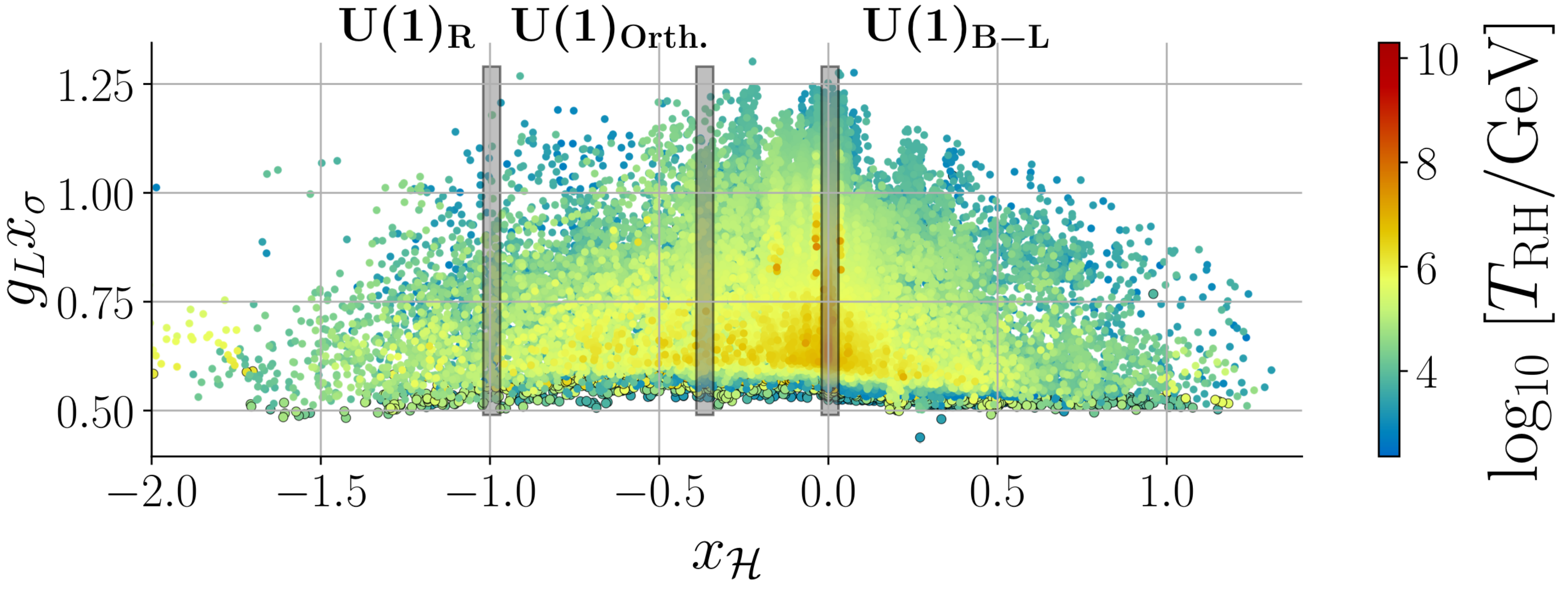
SGWB predictions for generic $U(1)'$ with charges (x_H, x_σ)

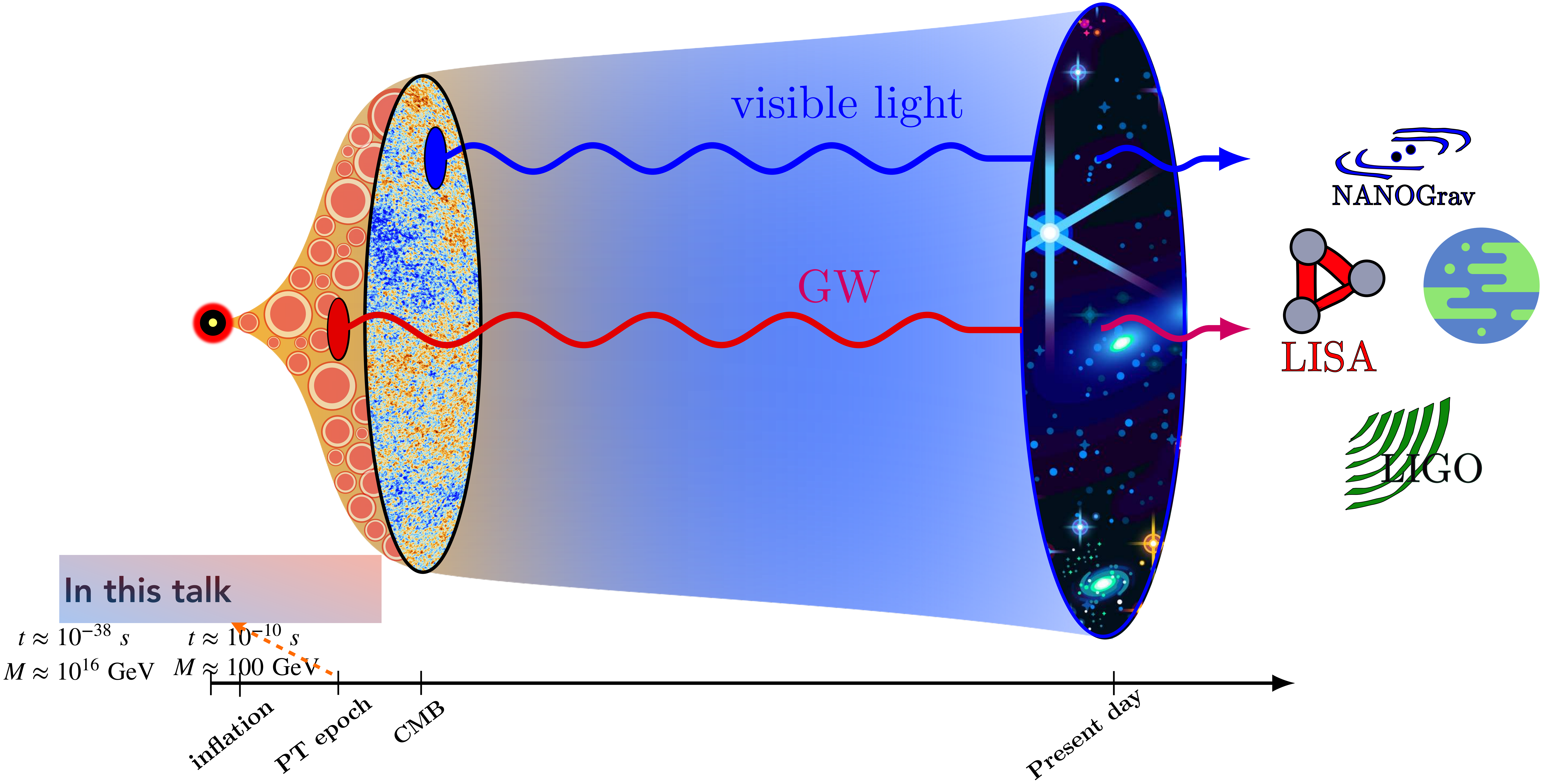


Thermodynamic parameters weakly dependent on x_H

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






visible light
GW
NANOGrav
LISA
LIGO
In this talk
$t \approx 10^{-38}\ s$
$M \approx 10^{16}$ GeV
$t \approx 10^{-10}\ s$
$M \approx 100$ GeV
inflation
PT epoch
CMB
Present day

From thermodynamic to SGWB geometric parameters

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

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

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

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

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

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

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

The role of the neutrino sector I

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

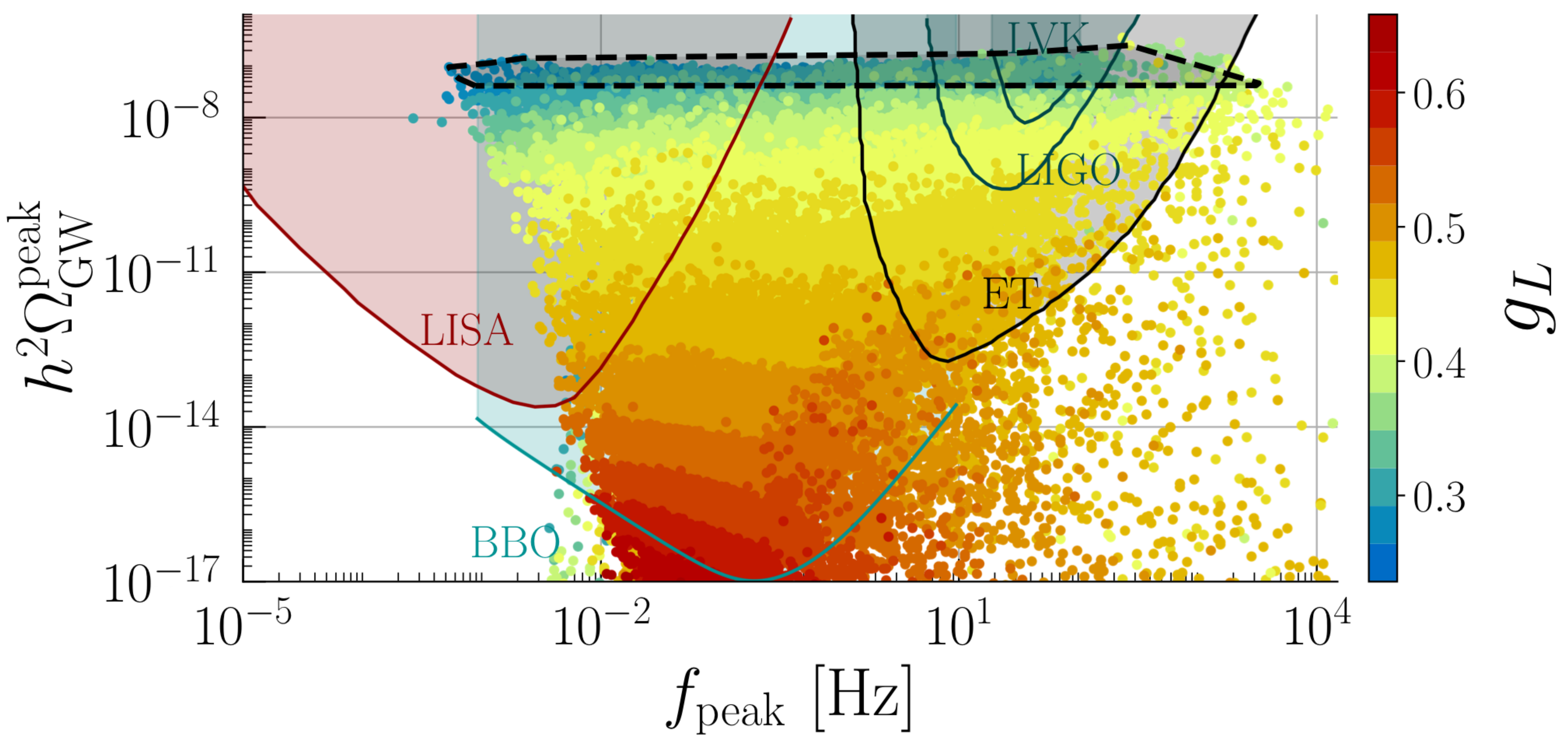
1. **At large filed values/frequencies:**

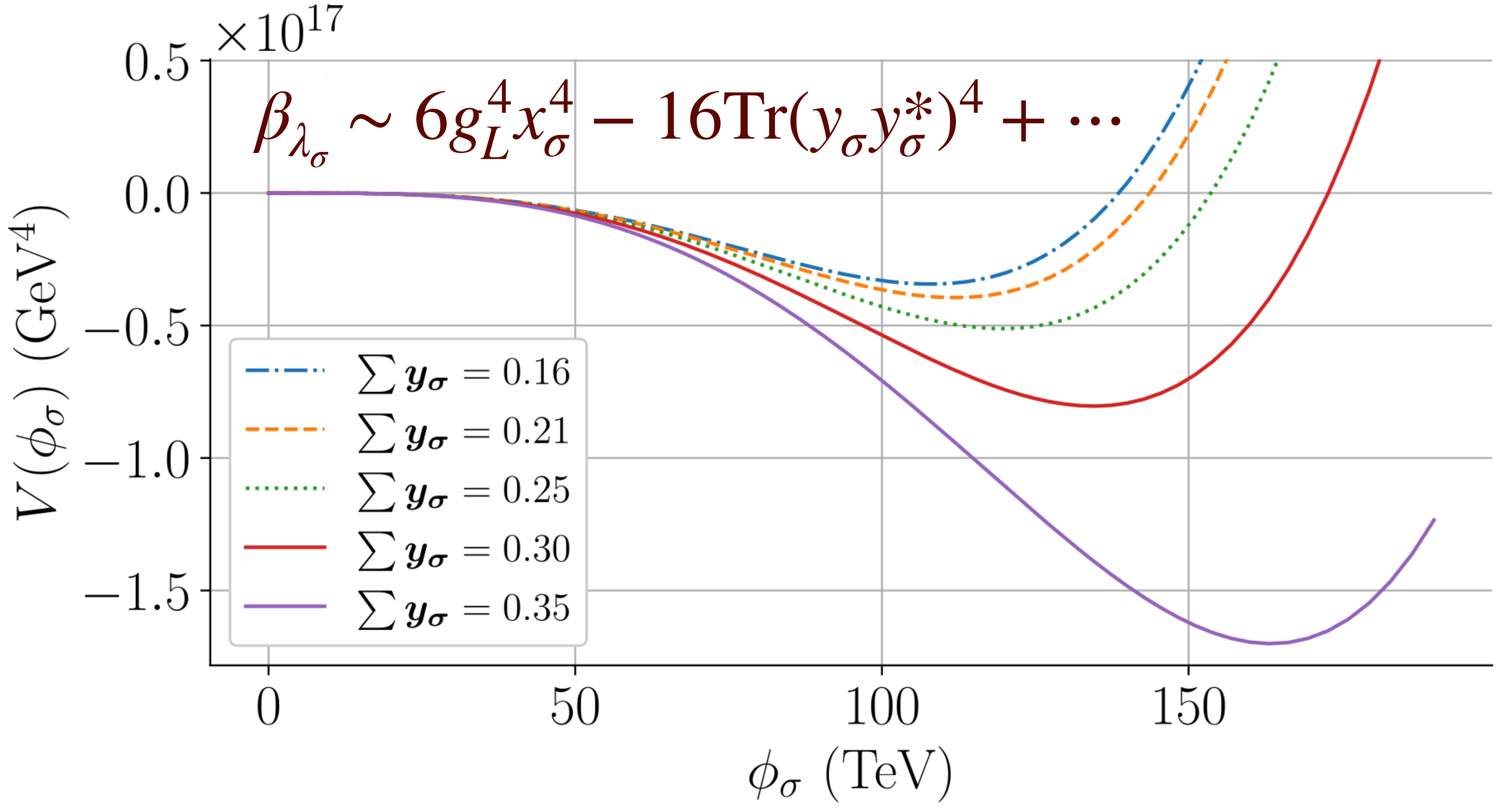
   A. Opposite sign in β_{λ_σ} slows down RG running with sign flip at larger ϕ_σ

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

2. This effect competes with $V_{\rm min}$ where large $\mathrm{Tr}(y_\sigma)$ increases $\Delta V \Rightarrow$ smaller $h^2\Omega_{\rm GW}^{\rm peak}$

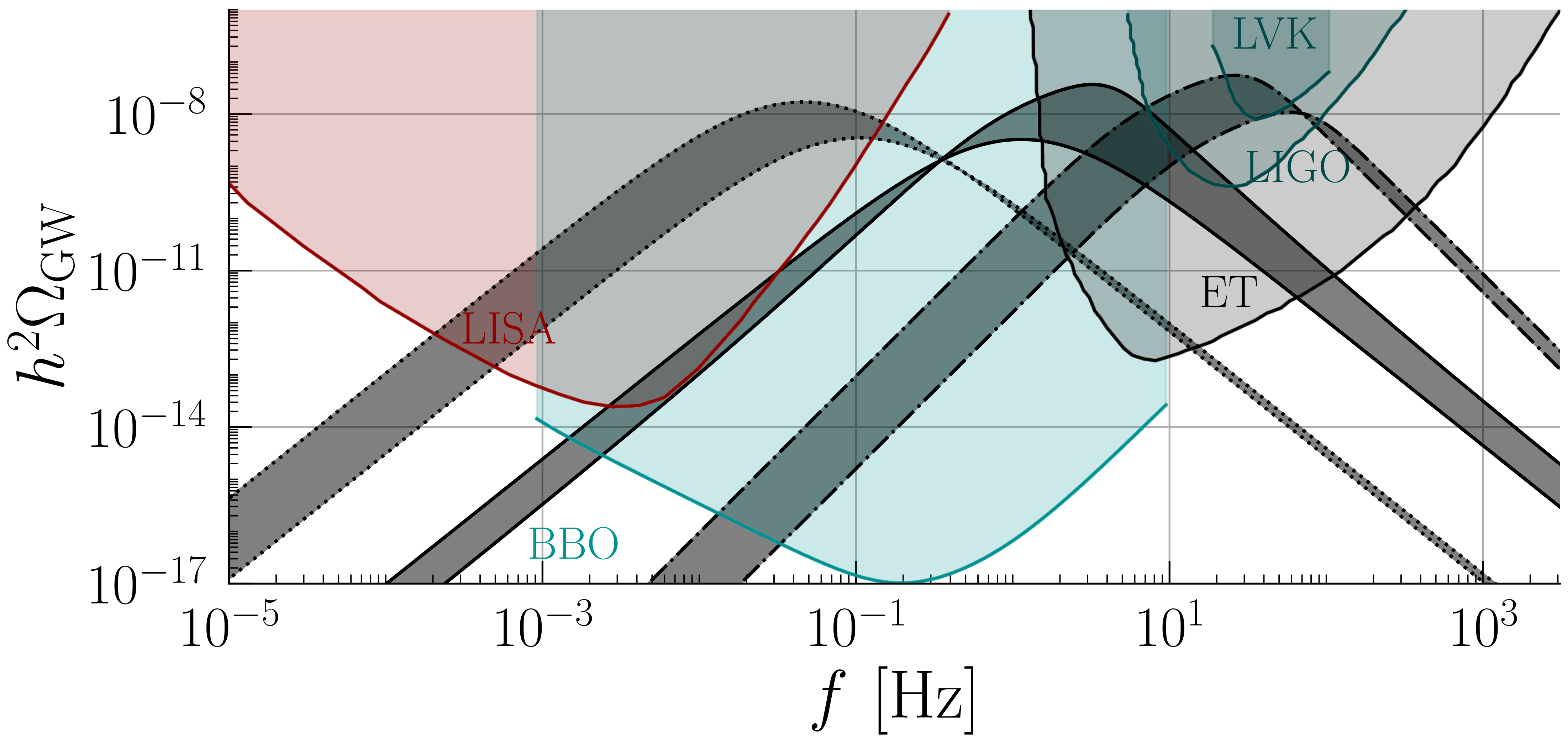
$$V_{\rm min} = \frac{v_\sigma^4}{256\pi^2}\left(-96 g_L^4 + \sum_{i=1}^{3} [\boldsymbol{y}_\sigma^4]_{ii}\right)$$



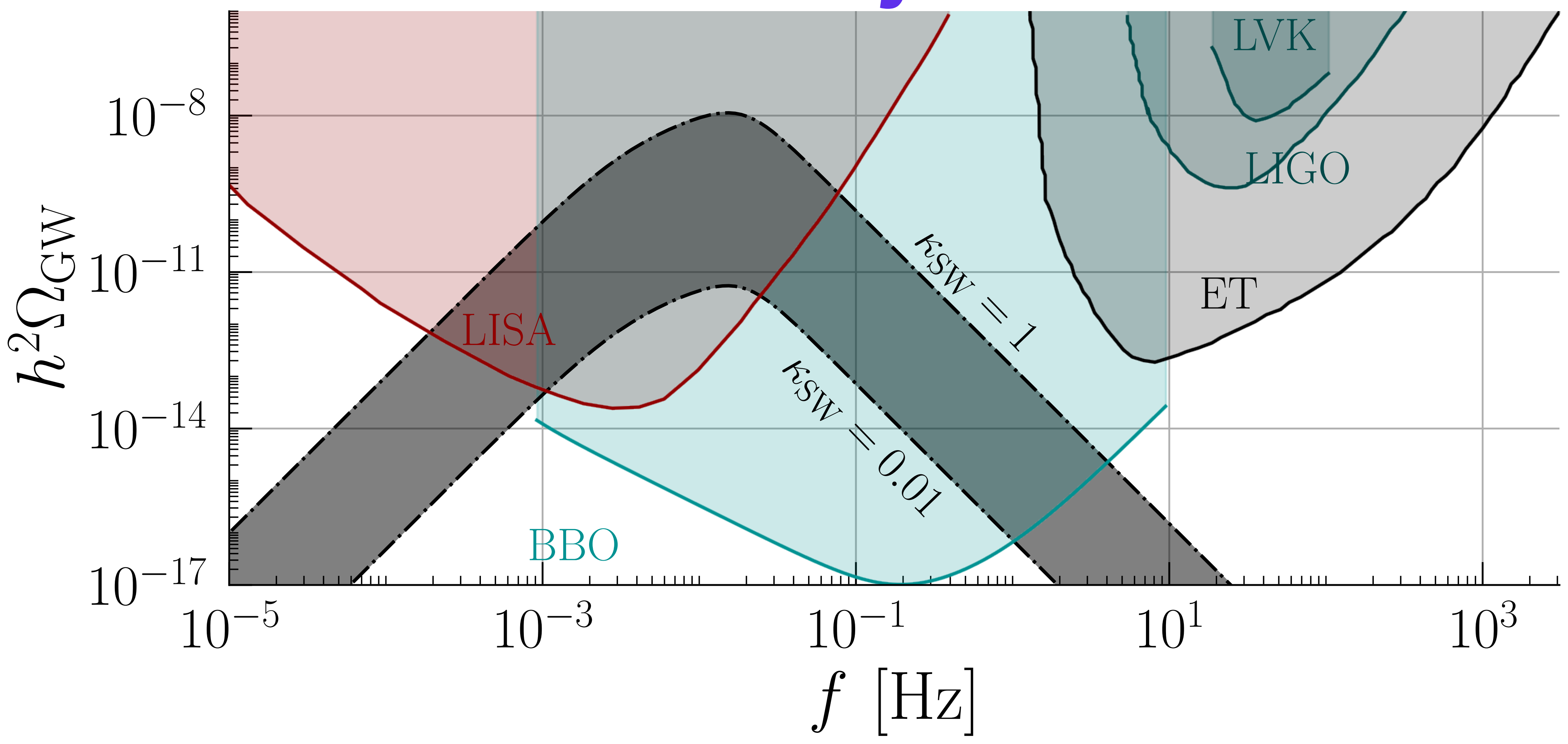


Sources of uncertainty

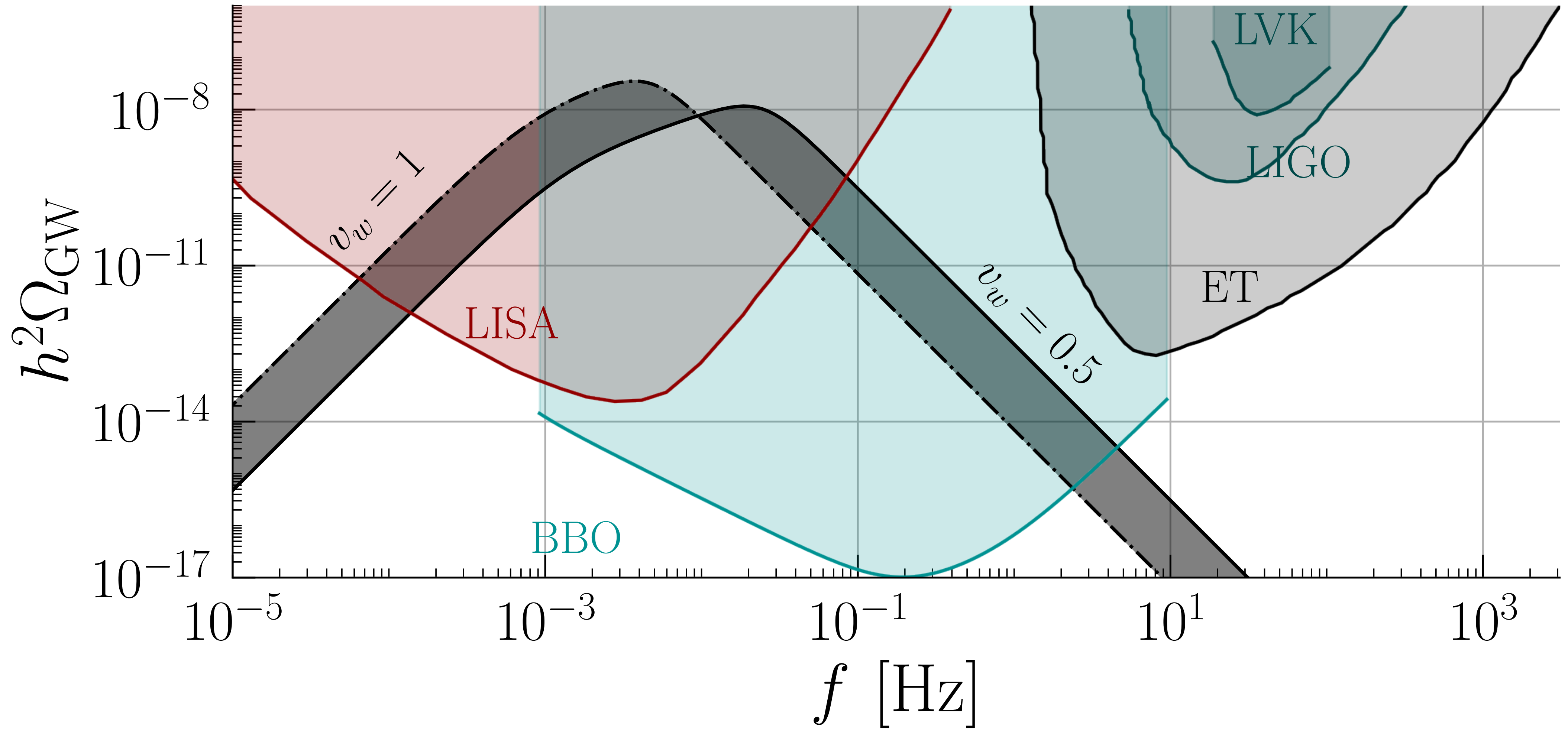
Bubble radius distribution



Efficiency factors



Wall velocity



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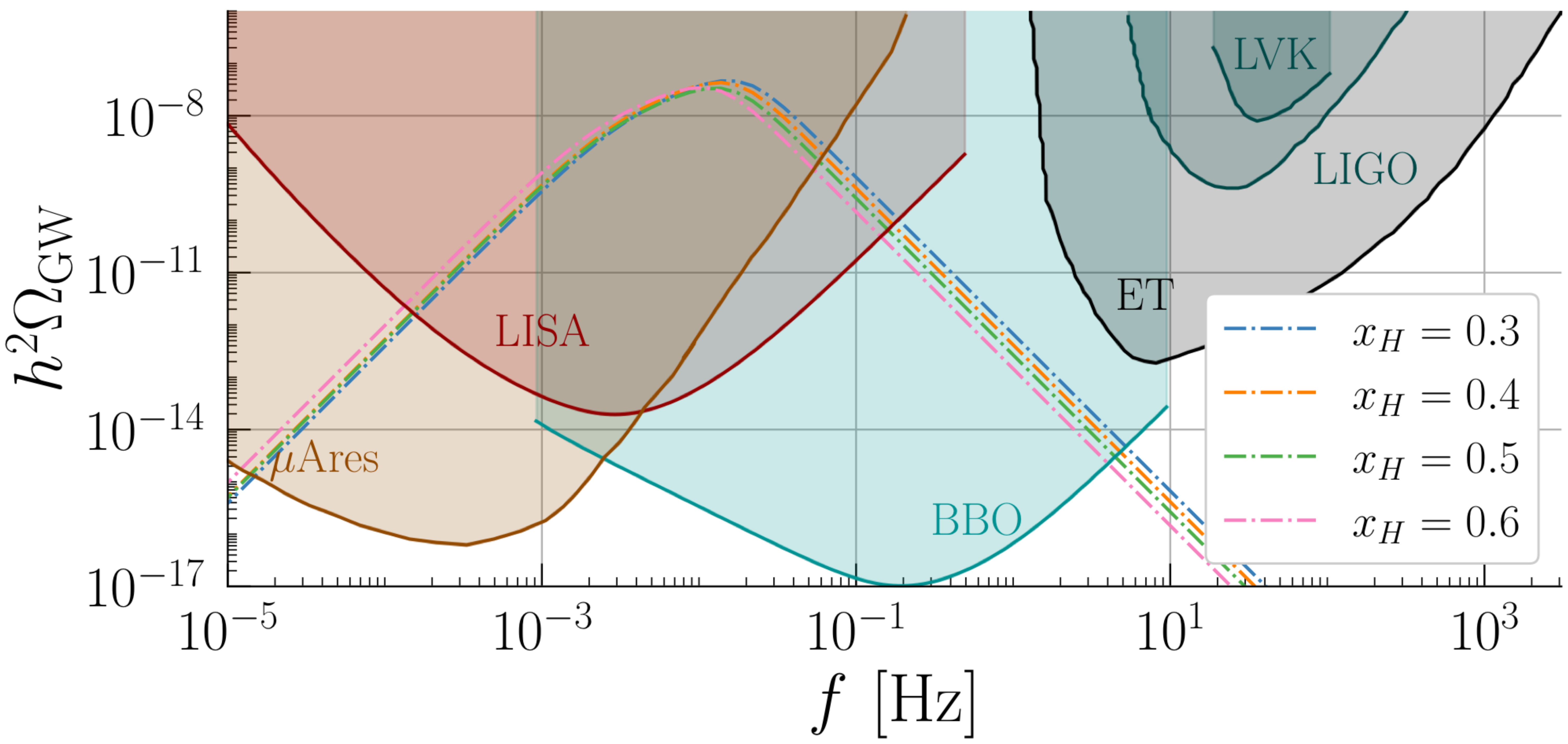

Different models for fixed $g_L x_\sigma$ have little impact, overshadowed by current uncertainties

x_H enters the scalar potential via V_{CW} and β-functions

Dimensional reduction

Improved calculation with dimensional reduction

Theoretical predictions are not robust as they strongly depend on the transition temperature

$$h^2\Omega_{\rm GW} \propto \frac{(\Delta V)^2}{T_*^8}$$

- **Why large uncertainties?**

$$m_{\rm eff}^2 = (m^2 + a_{\rm 1-loop} T^2) \ll m^2$$

$$b_{\rm 2-loop} T^2 \approx m_{\rm eff}^2$$

Large theoretical errors at the phase transition

$$\mu \frac{d}{d\log\mu} m_{\rm eff}^2 \approx m_{\rm eff}^2$$

Large scale dependency

$$\log\left(T^2/m_{\rm eff}^2\right) \gg 1$$

Large logs

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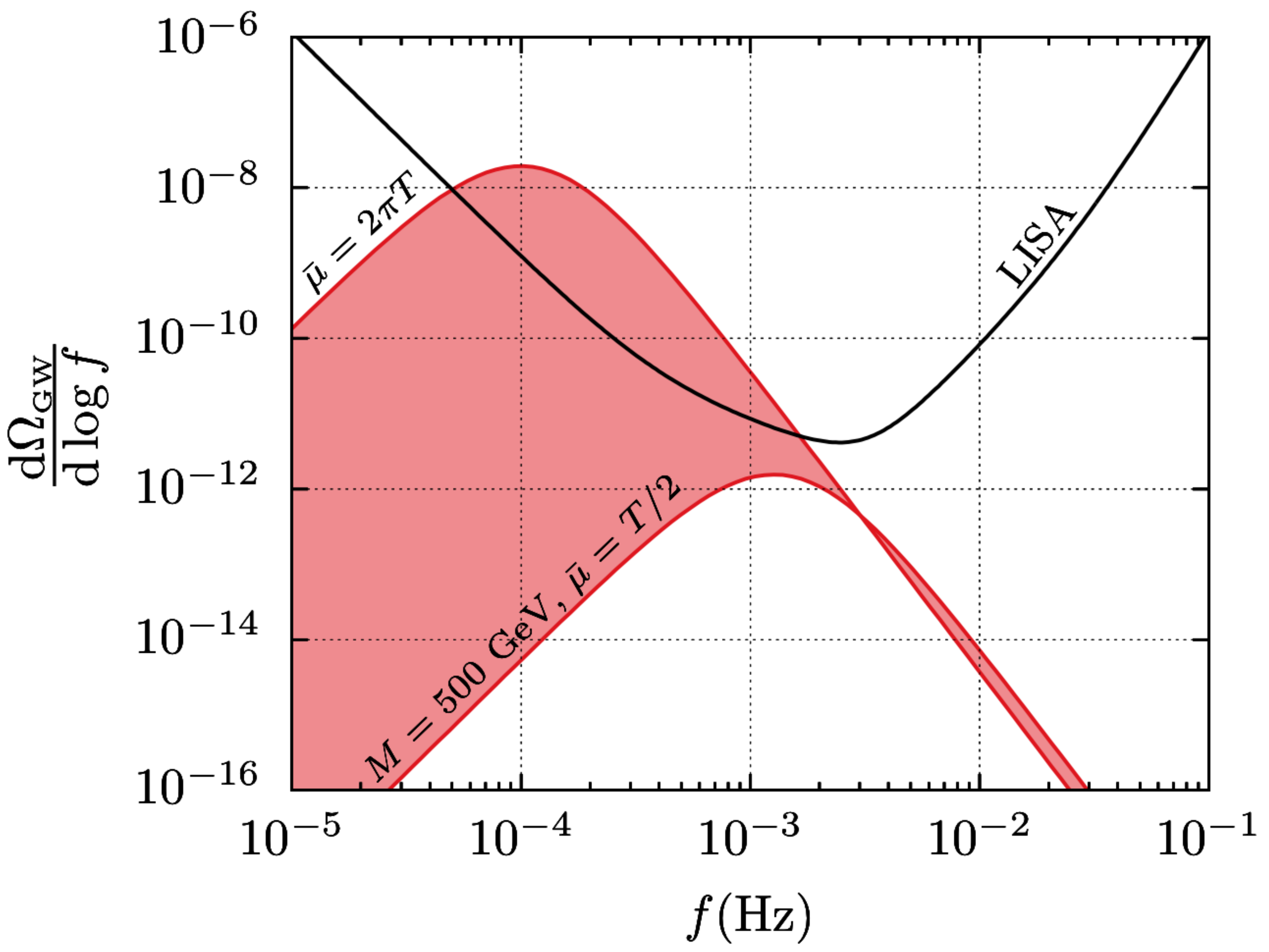
$$\log\left(T^2/m_{\rm eff}^2\right) \gg 1$$

Large logs



[Image credit: P. Schicho]

Improved calculation with dimensional reduction

Huge higher order corrections → **Use an effective field theory**

[Kajantie et al 9508379, Gould et al 2104.04399]

$$\log\left(T^2/m^2_{\rm eff}\right) \to \log\left(T^2/\mu^2\right) + \log\left(\mu^2/m^2_{eff}\right)$$

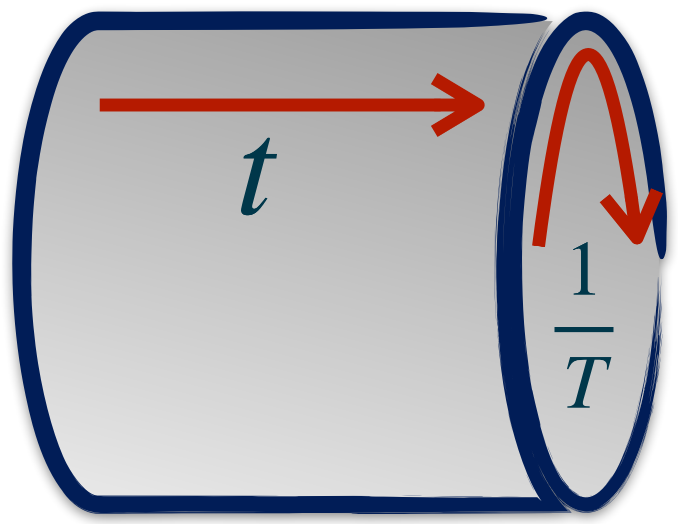
Match at $\mu \sim T$

RG-evolution in the EFT

- In thermal equilibrium heavy "particles" show up as an infinite tower of Matsubara (static) modes:

$$\partial_\mu \phi(x) \partial^\mu \phi(x) \to \vec{\nabla}\phi(\vec{x}) \cdot \vec{\nabla}\phi(\vec{x}) + \sum_{n=-\infty}^{+\infty} (2\pi n T)^2 \phi(\vec{x})^2$$

Integrate out heavy particles



- No time dependence

Improved calculation with dimensional reduction

In practice: write down the most general 3d-spacial Lagrangian and match the couplings

$$\frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4 \to \frac{1}{2}m_{3\mathrm{d}}^2(T, m, \lambda)\phi^2 + \frac{1}{4}\lambda_{3\mathrm{d}}(T, m, \lambda)\phi^4$$

→ Only valid at high-T

$$\phi \to \frac{\phi}{\sqrt{T}}$$

$$V_{4\mathrm{d}} = T V_{3\mathrm{d}}$$

Improved calculation with dimensional reduction

In practice: write down the most general 3d-spacial Lagrangian and match the couplings

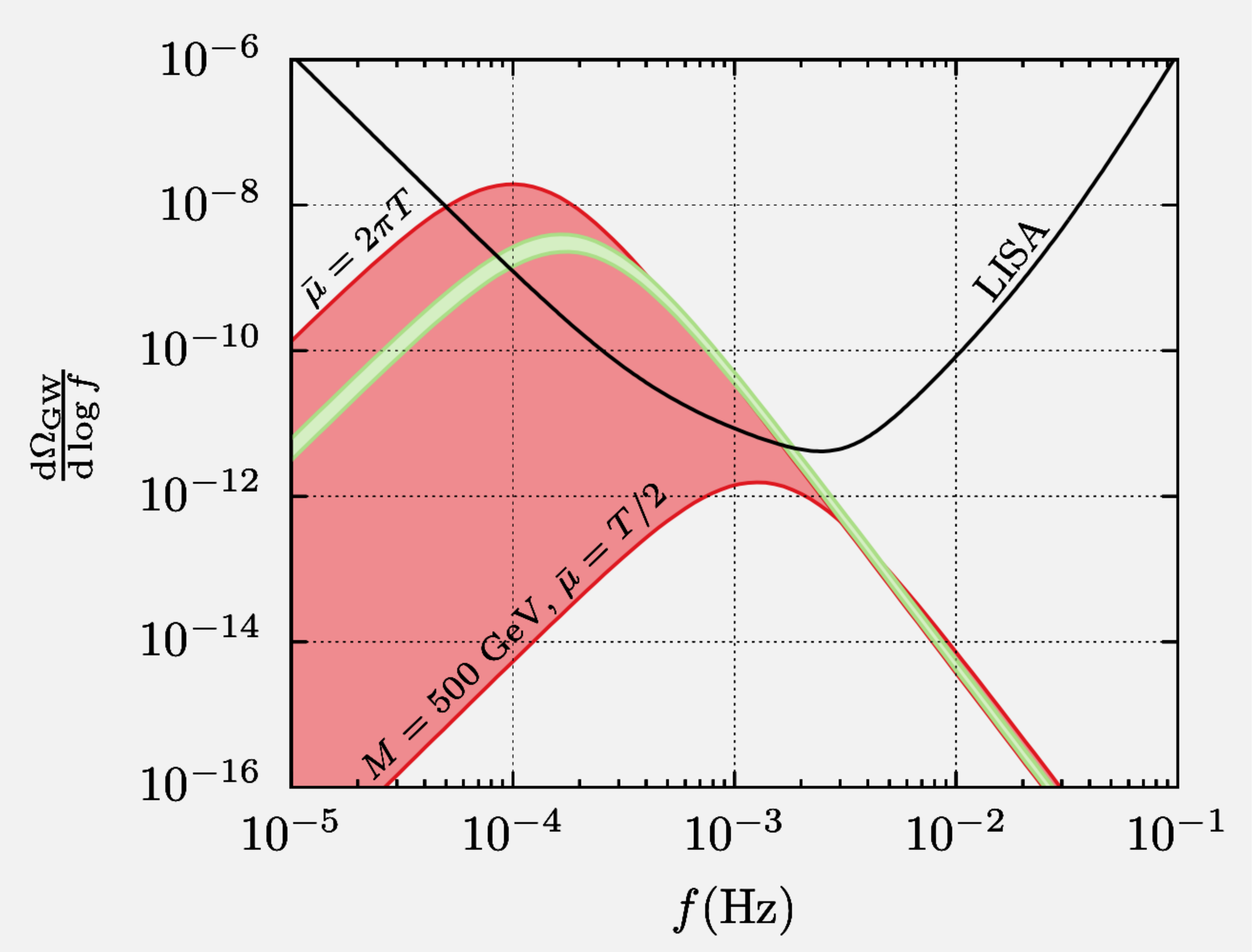
$$\frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4 \to \frac{1}{2}m^2_{3\mathrm{d}}(T,m,\lambda)\phi^2 + \frac{1}{4}\lambda_{3\mathrm{d}}(T,m,\lambda)\phi^4$$

$$\phi \to \frac{\phi}{\sqrt{T}}$$

$$V_{4\mathrm{d}} = TV_{3\mathrm{d}}$$

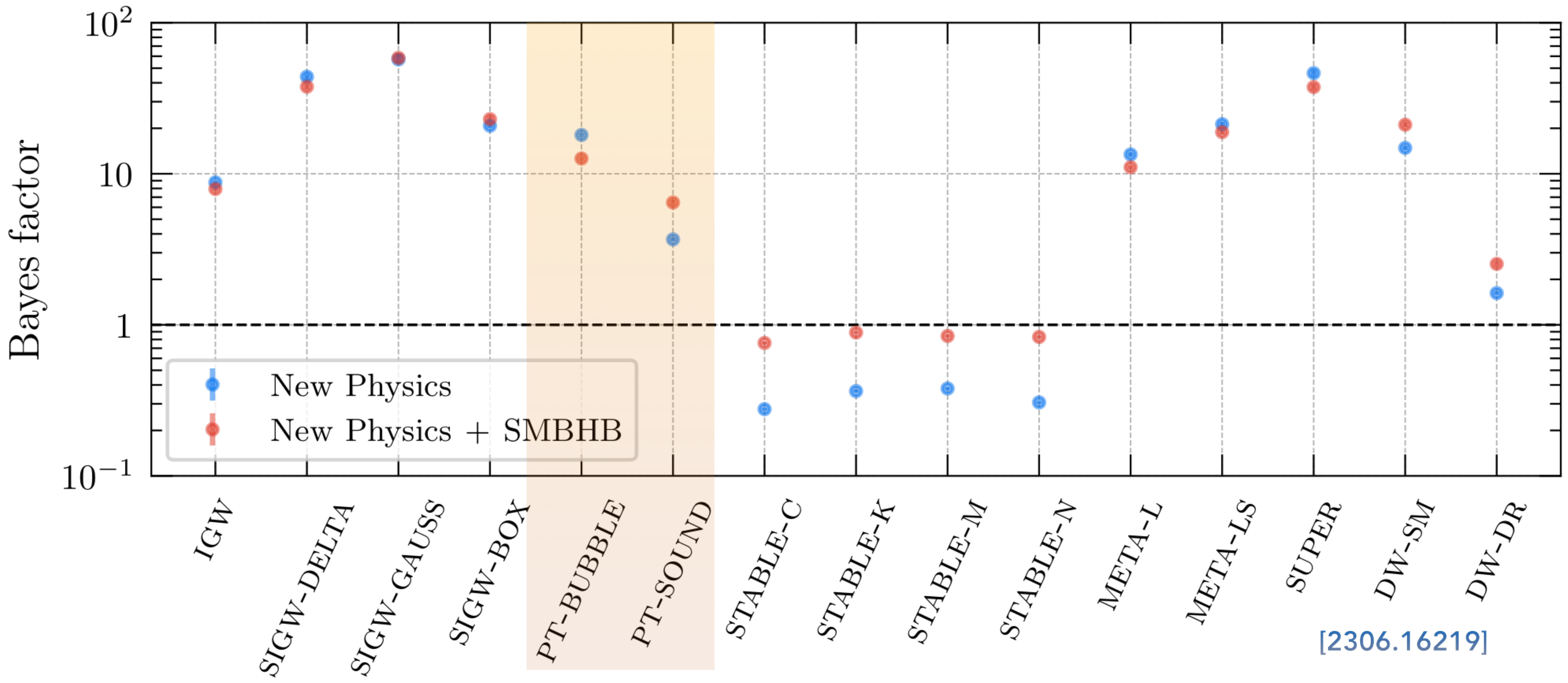
- **Procedure automatised in DRAlgo**

[A. Ekstedt et al, Comput. Phys. Commun 288 (2023) 108725, 2205.08815]



[Image credit: P. Schicho]

NANOGrav 15-year New-Physics Signals [2306.16213]



[2306.16219]

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