GRAVITATIONAL SIGNATURES OF SUPERCOOLING IN CONFORMAL HEAVY SINGLET HIGGS EXTENSIONS OF THE STANDARD MODEL

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To appear in 2409:XXXX

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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
- 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*

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

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- 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*

LHC sensitive to new scalars from tenths of GeV up to few TeV

Scalar field	Decay channel	Mass limits (GeV)	Comments	References
A	$A \to \tau^+\tau^-$	[200, 2500]	Limits given in terms of $\sigma \times$ BR	[8]
	$A \to \tau^+\tau^- b\bar{b}$	[200, 2500]	Limits given in terms of $\sigma \times$ BR	[8]
	$H_1 \to AZ^0$	[0.5, 4.0]	Hadronic decays with BR$(A \to gg) = 1$ or BR$(A \to s\bar{s}) = 1$	[11]
	$AA \to b\bar{b}b\bar{b}$	[20, 60]	Limits given in terms of $\sigma \times$ BR	[15]
	$A \to HZ^0$	...	Associated Z^0 production Limits m_H vs m_A Multiple channels $2\ell 2b$, $2\ell 4j$, $2\ell 4b$	[12]
	$A \to \gamma\gamma$	[160, 2800]	Limits given in terms of $\sigma \times$ BR	[3]
H	$H \to \tau^+\tau^-$	[200, 2500]	Limits given in terms of $\sigma \times$ BR	[8]
	$H \to \tau^+\tau^- b\bar{b}$	[200, 2500]	Limits given in terms of $\sigma \times$ BR	[8]
	$HH \to b\bar{b}b\bar{b}$	[260, 1000]	Vector-boson fusion	[6]
	$H \to VV$	[300, 3200] ggF [300, 760] VBF [300, 2000] ggF	Coupling constraints First two for Kaluza-Klein (KK) massive gravitons, third for radion. V indicates vector boson	[4]
	$H \to Z^0Z^0$	[400, 2000]	Various widths assumptions VBF and gluon fusion Fully and semileptonic	[5]
	$H \to \gamma\gamma$	[160, 2800]	Limits given in terms of $\sigma \times$ BR	[3]
	$H(H_1) \to AA$	[16, 62]	$H_1 \to AA \to b\bar{b}\mu^+\mu^-$	[16]
		[15, 60]	$H_1 \to AA \to \ell^+\ell^-\ell^+\ell^-$	[9]
		[3.6, 21]	$H(H_1) \to AA \to \mu^+\mu^-\tau^+\tau^-$	[10]
H $^{\pm}$	$pp \to tbH^+$	[200, 2000] [200, 3000]	In both: $H^+ \to tb$ Constraints of $m_H^{\pm}$ vs $\tan\beta$ (both) Limits as $\sigma \times$ BR (both)	[17] [18]
	$H^{\pm} \to W^{\pm}Z^0$	[200, 1500]	Considers VBF production Limits as $\sigma \times$ BR	[19]
	$H^{\pm} \to cs$	[80, 160]	Assumes BR$(H^{\pm} \to cs) = 1$ Limits as BR$(t \to H^+ b)$ vs m_{H^+}	[7]

All references in: [2211:10109], P.M.Ferreira, J.Gonçalves, A.P.Morais, A.Onofre, R.Pasechnik, V.Vatellis

New flavour universal U(1) gauge symmetries must be broken at scales above 5 TeV

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 139)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Limit			Reference
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	139	Z′ mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	36.1	Z′ mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z′ mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	$0\ e, \mu$	≥ 1 b, ≥ 2 J	Yes	139	Z′ mass	4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	139	W′ mass	6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	$1\ \tau$	–	Yes	36.1	W′ mass	3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	$1\ e, \mu$	2 j / 1 J	Yes	139	W′ mass	4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	$0\ e, \mu$	2 J	–	139	V′ mass	3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V′ mass	2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	$0\ e, \mu$	≥ 1 b, ≥ 2 J		139	W′ mass	3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass	3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	$2\ \mu$	1 J	–	80	W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679

↓

New flavour universal U(1) gauge symmetries must be broken at scales above 5 TeV

↓

New Higgs bosons can be well beyond the reach of the LHC

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New flavour universal U(1) gauge symmetries must be broken at scales above 5 TeV

New Higgs bosons can be well beyond the reach of the LHC

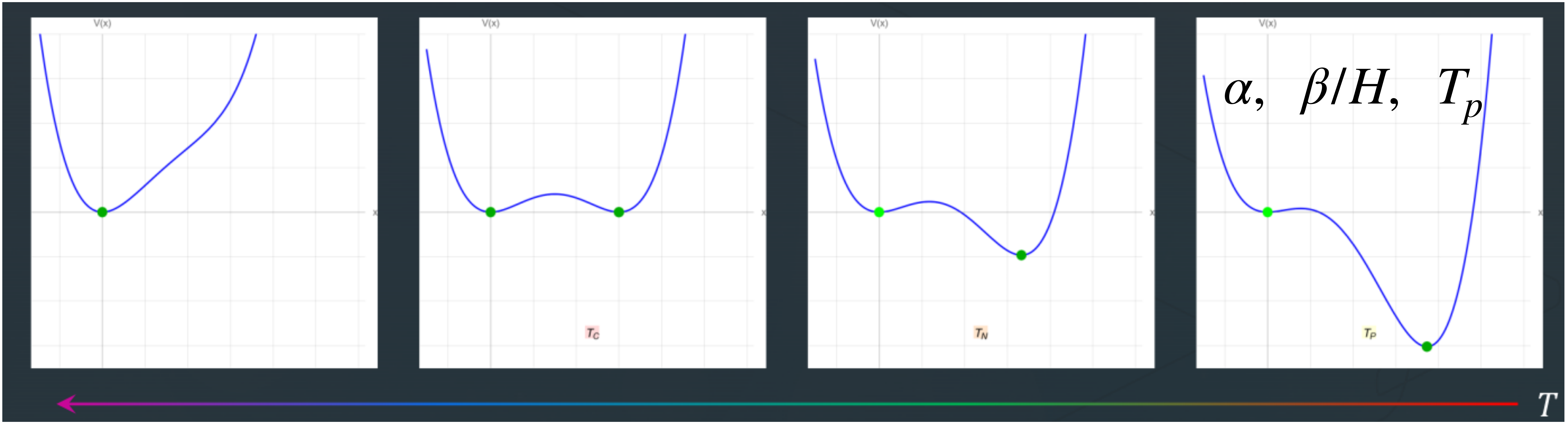
Can we indirectly test the presence of heavy or superheavy scalar sectors?

Short answer: YES

How? Measurement of stochastic gravitational waves background (SGWB) at interferometers — LISA, LIGO-Virgo-Kagra (LVK), Einstein Telescope (ET), BBO, muARES

Which source of SGWB? First order phase transitions (FOPT) in the early Universe e.g. in the presence of new gauge symmetries

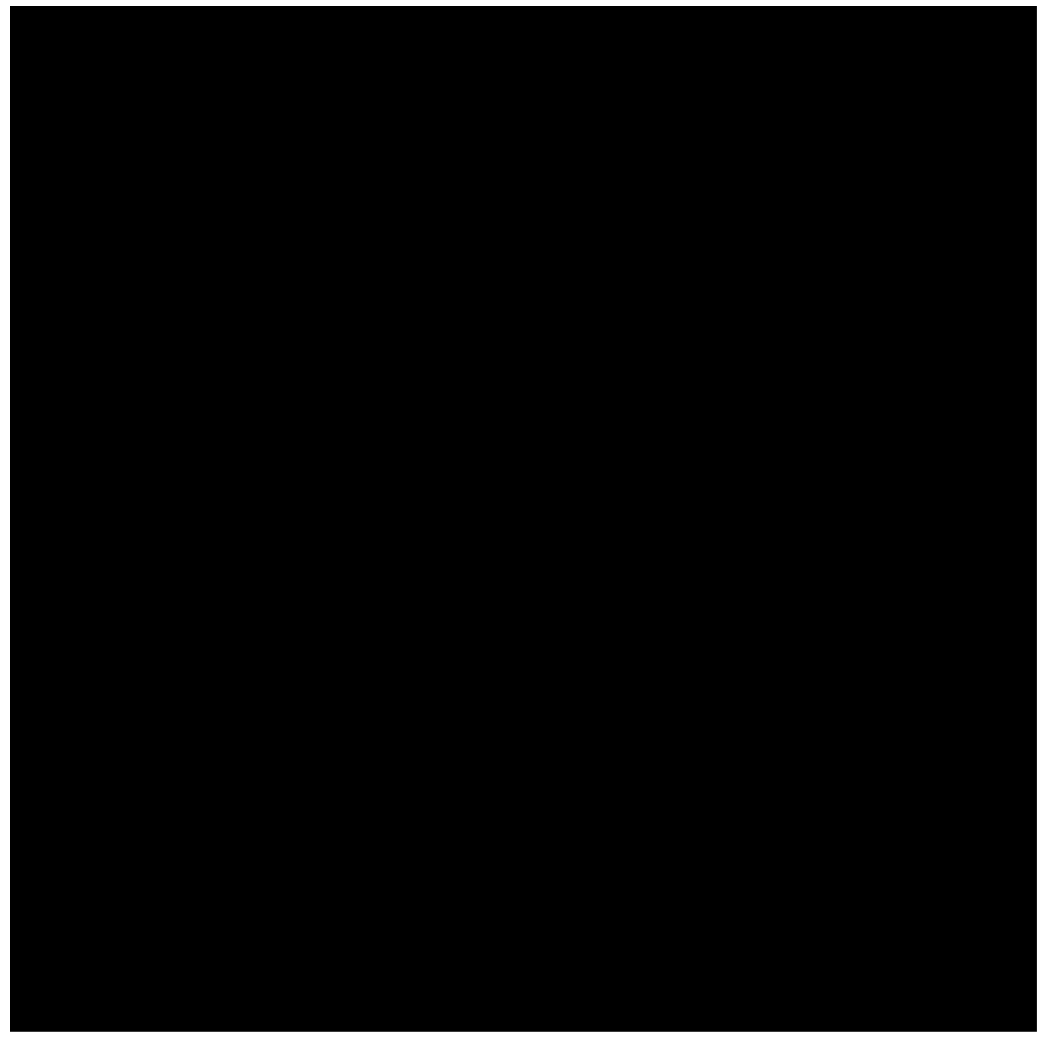
First order phase transition (FOPT)
(Illustration)

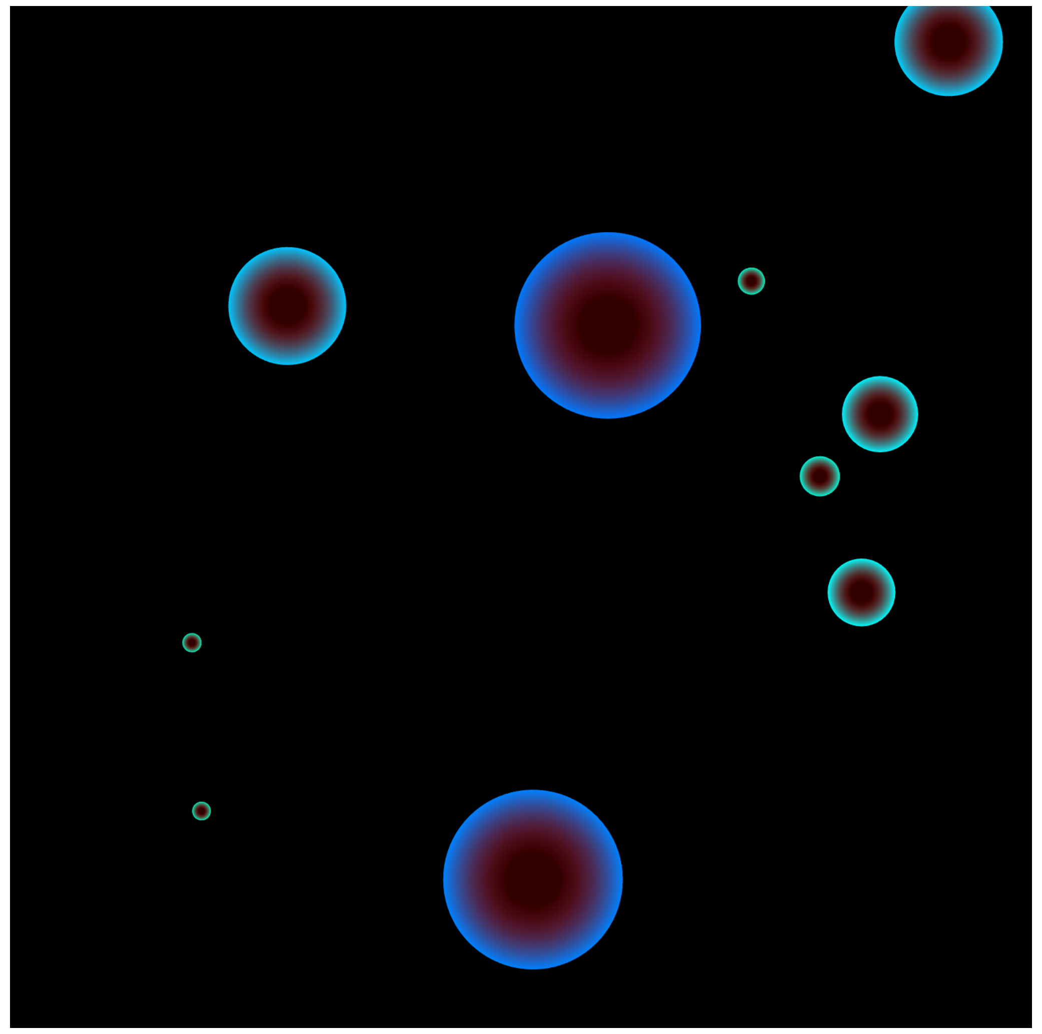


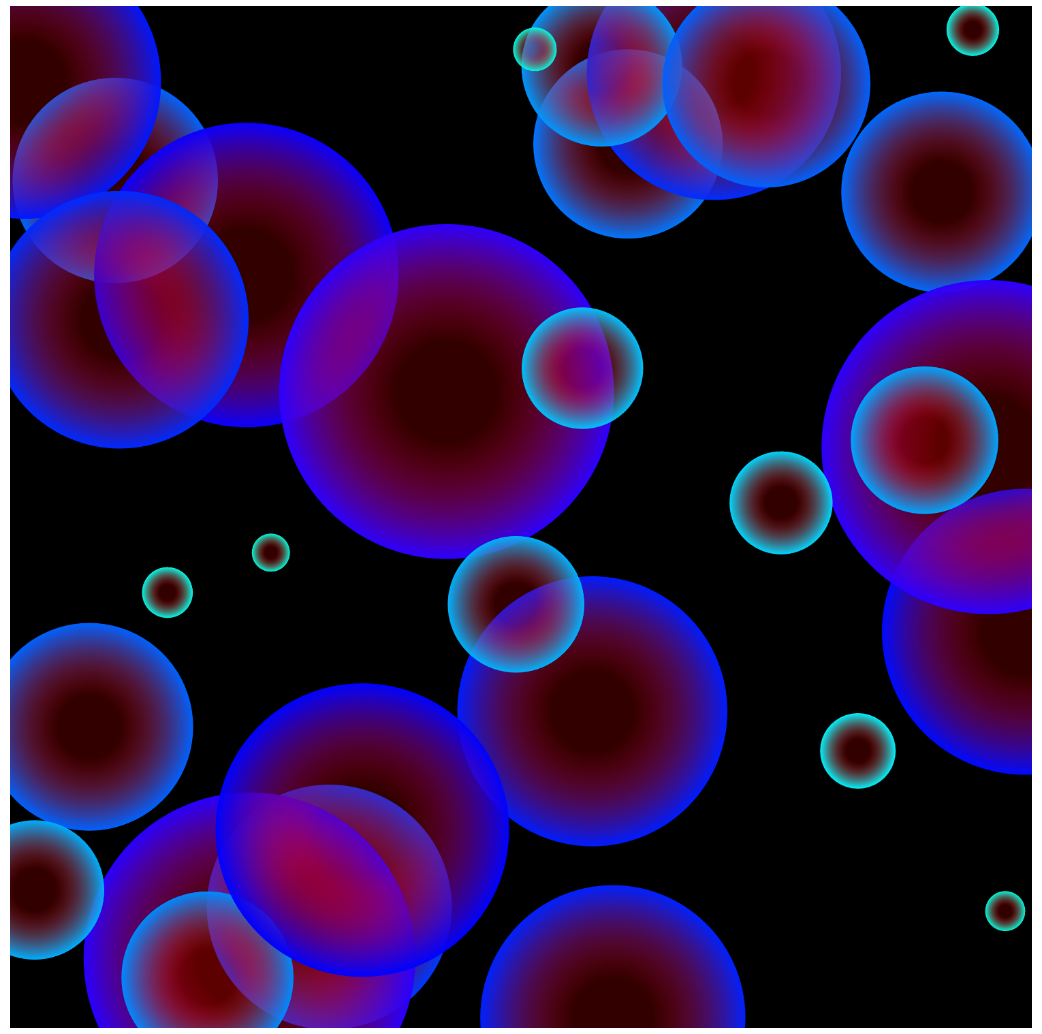
Strength α

Inverse duration β/H

Percolation temperature T_p

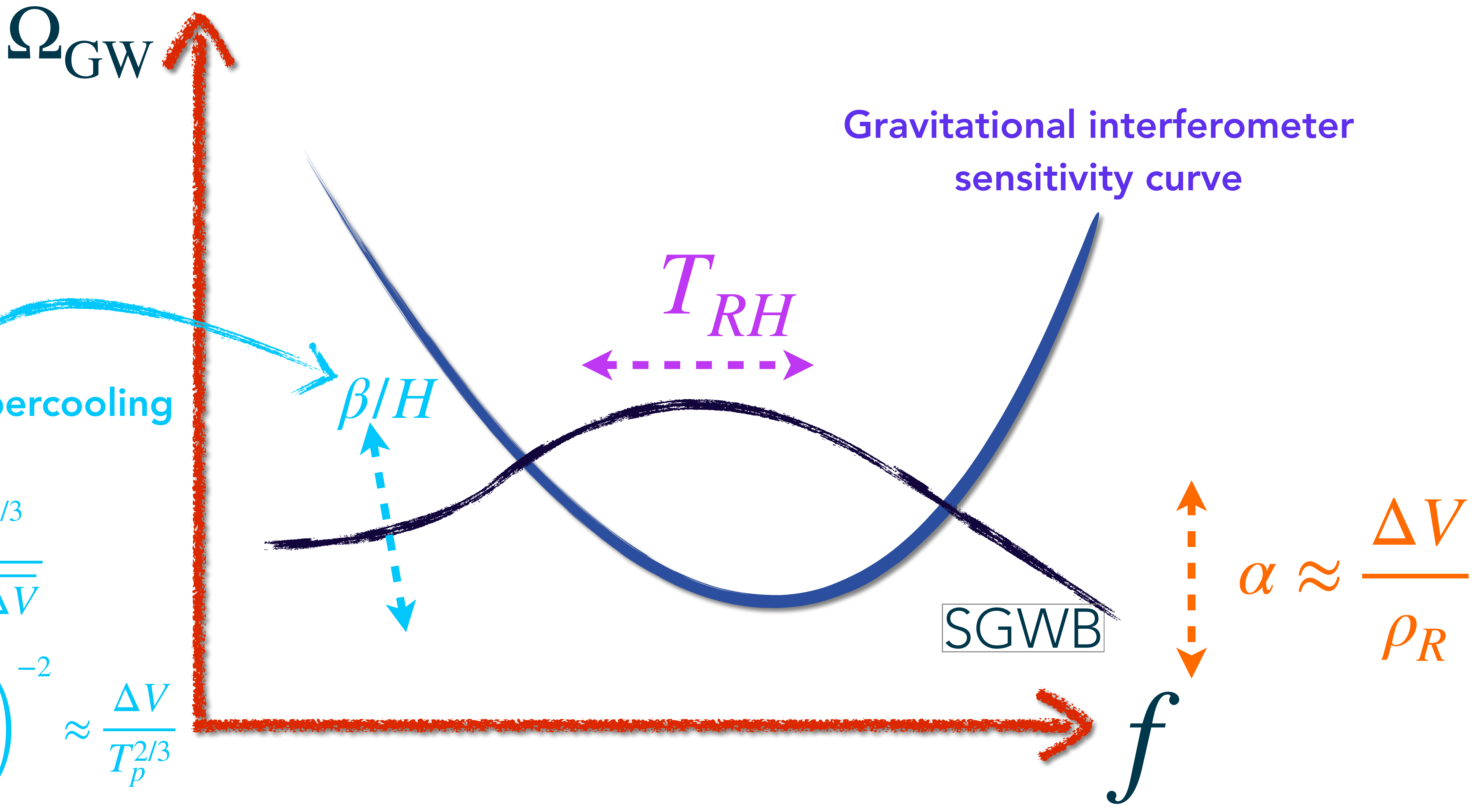






Credit: Marco Finetti

Effect of the thermodynamic parameters on the SGWB



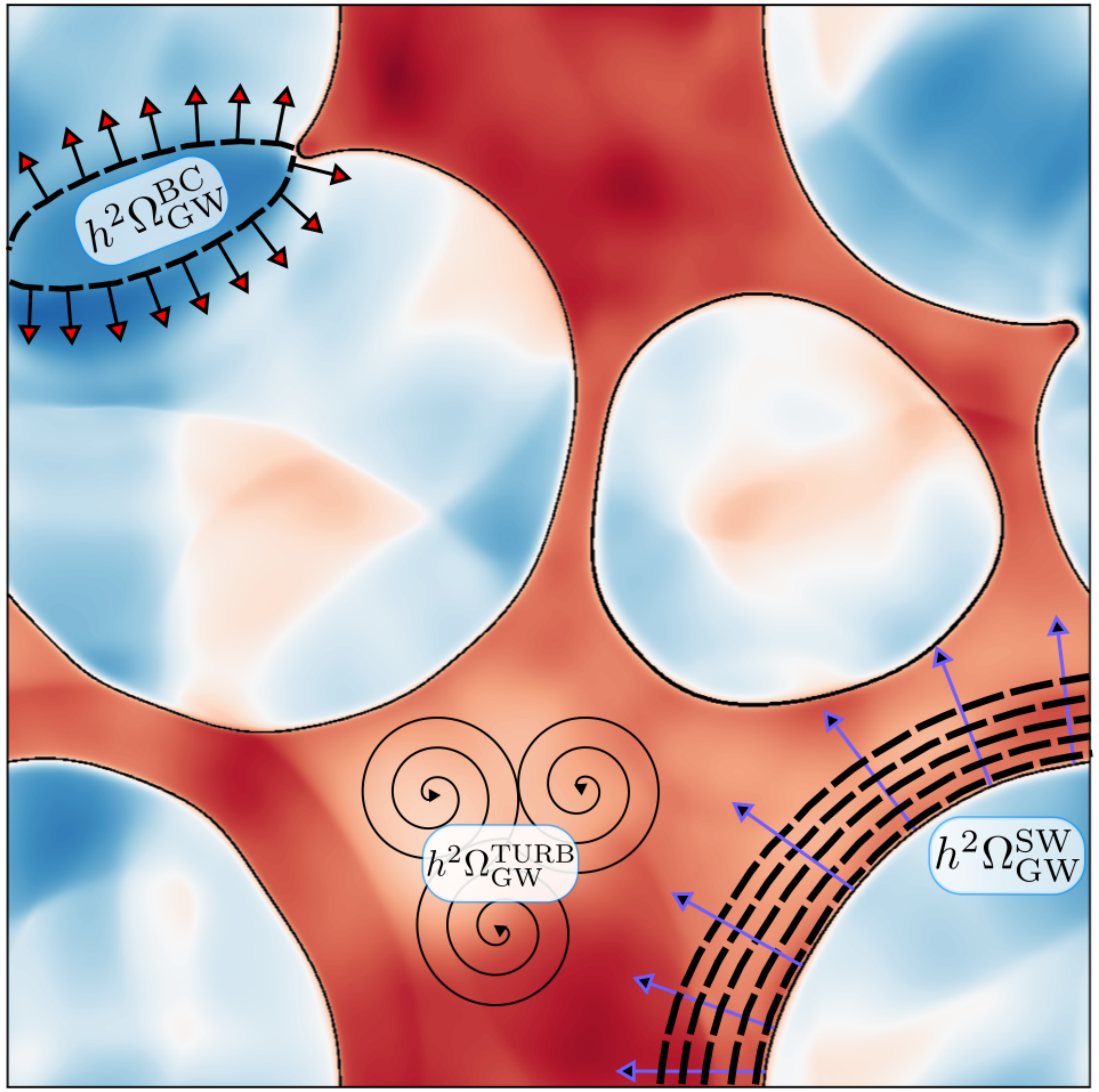
With strong supercooling

$$\alpha \gg 1$$

$$\frac{\beta}{H(T_p)} \approx \frac{T_p^{1/3}}{\sqrt{\Delta V}}$$

$$\Omega_{\rm GW} \approx \left(\frac{\beta}{H(T_p)}\right)^{-2} \approx \frac{\Delta V}{T_p^{2/3}}$$

Sources of SGWB



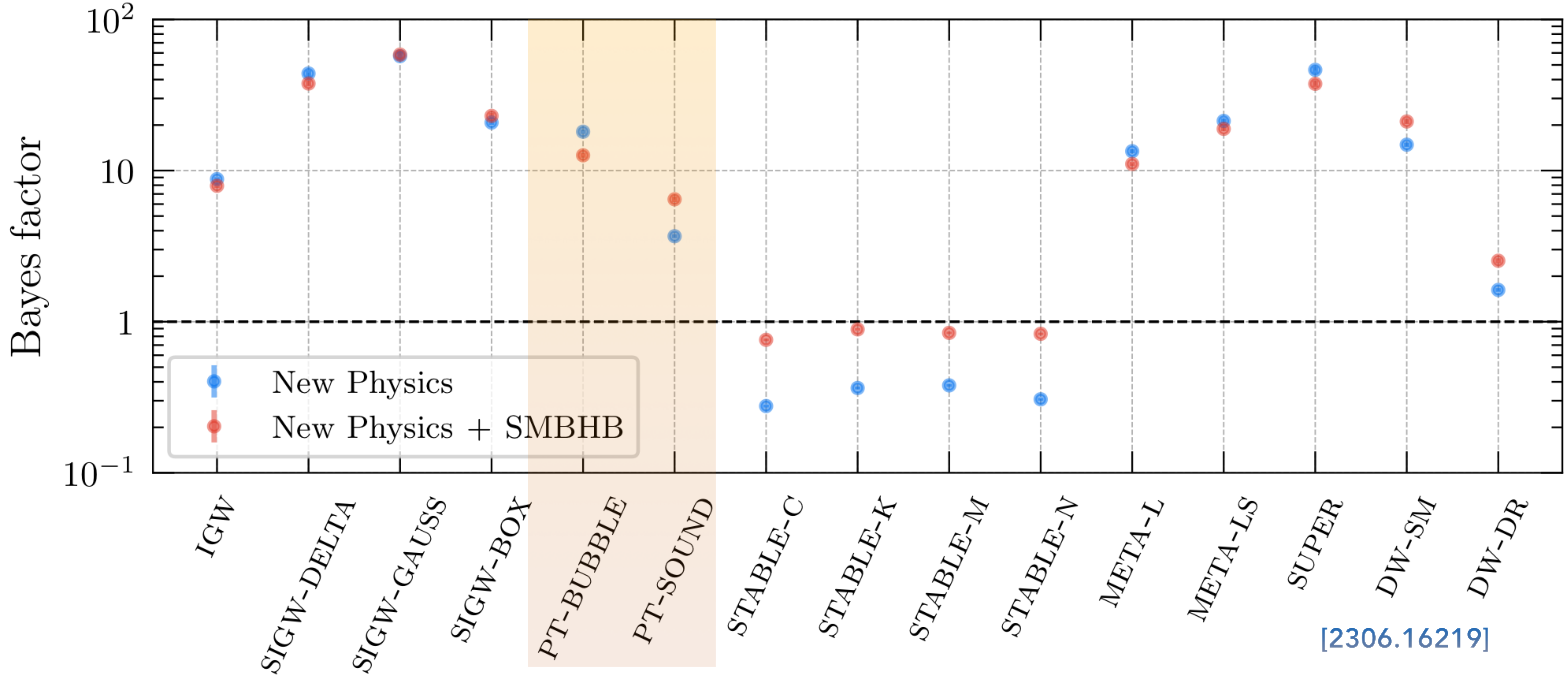
Adapted from Phys.Rev.Lett. 125 (2020) 2, 021302

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]

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

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

$$\mathcal{L}_\nu = y_\nu^{ij}\overline{L}_i\tilde{\mathcal{H}}\nu_{\mathrm{R}j} + y_\sigma^{ij}\bar{\nu}^c_{\mathrm{R}i}\nu_{\mathrm{R}j}\sigma + \mathrm{h.c.}$$

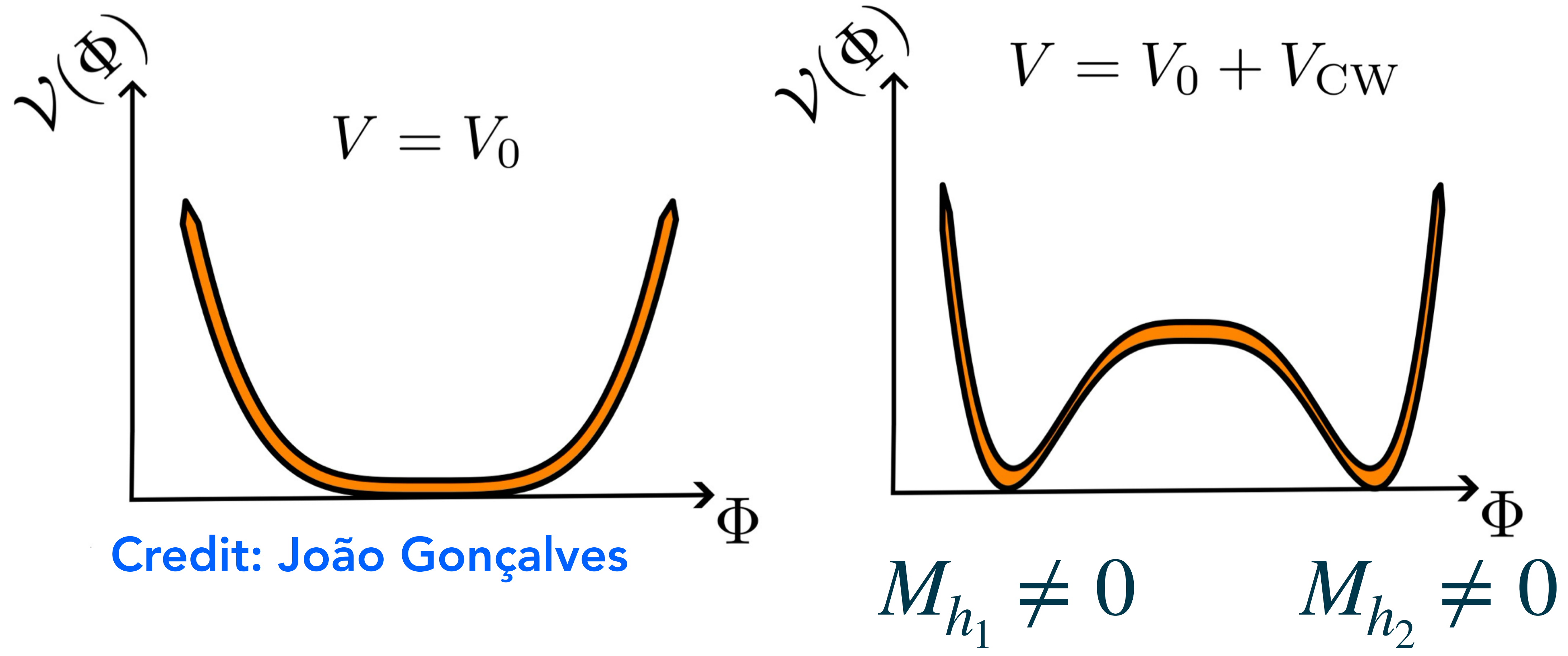
Neutrino masses and mixing via type-I seesaw

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

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

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.



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

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

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

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

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

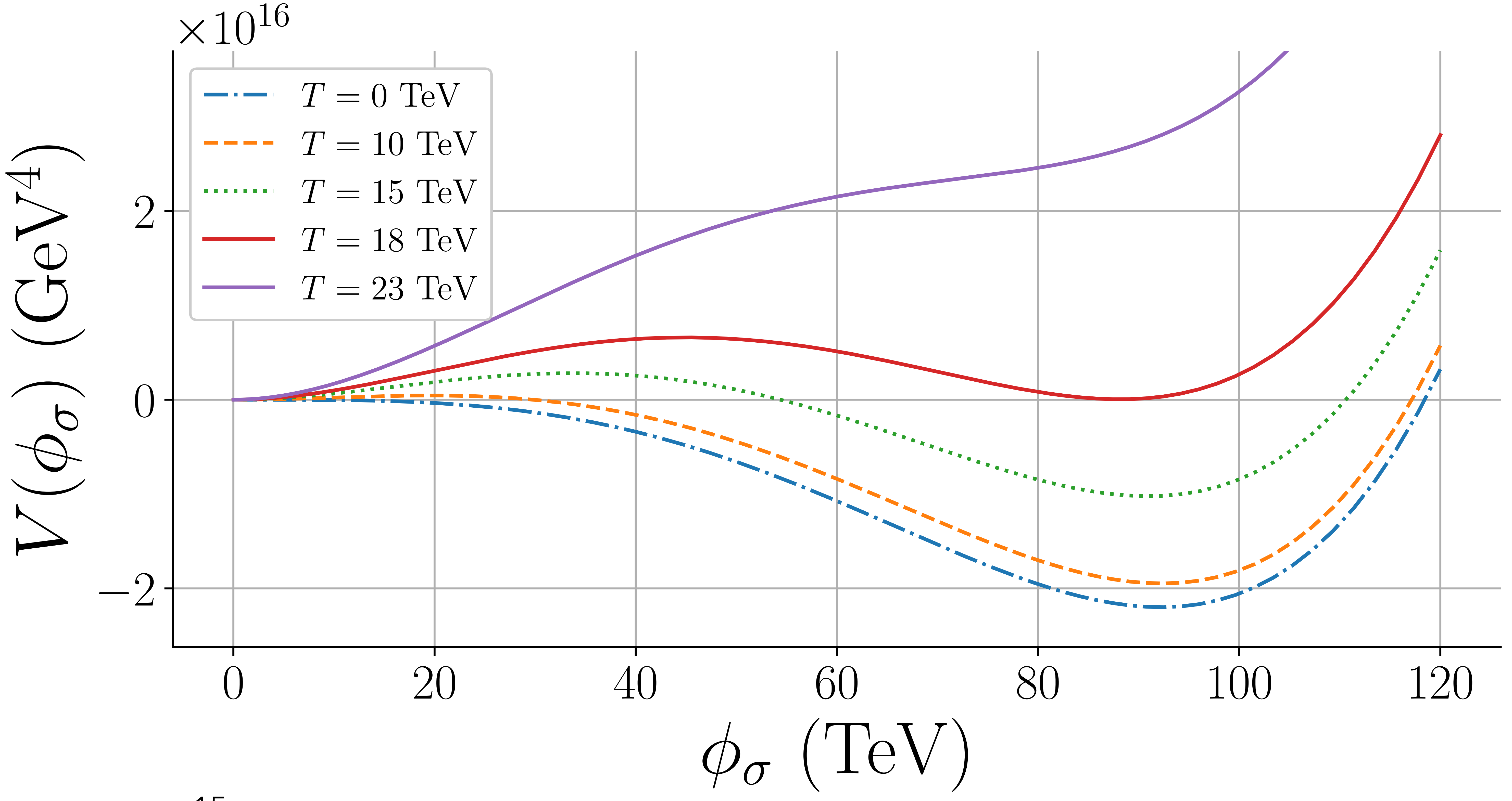
$$V_{\rm eff}^{\rm HT} = \phi_\sigma^4 \left(-\frac{g_L^4}{2\pi^2} - \frac{g_L^3}{2\sqrt{2}\pi} + \frac{\lambda_\sigma}{4} + \frac{\ln 2 \left([\sum_{i=1}^3 [\boldsymbol{y_\sigma^4}]_{ii} \right)}{32\pi^2} \right) - \phi_\sigma^3 \frac{4 g_L^3 T}{3\pi} + \phi_\sigma^2 \left(\frac{g_L^2 T^2}{2} - \frac{g_L^3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

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



Just a few technicalities

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

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

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

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

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

Use `CosmoTransitions` for phase tracing and bounce solution

From thermodynamic to SGWB geometric parameters

$$h^2\Omega_{\rm GW}^{\rm peak} \propto \left(\frac{\alpha}{1+\alpha}\right)^2 \left(\frac{\beta}{H(T_p)}\right)^{-2} \left(\frac{\Gamma_{h_2}}{H(T_p)}\right)^{2/3} \qquad f_{\rm peak} \propto \left(\frac{\beta}{H(T_p)}\right)\left(\frac{T_{\rm RH}}{\rm GeV}\right)\left(\frac{\Gamma_{h_2}}{H(T_p)}\right)^{-1/3}$$

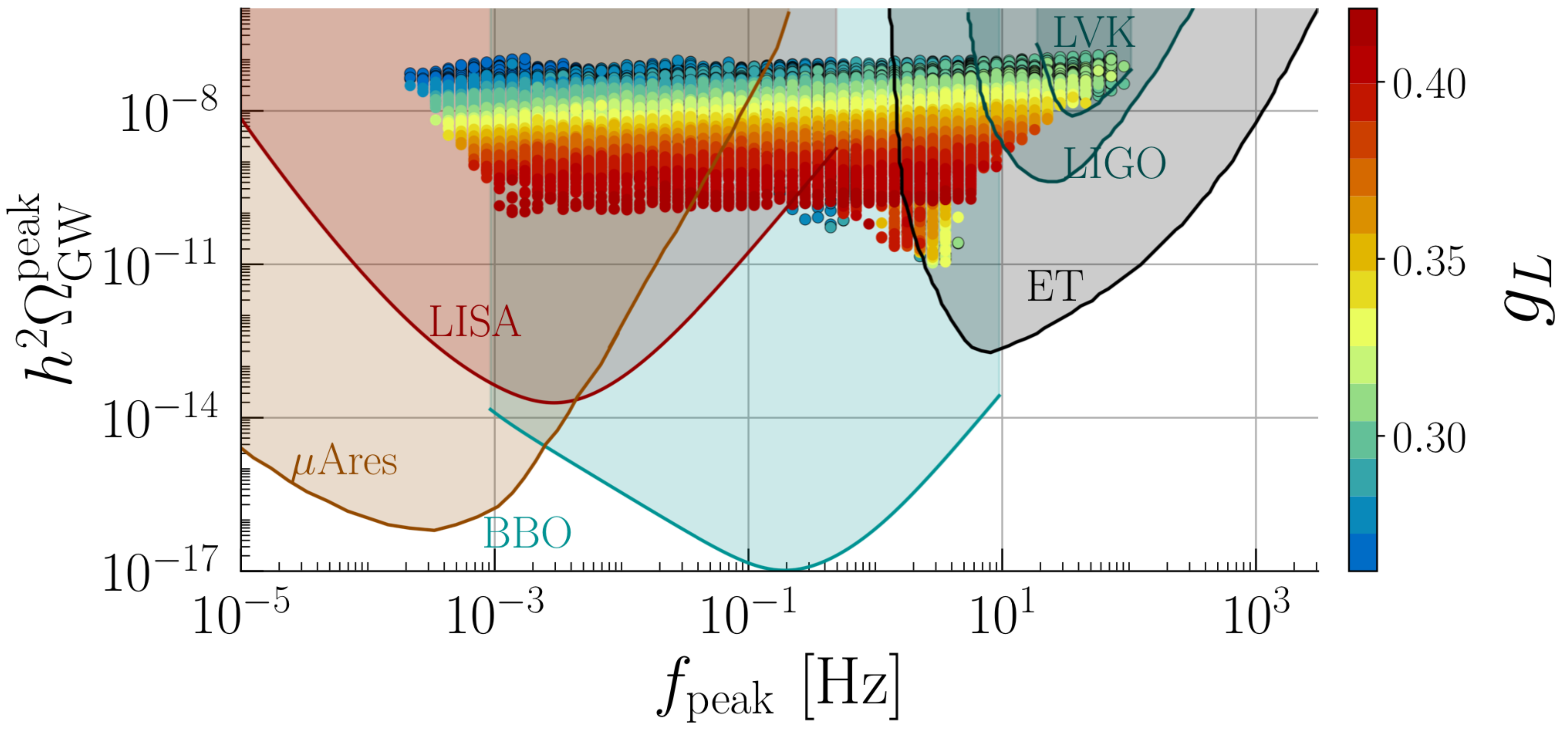
$$T_{\rm RH} \approx T_p(1+\alpha)^{1/4}\left(\frac{\Gamma_{h_2}}{H(T_p)}\right)^{1/2}$$

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

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

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

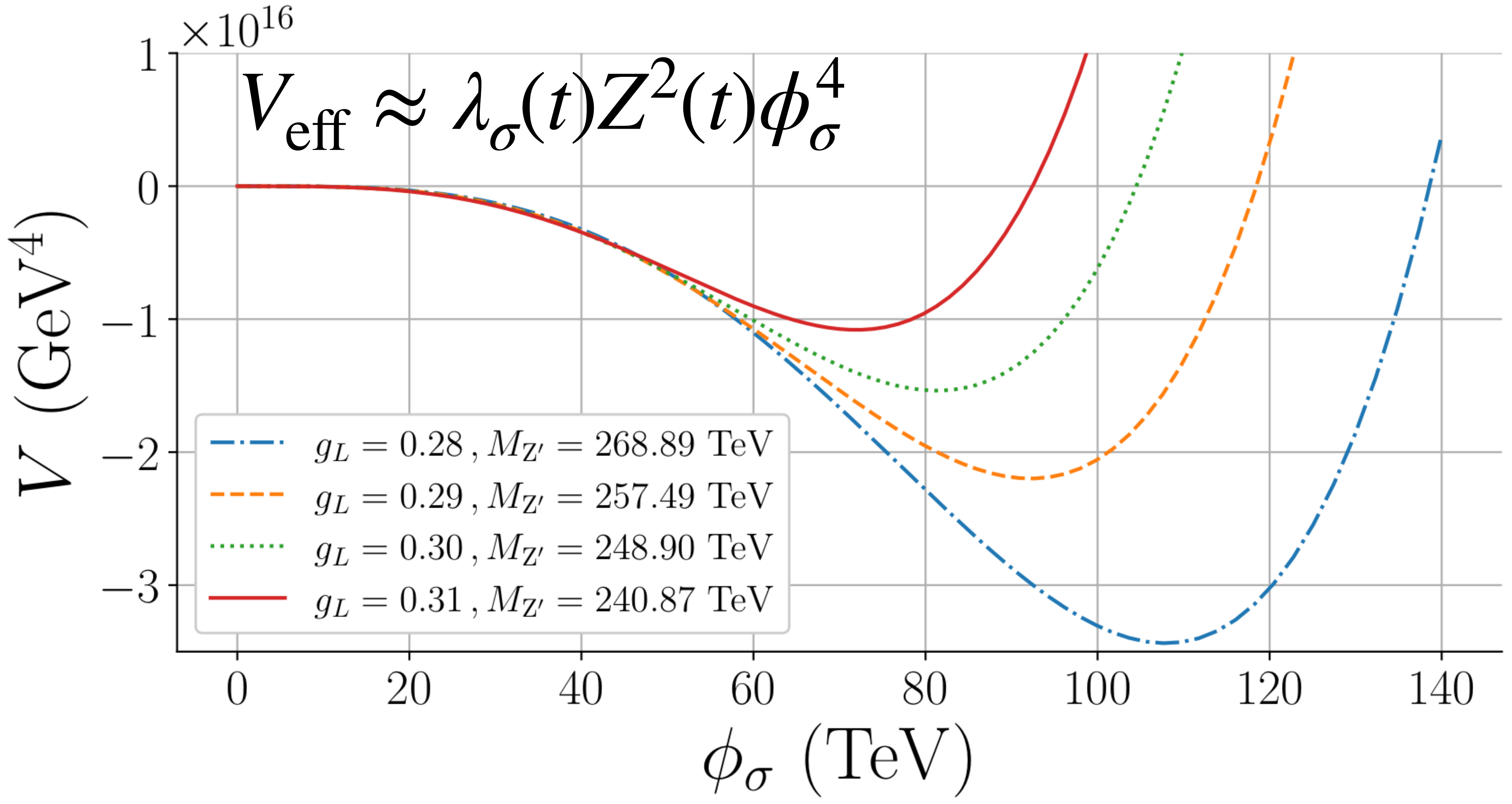
SGWB predictions: The $\mathrm{U}(1)_{\mathrm{B-L}}$ case $x_\sigma = 2$ and $x_H = 0$

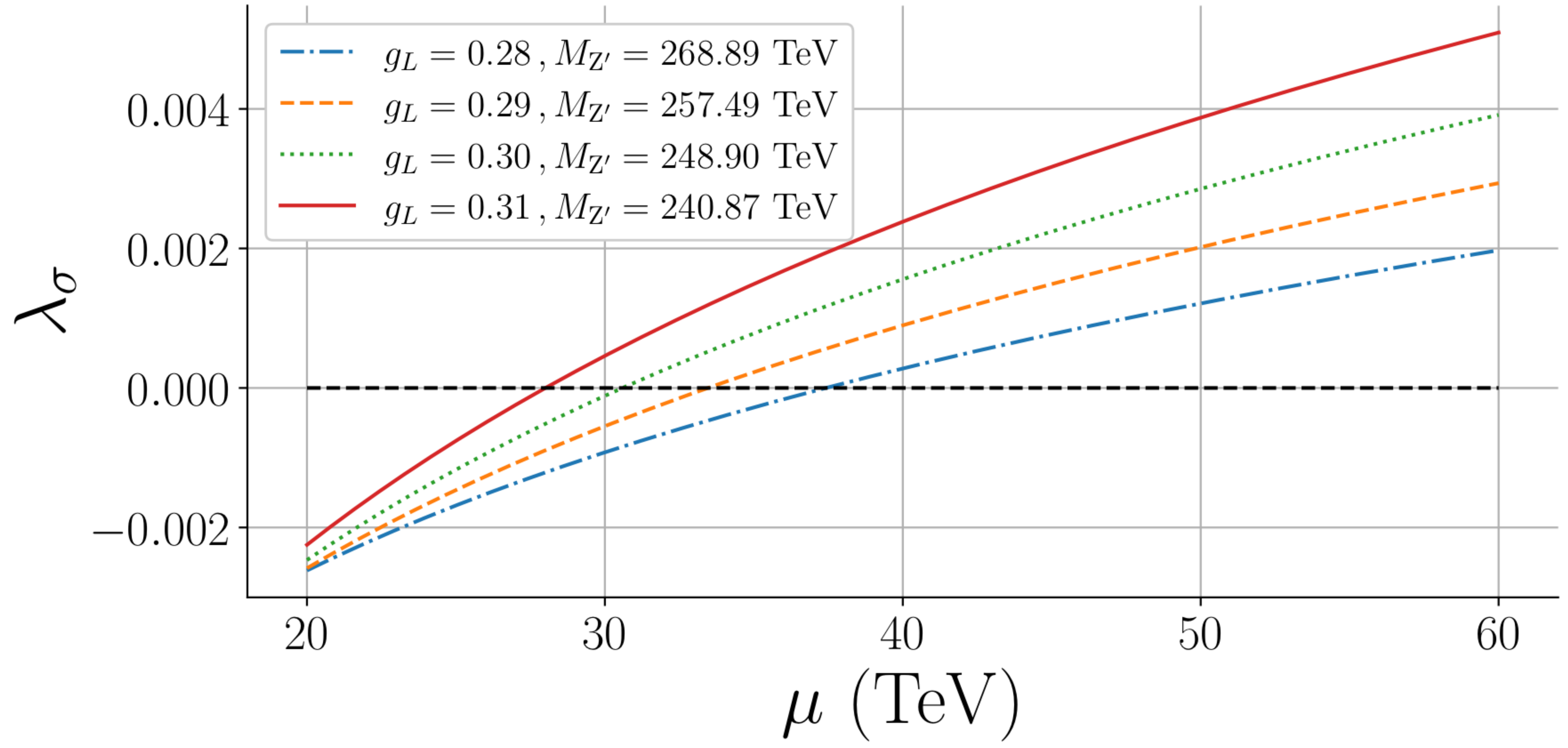


Gauge coupling controls the peak amplitude

Strong supercooled FOPTs with $\alpha > 10$ for $0.26 \lesssim g_L \lesssim 0.42$

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





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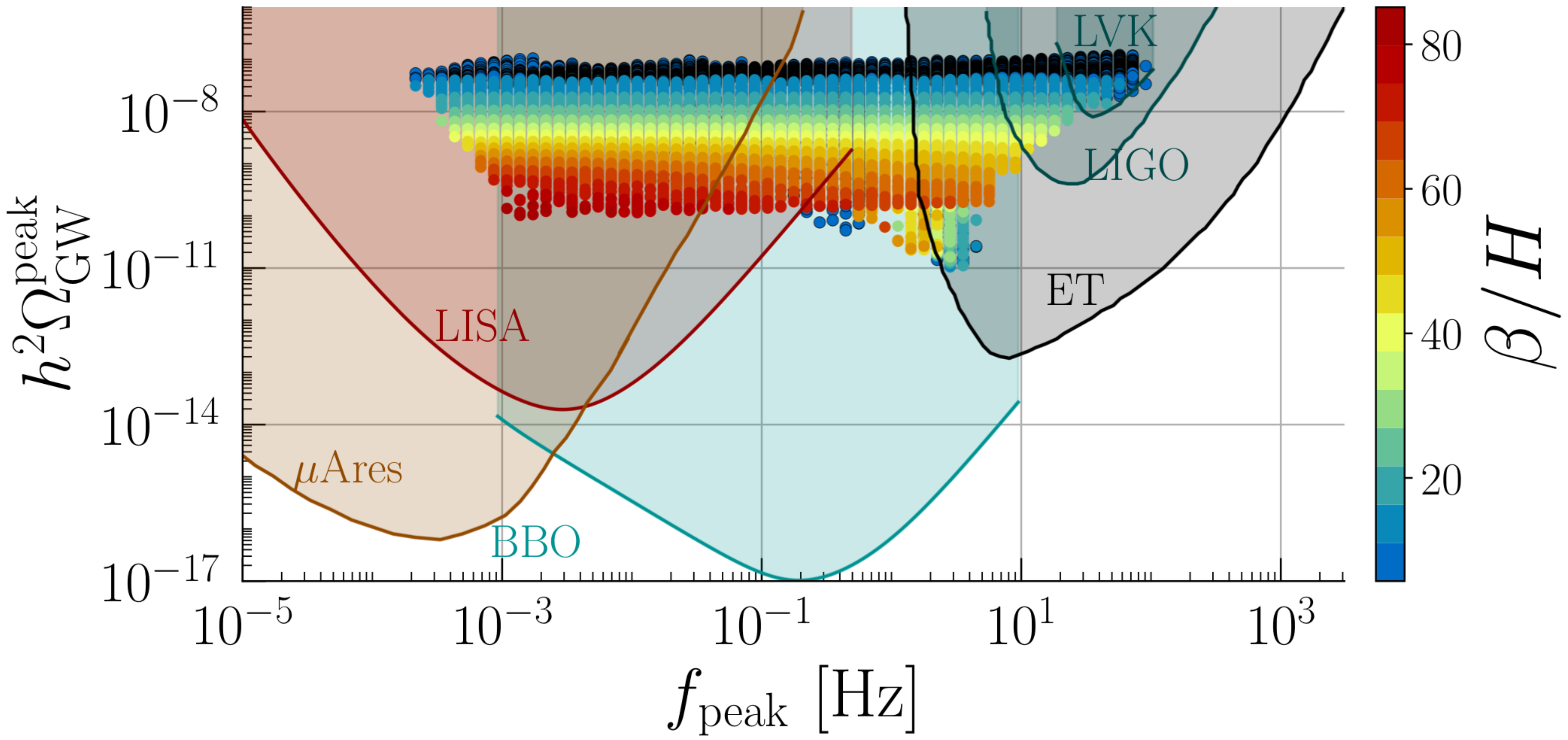
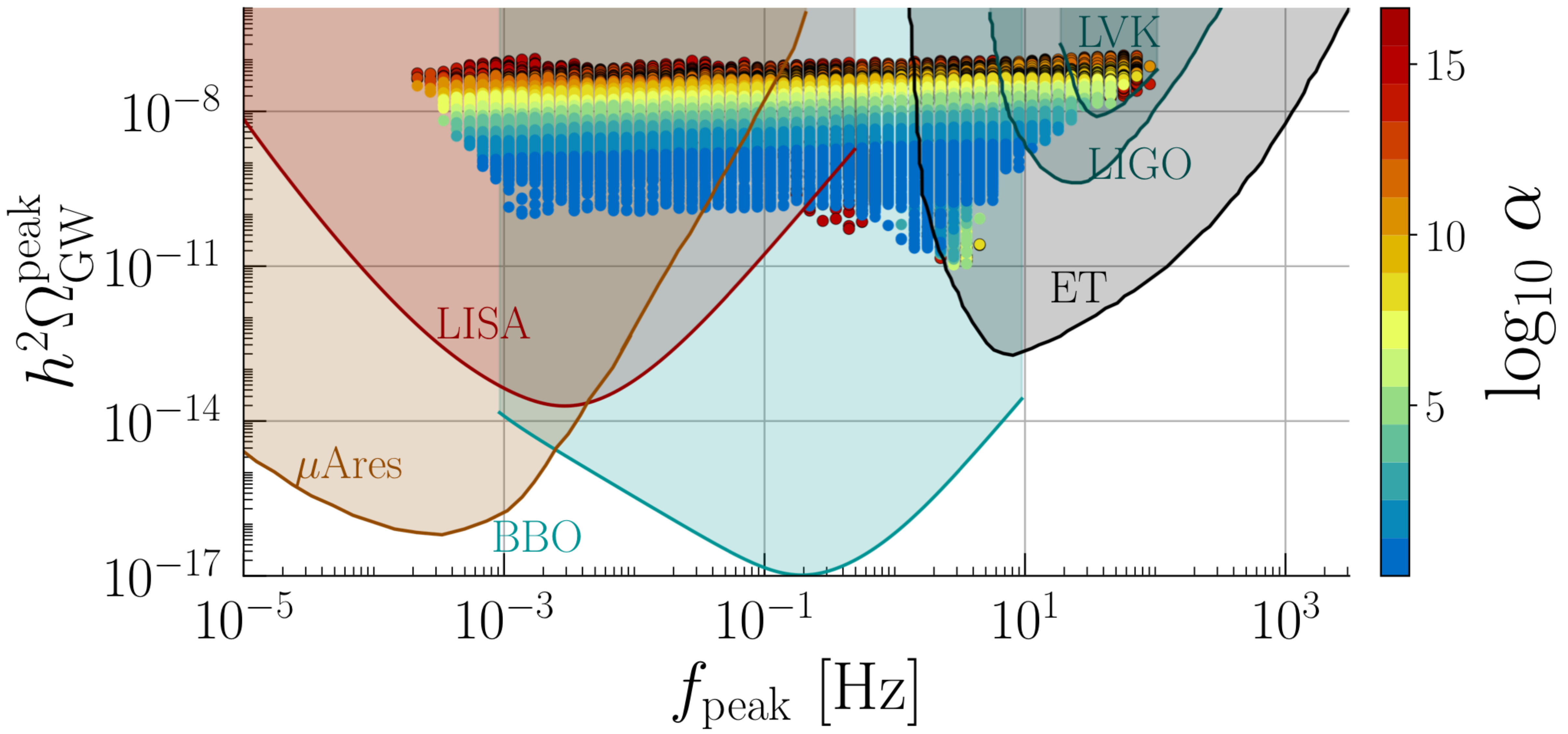




$$h^2\Omega_{\rm GW}^{\rm peak} \propto \left(\frac{\alpha}{1+\alpha}\right)^2 \left(\frac{\beta}{H(T_p)}\right)^{-2} \approx \frac{\Delta V}{T_p^{2/3}} \quad \text{for} \quad \alpha \gg 1$$

β/H dependency flattens out with strong supercooling

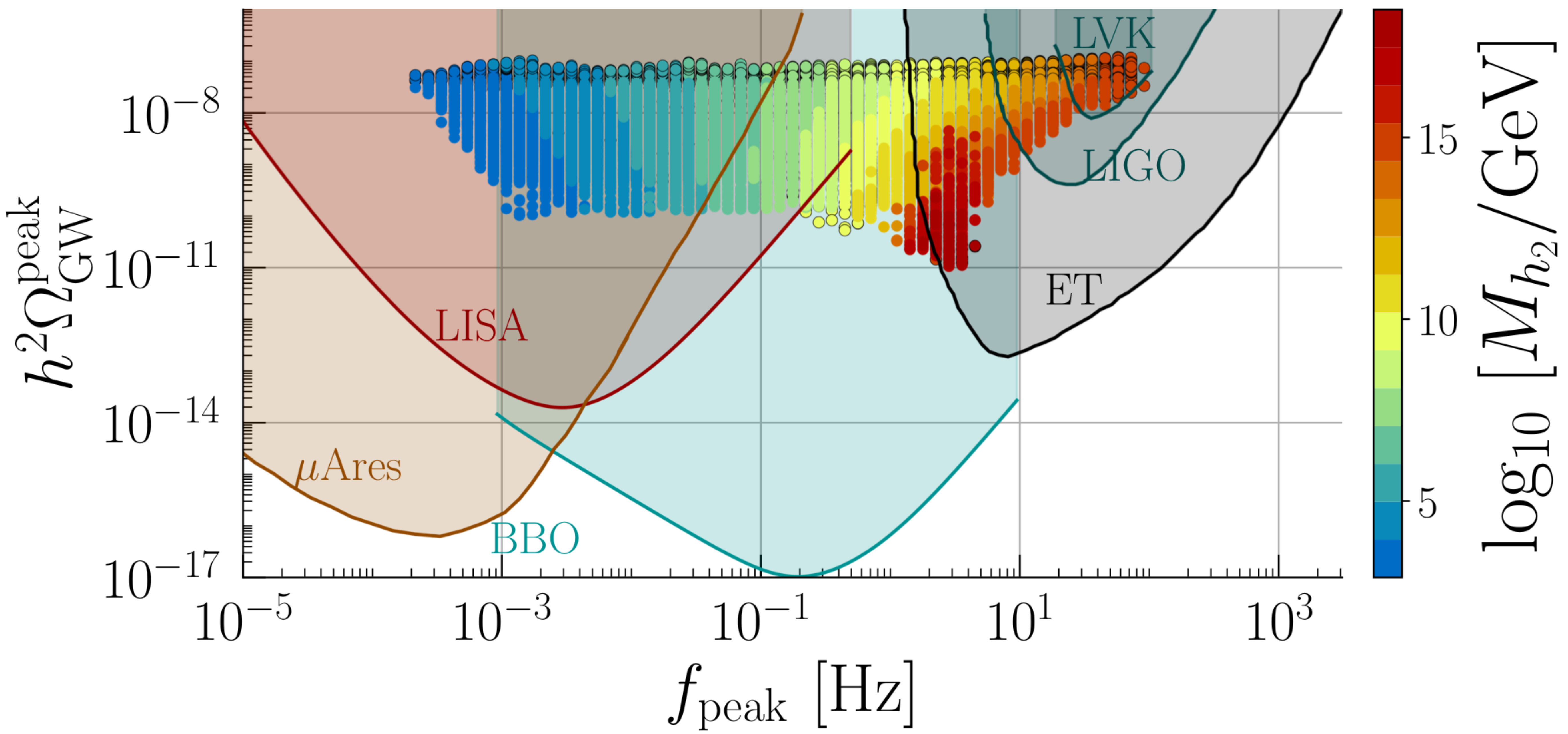
Full range of strong supercooling ($\alpha \gtrsim 100$) at the reach of LISA, ET and LIGO-O5 run (2028)

LVK data already puts constraints on heavy Higgs

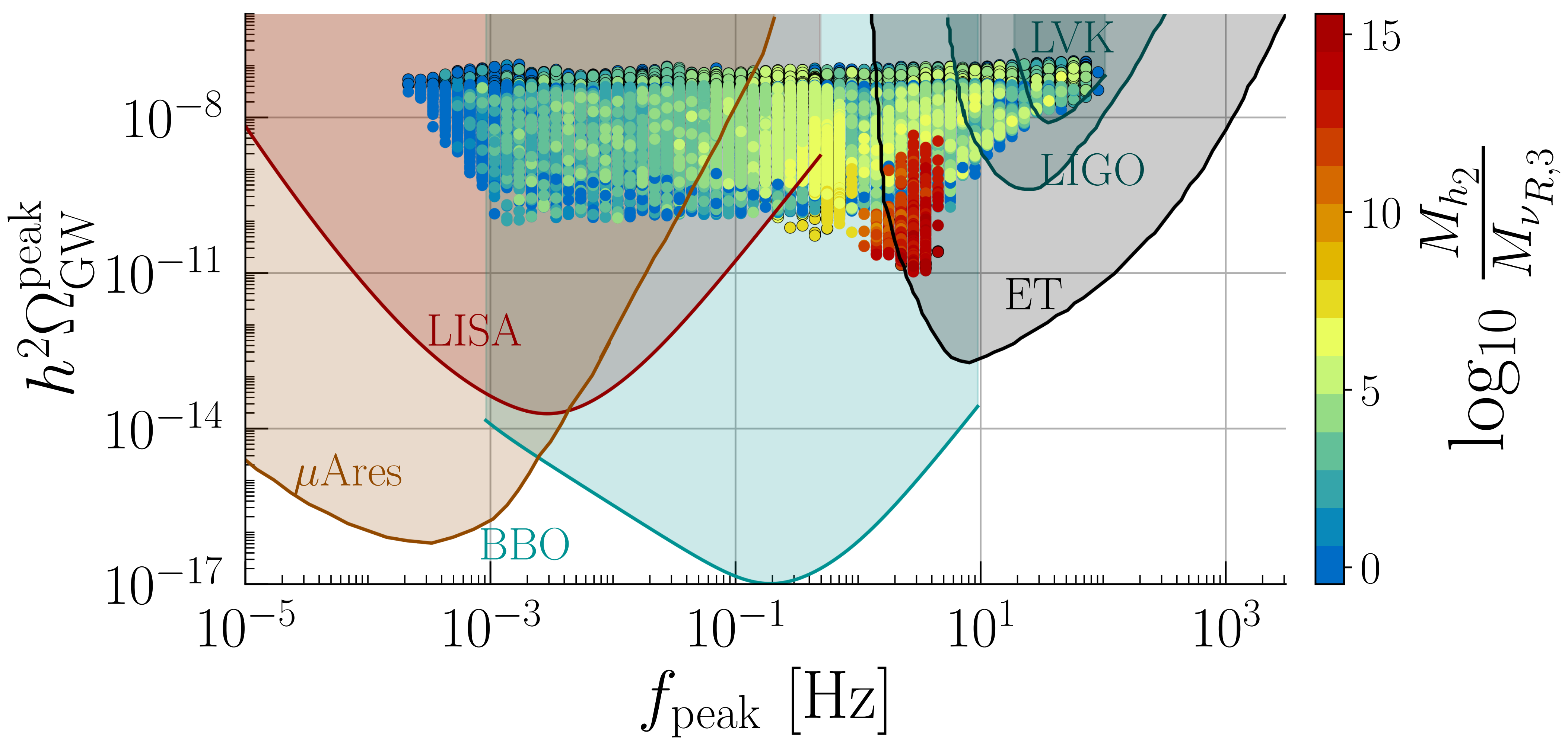
Lower bound on $\beta/H \gtrsim 8$ from PBH constraints
[Y. Gouttenoire, T. Volanski, 2305.04942]

In circled points the volume of false vacuum near T_p is not decreasing but only at $T < T_p$

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

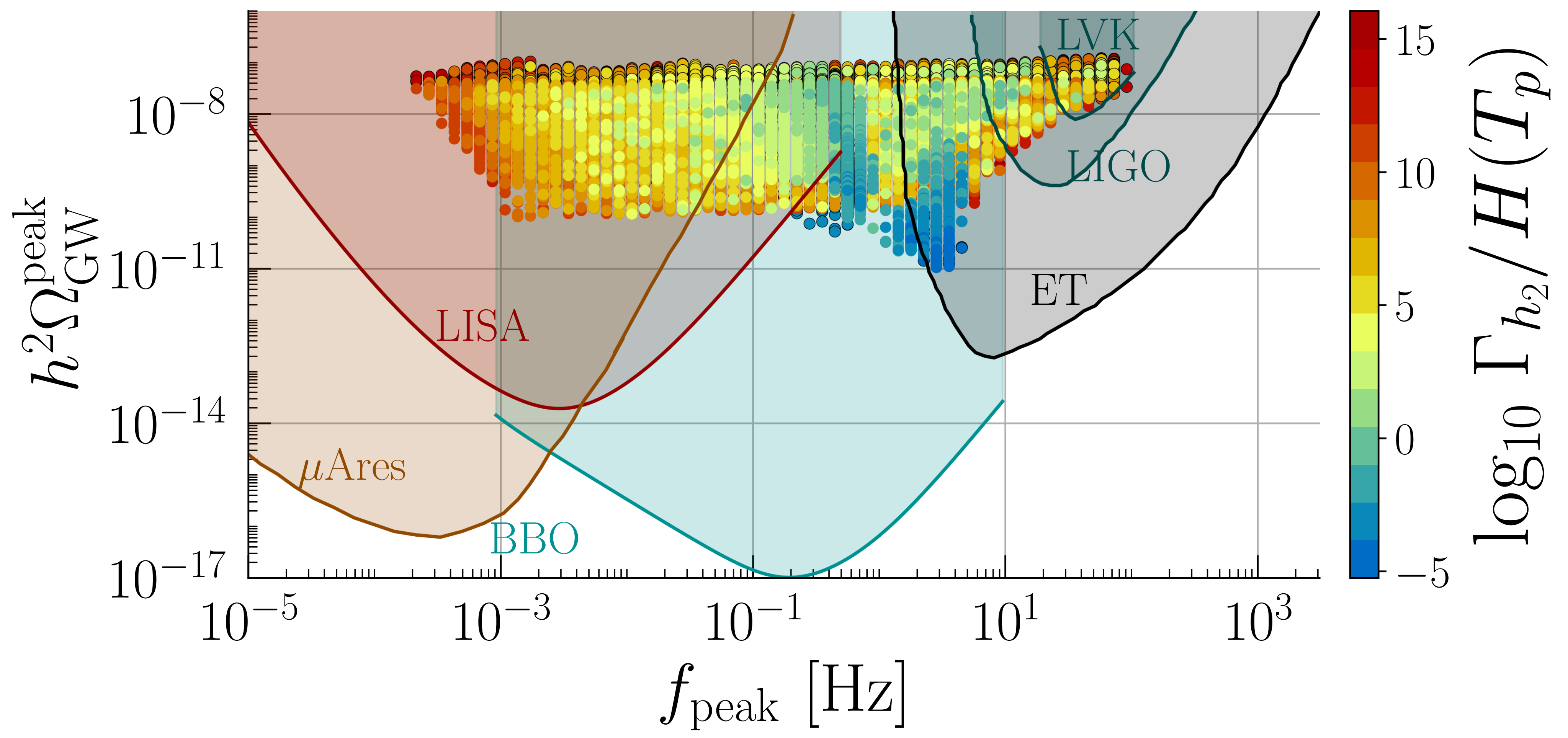


$$\Gamma_{h_2\to\bar{N}_i N_i} = \frac{M_{h_2}}{16\pi v_\sigma^2}\sum_{i=1}^{3} M_{N_i}^2\sqrt{1-\frac{4M_{N_i}^2}{M_{h_2}^2}}$$

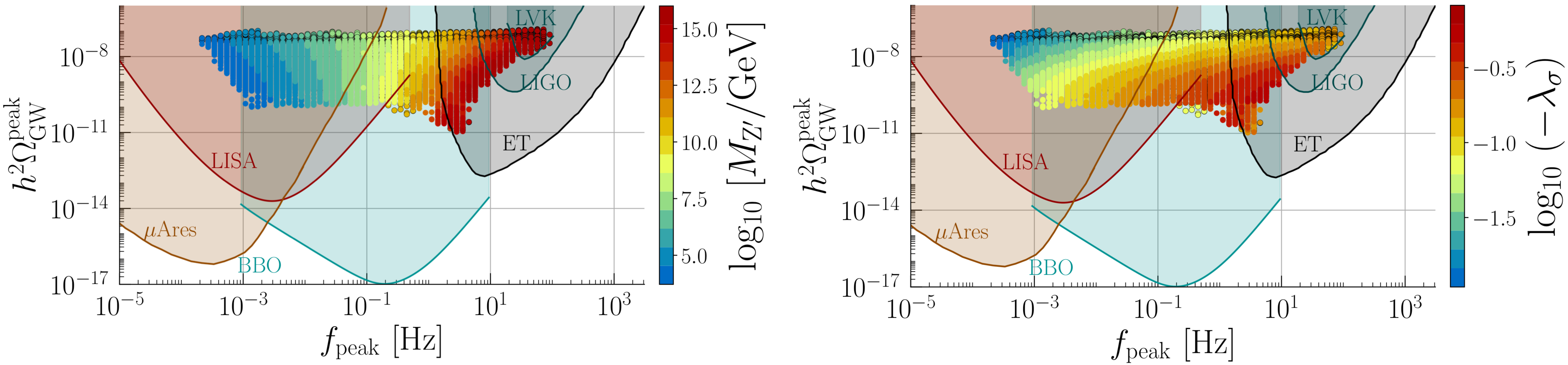


Heavy Higgs controls the peak frequency

Matter domination period suppresses the SGWB at high frequencies when $M_{h_2} \gg M_{\nu_{R,3}}$



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

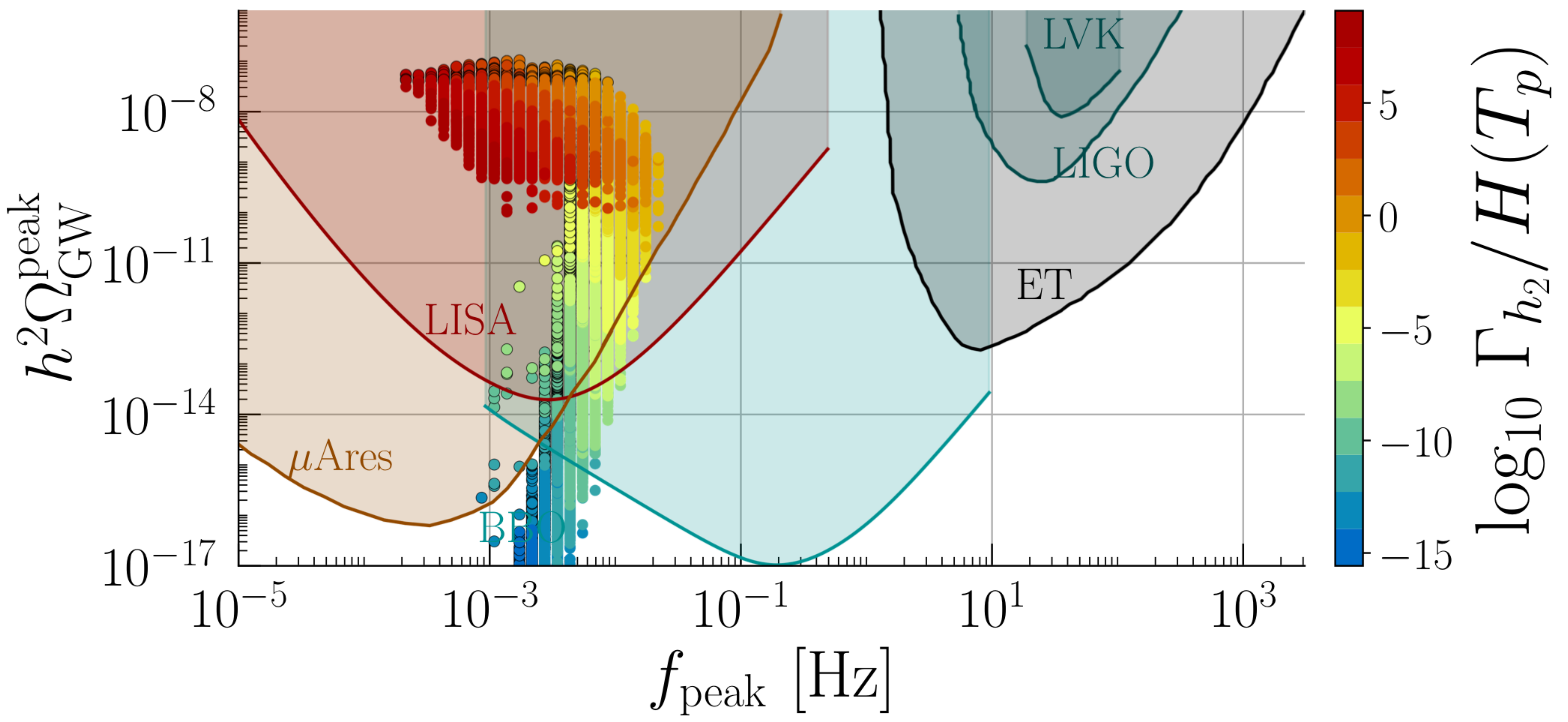


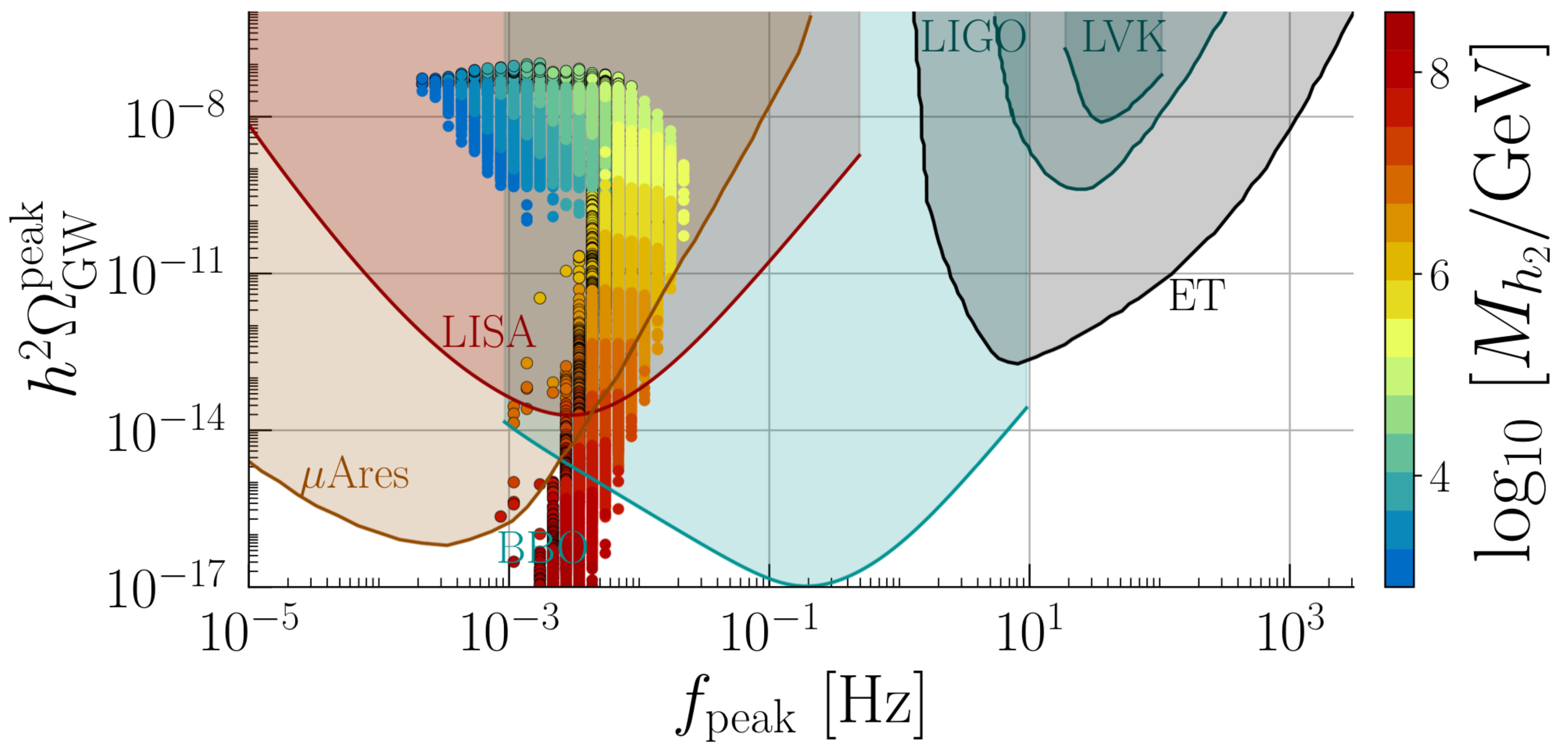
For fixed $g_L \Rightarrow$ fixed $h^2\Omega_{\rm GW}^{\rm peak} \Rightarrow$ similar $\beta_{\lambda_\sigma} \sim 3g_L^4 x_\sigma^4 + \cdots$

Similar behaviour with Z' mass since $M_{Z'} \sim M_{h_2} \sim v_\sigma$

- Low $f_{\rm peak}$: λ_σ must start at lower values to maximize ΔV
- High $f_{\rm peak}$: a larger breaking scale contributing to larger $\Delta V \sim v_\sigma^4$ implies larger λ_σ

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





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 signature of the neutrino sector in this class of models

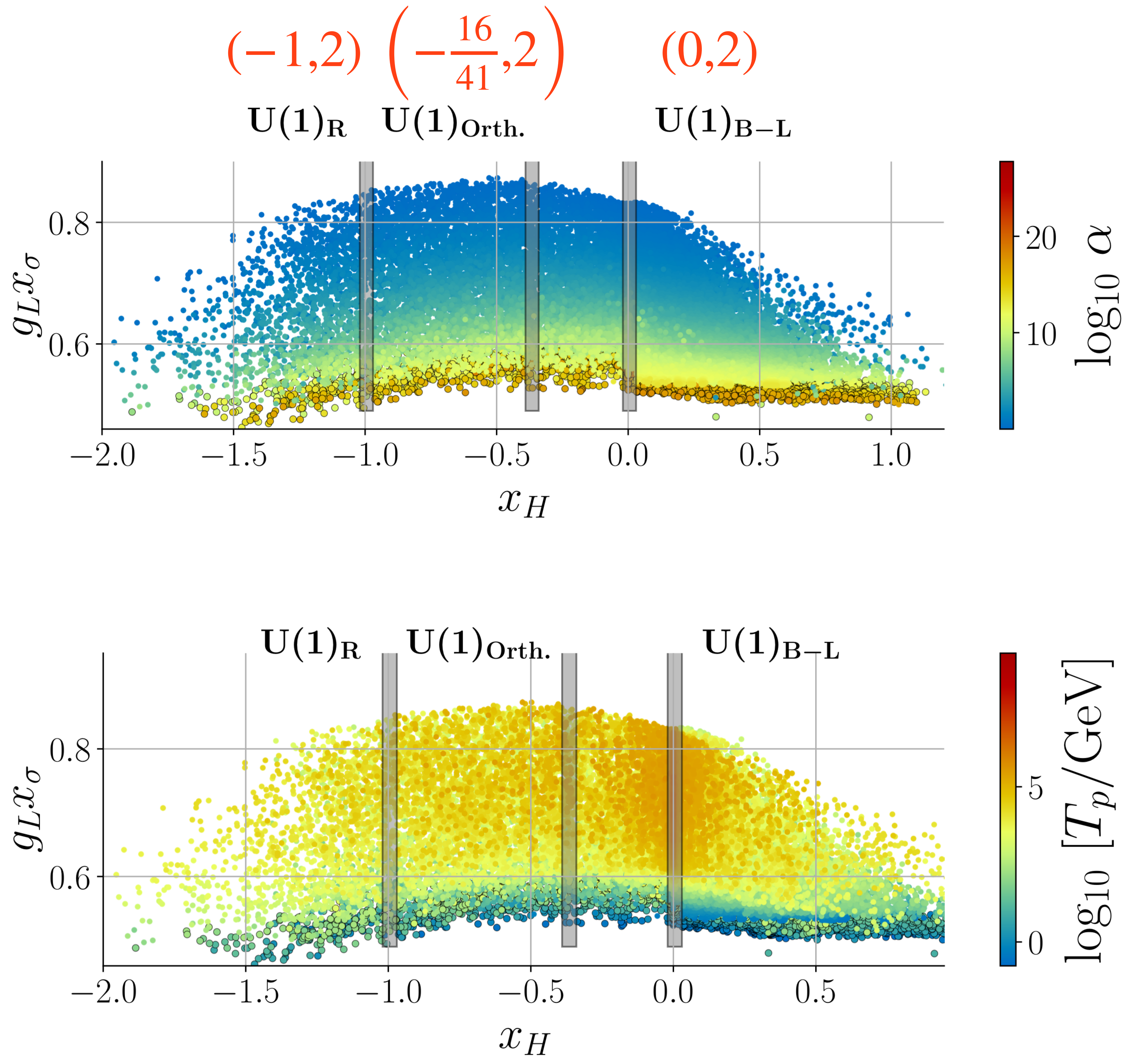
$$\Gamma_{h_2\to h_1 h_1} = \frac{\lambda_{\sigma h}^2 v_\sigma^2}{32\pi M_{h_2}}\sqrt{1-\frac{M_{h_1}^2}{M_{h_2}^2}}\,,$$

$$\Gamma_{h_2\to \bar f f} = \frac{M_{h_2}\sin^2\theta}{16\pi v^2}\sum_f M_f^2\sqrt{1-\frac{4M_f^2}{M_{h_2}^2}}\,,$$

$$\Gamma_{h_2\to VV} = \frac{C_V m_{h_2}^3\sin^2\theta}{16\pi v^2}\sqrt{1-\frac{4M_V^2}{M_{h_2}^2}}\left(1-\frac{4M_V^2}{M_{h_2}^2}+\frac{12M_V^4}{M_{h_2}^4}\right)$$

$$\sin 2\theta = \frac{2 v v_\sigma \lambda_{\sigma h}}{M_{h_1}^2 - M_{h_2}^2}$$

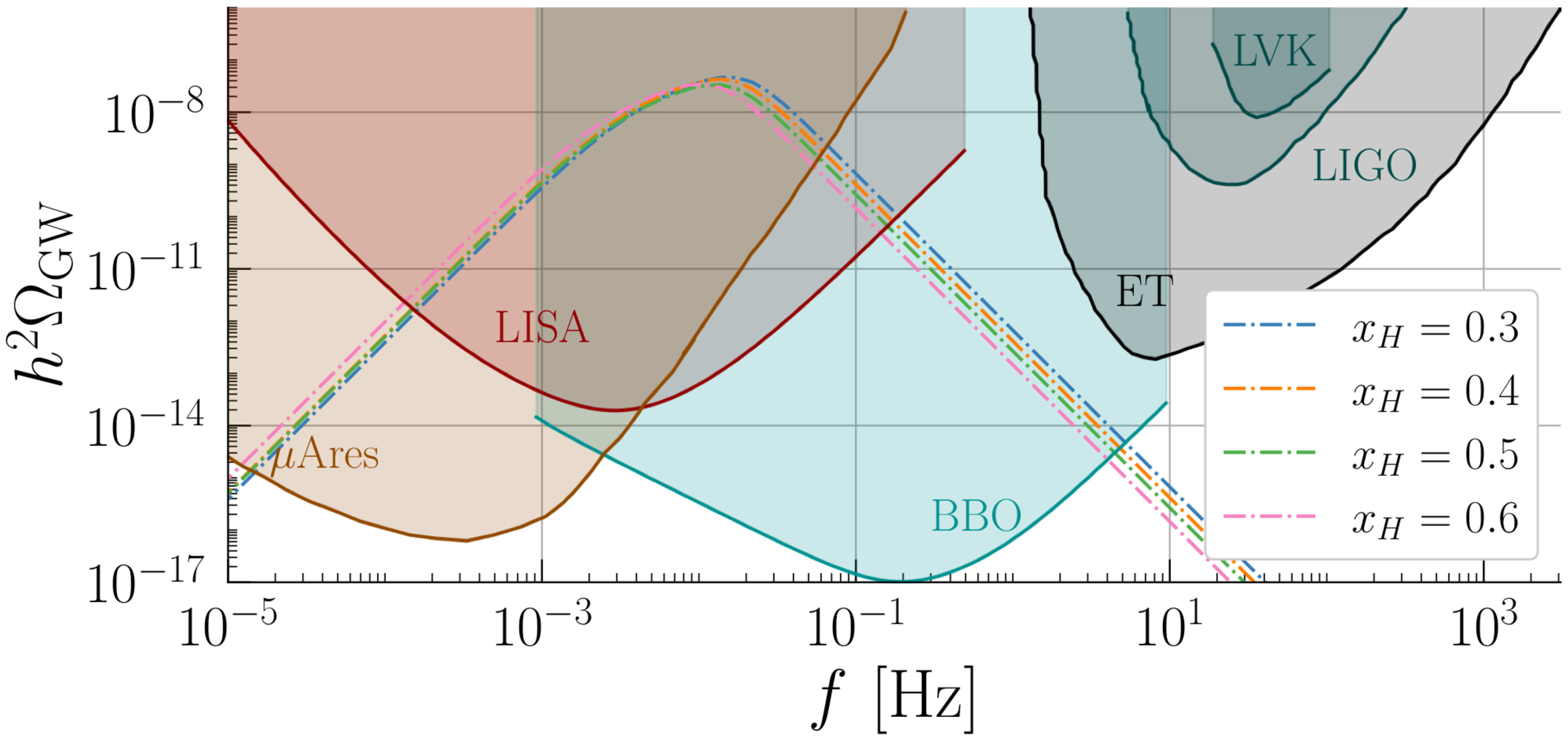
SGWB predictions for generic $\mathrm{U}(1)'$ with charges (x_H, x_σ)



Thermodynamic parameters weakly dependent on x_H

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

SGWB predictions for generic $\mathrm{U}(1)'$ with charges (x_H, x_σ)



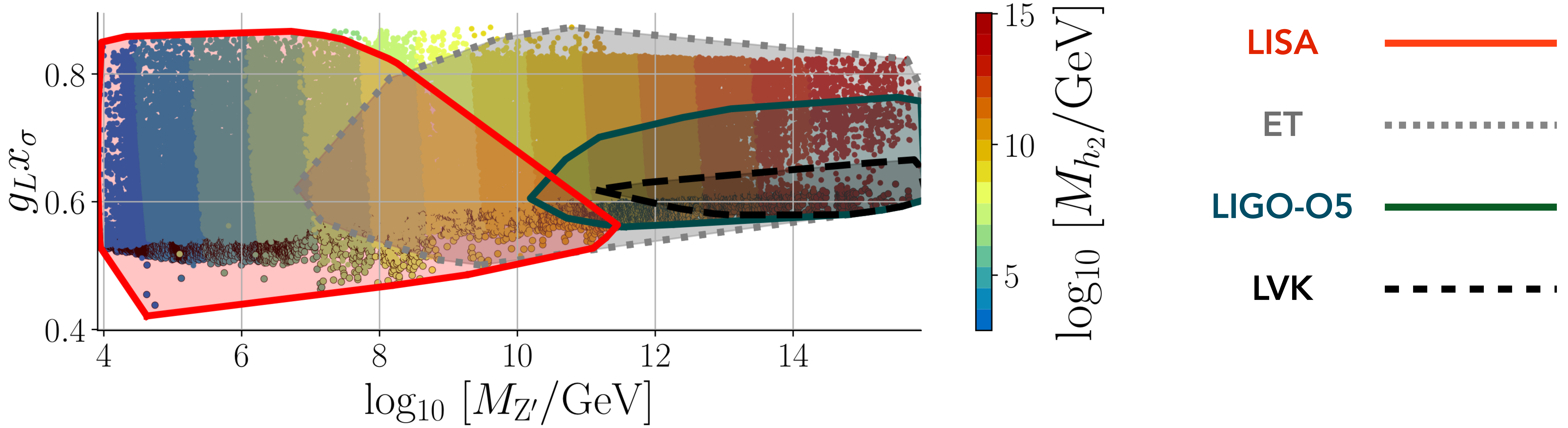
Different models for fixed $g_L x_\sigma$ have little impact, overshadowed by current uncertainties

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

Indirectly testing $\mathrm{U}(1)'$ models with SGWB

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

Require $\mathrm{SNR} > 10$ for observable SGWB



LVK excluded a region with 10^{12} GeV $< M_{h_2} \sim M_{Z'} < 10^{16}$ GeV **with** $g_L x_\sigma \sim 0.6$

LISA+ET+LIGO can cover the entire mass range $M_{h_2} > 1\mathrm{TeV}\,, M_{Z'} > 10$ TeV **with** $0.55 \lesssim g_L x_\sigma \lesssim 0.8$

Conclusions

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

   (i) Test the presence of strong supercooling with $\alpha \gtrsim 100$ in generic CSS $\mathrm{U}(1)'$ models

   (ii) Put constraints on the $g_L x_\sigma$ vs M_{h_2}, $M_{Z'}$ plane for a wide mass range above the TeV scale in the presence of supercooled FOPTs

   (iii) LVK data is already constraining this class of models for masses above 10^{12} GeV and $g_L x_\sigma \approx 0.6$

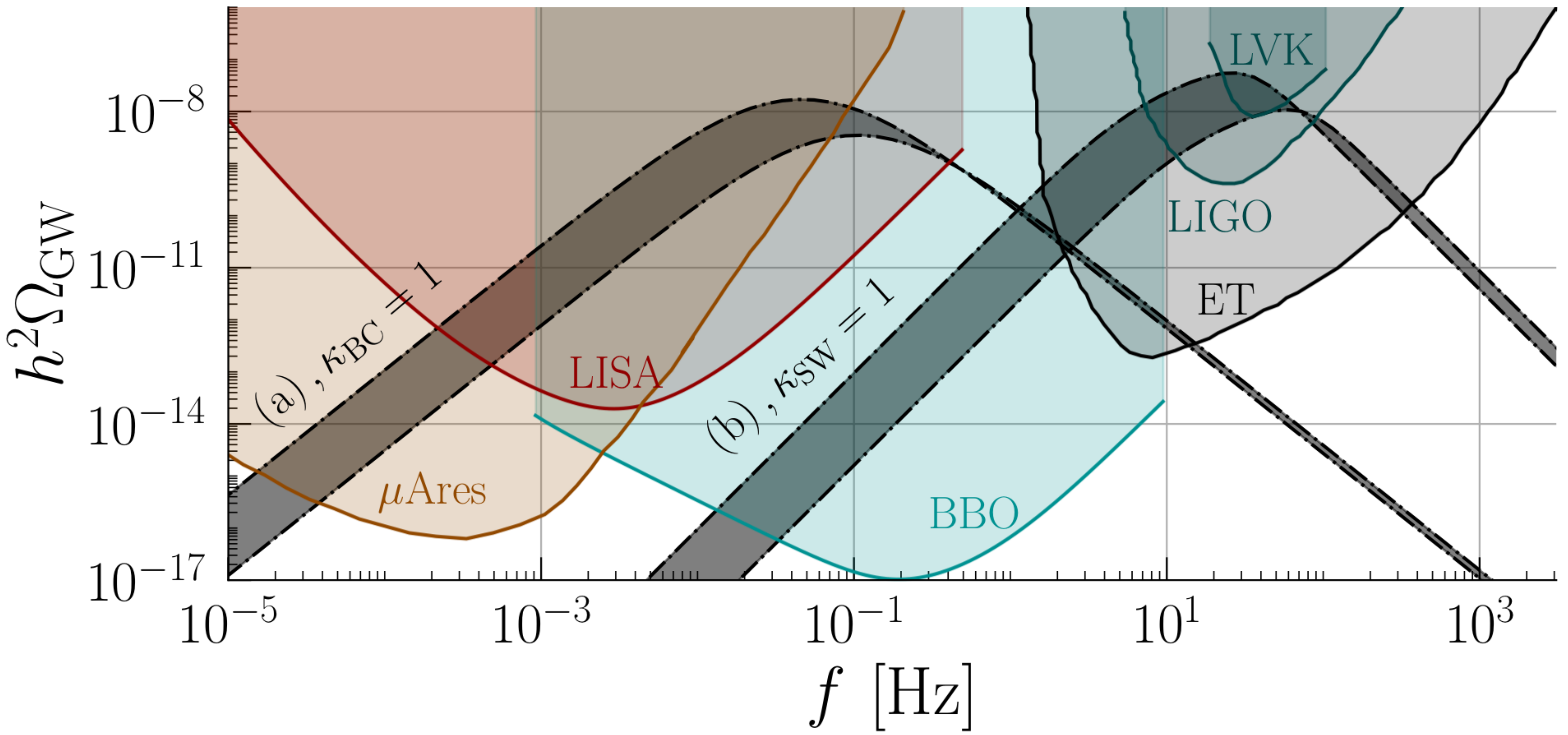
2. This class of models also explains active neutrino oscillation data

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

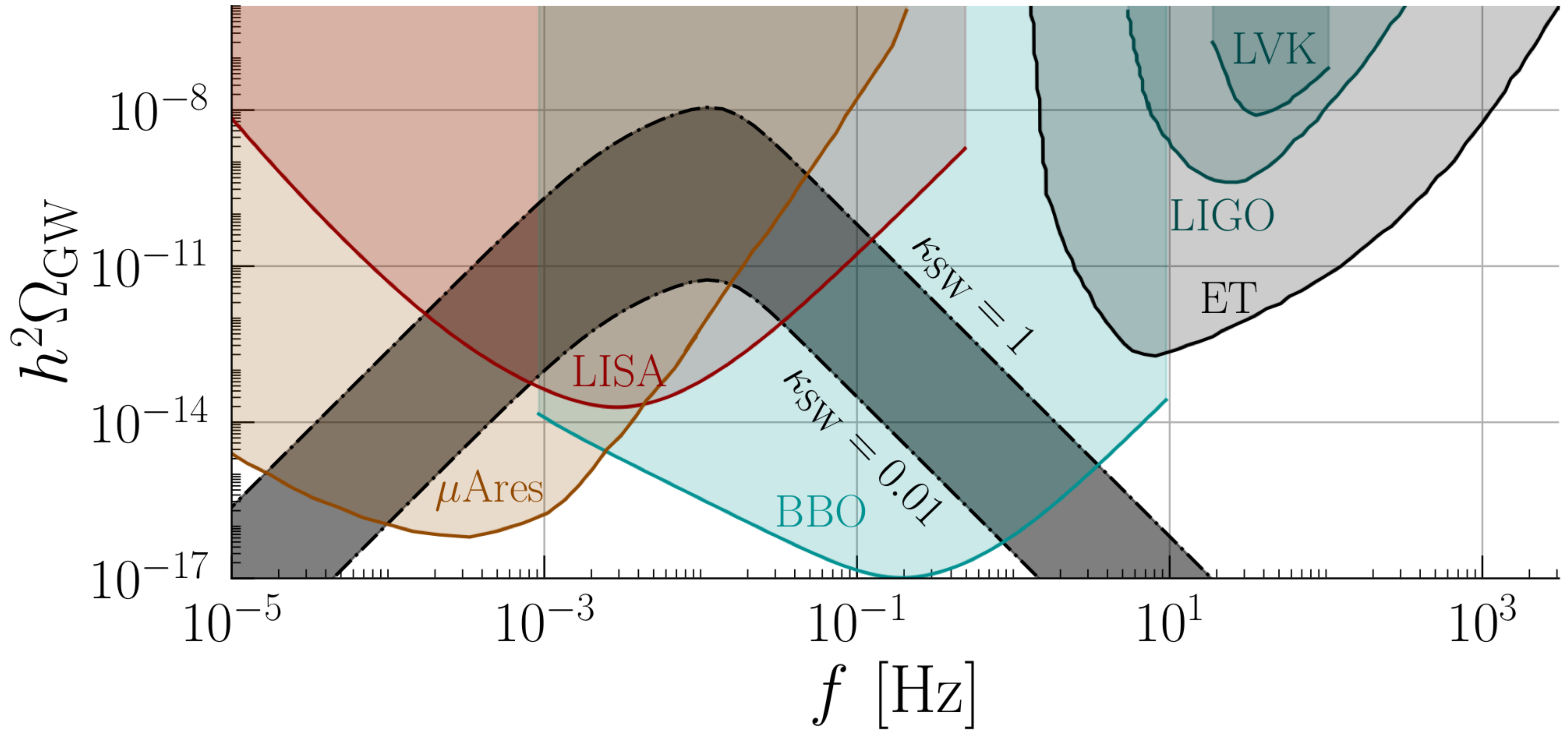
4. Overall, LISA+ET+LIGO can either rule out most of the parameter space challenging the hypothesis of supercooled FOPTs and CSS, or lead to a groundbreaking discovery

THANK YOU

Sources of uncertainty



Bubble radius distribution



Efficiency factors

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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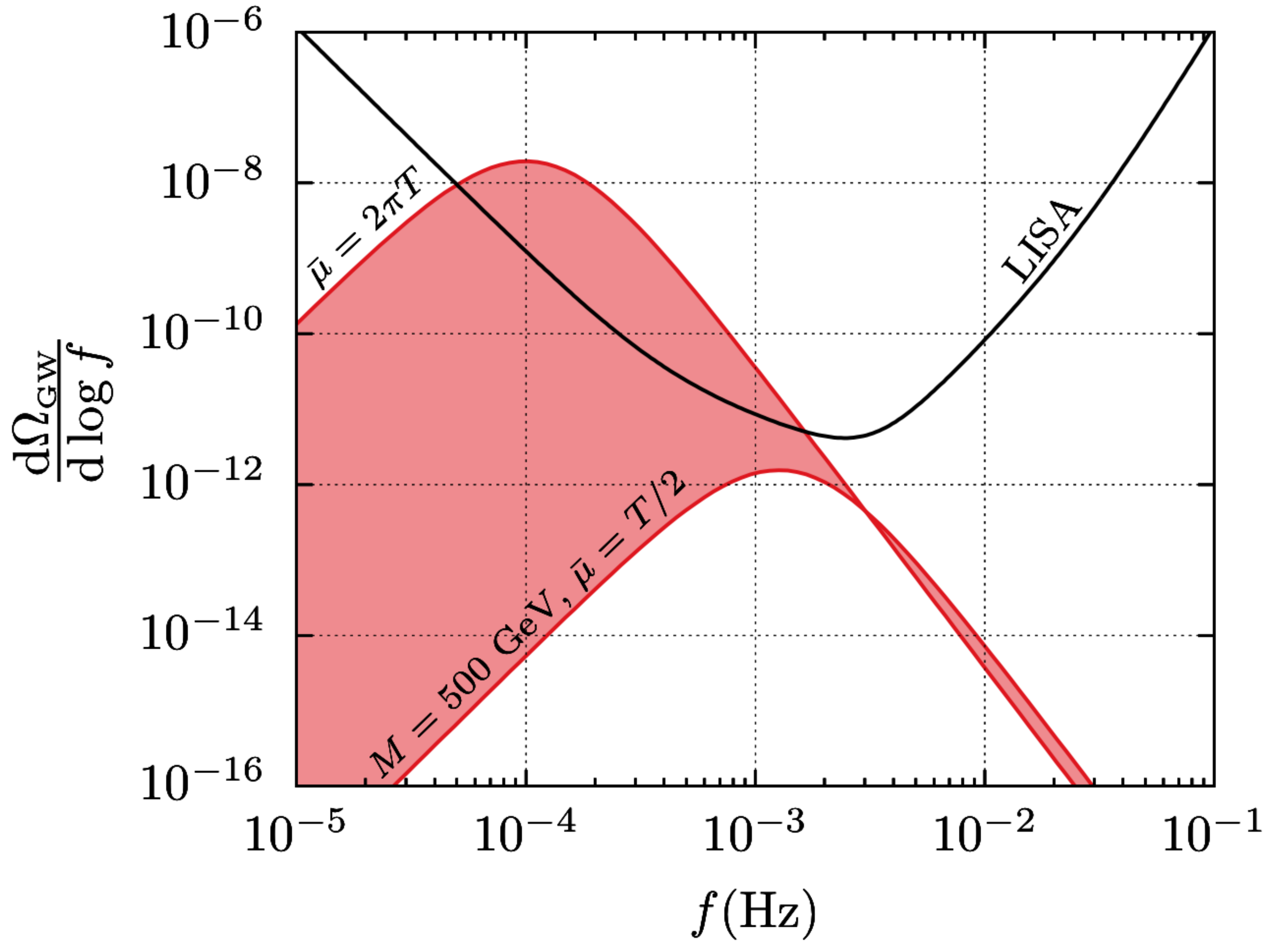


[Image credit: P. Schicho]

Improved calculation with dimensional reduction

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

[Kajantie et al 9508379, Gould et al 2104.04399]

$$\log\left(T^2/m_{\text{eff}}^2\right) \to \log\left(T^2/\mu^2\right) + \log\left(\mu^2/m_{eff}^2\right)$$

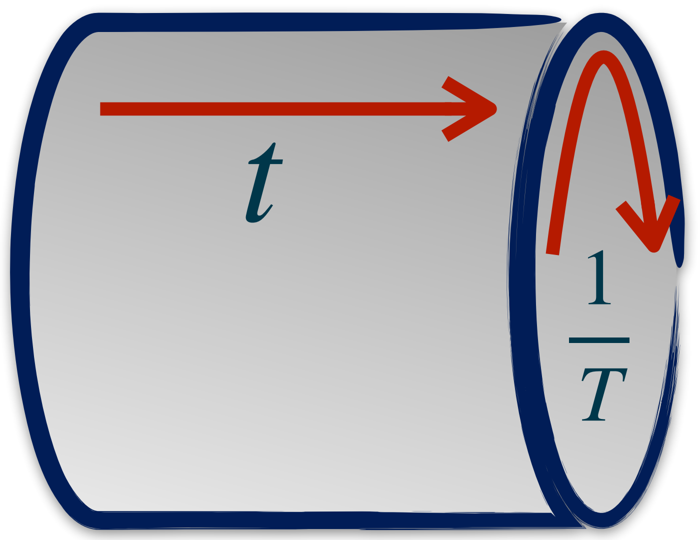
Match at $\mu \sim T$

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

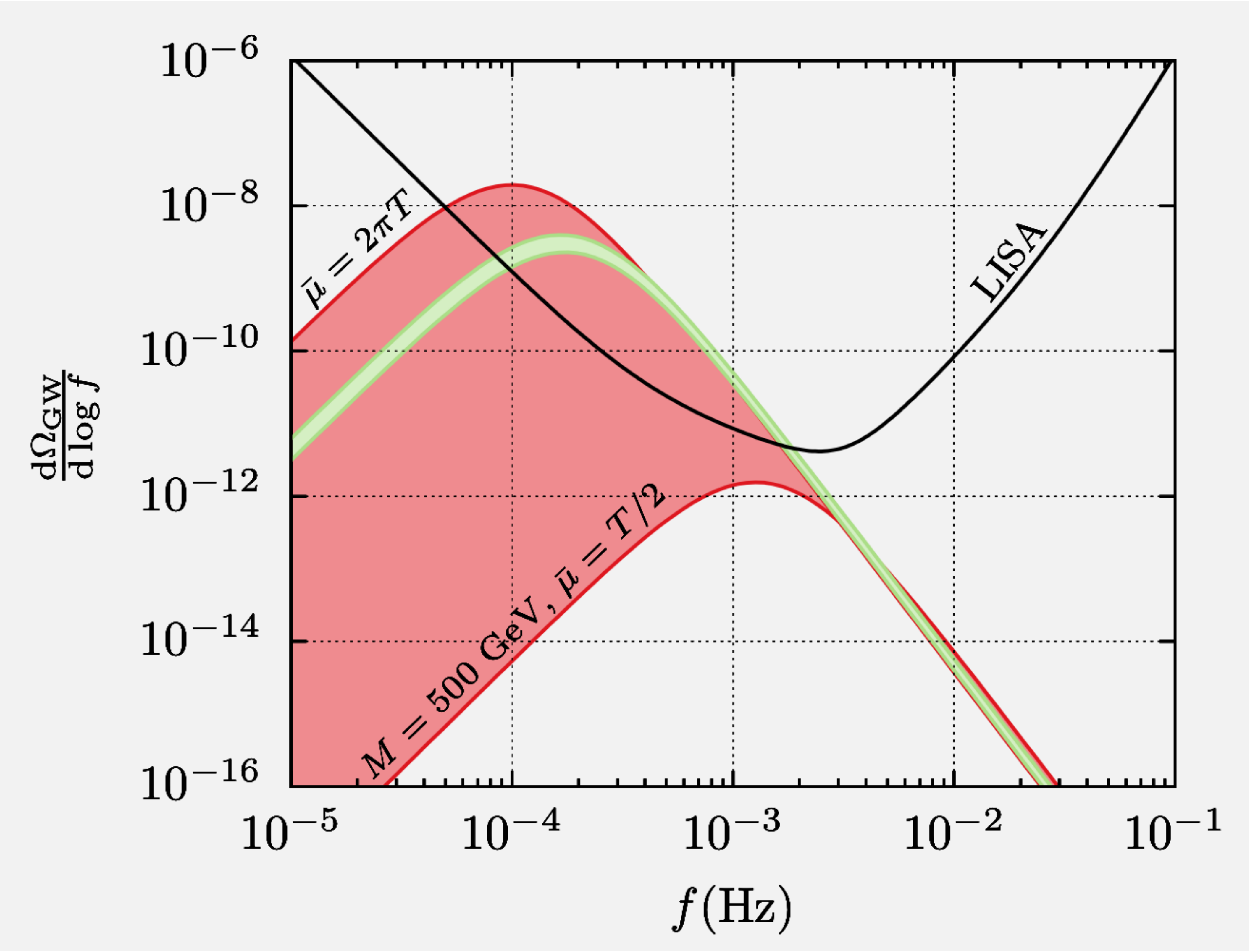
$$\frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4 \to \frac{1}{2}m_{3d}^2(T,m,\lambda)\phi^2 + \frac{1}{4}\lambda_{3d}(T,m,\lambda)\phi^4$$

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

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

- **Procedure automatised in DRAlgo**

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



[Image credit: P. Schicho]