Gravitational waves and neutrino masses in conformal models

Scale invariant U(1)′ models of neutrino mass

$$\Phi \to \Phi' = \rho^{-a}\Phi\,, \quad x \to x' = \rho x$$ a = -1 for bosons, -3/2 for fermions

Forbids mass terms at tree level

Anomaly-free generation-independent U(1)′ charges:

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

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- 3 right-handed neutrinos N
- Majoron σ (complex scalar singlet)
- B-L model: $x_{\mathscr{H}} = 0\,, x_\sigma = 2$

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

- Conformal anomaly breaks scale invariance and produces Coleman-Weinberg potential
- U(1)′ broken radiatively and σ develops a vev
- $\lambda_{\sigma h} \sim -(v/v_\sigma)^2$ induces a negative mass-squared for Higgs doublet, so SM-like Higgs acquires mass // to EWSB in SM
- New CP-even Higgs is pseudo-Goldstone boson of scale symmetry

Scale invariant Type-I seesaw mechanism

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

$$\boldsymbol{m}_{\nu} \approx \frac{1}{\sqrt{2}}\frac{v^2}{v_{\sigma}}\boldsymbol{y}_{\nu}{}^{\mathrm{T}}\boldsymbol{y}_{\sigma}{}^{-1}\boldsymbol{y}_{\nu} \qquad \boldsymbol{M}_N \approx \frac{v_{\sigma}}{\sqrt{2}}\boldsymbol{y}_{\sigma}$$

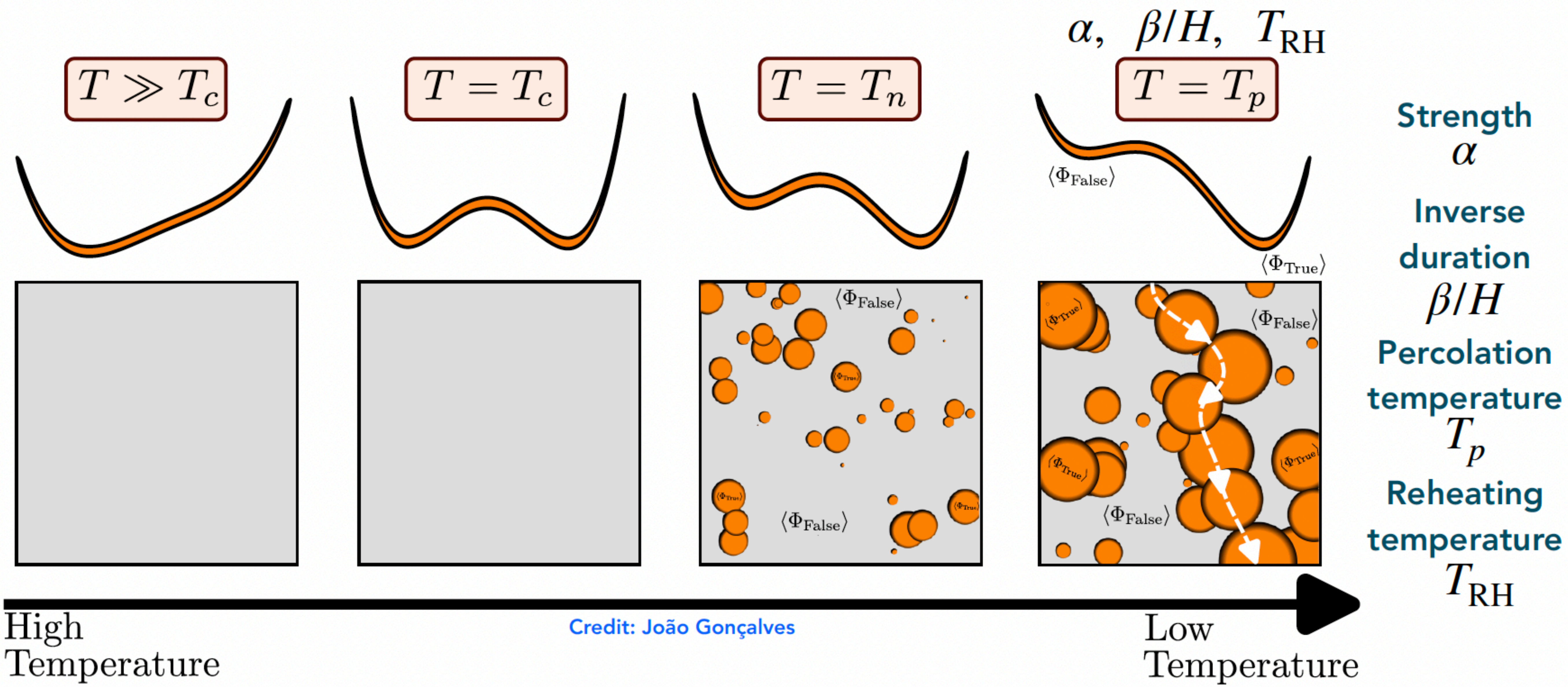
- Neutrino masses generated by SSB
- Assume normal mass hierarchy and diagonal $\boldsymbol{y}_{\sigma}$
- Require consistency with neutrino oscillation data and cosmological bounds

Minimize potential and evaluate mass spectrum at 1-loop

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

- Fix λ_σ and $\lambda_{\sigma h}$
- 1 parameter in scalar sector: M_{h_2}
- 3 params in gauge sector: $g_L, x_{\mathscr{H}}, x_\sigma$. Will focus here on B-L model. See 2412.02645 for generic models
- 3 params in neutrino sector
- No kinetic mixing at EW scale

First order phase transition

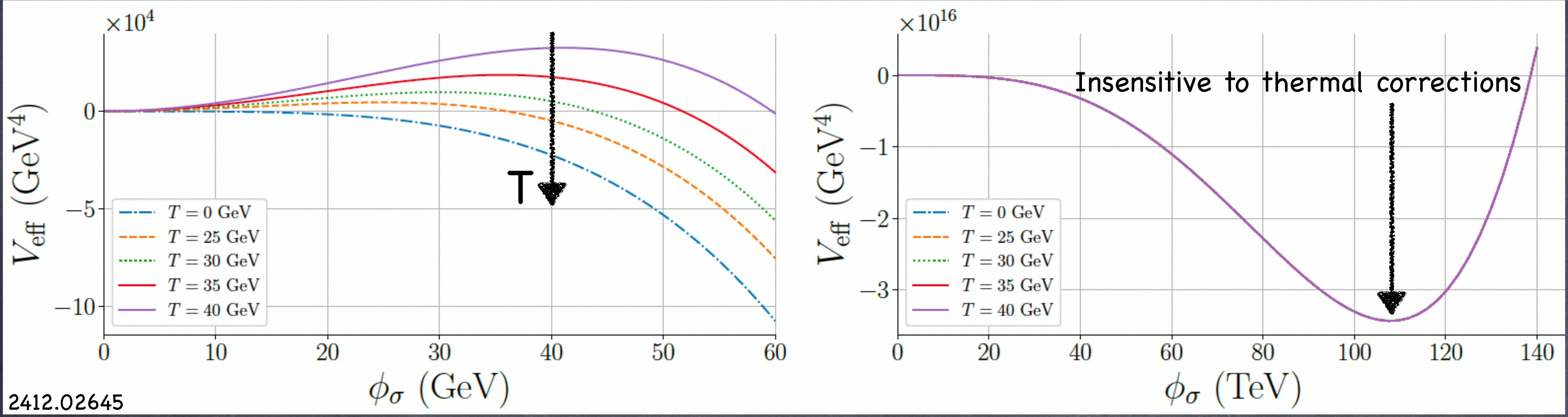


- FOPT associated with potential barrier and involves latent heat
- Thermal jump/quantum tunneling lead to true vacuum bubble nucleation
- Bubbles expand, transfer energy to plasma, collide, thereby producing gravitational waves

FOPTs in a conformal dark sector

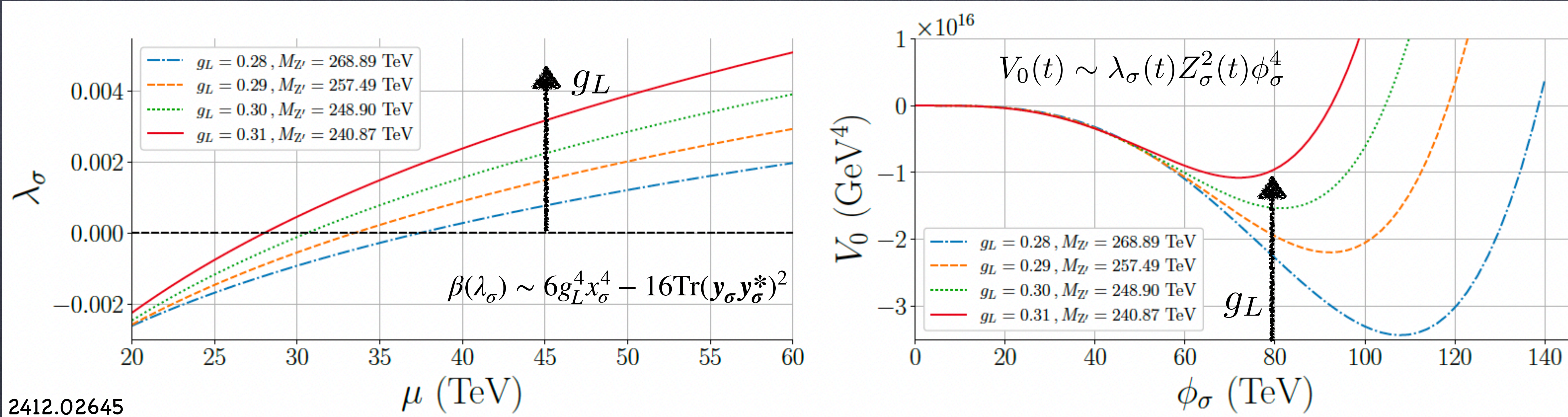
$$V_{\text{eff}} = V_0(\phi_\sigma) + V_{\text{CW}}(\phi_\sigma) + V_T(\phi_\sigma, T) + V_{\text{Daisy}}(\phi_\sigma, T)$$

- Phase transition governed by ϕ_σ only $\because v_\sigma \gg v$
- Use RG-improved thermal potential (couplings and ϕ_σ in the potential subject to RG evolution)
- Daisy corrections turn out to be small



$$V_{\rm eff}^{\rm HT} = \phi_\sigma^4 \left(\frac{g_L^4(1-3\gamma_E+6\ln 2)}{2\pi^2} - \frac{g_L^3}{2\sqrt{2}\pi} + \frac{\lambda_\sigma}{4} + \frac{\gamma_E \mathrm{Tr}(\boldsymbol{y_\sigma}^4)}{64\pi^2} \right) - \phi_\sigma^3 \frac{4 g_L^3 T}{3\pi} + \phi_\sigma^2 \left(\frac{g_L^2 T^2}{2} - \frac{g_L^3 T^2}{\sqrt{2}\pi} + \frac{T^2}{48} \mathrm{Tr}(\boldsymbol{y_\sigma}^2) \right)$$

- Quadratic and (negative) cubic term generated at finite temperature
- Barrier persists as $T \to 0$
- Gauge sector responsible for FOPT since barrier vanishes if $g_L = 0$



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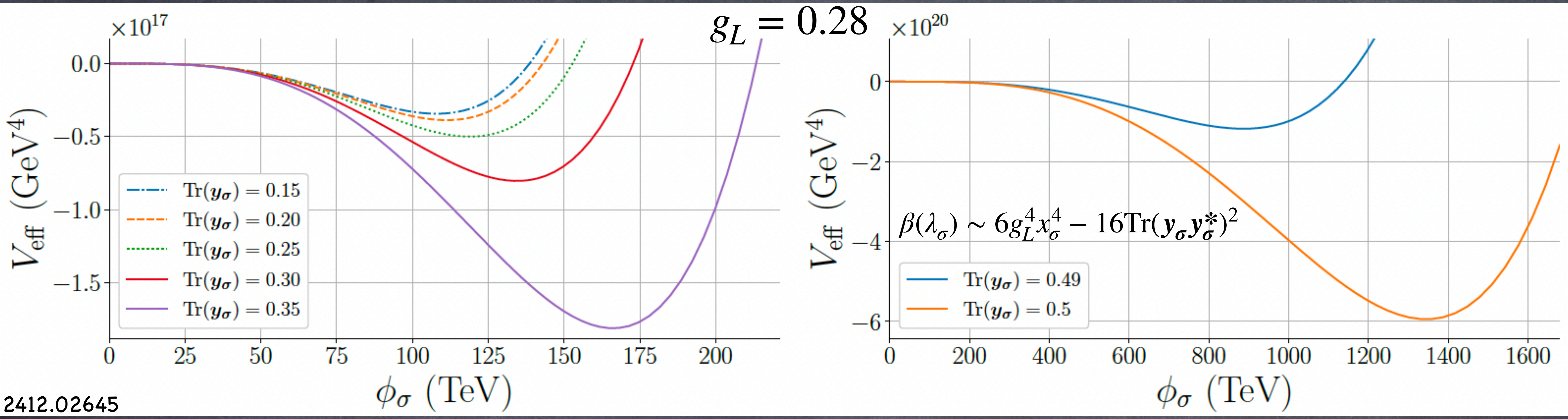
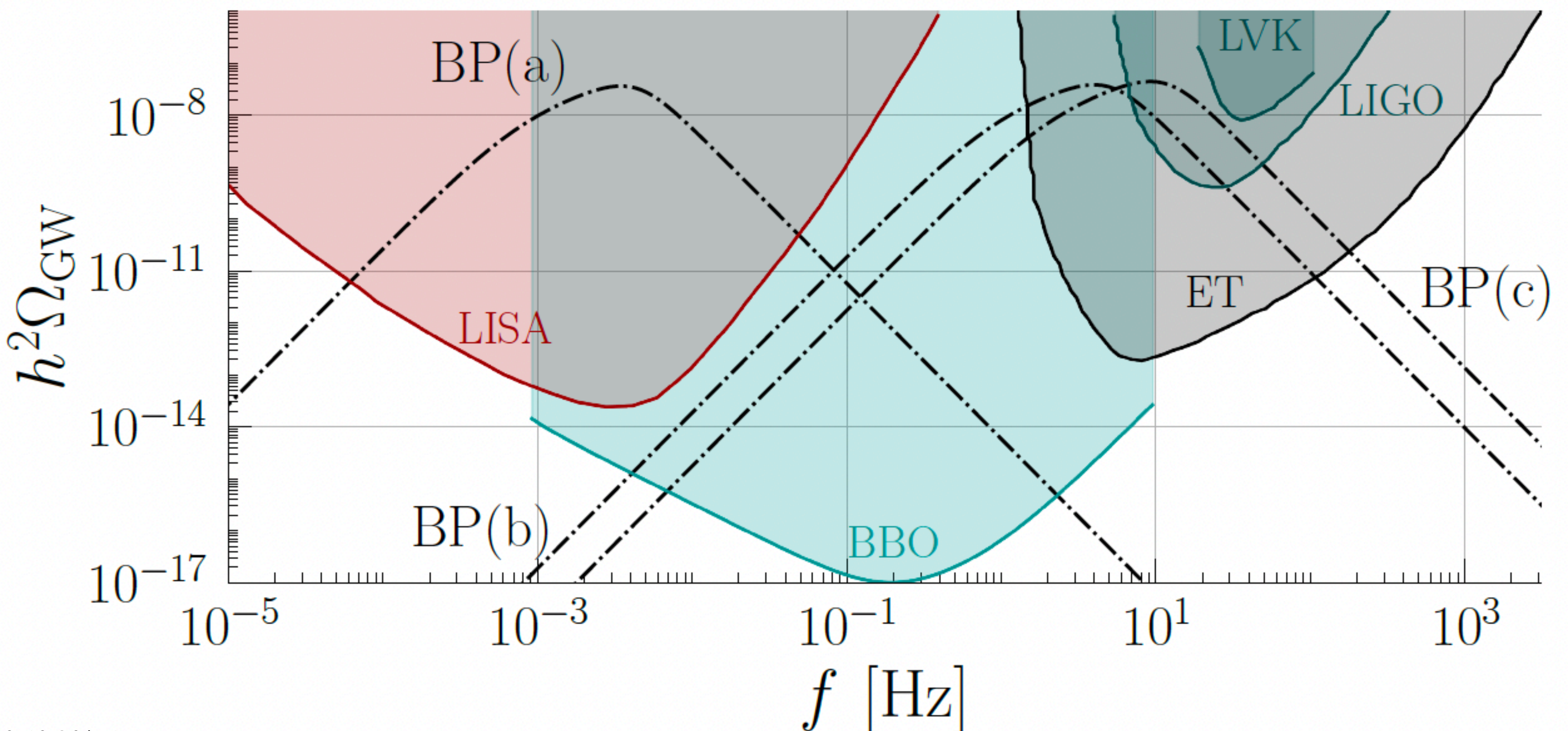
- Location of minimum determined by RG evolution of λ_σ
- Depth of minimum is greater for smaller g_L
- Larger v_σ for larger $M_{Z'}$

Role of neutrino sector



- Competition between gauge and Yukawa couplings affects location and depth of minimum
- Larger Yukawa pushes the minimum to higher scales and makes the potential deeper
- Dark sector fully thermalizes with SM sector: $\Delta N_{\rm eff} \simeq 0$



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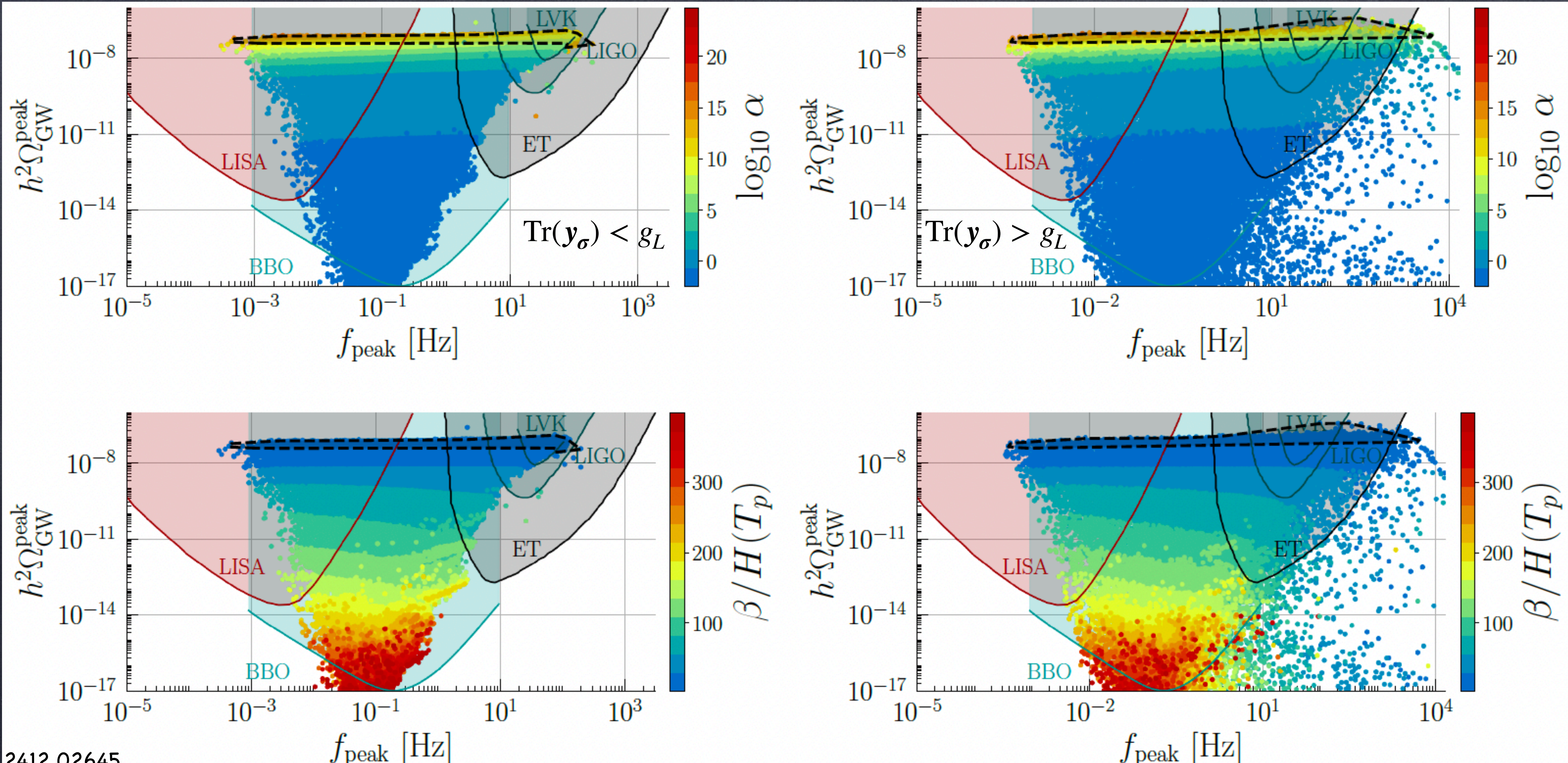
$$h^2\Omega_{\text{cosmic string}} \sim 10^{-7}\frac{M_{Z'}}{M_{\rm GUT}}$$



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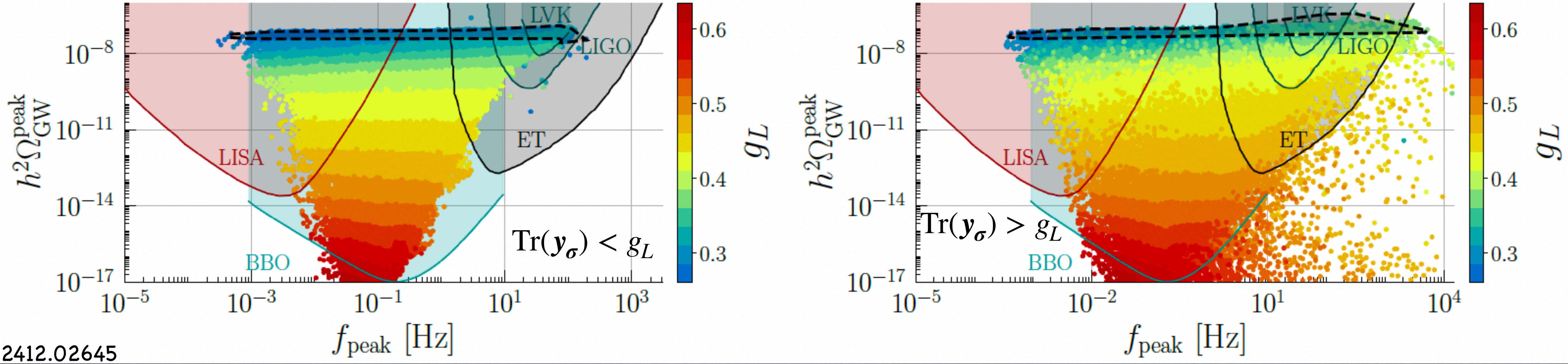
- Strong supercooling ($\alpha > 10$) testable at LIGO/LISA/ET
- $\beta/H(T_p) \approx$ constant for $\alpha \gg 1 \implies \Omega_{\rm GW}^{\rm peak} \approx$ constant
- Inside dashed contour, false vacuum volume is decreasing at a temperature below T_p



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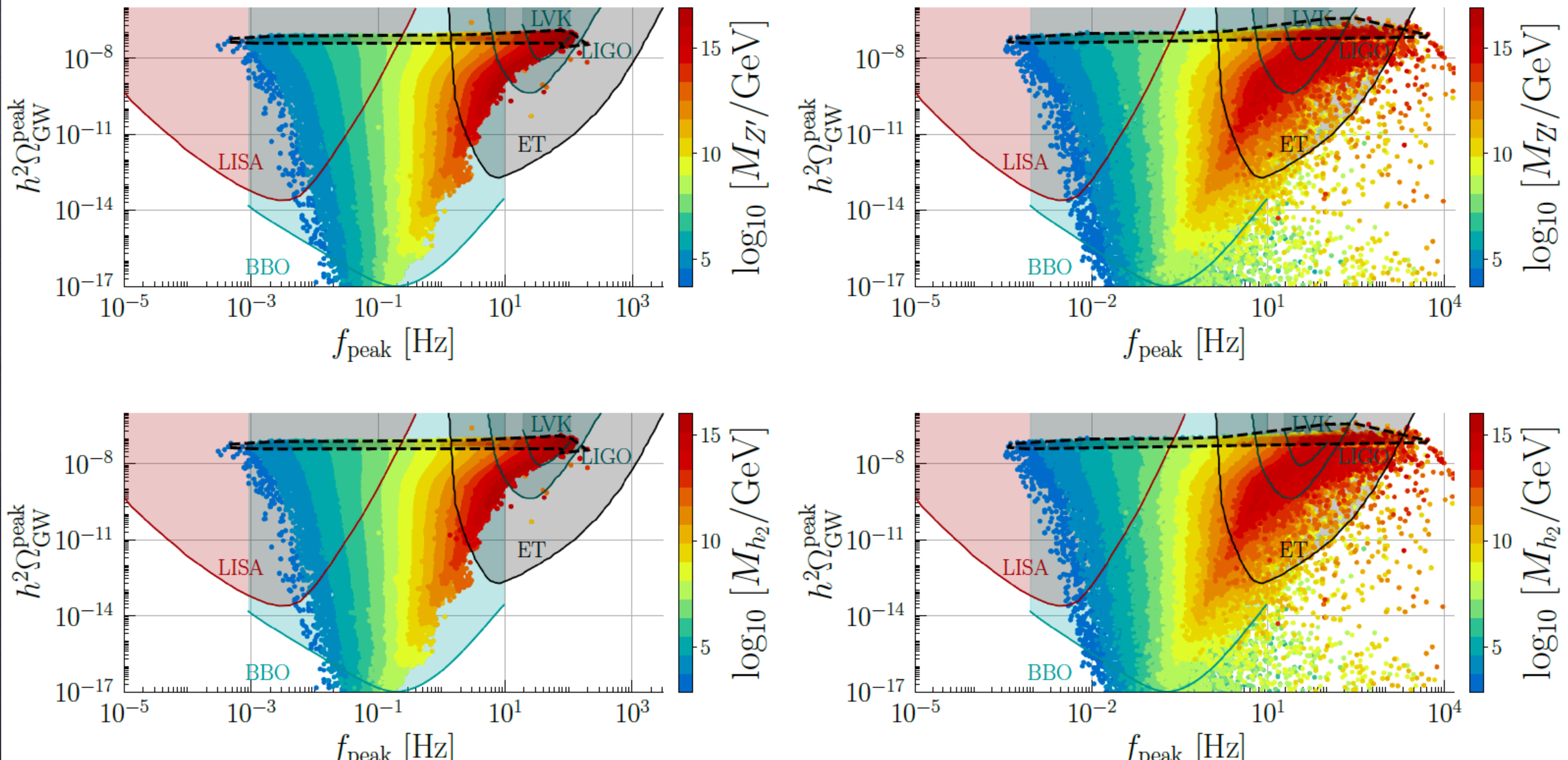
- Peak amplitude set by gauge coupling
- $0.26 \lesssim g_L \lesssim 0.63$
- Scatter in points in right panels because of competition between gauge and Yukawa couplings
- Larger Yukawa couplings shift v_σ higher, so higher $f_{\rm peak}$ values allowed in right panels
- LVK data exclude part of the parameter space



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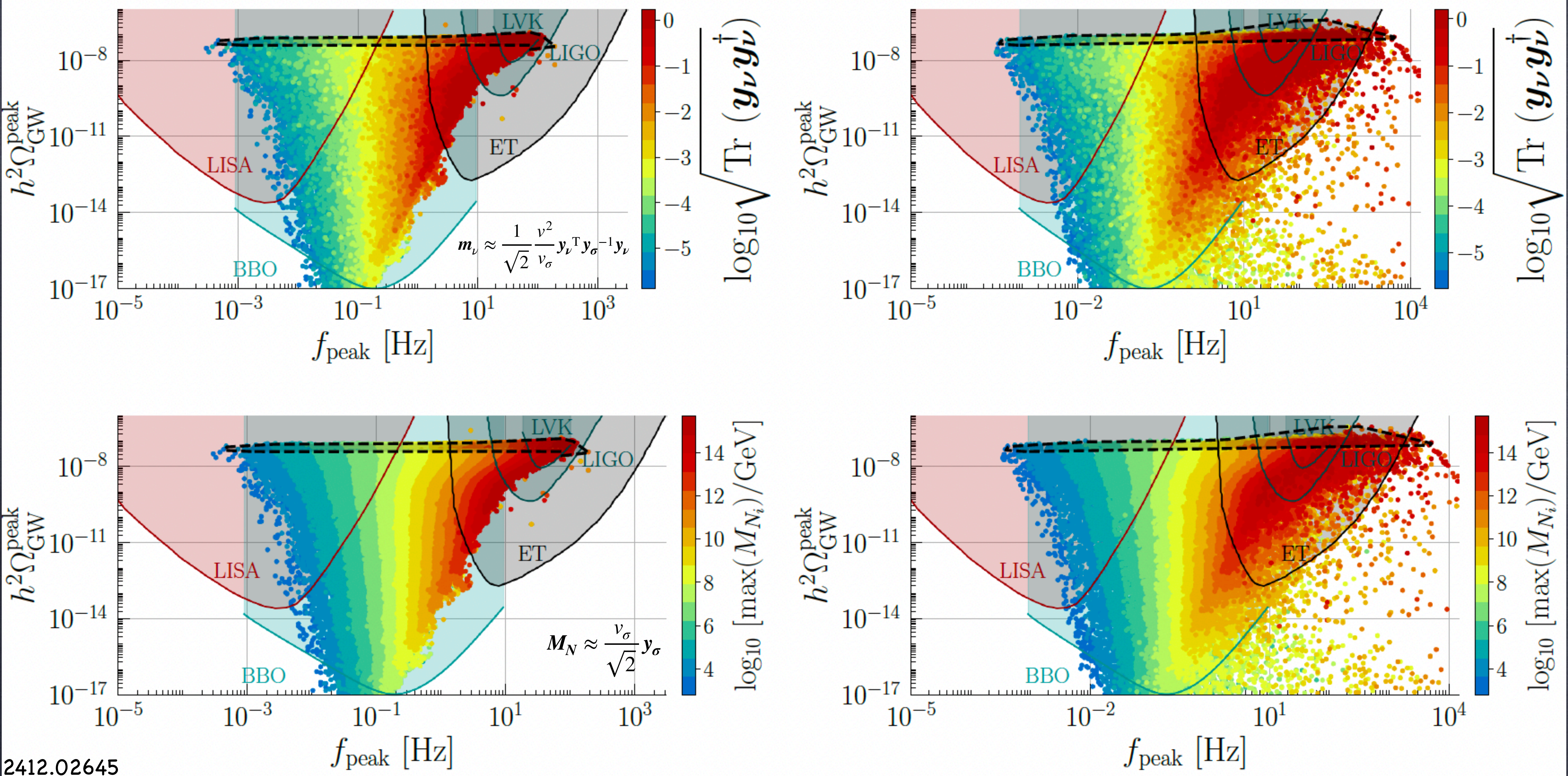
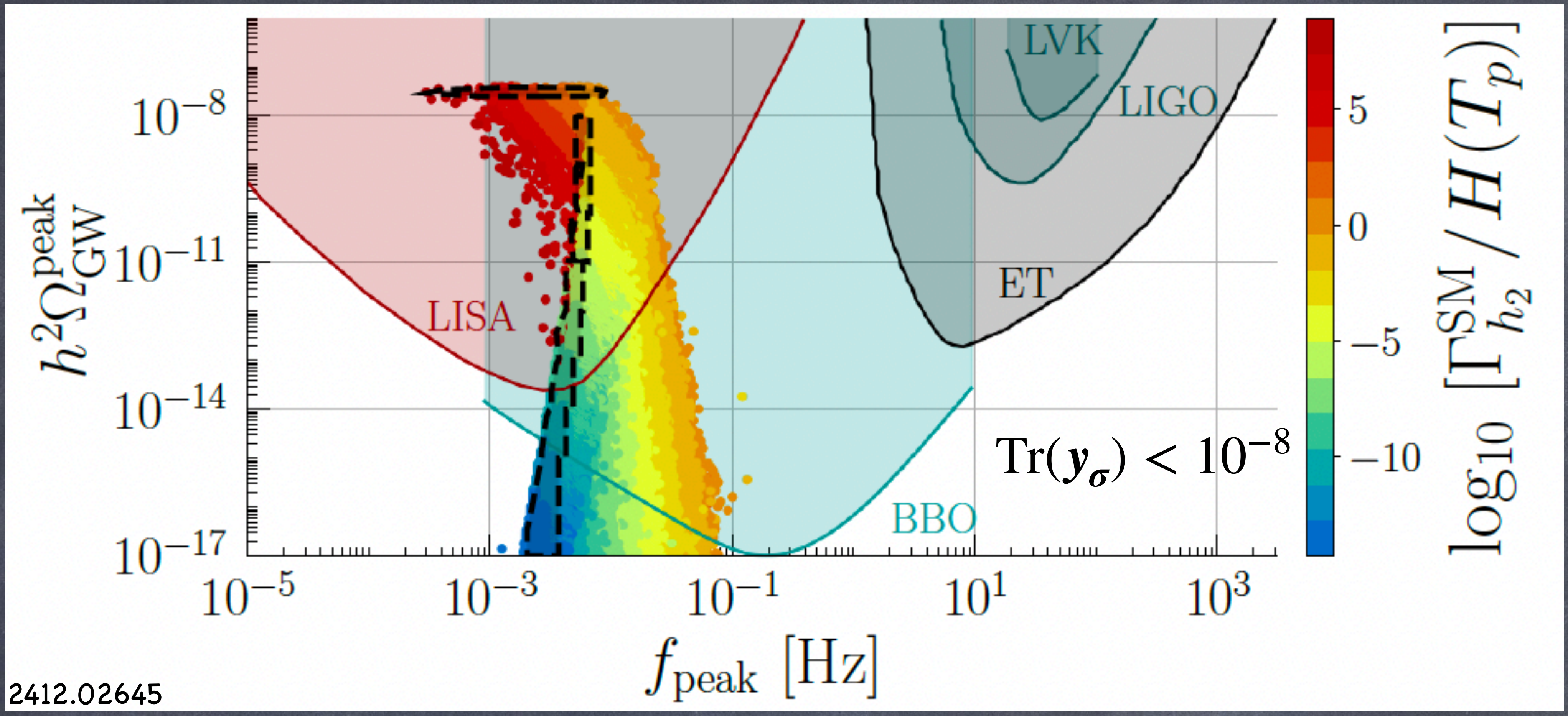
- Peak frequency set by the U(1)′ breaking scale
- Z' an order of magnitude heavier than h_2



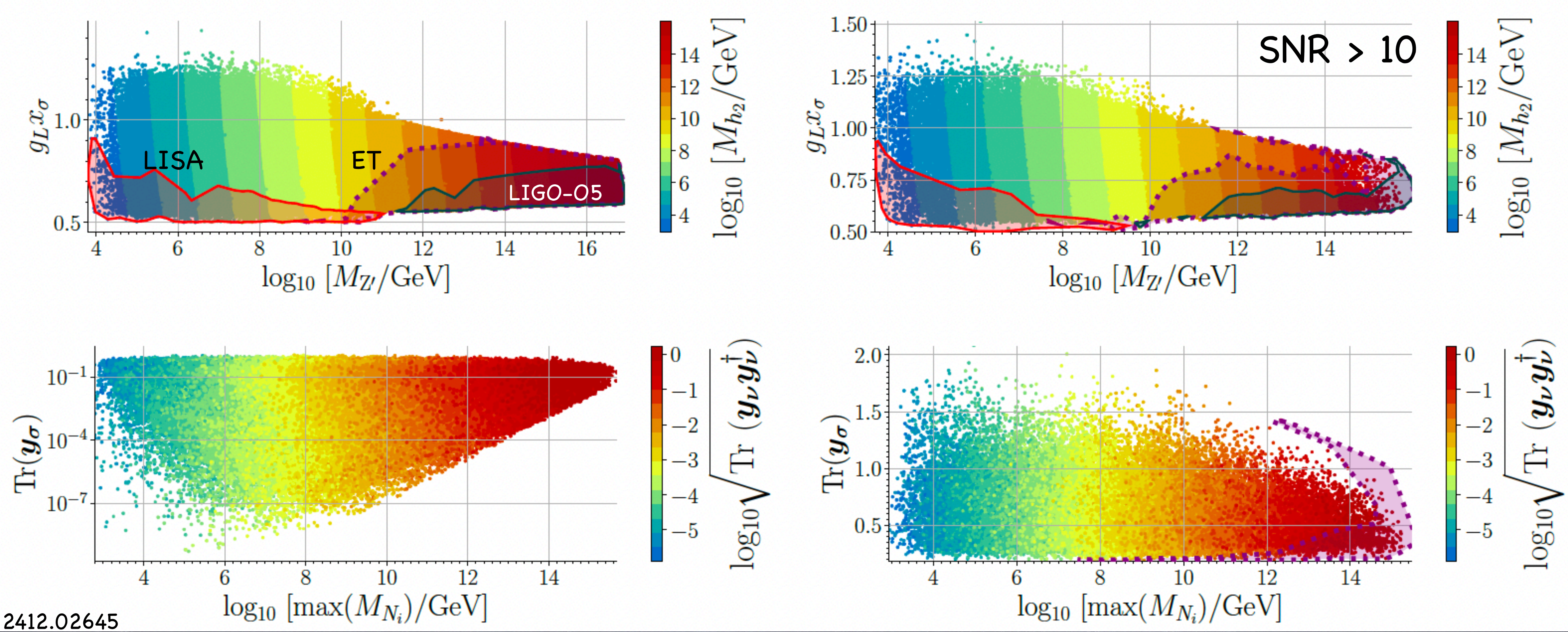
- Vertical bands show complementary sensitivity to seesaw scale of LISA ($10^3 - 10^8$ GeV) and LIGO/ET ($10^9 - 10^{15}$ GeV)
- LISA: $10^{-6} \lesssim y_\nu \lesssim 10^{-3}$, LIGO/ET: $10^{-3} \lesssim y_\nu \lesssim 1$

Decoupled RHNs



- h_2 decays only to SM particles with highly suppressed rate
- Universe enters era of matter-domination after percolation
- $T_{\rm RH}$ is lowered $\Longrightarrow$ peak frequency of SGWB is lowered
- LISA can detect GWs even if RHNs are decoupled
- Signal at LIGO/ET is evidence for coupled RHNs

Generic U(1)' models



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- Nonobservation of GWs will disfavor $0.5 \lesssim g_L x_\sigma \lesssim 0.6$ and $\mathrm{Tr}\left(y_\sigma\right) \gtrsim 0.1$ in entire mass range
- … and will exclude a seesaw scale $\gtrsim 10^{14}$ GeV for $\mathrm{Tr}\left(y_\sigma\right) \gtrsim 0.1$ and $y_\nu \sim \mathcal{O}(1)$

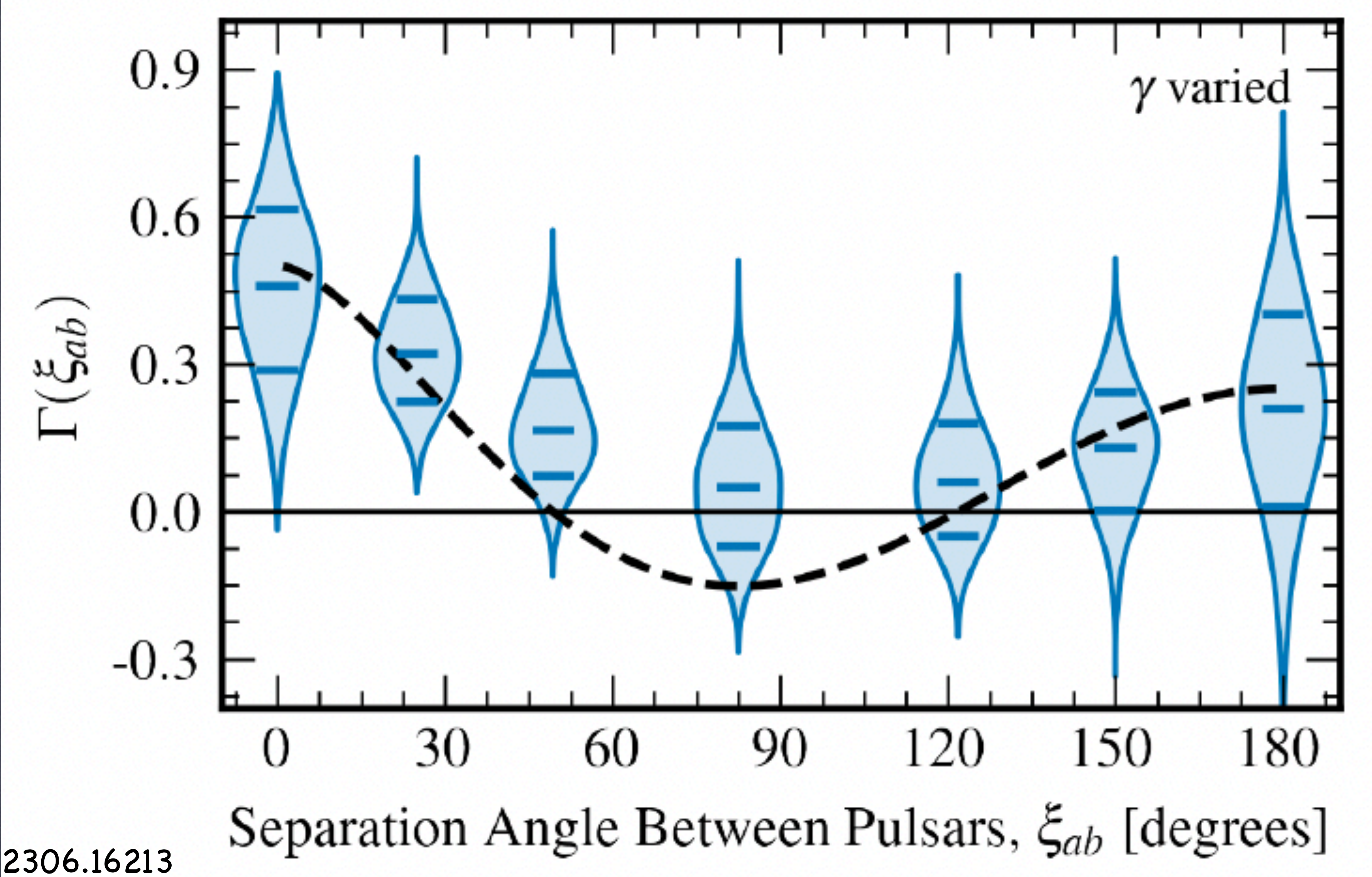
Pulsar Timing Arrays

- Galactic size GW detector made of millisecond pulsar array

- Precise rotation periods and radio pulses from poles of pulsars make them ultra-precise clocks

- GW perturbs spacetime between the pulsar and Earth and changes the time of arrival (TOA) of pulses
- Measure residuals in TOA: $R^a = TOA^a_{measured} - TOA^a_{model}$
- Cross-correlate timing residuals of pairs of pulsars separated by angle ξ_{ab}
- Sensitive to frequencies between 1/(total observation time) and 1/cadence i.e., [1/years, 1/weeks]

Hellings-Downs curve



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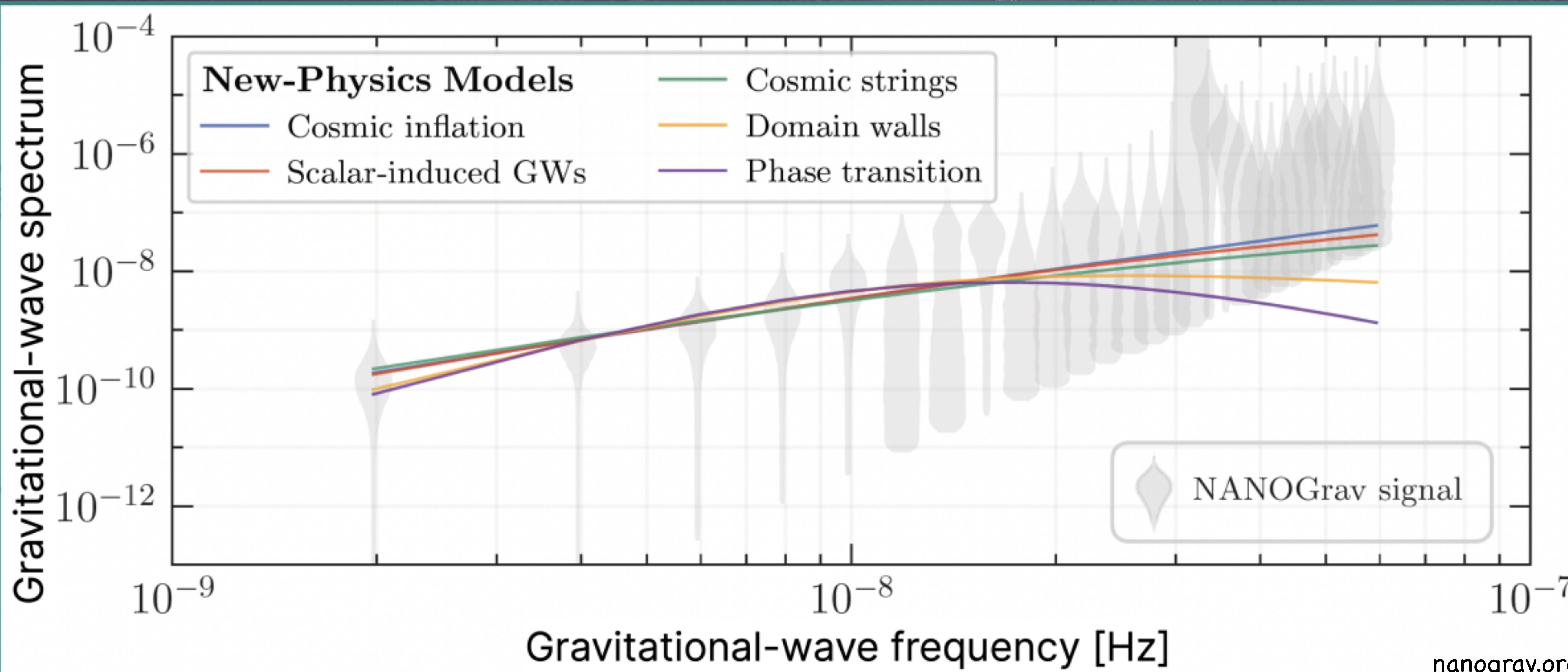
- PTAs see $\sim 3\sigma$ quadrupole correlation of timing residuals
- Smoking gun signal of stochastic GW background



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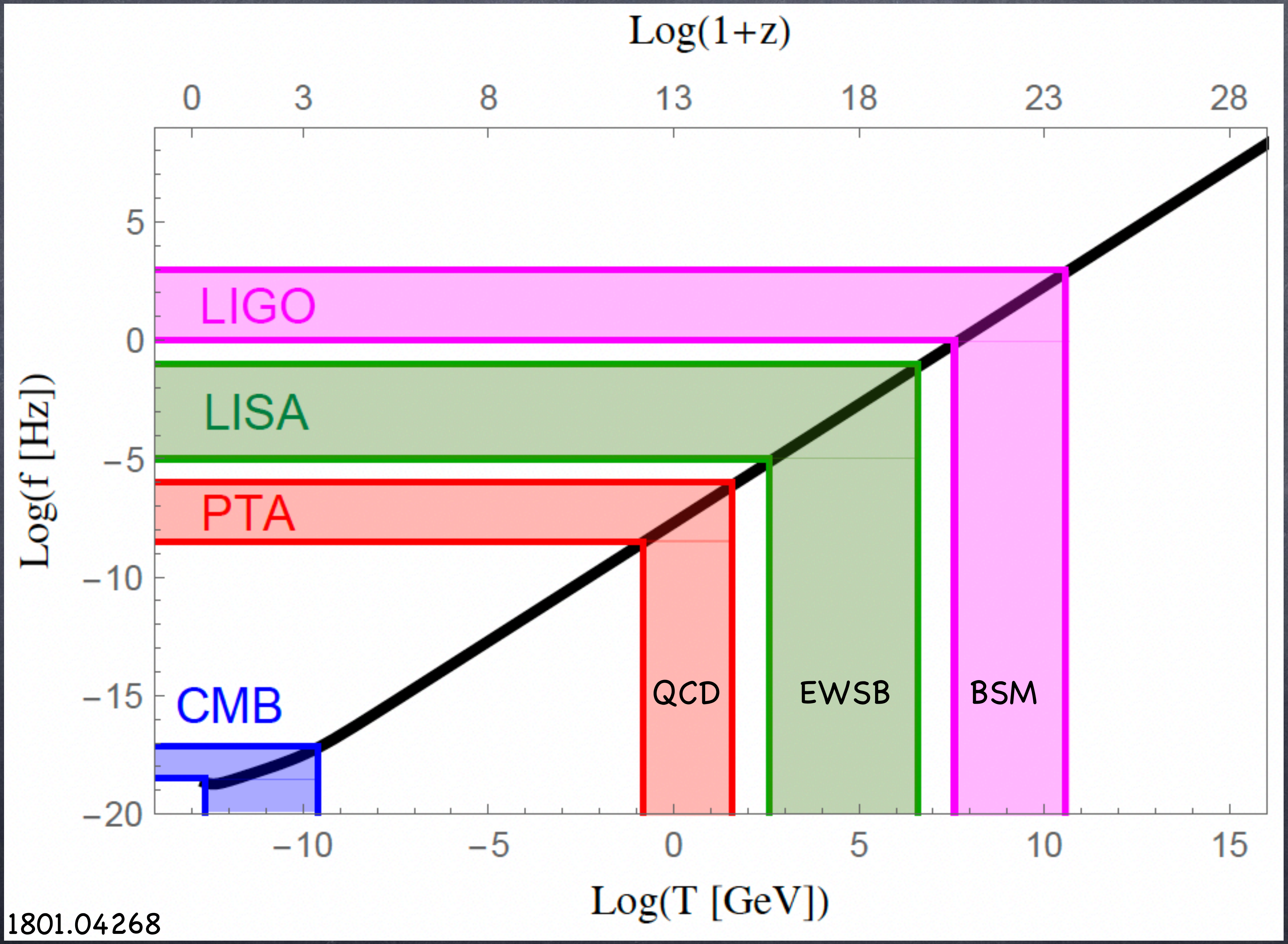
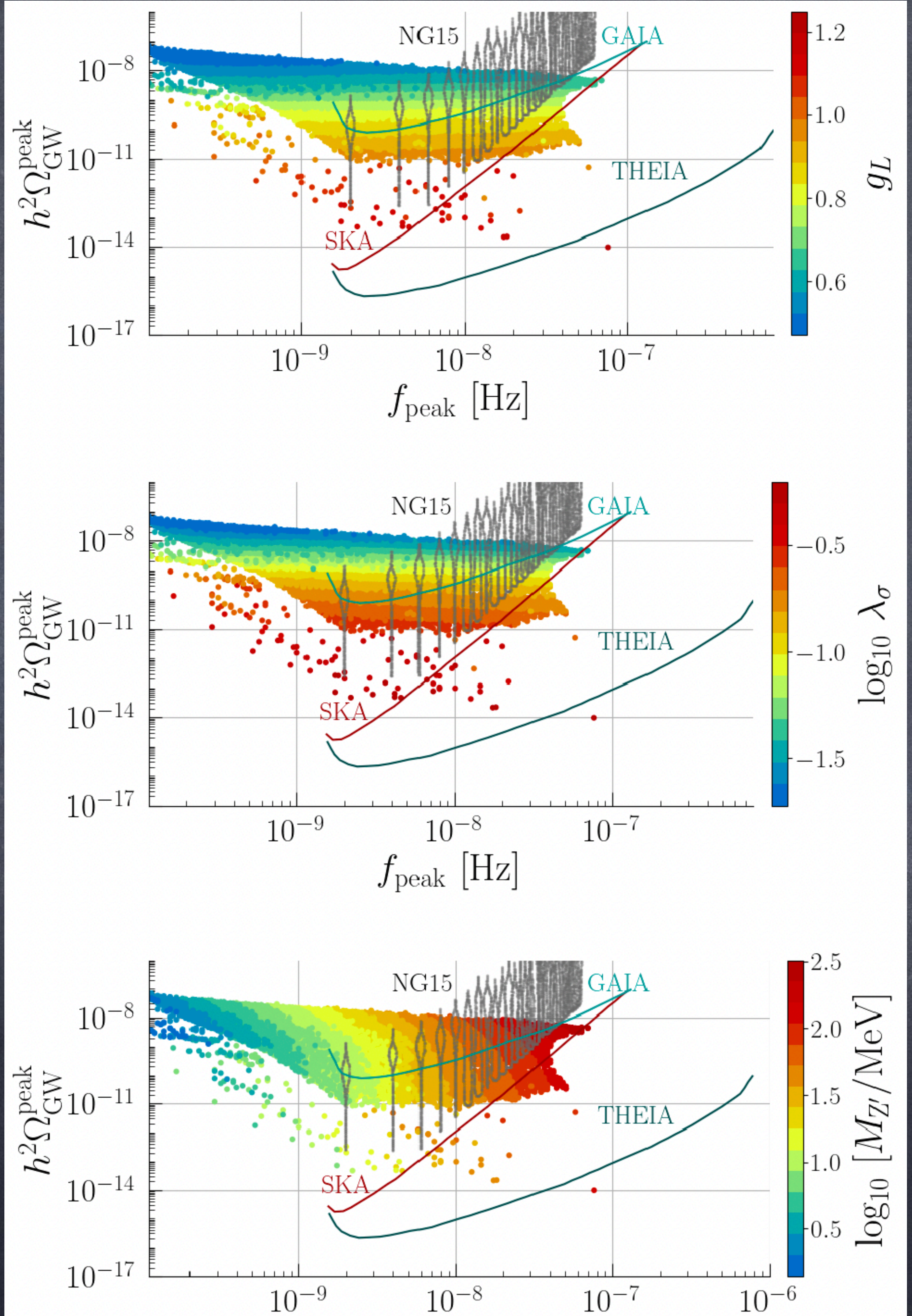
GWs emitted at temperature T have frequency f today



Dark U(1)′

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

- 10-100 MeV FOPT requires $v_\sigma \ll v$
- Cannot reproduce 125 GeV Higgs mass without quadratic Higgs term
- Only dark sector is conformal
- 2 parameters in scalar sector: $M_{h_2}, \lambda_{\sigma h}$
- Set kinetic mixing $\sim 10^{-10}$ to thermalize dark sector
- $\Longrightarrow$ model is valid up to 10^8 GeV


NG15
GAIA
THEIA
SKA
$h^2\Omega_{\rm GW}^{\rm peak}$
$f_{\rm peak}$ [Hz]
g_L
$\log_{10}\lambda_\sigma$
$\log_{10}[M_{Z'}/\rm MeV]$

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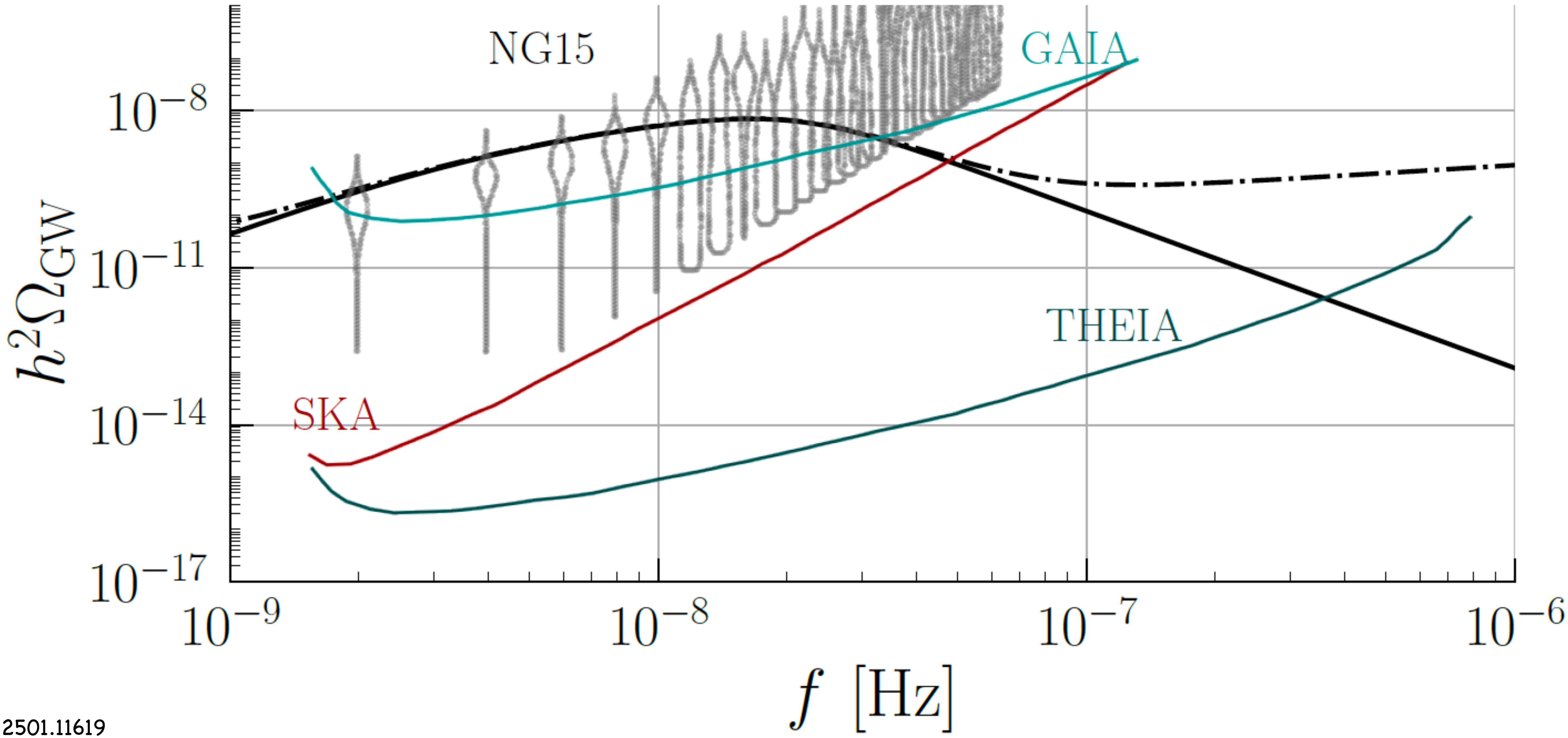
NG15
GAIA
THEIA
SKA
$h^2\Omega_{\mathrm{GW}}$
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
f [Hz]

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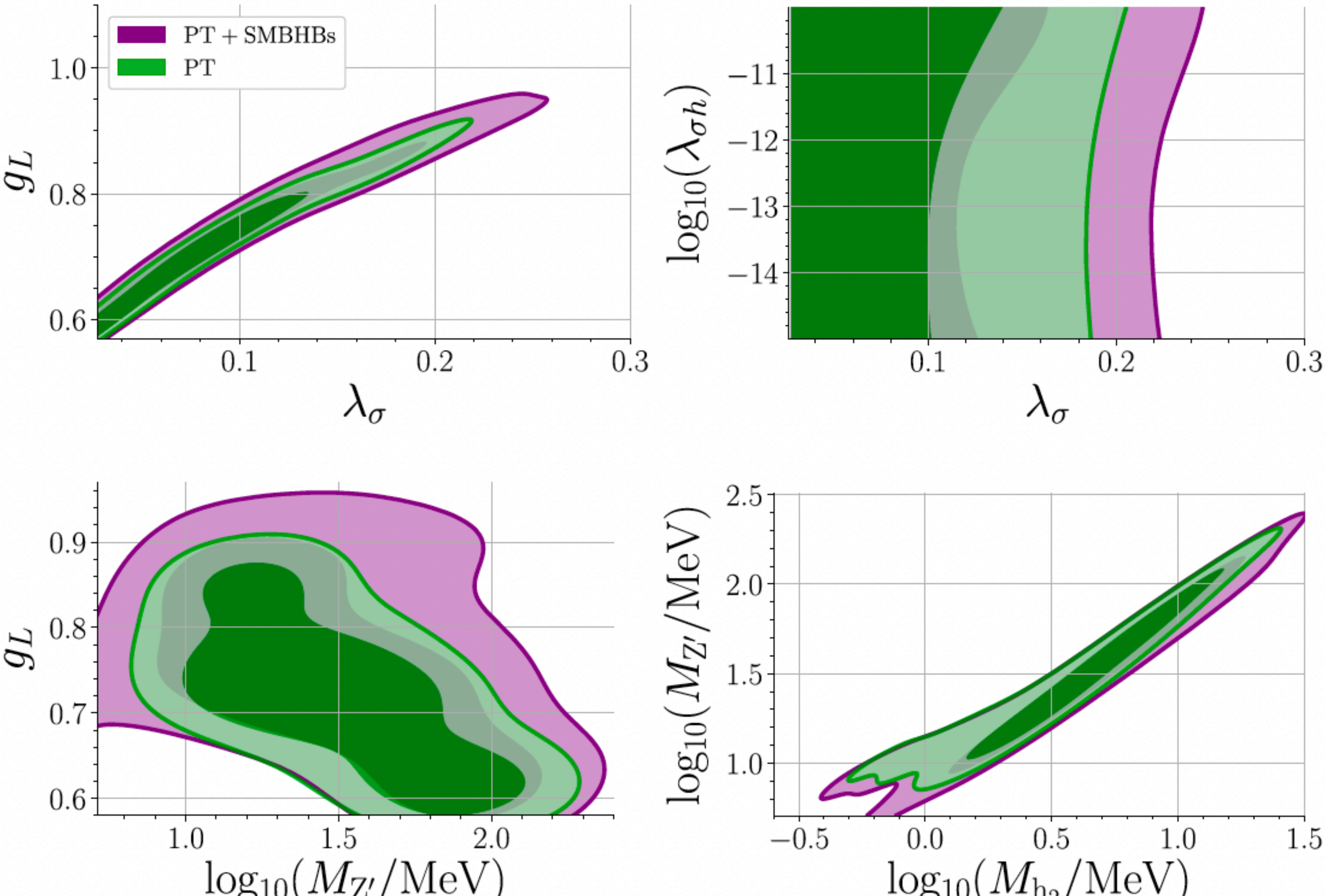
PT + SMBHBs
PT
g_L
λ_σ
$\log_{10}(\lambda_{\sigma h})$
$\log_{10}(M_{Z'}/\mathrm{MeV})$
$\log_{10}(M_{h_2}/\mathrm{MeV})$
0.6
0.8
1.0
0.1
0.2
0.3
−11
−12
−13
−14
0.7
0.9
1.5
2.0
2.5
−0.5
0.0
0.5

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Summary

- LVK data are already constraining these models
- Null signal at LIGO/ET will disfavor type-I seesaw scale above 10^{14} GeV
- Positive signal at LIGO/ET is a signature of RHNs
- LISA sensitive to seesaw scales as low as a TeV
- Supercooled MeV scale FOPTs in conformal dark sectors explain PTA data