Conformal Majoron models with supercooled phase transitions at LIGO

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Based on arXiv:24XX.XXXXX [hep-ph]

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BSM$^{\text{2nd Edition}}$ - Beyond the Standard Model BrainStorming Meeting: Particle Physics and Cosmology interface

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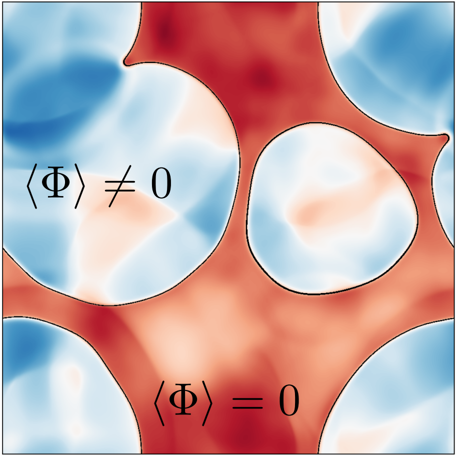
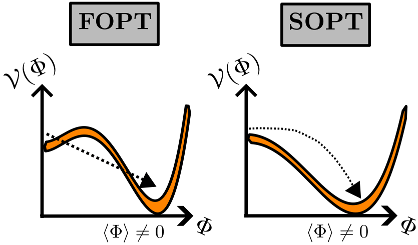


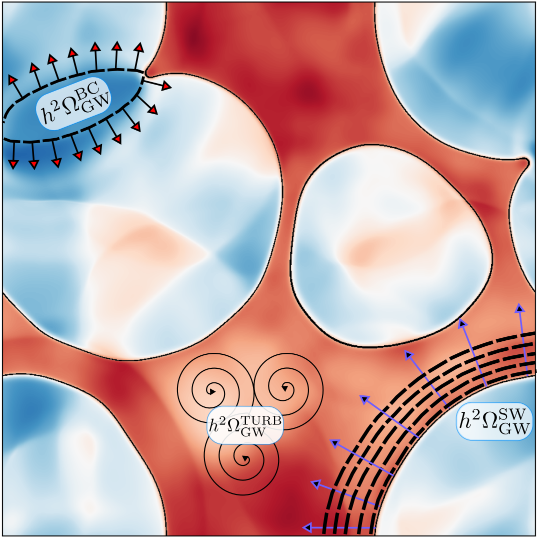
Adapted from Phys.Rev.Lett. 125 (2020) 2, 021302



Symmetry breaking $\longrightarrow$ Phase transitions (PT) in the early universe (**pre-CMB**)

- Smooth crossovers for EW and QCD transitions[a];
- BSM physics may induce 1st-order transitions $\rightarrow$ **Gravitational waves?**

[a] Phys. Rev. D **93**, 025003 (2016); JHEP **04**, 050 (2004)



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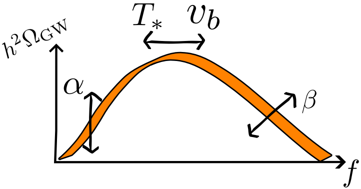
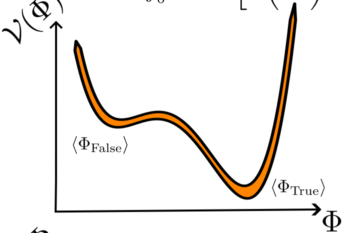
Three distinct contributions dominate the GW spectrum[a]:

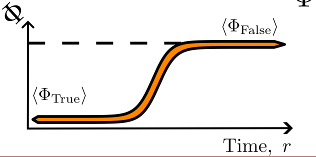
- Bubble collisions ($h^2\Omega_{\rm GW}^{\rm BC}$): Present in supercooled cases;
- Sound waves ($h^2\Omega_{\rm GW}^{\rm SW}$): Dominant and present in most scenarios;
- $h^2\Omega_{\rm GW}^{\rm TURB}$: Expected to be subdominant. Large uncertainties;

[a] 2403.03723 [astro-ph.CO]



$$S_3 = 4\pi \int_0^\infty dr\ r^2 \left[\frac{1}{2}\left(\frac{d\Phi}{dr}\right)^2 + \mathcal{V}(\Phi) \right]$$





Spectrum fully determined by 4 parameters $\boldsymbol{T_*}$, $\boldsymbol{\alpha}$, $\boldsymbol{v_b}$ and $\boldsymbol{\beta}$[a]

- Transition temperature: Temperature of universe at the end of the phase transition;
- Inverse time duration:

$$\frac{\beta}{H} = T \frac{d}{dT}\left(\frac{S_3}{T}\right)\bigg|_{T=T_p}.$$

- Transition strength:

$$\alpha = \left(\frac{\Delta V}{\rho_R} - \frac{T}{\rho_R}\frac{\partial \Delta V}{\partial T}\right)\bigg|_{T=T_p},$$

- Bubble wall velociy: $v_b = 1$ for supercooling. Analytical formulas can be derived assuming LTE[b].

[a] 2403.03723 [astro-ph.CO].

[b] JCAP 07 (2023) 002.

Neutrino mass/mixing via standard Type-I seesaw

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

Master formulas[a] for determining Yukawas from experimental mixing and mass differences.

Scalar potential

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

In the minimum, there is one physical Higgs and second BSM one.

Additional gauged $\mathrm{U}(1)'$. In the analysis, we set kinetic mixing to zero.

Field	$\mathbf{U(1)'}$
Q	$\frac{1}{3} x_H + \frac{1}{6} x_\sigma$
u_R	$\frac{4}{3} x_H + \frac{1}{6} x_\sigma$
d_R	$-\frac{2}{3} x_H + \frac{1}{6} x_\sigma$
L	$-x_H - \frac{1}{2} x_\sigma$
e_R	$-2x_H - \frac{1}{2} x_\sigma$
H	x_H
$\nu_{R,1\ldots3}$	$-\frac{1}{2} x_\sigma$
σ	x_σ

[a] Phys. Rev. D **101** (2020), no. 7 075032

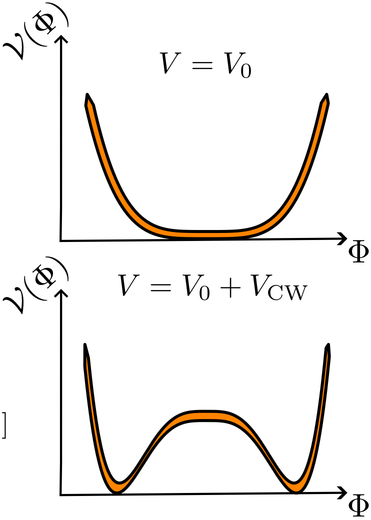
Conformal invariance → physical Higgs is massless at leading-order. Minimisation of the one-loop potential

$$\lambda_h v_h + \frac{1}{2}\lambda_{\sigma h} v_h v_\sigma^2 + \frac{\partial V_{\rm CW}}{\partial h}\Big|_{h=v_h,\sigma=v_\sigma} = 0\,,$$

$$\lambda_\sigma v_\sigma + \frac{1}{2}\lambda_{\sigma h} v_h^2 v_\sigma + \frac{\partial V_{\rm CW}}{\partial \sigma}\Big|_{h=v_h,\sigma=v_\sigma} = 0\,.$$

Mass spectrum also evaluated at 1-loop

$$M^2 = M^2_{\rm tree} + M^2_{\rm CW} + {\rm Re}[\Pi(p^2 = M^2) - \Pi(p^2 = 0)]$$



At finite temperature, the potential is extended: $V_{\rm th} = V_T(\sigma, T) + V_{\rm Daisy}(\sigma, T)$.

- 1-loop thermal:

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

For thermal PTs to happen, $\mathcal{O}(V_T) \approx \mathcal{O}(V_0)$. This indicates breakdown of perturbativity at high temperatures. Additional resummation is therefore needed.

- All-order thermal resummation:

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

where $\Pi(T)$ is 1-loop thermal mass, calculated from hard-modes self-energies. Scalar masses can also be calculated as $\Pi(T) = \partial_\sigma^2 V_T$.

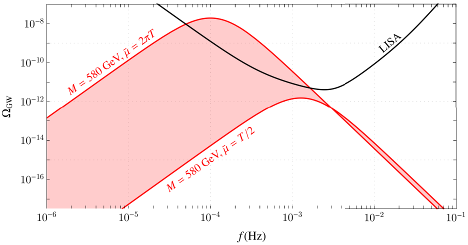
$h^2\Omega_{\rm GW}$ is strongly dependent on the renormalisation scale due to its sensitivity on the transition temperature

$$h^2\Omega_{\rm GW} \propto 1/T_*^8$$

Possible approaches

- Non-perturbative in lattice;
- 3D dimensional reduction;
- 4D RG-improved potential $\rightarrow$ **This work!**.

Unphysical scale dependence: 4d approach without RGE-running



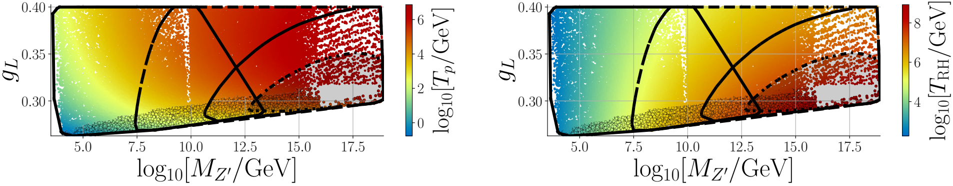
Taken from JHEP 04 (2021) 055

Couplings/fields are rescaled in accordance with renormalisation group equations

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

where $t = \ln(\mu/91~\text{GeV})$. The renormalisation scale follows the field/temperature $\mu = \max[M_{Z'}(\sigma), \pi T]$.

Scan with CosmoTransitions for fixed charges: $x_H = 0$ and $x_\sigma = 2$: B−L model



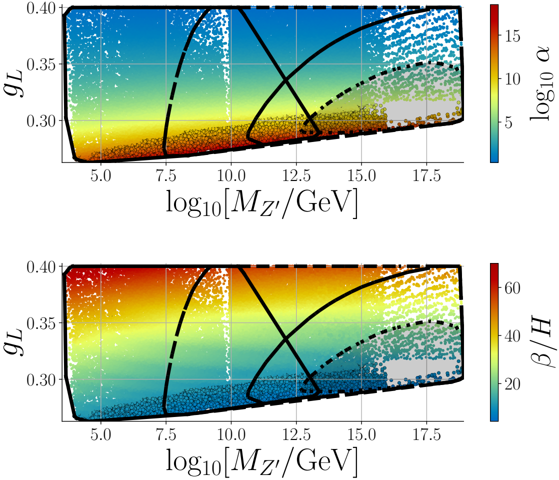
LISA: —— **ET**: — — **LIGO O5**: — · — **LVK**: · · · · · ·

- Black border coloured circles → Bubble expansion can not keep up with the thermal inflation, i.e. in this region[1]

$$\frac{1}{\mathcal{V}_{\mathrm{false}}}\frac{d\mathcal{V}_{\mathrm{false}}}{dt} > 0\,, \quad \mathcal{V}_{\mathrm{false}} : \text{False vacuum volume}\,;$$

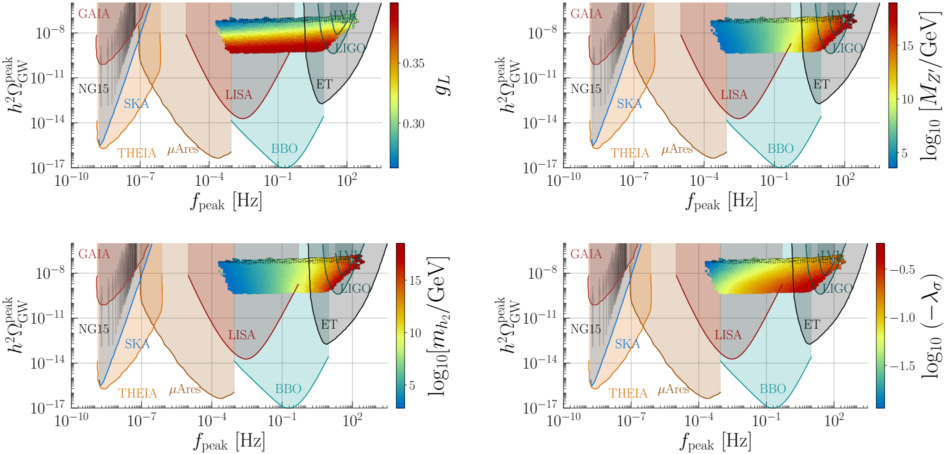
- Percolation temperatures ranging from $\mathcal{O}(0.1)$ GeV all the way to $\mathcal{O}(10^6)$ GeV;

[1] JCAP 04 (2019) 003



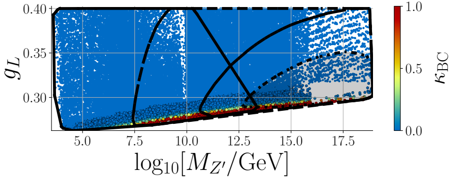
- Large amount of supercooling $\alpha \sim [1, 10^{13}]$;
- Small β/H implying long lasting transitions;

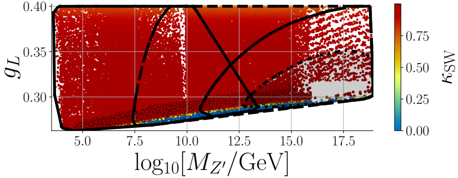
Thermodynamical parameters are largely independent of the mass of the Z' and depend exclusively on the size of g_L.



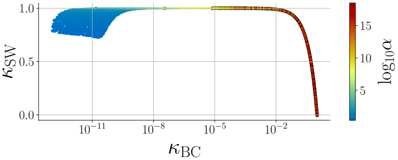
Effectively all parameter space relevant for phase transitions is expected to be observable at current/future GW experiments.

Bubble collisions vs. Sound waves

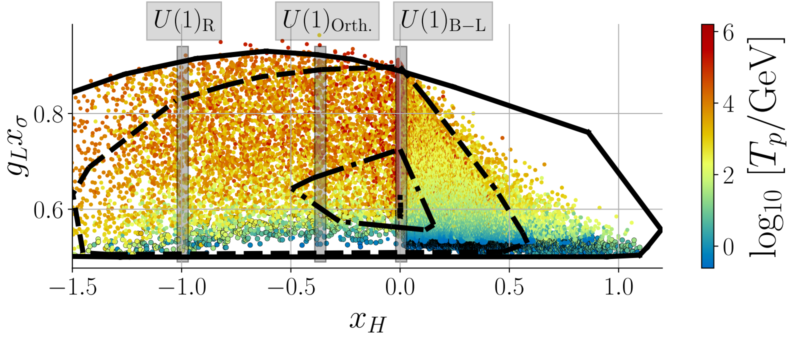




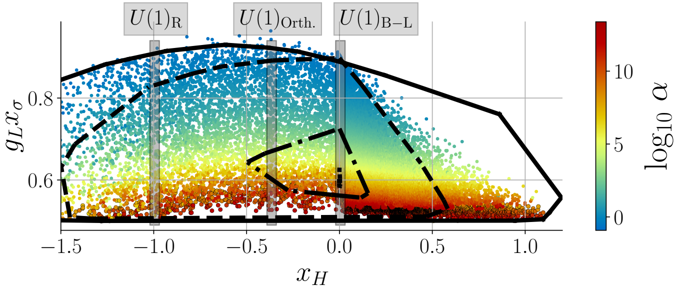
- Through out the entire allowed parameter space, sound-wave contribution always dominates $\kappa_{\rm SW} \sim 0.7 - 1.0$;
- Bubble collisions efficiency is always below $\kappa_{\rm BC} \lesssim 10^{-4}$;
- Bubble collisions is only of $\mathcal{O}(1)$ in the region where percolation does not finish.

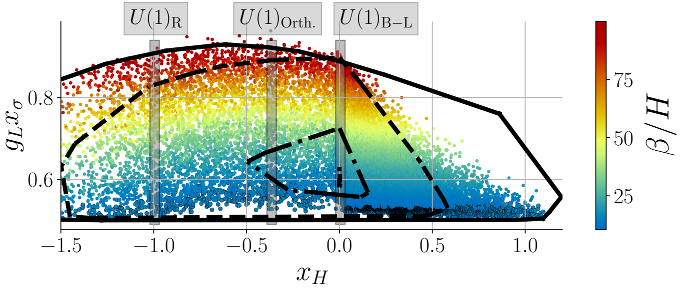


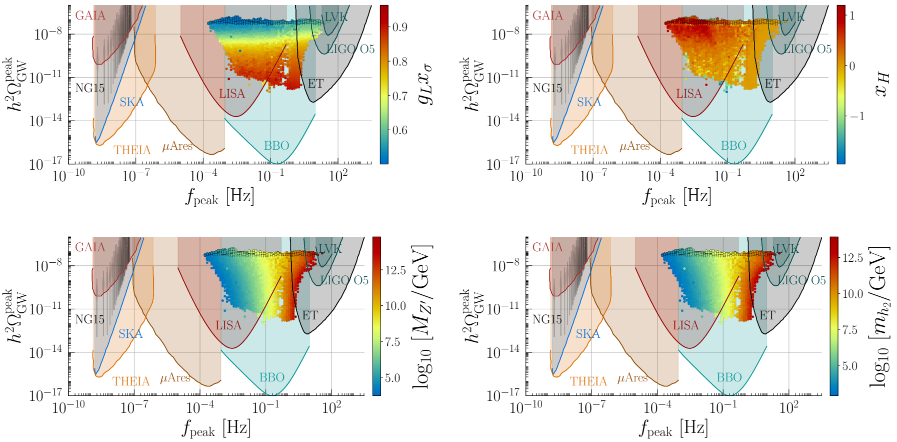
Scan with CosmoTransitions for generic charges: $x_H = [0, 1]$ and $x_\sigma = [0, 5]$



- Correlation between x_H and the temperature is weak. Mainly controlled by x_σ;
- For the smallest values $g_L x_\sigma$, the percolation condition is not respected;
- Can not have arbitrary values for (x_σ, x_H) due to Landau poles appearing in the UV at low scales.


$U(1)_{\mathrm{R}}$
$U(1)_{\mathrm{Orth.}}$
$U(1)_{\mathrm{B-L}}$
$g_L x_\sigma$
0.8
0.6
−1.5
−1.0
−0.5
0.0
0.5
1.0
x_H
$\log_{10}\alpha$
10
5
0


$U(1)_{\mathrm{R}}$
$U(1)_{\mathrm{Orth.}}$
$U(1)_{\mathrm{B-L}}$
$g_L x_\sigma$
0.8
0.6
−1.5
−1.0
−0.5
0.0
0.5
1.0
x_H
β/H
75
50
25



As in the B−L case, the masses of the BSM fields control the frequency of the spectrum, with the gauge coupling $g_L x_\sigma$ controlling the amplitude. Higher values of x_H tend to accumulate at higher amplitudes.

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Thank you for your attention

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