Gravitational Imprints of Left-Right Symmetry Breaking

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Introduction & Motivation

- Standard Model (SM) – very successful, but incomplete: e.g. neutrino masses
- $\rightarrow$ possible extension(s) desired and studied
- one of the most popular scenarios: Left-Right Symmetric Model (LRSM)
- lack of new physics signals close to the electroweak scale
- need of novel ways allowing to probe higher energies

Left-Right Symmetric Models

- gauge theory respecting the symmetry $\mathrm{SU}(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

Pati, Salam: PRD 10 (1974); Senjanovic, Mohapatra: PRD 12 (1975)

- possibly at energies near to the electroweak scale
  $\rightarrow$ of high interest, rich phenomenology, extensive literature

- right-handed neutrinos naturally included

$$(1,\ 2,\ 1,\ \text{-}1) \equiv L = (\nu_L \quad e_L)^T$$

$$(1,\ 1,\ 2,\ \text{-}1) \equiv R = (\nu_R \quad e_R)^T$$

- SM Higgs accommodated in the bi-doublet

$$(1,\ 2,\ 2,\ 0) \equiv \Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$$

- left-right symmetry broken down to the SM by an additional scalar

Left-Right Symmetric Models

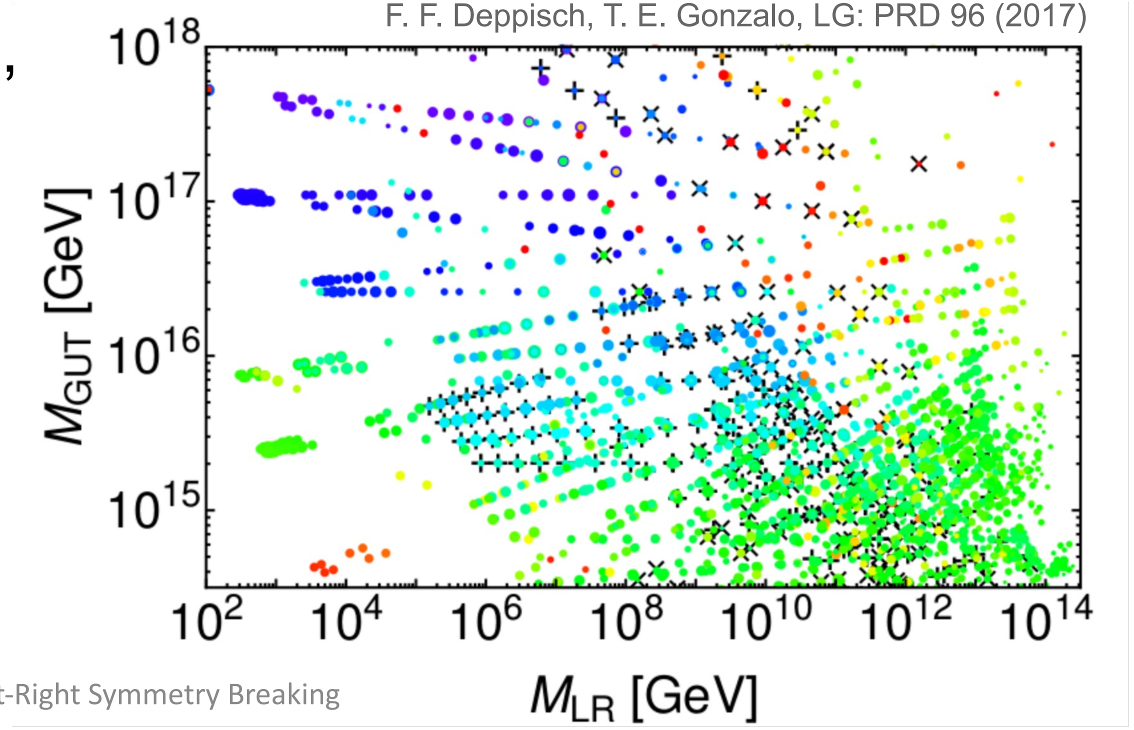
- usual picture: SU(2) triplet scalars on top of the bi-doublet

$$(1,\,3,\,1,\,0) \equiv \Delta_L = \begin{pmatrix} \frac{1}{\sqrt{2}}\delta_L^+ & \delta_L^{++} \\ \delta_L^0 & -\frac{1}{\sqrt{2}}\delta_L^+ \end{pmatrix} \qquad (1,\,1,\,3,\,0) \equiv \Delta_R = \begin{pmatrix} \frac{1}{\sqrt{2}}\delta_R^+ & \delta_R^{++} \\ \delta_R^0 & -\frac{1}{\sqrt{2}}\delta_R^+ \end{pmatrix}$$

- → neutrino masses – both type I and II seesaw possible
- can be viewed as the first step to unification, e.g. SO(10) GUT

$$SO(10)$$
$$\downarrow$$
$$SU(3)_C \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$
$$\downarrow$$
$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

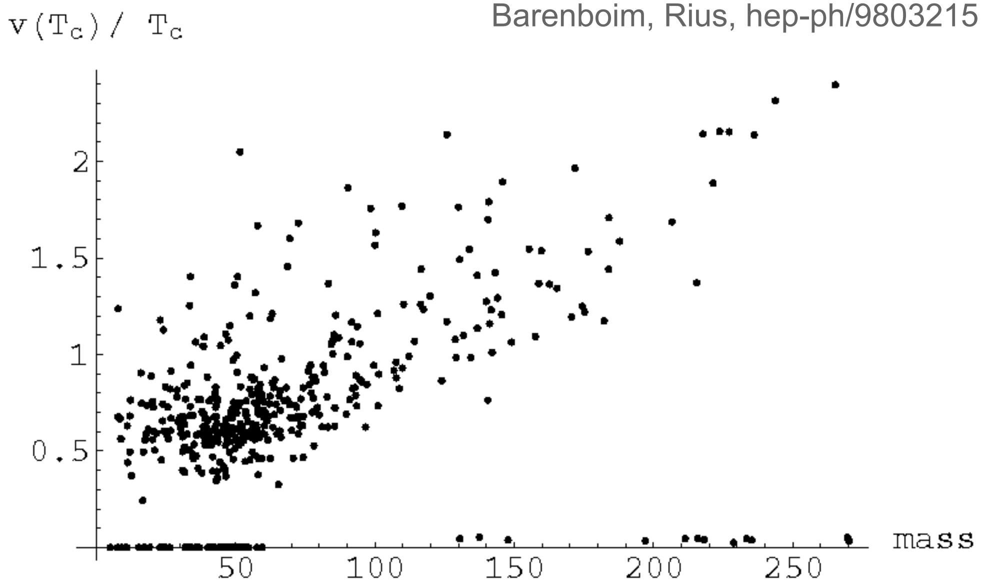
F. F. Deppisch, T. E. Gonzalo, LG: PRD 96 (2017)



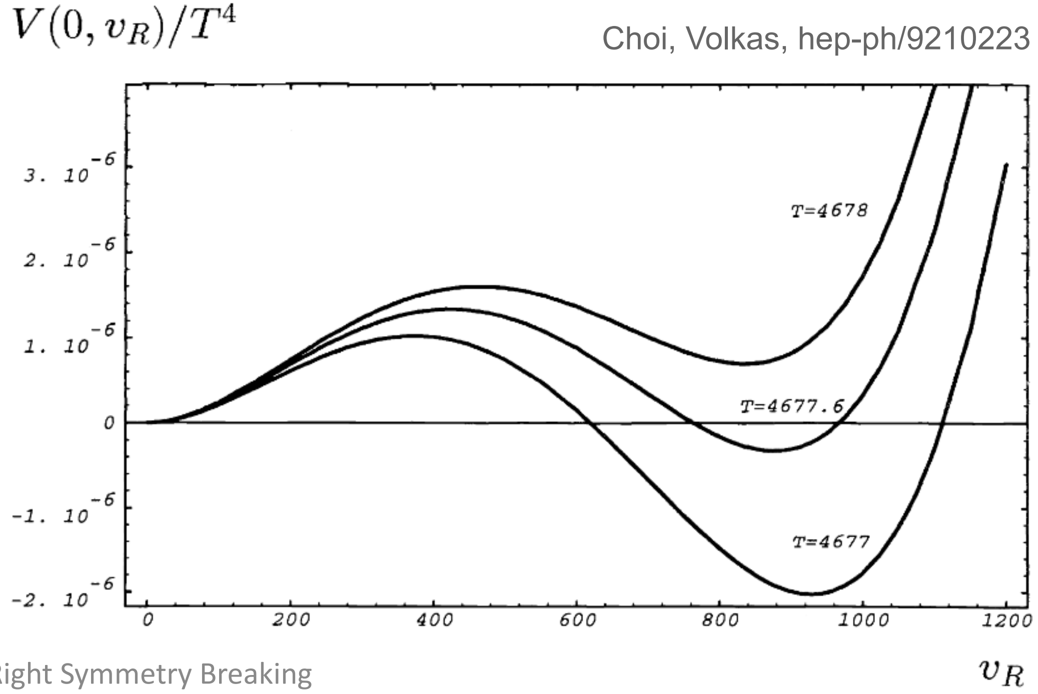
Our Focus

- infer whether L-R symmetric models yield observable gravitational wave signature from $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$ phase transition
- such a probe would be complementary to collider searches
- previous studies of L-R models at finite temperature focused on the possibility to generate baryon asymmetry of the Universe through electroweak baryogenesis

Barenboim, Rius, hep-ph/9803215



Choi, Volkas, hep-ph/9210223



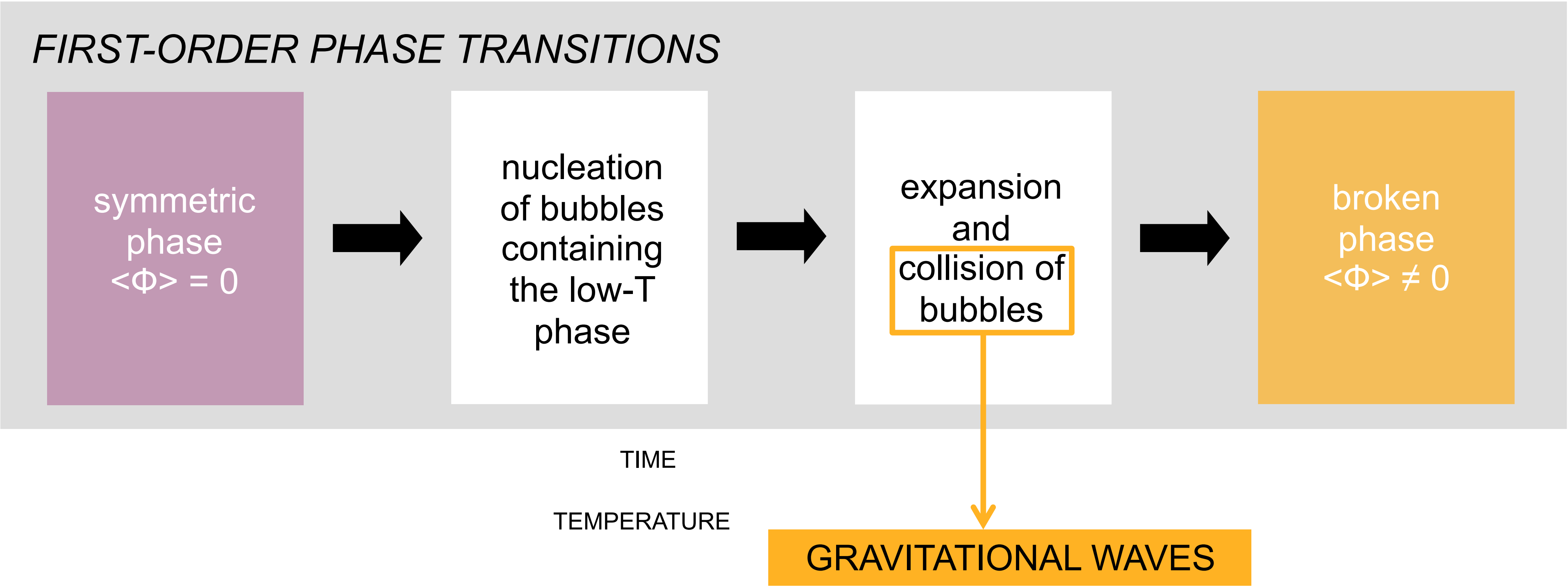
Gravitational Waves From PT

- first direct detection of GWs in 2016

Abbott et al., Phys. Rev. Lett. (2016)

- GWs can be also produced during first-order cosmic phase transitions

Witten, Phys. Rev. D (1984)



From Phase Transitions to GW

- 1. step: nucleation of bubbles containing the low-T phase
- decay rate of the false vacuum $\Gamma(T) \simeq T^4 \left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} \mathrm{e}^{-S_3/T}$
- O(3) symmetric Euclidean action

$$S_3 = \int_0^\infty \mathrm{d}r r^2 \left[\frac{1}{2}\left(\frac{\mathrm{d}\phi(r)}{\mathrm{d}r}\right)^2 + V(\phi, T)\right]$$

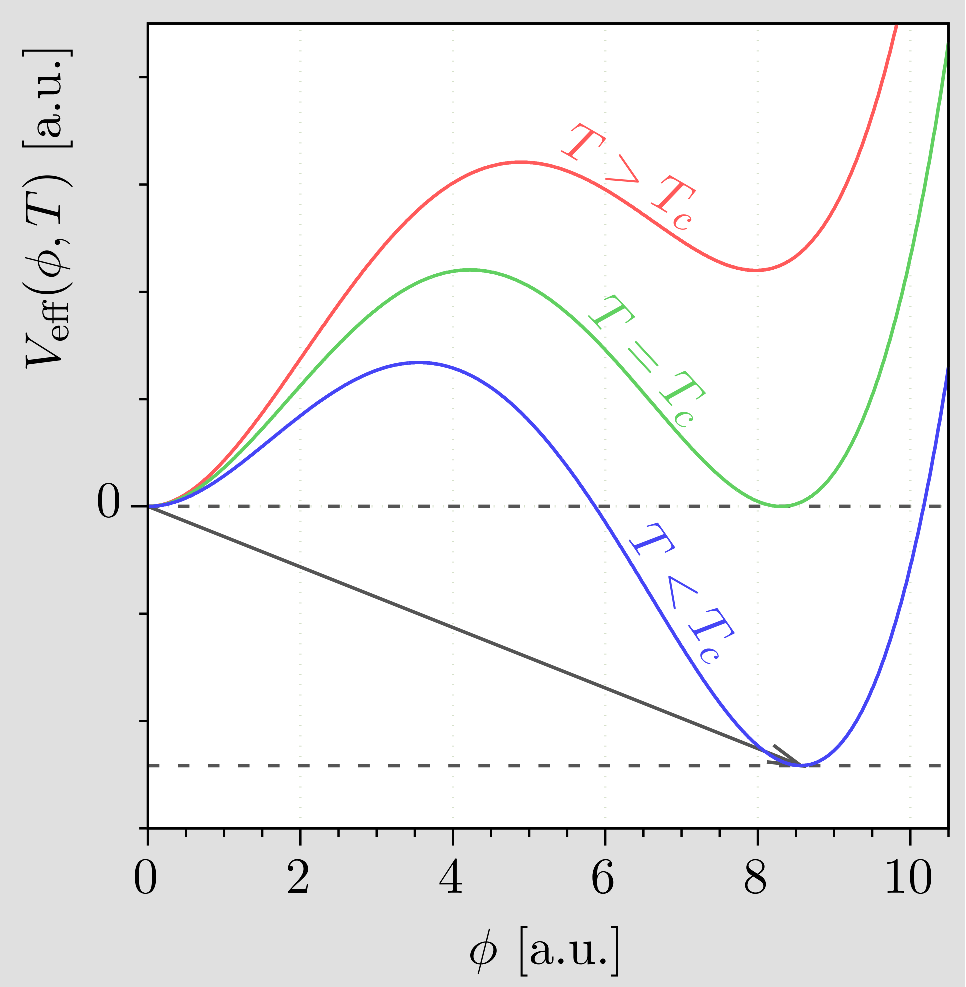
- bubble profile from equation of motion

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}r^2} + \frac{2}{r}\frac{\mathrm{d}\phi}{\mathrm{d}r} = \frac{\mathrm{d}V(\phi,T)}{\mathrm{d}r}$$

$$\lim_{r\to 0} \frac{\mathrm{d}\phi(r)}{\mathrm{d}r} = 0 \quad \lim_{r\to\infty} \phi(r) = 0$$

- nucleation temperature

$$\int_{T_n}^{T_c} \frac{\mathrm{d}T}{T} \frac{\Gamma(T)}{H(T)^4} \stackrel{!}{=} 1$$



From Phase Transitions to GW

- 2. step: expansion and collision of the bubbles

GRAVITATIONAL WAVE SOURCES

$$\Omega_{\rm GW}h^2 = \Omega_{\rm sw}h^2 + \Omega_{\rm turb}h^2 + \Omega_{\rm coll}h^2$$

- Collisions of bubble walls

  Kosowsky, Turner, Watkins, Phys. Rev. D (1992)

- Plasma sound waves

  Hindmarsh et al., Phys. Rev. Lett. (2014)

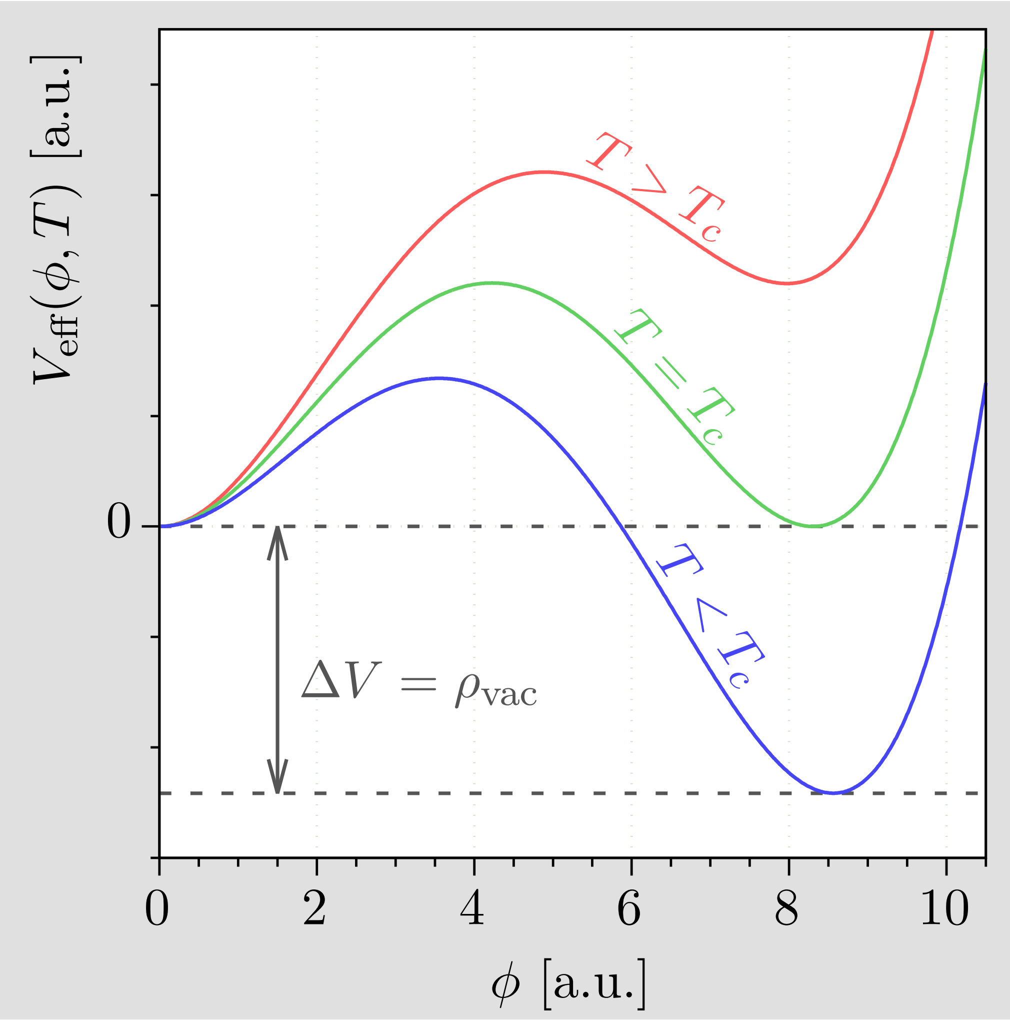
- Plasma turbulence

  Caprini, Durrer, Phys. Rev. D (2006)

numerical simulations

PT parameters

Spectrum: $h^2\Omega_{GW}(f; v_w, \alpha, \beta, T_n)$



Key Phase Transition Parameters

Gravitational wave background spectrum $h^2\Omega_{GW}(f; v_w, \alpha, \beta, T_n)$

- bubble wall velocity v_w
  - generally, depends on interaction between ϕ and plasma
  - typically, $v_w \to 1$ for strong phase transitions
- normalized available energy $$\alpha = \frac{1}{\rho_{\rm rad}(T_n)}\left(\Delta V(T_n) - \frac{T_n}{4}\left.\frac{\partial \Delta V(T)}{\partial T}\right|_{T=T_n}\right)$$
- inverse duration of the PT $$\beta = H(T_n)T_n \cdot \left.\frac{\mathrm{d}(S_3/T)}{\mathrm{d}T}\right|_{T=T_n}$$

General Approach

Particle physics model of interest

↓

Finite-temperature effective potential $V_{eff}(\phi, T)$ → Phase transition parameters v_w, α, β, T_n → Gravitational wave spectrum $h^2\Omega_{GW}(f)$

↓

Experimental sensitivity $h^2\Omega_{sens}(f)$ → **Signal-to-noise ratio (SNR)**

Can a model be tested using gravitational waves?

L-R Symmetry: The Usual Setup

- tree level scalar potential:

$$V_{\text{tree}} = V_\Phi + V_\Delta + V_{\Phi\Delta}$$

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}\kappa_1 & 0\\ 0 & \kappa_2\end{pmatrix}$$

$$\langle\Delta_L\rangle = 0$$

$$\langle\Delta_R\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0 & 0\\ v_R & 0\end{pmatrix}$$

$$\tan\beta = \frac{\kappa_2}{\kappa_1}$$

$$\begin{aligned}
V_\Phi = & -\mu_1^2\mathrm{Tr}[\Phi^\dagger\Phi] - \mu_2^2(\mathrm{Tr}[\tilde\Phi\Phi^\dagger] + \mathrm{Tr}[\tilde\Phi^\dagger\Phi]) - \mu_3^2(\mathrm{Tr}[\Delta_L\Delta_L^\dagger] + \mathrm{Tr}[\Delta_R\Delta_R^\dagger]) + \lambda_1\mathrm{Tr}[\Phi^\dagger\Phi]^2\\
& + \lambda_2\left(\mathrm{Tr}[\tilde\Phi\Phi^\dagger]^2 + \mathrm{Tr}[\tilde\Phi^\dagger\Phi]^2\right) + \lambda_3\mathrm{Tr}[\tilde\Phi\Phi^\dagger]\mathrm{Tr}[\tilde\Phi^\dagger\Phi] + \lambda_4\mathrm{Tr}[\Phi^\dagger\Phi](\mathrm{Tr}[\tilde\Phi\Phi^\dagger] + \mathrm{Tr}[\tilde\Phi^\dagger\Phi])\\
V_\Delta = & \;\rho_1\left(\mathrm{Tr}[\Delta_L\Delta_L^\dagger]^2 + \mathrm{Tr}[\Delta_R\Delta_R^\dagger]^2\right) + \rho_2(\mathrm{Tr}[\Delta_L\Delta_L]\mathrm{Tr}[\Delta_L^\dagger\Delta_L^\dagger] + \mathrm{Tr}[\Delta_R\Delta_R]\mathrm{Tr}[\Delta_R^\dagger\Delta_R^\dagger])\\
& + \rho_3\mathrm{Tr}[\Delta_L\Delta_L^\dagger]\mathrm{Tr}[\Delta_R\Delta_R^\dagger] + \rho_4(\mathrm{Tr}[\Delta_L\Delta_L]\mathrm{Tr}[\Delta_R^\dagger\Delta_R^\dagger] + \mathrm{Tr}[\Delta_L^\dagger\Delta_L^\dagger]\mathrm{Tr}[\Delta_R\Delta_R])\;,\\
V_{\Phi\Delta} = & \;\alpha_1\mathrm{Tr}[\Phi^\dagger\Phi](\mathrm{Tr}[\Delta_L\Delta_L^\dagger] + \mathrm{Tr}[\Delta_R\Delta_R^\dagger]) + \alpha_3(\mathrm{Tr}[\Phi\Phi^\dagger\Delta_L\Delta_L^\dagger] + \mathrm{Tr}[\Phi^\dagger\Phi\Delta_R\Delta_R^\dagger])\\
& + \alpha_2(\mathrm{Tr}[\Delta_L\Delta_L^\dagger]\mathrm{Tr}[\tilde\Phi\Phi^\dagger] + \mathrm{Tr}[\Delta_R\Delta_R^\dagger]\mathrm{Tr}[\tilde\Phi^\dagger\Phi] + \text{h.c.})\\
& + \beta_1(\mathrm{Tr}[\Phi\Delta_R\Phi^\dagger\Delta_L^\dagger] + \mathrm{Tr}[\Phi^\dagger\Delta_L\Phi\Delta_R^\dagger]) + \beta_2(\mathrm{Tr}[\tilde\Phi\Delta_R\Phi^\dagger\Delta_L^\dagger] + \mathrm{Tr}[\tilde\Phi^\dagger\Delta_L\Phi\Delta_R^\dagger])\\
& + \beta_3(\mathrm{Tr}[\Phi\Delta_R\tilde\Phi^\dagger\Delta_L^\dagger] + \mathrm{Tr}[\Phi^\dagger\Delta_L\tilde\Phi\Delta_R^\dagger])\;,
\end{aligned}$$

Generating Benchmark Points

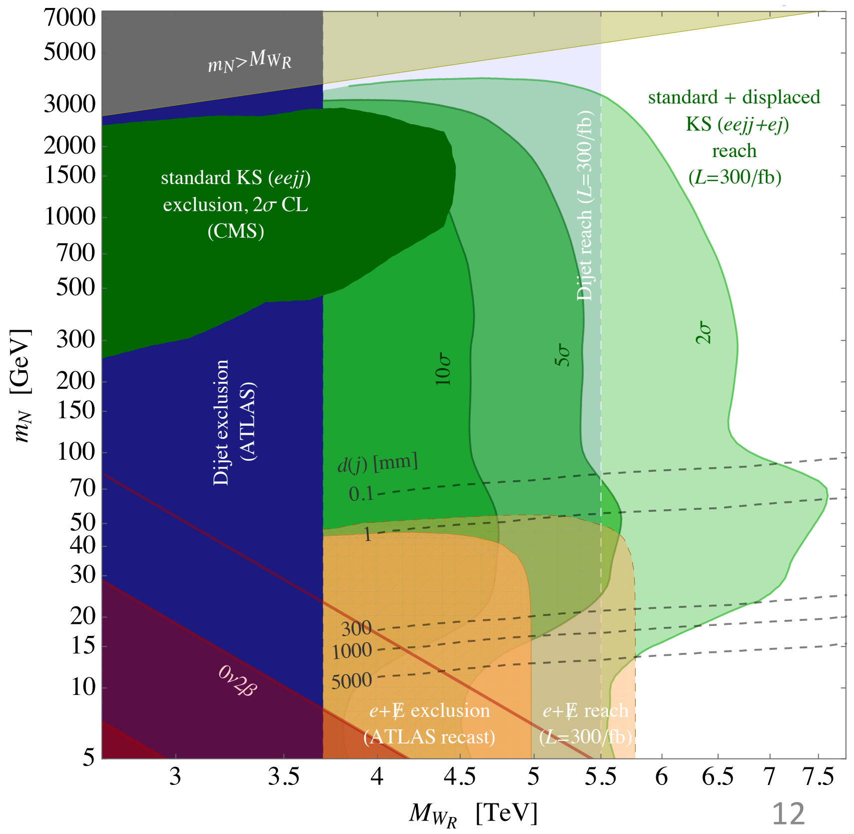
- the potential at the tree level is bounded from below and has a global minimum with the predefined VEVs

Dev et al., JHEP 02 (2019)

$$v = 246\text{ GeV},\; v_R \in [10^4,\; 10^6]\,\text{GeV},\; \tan\beta = \tan 10^{-3},$$
$$\lambda_1 = 0.13,\; \lambda_2 = 0,\; \lambda_3 \in [0,\; 2],\; \lambda_4 = 0,$$
$$\rho_1 \in [0,\; 0.5],\; \rho_2 \in [0,\; 2],\; \rho_3 \in [1,\; 2],\; \rho_4 = 0,$$
$$\alpha_1 = 0,\; \alpha_2 \in [0,\; 0.5],\; \alpha_3 \in [0,\; 1],$$
$$\beta_1 = \beta_2 = \beta_3 = 0.$$

- the VEVs satisfy: $v \approx 246$ GeV and $v_R \gtrsim 104$ GeV (to make W_R sufficiently heavy and thus satisfy the LHC bounds)

Nemevsek et al., Phys. Rev. D 97, 115018 (2018)



- the physical spectrum contains a scalar with mass $m_h \approx 125$ GeV and the properties of the SM Higgs boson; all the other bosons (except for the six Goldstone bosons) have masses at the same order as v_R

Left-Right Effective Potential

- the full potential: $\boxed{V_{\text{eff}}(r,T) = V_0(r) + V_{\text{CW}}(r) + V_{\text{FT}}(r,T) + V_{\text{D}}(r,T)}$

$$v_R \gg \kappa_1, \kappa_2 \longrightarrow V_0(r) = -\tfrac{1}{2}\mu_3^2 r^2 + \tfrac{1}{4}\rho_1 r^4 \quad \text{with} \quad r := \text{Re}\,\delta_R^0/\sqrt{2}$$

- Coleman-Weinberg:

$$V_{\text{CW}}(r) = \frac{1}{64\pi^2}\left[\sum_i m_i^4(r)\left(\log\frac{m_i^2(r)}{\mu^2} - \frac{3}{2}\right) + 6m_{W_R}^4(r)\left(\log\frac{m_{W_R}^2(r)}{\mu^2} - \frac{5}{6}\right)\right.$$
$$\left. + 3m_{Z_R}^4(r)\left(\log\frac{m_{Z_R}^2(r)}{\mu^2} - \frac{5}{6}\right) - 6m_{\nu_R}^4(r)\left(\log\frac{m_{\nu_R}^2(r)}{\mu^2} - \frac{3}{2}\right)\right]$$

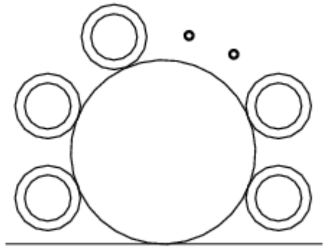
- 1-loop thermal contribution:

$$V_{\text{FT}}(r,T) = \frac{T^4}{2\pi^2}\left[\sum_i J_{\text{B}}\left(\frac{m_i^2(r)}{T^2}\right) + 6J_{\text{B}}\left(\frac{m_{W_R}^2(r)}{T^2}\right) + 3J_{\text{B}}\left(\frac{m_{Z_R}^2(r)}{T^2}\right) - 6J_{\text{F}}\left(\frac{m_{\nu_R}^2(r)}{T^2}\right)\right]$$

$$J_{\text{B/F}}(r^2) = \int_0^\infty \mathrm{d}x\, x^2 \log\left(1 \pm \mathrm{e}^{\sqrt{x^2+r^2}}\right)$$

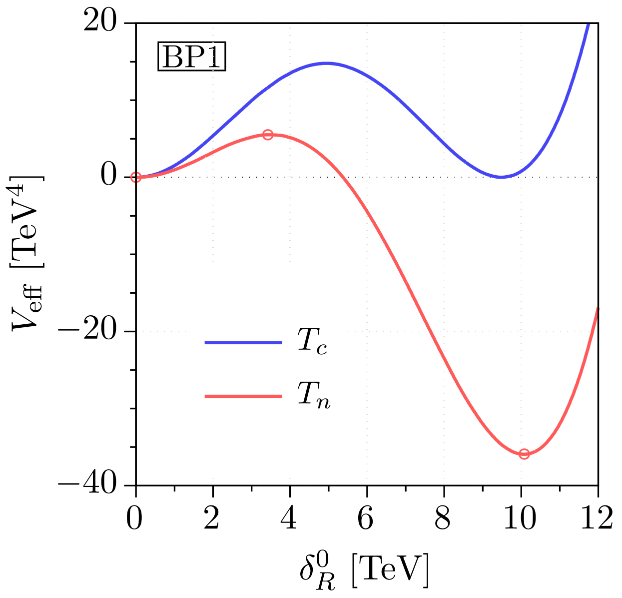
- perturbative expansion fails at large T
  $\rightarrow$ resumed daisy graphs

$$V_{\text{D}}(r,T) = -\frac{T}{12\pi}\sum_i\left[M_i^3(r) - m_i^3(r)\right]$$



M.Quiros, arXiv:hep-ph/9901312
M.E.Carrington Phys. Rev. D45 (1992)

Phase Transition – Dependence on ρ_1



V. Brdar, LG, A. J. Helmboldt, X. Xu: JCAP 12 (2019)

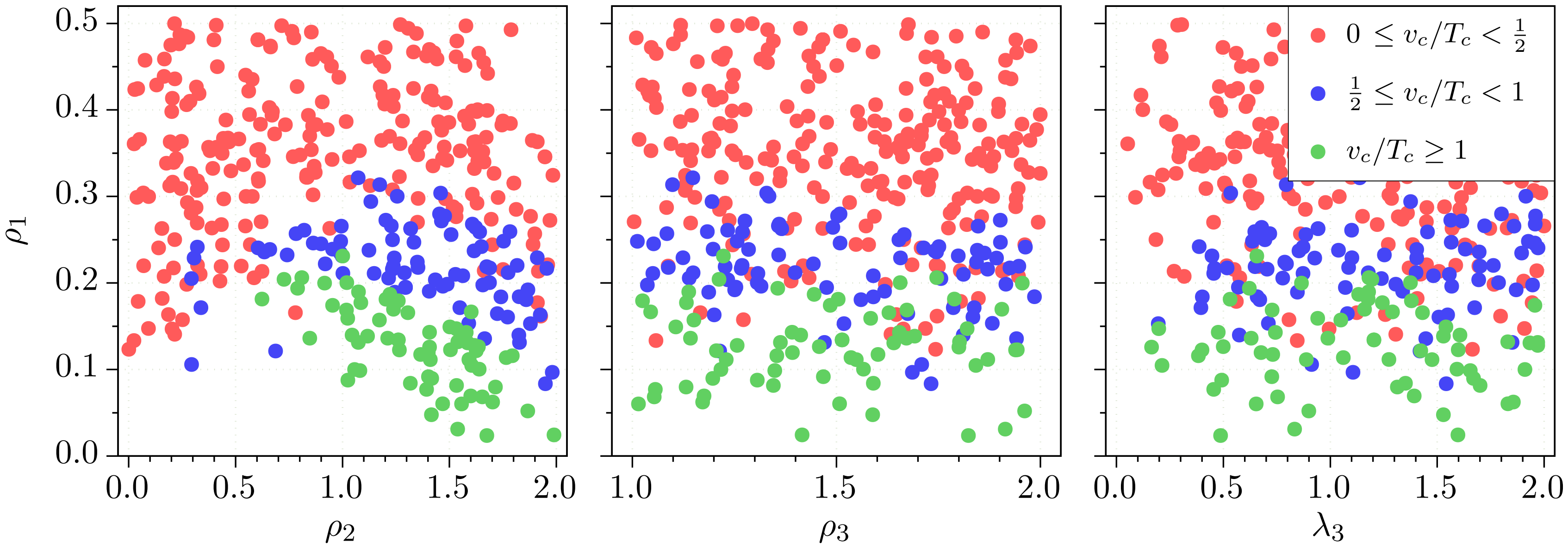
- phase transition gets stronger when ρ_1 decreases
- choosing ρ_1 to be small brings r sector near scale-invariant limit

$$\mu_3^2 = \rho_1 v_R^2 + \frac{1}{2}\alpha_1\left(\kappa_1^2+\kappa_2^2\right) + 2\alpha_2\kappa_1\kappa_2 + \frac{1}{2}\alpha_3\kappa_2^2$$

$$\rho_1 \ll 1 \qquad \Longrightarrow \qquad \mu_3 \ll v_R$$

- phase transitions in theories based on nearly conformal dynamics are typically strong and of first order

Konstandin, Servant arXiv:1104.4791



Stochastic Gravitational Wave Signal

Caprini et al. arXiv:1512.06239
Huber, Konstandin arXiv:0806.1828

- for all benchmark points we find the so-called “non-runaway” scenario ⇒ dominant production from sound waves and magnetohydrodynamic turbulence following bubble collisions

$$\Omega_{\rm GW} h^2 \simeq \Omega_{\rm sw}\, h^2 + \Omega_{\rm turb}\, h^2$$

- sound waves: $\Omega_{\rm sw} h^2 = 2.65 \cdot 10^{-6} \left(\frac{H}{\beta}\right) \left(\frac{\kappa_v\, \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} v_w \left(\frac{f}{f_{\rm sw}}\right)^3 \left(\frac{7}{4+3\,(f/f_{\rm sw})^2}\right)^{7/2}$

$\kappa_v = \alpha\left(0.73 + 0.083\sqrt{\alpha} + \alpha\right)^{-1}$

$\boxed{f \to 0 \Rightarrow \Omega_{\rm sw} h^2 \propto f^3}$ $\boxed{f \to \infty \Rightarrow \Omega_{\rm sw} h^2 \propto f^{-4}}$

- magnetohydrodynamic turbulence:

$$\Omega_{\rm turb} h^2 = 3.35 \cdot 10^{-4} \left(\frac{H}{\beta}\right) \left(\frac{\kappa_{\rm turb}\, \alpha}{1+\alpha}\right)^{3/2} \left(\frac{100}{g_*}\right)^{1/3} v_w \left(\frac{f}{f_{\rm turb}}\right)^3 \frac{1}{\left[1+(f/f_{\rm turb})\right]^{11/3}(1+8\pi f/h_*)}$$

$\boxed{f \to 0 \Rightarrow \Omega_{\rm turb} h^2 \propto f^3}$ $\boxed{f \to \infty \Rightarrow \Omega_{\rm turb} h^2 \propto f^{-5/3}}$

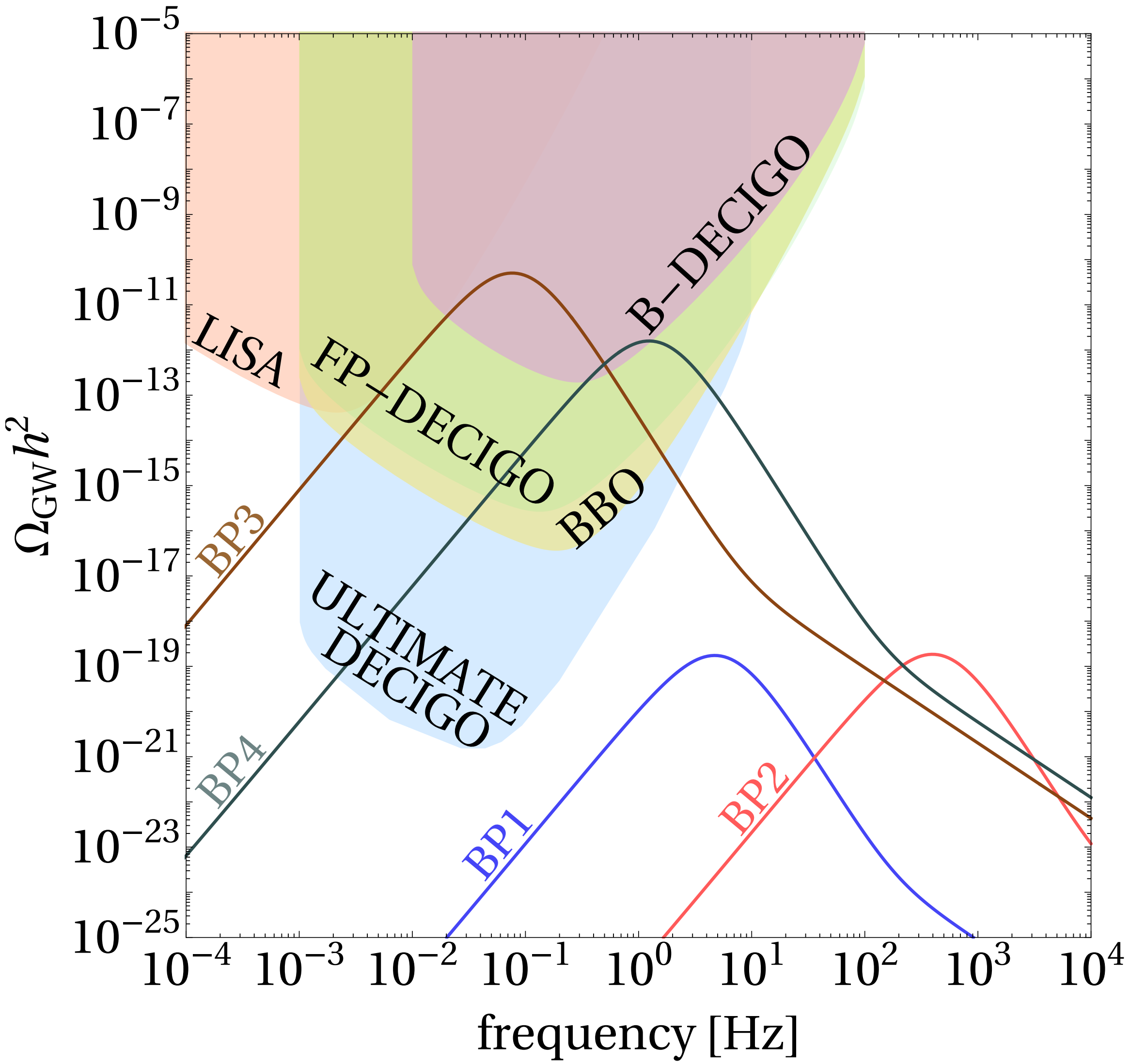
Gravitational Wave Spectrum

- space-based detectors will be able to probe the model for small value of ρ_1 (BP3, BP4)
- tree-level shallow potential is vulnerable to the CW correction: to this end, for BP3 and BP4 we fine-tune RH neutrino Yukawa coupling

Nemevsek et al., JHEP 1704 (2017) 114

- GW strength does not depend on this tuning

	α	β/H	T_n [GeV]	T_c [GeV]
BP1	0.0035	4007	5896	6216
BP2	0.0034	3458	5.754×10^5	6.063×10^5
BP3	0.46	626.2	608.3	9451
BP4	0.18	1386	4484	7469



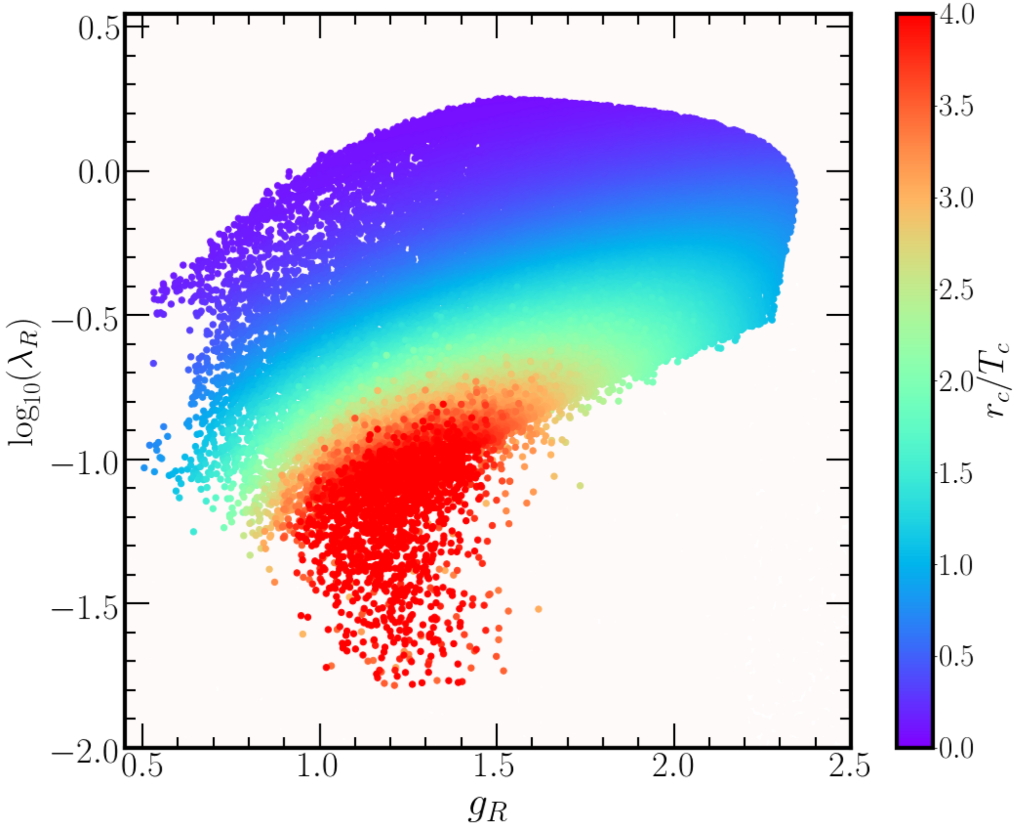
BP3 SNR: LISA (11.76), B-DECIGO (672.7)
BP4 SNR: LISA O(10^{-4}), B-DECIGO (16.69)

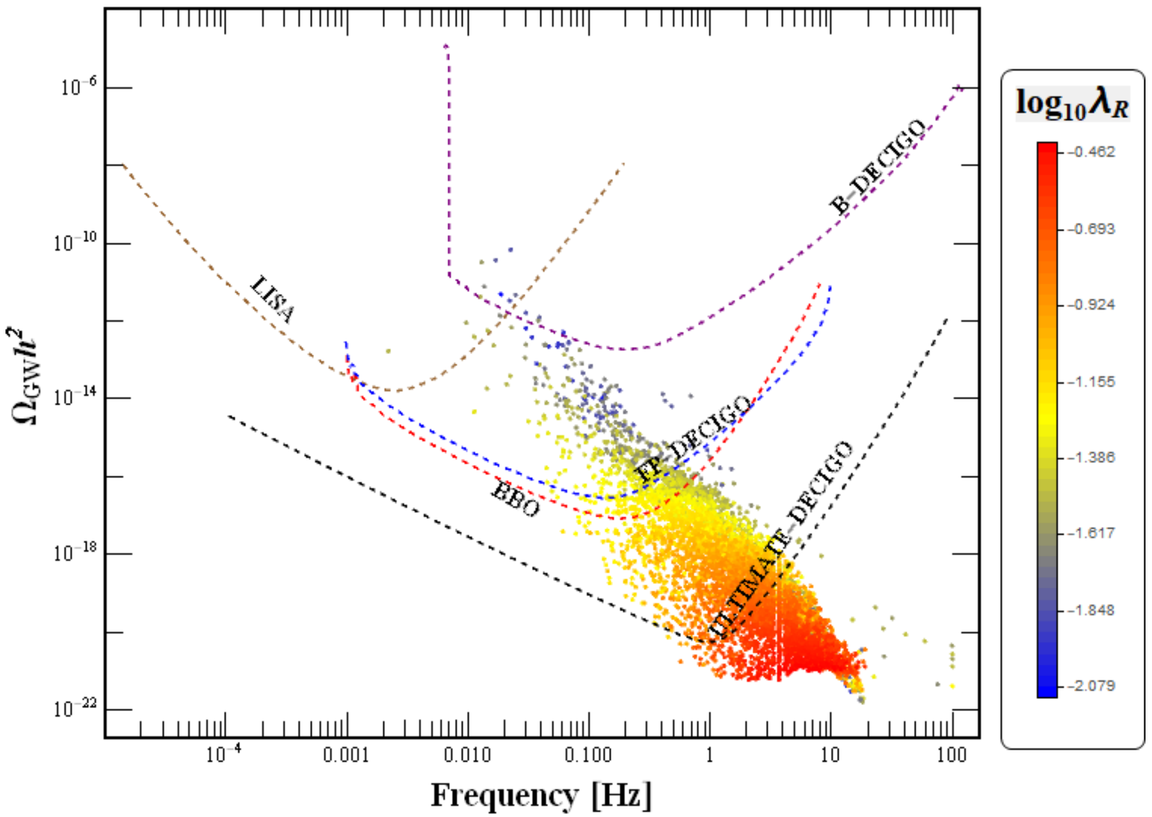
V. Brdar, LG, A. J. Helmboldt, X. Xu: JCAP 12 (2019)

LRSM with Minimal Scalar Sector

- scalar sector: only a pair of doublets: $\chi_L = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix} \sim (1,2,1,+1), \quad \chi_R = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix} \sim (1,1,2,+1)$

$$V = -(\mu_L^2 \chi_L^\dagger \chi_L + \mu_R^2 \chi_R^\dagger \chi_R) + \frac{\lambda_L}{2}(\chi_L^\dagger \chi_L)^2 + \frac{\lambda_R}{2}(\chi_R^\dagger \chi_R)^2 + \lambda(\chi_L^\dagger \chi_L)(\chi_R^\dagger \chi_R)$$





LG, S. Jana, A. Kaladharan, S. Saad: JCAP 05 (2022)

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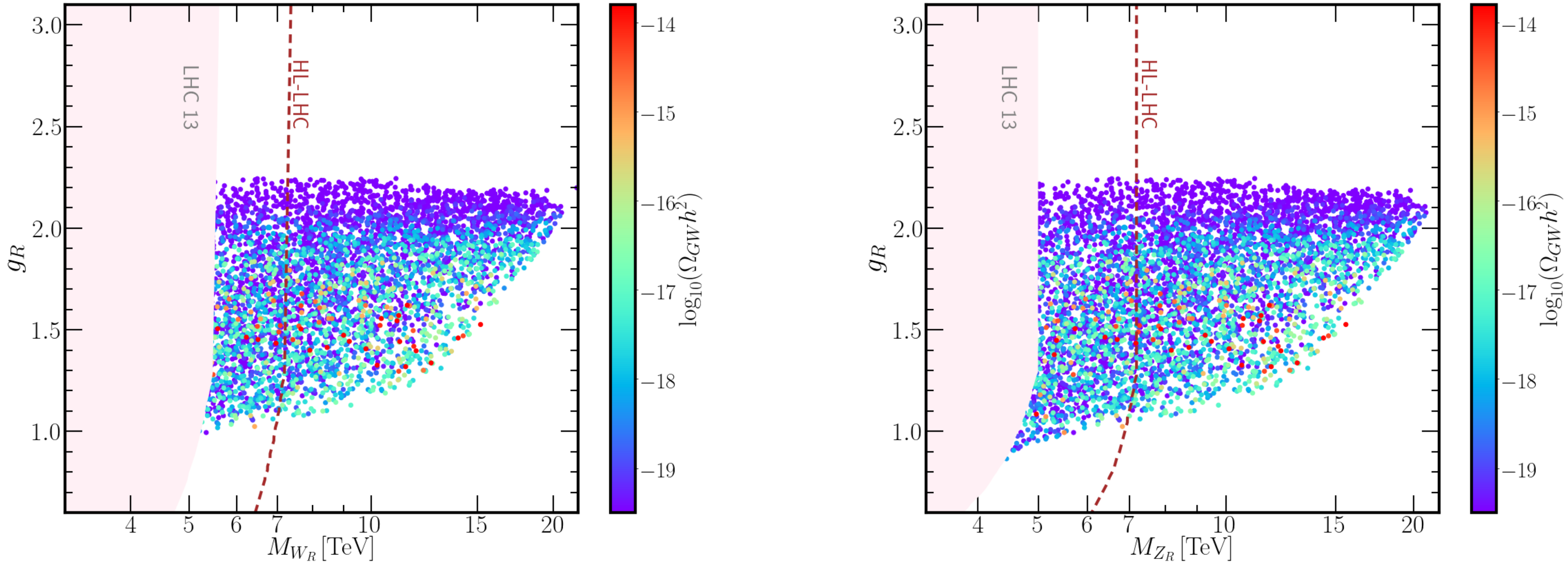

LG, S. Jana, A. Kaladharan, S. Saad: JCAP 05 (2022)

Summary

- gravitational wave signature from first-order phase transition associated to $SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$ investigated
- although the phase transition is relatively weak for a generic point of the parameter space, testable gravitational wave signature arises in $\rho_1 \ll O(1)$ “scale-invariant” limit
- gravitational wave searches will provide a test not only for the mechanism of LR symmetry breaking, but also for the generation of neutrino masses
- LR symmetric models therefore feature another powerful probe, which is complementary to collider searches, and which can lead to either novel constraints or remarkable discoveries

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Thank you for your attention!

Benchmark Points

	BP1	BP2	BP3	BP4
v/GeV	246	246	246	246
v_R/GeV	10^4	10^6	10^4	5×10^4
$\tan\beta$	10^{-3}	10^{-3}	0	0
λ_1	0.13	0.13	0.13	0.13
λ_2	0	0	0	0
λ_3	1.2040	0.88814	0.6	0.6
λ_4	0	0	0	0
ρ_1	0.13414	0.11146	0.001	0.002
ρ_2	1.2613	1.4109	0.900218	0.401126
ρ_3	1.5140	1.5489	0.900215	0.401126
ρ_4	0	0	0	0.040113
α_1	0	0	0	0
α_2	0.30246	0.15557	0	0
α_3	0.10765	0.11185	1.14815	0.378138
$\beta_{1,2,3}$	0	0	0	0
g	0.65	0.65	0.65	0.65
g_{B-L}	0.4324	0.4324	0.4324	0.4324
y_t	0.95	0.95	0.95	0.95
y_M	1	1	0.78595	0.52404

Gravitational Wave Detectors

- ground-based observatories: LIGO and Virgo (phases O2, O3 and “Design”)
- space-based detectors: LISA, Big Bang Observer, DECIGO (two stages: B-DECIGO and FP-DECIGO)
- we define signal-to-noise ratio (SNR):

  Thrane, Romano: arXiv: 1310.5300

$$\mathrm{SNR} = \sqrt{2t_{\mathrm{obs}} \int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} \mathrm{d}f \left[\frac{\Omega_{\mathrm{GW}}(f)\, h^2}{\Omega_{\mathrm{noise}}(f)\, h^2} \right]^2}$$

- $\Omega_{noise}h^2$ is effective strain noise power spectral density (different from sensitivity curves)
- for all space-based measurements t_{obs} = 5 years assumed