Testing Seesaw Models with Gravitational Waves

based on: 1810.12306 (JCAP 2019) and 1909.02018

Vedran Brdar

Max-Planck-Institut für Kernphysik Heidelberg

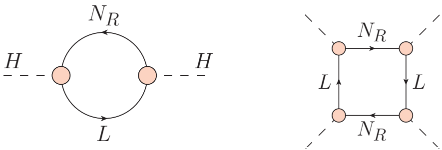
The Neutrino Option

- Brivio, Trott PRL '17 (arXiv:1703.10924, see also 1809.03450)
- why the Higgs is so light? why neutrinos are so light?
- connection?

type-I seesaw: $$-\mathcal{L} = \frac{1}{2} M \bar{N}_R N_R^c + y_\nu \bar{L} \tilde{H} N_R + h.c.$$

1) Assumptions: Majorana **scale** M; Higgs potential **vanishes** at M

2) Integrate out N_R



3) RG evolution

SM Higgs potential reproduced at EW scale for $M \simeq 10^7 \ldots 10^8$ GeV and $y_\nu \lesssim 10^{-4}$

Neutrino Option+Leptogenesis

arXiv.org > hep-ph > arXiv:1905.12634

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High Energy Physics - Phenomenology

Type-I Seesaw as the Common Origin of Neutrino Mass, Baryon Asymmetry, and the Electroweak Scale

Vedran Brdar, Alexander J. Helmboldt, Sho Iwamoto, Kai Schmitz

(Submitted on 29 May 2019)

The type-I seesaw represents one of the most popular extensions of the Standard Model. Previous studies of this model have mostly focused on its ability to explain neutrino oscillations as well as on the generation of the baryon asymmetry via leptogenesis. Recently, it has been pointed out that the type-I seesaw can also account for the origin of the electroweak scale due to heavy-neutrino threshold corrections to the Higgs potential. In this paper, we show for the first time that all of these features of the type-I seesaw are compatible with each other. Integrating out a set of heavy Majorana neutrinos results in small masses for the Standard Model neutrinos; baryogenesis is accomplished by resonant leptogenesis; and the Higgs mass is entirely induced by heavy-neutrino one-loop diagrams, provided that the tree-level Higgs potential satisfies scale-invariant boundary conditions in the ultraviolet. The viable parameter space is characterized by a heavy-neutrino mass scale roughly in the range $10^{6.5\cdots7.0}$ GeV and a mass splitting among the nearly degenerate heavy-neutrino states up to a few TeV. Our findings have interesting implications for high-energy flavor models and low-energy neutrino observables. We conclude that the type-I seesaw sector might be the root cause behind the masses and cosmological abundances of all known particles. This statement might even extend to dark matter in the presence of a keV-scale sterile neutrino.

arXiv.org > hep-ph > arXiv:1905.12642

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High Energy Physics - Phenomenology

Leptogenesis in the Neutrino Option

I. Brivio, K. Moffat, S. Pascoli, S.T. Petcov, J. Turner

(Submitted on 29 May 2019)

We examine the compatibility between the Neutrino Option, in which the electroweak scale is generated by PeV mass type I seesaw Majorana neutrinos, and leptogenesis. We find the Neutrino Option is consistent with resonant leptogenesis. Working within the minimal seesaw scenario with two heavy Majorana neutrinos $N_{1,2}$, which form a pseudo-Dirac pair, we explore the viable parameter space. We find that the Neutrino Option and successful leptogenesis are compatible in the cases of a neutrino mass spectrum with normal (inverted) ordering for $1.2 \times 10^6 < M\ (\mathrm{GeV}) < 8.8 \times 10^6$ $(2.4 \times 10^6 < M\ (\mathrm{GeV}) < 7.4 \times 10^6)$, with $M = (M_1 + M_2)/2$ and $M_{1,2}$ the masses of $N_{1,2}$. Successful leptogenesis requires that $\Delta M/M \equiv (M_2 - M_1)/M \sim 10^{-8}$. We further show that leptogenesis can produce the baryon asymmetry of the Universe within the Neutrino Option scenario when the requisite CP violation in leptogenesis is provided exclusively by the Dirac or Majorana low energy CP violation phases of the PMNS matrix.

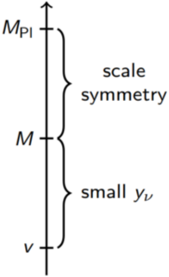
A realization based on symmetry?

VB, Emonds, Helmboldt, Lindner arXiv:1807.11490

Understanding neutrino option at a more fundamental level?

$\Longrightarrow$ Classical scale invariance

- no tree-level Higgs mass at high energies
- Majorana scale can be stabilized against high-energy scale



Minimal viable scenario:

$\Longrightarrow$ Extend the SM by 2 real scalar singlets and 3 RH neutrinos

$$-\mathcal{L} \supseteq \frac{1}{2} y_{\mathrm{M}} S \bar{N}_R N_R^c + y_\nu \bar{L} \tilde{H} N_R + \text{h.c.} + \lambda (H^\dagger H)^2 + \lambda_S S^4 + \lambda_R R^4$$
$$+ \lambda_{HS} S^2 (H^\dagger H) + \lambda_{HR} R^2 (H^\dagger H) + \lambda_{SR} S^2 R^2$$

Gildener, Weinberg Phys.Rev. (1976)

SSB pattern: $\langle H \rangle = \langle R \rangle = 0$ and $\langle S \rangle \equiv v_s \gtrsim 10^7$ GeV

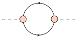
The model at different scales

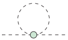
vacuum stability at Λ: $B > 0$ and no Landau poles $\Longrightarrow \lambda_{SR} \lesssim 0.39$ and $y_M \lesssim 0.51$

cosmological neutrino mass limit and correct Higgs mass $\Longrightarrow \langle S \rangle \gtrsim 10^7$ GeV and $y_\nu \lesssim \mathcal{O}(10^{-4})$

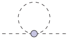
scale-invariant boundary conditions

spontaneous scale symmetry breaking
+
matching at m_N, m_R

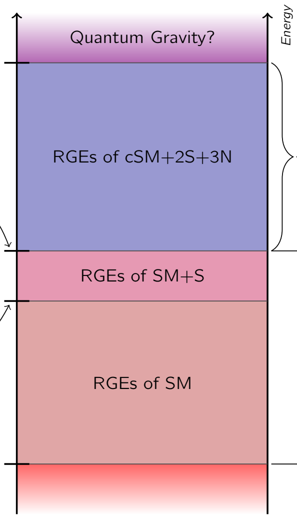




matching at m_S

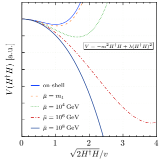


electroweak scale



check for Landau poles and instabilities
③

fix parameters ①



check Higgs potential and active neutrino masses
②

1-loop finite T effective potential

$$V_{\text{eff}}(S,T) = V_{\text{CW}}(S) + V_{\text{FT}}(S,T) + V_{\text{daisy}}(S,T)$$

- 1-loop thermal contribution

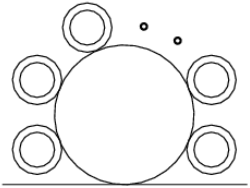
$$V_{\text{FT}}(S,T) = \frac{T^4}{2\pi^2}\left[J_{\text{B}}\left(\frac{m_R^2(S)}{T^2}\right) - 6J_{\text{F}}\left(\frac{m_N^2(S)}{T^2}\right)\right],$$

$$J_{\text{B,F}}(r^2) = \int_0^\infty dx\, x^2 \log\left(1 \mp \exp^{-\sqrt{x^2+r^2}}\right)$$

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

$$V_{\text{daisy}}(S,T) = -\frac{T}{12\pi}\left[\left(m_R^2(S) + \Pi_R(T)\right)^{\frac{3}{2}} - \left(m_R^2(S)\right)^{\frac{3}{2}}\right]$$

thermal mass $\Pi_R(T) = (6\lambda_R + \lambda_{SR})T^2/6$



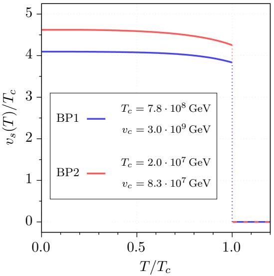
M.Quiros, arXiv:hep-ph/9901312
M.E.Carrington Phys. Rev. D45 (1992)

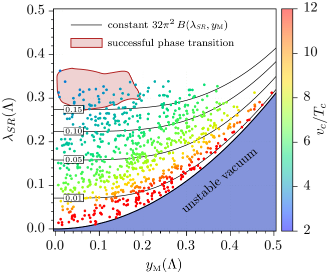
Phase Transition

Konstandin, Servant arXiv:1104.4791

- strongly first-order phase transitions implies supercooling $\rightarrow$ temperature of phase transition can be orders of magnitude below $\langle S \rangle$
- A first-order PT is typically referred to as strong if $v_c/T_c \gtrsim 1$
- satisfied for all considered parameter sets including two benchmark points

	Λ [GeV]	λ_{SR}	λ_R	y_{M}	v_s [GeV]	$32\pi^2 B$	T_n [GeV]	T_* [GeV]
BP1	$1.5 \cdot 10^9$	$3.2 \cdot 10^{-1}$	$2.1 \cdot 10^{-2}$	$9.2 \cdot 10^{-2}$	$3.2 \cdot 10^9$	0.21	$4.1 \cdot 10^4$	$1.8 \cdot 10^8$
BP2	$4.3 \cdot 10^7$	$3.0 \cdot 10^{-1}$	$8.4 \cdot 10^{-3}$	$1.4 \cdot 10^{-1}$	$9.0 \cdot 10^7$	0.17	$2.4 \cdot 10^3$	$4.8 \cdot 10^6$





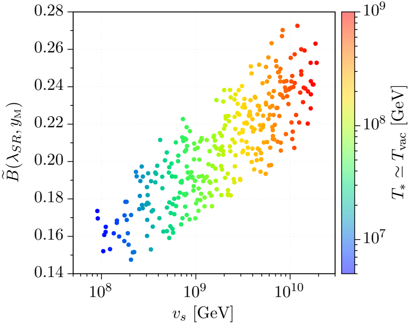
- bubble nucleation rate $\Gamma(T) \simeq T^4 \left(\frac{\mathcal{S}_3}{2\pi T}\right)^{\frac{3}{2}} \exp^{-\mathcal{S}_3/T}$
- $H^2(T) = \frac{\rho_{\mathrm{rad}}(T)+\rho_{\mathrm{vac}}(T)}{3M_{\mathrm{Pl}}^2} = \frac{1}{3M_{\mathrm{Pl}}^2}\left(\frac{\pi^2}{30} g_* T^4 + \Delta V(T)\right)$
- nucleation temperature $\int_{T_n}^{T_c} \frac{\mathrm{d}T}{T} \frac{\Gamma(T)}{H(T)^4} \overset{!}{=} 1$

Ellis, Lewicki, No arXiv:1809.08242

Ingredients for Gravitational Wave Signature

- inverse duration of the phase transition $\beta := H(T_n) T_n \cdot \frac{\mathrm{d}}{\mathrm{d}T}\left(\frac{\mathcal{S}_3}{T}\right)_{T=T_n}$
- we find $\beta/H \sim 3 - 10$ corresponding to relatively fast phase transition
- vacuum energy released during the transition normalized to the energy density of relativistic plasma

$$\rho_{\mathrm{rad}}(T_*) \simeq \rho_{\mathrm{rad}}(T_n) + \rho_{\mathrm{vac}}(T_n) \Longleftrightarrow T_* \simeq T_n (1+\alpha)^{\frac{1}{4}} \simeq T_{\mathrm{vac}}$$



$$\alpha := \frac{\Delta V}{\rho_{\mathrm{rad}}(T_n)} = \frac{\rho_{\mathrm{rad}}(T_{\mathrm{vac}})}{\rho_{\mathrm{rad}}(T_n)} = \frac{T_{\mathrm{vac}}^4}{T_n^4}$$

$$T_{\mathrm{vac}} = 5.5 \times 10^7 \mathrm{GeV} \cdot \left(\frac{\tilde{B}}{0.2}\right)^{\frac{1}{4}} \cdot \left(\frac{v_s}{10^9 \mathrm{GeV}}\right)$$

$$\tilde{B} = 32\pi^2 B$$

Stochastic Gravitational Wave Signal

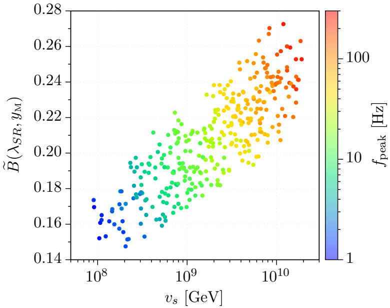
- (i) production from collisions of shells of the scalar field S
- (ii) sound waves and magnetohydrodynamic turbulence following bubble collisions
- the phase transition happens during the vacuum-dominated epoch implying preference for (i). Spectrum (from simulations) reads

$$\Omega_{\rm GW}(f)\, h^2 = 1.67\times 10^{-5}\left(\frac{\beta}{H_*}\right)^{-2}\left(\frac{\kappa\,\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.11\, v_w^3}{0.42+v_w^2}\right)\frac{3.8\,(f/f_{\rm peak})^{2.8}}{1+2.8\,(f/f_{\rm peak})^{3.8}}$$

$$f_{\rm peak} = 16.5\times 10^{-6}\left(\frac{\beta}{H_*}\right)\left(\frac{0.62}{1.8-0.1\, v_w+v_w^2}\right)\left(\frac{T_*}{100\,\text{GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\ \text{Hz}$$

- $\kappa\approx 1\,,\ v_w\to 1\,,\ \alpha/(\alpha+1)\to 1$

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



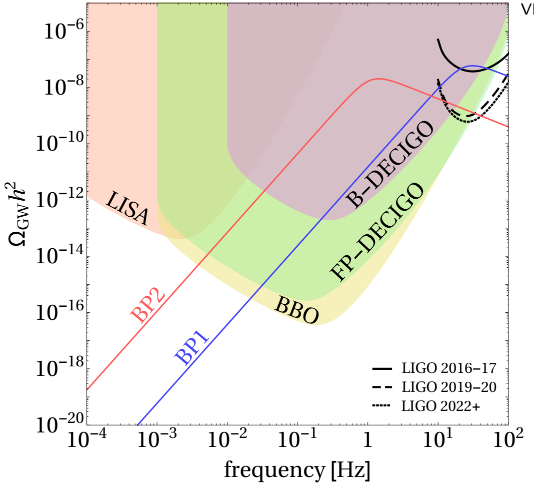
Stochastic Gravitational Wave Signal II

- 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

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

- $\Omega_{\mathrm{noise}} h^2$ is effective strain noise power spectral density (different from sensitivity curves)
- for all space based measurements $t_{\mathrm{obs}} = 5$ years assumed
- no unresolvable foreground (neutron star, black hole mergers) in the $f > \mathcal{O}(1Hz)$ frequency range (Rosado, PRD 2011)

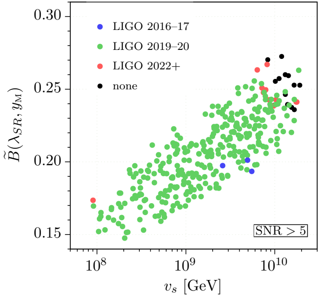
Gravitational Wave Spectrum

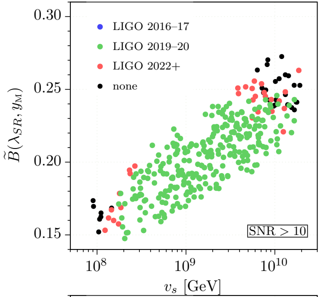


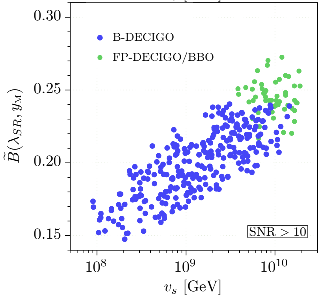
VB, Helmboldt, Kubo 1810.12306

- parameter points in our model can have $f_{\rm peak}$ at frequencies where LIGO is most sensitive (SNR for BP1 and O2 phase is 2.7)

Gravitational Wave Testability







- about 85% of all viable points will be tested in LIGO's currently ongoing O3 phase
- FP-DECIGO sensitive to full parameter region while LISA will be more appropriate to test TeV-scale new physics

Left-Right Symmetric Model

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

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

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}\kappa_1 & 0 \\ 0 & \kappa_2\end{pmatrix}, \qquad \langle\Delta_L\rangle = 0\,, \qquad \langle\Delta_R\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0 & 0 \\ v_R & 0\end{pmatrix}$$

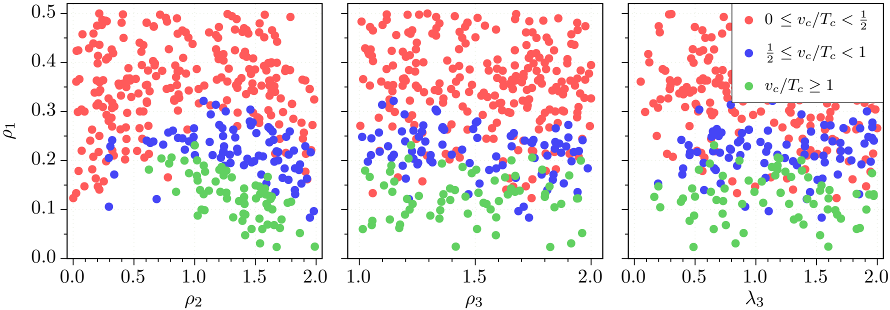
$$v_R \gg \kappa_1\,, \kappa_2 \Longrightarrow V_0(r) = -\tfrac{1}{2}\mu_3^2 r^2 + \tfrac{1}{4}\rho_1 r^4 \quad \text{with} \quad r := \mathrm{Re}\,\delta_R^0/\sqrt{2}$$

Effective Potential

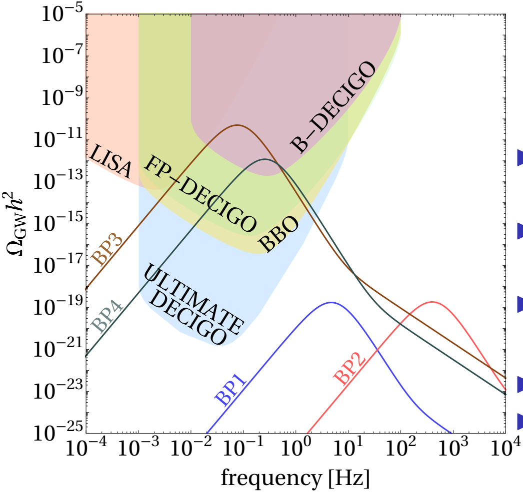
$$V_{\text{eff}}(r,T) = V_0(r) + V_{\text{CW}}(r) + V_{\text{FT}}(r,T) + V_{\text{D}}(r,T)$$

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

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



Gravitational Wave Spectrum



	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	0.17	1433	897.3	1468

- generally, space-based detectors will not be able to probe the model (BP1,BP2)
- situation changes for small value of ρ_1 (BP3,BP4)
- $\mu_3^2 = \rho_1 v_R^2 + \frac{1}{2}\alpha_1\left(\kappa_1^2+\kappa_2^2\right) + 2\alpha_2\kappa_1\kappa_2 + \frac{1}{2}\alpha_3\kappa_2^2$
- $\rho_1 \ll 1 \Longrightarrow \mu_3 \ll v_R$
- choosing ρ_1 to be small brings model's r sector near scale-invariant limit

Summary

"Neutrino option" scale-invariant model:

- phase transition is of strong first order which implies a significant supercooling
- for the viable parameter points, our model can be robustly probed by ground-based gravitational wave detectors
- the currently ongoing science run of LIGO will test practically the full parameter space

Left-Right Symmetric model:

- dominant contribution from sound waves and magnetohydrodynamic turbulence
- model can be tested in the limit $\rho_1 \ll 1 \Longrightarrow \mu_3 \ll v_R$, otherwise phase transition is too weak
- potential future discoveries may hint scale-invariant dynamics

BACKUP SLIDES

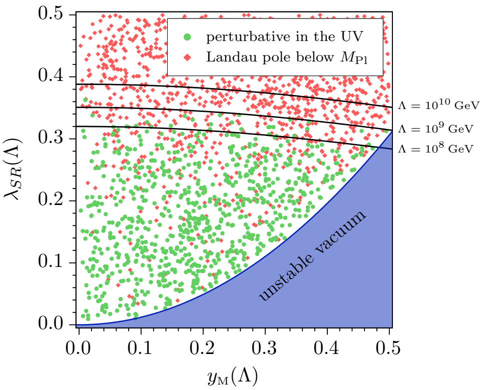
Scale symmetry breaking

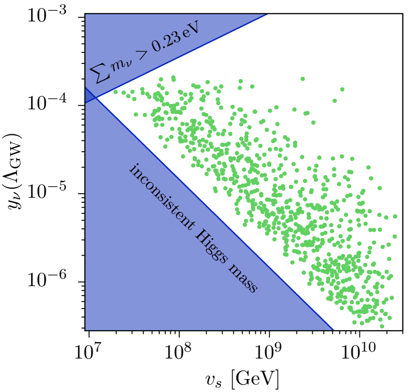
Goal: $\langle H \rangle = \langle R \rangle = 0$ and $\langle S \rangle \equiv v_s \gtrsim 10^7\,\mathrm{GeV}$

Gildener-Weinberg formalism:

- assume that V_{tree} has a flat direction along S field axis at a scale Λ $\Longrightarrow \lambda_S(\Lambda) = 0$
- approximation: take into account quantum corrections only along the flat direction
- $V_{\text{eff}}(S) = A\,S^4 + B\,S^4\ \mathrm{Log}[S^2/\Lambda^2]$ where A and B are loop functions
- minimum at $\langle S \rangle = \Lambda\ \exp[-\frac{1}{4} - \frac{A}{2B}]$
- S acquires mass at one-loop: $m_S^2 = 8\,B\,\langle S \rangle^2$

Viable parameter space - scatter plots





vacuum stability at Λ: $B > 0$ and no Landau poles $\Longrightarrow$ $\lambda_{SR} \lesssim 0.39$ and $y_M \lesssim 0.51$

cosmological neutrino mass limit and correct Higgs mass $\Longrightarrow$ $\langle S \rangle \gtrsim 10^7$ GeV and $y_\nu \lesssim \mathcal{O}(10^{-4})$

Benchmark points for L-R model

	BP1	BP2	BP3	BP4
v/GeV	246	246	246	246
v_R/GeV	10^4	10^6	10^4	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	0.4
ρ_3	1.5140	1.5489	0.900215	0.4
ρ_4	0	0	0	0.4
α_1	0	0	0	0
α_2	0.30246	0.15557	0	0
α_3	0.10765	0.11185	1.14815	0.376385
$\beta_{1,2,3}$	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	0.52422