Electroweak Phase Transition and Gravitational waves in an Extended Supersymmetric Model

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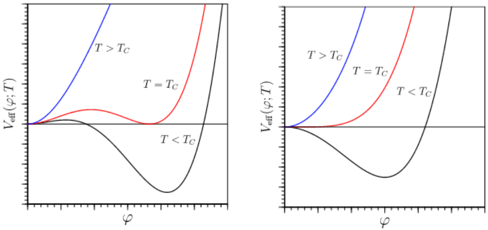
IITD

Outline

What Standard Model of Particle Physics cannot answer

- No explanation for non-zero neutrino masses and mixing.
- No viable Dark Matter candidate.
- More matter than antimatter.



E. Senaha, Symmetry 2020, 12, 733

Electroweak Phase Transition (EWPT)

$\downarrow$ (strong) 1st order

Electroweak Baryogenesis (EWBG)

$\downarrow$

Baryon Asymmetry of the Universe (BAU)

- In the SM, EWPT is smooth cross-over.

  K. Kajantie et al., Phys. Rev. Lett. 77 (1996) 2887

- $V(\phi, T) = \frac{1}{2}(-\mu_h^2 + cT^2)\phi^2 + \frac{\lambda}{4}\phi^2 - ET\phi^3$,

  $\boxed{ET\phi^3 \propto \sum_i m_i^3(\phi)}$ $\rightarrow$ sum over all bosons which couple to the SM-Higgs.

■ For Higgs mass $>$ 72 GeV, no 1st order phase transition within the SM!

Motivation for Beyond the Standard Model

Back to the question:

- What is the nature of the Electroweak Phase Transition in the early Universe?

$\Longrightarrow$ Predictions depend on the Particle Physics Model.

- **Not MSSM**
  - For a strong first order EWPT (SFOEWPT), it requires one lighter stop with mass $\mathcal{O}(100\,\mathrm{GeV})$, *A. Menon and D. E. Morrissey, Phys. Rev. D 79 (2009)*

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- **NMSSM, nMSSM, $\mu\nu$SSM... ?**
  - SFOEWPT possible $\rightarrow$ single- or multi-step.
  - Detectable Gravitational Wave (GW) signature: possible in some variants of NMSSM, e.g., split NMSSM, nMSSM; not fully realized in Z_3-NMSSM, $\mu\nu$SSM, etc. *JCAP 05 (2008) 017, JHEP 01 (2015) 144, Phys.Lett.B 779 (2018) 191-194, JHEP 06 (2022) 108 and many more...*

✗ The above mentioned models cannot incorporate non-zero neutrino masses and mixing (except $\mu\nu$SSM).

NMSSM + a Right Handed Neutrino (RHN)

NMSSM + RHN is a well motivated model. *Kitano and Oda, Phys.Rev.D 61 (2000)*

- ✓ neutrino masses and mixing
- ✓ viable DM candidate (e.g., R-handed sneutrino)
- ■ $\boxed{\text{EWPT and GW signature}}$ $\longrightarrow$ *in this work.*

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NMSSM + an RHN Superpotential

$$
\begin{aligned}
W &= W'_{\mathrm{MSSM}}(\mu=0) + \lambda\, \widehat{S}\, \widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\, \widehat{S}^3 + Y_N^i\, \widehat{N}\, \widehat{L}_i \cdot \widehat{H}_u + \frac{\lambda_N}{2}\, \widehat{S}\, \widehat{N}\, \widehat{N} \\
-\mathcal{L}_{\mathrm{soft}} &= -\mathcal{L}'_{\mathrm{soft}} + m_S^2\, S^* S + M_N^2 \widetilde{N}^* \widetilde{N} + \Big(\lambda A_\lambda S\, H_u \cdot H_d + h.c.\Big) \\
&\quad + \Big(\frac{\kappa A_\kappa}{3} S^3 + (A_N Y_N)^i\, \widetilde{L}_i \cdot H_u\, \widetilde{N} + \frac{A_{\lambda_N} \lambda_N}{2}\, S \widetilde{N} \widetilde{N} + h.c.\Big)
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- Along with H_u, H_d and S, the RH-sneutrino, $\widetilde{N}$ also develops a VEV ($v_{\widetilde{N}}$) in our setup $\Longrightarrow$ R_p spontenously broken.

Physical States

Presence of new mixing terms in the EW-sector enhance the order of neutral scalar, neutral pseudoscalar, charged scalar, neutral and charged fermion mass matrices.

- H_u^0, H_d^0, S states mixes with $\widetilde{N}$ and $\widetilde{\nu}_i \implies 7 \times 7$ CP-even and CP-odd neutral scalar mass matrices.
- Mixing of $H_u^{\pm}$, $H_d^{\mp}$ states with $\widetilde{e}_{L_i}^{\pm}$, $\widetilde{e}_{R_i}^{\pm} \implies 8 \times 8$ uncolored charge scalars.
- Mixing among neutral gauginos, $\widetilde{H_u^0}$, $\widetilde{H_d^0}$, $\widetilde{S}$ states with the RHN and $\nu_i \implies 9 \times 9$ neutral fermions.
- The charged higgsino, gaugino states mixes with $e_{L_i}^{\pm}$, $e_{R_i}^{\pm} \implies 5 \times 5$ charged fermions.

Effective Potential and Our Approach

- To study the EWPT within a model, the central object to consider is the finite-temperature effective potential.
- We need neutral scalar dynamical degrees of freedoms to study the PT patterns. (**Too many!**)

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However,

- Assuming all trilinear A-terms, soft-squared mass terms $\sim \mathcal{O}(TeV)$ and $\lambda_N \sim \mathcal{O}(1) \rightarrow RHN$ mass in the TeV regime.
- Neutrino mass generation via the TeV scale seesaw mechanism $\rightarrow$ constraints $Y_N^i \sim \mathcal{O}\ (10^{-6} - 10^{-7})$ and $\langle \widetilde{\nu}_i \rangle \sim \mathcal{O}\ (10^{-4} - 10^{-5})$ GeV.
- Tiny R_P violation ($\sim \mathcal{O}\ (10^{-3} - 10^{-4})$ GeV); weak mixing of the left-handed leptons and sleptons (neutral and charged).

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Dynamical fields $\Longrightarrow \boxed{H_u, H_d, S, \tilde{N}}$ instead of $\boxed{H_u, H_d, S, \widetilde{N}, \widetilde{L}_i}$

Effective Potential

The finite-temperature effective potential is,

$$\boxed{V_{\rm eff}^{T} = V_{\rm tree} + \Delta V + V'^{\,1-\rm loop}_{\rm CW} + V^{1-\rm loop}_{T\neq 0} + V_{\rm ct}}$$

- $V_{\rm tree} = V_F + V_D + V_{\rm soft}$
- $\Delta V =$ leading contribution to $V_{\rm tree}$ after integrating out heavier mass states
- $V'^{\,1-\rm loop}_{\rm CW} = \frac{1}{64\pi^2}\sum_{i=B,F}(-1)^{F_i} n_i m_i^4(\phi_\alpha, T)\left[\log\left(\frac{m_i^2(\phi_\alpha,T)}{\Lambda^2}\right) - \mathcal{C}_i\right]$
  - $m_i^2(\phi_\alpha, T) = m_i^2(\phi_\alpha) + c_i T^2$, $c_i \to$ Daisy coefficients.
- $V^{1-\rm loop}_{T\neq 0} = \frac{T^4}{2\pi^2}\sum_{i=B,F}(-1)^{F_i} n_i J_{B/F}\left(\frac{m_i^2(\phi_\alpha,T)}{T^2}\right)$
- $V_{ct} =$ counter term potential

- $B \equiv S^0_{1,..,4},\ P^0_{1,2,3},\ H^{\pm},\ G^0,\ G^{\pm},\ Z^0, W^{\pm}$ with $n_B = 4\times 1,\ 3\times 1,\ 2,\ 1,\ 2,\ 3,\ 2\times 3$
- $F \equiv \widetilde{\chi}^0_{1,..,9},\ \widetilde{\chi}^{\pm}_{4,5},\ t$ with $n_B = 2,\ 4,\ 3\times 4$

Experimental Constraints and Parameter Scan

Generate random parameters and calculate particle spectrum, decay widths, etc. → Impose constraints from Higgs sector, collider searches, CLFV processes → Select passed parameters and feed to `cosmoTransitions` → Impose FOEPT constraints

- Input parameters $\boxed{\lambda,\ \lambda_N,\ \kappa,\ \tan\beta,\ \mu,\ v_{\tilde{N}},\ A_\lambda,\ A_\kappa,\ A_{\lambda_N}}$ (`SARAH`, `SPheno`)
- Experimental constraints:
  - Higgs sector constraints (LEP, Tevatron, LHC) $\Longrightarrow$ `HiggsBounds`
  - CLFV processes:

$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}\ (\mathrm{MEG2016}),$$
$$\mathrm{BR}(\mu \to eee) < 1.0 \times 10^{-12}\ (\mathrm{SINDRUM}),$$
$$\mathrm{CR}(\mu N \to eN') < 10^{-16}\ (\mathrm{SINDRUM\,II})$$

  - Constraints from rare B-meson decays*,

$$\mathrm{BR}(B \to X_s\gamma) = (3.49 \pm 0.57) \times 10^{-4}\ (3\sigma),$$
$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = (3.45 \pm 0.87) \times 10^{-9}\ (3\sigma).$$

**PDG 2022, HFLAV collaboration*

Calculation of Critical and Nucleation Temperature

- We work in the extended Higgs basis; $\{H_u, H_d\} \xrightarrow{rotated} H_{\rm SM}, H_{\rm NSM}$.
- The critical temperature can be obtained,

$$V_{\rm eff}^{T}(v'_{\rm SM}, v'_{\rm NSM}, v'_S, v'_{\widetilde{N}}, T_c) = V_{\rm eff}^{T}(v_{\rm SM}, v_{\rm NSM}, v_S, v_{\widetilde{N}}, T_c)$$

- Minimization requirement:

$$\partial_{H_i} V_{\rm eff}^{T}(v'_{\rm SM}, v'_{\rm NSM}, v'_S, v'_{\widetilde{N}}, T_c),\ \partial_{N_R} V_{\rm eff}^{T}(v'_{\rm SM}, v'_{\rm NSM}, v'_S, v'_{\widetilde{N}}, T_c) = 0$$
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- A FOPT proceeds via bubble nucleation.
- The nucleation rate, $\Gamma \propto T^4 \exp\left(-S_E/T\right)$
- $S_E = \int_0^\infty 4\pi r^2 dr \left(V_T(\phi, T) + \frac{1}{2} \left(\frac{d\phi(r)}{dr}\right)^2 \right)$

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- For succesful bubble nucleation, $\frac{S_E(T_n)}{T_n} \simeq 140$
- $\gamma_c \equiv \frac{v_c(T_c)}{T_c} = \frac{\sqrt{\langle H_{\rm SM}\rangle^2 + \langle H_{\rm NSM}\rangle^2}}{T_c} \gtrsim 1.0$
- $\frac{\Delta\phi_i}{T_n} \equiv \frac{\sqrt{\sum(\phi_i^{lT} - \phi_i^{hT})^2}}{T_n} \gtrsim 1.0$

Phase Transition Patterns

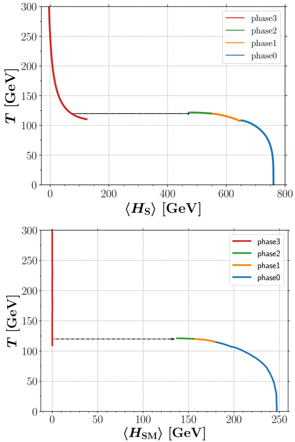
- A few possible PT patterns:

- **Type**-I: $\Omega_0 \xrightarrow{\text{PT}} \Omega_{H_{\rm SM}}$
- **Type**-IIa: $\Omega_0 \to \Omega'_{H_S} \xrightarrow{\text{PT}} \Omega_{H_{\rm SM}} + \Omega_{H_S}$
- **Type**-IIb: $\Omega_0 \to \Omega'_{H_S} \xrightarrow{\text{PT}} \Omega_{H_S}$
- **Type**-IIc: $\Omega_0 \to \Omega'_{H_S} \xrightarrow{\text{PT}} \Omega_{H_S} + \Omega_{\widetilde{N}}$
- **Type**-IIIa: $\Omega_0 \to \Omega_{H'_{SM}} + \Omega'_{H_S} \xrightarrow{\text{PT}} \Omega_{H_{\rm SM}} + \Omega_{H_S}$
- **Type**-IIIb: $\Omega_0 \to \Omega'_{H_{SM}} + \Omega'_{H_S} \xrightarrow{\text{PT}} \Omega_{H_{SM}} + \Omega_{H_S} + \Omega_{\widetilde{N}}$

	BP-I	BP-IV
$\tan\beta$	2.81	5.77
λ	0.4162	0.3844
κ	0.022	0.012
λ_N	0.146	0.130
A_λ [GeV]	775.48	1184.87
A_κ [GeV]	-62.74	-107.1
A_{λ_N} [GeV]	-349.68	-363.16
μ_{eff} [GeV]	224.56	203.12
$v_{\widetilde{N}}$ [GeV]	308.79	386.45
A_N [GeV]	-750.0	-750.0
$m_{h_{125}}$ [GeV]	125.48	123.175
m_H [GeV]	752.67	1208.2
m_{h_s} [GeV]	86.60	106.56
$m_{\widetilde{N}}$ [GeV]	49.95	24.49
$\mathrm{BR}(b \to X_s\gamma) \times 10^{-4}$	3.59	3.42
$\mathrm{BR}(B_s \to \mu^+\mu^-) \times 10^{-9}$	3.24	3.19

PT Results

	BP-I	BP-IV
Transition Type	Type-IIa	Type-IIc
v_c/T_c	1.30 (In) ; 0 (Out)	0.0 (In) ; 0.0 (Out)
$\Delta\phi_{SU(2)}/T_n$	1.58	0
$\Delta\phi_{\mathrm{S}}/T_n$	4.70	1.01
$\Delta\phi_{\widetilde{\mathrm{N}}}/T_n$	0	2.81
T_c (GeV)	117.8	184.5
T_n (GeV)	109.9	165.8
high-T_n VEV	(0,0,113.8,0)	(0,0,529.9,0)
low-T_n VEV	(173.1,9.5,631.3,0)	(0,0,696.6,-465.28)
high-T_c VEV	(0,0,72.6,0)	(0,0,459.9,0)
low-T_c VEV	(152.9,11.8,572.5,0)	(0,0,671.2,-429.5)



Type-IIa
SFOPT along H_{SM}, H_S direction

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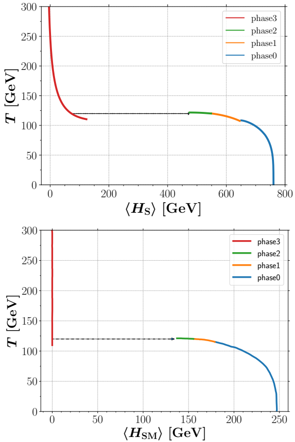

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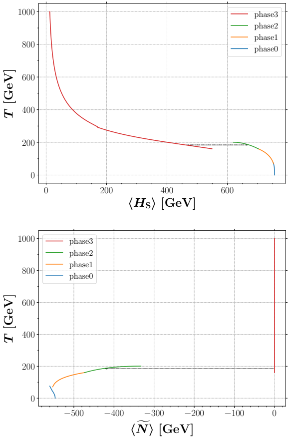
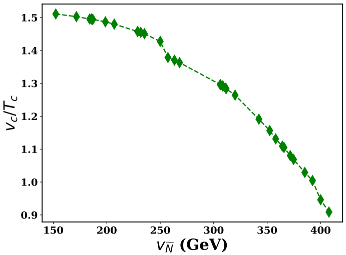
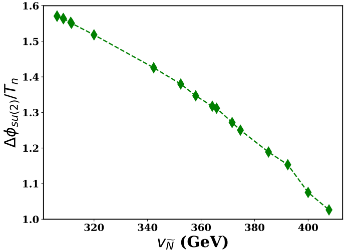


Type-`IIc`
SFOPT along $H_S, \widetilde{N}$ direction

Role of the new parameters in PT dynamics

Along $SU(2)_L$ Higgs direction





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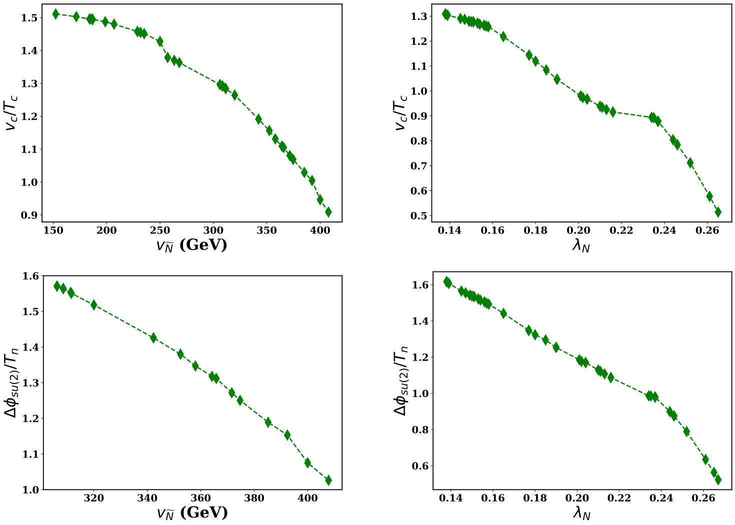

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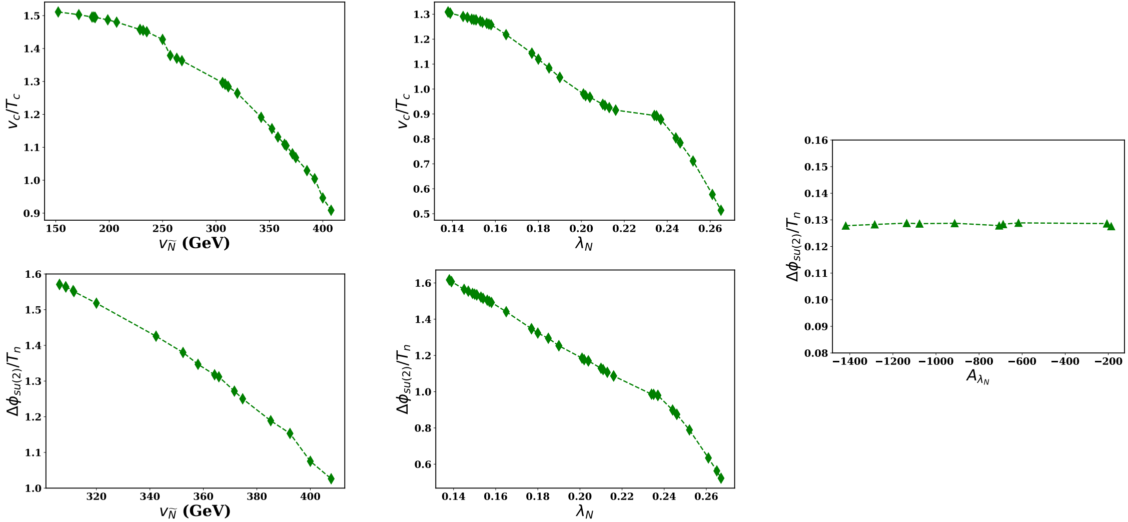

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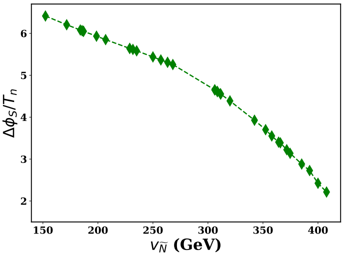

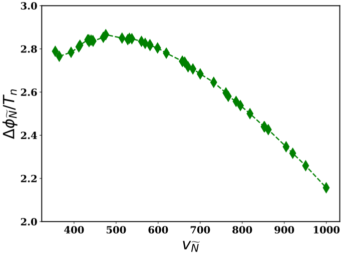

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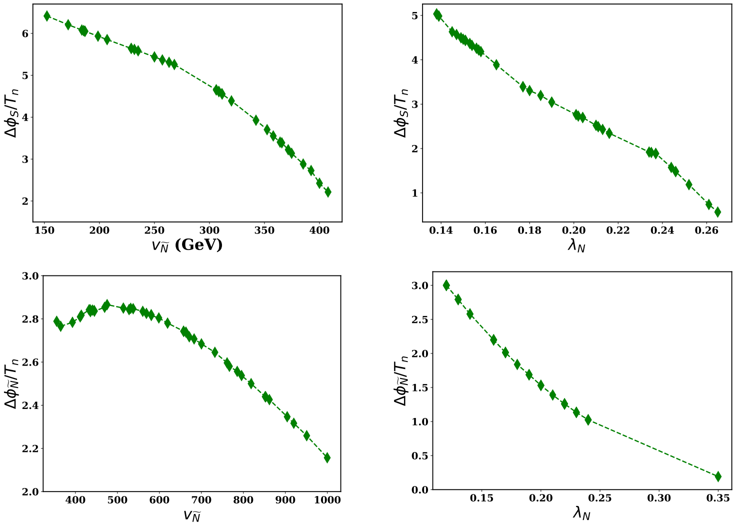

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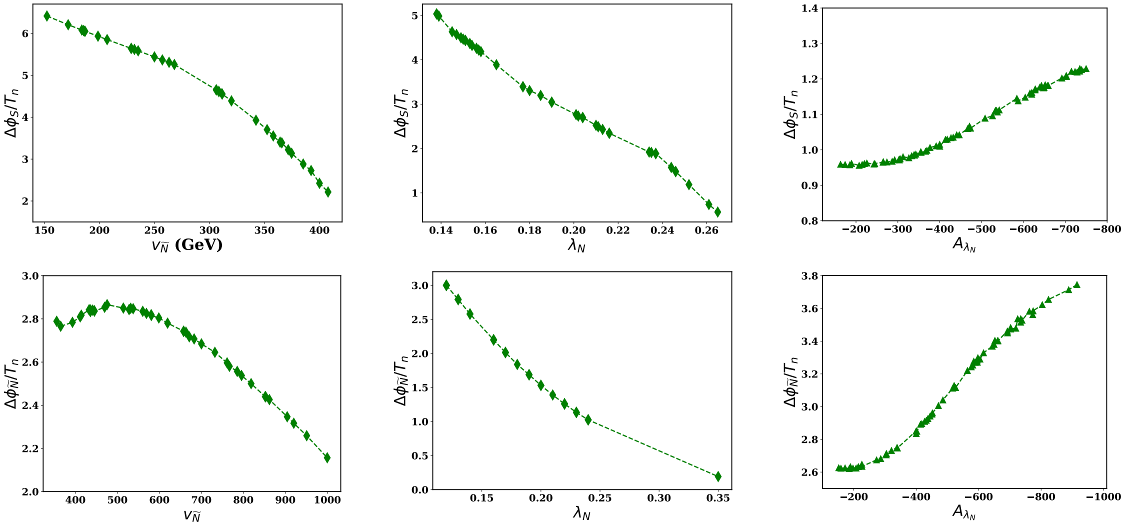
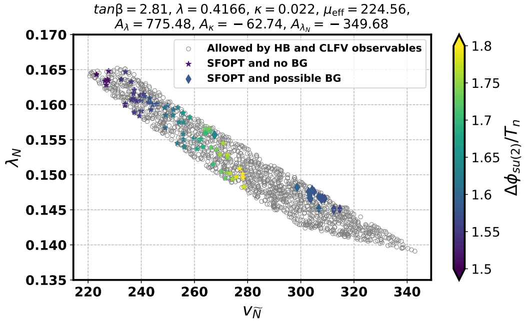


Role of the new parameters in PT dynamics

Correlations between λ_N and $v_{\widetilde{N}}$



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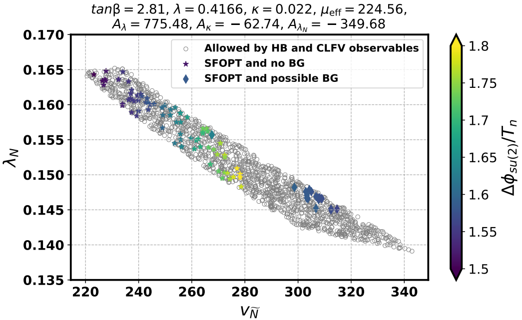
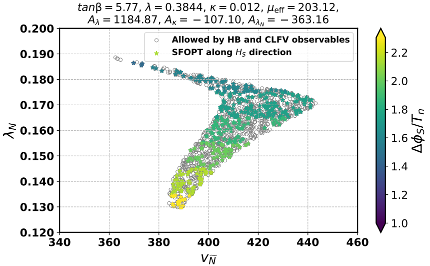
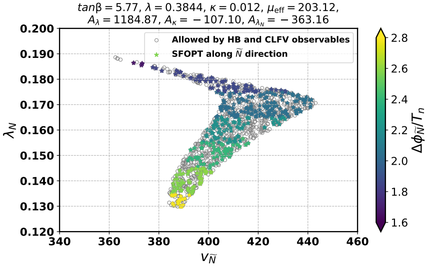
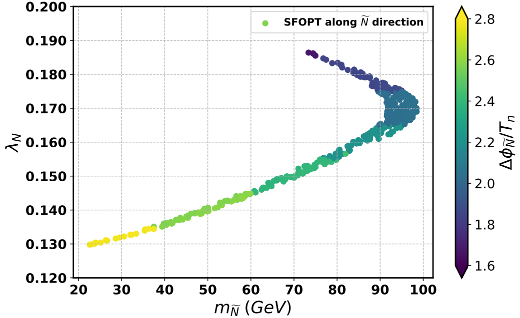


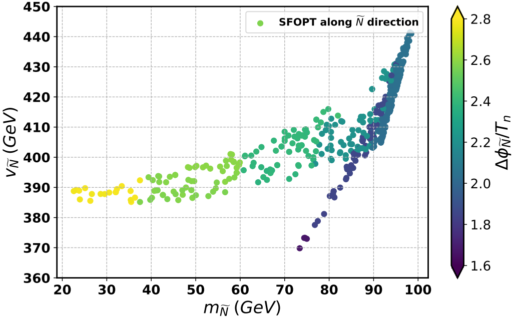




Role of the new parameters in PT dynamics

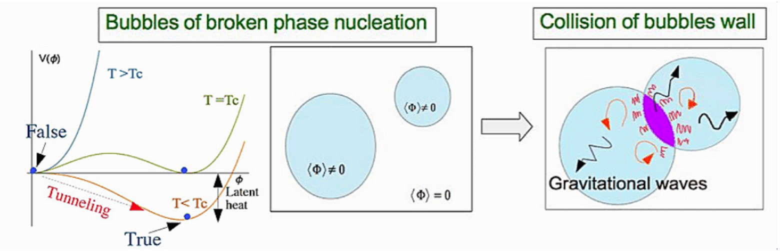
Lighter $m_{\widetilde{N}}$ states and PT along $\widetilde{N}$





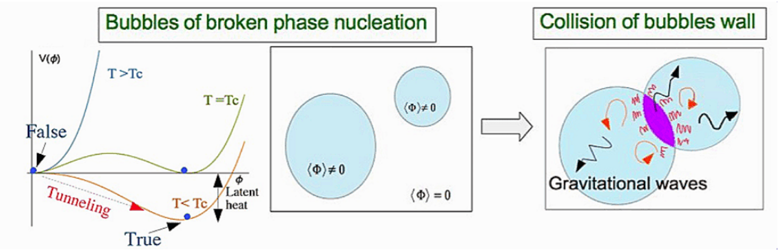
GW spectrum from SFOPT

- The GWs are generated by a SFOPT in the early universe. The main production processes are **bubble collisions, turbulence and sound waves**. *(*photo courtesy: Google Images)*



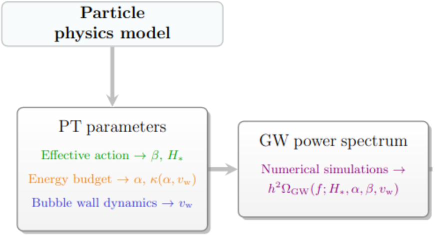
GW spectrum from SFOPT

- The GWs are generated by a SFOPT in the early universe. The main production processes are **bubble collisions, turbulence and sound waves**. *(*photo courtesy: Google Images)*



Analyse the tunneling probabilities and nucleation temperatures (T_n),

- $\alpha = \frac{\Delta\rho}{\rho_{rad}}$, latent heat released by the PT process, with $\rho_{rad} = \frac{g^* \pi^2}{30} T_n^2$
- $\beta = 1/\text{duration of PT}$
- $\frac{\beta}{H} = \left[T.\frac{d(S_E/T)}{dT}\right]_{T=T_n}$
- $v_w \to 1$



Caprini et al, arXiv:1910.13125

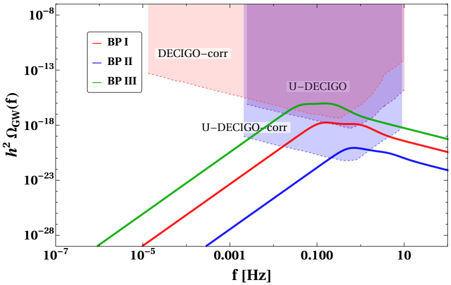
GW spectrum in NMSSM + an RHN

- α and β/H depends on particle physics model,

$$\Delta\rho = \left[V_{\rm eff}^T(\phi_0, T) - T\frac{dV_{\rm eff}^T(\phi_0, T)}{dT}\right]_{T=T_n} - \left[V_{\rm eff}^T(\phi_n, T) - T\frac{dV_{\rm eff}^T(\phi_n, T)}{dT}\right]_{T=T_n}$$

BPs	α	β/H
BP I	0.0456	37535.2
BP IV	0.0101	7596.0

- BP-I is interesting from **EWBG** viewpoint.
- BP-IV is due to SFOPT along $\widetilde{N}$.



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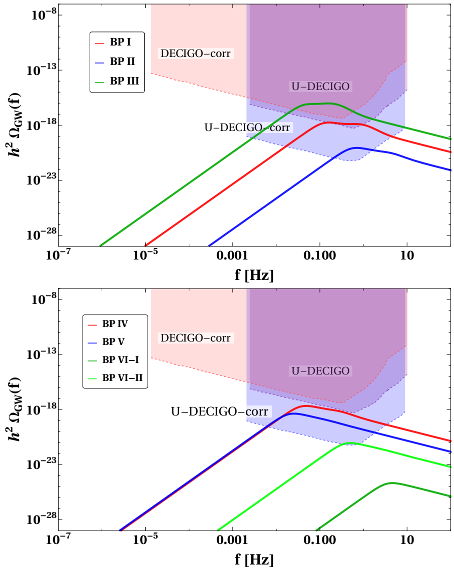
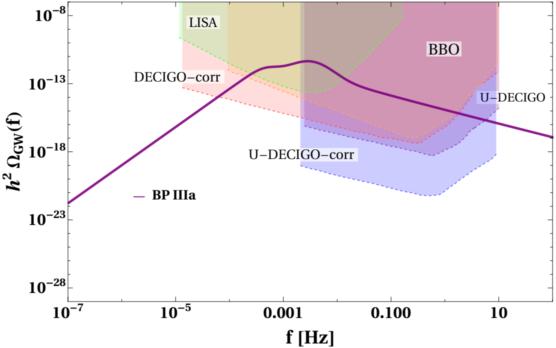


GW spectrum in NMSSM + an RHN

	BP-IIIa
Transition Type	Type-IIIa
v_c / T_c	2.39 (In) ; 1.15 (Out)
$\Delta\phi_{SU(2)} / T_n$	2.45
$\Delta\phi_S / T_n$	17.5
$\Delta\phi_{\widetilde{N}} / T_n$	0
T_c (GeV)	82.8
T_n (GeV)	37.1
high-T_n VEV	(131.6,39.7,99.7,0)
low-T_n VEV	(214.8,3.0,749.1,0)
high-T_c VEV	(95.2, 32.0, 36.5,0)
low-T_c VEV	(198.8, 7.8, 675.8,0)
α	0.7932
β / H	4232.3



✗ **SNR** $\simeq$ **5** $< \mathrm{SNR_{th}(LISA)}$

Summery and Conclusion

- A Right Handed Neutrino (RHN) superfield is introduced in the NMSSM framework and the possibility of SFOPT is analysed.
- SFOPT along $SU(2)_L$ Higgs, singlet Higgs (H_S) and $\widetilde{N}$ is possible with richer PT patterns compared to $\mathcal{Z}_3$-NMSSM in different corner of parameter space along with the possibility of EWBG in some points.
- In all of the parameter regions, comparatively low values of λ_N (< 0.4) and $v_{\widetilde{N}}$ ($\lesssim \mathcal{O}(1\,TeV)$) is preferred for a SFOPT which also indicates the presence of lighter $m_{\widetilde{N}}$ ($< m_{h_{125}}$) states.
- GW signals within reach of LISA, U-DECIGO, U-DECIGO-corr. However, due to less SNR ($\lesssim 10$), it is less likely to be detected at LISA, while it is promising at the other two detectors.

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THANK YOU FOR YOUR ATTENTION!

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Scalar Potential

$$V_F = \Big| -\lambda H_u^0 H_d^0 + \kappa S^2 + \frac{\lambda_N}{2}\widetilde{N}^2\Big|^2 + |Y_N^i|^2\ |H_u^0|^2|\widetilde{N}|^2 + |\lambda|^2|S|^2|H_u^0|^2 + \Big|\sum_{i=1}^{3} Y_N^i\widetilde{\nu}_i H_u^0 + \lambda_N S\widetilde{N}\Big|^2 + \Big|\sum_{i=1}^{3} Y_N^i\widetilde{\nu}_i\widetilde{N} - \lambda S H_d^0\Big|^2,$$

$$V_D = \frac{g_1^2+g_2^2}{8}\left(|H_d^0|^2 + \sum_{i=1}^{3}|\widetilde{\nu}_i|^2 - |H_u^0|^2\right)^2,\ V_{soft} = -\mathcal{L}_{soft} \tag{1}$$

$$\begin{aligned}
V_{\text{scalar}}^{\text{uncolored}} = &\Big|\sum_{i=1}^{3} Y_N^i\widetilde{\nu}_i\widetilde{N} - \lambda S H_d^0\Big|^2 + \Big|\sum_{i,j=1}^{3} Y_e^{ij}\widetilde{l}_i\widetilde{e}_j^c - \lambda S H_u^0\Big|^2 + \Big|Y_N^i H_u^0\widetilde{N} - \sum_{j=1}^{3} Y_e^{ij} H_d^-\ \widetilde{e}_j^c\Big|^2 \\
&+ \Big|\lambda H_u\cdot H_d + \kappa S^2 + \frac{\lambda_N}{2}\widetilde{N}^2\Big|^2 + \Big|\sum_{i=1}^{3} Y_N^i\widetilde{L}_i\cdot H_u + \lambda_N S\widetilde{N}\Big|^2 + \Big|\sum_{i=1}^{3} Y_e^{ij} H_d\cdot\widetilde{L}_i\Big|^2 \\
&+ \Big|\lambda S H_u^+ - \sum_{i,j=1}^{3} Y_e^{ij}\widetilde{\nu}_i\widetilde{e}_j^c\Big|^2 + \Big|\lambda S H_d^- - \sum_{i=1}^{3} Y_N^i\widetilde{l}_i\widetilde{N}\Big|^2 + \Big|\sum_{j=1}^{3} Y_e^{ij} H_d^0\widetilde{e}_j^c - Y_N^i H_u^+\widetilde{N}\Big|^2 \\
&+ \frac{g_1^2}{8}(|H_d|^2 - |H_u|^2 + |\widetilde{L}_i|^2 - 2|\widetilde{e}_i^c|^2)^2 + \frac{g_2^2}{2}\sum_{a=1}^{3}(H_d^\dagger\frac{\tau^a}{2}H_d + H_u^\dagger\frac{\tau^a}{2}H_u + \widetilde{L}_i^\dagger\frac{\tau^a}{2}\widetilde{L}_i)^2 \\
&+ m_{H_d}^2|H_d|^2 + m_{H_u}^2|H_u|^2 + m_S^2|S|^2 + M_N^2|\widetilde{N}|^2 + \sum_{i,j=1}^{3} m_{\widetilde{L}_{ij}}^2\widetilde{L}_i^{m*}\widetilde{L}_j^m + \sum_{i,j=1}^{3} m_{\widetilde{e}_{ij}^c}^2\widetilde{e}_i^{c\,m*}\ \widetilde{e}_j^{c\,m} \\
&+ \sum_{i=1}^{3}(A_e Y_e)^{ij} H_d\cdot\widetilde{L}_i\widetilde{e}_j^c + \lambda A_\lambda S H_u\cdot H_d + (A_N Y_N)^i\widetilde{L}_i\cdot H_u\widetilde{N} + \frac{\kappa A_\kappa}{3}S^3 + \frac{\lambda_N A_{\lambda_N}}{2}S\widetilde{N}^2 + h.c
\end{aligned} \tag{2}$$

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Higgs Basis

- Extended Higgs basis

$$
\begin{aligned}
H_d &= \begin{pmatrix} \frac{1}{\sqrt{2}}(c_\beta H_{\rm SM} - s_\beta H_{\rm NSM}) + \frac{i}{\sqrt{2}}(-c_\beta G^0 + s_\beta A_{\rm NSM}) \\ -c_\beta G^- + s_\beta H^- \end{pmatrix}, \\
H_u &= \begin{pmatrix} s_\beta G^+ + c_\beta H^+ \\ \frac{1}{\sqrt{2}}(s_\beta H_{\rm SM} + c_\beta H_{\rm NSM}) + \frac{i}{\sqrt{2}}(s_\beta G^0 + c_\beta A_{\rm NSM}) \end{pmatrix}, \\
S &= \frac{1}{\sqrt{2}}(H_S + iA_S), \\
\widetilde{N} &= \frac{1}{\sqrt{2}}(N_R + i\, N_I),
\end{aligned}
\tag{3}
$$

- Zero-temperature VEVs

$$
\langle H_u^0 \rangle = v_u,\ \langle H_d^0 \rangle = v_d,\ \langle \widetilde{\nu}_i \rangle = v_i,\ \langle S \rangle = v_S,\ \langle \widetilde{N} \rangle = v_N, \quad i = 1, 2, 3 \quad \text{or} \quad e, \mu, \tau. \tag{4}
$$

- Counter-term potential

$$
\begin{aligned}
V_{ct} &= \delta_{m^2_{H_d}} |H_d|^2 + \delta_{m^2_{H_u}} |H_u|^2 + \delta_{m^2_S} |S|^2 + \delta_{M^2_N} |\widetilde{N}|^2 + \delta_{\lambda A_\lambda} (SH_u \cdot H_d + h.c.) \\
&+ \delta_{\lambda_N A_{\lambda_N}} (S\widetilde{N}\widetilde{N} + h.c.) + \frac{\delta\lambda_2}{2} |H_u|^4,
\end{aligned}
\tag{5}
$$

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BPs

	BP-I	BP-II	BP-III	BP-IV	BP-V	BP-VI
$\tan\beta$	2.81	2.74	2.81	5.77	4.78	5.86
λ	0.4162	0.4123	0.4162	0.3844	0.1184	0.1106
κ	0.022	0.019	0.022	0.012	0.013	0.05
λ_N	0.146	0.150	0.146	0.130	0.259	0.238
A_λ [GeV]	775.48	705.32	775.48	1184.87	988.07	920.08
A_κ [GeV]	-62.74	-25.37	-95.60	-107.1	-11.00	-41.60
A_{λ_N} [GeV]	-349.68	-337.76	-326.59	-363.16	-1358.30	-1528.57
μ_{eff} [GeV]	224.56	220.86	224.56	203.12	153.58	162.63
$v_{\tilde{N}}$ [GeV]	308.79	325.20	284.50	386.45	136.57	355.66
A_N [GeV]	-750.0	-750.0	-750.0	-750.0	-750.0	-750.0
$m_{h_{125}}$ [GeV]	125.48	124.49	125.45	123.17	123.08	123.55
m_H [GeV]	752.67	710.48	750.51	1208.2	882.27	993.08
m_{h_s} [GeV]	86.60	90.51	73.58	106.56	84.23	195.69
$m_{\tilde{N}}$ [GeV]	49.95	62.73	52.20	24.49	44.25	114.92
$\mathrm{BR}(\mu \to e\gamma)$	1.06×10^{-26}	2.54×10^{-25}	7.79×10^{-24}	9.18×10^{-24}	7.97×10^{-23}	9.49×10^{-18}
$\mathrm{BR}(\mu \to eee)$	1.41×10^{-27}	6.76×10^{-26}	5.23×10^{-26}	6.13×10^{-26}	5.57×10^{-24}	6.26×10^{-20}
$\mathrm{BR}(b \to X_s\gamma)$	3.59×10^{-4}	3.61×10^{-4}	3.60×10^{-4}	3.42×10^{-4}	3.54×10^{-4}	3.55×10^{-4}
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	3.24×10^{-9}	3.27×10^{-9}	3.25×10^{-9}	3.19×10^{-9}	3.21×10^{-9}	3.18×10^{-9}

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GW equations

$$\Omega_{\rm GW} h^2 \approx \Omega_{\rm col} h^2 + \Omega_{\rm sw} h^2 + \Omega_{\rm tur} h^2 \ ,$$

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

$$\Omega_{\rm sw} h^2 = 2.65 \times 10^{-6}\, \Upsilon(\tau_{\rm sw}) \left(\frac{\beta}{H_*}\right)^{-1} v_w \left(\frac{\kappa_{\rm sw} \alpha}{1+\alpha}\right)^2 \left(\frac{g^*}{100}\right)^{1/3} \left(\frac{f}{f_{\rm sw}}\right)^3 \left[\frac{7}{4+3(f/f_{\rm sw})^2}\right]^{7/2} ,$$

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

$$f_{\rm col} = 16.5 \times 10^{-6} \left(\frac{f_*}{\beta}\right) \left(\frac{\beta}{H_*}\right) \left(\frac{T_n}{100\,{\rm GeV}}\right) \left(\frac{g^*}{100}\right)^{1/6} {\rm Hz},$$

$$f_{\rm sw} = 1.9 \times 10^{-5} \left(\frac{1}{v_w}\right) \left(\frac{\beta}{H_*}\right) \left(\frac{T_n}{100\ {\rm GeV}}\right) \left(\frac{g^*}{100}\right)^{1/6 {\rm Hz}} ,$$

$$f_{\rm tur} = 2.7 \times 10^{-5} \frac{1}{v_w} \left(\frac{\beta}{H_*}\right) \left(\frac{T_n}{100\ {\rm GeV}}\right) \left(\frac{g^*}{100}\right)^{1/6} {\rm Hz}.$$

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Other equations

$$E_{sp}(T) = \frac{8\pi v(T)}{g} f(m_h/m_w),$$

$$\Gamma_{sp} \simeq A(\alpha_w T)^4 \left(\frac{E_{sp}(T)}{T}\right)^4 e^{-E_{sp}(T)/T},$$

$$\langle \widetilde{\nu}_i \rangle = \frac{4 v_{\widetilde{N}} Y_N^i (v_u(A_N + \lambda_N v_S) + \lambda v_d v_S)}{(g_1^2 + g_2^2)(v_d^2 - v_u^2) + 4 m_{\widetilde{L}_i}^2},$$