Electroweak phase transition in the Z_3-invariant NMSSM: Implications of LHC and Dark matter searches and prospects of detecting the gravitational waves

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Requirements for EWBG

Baryon asymmetry parameter $Y_B \equiv \frac{n_B}{s} \sim \frac{1}{7.04}\frac{n_B}{n_\gamma} \sim 10^{-10}$

Three necessary ingredients needed to create a baryon asymmetry (Sakharov's conditions):

1> B-violation → Possible from SU(2) sphalerons

2> C and CP-violation → Present in SM but not large enough

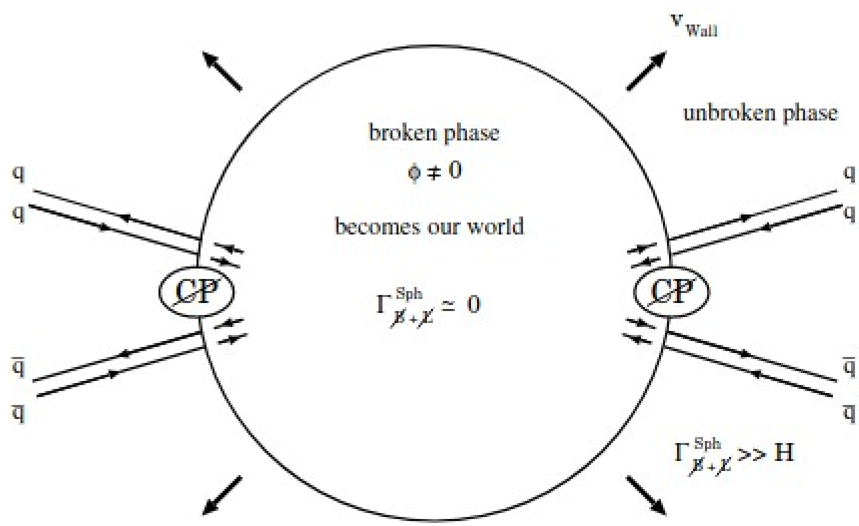
3> Departure from Thermal equilibrium → No First Order Phase transition in the Higgs sector in SM

⟹ Need to go Beyond SM

Requires Strong FOPT in the Higgs sector

$$\frac{\phi(T_n)}{T_n} > 1.0$$

New sources of CP-violation and SFOEWPT may arise in supersymmetry.



Bernreuther,0205279

SFOPT and NMSSM

SFOPT requires large cubic term in the scalar porential

→ Bosonic dof add extra cubic terms to the finite temperature effective potential.

light squarks (as bosons loop contribution) are needed to satisfy SFOEWPT in MSSM.

$\longrightarrow$ Ruled out from LHC direct search conditions

singlet extention of MSSM $\longrightarrow$ NMSSM could satisfy SFOEWPT without light squarks due to additional tree-level cubic interaction $(\widehat{S}\widehat{H}_u.\widehat{H}_d)$ plus thermal loop corrections.

extra one CP -even (h_S) and CP -odd state (a_S) in the neutral Higgs sector and one additional neutralino state, called singlino $(\widetilde{S})$

$$\mathcal{W} = \mathcal{W}_{\mathrm{MSSM}}|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u.\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

$$\lambda < S > \widehat{H}_u.\widehat{H}_d \rightarrow \mu_{eff}\widehat{H}_u.\widehat{H}_d$$

Solution to the well-known 'μ'-problem

$$m^2_{h_{SM}} = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta_{\mathrm{mix}} + \Delta_{\mathrm{rad.corr}}$$

Extra tree-level correction in NMSSM.

$$-\mathcal{L}^{\mathrm{soft}} = -\mathcal{L}^{\mathrm{soft}}_{\mathrm{MSSM}}|_{B\mu=0} + m_S^2|S|^2 + (\lambda A_\lambda S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa S^3 + \mathrm{h.c.}).$$

Additional tree-level cubic terms

125 GeV Higgs mass without significant radiative corrections at relatively larger λ

Ellwanger et al., Phys.Rept. 496 (2010) 1-77

Larger trilinear couplings increase the tree-level cubic terms

Pietroni, 9207227

SFOPT and NMSSM

FT loop calculation prefers relatively light singlet-like m_{a_S, h_S} $\longrightarrow$ Relatively low κ, A_κ
and doublet-like $m_{A,H}$ $\longrightarrow$ low A_λ
Higgs masses which tend to Become EWPT first order and strong

Carena et al., Phys.Rev.D 85 (2012) 036003
Kozaczuk et al., Phys.Rev.D 87 (2013) 7, 075011
Huang et al, Phys.Rev.D 91 (2015) 2, 025006

$$V_{\text{Total}} = V_{\text{Tree}} + V_{\text{CW}}^{\text{1-loop}} + V_{\text{counter terms}} + V_{\text{T}}^{\text{1-loop}} + V_{\text{daisy}}$$

$$(-1)^F g_i \frac{T^4}{2\pi^2} J_{\text{B/F}}\left(\frac{m_i^2(\Phi)}{T^2}\right)$$

$$\begin{cases} J_B^{\text{high}-T}(y^2) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}y^2 - \frac{\pi}{6}y^3 - \frac{1}{32}y^4 \log\left(\frac{y^2}{a_b}\right) \\ J_F^{\text{high}-T}(y^2) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}y^2 - \frac{1}{32}y^4 \log\left(\frac{y^2}{a_f}\right) \end{cases},$$

Constraints on SFOEWPT parameter space
- → SM-like Higgs Boson precision study
- → BSM heavy Higgs seaches (in the tb (for $H^\pm$) and $\tau\tau$ (for H, A) final states) $\Longrightarrow (m_A - \tan\beta)$

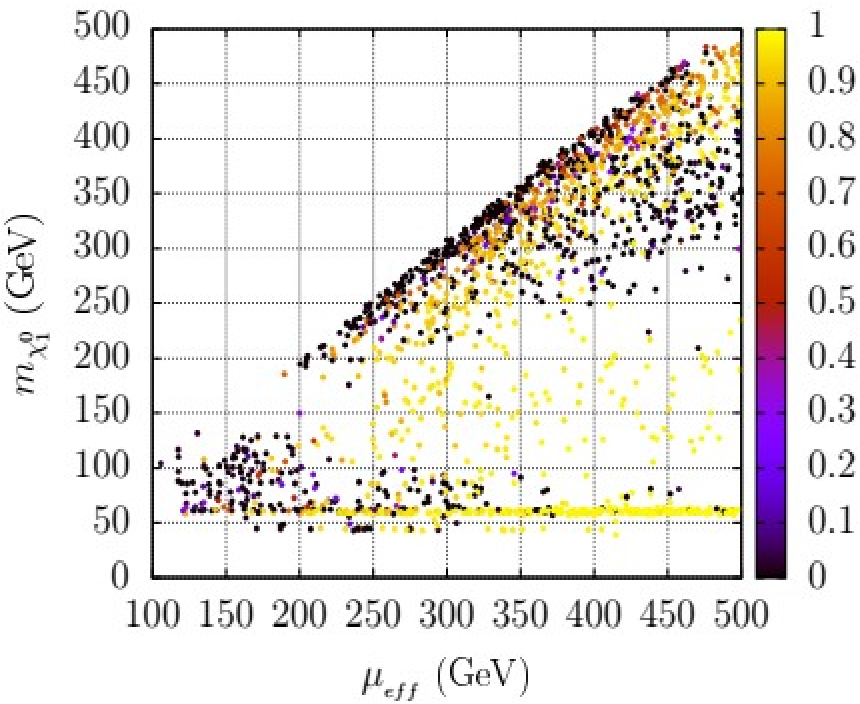
Athron et al., JHEP 11 (2019) 151
Baum et al., JHEP 03 (2021) 055

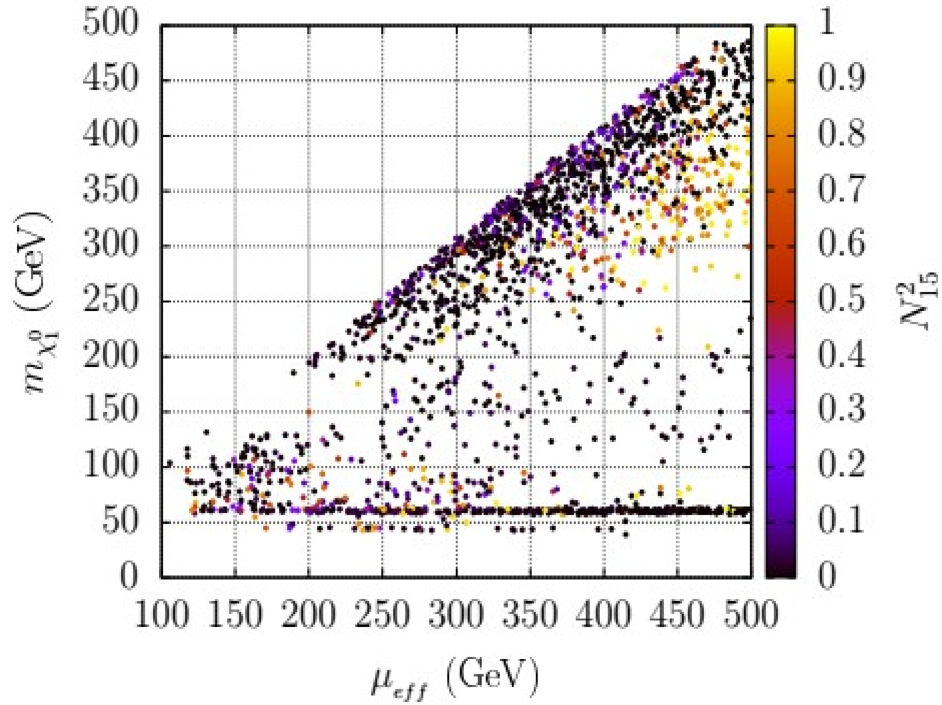
$\longrightarrow$ Light $m_{H,A,H^\pm}$ $\Longleftrightarrow$ low $\tan\beta$

larger λ, smaller κ
$v_S \backsim$ EW scale
} light $\widetilde{S}$
$m_{\widetilde{S}} = 2\kappa v_S = 2\kappa \frac{\mu_{eff}}{\lambda}$
$\Longrightarrow$ Possible Dark Matter } → DM relic density, Constraits from DMDD-SI and DMDD-SD cross-section

Electroweakino searches put constraints on the the parameter space of the relatively low μ_{eff} (Higgsino-like states) with relatively lighter bino, singlino-like states.

Allowed primary sample





All points pass relevant Higgs and Dark Matter constraints

Significant amount of SFOEWPT favoured parameter space is ruled out

Electroweakino searches at the LHC would rule out more parameter points

Disallowed scenarios with low μ_{eff}

Inputs/Observables	BP-D1	BP-D2	BP-D3
λ, κ, $\tan\beta$	0.683, 0.060, 4.77	0.547, 0.044, 2.87	0.565, 0.071, 2.87
A_λ, A_κ (GeV)	−1352.3, 134.5	978.4, −110.0	963.5, −112.5
$\mu_{\rm eff}$, M_1 (GeV)	−274.4, 478.8	308.0, 460.3	308.0, −57.2
$m_{\chi^0_{1,2,3,4},\chi^\pm_1}$ (GeV)	60.9, −304.3, 307.9, 479.4, −284.1	60.6, 312.7,-338.3, 468.1, 316.3	−59.6, 91.1, 327.2, −338.4, 316.0
$m_{h_1,h_2,a_1,H^\pm}$ (GeV)	79.2, 124.4, 126.6, 1359.0	78.1, 122.2, 109.5, 963.8	86.9, 123.0, 142.6, 963.6
Ωh^2	4.9×10^{-4}	4.4×10^{-4}	4.8×10^{-3}
$\sigma^{\rm SI}_{\chi^0_1-p(n)} \times \xi$ (cm^2)	$4.5(4.6) \times 10^{-47}$	$2.4(2.5) \times 10^{-47}$	$2.5(2.6) \times 10^{-47}$
$\sigma^{\rm SD}_{\chi^0_1-p(n)} \times \xi$ (cm^2)	$3.5(3.2) \times 10^{-42}$	$7.6(5.8) \times 10^{-43}$	$1.9(1.5) \times 10^{-43}$
First T_c (GeV)	129.4 / 1st-order	151.5 / 1st-order	165.7 / 1st-order
$\{h_d, h_u, s\}_{\rm False\_vac.}$ (GeV)	{0, 0, 0}	{0, 0, 0}	{0, 0, 0}
$\{h_d, h_u, s\}_{\rm True\_vac.}$ (GeV)	{25.5, 145.6, −474.4}	{0, 0, 539.9}	{0, 0, 557.5.9}
Second T_c (GeV)	–	112.7 / 2nd-order	105.6 / 1st-order
$\{h_d, h_u, s\}_{\rm False\_vac.}$ (GeV)	–	{0, 0, 661.7}	{0, 0, 662.3}
$\{h_d, h_u, s\}_{\rm True\_vac.}$ (GeV)	–	{9.5, 31.5, 668.2}	{12.8, 41.6, 669.0}
T_n (GeV) (Nucleation)	No nucleation	96.2 / 1st-order	55.9 / 1st-order
$\{h_d, h_u, s\}_{\rm False\_vac.}$ (GeV)	–	{0, 0, 0}	{0, 0, 0}
$\{h_d, h_u, s\}_{\rm True\_vac.}$ (GeV)	–	{67.0, 197.8, 774.8}	{68.1, 199.2, 759.2}
$\gamma_{\rm EW} = \Delta_{SU(2)}/T_n$	–	2.2	3.8
CheckMATE result	Excluded	Excluded	Excluded
r-value	1.12	1.01	2.13
Analysis ID	CMS_SUS_16_039	CMS_SUS_16_039	CMS_SUS_16_039
Signal region ID	SR_A30	SR_A30	SR_G05

'Nucleation is More than Critical' Baum et al., JHEP 03 (2021) 055

Exclusion of Parameter space of $\mu_{eff} \lesssim$300 GeV with light singlino/bino -like states from the electroweakino searches.

Allowed benchmark scenarios

Input/Observables	BP-A1	BP-A2	BP-A3
$\lambda,\ \kappa,\ \tan\beta$ $A_\lambda,\ A_\kappa$ (GeV) $\mu_{\rm eff}, M_1$ (GeV)	0.609, 0.326, 1.98 477.0, 37.8 421.8, 365.1	0.633, 0.216, 1.79 −558.7, −46.3 −398.7, 286.3	0.523, 0.041, 3.65 −1253.9, 138.1 −334.5, −143.8
$m_{\chi^0_{1,2,3,4}, \chi^\pm_1}$ (GeV) $m_{h_1,h_2,a_1,H^\pm}$ (GeV)	−360.9, 415.1, −447.5, 493.2, 431.5 122.7, 449.0, 79.0, 818.4	284.5, −289.5, −421.8, −426.9, −412.1 126.9, 288.5, 84.8, 800.9	−61.3, −139.2, −359.3, 359.7, −345.3 74.0, 124.7, 121.0, 1293.3
Ωh^2 $\sigma^{\rm SI}_{\chi^0_1-p(n)} \times \xi$ (cm^2) $\sigma^{\rm SD}_{\chi^0_1-p(n)} \times \xi$ (cm^2)	0.107 $7.2(7.6) \times 10^{-48}$ $9.4(7.3) \times 10^{-42}$	0.119 $1.2(1.2) \times 10^{-46}$ $3.5(2.8) \times 10^{-42}$	1.96×10^{-3} $4.1(4.3) \times 10^{-47}$ $1.1(0.8) \times 10^{-41}$
CheckMATE result r-value Analysis ID Signal region ID	Allowed 0.08 CMS_SUS_16_039 SR_A08	Allowed 0.14 CMS_SUS_16_039 SR_A28	Allowed 0.55 CMS_SUS_16_039 SR_A31

Relatively larger mueff pass the constraints from the electroweakino seraches in LHC

LSP DM can be highly bino or singlino-like and its relic abundance can fall within the Planck-observed band.

Under favorable circumstances, upwards of μ_{eff} ~335 GeV could survive

Pattern of Phase Transition

BM No.	T_n (GeV)	$\{h_d, h_u, h_s\}_{\text{false}}$ (GeV)	$\xrightarrow[\text{type}]{\text{Transition}}$	$\{h_d, h_u, h_s\}_{\text{true}}$ (GeV)	$\gamma_{\text{EW}} = \frac{\Delta_{SU(2)}}{T_n}$
BP-A1	945.6	{0, 0, 0}	FO	{0, 0, 66.2}	
	86.2	{0, 0, 1000.8}	,,	{57.1, 112.5, 1000.3}	1.46
BP-A2	644.3	{0, 0, 0}	,,	{0, 0, −104.8}	
	94.5	{0, 0, −914.9}	,,	{48.5, 85.6, −914.8}	1.04
BP-A3	116.9	{0, 0, 0}	,,	{30.3, 113.8, −877.4}	1.01

For μ_{eff} on the larger side, a two-step phase transition is a more likely phenomenon with the first transition taking place in the singlet field direction followed by the other in the SU(2) field directions.

This is somewhat typical when the trivial and the global minima have a large separation between them in the field space. This is since a larger μ_{eff} corresponds to a larger v_S at zero temperature for a given λ, a feature that governs the field-separation at T_C.

Gravitational waves from FOPT

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

sourced by
collisions of bubble walls

Kosowsky, et. al., PRL 69 (1992) 2026;
PRD 45 (1992) 4514
Huber, Konstandin, JCAP 0809 (2008) 022

sourced by
plasma sounds waves
(usually the dominent one)

Hindmarsh, et. al., PRL 112 (2014) 041301;
Hindmarsh, Hijazi, JCAP 12 (2019) 062

sourced by
plasma turbulence

Gogoberidze, et. al., PRD 76 (2007) 083002
Caprini, at. al., JCAP 0912 (2009) 024

Important quatities:

$$\alpha = \frac{\rho_{\rm vac}}{\rho^*_{\rm rad}} = \frac{1}{\rho^*_{\rm rad}}\left[T\frac{\Delta V(T)}{\rm T} - \Delta V(T)\right]\Bigg|_{T_n}$$

→ Related to the energy budget of the FOPT

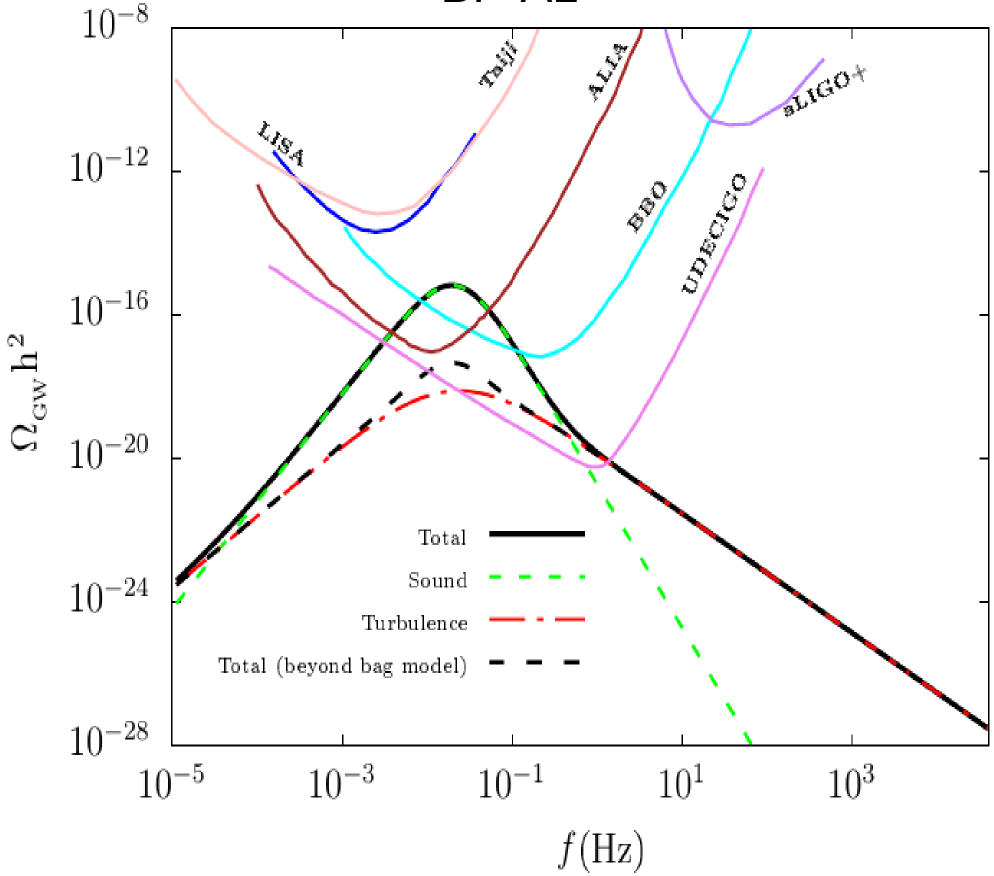
$$\beta = -\frac{dS_3(T)}{dt}\Bigg|_{t_n} \simeq H_n T_n \frac{d(S_3(T)/T)}{dT}\Bigg|_{T_n}$$

→ Related to the inverse duration of the transition

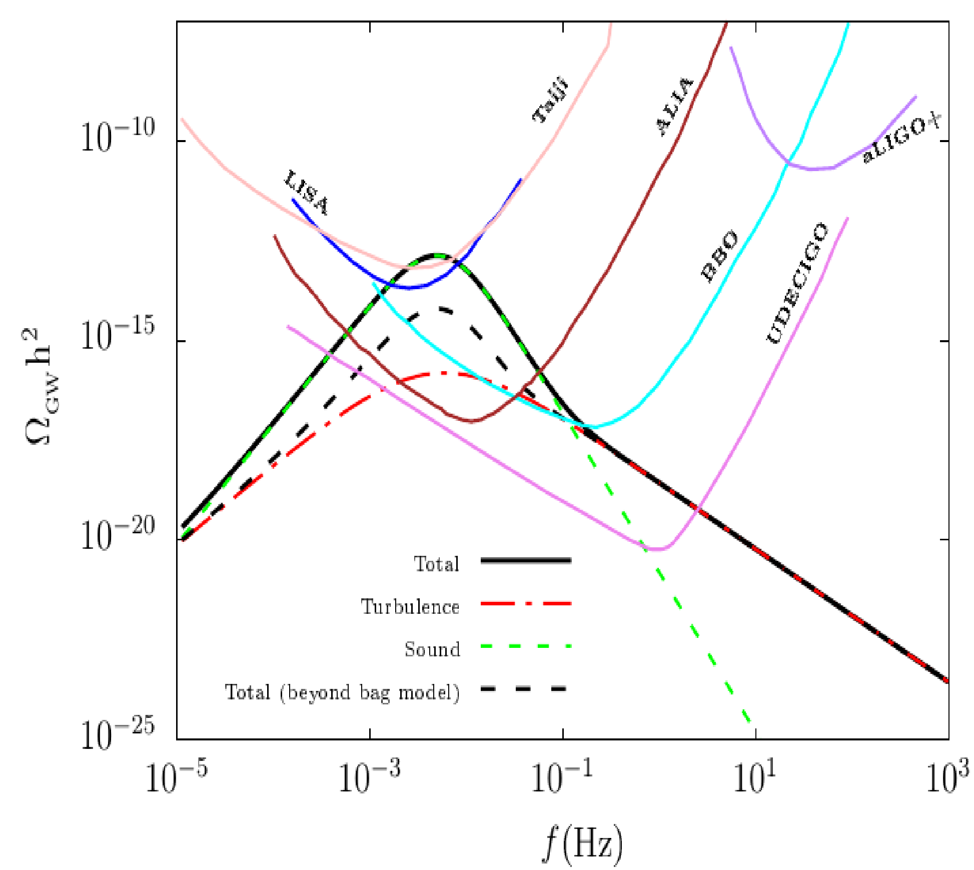
v_w → the wall-velocity of the expanding bubble

BP No.	T_n (GeV)	α	β/H_n
BP-A1	945.9	2.15×10^{-5}	1.19×10^{7}
	86.2	4.33×10^{-2}	1.21×10^{3}
BP-A2	644.3	1.12×10^{-4}	2.06×10^{6}
	94.5	1.82×10^{-2}	3.71×10^{4}
BP-A3	116.9	8.63×10^{-2}	2.22×10^{2}

BP-A1



BP-A3



Plots of GW energy density spectrum within and beyond the bag model with respect to frequency

Gaise, et. al, JCAP 07 (2020)057

The peak of GW spectrum lies within the sensitivity of various future proposed GW experiments

However, the SNR values are not found to be healthy enough to guarantee a positive detection in LISA and BBO.

Conclusion

The physics of the EWPT (and hence EWBG) becomes intricately connected to the DM and collider (LHC) phenomenologies.

Due to DM and collider constraints the SFOEWPT favoured parameter space (light $\mu_{\mathrm{e}ff}$) is in tension. Electroweakino searches at the LHC pushes $\mu_{\mathrm{e}ff}$ towards higher side.

EWPT could still remain to be of strong, first-order type even for $\mu_{\mathrm{e}ff}$ as large as $\sim$ 425 GeV

Two-step phase transition is a more likely phenomenon at larger $\mu_{\mathrm{e}ff}$

Satisfying all experimental constraints SFOEWPT is still possible in NMSSM

The GW signals resulting from the strong FOPTs in these scenarios are likely to remain too weak to be detected at future dedicated experiments.