Gravitational waves from first-order electroweak phase transition in a model with light sgoldstinos
(based on arXiv:2112.06083)

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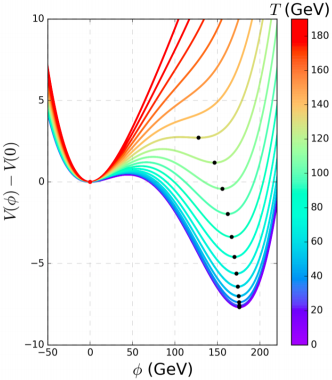
Sgoldstino and the 1st-order EW phase transition

- Model with the low-energy SUSY breaking (10-100 TeV) in the hidden sector.
- Supermultiplet of the Goldstone fermion **goldstino** and the scalar **sgoldstino** $\Phi = \phi + \sqrt{2}\theta G + F_\phi \theta^2$.
- $\langle F_\phi \rangle = F \neq 0$ — spontaneous SUSY breaking.
- Can we search for sgoldstino using some **cosmological** signatures?



- In the extended SM with an additional scalar: 1st-order electroweak phase transition $\rightarrow$ gravitational waves.
- **Questions:** Is the 1st-order EWPT possible in this model? What are the expected GW signals?

Lagrangian of supersymmetric model with sgoldstino

$$\mathcal{L} = \mathcal{L}_K + \mathcal{L}_W + \mathcal{L}_{gauge} + \mathcal{L}_\Phi,$$

$$\mathcal{L}_K = \int d^2\theta d^2\bar{\theta} \sum_k \left(1 - \frac{m_k^2}{F^2}\Phi^\dagger\Phi\right) \Phi_k^\dagger e^{g_1 V_1 + g_2 V_2 + g_3 V_3} \Phi_k,$$

$$\mathcal{L}_W = \int d^2\theta \epsilon_{ij} \left(\left(\mu - \frac{B}{F}\Phi\right) H_D^i H_U^j + \left(Y_{ab}^L + \frac{A_{ab}^L}{F}\Phi\right) L_a^j E_b^c H_D^i + \right.$$

$$\left. + \left(Y_{ab}^D + \frac{A_{ab}^D}{F}\Phi\right) Q_a^j D_b^c H_D^i + \left(Y_{ab}^U + \frac{A_{ab}^U}{F}\Phi\right) Q_a^i U_b^c H_U^j \right) + h.c.,$$

$$\mathcal{L}_{gauge} = \frac{1}{4} \sum_a \int d^2\theta \left(1 + \frac{2M_a}{F}\Phi\right) \mathrm{Tr} W_\alpha W^\alpha + h.c.\,,$$

$$\mathcal{L}_\Phi = \int d^2\theta d^2\bar{\theta} \left(\Phi^\dagger\Phi - \frac{\widetilde{m_s}^2 + \widetilde{m_p}^2}{8F^2} (\Phi^\dagger\Phi)^2 - \frac{\widetilde{m_s}^2 - \widetilde{m_p}^2}{12F^2} (\Phi^\dagger\Phi^3 + \Phi^{\dagger 3}\Phi) - \right.$$

$$- \frac{\delta_{\lambda_2}}{4F^2} H_u^\dagger H_u (\Phi^\dagger\Phi)^2 - \frac{\delta_{\lambda_3}}{9F^2} (\Phi^\dagger\Phi)^3 - \frac{\delta_{\lambda_4}}{3F^2} H_u^\dagger H_u (\Phi^\dagger\Phi^3 + \Phi^{\dagger 3}\Phi) -$$

$$- \frac{\delta_{\lambda_5}}{5F^2} (\Phi^\dagger\Phi^5 + \Phi^{\dagger 5}\Phi) - \frac{\delta_{\lambda_6}}{8F^2} (\Phi^{\dagger 2}\Phi^4 + \Phi^{\dagger 4}\Phi^2) - \frac{\delta_{\mu_1}}{2F^2} H_u^\dagger H_u (\Phi^\dagger\Phi^2 + \Phi^{\dagger 2}\Phi) -$$

$$\left. - \frac{\delta_{\mu_2}}{6F^2} (\Phi^{\dagger 3}\Phi^2 + \Phi^{\dagger 2}\Phi^3) - \frac{\delta_{\mu_3}}{4F^2} (\Phi^{\dagger 4}\Phi + \Phi^\dagger\Phi^4) - \frac{\delta_{C_3}}{2F^2} (\Phi^{\dagger 2}\Phi + \Phi^\dagger\Phi^2) \right) - \left(\int d^2\theta F\Phi + h.c. \right)$$

Tree-level potential in model with sgoldstino

1. Model with low-energy SUSY breaking: MSSM, goldstino-MSSM interaction, goldstino multiplet

$$\mathcal{L} = \mathcal{L}_{MSSM} + \mathcal{L}_{soft} + \mathcal{L}_{\Phi}$$

2. Scalar fields tree-level potential

$$V = V(h_d, h_u, \phi), \quad h_d = \begin{pmatrix} h_d^0 \\ H^- \end{pmatrix}, \quad h_u = \begin{pmatrix} H^+ \\ h_u^0 \end{pmatrix}$$

3. Decoupling limit at low energies

$$h_u \to \mathcal{H} \sin\beta, \quad h_d \to -\epsilon \mathcal{H}^* \cos\beta, \quad \tan\beta \equiv v_u/v_d$$

G. F. Giudice and A. Romanino, *Nucl. Phys. B* **699** (2004), 65-89 [arXiv:hep-ph/0406088].

4. Extract Higgs field, Goldstone bosons, scalar and pseudoscalar sgoldstino

$$\mathcal{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} G^+ \\ h + iG^0 \end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}(s + ip) \,.$$

5. Potential of three scalar fields $V_0 = V_0(h, s, p)$

Potential at zero temperature

$$V_{T=0}(h,s,p) = V_0 + V_{CW} + V_{CT}$$

Tree-level potential

$$V_0(h,s,p) = \frac{\lambda_1}{4}h^4 + \frac{\lambda_{hs}}{4}h^2 s^2 + \frac{\lambda_{hp}}{4}h^2 p^2 + \frac{\lambda_s}{4}s^4 + \frac{\lambda_p}{4}p^4 + \frac{\lambda_{sp}}{4}s^2 p^2 + + \frac{\mu_1}{2}sh^2 + \frac{\mu_s}{6}s^3 + \frac{\mu_{sp}}{2}sp^2 - \frac{\widetilde{M}_1^2}{2}h^2 + \frac{M_s^2}{2}s^2 + \frac{M_p^2}{2}p^2 + C_3 s\,.$$

One-loop corrections at $T = 0$

$$V_{CW}(h,s,p) = \frac{1}{64\pi^2}\sum_i (-1)^{s_i} n_i m_i^4(h,s,p)\left(\log\frac{m_i^2(h,s,p)}{Q^2} - c_i\right).$$

Counterterms: potential minimum at $T = 0$ in $(v,0,0)$

$$V_{CT}(h,s,p) = \frac{\delta\lambda_1}{4}h^4 + \frac{\delta\lambda_{hs}}{4}h^2 s^2 + \frac{\delta\lambda_{hp}}{4}h^2 p^2 + \frac{\delta\mu_1}{2}sh^2 - \frac{\delta\widetilde{M}_1^2}{2}h^2 + \delta C_3 s\,.$$

Effective potential at finite temperature

$$V_{\text{eff}}(T,h,s,p) = V_{T=0} + V_T + V_d$$

One-loop **thermal** corrections

$$V_T(T,h,s,p) = \frac{T^4}{2\pi^2}\sum_i n_i J_{B/F}\left(\frac{m_i(h,s,p)}{T}\right),$$

L. Dolan and R. Jackiw, *Phys. Rev. D* **9** (1974) 3320.

Corrections from **daisy diagrams** resummation

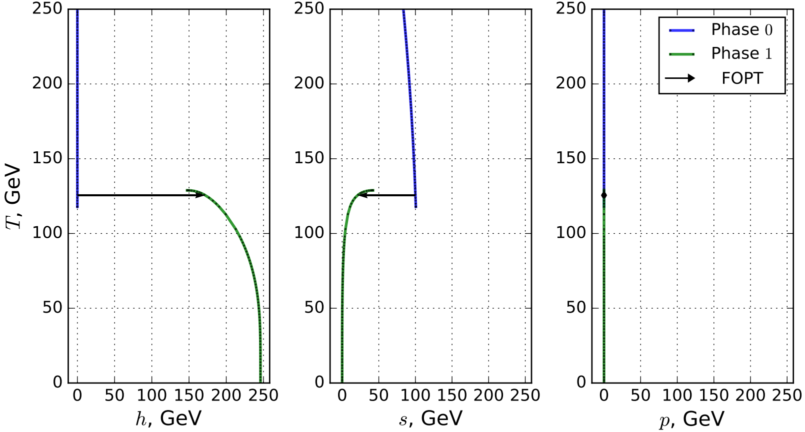
$$V_d(T,h,s,p) = -\frac{T}{12\pi}\sum_i a_i n_i \left(\left(m^2_{T\,i}(T,h,s,p)\right)^{3/2} - \left(m^2_i(h,s,p)\right)^{3/2}\right),$$

M. E. Carrington, *Phys. Rev. D* **45** (1992) 2933,
P. B. Arnold and O. Espinosa, *Phys. Rev. D* **47** (1993) 3546.

Benchmark model with the first-order phase transition

Minima of effective potential are plotted using the package `PhaseTracer`

P. Athron et al., *Eur. Phys. J. C* **80** (2020) no.6, 567 [arXiv:2003.02859]



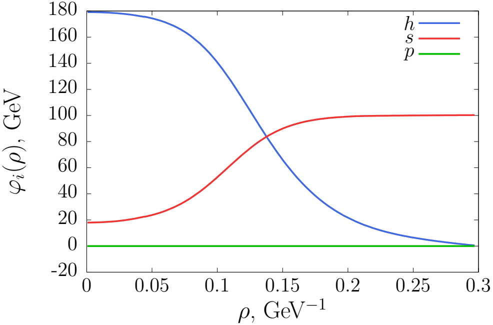
Bubbles of new phase: nucleation and percolation

Bubble production rate per unit volume

$$P \sim \mathcal{A}(T)\exp\left\{-\frac{S_3}{T}\right\}, \qquad \left.\frac{S_3}{T}\right|_{T=T_{\rm nuc}} = 140.$$

Phase transition characteristics: T_{nuc}, T_{perc}, α, β/H_c.

$$\alpha \equiv \left.\frac{\text{latent heat}}{\text{radiation energy}}\right|_{T=T_{\rm perc}}, \quad \frac{\beta}{H_c} \equiv T\frac{\mathrm{d}}{\mathrm{d}T}\left(\frac{S_3}{T}\right)\Big|_{T_{\rm perc}}.$$

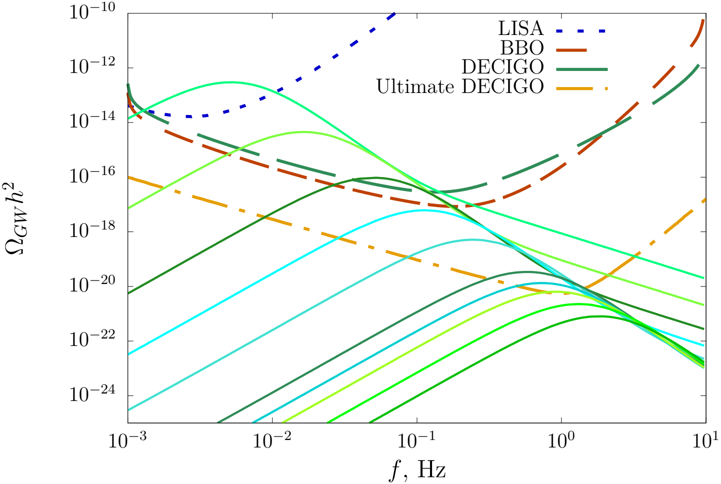


Bounce solutions are found using the package `FindBounce`
V. Guada, M. Nemevšek and M. Pintar, *Comput. Phys. Commun.* **256** (2020), 107480 [arXiv:2002.00881]

Gravitational wave spectra

Bubbles nucleate and collide → sound waves and MHD turbulence in plasma → gravitational waves

$$\Omega_{GW} h^2 = \Omega_{sw} h^2 + \Omega_m h^2$$

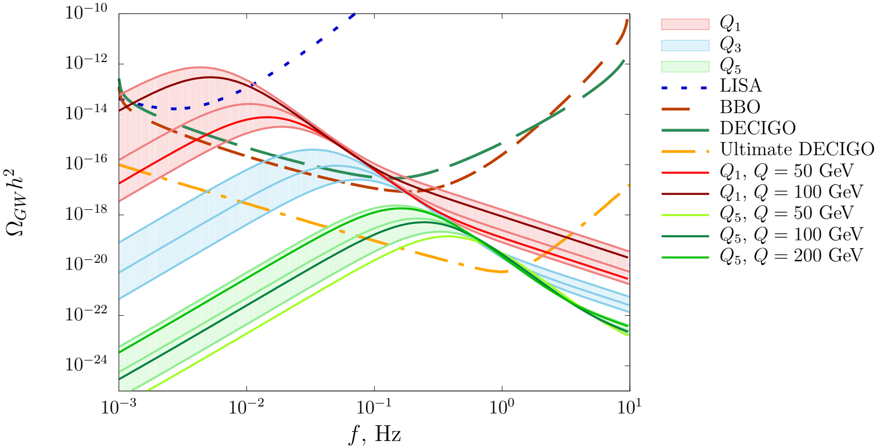


Theoretical uncertainties in GW spectra predictions

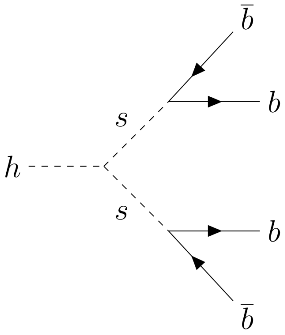
BM	Q, GeV	T_{nuc}, GeV	T_{perc}, GeV	$\alpha \cdot 10^3$	β/H_c
Q_1	109.7	60.71	54.88	168	228
	68.4	72.59	68.49	62.5	442
	39.3	81.75	78.63	35.9	683
Q_3	181.4	93.17	90.71	20.8	1040
	97.9	99.80	97.86	15.0	1490
	51.9	105.28	103.74	11.6	2060
Q_5	231.9	116.94	115.93	7.06	3670
	120.3	121.02	120.27	5.77	5190
	62.0	124.53	123.98	4.80	7530

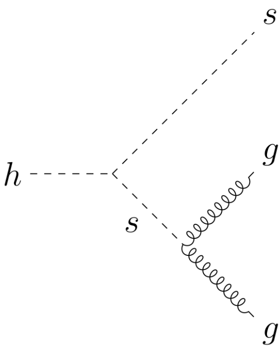
Table: The renormalization scale Q, nucleation and percolation temperatures, parameters α and β/H_c for BM Q_1, Q_3, Q_5 . For each point we calculate the first order electroweak phase transition parameters taking the renormalization scale $2T_{perc}$, T_{perc} and $T_{perc}/2$.

Theoretical uncertainties in GW spectra predictions



Possible exotic Higgs boson decays with sgoldstino





Results

- We have shown that the first-order electroweak phase transition is possible in the model with low-scale supersymmetry breaking.
- In benchmark models the 1st-order PT takes place at $T \approx 60 - 140$ GeV.
- It may be possible for LISA and the suggested observatories BBO, DECIGO to search for gravitational waves produced during the PT in benchmark models.

Thank you for your attention!

Counterterms potential

The field values in the minimum of zero-temperature potential $V_0 + V_{CW} + V_{CT}$ are $h = v$, $s = 0$, $p = 0$ if we choose

$$V_{CT} = \frac{\delta\lambda_1}{4} h^4 + \frac{\delta\lambda_{hs}}{4} h^2 s^2 + \frac{\delta\lambda_{hp}}{4} h^2 p^2 + \frac{\delta\mu_1}{2} s h^2 - \frac{\delta M_1^2}{2} h^2 + \delta C^3 s,$$

$$\delta\lambda_1 = -\frac{1}{2v^2} \left.\frac{\partial^2 V_{CW}}{\partial h^2}\right|_{(v,0,0)} + \frac{1}{2v^3} \left.\frac{\partial V_{CW}}{\partial h}\right|_{(v,0,0)},$$

$$\delta\lambda_{hs} = -\frac{2}{v^2} \left.\frac{\partial^2 V_{CW}}{\partial s^2}\right|_{(v,0,0)}, \qquad \delta\lambda_{hp} = -\frac{2}{v^2} \left.\frac{\partial^2 V_{CW}}{\partial p^2}\right|_{(v,0,0)},$$

$$\delta\mu_1 = -\frac{1}{v} \left.\frac{\partial^2 V_{CW}}{\partial h \partial s}\right|_{(v,0,0)}, \quad \delta C^3 = -\left.\frac{\partial V_{CW}}{\partial s}\right|_{(v,0,0)} + \frac{v}{2} \left.\frac{\partial^2 V_{CW}}{\partial h \partial s}\right|_{(v,0,0)},$$

$$\delta M_1^2 = -\frac{1}{2} \left.\frac{\partial^2 V_{CW}}{\partial h^2}\right|_{(v,0,0)} + \frac{3}{2v} \left.\frac{\partial V_{CW}}{\partial h}\right|_{(v,0,0)}.$$

Benchmark models

BM	λ_{hs}	λ_{hp}	λ_s	λ_p	λ_{sp}	$T_{\rm nuc}$	$T_{\rm perc}$	$\alpha \cdot 10^3$	β/H_c
Q_1	0.88	0.78	0.70	0.60	0.70	63.58	58.30	119	254
Q_2	0.85	0.75	0.70	0.60	0.70	81.51	78.22	37.4	602
Q_3	0.80	0.70	0.70	0.60	0.70	99.60	97.64	15.2	1470
Q_4	0.75	0.65	0.70	0.60	0.70	112.25	111.05	8.61	2920
Q_5	0.70	0.65	0.70	0.60	0.70	122.06	121.36	5.48	5760
Q_6	0.65	0.60	0.70	0.60	0.70	130.07	129.72	3.52	12700
Q_7	0.60	0.50	0.55	0.45	0.60	133.45	133.13	2.88	15700
Q_8	0.60	0.50	0.60	0.50	0.70	134.84	134.61	2.56	19400
Q_9	0.60	0.50	0.65	0.55	0.70	135.85	135.66	2.26	27800
Q_{10}	0.60	0.40	0.70	0.60	0.70	136.74	136.61	1.95	38100

Table: Dimensionless parameters of selected benchmark models (BM) with the first order electroweak phase transition as well as nucleation and percolation temperatures $T_{\rm nuc}$, $T_{\rm perc}$ (in GeV), strength α and ratio β/H_c.

Bounce solution

$$\frac{\mathrm{d}^2\varphi_i}{\mathrm{d}\rho^2} + \frac{2}{\rho}\frac{\mathrm{d}\varphi_i}{\mathrm{d}\rho} = \frac{\partial V_{\text{eff}}}{\partial \varphi_i}\,,$$

boundary conditions:
1) $\frac{\mathrm{d}\varphi_i(\rho)}{\mathrm{d}\rho} = 0$ at $\rho = 0$; 2) $\varphi_i(\rho) \to \varphi_i^{\text{false}}$ at $\rho \to \infty$
Euclidean action calculated on bounce solution

$$S_3 = \int_0^\infty 4\pi\rho^2\,\mathrm{d}\rho\,\Big(V_{\text{eff}}(T,h,s,p) + \\ + \frac{1}{2}\left(\frac{\mathrm{d}h}{\mathrm{d}\rho}\right)^2 + \frac{1}{2}\left(\frac{\mathrm{d}s}{\mathrm{d}\rho}\right)^2 + \frac{1}{2}\left(\frac{\mathrm{d}p}{\mathrm{d}\rho}\right)^2\Big)$$