Fermion-induced Electroweak Symmetry Non-restoration via Temperature-dependent Masses

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Motivations and Challenges

Motivations:

- In SM, EW symmetry is restored around T=160 GeV[1]. What kind of BSM theories can have distinctly different electroweak epoch? What are the predictions of these theories?
- Intimate relationship between EW symmetry and baryon asymmetry of the universe (BAU).
  - $U(1)_B$ and $U(1)_L$ are anomalous symmetry in SM

$$\partial_\mu j^\mu_B = \partial_\mu j^\mu_L = \frac{N_f}{32\pi^2}\left(g^2 W\tilde{W} - g'^2 Y\tilde{Y}\right)$$

$$\Gamma = 4\pi f(\lambda/g^2) g T^4 \xi^7 \exp\left(-\frac{4\pi B}{g}\xi\right), \qquad \text{if} \quad v_h \neq 0$$
$$\Gamma = k\,(\alpha_W T)^4, \qquad \text{if} \quad v_h = 0$$
$$\xi \equiv v_h(T)/T$$

Challenges:

- At high temperatures, EW symmetry was always broken or only temporarily restored in some scalars models (e.g. SM+O(N_s) singlet scalars[2], I2HDM+O(N_s) singlet scalars[3], 2HDM+real singlet scalar[4]).

$$V = V_{SM} + \frac{1}{2}\mu_s^2(s_i s_i) + \frac{1}{4}\lambda_s (s_i s_i)^2 + \frac{1}{2}\lambda_{hs} h^2 (s_i s_i)$$
$$\left.\frac{\partial^2 V_1^{th}}{\partial h^2}\right|_{h=0} = T^2\left(\frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}\lambda_t^2 + \frac{1}{2}\lambda + \frac{N_s}{12}\lambda_{hs}\right)$$

- Difficult to induce EWSB by fermions from renormalizable models: (When $m_i^2 << T^2$)

$$\left.\frac{\partial^2 V_{1,F}^{th}}{\partial h^2}\right|_{h=0} = \sum_i T^2 \frac{n_F}{48}\frac{\partial^2 m_i^2}{\partial h^2} = T^2 \frac{n_F}{48}\frac{\partial^2}{\partial h^2}\sum_i m_i^2$$
$$= T^2 \frac{n_F}{48}\frac{\partial^2}{\partial h^2}\mathrm{Tr}\left(M_f^\dagger M_f\right) = T^2\frac{n_F}{48}\frac{\partial^2}{\partial h^2}\sum_{i,j}|M_{ij}|^2$$

In renormalizable models, $M_{ij} = a_0 + a_1 h$, hence $\left.\frac{\partial^2 V_{1,F}^{th}}{\partial h^2}\right|_{h=0} \geq 0$. Thus, it is impossible to achieve EWSNR by adding only new fermions.

> But what if some of the new fermions have $m^2(T) \gg T^2$?

[1] D'Onofrio etc., 1508.07161.
[2] Meade, Ramani, 1807.07578.
[3] Carena et al.,2104.00638
[4] Heinemeyer et at.,2103.12707
[5] Schmitz, 2002.04615

Mechansim and models

$$L^i_{L,R} = \begin{bmatrix} N^i \\ E^i \end{bmatrix}_{L,R} \sim (1,2)_{-\frac{1}{2}}, \quad N'^i_{L,R} \sim (1,1)_0,$$
$$E'^i_{L,R} \sim (1,1)_{-1}$$

$$\mathcal{L}^i_{yuk} = -y^i_{NN'1}\overline{L^i_L}\tilde{\phi}N'^i_R - y^i_{NN'2}\overline{N'^i_L}\tilde{\phi}^\dagger L^i_R$$
$$-y^i_{EE'1}\overline{L^i_L}\phi E'^i_R - y^i_{EE'2}\overline{E'^i_L}\phi^\dagger L^i_R$$
$$-m_{Li}(\sigma)\overline{L^i_L}L^i_R - m_{N'i}(\sigma)\overline{N'^i_L}N'^i_R$$
$$-m_{E'i}(\sigma)\overline{E'^i_L}E'^i_R + h.c.$$

In UV-complete models, m_X ($X = N', E', L$) can be parameterized as

$$m_X(\sigma) = m_{X0} + y_X \sigma\,.$$

$$v_\sigma(T) = \begin{cases} b_0\,, & \text{if } T < T_1 \\ b_0 + b_1(T-T_1)^{n_1} + b_2(T-T_2)^{n_2}\,, & \text{if } T_1 \leq T \leq T_2\,. \end{cases}$$

When $m_L^2 \gg m_{N'}^2,\ m_{E'}^2,\ \frac{1}{2}|y_{NN'1}y_{NN'2}|h^2$, the mass eigenvalues are

$$m_{N1}^2 \approx m_{N'}^2 - \frac{m_{N'}\,\mathrm{Re}(y_{NN'1}y_{NN'2})}{m_L}h^2\,,$$
$$m_{N2}^2 \approx m_L^2\,,$$

and similarly for m_{E1}, m_{E2}.

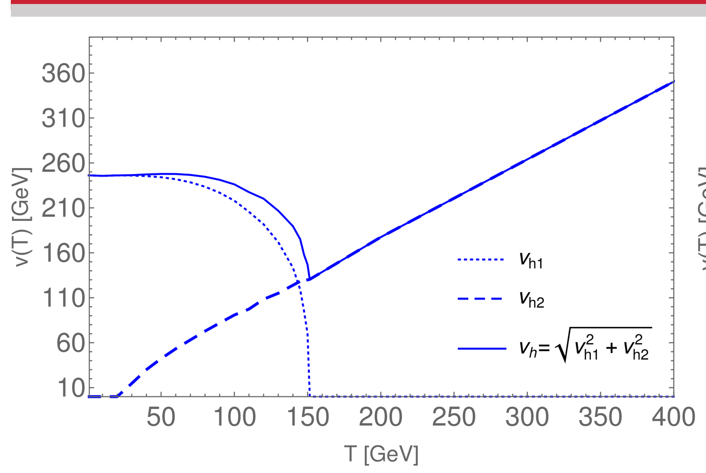
$$\left.\frac{\partial^2 V_1^{th}}{\partial h^2}\right|_{h=0} = -a_h T^2$$

where

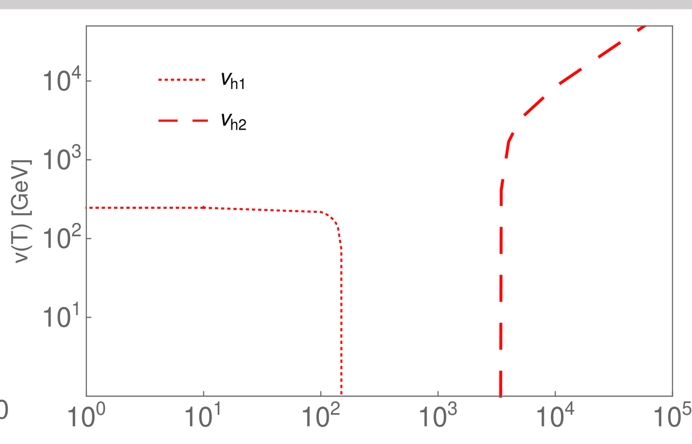
$$a_h = \frac{N_F}{6m_L}\left(m_{N'}y_{NN'1}y_{NN'2} + m_{E'}y_{EE'1}y_{EE'2}\right) - \left(\frac{3}{16}g^2 + \frac{1}{16}g'^2 + \frac{1}{4}y_t^2 + \frac{1}{2}\lambda_h\right)\,.$$

In parameter space where $a_h > 0$, EW symmetry remains broken at high temperature.

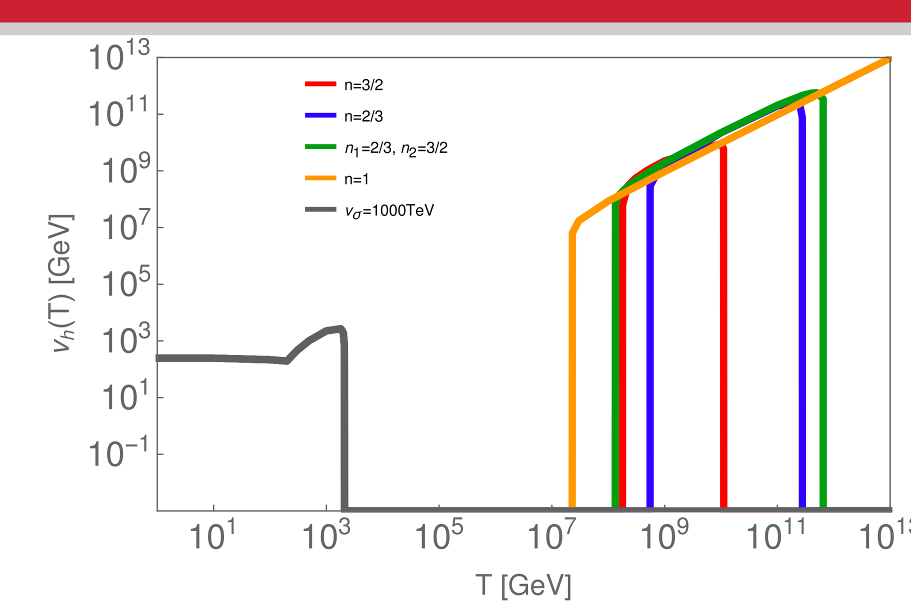
Thermal Histories



Thermal history in which the electroweak symmetry is always broken.



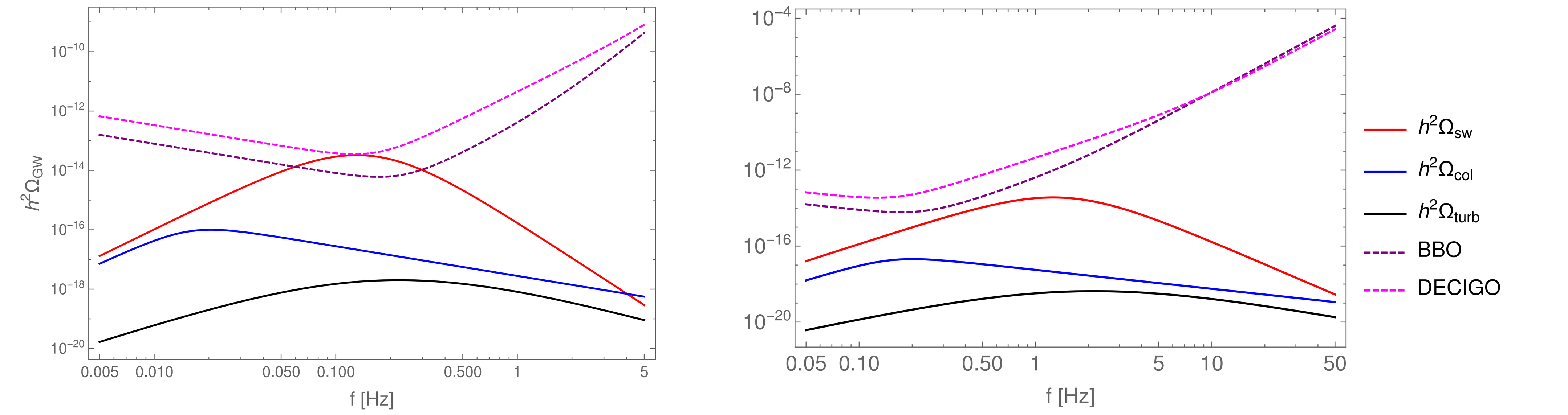
Thermal history in which the electroweak symmetry is only temporarily restored.



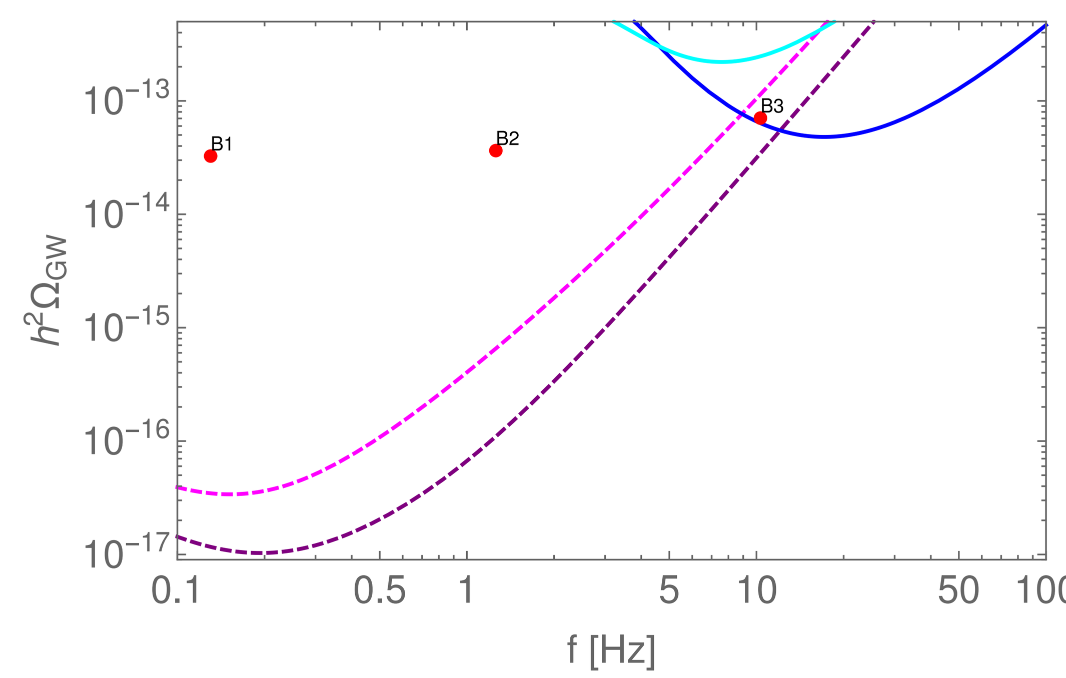
Effects of the functional forms of $v_\sigma(T)$ on the thermal histories.

Gravitational Wave Signals

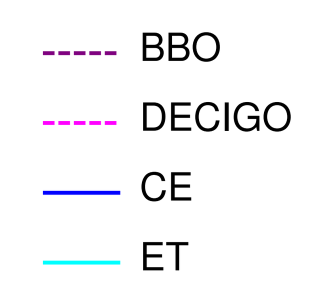
The gravitational wave spectrum of benchmarks B1 (left panel), B2 (right panel), and the noise spectrum of the Big Bang Observer(BBO) and DECi-hertz Interferometer Gravitational wave Observatory(DECIGO).



Peak-integrated sensitivity curves (left panel) for several future gravitational wave observatories[5]. The red dots are some benchmarks (some details are given in the table on right panel). The x-coordinate of each benchmark is its peak frequencies, and y-coordinate is its peak GW strength.



$$\rho_{SNR} = \sqrt{\frac{t_{obs}}{1\text{y}}}\,\frac{\Omega^{peak}_{signal}}{\Omega^{PIS}_{detector}}$$



	B1	B2	B3
N_F	60	60	55
$y_{NN'i} = y_{EE'i}$	0.15	0.2	0.2
$y_{N'}$	0.0015	0.0015	0.0015
y_L	0.003	0.003	0.003
m_{N1}(GeV)	150	150	150
λ_2	4×10^{-4}	4×10^{-4}	4×10^{-4}
n	6/7	6/7	6/7
n_L	2.4	2.4	2.4
T_2(GeV)	1000	1000	2.3×10^4
T_c(GeV)	1800	2444	3.7×10^4
T_n(GeV)	724.5	1877	2.5×10^4
α	0.016	0.028	0.029
$\beta/H(T_n)$	447	1700	1065
f_{peak}(Hz)	0.13	1.3	10.3
$h^2\Omega^{peak}_{GW}$	3.3×10^{-14}	6.1×10^{-14}	7.1×10^{-14}

$$b_n = T_2^{1-n} n_L / y_L$$

Summary

- **New fermions from renormalizable models can induce EW symmetry non-restoration, or push the EWPT temperature well above the EW scale.**
- **These models have intriguing cosmological implications: origin of matter-antimatter asymmetry (e.g. high-temperature EWBG), gravitational wave signatures.**

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