Electroweak-like Baryogenesis with New Chiral Matter

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Baryon Asymmetry of the Universe (BAU)

$$\frac{n_B}{s} \sim 10^{-11}$$

n_B : baryon number density

s : entropy density

We need a baryon asymmetry!

Sakharov's conditions

- Baryon number violation

- CP violation

- Out-of-thermal equilibrium process

Baryogenesis in the SM

[Kuzmin, V. A., Rubakov, V. A. and Shaposhnikov, M.E.(1993)]

- Baryon number violation

  Sphaleron process (B+L violation process)

- CP violation

  Cabbibo-Kobayashi-Maskawa (CKM) phase

- Out-of-thermal equilibrium process

  “strong” first-order electroweak phase transition

Electroweak Baryogenesis in the SM

- **CP violation only from CKM phase is insufficient:**

[M. B. Gavela, P. Hernandez, J. Orloff and O. Pene (1993)]
[P. Huet and E. Sather (1994)]
[M. B. Gavela, P. Hernandez, J. Orloff, O. Pene and C. Quimbay (1994)]

$$d_{\mathrm{CP}} \sim J \times (m_u^2 - m_c^2)(m_c^2 - m_t^2)(m_t^2 - m_u^2) \times (m_d^2 - m_s^2)(m_s^2 - m_b^2)(m_b^2 - m_d^2)$$

$$\frac{n_B}{s} < \frac{d_{\mathrm{CP}}}{T_c^{12}} \sim 10^{-27} \ll 10^{-10}$$

Critical temperature of EWPT

J : Jarlskog invariant $\qquad T_C \sim 100\mathrm{GeV}$

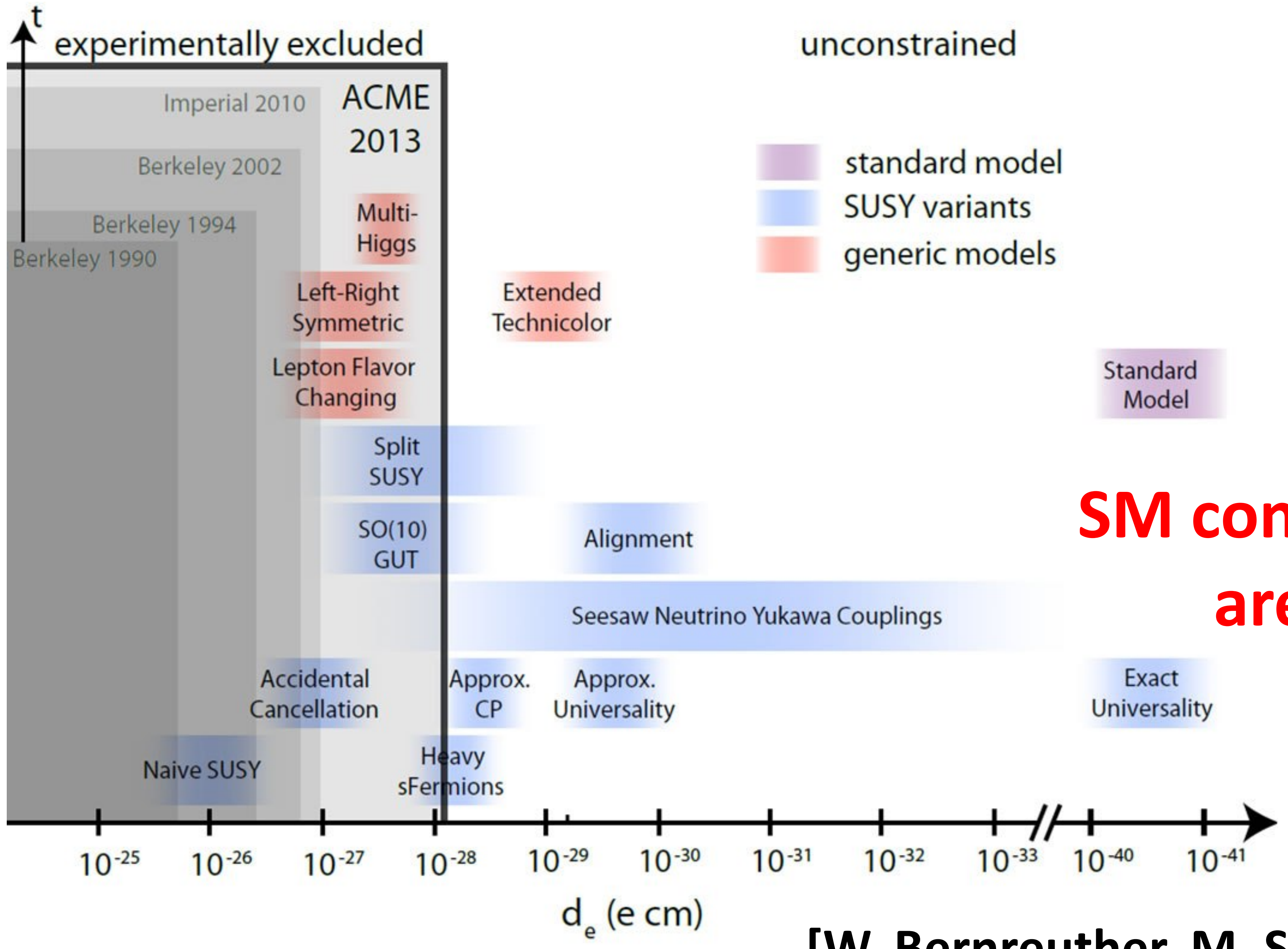
- $m_h \simeq 125\mathrm{GeV}$: **EWPT is not of strong first order. (Lattice simulation)**

[A. I. Bochkarev and M.E. Shaposhnikov (1987)]
[K. Kajantie, M. Laine, K. Rummukainen and M.E. Shaposhikov(1996)]

Electric dipole moment (EDM) measurement

EWBG needs:

- An additional CP violation
- ”Strong” first-order EWPT



SM contributions are tiny.

[W. Bernreuther, M. Suzuki (1991)]

However, an additional CP violation is stringently constrained by EDM measurement!

How do we generate the observed BAU by EWBG consistent with the EDM measurement?

Electroweak-like Baryogenesis

- We consider the extension of the SM with $SU(3)_C \times SU(2)_R \times SU(2)_L \times U(1)_X$, which is spontaneously broken to $SU(3)_C \times SU(2)_L \times U(1)_Y$

- First-order $SU(2)_R \times U(1)_X \to U(1)_Y$ phase transition generates B-L asymmetry by a SU(2)R sphaleron process.
(Generated B-L asymmetry is transferred by a SU(2)L sphaleron process.)

- The breaking scale of $SU(2)_R \times U(1)_X \to U(1)_Y$ is around 10TeV scale!

Model (1)

- **Higgs sector:**

$$G_{\mathrm{LR}} \equiv SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$$

$$G_{\mathrm{SM}} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$\boldsymbol{(SU(3)_C,\ SU(2)_L,\ SU(2)_R,\ U(1)_X)}$$

$$H_R(\mathbf{1},\mathbf{1},\mathbf{2},\frac{1}{2}) : G_{\mathrm{LR}} \to G_{\mathrm{SM}}$$

$$H_L(\mathbf{1},\mathbf{2},\mathbf{1},\frac{1}{2}) \text{ or } \Phi(\mathbf{1},\mathbf{2},\mathbf{2},0) : G_{\mathrm{SM}} \to SU(3)_c \times U(1)_{\mathrm{EM}},$$

Model (2)

- **SM quarks and leptons:**

$$q_i = \begin{pmatrix} u_i \\ d_i \end{pmatrix} : (\mathbf{3}, \mathbf{2}, \mathbf{1}, \frac{1}{6})_{B=1/3}, \qquad \bar{q}_i = \begin{pmatrix} \bar{u}_i \\ \bar{d}_i \end{pmatrix} : (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{2}, -\frac{1}{6})_{B=-1/3},$$

$$\ell_i = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix} : (\mathbf{1}, \mathbf{2}, \mathbf{1}, -\frac{1}{2})_{L=1}, \qquad \bar{\ell}_i = \begin{pmatrix} \bar{\nu}_i \\ \bar{e}_i \end{pmatrix} : (\mathbf{1}, \mathbf{1}, \mathbf{2}, \frac{1}{2})_{L=-1},$$

- **In this minimal extension, B-L is not broken by SU(2)R chiral anomalies.**

➡ **B-L is not generated by the SU(2)R sphaleron process!**

➡ **We need additional chiral fermions to violate B-L !**

Model (3)

- **New leptons:** [J.E. Kim (2017) arXiv:1703.10925]

$$\bar{L}_i = \begin{pmatrix} \bar{E}_i \\ \bar{N}_i \end{pmatrix} : (\mathbf{1},\mathbf{1},\mathbf{2},\frac{1}{2})_{L=-1}, \qquad \widetilde{L} = \begin{pmatrix} \mathcal{E} \\ \mathcal{X} \end{pmatrix} : (\mathbf{1},\mathbf{1},\mathbf{2},-\frac{3}{2})_{L=1},$$

$$E_i : (\mathbf{1},\mathbf{1},\mathbf{1},-1)_{L=1}, \quad N_i : (\mathbf{1},\mathbf{1},\mathbf{1},0)_{L=1}, \quad \bar{\mathcal{E}} : (\mathbf{1},\mathbf{1},\mathbf{1},1)_{L=-1}, \quad \bar{\mathcal{X}} : (\mathbf{1},\mathbf{1},\mathbf{1},2)_{L=-1},$$

$$\mathcal{L}_R = \underline{y_E^{ij} H_R \bar{L}_i E_j + y_N^{ij} H_R^\dagger \bar{L}_i N_j} + \underline{y_{\mathcal{E}} H_R \widetilde{L}\, \bar{\mathcal{E}} + y_{\mathcal{X}} H_R^\dagger \widetilde{L}\, \bar{\mathcal{X}} + \mathrm{h.c.}}$$

New fermions (three generations)!

CKM phase in the new lepton sector.

To cancel the gauge anomaly

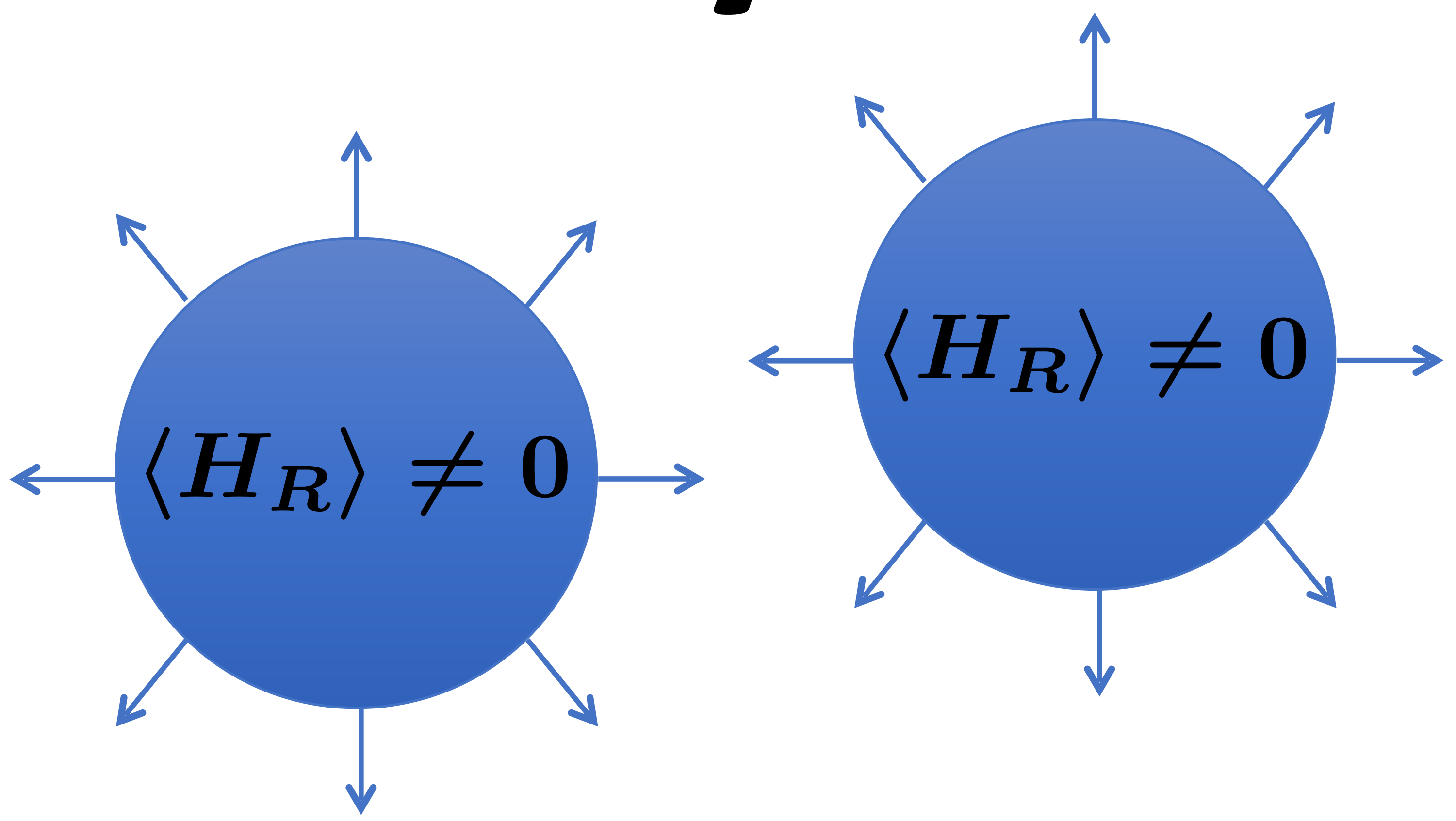
- **A portal coupling between new leptons and SM leptons:**

$$\mathcal{L}_{\mathrm{int}} = g^i_{\bar{\mathcal{E}}} H_L \ell_i\, \bar{\mathcal{E}} + \underline{g_E^{ij} H_R \bar{\ell}_i E_j + g_N^{ij} H_R^\dagger \bar{\ell}_i N_j} + \mathrm{h.c.},$$

E and N asymmetries are transferred into SM lepton asymmetry.

Generation of B-L asymmetry

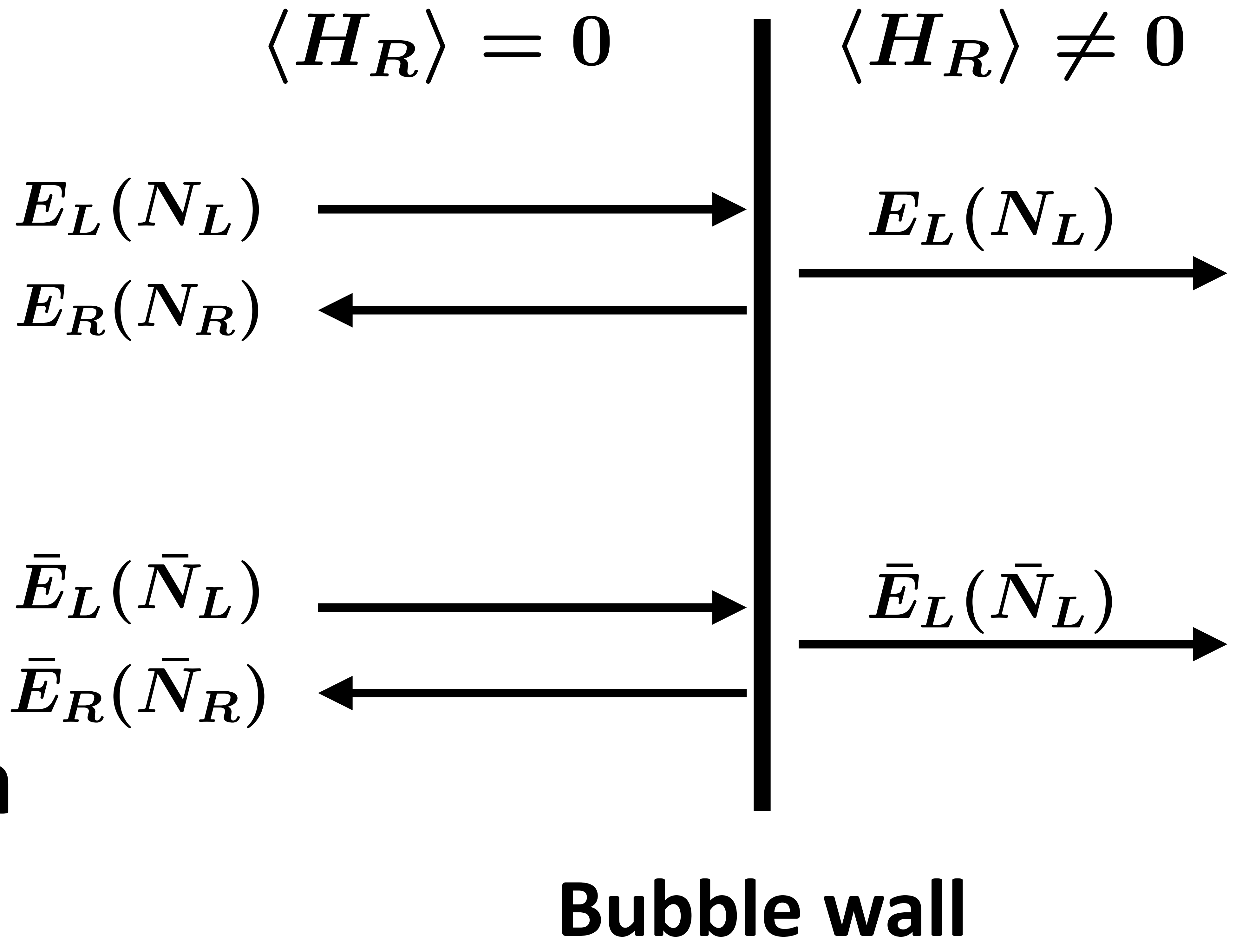
- A first-order phase transition proceeds through a bubble nucleation.



- A bubble wall reflects new leptons and anti-new leptons.

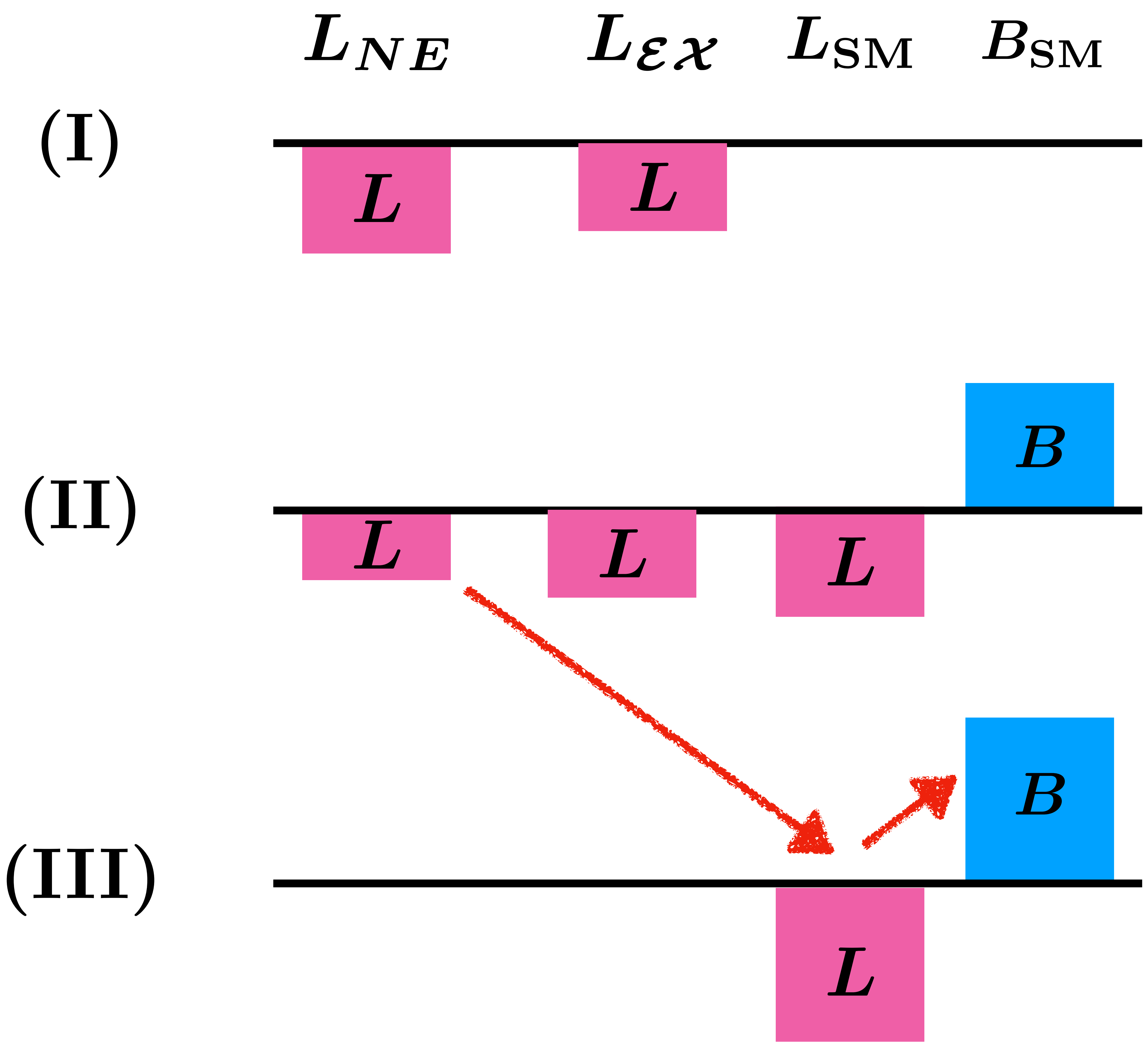
- A reflection coefficients of new lepton and their antiparticles are different.

- B-L can be generated if the SU(2)R sphaleron process is decoupled in the symmetric phase.



Generation of the baryon asymmetry

- (I) L_{NE} asymmetry is generated by the moving bubble wall.
- (I) The $SU(2)_R$ sphaleron process converts a part of L_{NE} asymmetry into SM B+L and $L_{\mathscr{E}\mathscr{X}}$ asymmetries.
- (II) These asymmetries are transferred to the SM lepton and baryon asymmetries by the ordinary $SU(2)_L$ sphaleron process.
- (III) Finally, new leptons decay into the SM leptons!



Baryon asymmetry in our model

$$d_{\rm CP} = J'(m_{E_1}^2 - m_{E_2}^2)(m_{E_2}^2 - m_{E_3}^2)(m_{E_3}^2 - m_{E_1}^2)$$
$$\times(m_{N_1}^2 - m_{N_2}^2)(m_{N_2}^2 - m_{N_3}^2)(m_{N_3}^2 - m_{N_1}^2)$$

$$J' \sim 10^{-2} \quad y_{E_{1,2,3}} \sim 0.1 \quad y_{N_{1,2}} \sim 0.1 \quad y_{N_3} \sim 1$$

$$\frac{n_B}{s} \sim \frac{d_{\rm CP}}{T_C^{12}} \sim 10^{-10}$$

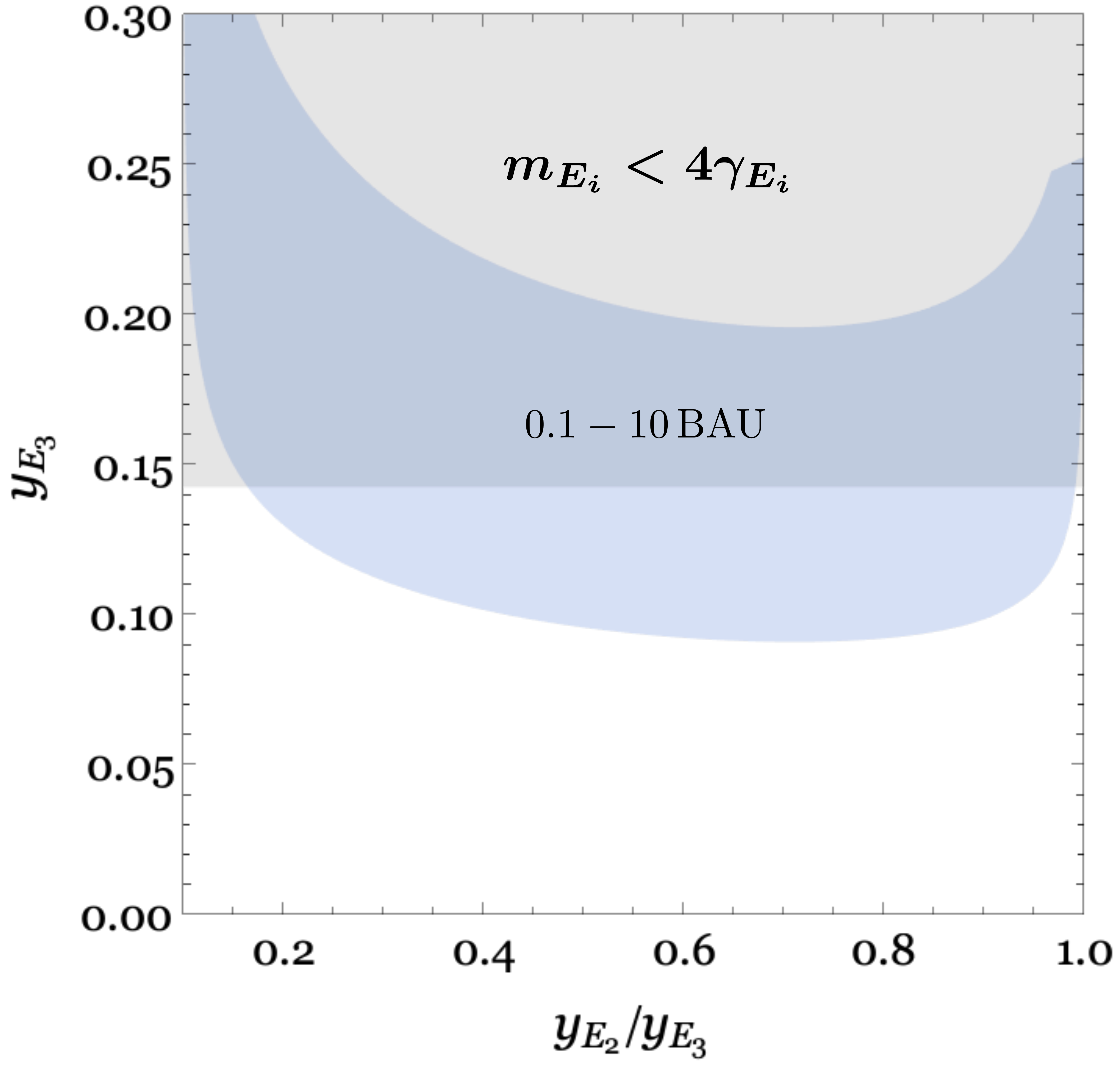
Dimensionless quantity

Critical temperature of the phase transition.

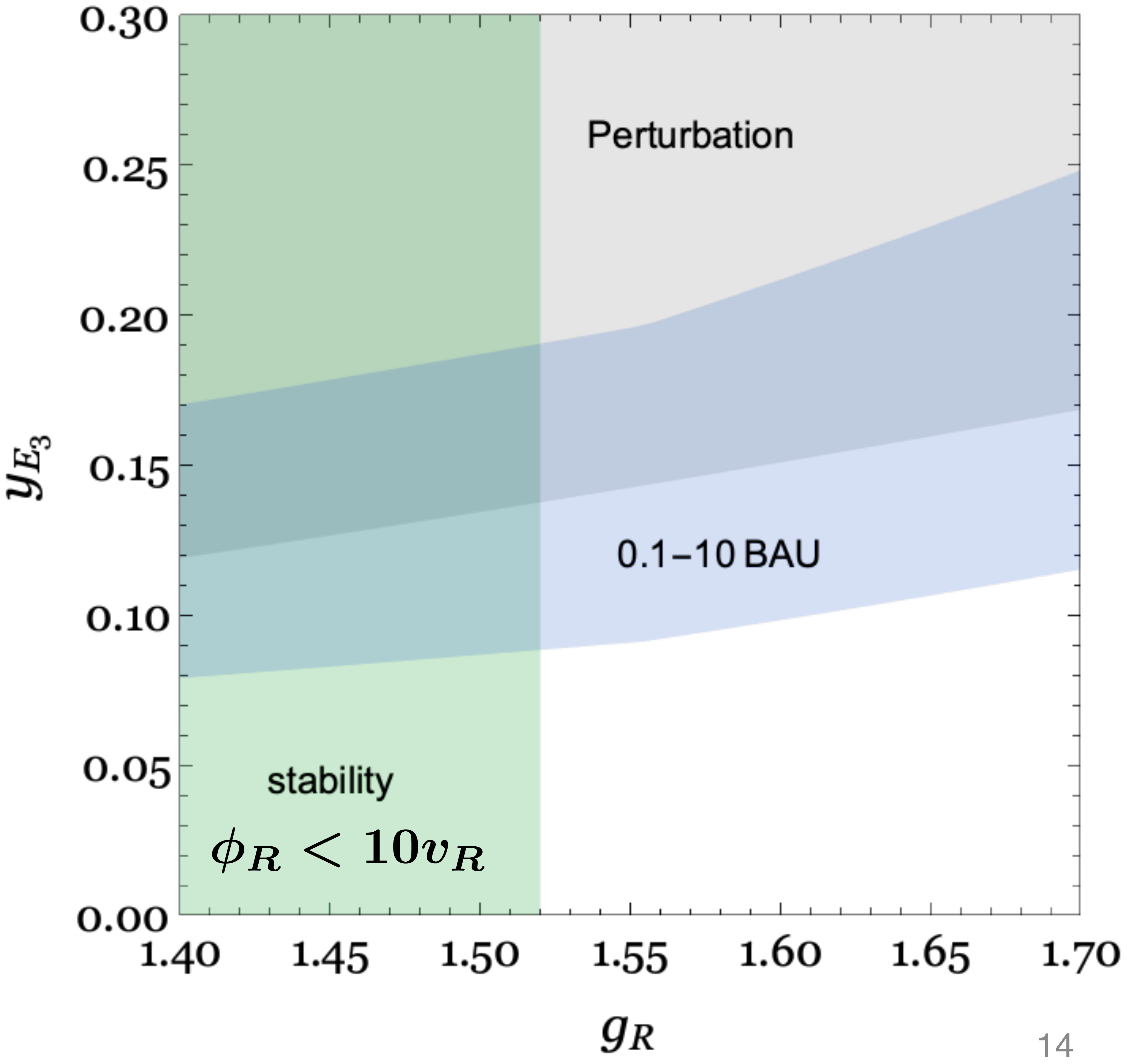
Large Yukawa couplings can generate the observed BAU !

Result

$$g_R = 1.55,\ \lambda_R = 0.014,\ \tilde{g}_E = 1.17\ v_w = 0.48$$
$$J' = 0.08,\ y_{N_1} = 0.03,\ y_{N_2} = 0.89,\ y_{N_3} = 1.35$$



$$y_{E_1} = 0.1 y_{E_2},\ \lambda_R = 0.014,\ J' = 0.08,$$
$$y_{N_1} = 0.03,\ y_{N_2} = 0.89,\ y_{N_3} = 1.35\ v_w = 0.48$$



Phenomenology (1): Collider constraints

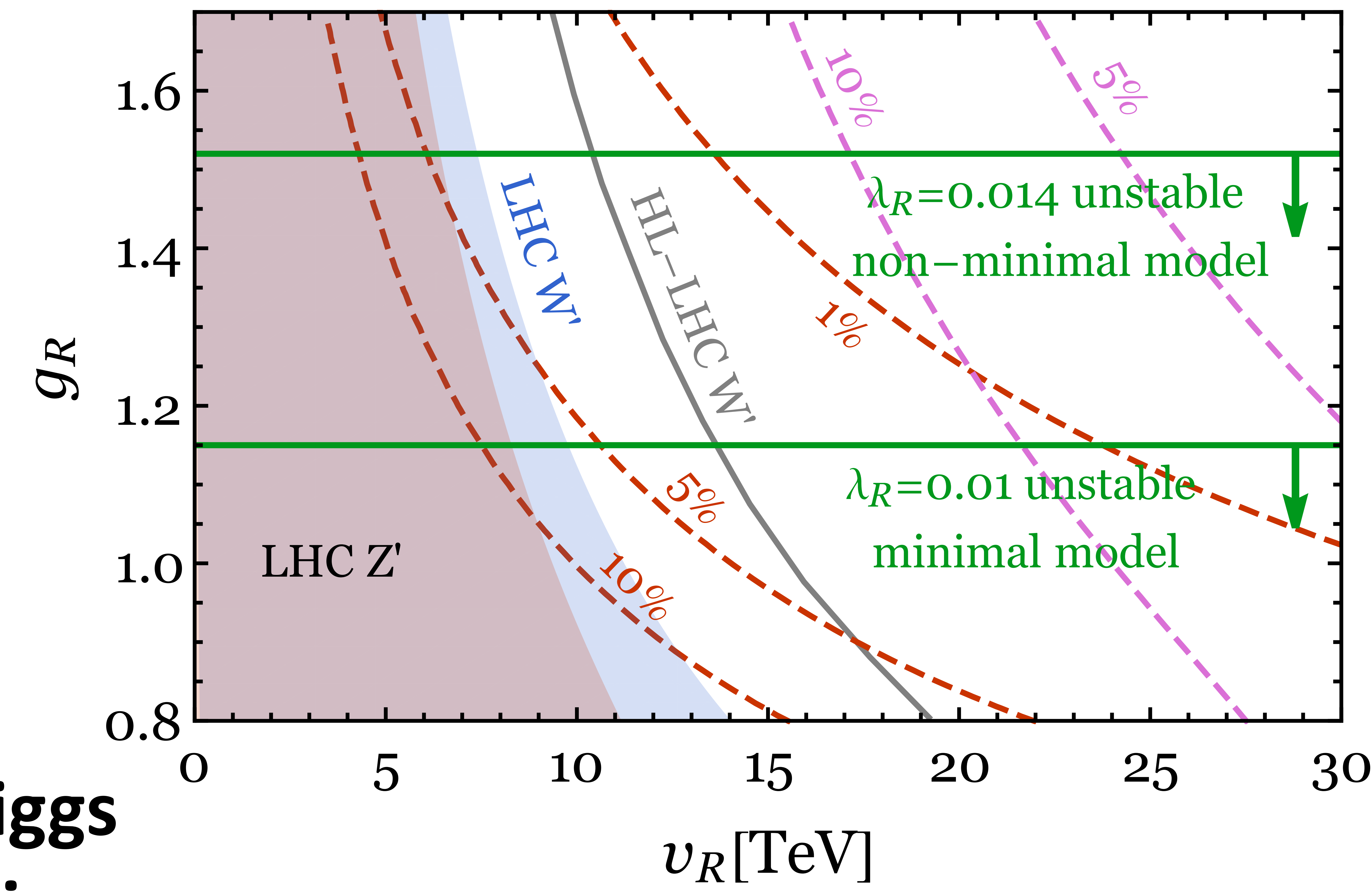
- New gauge bosons Z', $W_R^{\pm}$ are produced by colliders and decay into pair of SM fermions.

$v_R \gtrsim 15\ \mathrm{TeV}$ is required!

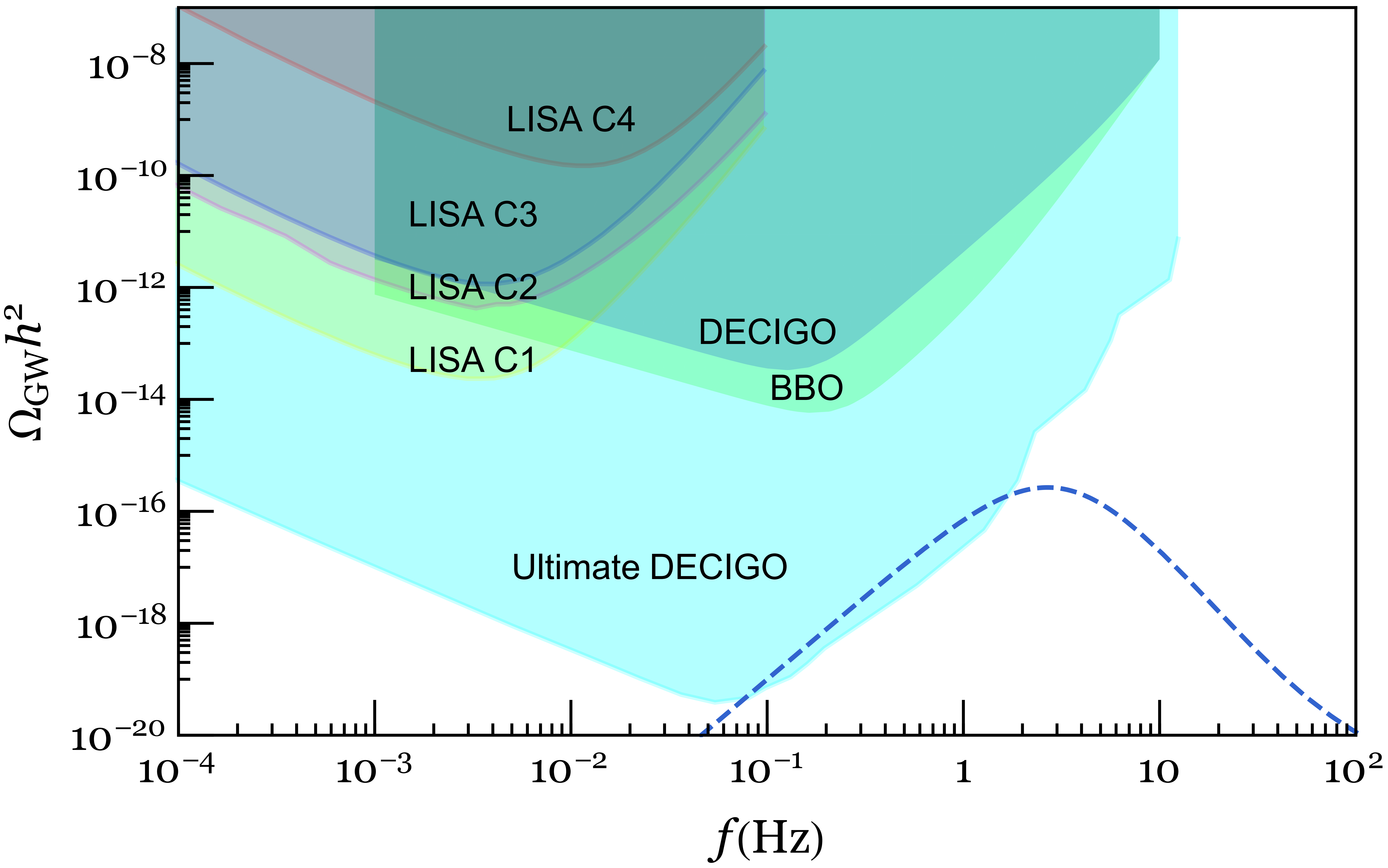
- Below green solid line, the Higgs potential is unstable at $\phi_R < 10 v_R$.

- Radiative corrections to the SM Higgs mass from Z', $W_R^{\pm}$ require a fine-tuning.

$H_L(1, 2, 1, \frac{1}{2})$ $\Phi(1, 2, 2, 0)$



Phenomenology (2): The GW spectrum



Phenomenology (3): Dark Matter candidate?

- N_1 lepton is singlet under the SM gauge group, and hence, it can be dark matter candidate if it is stable.

Z_2 symmetry: $(\boldsymbol{L_i}, \bar{\boldsymbol{E}}_i, \bar{\boldsymbol{N}}_i) \to -(\boldsymbol{L_i}, \bar{\boldsymbol{E}}_i, \bar{\boldsymbol{N}}_i)$

- With this Z_2 symmetry, BAU may be generated.

$$\mathcal{L}_R = y_E^{ij} H_R \bar{L}_i E_j + y_N^{ij} H_R^\dagger \bar{L}_i N_j + y_{\mathcal{E}} H_R \widetilde{L}\, \bar{\mathcal{E}} + y_{\mathcal{X}} H_R^\dagger \widetilde{L}\, \bar{\mathcal{X}} + \text{h.c.}$$

$$\mathcal{L}_{\text{int}} = \underline{g_{\bar{\mathcal{E}}}^i H_L \ell_i\, \bar{\mathcal{E}}} + \cancel{g_E^{ij} H_R \bar{\ell}_i E_j + g_N^{ij} H_R^\dagger \bar{\ell}_i N_j} + \text{h.c.},$$

E and N asymmetries are transferred into $\mathcal{E}$ asymmetry.

Then, $\mathcal{E}$ asymmetry is transferred into the SM lepton asymmetry!

Ongoing work!

Conclusion

- **EWBG needs an additional CP violation, which is stringently constrained by the EDM measurement.**

- **We consider a first-order phase transition associated with new chiral gauge symmetry breaking occurring at around 10TeV scale.**

- **Our model can produce the observed baryon asymmetry.**