Gravitational wave generation by B-L symmetry breaking

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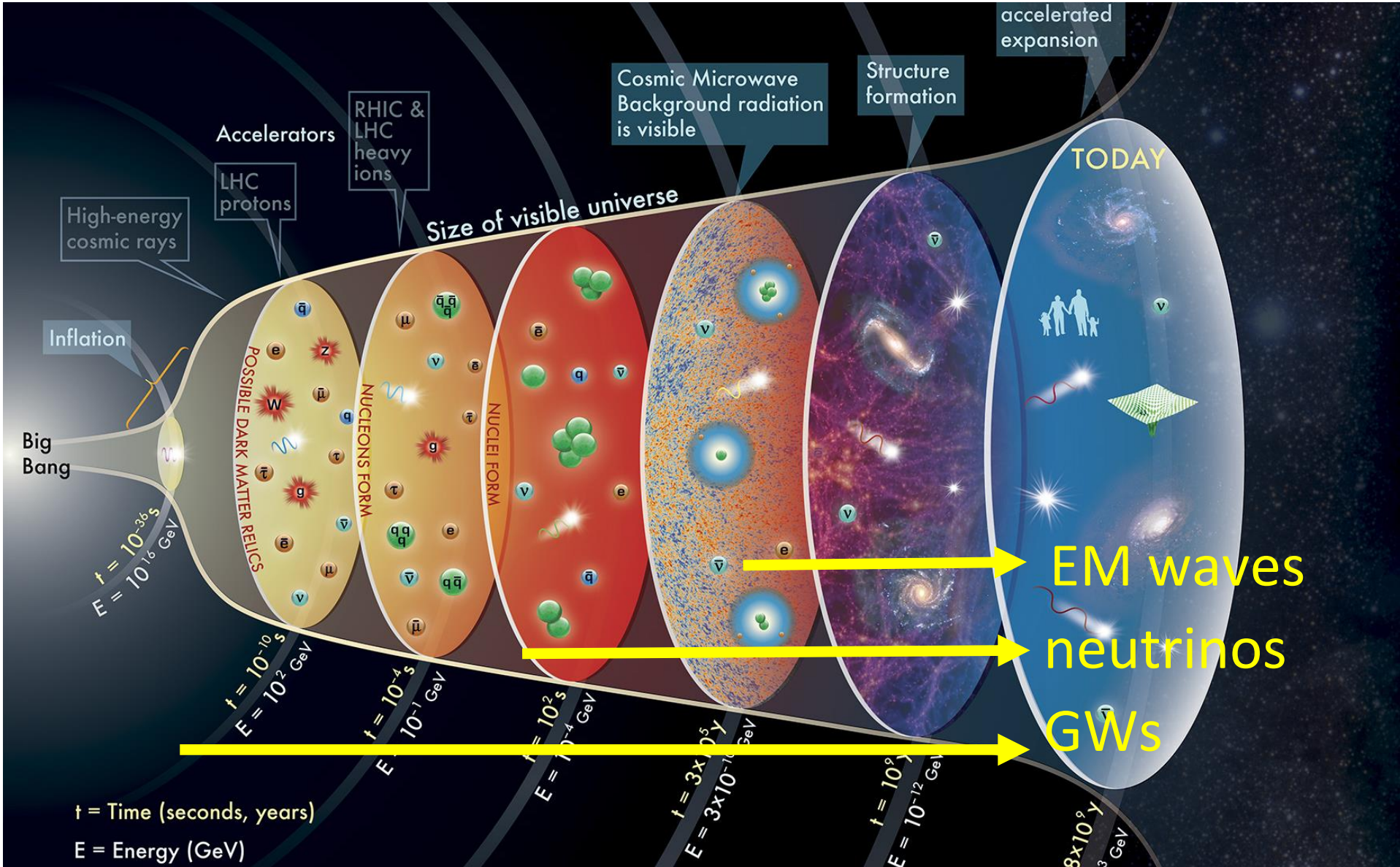
§ Introduction

The most penetrable

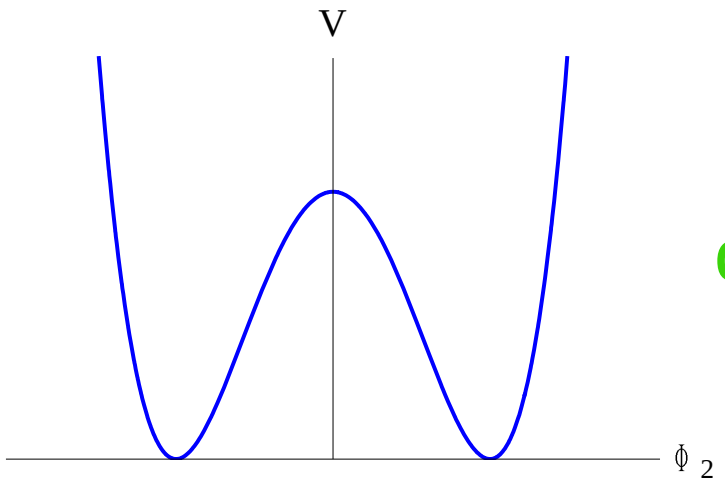


Phase transitions in the early Universe

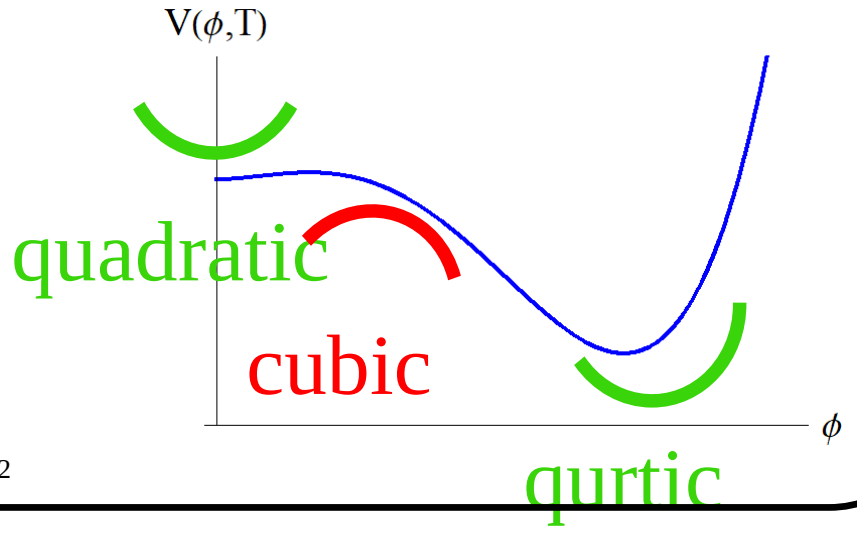
Energy time

Transition ? EW QCD

2nd order



To be 1st order



Nonvanishing neutrino mass

- Neutrino oscillation

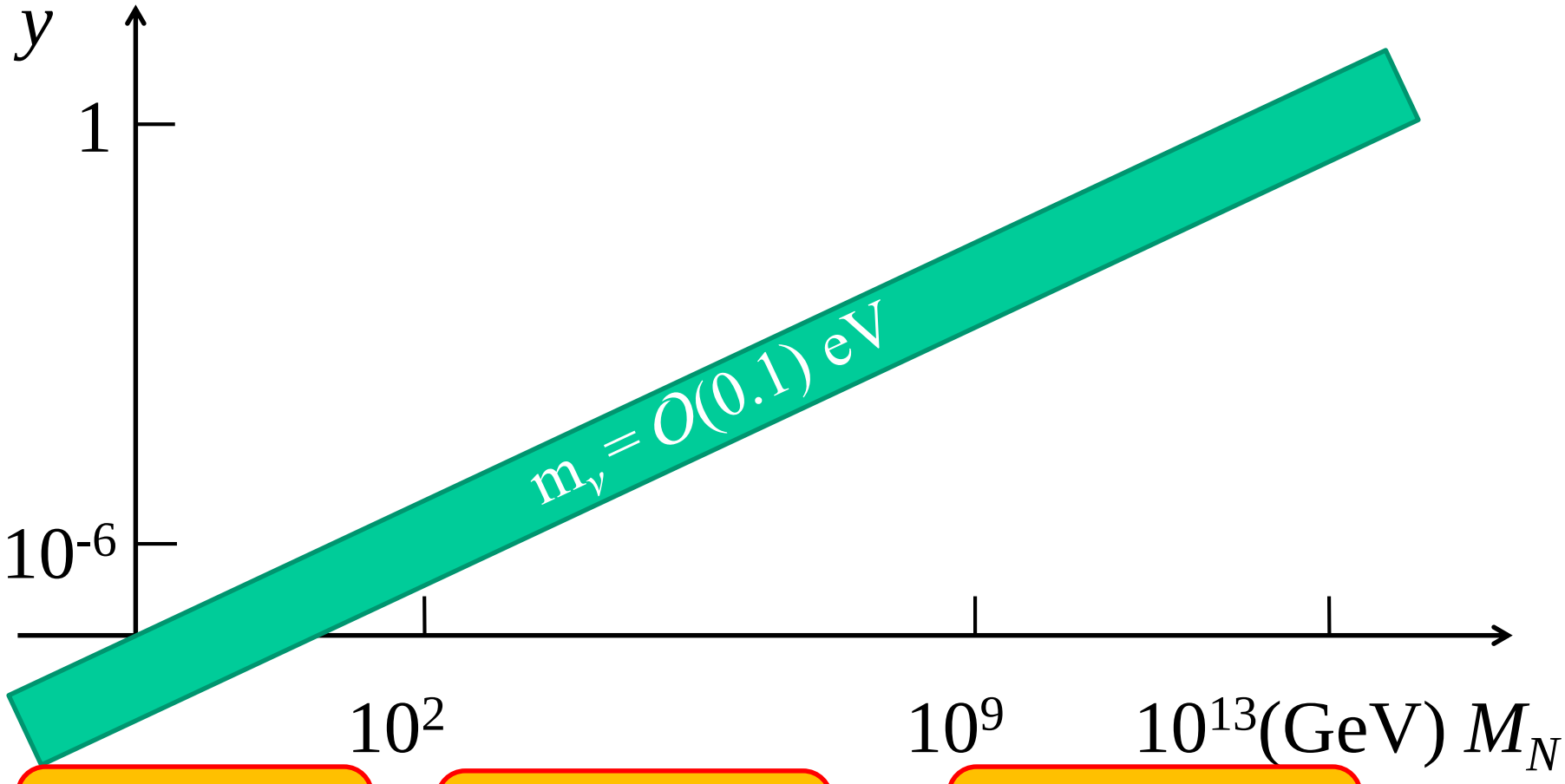
  $\longrightarrow$ tiny (< 0.1 eV) but massive neutrino
- No mass in the renormalizable SM

- **Seesaw mechanism** for Majorana neutrino

  [Yanagida, Gell-Mann et al (1979)]

$$\begin{pmatrix} 0 & yv \\ yv & M_N \end{pmatrix} \rightarrow \begin{pmatrix} -(yv)^2/M_N & 0 \\ 0 & M_N \end{pmatrix}$$

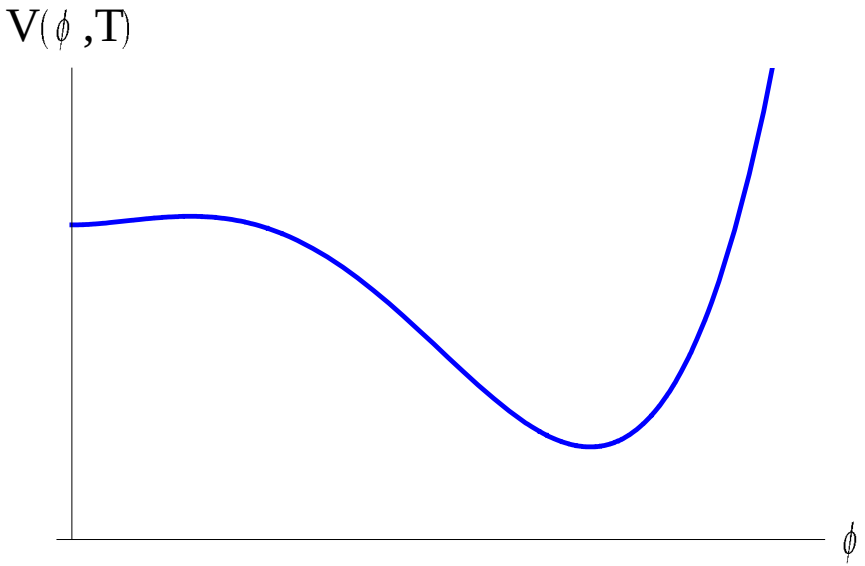
M_N in Cosmology: Baryogenesis



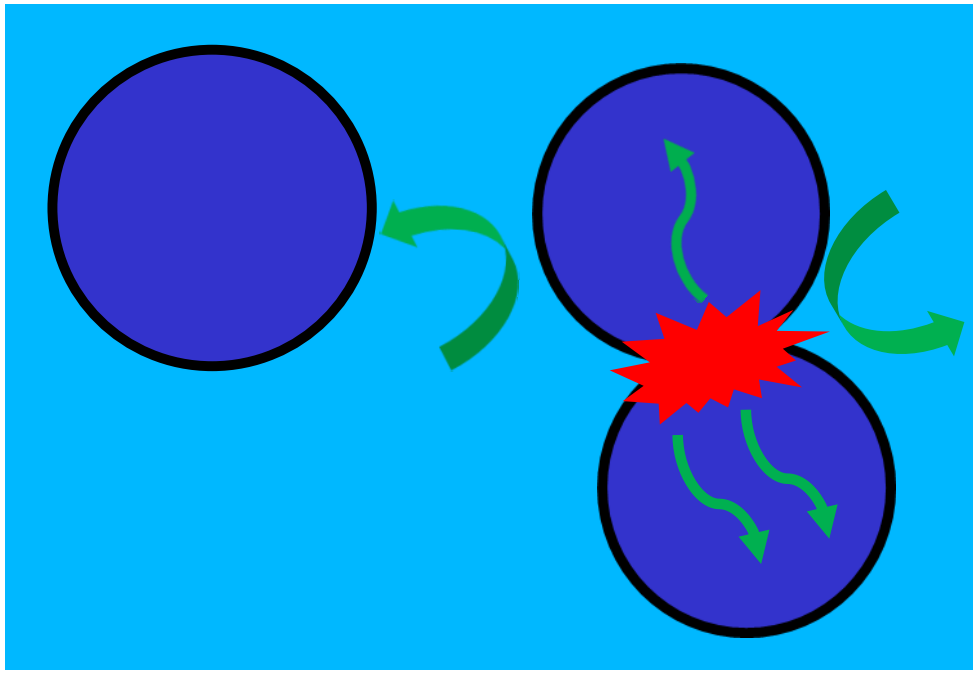
§ GW

GW from 1st order phase transitions

- Potential barrier and 1st order phase transition



- Bubble formation



- Bubble collision
- Sound waves in the fluid
- Turbulence in the fluid

GWs spectrum

- At radiation dominated Universe
- The energy density of radiation $\rho_{\rm rad} = \frac{\pi^2 g_*}{30} T^4$
- The latent heat density

$$\epsilon = \left(V - T\frac{\partial V}{\partial T} \right)\Big|_{\{\phi_{\rm high}, T_\star\}} - \left(V - T\frac{\partial V}{\partial T} \right)\Big|_{\{\phi_{\rm low}, T_\star\}}$$

$$\alpha \equiv \frac{\epsilon}{\rho_{\rm rad}}$$

- Transition time
  - Bubble nucleation rate $\Gamma(T) = \Gamma_0 e^{-S(T)} \simeq \Gamma_0 e^{-S_E^3(T)/T}$

$$\frac{\beta}{H_\star} \simeq T\frac{dS}{dT}\Big|_{T_\star} = T\frac{d(S_E^3/T)}{dT}\Big|_{T_\star}$$

GWs spectrum

- Bubble collision [Kosowsky and Turner (1993), Huber and Konstandin (2008)]

$$f_{\rm peak} \simeq 17 \left(\frac{f_\star}{\beta}\right) \left(\frac{\beta}{H_\star}\right) \left(\frac{T_\star}{10^8\,{\rm GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6} {\rm Hz},$$

$$h^2\Omega_{GW}(f_{\rm peak}) \simeq 1.7\times 10^{-5}\kappa^2\Delta \left(\frac{\beta}{H_\star}\right)^{-2} \left(\frac{\alpha}{1+\alpha}\right)^2 \left(\frac{g_*}{100}\right)^{-1/3},$$

- Sound waves [Hindmarsh et al (2014, 2015), Caprini et al (2016)]

$$f_{\rm peak} \simeq 19\frac{1}{v_b} \left(\frac{\beta}{H_\star}\right) \left(\frac{T_\star}{10^8\,{\rm GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6} {\rm Hz},$$

$$h^2\Omega_{GW}(f_{\rm peak}) \simeq 2.7\times 10^{-6}\kappa_v^2 v_b \left(\frac{\beta}{H_\star}\right)^{-1} \left(\frac{\alpha}{1+\alpha}\right)^2 \left(\frac{g_*}{100}\right)^{-1/3}.$$

- Turbulence [Kamionkowski et al (1994), Caprini et al (2009)]

$$f_{\rm peak} \simeq 27\frac{1}{v_b} \left(\frac{\beta}{H_\star}\right) \left(\frac{T_\star}{10^8\,{\rm GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6} {\rm Hz},$$

$$h^2\Omega_{GW}(f_{\rm peak}) \simeq 3.4\times 10^{-4} v_b \left(\frac{\beta}{H_\star}\right)^{-1} \left(\frac{\kappa_{\rm turb}\alpha}{1+\alpha}\right)^{3/2} \left(\frac{g_*}{100}\right)^{-1/3}.$$

§ GW from $U(1)_{B-L}$ breaking

$U(1)_{B\text{-}L}$ gauge symmetry

- A simplest anomaly-free U(1) gauge theory
  - Three generations of RH neutrino
  - The origin of RH neutrino masses

$$m_{N_R^i} = \frac{Y_{N^i}}{\sqrt{2}} v_2$$

    - Higgs field with B-L charge "+2" Φ_2
    - $\mathcal{L} = y\, L\, \Phi\, N + \frac{1}{2}\, Y_N\, N\, \Phi_2\, N$

      -1 +2 -1
  - One extra neutral gauge boson

$$M_{Z'}^2 = 4 g_{B-L}^2 v_2^2$$

Model: next to minimal

Content

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	**3**	**2**	1/6	1/3
u_R^i	**3**	**1**	2/3	1/3
d_R^i	**3**	**1**	−1/3	1/3
ℓ_L^i	**1**	**2**	−1/2	−1
e_R^i	**1**	**1**	−1	−1
H	**1**	**2**	−1/2	0
N_R^i	**1**	**1**	0	−1
Φ_1	**1**	**1**	0	+1
Φ_2	**1**	**1**	0	+2

Yukawa interaction

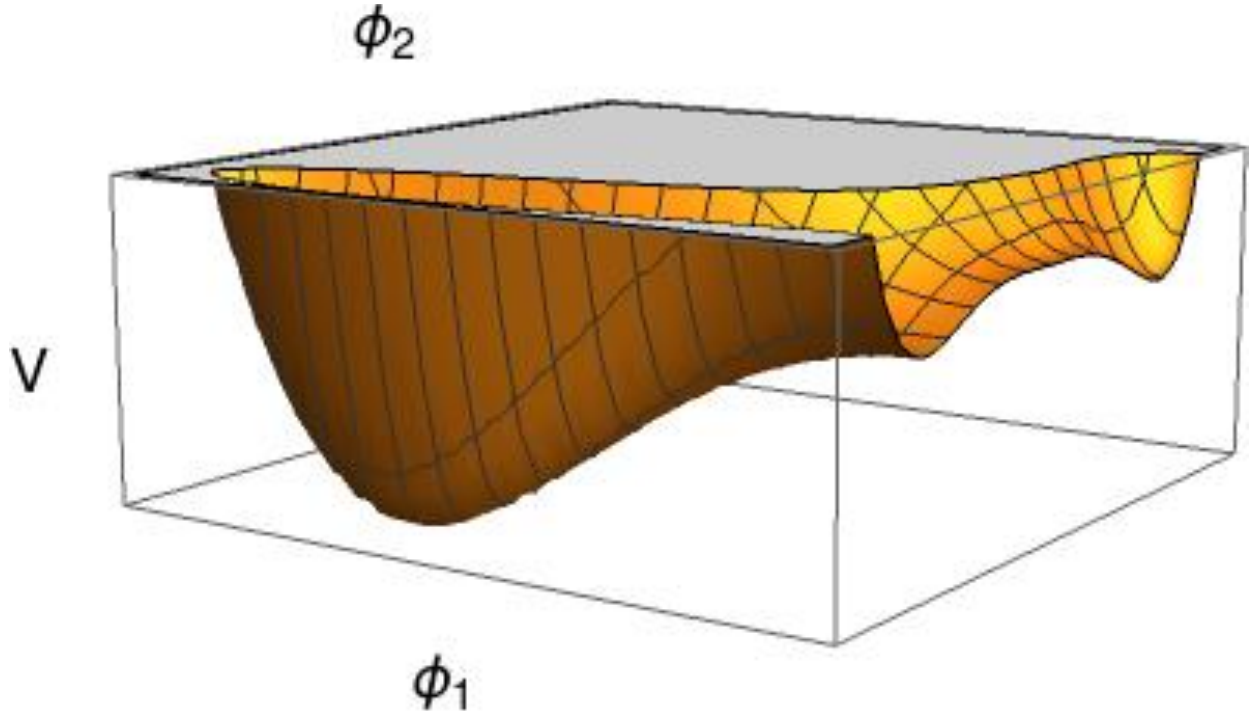
$$\mathcal{L}_{Yukawa} \supset -\sum_{i=1}^{3}\sum_{j=1}^{3} Y_D^{ij}\overline{\ell_L^i} H N_R^j - \frac{1}{2}\sum_{k=1}^{3} Y_{N^k}\Phi_2\overline{N_R^{k\ C}}N_R^k + \text{H.c.}$$

Higgs potential

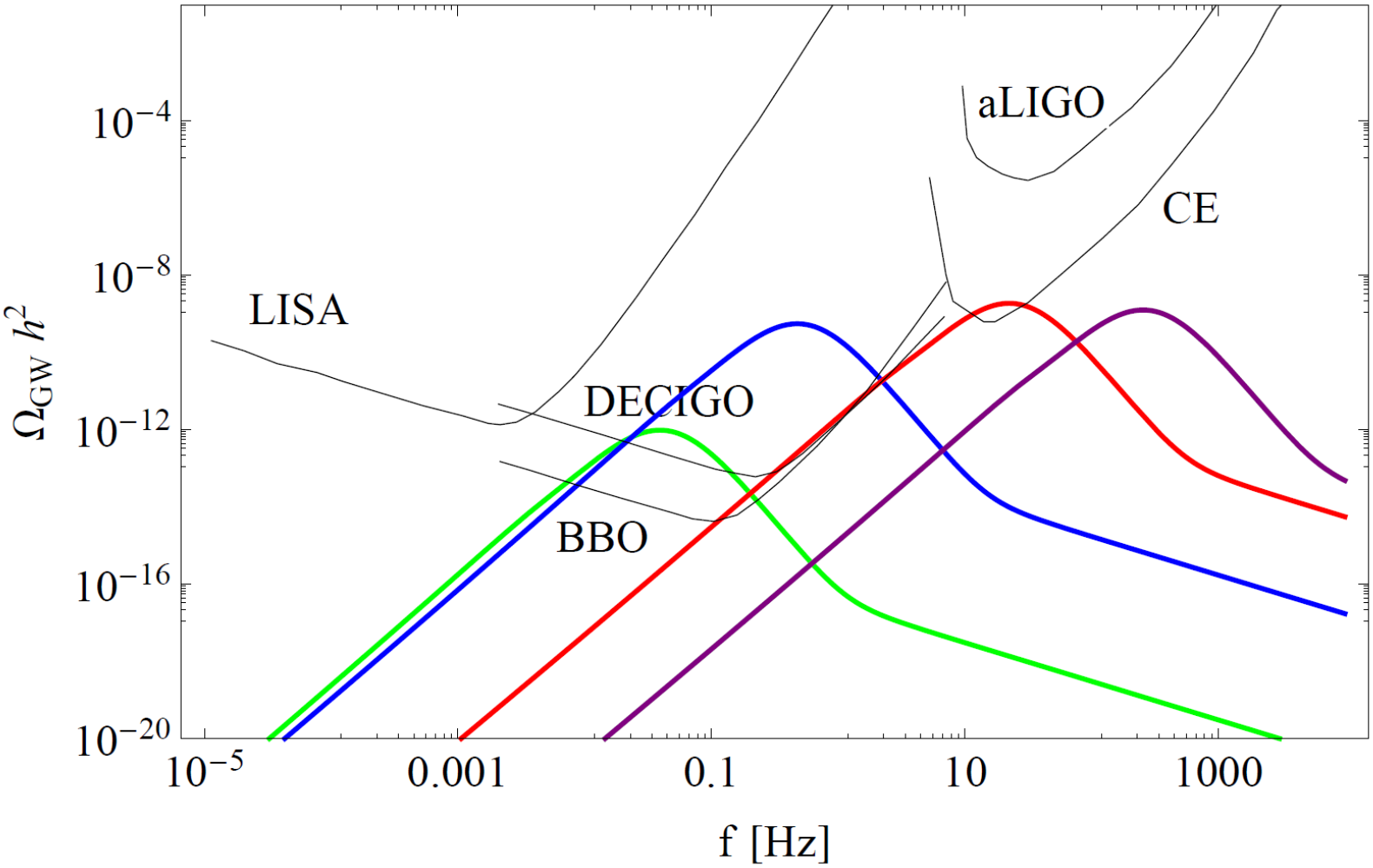
$$V(\Phi_1,\Phi_2) = \frac{1}{2}\lambda_1(\Phi_1\Phi_1^\dagger)^2 + \frac{1}{2}\lambda_2(\Phi_2\Phi_2^\dagger)^2 + \lambda_3\Phi_1\Phi_1^\dagger(\Phi_2\Phi_2^\dagger)$$
$$+ M_{\Phi_1}^2\Phi_1\Phi_1^\dagger - M_{\Phi_2}^2\Phi_2\Phi_2^\dagger - A(\Phi_1\Phi_1\Phi_2^\dagger + \Phi_1^\dagger\Phi_1^\dagger\Phi_2).$$

Higgs potential

$$V(\Phi_1,\Phi_2) = \frac{1}{2}\lambda_1(\Phi_1\Phi_1^\dagger)^2 + \frac{1}{2}\lambda_2(\Phi_2\Phi_2^\dagger)^2 + \lambda_3\Phi_1\Phi_1^\dagger(\Phi_2\Phi_2^\dagger)$$
$$+ M_{\Phi_1}^2\Phi_1\Phi_1^\dagger - M_{\Phi_2}^2\Phi_2\Phi_2^\dagger - A(\Phi_1\Phi_1\Phi_2^\dagger + \Phi_1^\dagger\Phi_1^\dagger\Phi_2).$$



GW spectrum



$v\ (=v_1=v_2) = 4,\ 10^2,\ 10^4,\ 10^5$ TeV

§ Summary

- The scale of gauged B-L symmetry could be probed by GWs
  - RH neutrino masses:
    - maybe much higher than the EW scale
  - ~~B-L~~ may be strong 1st order
  - Sources of cosmological GWs from an intermediate scale phase transition
    - Thermal history of the Universe
    - Implication to Baryogenesis
    - Inaccessible high scale particle physics for colliders
- Caveat
  - Gauge dependence problem [e.g., Chiang and Senaha (2017)]