Gravitational Wave Pathway for Testable Leptogenesis

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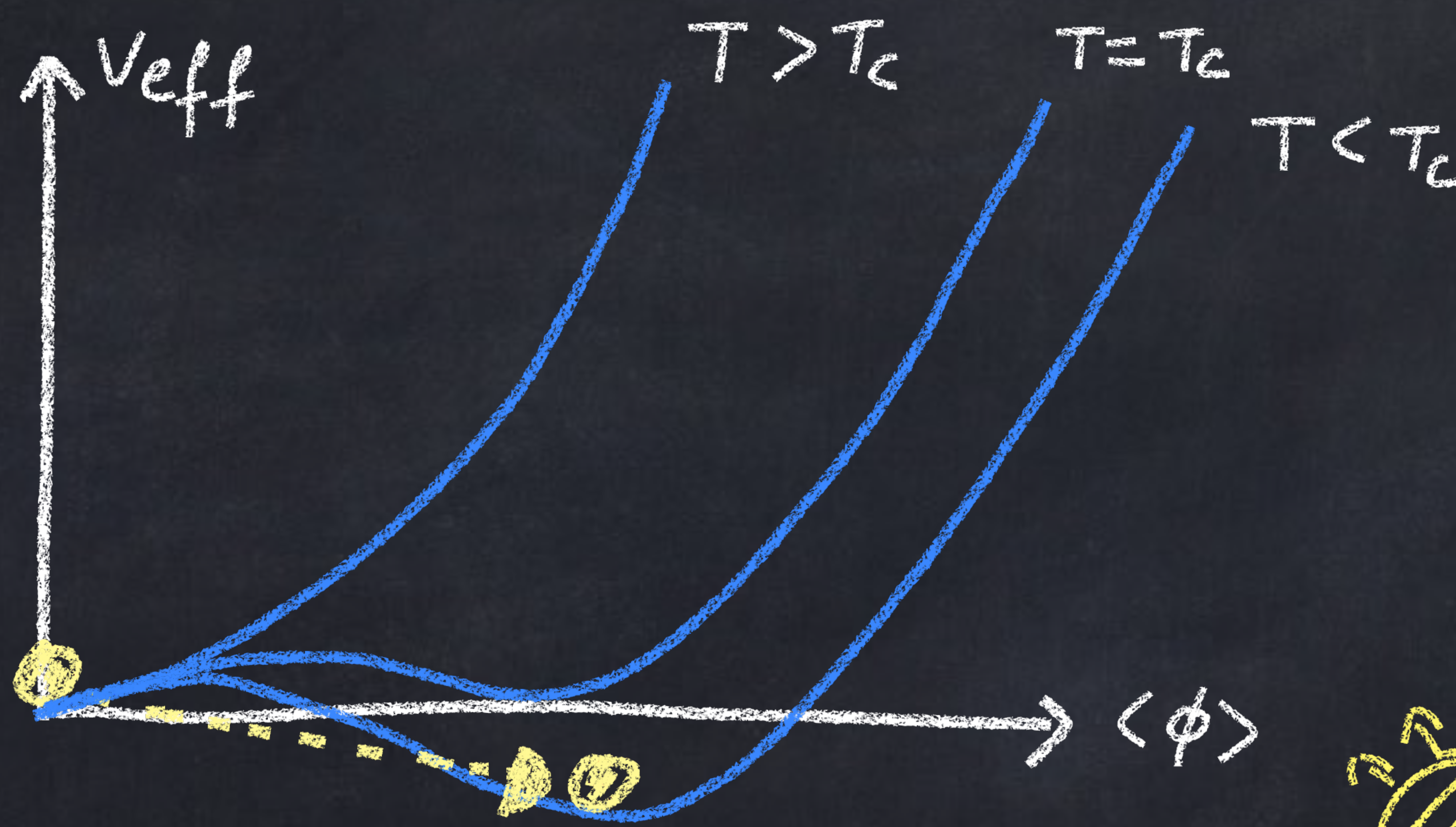
Outline

- Gravitational Wave from Strongly First-Order Phase transition
- Classically scale invarient paradigm
- Matter-Antimatter Asymmetry
  - $U(1)_{B-L}$ conformal Model
- Asymmetry via Mass-Gain mechanism.
- Results

Sources for Stochastic GW

- Emission of GW from Cosmic strings
- From the collision of unstable domain walls
- Production of GW during or after inflation
  - Due to extra particle Production.
  - Quantum fluctuations.
- From Strongly First-order Phase transitions.

First-Order Phase transition



- First-order phase transition proceeds through bubble nucleation

- One of the sources of Gravitional Wave is from Bubble Collision [Kosowski et. al. 1992]

- The other two sources are
  - Sound waves of the plasma [Hindmarsh et. al. 2004]
  - Turbulance of the plasma [Kamionkowski et. al. 1993]

Contribution to the GW

Sounb wave contribution

$$\Omega_{GW} h^2 \simeq \underbrace{\Omega_{\phi} h^2}_{\text{Bubble Collision}} + \overbrace{\Omega_{sw} h^2}^{\text{Sound wave contribution}} + \underbrace{\Omega_{turb} h^2}_{\text{Contribution from Magnetic Hydrodynamics}}$$

Bubble Collision

Contribution from Magnetic Hydrodynamics

Parameters

- α is proportional to the change in the trace of the energy-momentum tensor, ΔT^{μ}_{μ}, across the phase transition

$$\alpha = \frac{1}{\rho_\gamma^*}\left[\left(\rho_V\Big|_{false} - \rho_V\Big|_{true}\right) - \frac{T}{4}\left(\frac{\partial \rho_V}{\partial T}\Big|_{false} - \frac{\partial \rho_V}{\partial T}\Big|_{true}\right)\right]_{T=T_*}$$

ρ_V → temperature-dependent effective potential

ρ_γ^* → energy density of relativistic radiation

$T_* :=$ Nucleation/Percolation temperature

- β/H_* : Inverse of the duration of the phase transition in units of the Hubble time H_*^{-1} at the time GW production.

$$\frac{\beta}{H_*} = T_* \frac{dS}{dT}\Big|_{T=T_*}$$

In case of strong supercooling (i.e for $T_n \ll T_*$)

$$\frac{\beta}{H_*} = \frac{H_n}{H_*} T_n \frac{dS}{dT}\Big|_{T=T_n}$$

Parameters

- v_w: Bubble wall velocity

- κ_i : Fraction of the released vacuum energy that are converted into energy of
  - $i=b$: Scalar-field gradients
  - $i=s$: Sound waves
  - $i=t$: turbulence

κ_s & κ_t are expressed in terms of κ_{kin}

$\kappa_s = \kappa_{kin}$; $\kappa_t = \epsilon \, \kappa_{kin}$ ($\epsilon \to 0.1$)

These efficiency depends on type of phase transition

a) Non-runaway phase transitions in a plasma (NP) $\alpha \ll 1$

b) Runaway phase transitions in a plasma (RP) $\alpha \sim \mathcal{O}(10)$

c) Runaway phase transitions in vacuum (RV) $\alpha \to \infty$

Observables

- The three contribution can be parametrized in a model independent way

$$\Omega_b(f)h^2 = \Omega_b^{peak}h^2 \, \mathcal{S}_b(f,f_b)$$

$$\Omega_b^{peak}h^2 \simeq 1.67\times10^{-5}\left(\frac{v_w}{\beta/H_*}\right)^2\left(\frac{100}{g_*(T_*)}\right)^{1/3}\left(\frac{\kappa_b\alpha}{1+\alpha}\right)^2\left(\frac{0.11v_w}{0.42+v_w^2}\right)$$

$$\Omega_s(f)h^2 = \Omega_s^{peak}h^2 \, \mathcal{S}_s(f,f_s)$$

$$\Omega_s^{peak}h^2 \simeq 2.65\times10^{-6}\left(\frac{v_w}{\beta/H_*}\right)\left(\frac{100}{g_*(T_*)}\right)^{1/3}\left(\frac{\kappa_s\alpha}{1+\alpha}\right)^2$$

$$\Omega_t(f)h^2 = \Omega_t^{peak}h^2 \, \mathcal{S}_t(f,f_t)$$

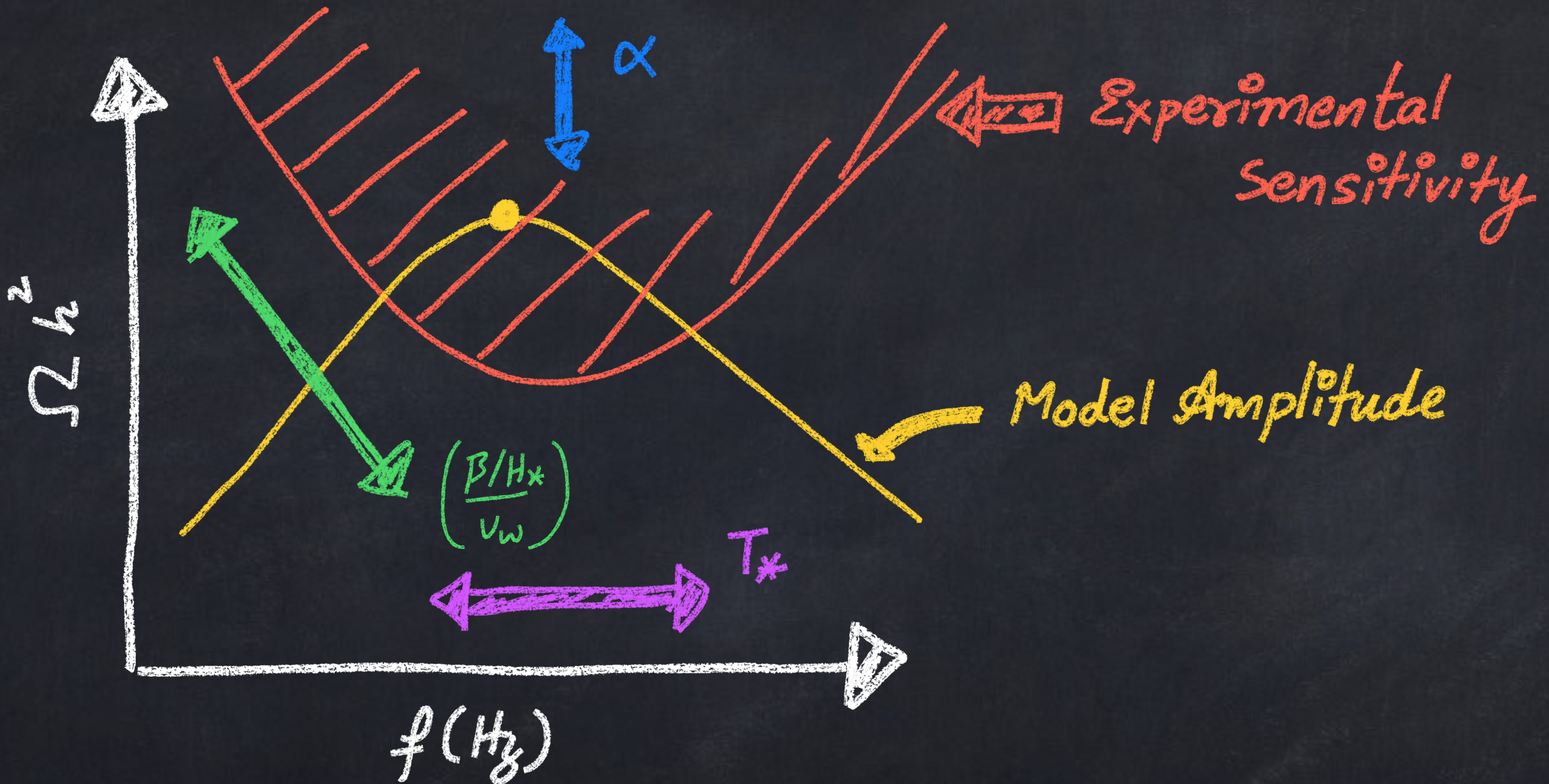
$$\Omega_t^{peak}h^2 \simeq 3.35\times10^{-4}\left(\frac{v_w}{\beta/H_*}\right)\left(\frac{100}{g_*(T_*)}\right)^{1/3}\left(\frac{\kappa_t\alpha}{1+\alpha}\right)^{3/2}$$

$$f_b = 1.6\times10^{-2}\,\text{mHz}\left(\frac{g_*(T_*)}{100}\right)^{1/6}\left(\frac{T_*}{100\,\text{GeV}}\right)\left(\frac{\beta/H_*}{v_w}\right)\left(\frac{0.62v_w}{1.8-0.1v_w+v_w^2}\right)$$

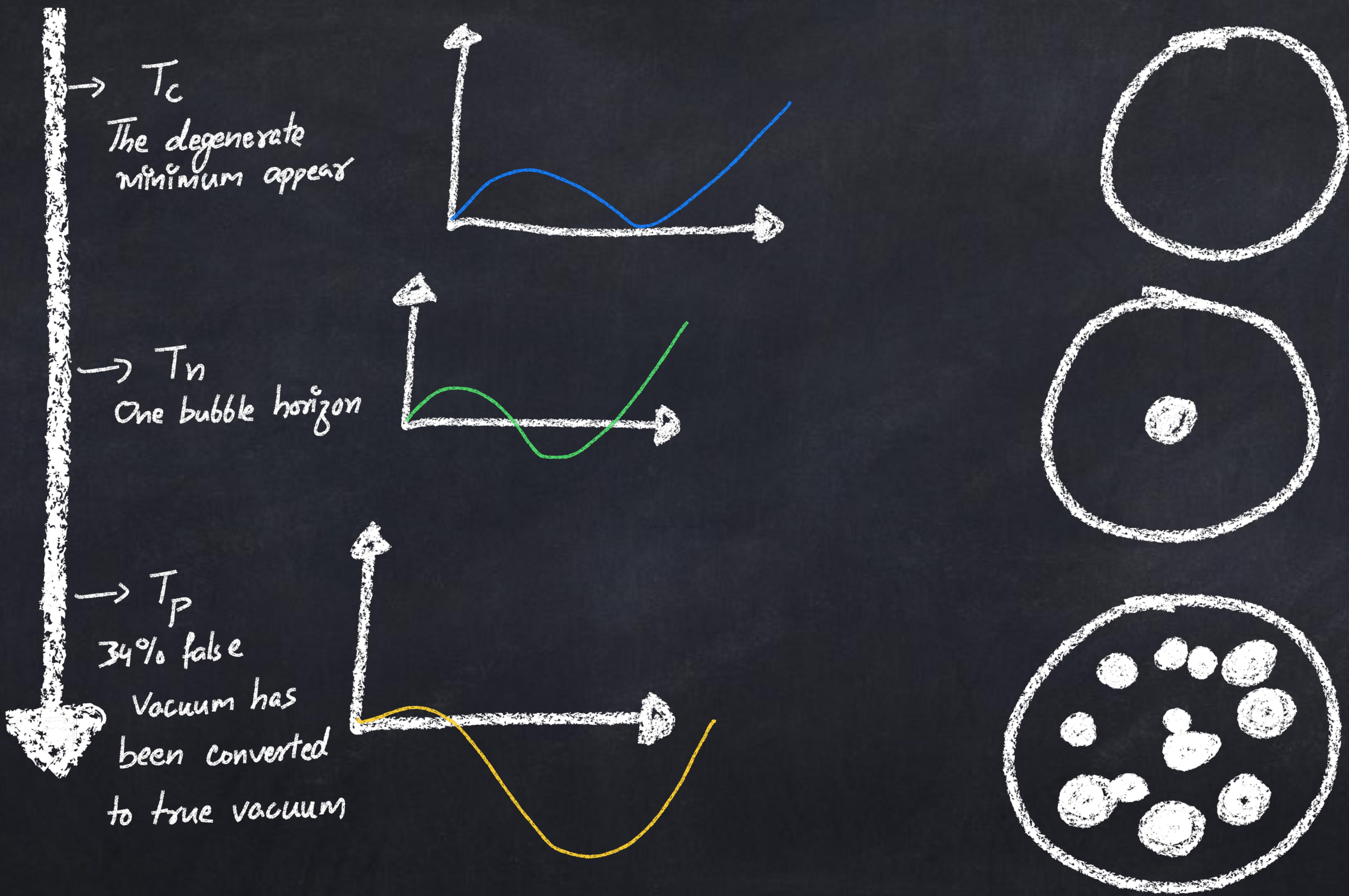
$$f_s = 1.9\times10^{-2}\,\text{mHz}\left(\frac{g_*(T_*)}{100}\right)^{1/6}\left(\frac{T_*}{100\,\text{GeV}}\right)\left(\frac{\beta/H_*}{v_w}\right)$$

$$f_t = 2.7\times10^{-2}\,\text{mHz}\left(\frac{g_*(T_*)}{100}\right)^{1/6}\left(\frac{T_*}{100\,\text{GeV}}\right)\left(\frac{\beta/H_*}{v_w}\right)$$

Amplitude Behavior



Characteristic Temperature



Classical scale Invarient Paradigm

- The basic zero temperature potential is

$$V_{tree} = \lambda_H |H|^4 + \lambda |\Phi|^4 - \lambda' |\Phi|^2 |H|^2$$

  - The running of the quartic coupling λ breaks the gauge symmetry $\langle \Phi \rangle = \frac{M}{\sqrt{2}}$

- The total effective potential can be schematically divided into the following form:

$$V_{tot} = V_{tree} + \underbrace{V_{CW}}_{\text{one-loop Coleman-Weinberg potential}} + V_{th}$$

V_{th} } thermal effective potential

$$V_0 = V_{tree} + V_{CW} = \frac{1}{4} \lambda(t)\, G^4(t)\, \phi^4 \quad : \quad t = \log(\phi/\mu)$$

$$G = e^{-\int_0^t dt' \gamma(t')} \qquad \gamma(t) = -\frac{a_2}{32\pi^2} g_D^2(t)$$

Classical scale Invarient Paradigm

- The running of the gauge coupling $g_D(t)$ and quartic coupling $\lambda(t)$ is given as

$$\frac{d\alpha_D(t)}{dt} = \frac{b}{2\pi}\alpha_D^2(t) \qquad \alpha_D = \frac{g_D^2}{4\pi} \; ; \; \alpha_\lambda = \frac{\lambda}{4\pi}$$

$$\frac{d\alpha_\lambda(t)}{dt} = \frac{1}{2\pi}\left(a_1\alpha_\lambda^2(t) + 8\pi\alpha_\lambda(t)\gamma(t) + a_3\alpha_D^2(t)\right)$$

- Now, taking the renormalization scale μ to be M, the condition $\left.\frac{dV}{d\phi}\right|_{\phi=M} = 0$ lead us to

$$a_1\alpha_\lambda(0)^2 + a_3\alpha_D(0)^2 + 8\pi\alpha_\lambda(0) = 0 \qquad -①$$

Classical scale Invarient Paradigm

- The running can be solved analytically, the scalar potential can be given by

$$V_0(\phi,t) = \frac{\pi\,\alpha_\lambda(t)}{\left(1-\frac{b}{2\pi}\alpha_D(0)\,t\right)^{a_2/b}}\,\phi^4$$

where

$$\alpha_D(t) = \frac{\alpha_D(0)}{1-\frac{b}{2\pi}\alpha_D(0)\,t} \; ; \; \alpha_\lambda(t) = \frac{a_2+b}{2a_1}\alpha_D(t) + \frac{A}{a_1}\alpha_D(t)\tan\left[\frac{A}{b}\ln\left[\alpha_D(t)/\pi\right] + C\right]$$

$$A \equiv \left[a_1 a_3 - (a_1+b)^2/4\right]^{1/2}$$

Determined from eq (1) (for C)

$$V_{tot}(\phi,t) = V_0(\phi,u) + V_T(\phi,T)$$

↳ $u \equiv \log(\Lambda/M)$ where $\Lambda \equiv \mathrm{Max}(\phi,T)$

$$V_T(\phi,T) = V_{th} + V_{daisy}(\phi,T)$$

$$\begin{cases} V_{th} = \sum_i \frac{n_{Bi}}{2\pi^2} T^4 J_B\left[\frac{M_{Bi}}{T}\right] \\ V_{daisy}(\phi,T) = -\sum_i \frac{g_i T}{12\pi}\left[M_i^3(\phi,T) - M_i^3(\phi)\right] \end{cases}$$

Classical scale Invarient Paradigm

- The action S_3 can be easily evaluated from the effective potential at sufficiently low temperature i.e $T \ll M$

$$V_{tot} \simeq \frac{g_D^2(t')}{2} T^2 \phi^2 + \frac{\lambda_{eff}(t')}{4} \phi^4$$

with $$\lambda_{eff}(t') = \frac{4\pi \alpha_\lambda(t')}{\left(1 - \frac{b}{2\pi}\alpha_D(0)t'\right)^{a_2/b}} \qquad t' = \ln(T/M)$$

$$S = \frac{S_3}{T} - 4\ln(T/M) \quad ; \quad \frac{S_3}{T} \simeq -9.45 \frac{g_D(t')}{\lambda_{eff}(t')}$$

- And the decay width is given as:

$$\Gamma(T) \simeq M^4 \exp(-S(T)) ; \quad S(T) \equiv S_3(T)/T - 4\log(T/M)$$

Classical scale Invarient Paradigm

VI $U(1)_{B-L}$

$b = 12$

$a_1 = 10$

$a_3 = 48$

$a_2 = 24$

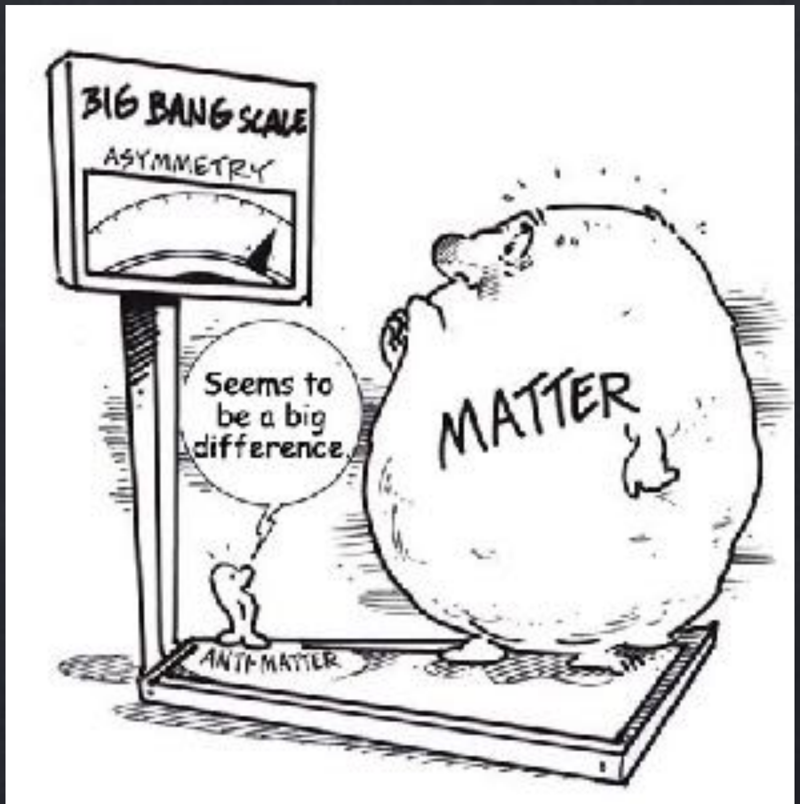
	$SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
N	$(1, 0, -1)$
ϕ	$(1, 0, 2)$

$$V = \lambda_H |H|^4 + \lambda |\Phi|^4 - \lambda' |\Phi|^2 |H|^2$$

$$\mathcal{L}_y \supset - Y_D H^\dagger L_i N - Y_N \Phi N N + h.c$$

One of the Problems in the SM

- The Standard Model does not explain the present asymmetry.
  1. The CP violation coming from Jarlskog invarient is of the order 10^{-20}.
  2. The experimental lower bound on the Higgs mass implies the transition is not strongly first order.



Baryon Asymmetry of the Universe

- The observed BAU is often quoted in terms of baryon to photon ratio

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.04 \pm 0.08 \times 10^{-10}$$

- The prediction for this ratio from Big Bang Nucleosynthesis (BBN) agrees well with the observed value from Cosmic Microwave Background Radiation (CMBR) measurements (Planck, arXiv:1502.01589).

Kinds of Mechanism in generating Asymmetry

- Baryogenesis from Decay/Scattering
- Baryogenesis from Electroweak Phase Transitions
- Spontaneous Baryogenesis
- ... (Affleck-Dine, Gravitational Baryogenesis, etc.)

Sakharov's Conditions

- The three basic ingredients necessary to generate a net baryon asymmetry from an initially baryons symmetric Universe (Sakharov 1967):

1) Baryon Number (B) violation $X \to Y + B$

2) C and CP violation

$$\Gamma(X \to Y + B) \neq \Gamma(\bar{X} \to \bar{Y} + \bar{B})$$

3) Deperature from thermal Equilibrium.

Additional Subtleties on asymmetry

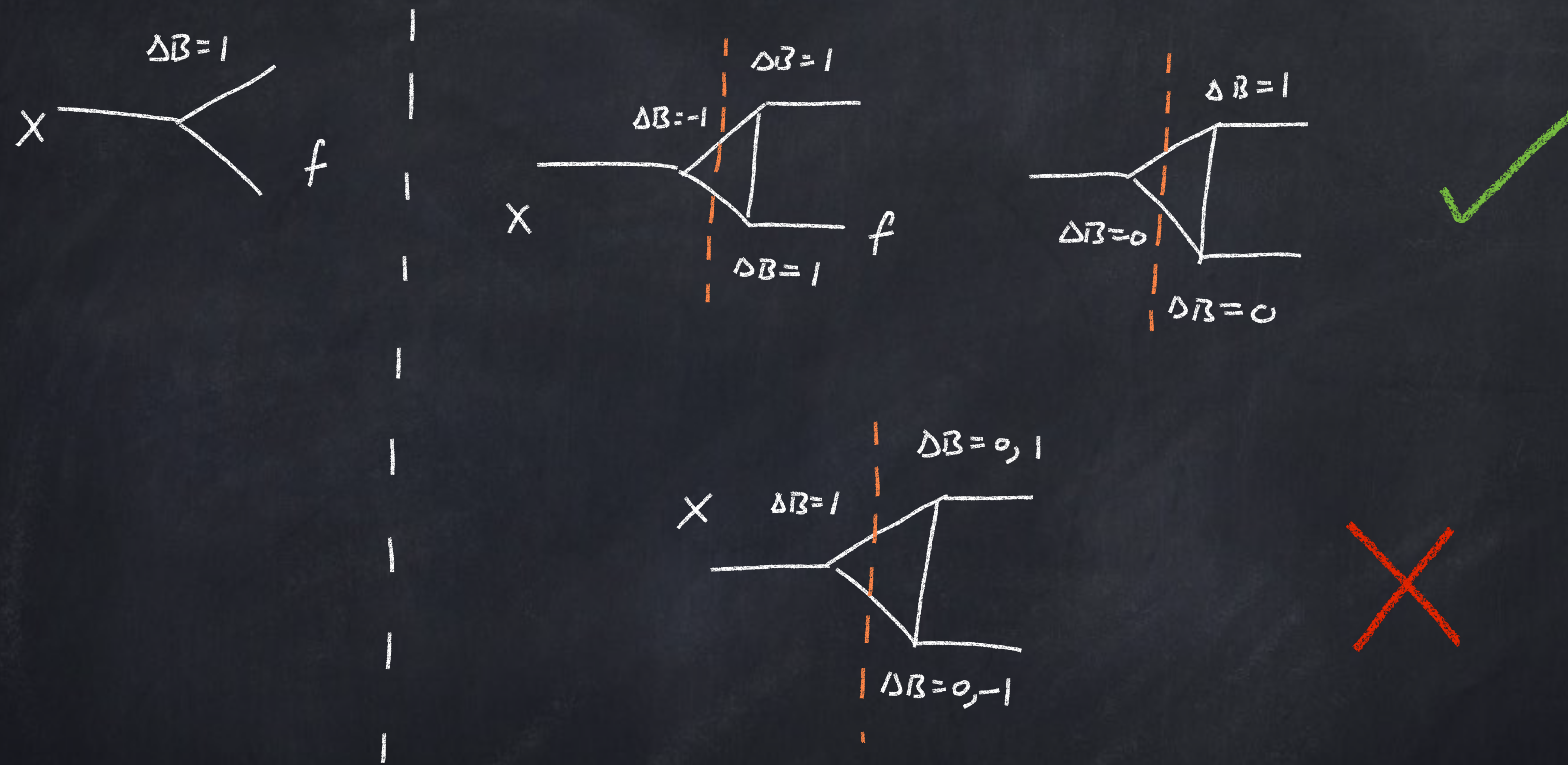
- Additional to the Sakharov's conditions one needs to take care of two more important issues.

  1. In order to get asymmetry one needs to be sure to have atleast 2 $\not{B}$* coupling in the loop diagram.

  2. The 2 $\not{B}$ violating coupling should be to the right of the "cut" of the loop.

* this is necessary if the decaying (scattering) particle(s) does not have any other channel. If it does have a channel without the $\not{B}$ coupling then one needs only 1 coupling in the loop.

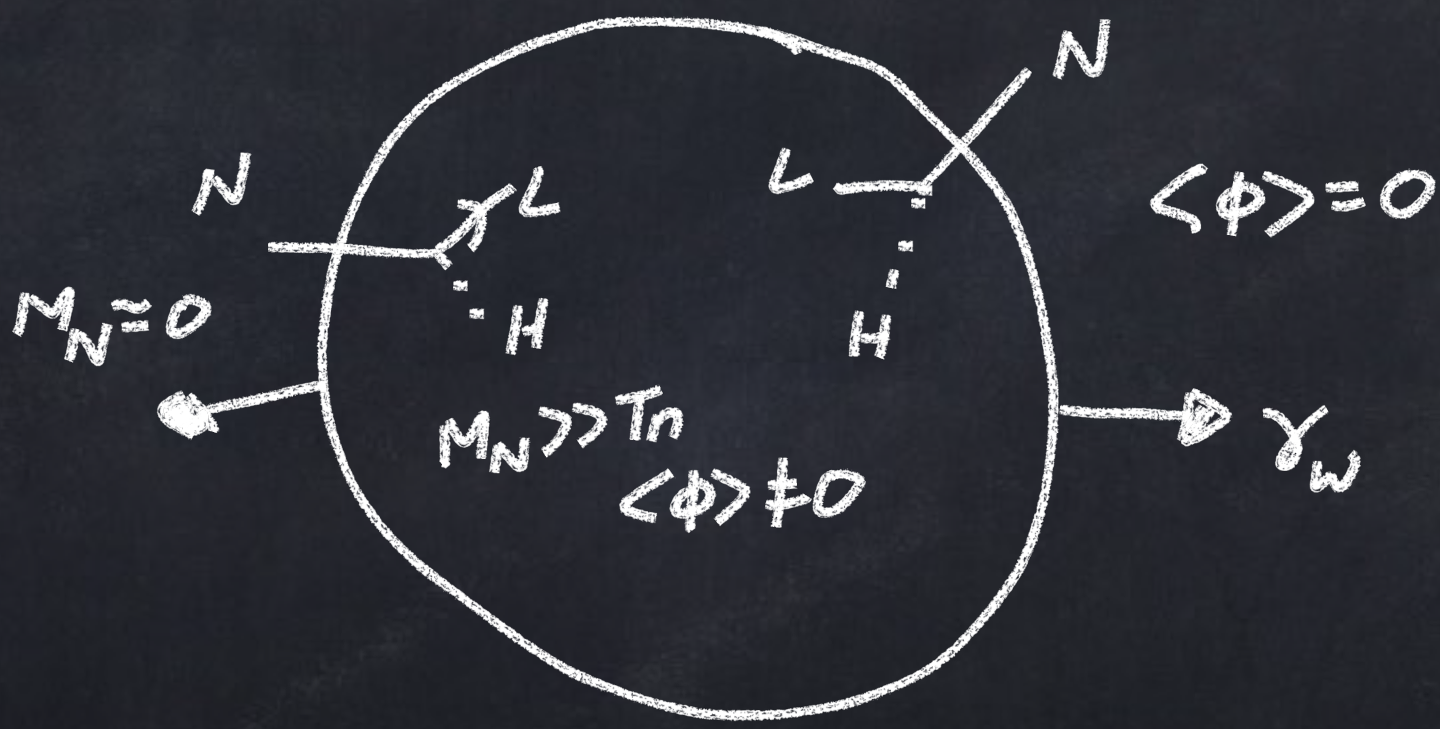
Which Diagrams this Applies?



Leptogenesis in Conformal B-L

[Phys Rev D, 104, 115029]

- The leptogenesis **does not** occur $T > T_n$
- Schematically



- Subject to sufficiently high Lorentz factor $\gamma_w > M_N / T_n$

Leptogenesis in Conformal B-L

[Phys Rev D, 104, 115029]

Basic Mechanism

In thermal equilibrium prior to the Phase transition (PT)

$$Y_N \equiv \frac{135}{8\pi^4}\zeta(3)\frac{g_N}{g_*}$$

- Now, provided the Lorentz boost of the wall $\gamma_w > M_N/T_n$, the Y_N is maintained across the bubble wall.

- The N's are then out of equilibrium, massive, and can decay in a CP and B-L violating way

$$\frac{Y_B}{Y_B^{obs}} = \epsilon_N \, K_{sph.} \, \frac{Y_N}{Y_B^{obs}} \left(\frac{T_n}{T_{RH}}\right)^3$$

Leptogenesis in Conformal B-L

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$$\frac{Y_B}{Y_B^{obs}} = \epsilon_N \, \kappa_{sph.} \frac{Y_N}{Y_B^{obs}} \left(\frac{T_n}{T_{RH}}\right)^3 \Rightarrow$$

takes care into account the entropy production from reheating following PT

Leptogenesis in Conformal B-L

[Phys Rev D, 104, 115029]

Basic Mechanism

- The wash-out from Inverse decay is given as

$$\Gamma_{ID} \approx \frac{3y^2}{16\pi} M_N \left(\frac{M_N}{T_{RH}}\right)^{3/2} Exp\left[-\frac{M_N}{T_{RH}}\right]$$

which is safely below H provided

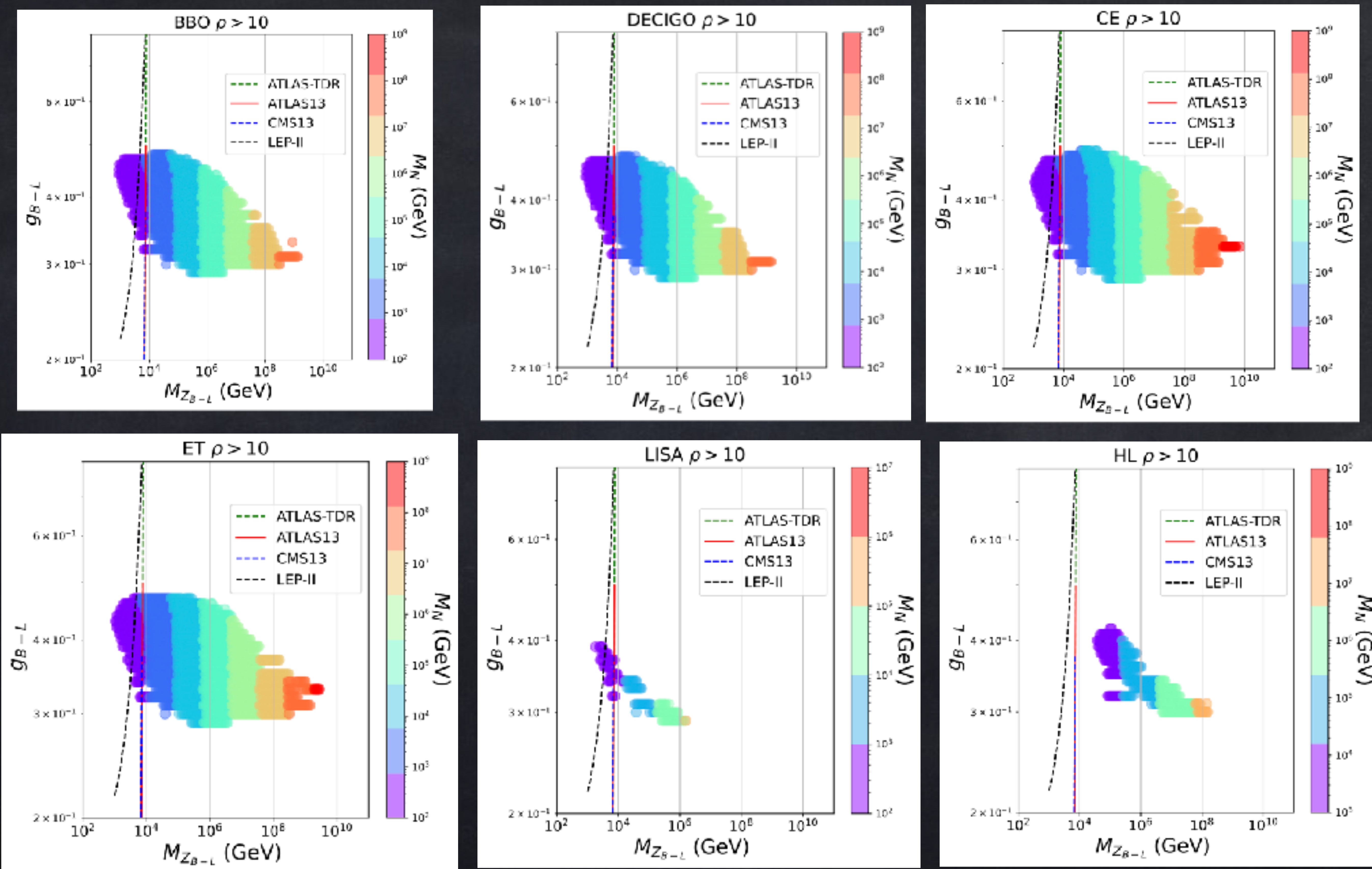
$$\frac{M_N}{T_{RH}} \gtrsim Log\left[\frac{y^2}{8\pi}\frac{M_{Pl}}{T_{RH}}\left(\frac{M_N}{T_{RH}}\right)^{5/2}\right]$$

Results

- The plausibility for detecting the Gravitational Wave (GW) is by calculating the signal-to-noise ratio (SNR)

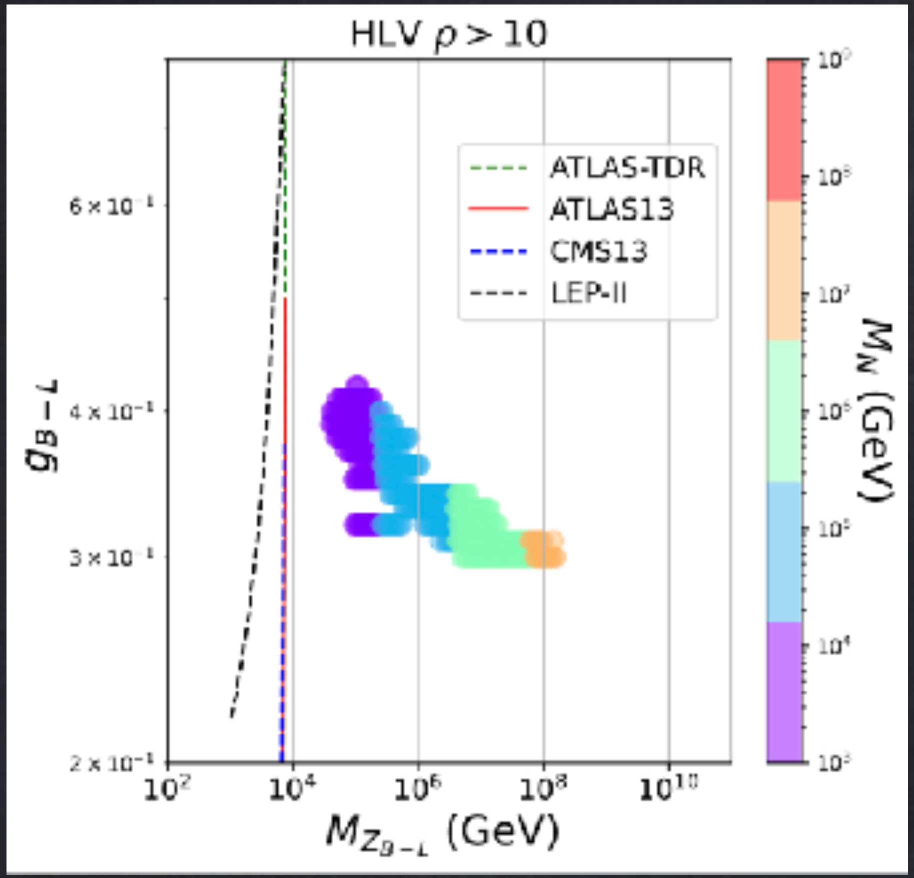
$$\rho = \left[t_{obs} \int_{f_{min}}^{f_{max}} df \left(\frac{\Omega_{signal}(f)}{\Omega_{noise}(f)} \right) \right]$$

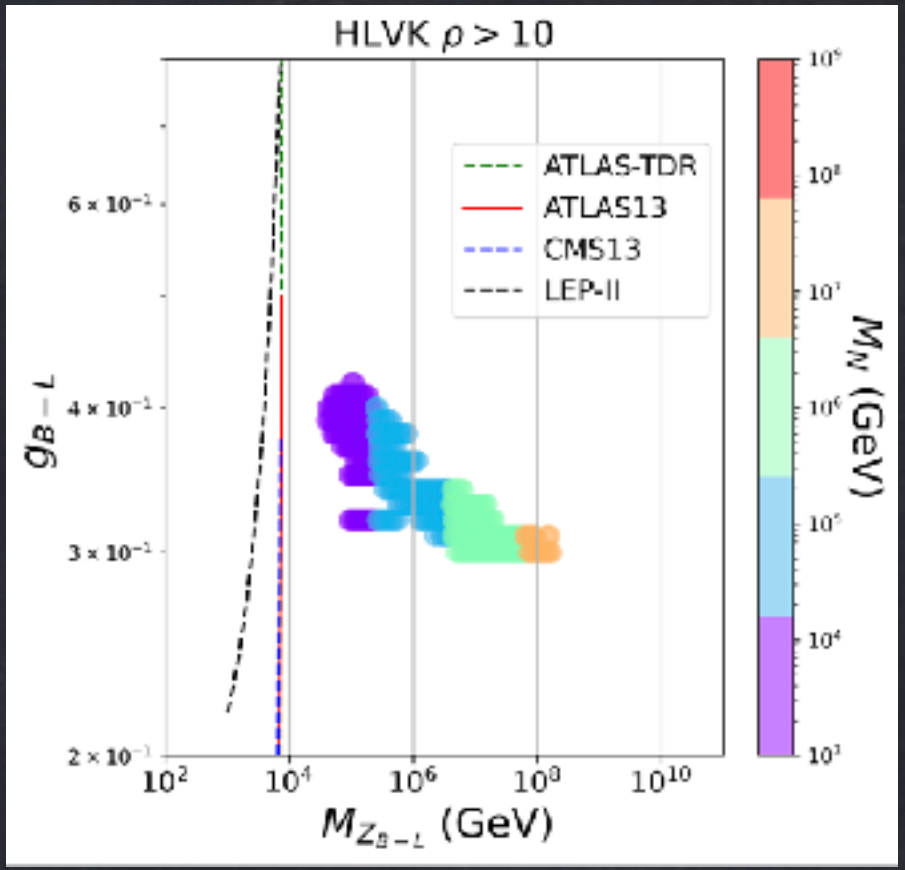
Results

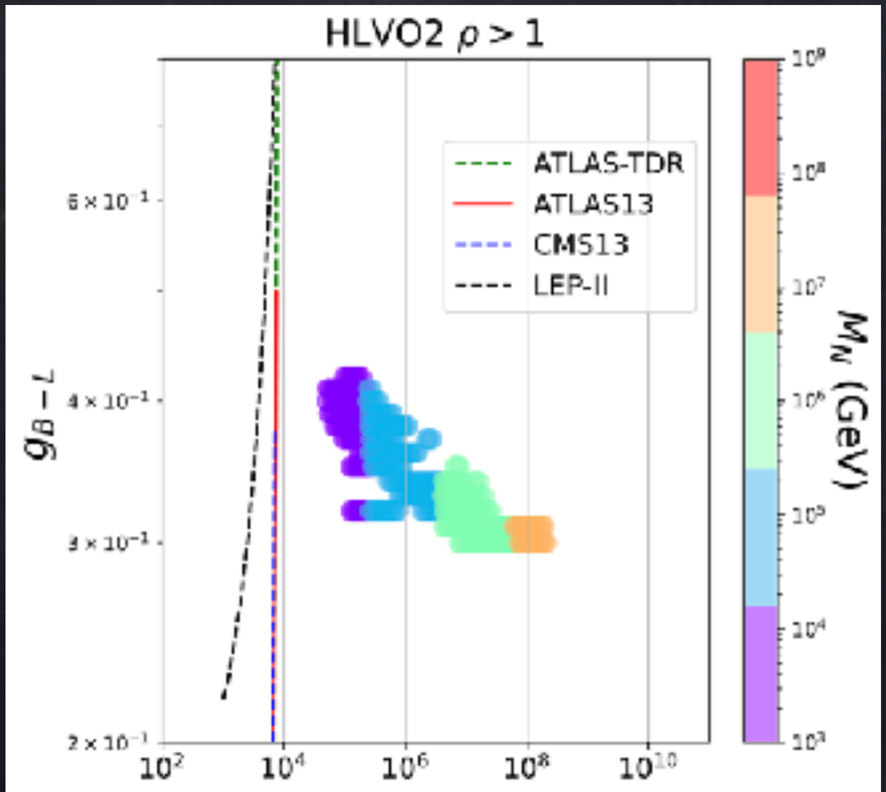


BBO $\rho > 10$
DECIGO $\rho > 10$
CE $\rho > 10$
ET $\rho > 10$
LISA $\rho > 10$
HL $\rho > 10$
ATLAS-TDR
ATLAS13
CMS13
LEP-II
g_{B-L}
$M_{Z_{B-L}}$ (GeV)
M_N (GeV)

Results

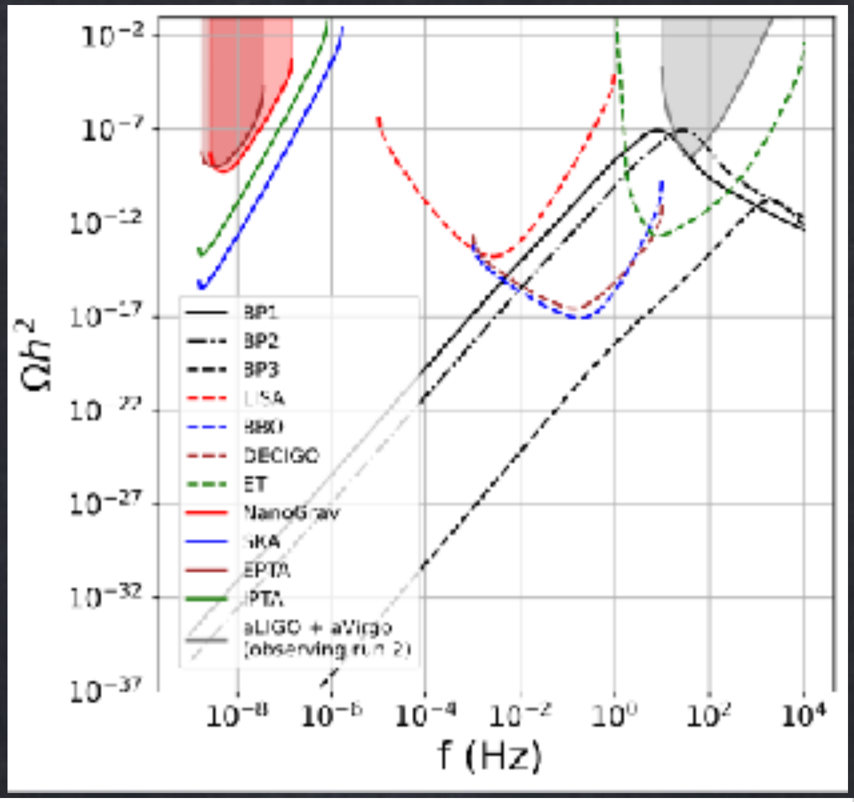

HLV $\rho > 10$
ATLAS-TDR
ATLAS13
CMS13
LEP-II
g_{B-L}
$M_{Z_{B-L}}$ (GeV)
M_N (GeV)

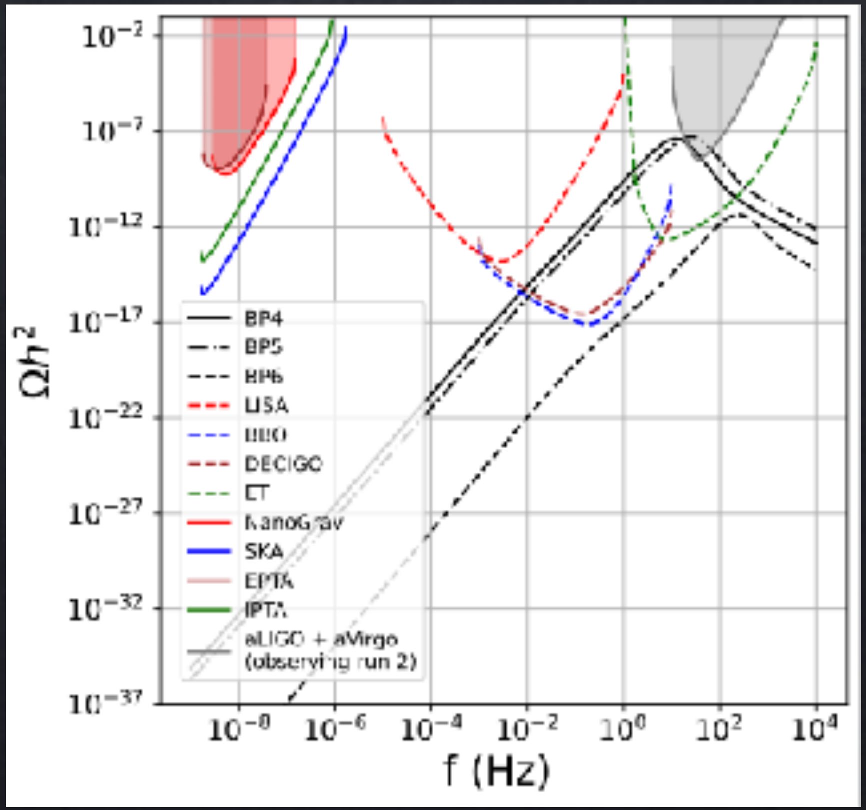

HLVK $\rho > 10$
ATLAS-TDR
ATLAS13
CMS13
LEP-II
g_{B-L}
$M_{Z_{B-L}}$ (GeV)
M_N (GeV)


HLVO2 $\rho > 1$
ATLAS-TDR
ATLAS13
CMS13
LEP-II
g_{B-L}
M_N (GeV)

Results

	α_{B-L}	v_{B-L}
BP1	0.0065	10^6 GeV
BP2	0.0087	10^6 GeV
BP3	0.02	10^6 GeV
BP4	0.0061	10^5 GeV
BP5	0.012	10^5 GeV
BP6	0.02	10^5 GeV





Thank You!!