Gravitational waves from the first-order phase transition as probe of Leptogenesis

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Hearing beyond the standard model with cosmic sources of Gravitational Waves
30 December 2024 to 10 January 2025 at ICTS, Bengaluru.

1. Motivation
2. Leptogenesis from Heavy Scalar Decay
3. Gravitational Waves From FOPT
4. Results-GW as a probe of Leptogenesis
5. Summary

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- We need to look at the Cosmological prospective...

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- We consider GW that are produced from First Order Phase Transition
- We assume after the phase transition, a heavy scalar ϕ dominates the energy budget of the Universe.

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- As the T_{RH} of the Universe passes mass scale of right-handed neutrino M_N, *i.e.*, $T_{RH} < M_N$, it behaves as a non-relativistic.

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- As the T_{RH} of the Universe passes mass scale of right-handed neutrino M_N, *i.e.*, $T_{RH} < M_N$, it behaves as a non-relativistic.
- **Sakharov conditions:(i)B (or L) number violation, (ii) C and CP violation, (iii) Departure from thermal equilibrium.

Boltzmann Equations-Leptogenesis

$$
\begin{aligned}
\frac{d\rho_\phi}{dt} + 3H\rho_\phi &= -\Gamma_\phi^{NN}\,\rho_\phi - \Gamma_\phi^{R}\,\rho_\phi \\
\frac{d\rho_R}{dt} + 4H\rho_R &= \Gamma_\phi^{R}\,\rho_\phi + \Gamma_N(\rho_N - \rho_N^{eq}) \\
\frac{d\rho_N}{dt} + 3H\rho_N &= \Gamma_\phi^{NN}\,\rho_\phi - \Gamma_N(\rho_N - \rho_N^{eq}) \\
\frac{dn_{B-L}}{dt} + 3H\,n_{B-L} &= \frac{\epsilon}{M_N}\Gamma_N(\rho_N - \rho_N^{eq}) - \Gamma_{\rm ID}\,n_{B-L}
\end{aligned}
$$

$$
\Gamma_\phi^{NN} = \frac{|\lambda|^2}{4\pi} M_\phi \left(1 - \frac{4M_N^2}{M_\phi^2}\right)^{\frac{3}{2}}, \Gamma_\phi^{R} = \frac{|\lambda_R|^2}{4\pi M_\phi},\ \Gamma_{(N\to L+{\rm H})} = \frac{|Y|^2}{8\pi} M_N
$$

The total decay width $\Gamma_\phi \equiv \Gamma_\phi^{NN} + \Gamma_\phi^{R}$

The CP-asymmetry:

$$
\epsilon = \sum_i \epsilon_i = \frac{3}{16\pi (Y^\dagger Y)_{ii}} \sum_{j\neq i} {\rm Im}\left[(Y^\dagger Y)_{ji}^2\right]\left(\frac{M_i}{M_j}\right).
$$

Light neutrino mass-Type-I seesaw

The relevant Lagrangian for Type-I seesaw:

$$-\mathcal{L} \quad \supset \quad Y\,\overline{N}\tilde{H}^{\dagger}L + M\overline{N^c}N + h.c.$$

where Y is the Yukawa coupling, H and L are SM-Higgs and lepton doublets.

The light neutrino mass matrix:

$$m_\nu \simeq m_D M^{-1} m_D^T$$

where $m_D = Yv/\sqrt{2}$, with $v = 246$ GeV being the SM Higgs VEV.

We can diagonalize this matrix by a unitary transformation

$$D_\nu = \mathrm{diag}(m_1, m_2, m_3) = U^T m_\nu U,$$

where U is the PMNS matrix. The Yukawa coupling matrix in terms of Casas-Ibarra parametrization

$$Y = \frac{\sqrt{2}}{v} U \sqrt{D_\nu} R^T \sqrt{M},$$

where R is a complex orthogonal matrix.

Redefinitions-Leptogenesis

Redefined variables,

$$\begin{aligned} E_\phi &= \rho_\phi a^3, \qquad R = \rho_R a^4, \\ E_N &= \rho_N a^3, \qquad \widetilde{N}_{B-L} = n_{B-L} a^3 \end{aligned}$$

Ratio of the scale factor to its initial value,

$$y = \frac{a}{a_I}$$

With redefinitions, the Hubble parameter

$$H = \sqrt{\frac{8\pi}{3M_{Pl}^2} \frac{(a_I E_\phi y + a_I E_N y + R)}{a_I^4 y^4}}$$

dimensionless variable,

$$z = \frac{M_{N_1}}{T} = M_{N_1} \left[\frac{\pi^2 g_*}{30\, R}\right]^{1/4} a_I\, y$$

Re-expressed Boltzmann Equations-Leptogenesis

The equilibrium density in terms of z

$$E_N^{eq} = \rho_N^{eq} a^3 = \frac{M_N^4}{\pi^2}\left[\frac{3}{z^2}K_2(z) + \frac{1}{z}K_1(z)\right] a_I^3 y^3$$

In terms of newly defined rescaled quantities the set of Boltzmann equations

$$\begin{aligned}
\frac{dE_\phi}{dy} &= -\frac{\Gamma_\phi^{NN}}{Hy}E_\phi - \frac{\Gamma_\phi^R}{Hy}E_\phi \\
\frac{dR}{dy} &= \frac{\Gamma_\phi^R}{H}a_I E_\phi + \frac{\Gamma_N}{H}a_I\left(E_N - E_N^{eq}\right) \\
\frac{dE_N}{dy} &= \frac{\Gamma_\phi^{NN}}{Hy}E_\phi - \frac{\Gamma_N}{Hy}\left(E_N - E_N^{eq}\right) \\
\frac{d\widetilde{N}_{B-L}}{dy} &= \frac{\Gamma_N}{Hy}\frac{\epsilon}{M_N}\left(E_N - E_N^{eq}\right) - \frac{\Gamma_{ID}}{Hy}\widetilde{N}_{B-L}
\end{aligned}$$

Initial conditions-Leptogenesis

The initial energy density of the heavy scalar field obtained from the condition $\Gamma_\phi = H(a_I)$:

$$\rho_{\phi_I} = \frac{3M_{Pl}^2}{8\pi} M_\phi^2.$$

The initial conditions at $a = a_I$:
$R(a_I) = 0, E_N(a_I) = 0, \widetilde{N}_{B-L}(a_I) = 0$ and
$E_\phi(a_I) \equiv E_{\phi_I} = (3/8\pi) M_{Pl}^2 M_\phi^2 a_I^3$.
The $\widetilde{N}_{B-L}$ asymmetry is related to the total N_{B-L} via,

$$N_{B-L} = \frac{n_{B-L}}{n_\gamma} = \left(\frac{\pi^4}{30\,\zeta(3)}\right) \left(\frac{30}{\pi^2}\right)^{1/4} \frac{g_*^{3/4}}{g_\gamma} R^{-3/4} \widetilde{N}_{B-L}.$$

$$n_\gamma = \frac{g_\gamma \zeta(3)}{\pi^2} T^3 \quad , \quad \rho_\gamma = \frac{\pi^2 g_\gamma}{30} T^4 \quad , \quad \rho_R = \frac{\pi^2 g_*}{30} T^4$$

BAU via Leptogenesis

The predicted N_{B-L} is related to the η_B measured at recombination given as

$$\eta_B = \left(\frac{a_{sph}}{f}\right) N_{B-L}\,,$$

where $a_{sph} = 28/79$, and $f = N_\gamma^{\mathrm{rec}}/N_\gamma^{*} = 2387/86$.

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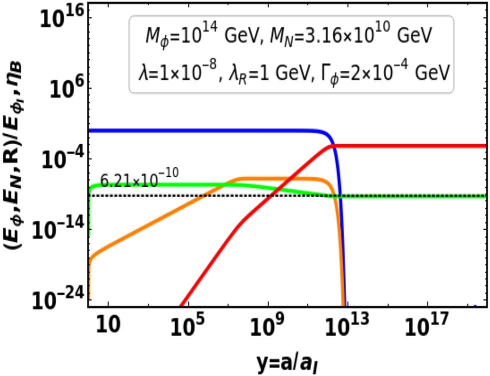

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Gravitational Waves From FOPT

The total GW abundance come from the Bubble collision, Sound waves and Turbulence (Ellis, et.al):

$$\begin{aligned}\Omega_{col,*}h^2(f) &= 2.3\times10^3\,(R_*H_*)^2\left(\frac{\kappa_{col}\alpha}{1+\alpha}\right)^2\left[1+\left(\frac{f}{f_d}\right)^{-1.61}\right]\\ &\times \left(\frac{f}{f_{col}}\right)^{2.54}\left[1+1.13\left(\frac{f}{f_{col}}\right)^{2.08}\right]^{-2.3}\end{aligned}$$

$$\Omega_{sw,*}h^2(f) = 0.384\,(R_*H_*)\,(\tau_{sw}H_*)\left(\frac{\kappa_{\mathrm{sw}}\alpha}{1+\alpha}\right)^2\left(\frac{f}{f_{sw}}\right)^3\left[1+\frac{3}{4}\left(\frac{f}{f_{sw}}\right)^2\right]^{-7/2},$$

$$\Omega_{turb,*}h^2(f) = 6.85\,(R_*H_*)\,(1-\tau_{sw}H_*)\left(\frac{\kappa_{\mathrm{sw}}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{f}{f_{turb}}\right)^3\frac{\left[1+\left(\frac{f}{f_{turb}}\right)\right]^{-11/3}}{1+8\pi f/H_*},$$

$$f_d\simeq\left(\frac{0.044}{R_*}\right),\quad f_{col}\simeq\left(\frac{0.28}{R_*}\right),\quad f_{sw}\simeq\left(\frac{3.4}{R_*}\right),\quad f_{turb}\simeq\left(\frac{5.1}{R_*}\right),$$

$$\tau_{sw}=\frac{R_*}{U_f}\,,\,U_f\simeq\sqrt{\frac{3}{4}\frac{\alpha_{\rm eff}}{1+\alpha_{\rm eff}}\kappa_{sw}},\ \kappa_{sw}=\frac{\alpha_{\rm eff}}{\alpha}\frac{\alpha_{\rm eff}}{0.73+0.083\sqrt{\alpha_{\rm eff}}+\alpha_{\rm eff}},$$

$$\alpha_{\rm eff}=\alpha(1-\kappa_{col}).$$

Gravitational Waves-Redshift

- Once the gravitational waves produced propagates from the phase transition until today.
- The ratio of the scale factor at the transition to the scale factor today

$$f_0 = f_* \left(\frac{a_*}{a_0}\right) = 1.65 \times 10^{-5} Hz \left(\frac{f_*}{H_*}\right) \left(\frac{T_*}{100\,\mathrm{GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6}$$

$$\Omega_{GW,0} = \left(\frac{a_*}{a_0}\right)^4 \left(\frac{H_*}{H_0}\right)^2 \Omega_{GW,*} = 1.67 \times 10^{-5} h^{-2} \left(\frac{100}{g_*}\right)^{1/3} \Omega_{GW,*}$$

After production the GWs redshift in the same way as radiation.

Gravitational Waves-Matter Domination

A period of matter-domination modifies the GW abundance observed today. The GW spectrum redshifts as:

$$\Omega_{\mathrm{GW},0}(f) = \begin{cases} \left(\frac{a_*}{a_0}\right)^4 \left(\frac{H_*}{H_0}\right)^2 \Omega_{\mathrm{GW},*}\left(\frac{a_0}{a_*} f\right) & \text{for } f > f_*, \\ \left(\frac{a_f}{a_0}\right)^4 \left(\frac{H_f}{H_0}\right)^2 \Omega_{\mathrm{GW},*}\left(\frac{a_0}{a_*} f_*\right) \left(\frac{f}{f_*}\right)^3 & \text{for } f < f_*, \end{cases}$$

The GW amplitude redshift factor:

$$\left(\frac{a}{a_0}\right)^4 \left(\frac{H}{H_0}\right)^2 = 1.67 \times 10^{-5} h^{-2} \left(\frac{100}{g_{eff}(T_{\mathrm{reh}})}\right) \left(\frac{a}{a_{\mathrm{reh}}}\right)^4 \left(\frac{H}{H_{\mathrm{reh}}}\right)^2$$

and the frequency redshift factor:

$$\frac{a_*}{a_0} = 7.96 \times 10^{-16} \left(\frac{100\,\mathrm{GeV}}{T_{reh}}\right) \left(\frac{100}{g_{\mathrm{eff}}}\right)^{\frac{1}{3}} \left(\frac{a_*}{a_{\mathrm{reh}}}\right)$$

Gravitational Waves-Matter Domination

The evolution of the energy densities

$$\begin{aligned}\frac{d\rho_\phi}{dt} + 3H\rho_\phi &= -\Gamma_\phi^{NN}\,\rho_\phi - \Gamma_\phi^{R}\,\rho_\phi \\ \frac{d\rho_R}{dt} + 4H\rho_R &= \Gamma_\phi^{R}\,\rho_\phi + \Gamma_N(\rho_N - \rho_N^{eq}) \\ H^2 &= \frac{\rho_\phi + \rho_R}{3M_p^2}\end{aligned}$$

By approximating the solution of the above system,

$$H(a) = H_* \left(\frac{a_*}{a_{reh}}\right)^{\frac{3}{2}} \left(\frac{a_{reh}}{a}\right)^2 \left[1 + \left(\frac{a_{reh}}{a}\right)^2\right]^{-\frac{1}{4}}$$

Expansion is dominated by ϕ field from H_* ,

$$t_{reh} - t_* = \tau_\phi = \int_{a_*}^{a_{reh}} \frac{da}{a\,H} = \frac{2}{3}\frac{1}{H_*}\left[\left(\frac{a_{reh}}{a_*}\right)^{\frac{3}{2}} - 1\right]$$

Gravitational Waves-Matter Domination

Duration of the ϕ domination $\tau_\phi = \frac{1}{\Gamma_\phi}$ and assuming $\Gamma_\phi \ll H_*$,

$$\Rightarrow \quad \frac{a_{reh}}{a_*} = \left(\frac{3H_*}{2\Gamma_\phi}\right)^{\frac{2}{3}}$$

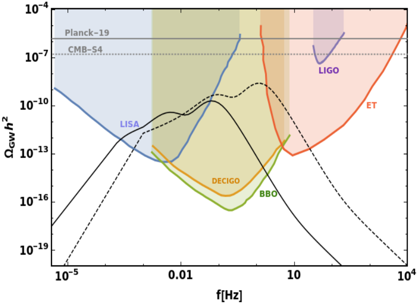
Using Hubble expansion approximation, the evolution of the scale factor, $(2\pi\, f_{H_{reh}} = a_{reh} H(a_{reh}),\, 2\pi f_* = a_* H(a_*)\,)$

$$\frac{a}{a_{\rm reh}} = \sqrt{\frac{\chi(f)}{2} - \frac{1}{2}}\,, \quad \text{where} \quad \chi(f) = \sqrt{8\left(\frac{f_{H_{reh}}}{f}\right)^4 + 1}$$

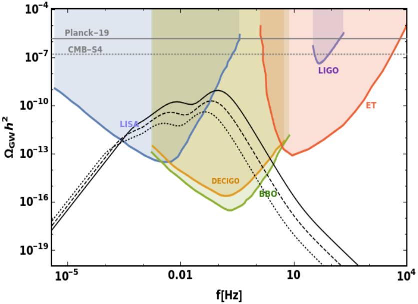
The redshifting up to $a_{\rm reh}$,

$$\left(\frac{a}{a_{\rm reh}}\right)^4 \left(\frac{H}{H_{\rm reh}}\right)^2 \approx \begin{cases} 1 & \text{for } f < f_{H_{\rm reh}}, \\ \sqrt{\frac{\chi(f)-1}{\chi(f)+1}} & \text{for } f_{H_{\rm reh}} < f < f_*, \\ \sqrt{\frac{\chi(f_*)-1}{\chi(f_*)+1}} & \text{for } f > f_* \quad . \end{cases}$$

Gravitational Waves-Matter Domination



$$\alpha = 100,\ \beta/H_* = 10,\ \kappa_{\text{col}} = 0.9,$$
$$H_* = 10^{-8},\ f_* = 10^{-3},$$
$$M_\phi = 10^{12}\ \text{GeV},$$
$$M_{N_1} = 10^{10}\ \text{GeV},\ \lambda = 10^{-10}$$
$$\because\ \Gamma_\phi^{NN} = \frac{|\lambda|^2}{4\pi} M_\phi \left(1 - \frac{4M_N^2}{M_\phi^2}\right)^{\frac{3}{2}}$$



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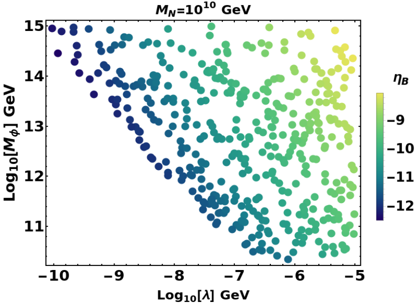

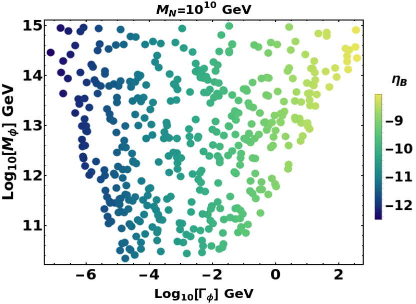

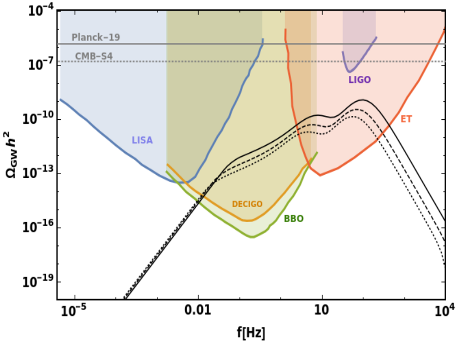

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$M_\phi = 3.98 \times 10^{11}$ GeV (dotted),
$M_{N_1} = 10^{10}$ GeV, $\lambda = 10^{-7}$.

Signal-to-Noise Ratio

- To quantify the detection probability of the GW signal, we compute the signal-to-noise ratio (SNR) for a given experimental sensitivity $\Omega_{\rm sens}(f)h^2$:

  $$\text{SNR} \equiv \sqrt{\tau \int_{f_{min}}^{f_{max}} \left[\frac{\Omega_{\rm GW}(f)h^2}{\Omega_{\rm sens}(f)h^2}\right]^2 df}$$

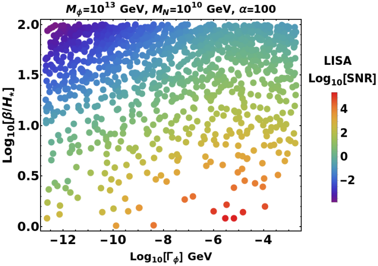
  where

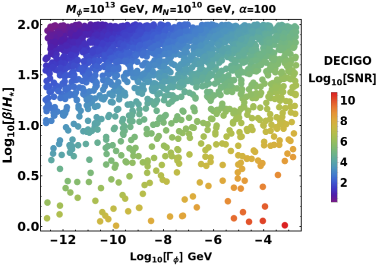
  $$h^2\,\Omega_{\rm Sens}(f) = \frac{2\pi^2}{3H_0^2} f^3 S_h(f).$$

  where $\tau = 4$ years is the observation time, $H_0 = 100\text{h km}\, s^{-1}\text{Mpc}^{-1}$ with $h = 0.678 \pm 0.009$, $S_h(f)$ is the power spectral density (PSD).

- The signal can be claimed to be detectable if SNR reaches a threshold SNR ≥ 10 of a detector.

GW as a probe of Leptogenesis


M_ϕ=10^{13} GeV, M_N=10^{10} GeV, α=100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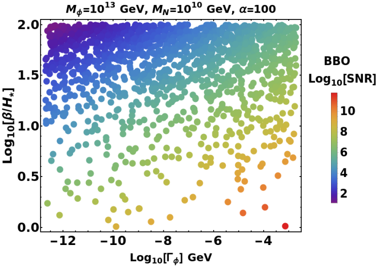
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Summary

- To explain the baryon asymmetry of the Universe via Leptogenesis while addressing the non-zero light neutrino masses through Type-I Seesaw mechanism, we require the mass scale of RHN to be very high.
- Such high scale of Leptogenesis challenging to probe in lab experiments, therefore we may require to see for the GW signals as an alternative pathways to test Leptogenesis.
- We observe that LISA, DECIGO, BBO and ET may hint towards the successful Leptogenesis at the high scale in the near future.

Thank you for you attention!