Testing leptogenesis and dark matter production during reheating with primordial gravitational waves

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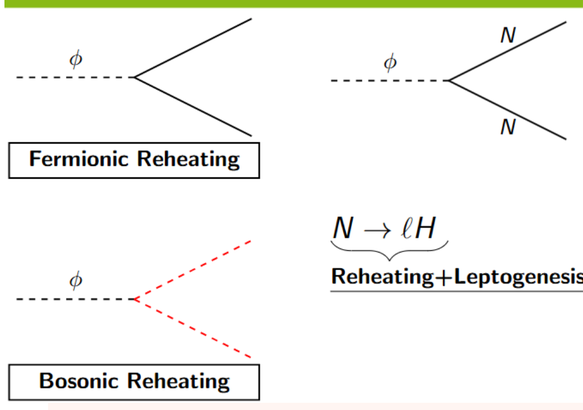
What we are doing..

Feynman Diagrams:



$N \to \ell H$

Reheating+Leptogenesis

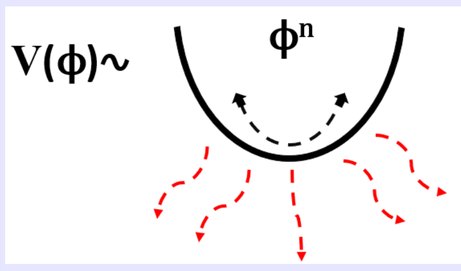
- $\mathcal{L} \supset -\mu\,\phi\,|\varphi|^2$, Bosonic Decay, $\quad$ $\mathcal{L} \supset -y_\psi\,\overline{\Psi}\,\Psi\,\phi$, Fermionic Decay

- $\mathcal{L}_{\phi NN} \supset -y_{\phi NN}\,\phi\,\overline{N^c}\,N + \text{H.c.}$, RHN Production

- The vanilla leptogenesis scenario studied with canonical seesaw framework

$$\left[\mathcal{L} \supset i\,\overline{N_R^c}\,\partial\!\!\!/ N_R - \left(\tfrac{1}{2}M_N\overline{N_R^c}N_R + \text{H.c}\right) + \left(-y_N\,\overline{\ell_L}\,\widetilde{\mathbb{H}}\,N_R + \text{H.c.}\right)\right].$$

How we are doing..:Inflaton Dynamics during Reheating



At the end of inflation, oscillation of the inflaton occurs at the bottom of a potential $V(\phi)$ of the form

$$V(\phi) = \lambda\,\frac{\phi^n}{\Lambda^{n-4}}\,,$$

The analytical solution for the Inflaton density is,

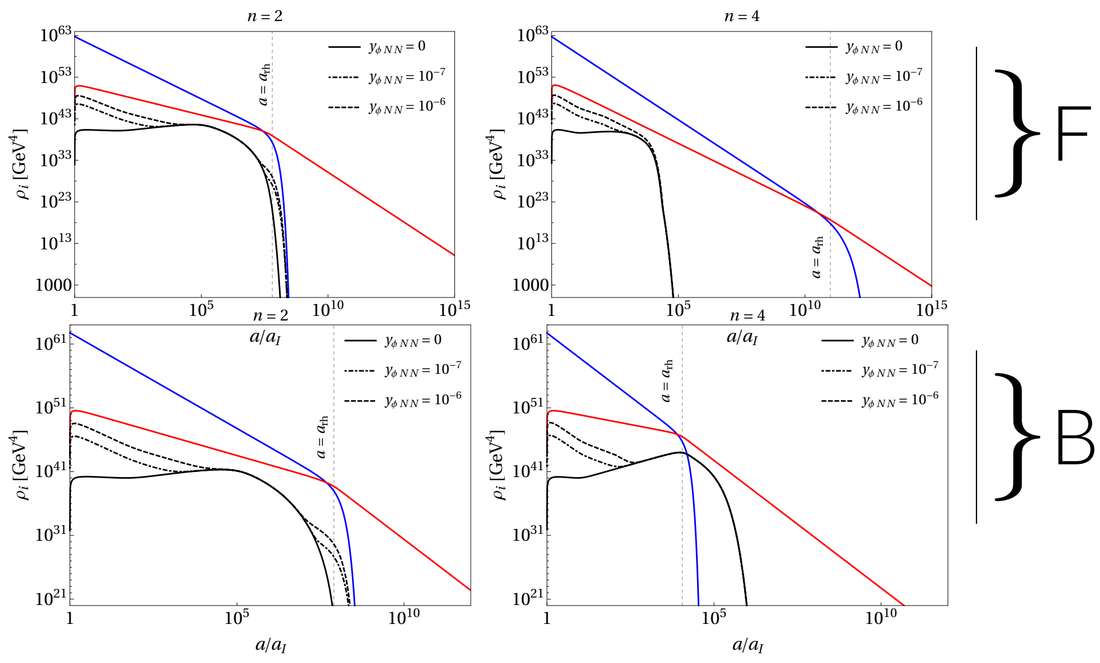
$$\rho_\phi(a) \simeq \rho_\phi(a_{rh})\left(\frac{a_{rh}}{a}\right)^{\frac{6n}{2+n}}.$$

- The analytical solution for the radiation energy density for the $\phi \to f\bar{f}$ is, $\quad \rho_R(a) \simeq \frac{3n}{7-n}\,M_P^2\,\Gamma(a_{rh})\,H(a_{rh})\left(\frac{a_{rh}}{a}\right)^{\frac{6(n-1)}{n+2}}\left[1-\left(\frac{a_I}{a}\right)^{\frac{2(7-n)}{2+n}}\right]$,

- $\phi \to bb$ is, $\quad \rho_R(a) \simeq \frac{3n}{1+2n}\,M_P^2\,\Gamma(a_{rh})\,H(a_{rh})\left(\frac{a_{rh}}{a}\right)^{\frac{6}{2+n}}\left[1-\left(\frac{a_I}{a}\right)^{\frac{2(1+2n)}{2+n}}\right]$,

- Following $T \propto \rho_R^{1/4}$, the Reheating Temperature for various cases are,

$T(a)$	$n=2$	$n=4$	$n=6$
Fermionic	$a^{-3/8}$	$a^{-3/4}$	$a^{-15/16}$
Bosonic	$a^{-3/8}$	$a^{-1/4}$	$a^{-3/16}$



→ For $n > 2$ case, $m_\phi(n>2) = f(a)$. ↪ $a_\star = a_I\left(\frac{M_N}{2\,m_I}\right)^{\frac{n+2}{3(2-n)}}$ ↪ For $a > a_\star$, $m_\phi < 2M_N$ ↪ $\phi \to NN$ process kinematically forbidden.

→ Comparing $\Gamma_{\phi\to f\bar{f}}$ and $\Gamma_{\phi\to\varphi\varphi}$ with $\Gamma_{\phi\to NN}$, ↪ $y_{\phi NN} > \begin{cases}\mu/\sqrt{m_\phi\,M_N} & \text{bosonic reheating}\\ y\,\sqrt{m_\phi/M_N} & \text{fermionic reheating}\end{cases}$

What is next..:Leptogenesis during reheating

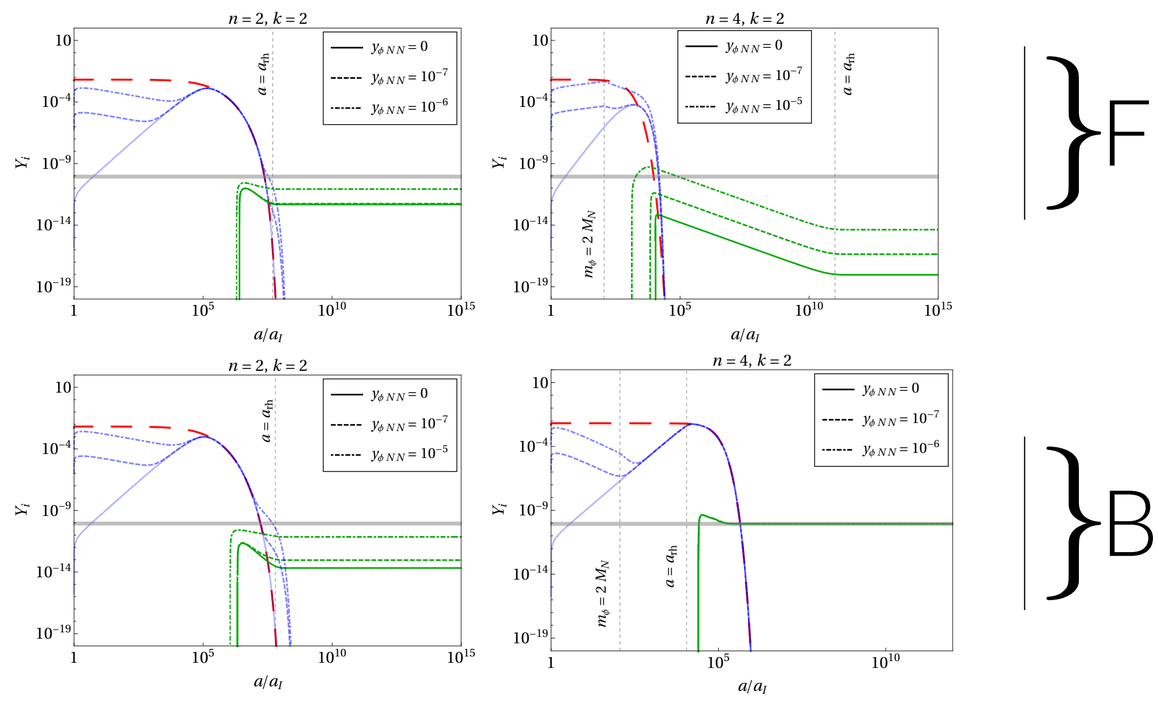
- Coupled BEQs for ρ_ϕ, ρ_R, RHN number density n_N, $B-L$ number density n_{B-L}.

$$\begin{aligned}
&\dot{\rho}_\phi + 3\,H\,(1+w)\,\rho_\phi = -(\Gamma_{\phi\to ii} + \Gamma_{\phi\to N_1N_1})\,(1+w)\,\rho_\phi\\
&\dot{\rho}_R + 4\,H\,\rho_R = \Gamma_{\phi\to ii}\,(1+w)\,\rho_\phi + \langle\Gamma_N\rangle\,\left(n_{N_1} - n_{N_1}^{\rm eq}\right)\\
&\dot{n}_{N_1} + 3\,H\,n_{N_1} = -\langle\Gamma_N\rangle\,\left(n_{N_1} - n_{N_1}^{\rm eq}\right) + \frac{\Gamma_{\phi\to N_1N_1}}{m_\phi}(1+w)\rho_\phi + \gamma_{ii\to N_1N_1}\\
&\dot{n}_{B-L} + 3\,H\,n_{B-L} = -\langle\Gamma_N\rangle\,\left[\epsilon_{\Delta L}\,(n_{N_1} - n_{N_1}^{\rm eq}) + \frac{n_{N_1}^{\rm eq}}{2\,n_\ell^{\rm eq}}\,n_{B-L}\right]\\
&3\,H^2\,M_P^2 = \rho_\phi + \rho_R + n_{N_1}\,E_N\\
&E_N^2 = M_N^2 + \left(\frac{m_\phi(a)}{2}\,\frac{a_I}{a}\right)^2. \qquad (1)
\end{aligned}$$

- The DM number can then be tracked with, $\quad \frac{dn_{dm}}{dt} + 3\,H\,n_{dm} = \gamma\ (where, \gamma = \frac{T^{k+6}}{\Lambda_{\rm NP}^{k+2}})$

- The comoving density, $Y(T) \equiv n(T)/s(T)$, with $s(T) = \frac{2\pi^2}{45}\,g_{*s}(T)\,T^3$ →SM entropy density. $g_{*s}(T)$ →number of relativistic d.o.f contributing to the SM entropy.

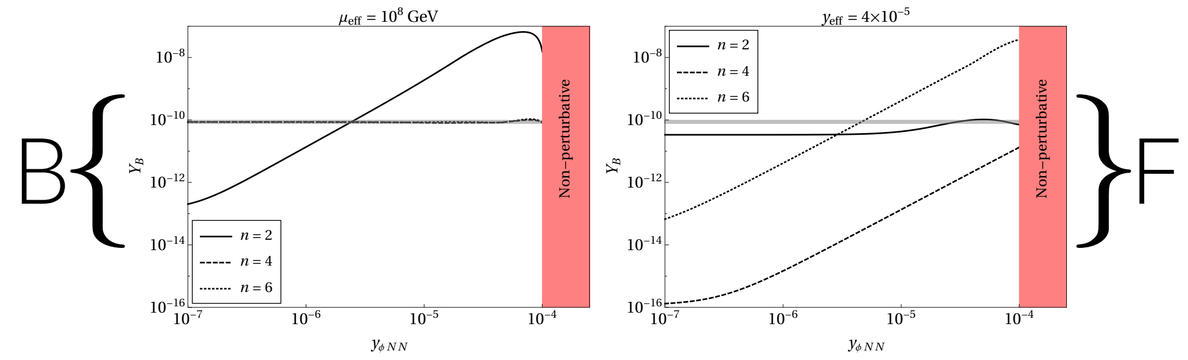
What is next..:Leptogenesis during reheating



→ Fixed parameters: $\mu_{eff} = 10^8$ GeV, $y_{eff} = 4\times10^{-5}$, $k=2$, $M_N = 10^{11}$GeV and $\Lambda_{NP} = 10^{15}$GeV.

→ For fermionic reheating, ↪ for any shape of potential ↪ asymmetry produced during reheating.
→ For bosonic reheating :: n=2 case, ↪ $\Gamma_{\phi\to NN}$ is completed before Reheating ↪ asymmetry produced during reheating.
→ For Bosonic $n > 2$ case, ↪ The assymetry produced during radiation domination.

Baryon Assymmetry

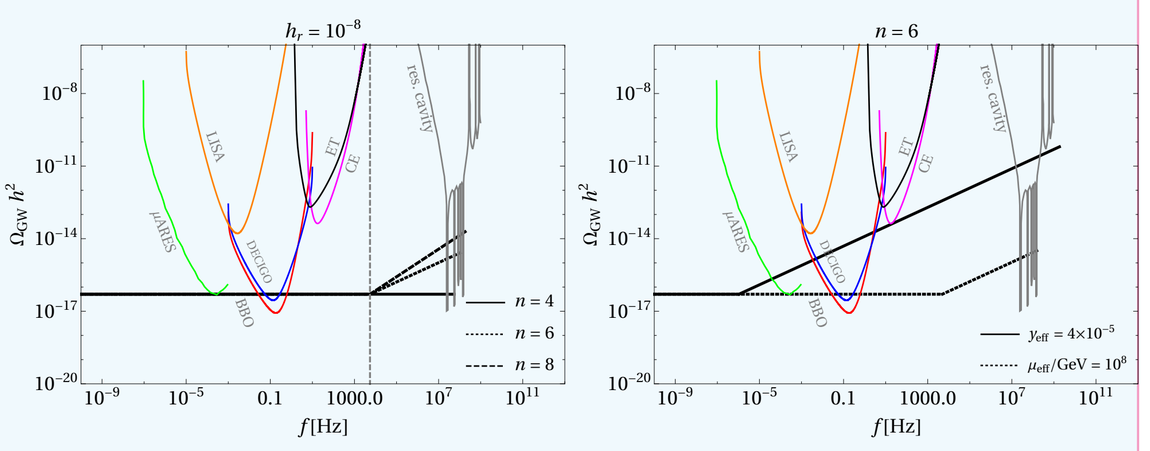


→ n=2 case, (for both) ↪ reheating scenarios are identical.
→ The asymmetry produced during radiation domination. ↪ Y_B approximately independent of $y_{\phi NN}$

How to observe..:Spectrum of inflationary gravitational wave

GW spectral energy density as a function of its frequency,

$$\Omega_{gw}(f) \simeq \Omega_\gamma^{(0)}\,\frac{\mathcal{P}_{T,\rm prim}}{24}\,\frac{g_*(T_{\rm hc})}{2}\left(\frac{g_{*s}(T_0)}{g_{*s}(T_{\rm hc})}\right)^{\frac{4}{3}} \times \begin{cases}\frac{g_*(T_{rh})}{g_*(T_{\rm hc})}\left(\frac{g_{*s}(T_{\rm hc})}{g_{*s}(T_{rh})}\right)^{\frac{4}{3}}\left(\frac{f}{f_{rh}}\right)^{\frac{n-4}{n-1}} & \text{for } f_{rh} \le f < f_{\rm max}\,,\\ 1 & \text{for } f_{\rm eq} \le f \le f_{rh}\,,\end{cases}$$



→ $f_{rh} = f(a_{rh}) \propto h_{rh} = \frac{H(a_{rh})}{H_I}$ ↪ GW spectral energy density depends upon the couplings.

→ mode reenters the horizon at radiation epoch ↪ GW spectral enegry ∝ original primordial spectrum $\mathcal{P}_{T,\rm prim}$

→ mode reenters the horizon at reheating epoch ↪$\Omega_{gw}(f)$ gets a boost ∝ $f^{\frac{n-4}{n-1}}$, which implies that the spectrum becomes ***blue tilted*** with respect to the primordial one.

- **In Summary..** ↪ Picture of reheating with different potential shapes.
↪ Successful DM genesis and baryogenesis (in the perturbative limit) ↪ checked through PGW.

- **For Details..:Reference**

[1] Basabendu Barman, Arindam Basu, Debasish Borah, Amit Chakraborty, and Rishav Roshan.
Testing leptogenesis and dark matter production during reheating with primordial gravitational waves.
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