Testing Leptogenesis during reheating with primordial gravitational waves

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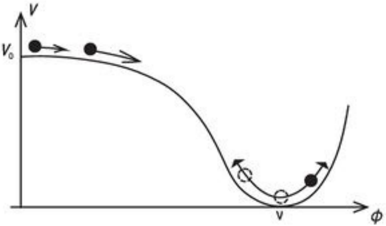
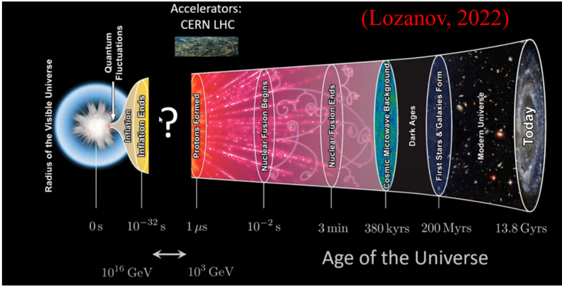
Andhra Pradesh

Prologue



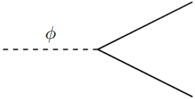
V
V_0
v
ϕ



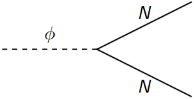
Accelerators:
CERN LHC
(Lozanov, 2022)
Radius of the Visible Universe
Quantum Fluctuations
Inflation
Inflation Ends
?
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Dark Ages
First Stars & Galaxies Form
Modern Universe
Today
0 s
10^{-32} s
1 μs
10^{-2} s
3 min
380 kyrs
200 Myrs
13.8 Gyrs
Age of the Universe
10^{16} GeV
10^{3} GeV

The setup

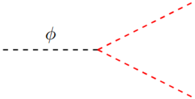
Feinmann Diagrams:



Fermionic Reheating



$\underbrace{N \to \ell H}_{\text{Reheating+Leptogenesis}}$



Bosonic Reheating

$\to \mathcal{L} \supset -\mu\,\phi\,|\varphi|^2\,,$
Bosonic Decay

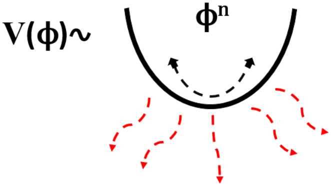
$\to \mathcal{L} \supset -y_\psi\,\overline{\Psi}\,\Psi\,\phi\,,$
Fermionic Decay

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

$\to$ The vanilla leptogenesis scenario studied with canonical seesaw framework

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

Inflaton Dynamics During Reheating:



• *Inflation potential* $V(\phi) = \lambda \frac{\phi^n}{\Lambda^{n-4}}$.

• *The analytical solution for the Inflaton density* $\rho_\phi(a) \simeq \rho_\phi(a_{rh}) \left(\frac{a_{rh}}{a}\right)^{\frac{6\,n}{2+n}}$.

$$\underline{\phi \to f\bar{f},} \quad \rho_R(a) \simeq \frac{3\,n}{7-n} M_P^2 \, \Gamma(a_{rh}) \, H(a_{rh}) \left(\frac{a_{rh}}{a}\right)^{\frac{6(n-1)}{n+2}} \left[1 - \left(\frac{a_I}{a}\right)^{\frac{2(7-n)}{2+n}}\right]$$

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

BEQs

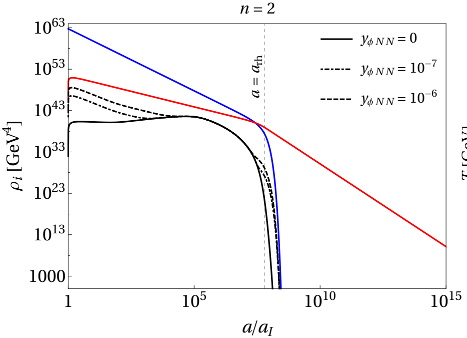
$\rightarrow$ For exact solution to the energy densities;

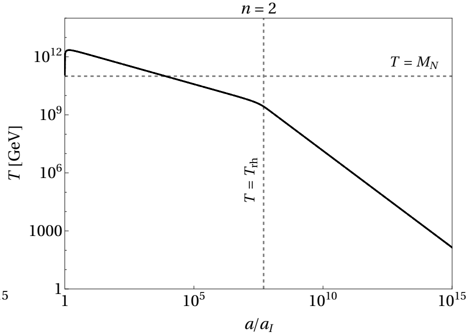
$$\begin{aligned}
&\dot{\rho}_\phi + 3\,H\,(1+w)\,\rho_\phi = -\left(\Gamma_{\phi\to ii} + \Gamma_{\phi\to N_1 N_1}\right)\,(1+w)\,\rho_\phi \\
&\dot{\rho}_R + 4\,H\,\rho_R = \Gamma_{\phi\to ii}\,(1+w)\,\rho_\phi + \langle\Gamma_N\rangle\,\left(n_{N_1} - n_{N_1}^{\rm eq}\right) \\
&\dot{n}_{N_1} + 3\,H\,n_{N_1}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

$$\frac{dn_{dm}}{dt} + 3Hn_{dm} = \gamma, \quad \gamma = \frac{T^{k+6}}{\Lambda_{\rm NP}^{k+2}}$$

- *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	$a^{-3/8}$	$a^{-1/4}$	$a^{-3/16}$





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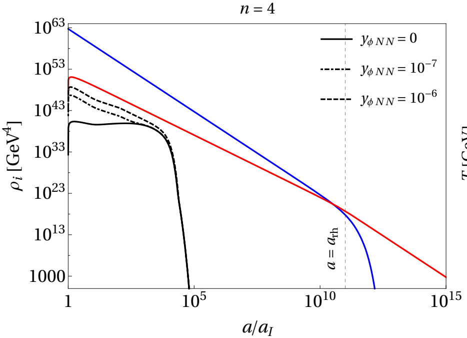

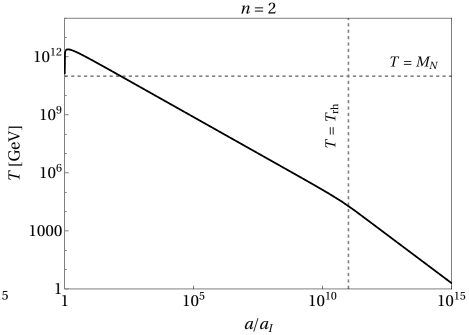

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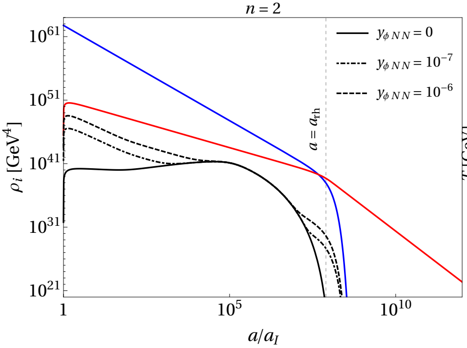

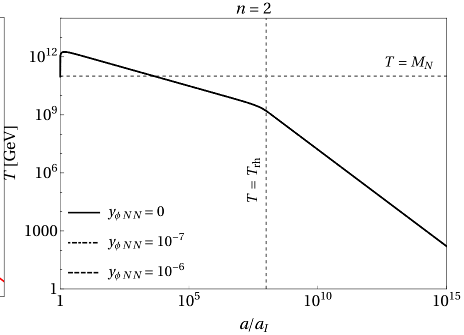

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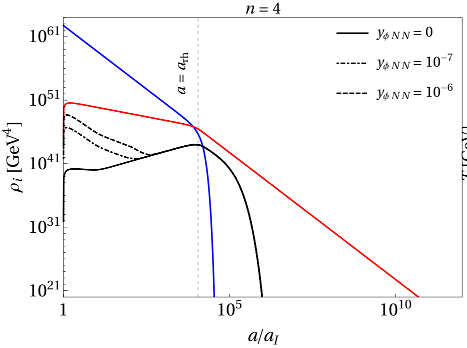
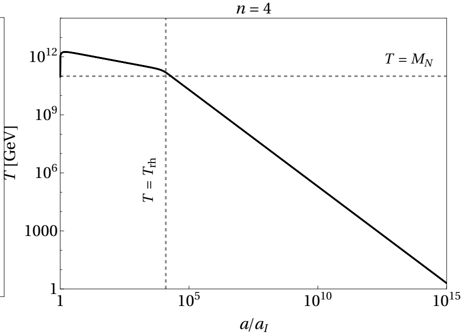




Inflaton Dynamics During Reheating: Discussion

$\rightarrow$ For $n > 2$ case $m_\phi(n > 2) = f(a)$.

$\hookrightarrow$ $a_\star = a_I \left(\frac{M_N}{2\, m_I}\right)^{\frac{n+2}{3\,(2-n)}}$

$\hookrightarrow$ For $a > a_\star$, $m_\phi < 2M_N$

$\hookrightarrow$ $\phi \rightarrow NN$ process kinematically forbidden.

$\rightarrow$ $T_{rh} \geq 4$ MeV from CMB measurements

$\hookrightarrow$ Sets the lower bound on the couplings

$\hookrightarrow$ $y_{eff} \geq 10^{-7}$ and $\mu_{eff} \geq 10^{7}$ GeV.

Comparing $\Gamma_{\phi\rightarrow f\bar{f}}$ and $\Gamma_{\phi\rightarrow\varphi\varphi}$ with $\Gamma_{\phi\rightarrow NN}$,

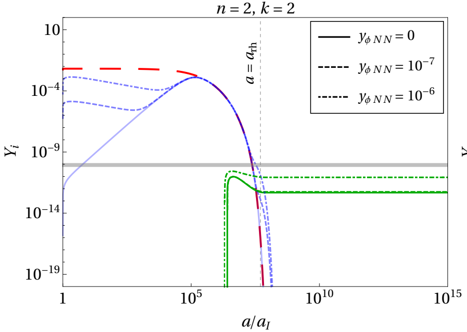
$$\hookrightarrow y_{\phi NN} > \begin{cases} \mu/\sqrt{m_\phi\, M_N} & \text{bosonic reheating} \\ y\,\sqrt{m_\phi/M_N} & \text{fermionic reheating} \end{cases}$$

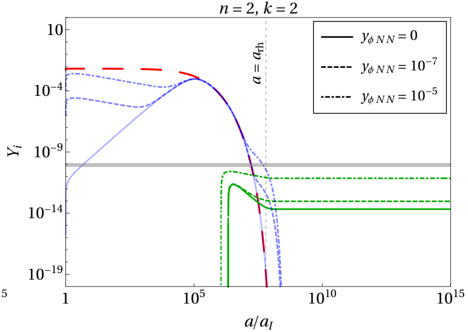
Yield

- *Comovingdensity*, Y(T) $\equiv n(T)/s(T)$.

$s(T) = \frac{2\pi^2}{45}\, g_{*s}(T)\, T^3 \rightarrow$ SM entropy density

$g_{*s}(T) \rightarrow$ number of relativistic d.o.f





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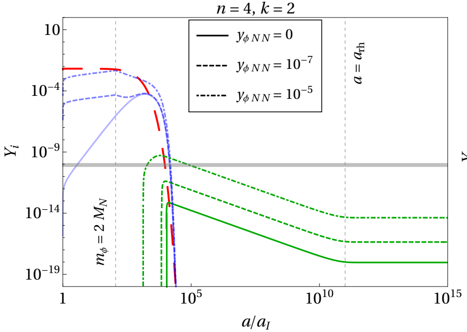
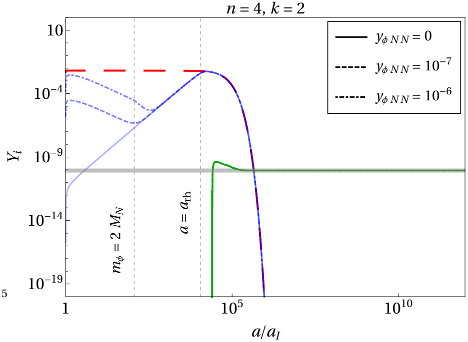




Yield: Discussion

$\rightarrow$ For fermionic reheating,

$\hookrightarrow$ n=2 case,

$\hookrightarrow$ asymmetry produced during reheating.

$\rightarrow$ For bosonic reheating,

$\hookrightarrow$ $\Gamma_{\phi \rightarrow NN}$ is completed before Reheating :: n=2 case.

$\hookrightarrow$ Reheating ends earlier $\rightarrow$ asymmetry produced during radiation domination :: $n > 2$ case.

$\rightarrow$ For n=2 case, (for both)

$\hookrightarrow$ $\phi \rightarrow NN$ decays contributes to RHN production

$\hookrightarrow$ larger $y_{\phi NN}$ $\rightarrow$ larger assymetry.

$\rightarrow$ For $n > 2$ case,

$\hookrightarrow$ The assymetry produced during reheating.

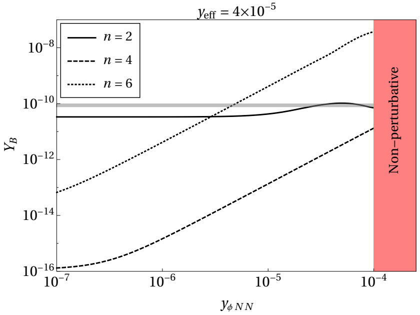
$\rightarrow$ For $n > 2$ case,

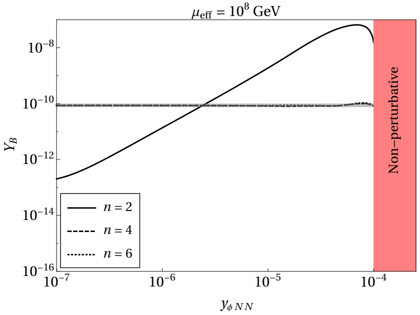
$\hookrightarrow$ The asymmetry produced during radiation domination.

Baryon Assymetry:

→ n=2 case, (for both)
↪ reheating scenarios are identical.

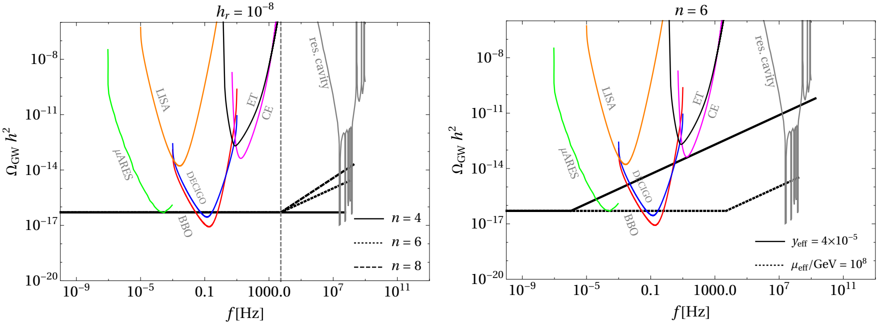
→ For $n > 2$ case,
↪ The asymmetry produced during radiation domination. ↪ Y_B approximately independent of $y_{\phi NN}$



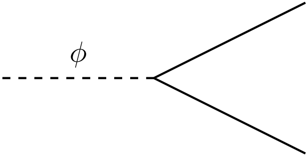


PGW

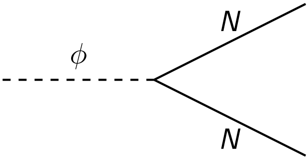
$$\Omega_{gw}(f) \simeq \Omega_\gamma^{(0)} \, \frac{\mathcal{P}_{T,\text{prim}}}{24} \, \frac{(T_{\text{hc}})}{2} \left(\frac{g_{*s}(T_0)}{g_{*s}(T_{\text{hc}})}\right)^{\frac{4}{3}} \times \begin{cases} \frac{g_s(T_{rh})}{g_s(T_{\text{hc}})} \left(\frac{g_{*s}(T_{\text{hc}})}{g_{*s}(T_{rh})}\right)^{\frac{4}{3}}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

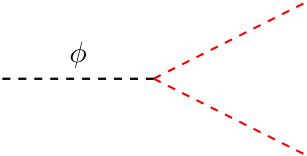


Conclusion:



Fermionic Reheating





Bosonic Reheating

$$\underbrace{N \rightarrow \ell H}$$

Reheating+Leptogenesis