Gravitational Waves
from a B-L Phase Transition

GWs as a key to the early universe and BSM physics

arxiv[hep-ph] 1305.3392, 1309.7788

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The eye of a needle for model builders

inflation

\[ 3 \times 10^{16} \text{ GeV} \]

thermal leptogenesis

\[ T_{RH} > 10^9 \text{ GeV} \]

(p)reheating

\[ 2 \times 10^{16} \text{ GeV} - \ldots \]

topological defects

\[ E \sim \Lambda_{SSB} \]

- strong motivation for new physics at very high energy scales
  \( \Rightarrow \) potential GW sources
- Spectrum determined with no* new parameters
- In this talk: inflation, preheating, cosmic strings

Gravitational waves as a unique window to the very early universe
Outline

- a minimal supersymmetric model of particle physics and the early universe

- gravitational waves from
  - inflation
  - preheating
  - cosmic strings

- comparison with observational prospects and caveats
An example: SSB of $U(1)_{B-L}$ at the GUT scale

$$W = \frac{\sqrt{\lambda}}{2} \Phi (v_{B-L}^2 - 2 S_1 S_2) + \frac{1}{\sqrt{2}} h_i^n n_i^c n_i^c S_1 + h_{ij}^\nu n_i^c 5_j^* H_u + W_{MSSM}$$

**Before**
- hybrid inflation

**Phase transition**
- tachyonic preheating
- cosmic strings

**After**
- reheating
- leptogenesis
- dark matter
An example: SSB of $U(1)_{B-L}$ at the GUT scale

$$W = \frac{\sqrt{\lambda}}{2} \Phi \left(v_{B-L}^2 - 2 S_1 S_2 \right) + \frac{1}{\sqrt{2}} h^c_i n^c_i n^c_i S_1 + h^\nu_{ij} n^c_i 5^*_j H_u + W_{MSSM}$$

Before
- hybrid inflation

Phase transition
- tachyonic preheating
- cosmic strings
Three sources of gravitational waves

**Inflation**
- scale independent quantum tensor perturbations
- red-shifted after horizon re-entry

[Rubakov et al. '82, Turner et al. '93]

**Preheating**
- GWs from bubble-collisions during phase transition
- at high frequencies, governed by small length-scales at preheating

[Garcia-Bellido, Figueroa '07, Kofman et al. '09, '10]

**Cosmic strings**
- extremely high energy density along cosmic strings $\sim V_{\text{inf}} \rightarrow$ GWs
- evolution of network complicated $\rightarrow$ need lattice simulations

[Vilenkin '81, Hindmarsh et al. '12]

Consistent picture at hand $\rightarrow$ calculate complete spectrum
perturbations of the homogeneous background metric

\[ ds^2 = a^2(\tau)(\eta_{\mu\nu} + h_{\mu\nu}(x, \tau))dx^\mu dx^\mu \]

governed by linearized Einstein equation (\( \tilde{h}_{ij} = ah_{ij}, \) TT - gauge)

\[ \tilde{h}''_{ij}(k, \tau) + \left(k^2 - \frac{a''}{a}\right)\tilde{h}_{ij}(k, \tau) = 16\pi G a \Pi_{ij}(k, \tau) \]

source term from \( \delta T_{\mu\nu} \)

\( k \gg aH : h_{ij} \sim \cos(\omega \tau)/a, \quad k \ll aH : h_{ij} \sim \text{const.} \)

useful plane wave expansion

\[ h_{ij}(x, \tau) = \sum_{P=+, \times} \int_{-\infty}^{+\infty} \frac{dk}{2\pi} \int d^2\hat{k} \ h_P(\hat{k}) \ T_k(\tau) \ e^{P}_{ij}(\hat{k}) e^{-ik(\tau-\hat{k}x)} \]

transfer function, expansion coefficients, polarization tensor \( P = +, \times \)
Observable quantities:

\[ \Omega_{GW} = \frac{1}{\rho_c} \frac{\partial \rho_{GW}(k, \tau)}{\partial \ln k}, \quad \rho_{GW}(\tau) = \frac{1}{32\pi G} \left\langle \dot{h}_{ij}(x, \tau) \dot{h}^{ij}(x, \tau) \right\rangle \]

In principle: Calculate \( T_{\mu\nu} \), work through equations above

In practice:

\[ \rho_{GW}(\tau) = \rho_{GW}^{\text{qu}}(\tau) + \rho_{GW}^{\text{cl}}(\tau). \]

- classical sources (e.g. preheating, cosmic strings):

\[ h_{ij}(k, \tau) = 16\pi G \frac{1}{a(\tau)} \int_{\tau_i}^{\tau} d\tau' a(\tau') G(k, \tau, \tau') \Pi_{ij}(k, \tau') \]

- inflation (e.g. stochastic source):

\[ \Omega_{GW}(k, \tau) = \frac{r^2 A_s^2}{12} \frac{k^2}{a_0^2 H_0^2} T_k^2(\tau) \]
The transfer function $T_k$: 
\[
\frac{a(\tau_{\text{cr}})}{a_0} = \frac{a(\tau_{\text{cr}})}{a_{\text{RH}}} \frac{a_{\text{eq}}}{a_0}, \quad k_x = a_x H_x
\]

- Adiabatic expansion of the universe:
\[
\frac{H_1}{H_2} = \left(\frac{a_1}{a_2}\right)^{-\frac{3}{2}(1+\omega)}
\]
with e.g. 
\[
\frac{a_{\text{eq}}}{a_0} = \left(\frac{g_{*}^{\text{eq}}}{g_*^0}\right) \left(\frac{g_{*,s}^{0}}{g_{*,s}^{\text{eq}}}\right)^{4/3} \frac{\Omega_r}{\Omega_m}
\]
GWs from inflation

The transfer function \( T_k : \frac{a(\tau_{cr})}{a_0} = \frac{a(\tau_{cr})}{a_{RH}} \frac{a_{eq}}{a_0} \), \( k_x = a_x H_x \)

- Adiabatic expansion of the universe:
  \[
  \frac{H_1}{H_2} = \left( \frac{a_1}{a_2} \right)^{-\frac{3}{2}(1+\omega)}, \text{ with e.g. } \frac{a_{eq}}{a_0} = \left( \frac{g^{eq}_{*}}{g^{0}_{*}} \right) \left( \frac{g^{eq}_{*,s}}{g^{0}_{*,s}} \right)^{\frac{4}{3}} \frac{\Omega_r}{\Omega_m}
  \]

- mode \( k \) entering during radiation domination \((\omega = 1/3)\)
  \[
  \frac{a(\tau_{cr})}{a_{eq}} = \frac{k H_{eq}}{k_{eq} H} \sim \frac{k}{k_{eq}} \left( \frac{a(\tau_{cr})}{a_{eq}} \right)^{4/2}
  \]

  \[
  \rightarrow \frac{a(\tau_{cr})}{a_{eq}} = \frac{k_{eq}}{k} \left( \frac{g^{*}_{*}}{2g^{*}_{eq}} \right)^{1/2} \left( \frac{g^{eq}_{*,s}}{g^{0}_{*,s}} \right)^{2/3} \propto \frac{1}{k} \rightarrow \Omega_{GW} \propto k^0
  \]
GWs from inflation

The transfer function $T_k$: $\frac{a(\tau_{cr})}{a_0} = \frac{a(\tau_{cr})}{a_{RH}} \frac{a_{eq}}{a_0} \frac{a_{eq}}{a_{eq}}$, $k_x = a_x H_x$

- Adiabatic expansion of the universe:

$$\frac{H_1}{H_2} = \left(\frac{a_1}{a_2}\right)^{-\frac{3}{2}(1+\omega)}$$

with e.g. $\frac{a_{eq}}{a_0} = \left(\frac{g_{eq}}{g_0}\right) \left(\frac{g_{eq,s}}{g_{eq},s}\right)^{4/3} \frac{\Omega_r}{\Omega_m}$

- mode $k$ entering during radiation domination ($\omega = 1/3$)

$$\frac{a(\tau_{cr})}{a_{eq}} = \frac{k H_{eq}}{k_{eq} H} \sim \frac{k}{k_{eq}} \left(\frac{a(\tau_{cr})}{a_{eq}}\right)^{4/2}$$

$$\rightarrow \frac{a(\tau_{cr})}{a_{eq}} = \frac{k_{eq}}{k} \left(\frac{g_{eq}}{2 g_0}\right)^{1/2} \left(\frac{g_{eq,s}}{g_{eq},s}\right)^{2/3} \propto 1/k \rightarrow \Omega_{GW} \propto k^0$$

- mode $k$ entering during matter domination ($\omega = 0$)

$$\frac{a(\tau_{cr})}{a_{RH}} = \frac{k H_{RH}}{k_{RH} H} = \frac{k}{k_{RH}} \left(\frac{a}{a_{RH}}\right)^{3/2}$$

$$\rightarrow \frac{a}{a_{RH}} = \left(\frac{k_{RH}}{k}\right)^2 \propto 1/k^2 \rightarrow \Omega_{GW} \propto k^{-2}$$

simple scale/frequency dependence, sensitive to expansion history
GWs from inflation

$\Omega_{GW} h^2$ vs $f [\text{Hz}]$

$k [\text{Mpc}^{-1}]$

$10^{-20}$ $10^{-15}$ $10^{-10}$ $10^{-5}$ $10^0$ $10^5$ $10^{10}$ $10^{15}$ $10^{20}$ $10^{25}$

$10^{-25}$ $10^{-20}$ $10^{-15}$ $10^{-10}$ $10^{-5}$ $10^0$ $10^5$ $10^{10}$ $10^{15}$ $10^{20}$ $10^{25}$

$10^{-20}$ $10^{-15}$ $10^{-10}$ $10^{-5}$ $10^0$ $10^5$ $10^{10}$

inflation
GWs from inflation

cosmological history imprinted on scale-invariant primordial spectrum

\[ k [ \text{Mpc}^{-1}] \]

\[ f [\text{Hz}] \]

\[ \Omega_{GW} h^2 \]

\[ f_{-2} \]

- - - - - radiation - - - -

\[ \sim r^2 \Delta_s^2 f^0 \]

\[ f_{RH} \sim T_{RH}^* \]

matter-radiation equality \[ f_{eq} \sim \Omega_m \]

\[ \Lambda_{QCD} \]

\[ \Lambda_{\text{susy}} \]
GWs from inflation

\[ f^{-2} \]

\[ f_{\text{eq}} \sim \Omega_m \]

\[ f_{\text{RH}} \sim T_{\text{RH}}^* \]

\[ \sim r^2 \Delta_s^2 f^0 \]

\[ \Lambda_{\text{QCD}} \]

\[ \Lambda_{\text{susy}} \]

Matter-radiation equality

Matter-radiation equality

reheating completed

\[ f^{-2} \]

\[ f_{\text{eq}} \sim \Omega_m \]

\[ \Lambda_{\text{QCD}} \]

\[ \Lambda_{\text{susy}} \]

\[ \sim r^2 \Delta_s^2 f^0 \]

\[ \Lambda_{\text{QCD}} \]

\[ \Lambda_{\text{susy}} \]

cosmological history imprinted on scale-invariant primordial spectrum
GWs from cosmic strings

- translational invariance and isotropy of the source
- scaling (self-similar) regime

\[ \Rightarrow \left\langle \Pi_{ij}(k, \tau) \Pi_{ij}'(k', \tau') \right\rangle \approx (2\pi)^3 \frac{4v^4}{B-L} \frac{\delta(k + k') \delta(x - x')}{\sqrt{\tau \tau'}} \tilde{C}(x) \]

with \( x = k\tau > 1 \) on sub-horizon scales.

- recall:

\[ \rho_{GW}(\tau) = \frac{1}{32\pi G} \left\langle \dot{h}_{ij}(x, \tau) \dot{h}_{ij}(x, \tau) \right\rangle \]

\[ h_{ij}(k, \tau) = 16\pi G \frac{1}{a(\tau)} \int_{\tau_i}^{\tau} d\tau' a(\tau') G(k, \tau, \tau') \Pi_{ij}(k, \tau') \]

with \( G(k, \tau, \tau') = \sin(k(\tau - \tau'))/k \) for sub-horizon scales
GWs from cosmic strings

- translational invariance and isotropy of the source
- scaling (self-similar) regime

\[ \Rightarrow \langle \Pi_{ij}(k, \tau) \Pi_{i'j'}(k', \tau') \rangle \approx (2\pi)^3 \frac{4v_B^4}{\sqrt{\tau \tau'}} \delta(k + k') \delta(x - x') \tilde{C}(x) \]

with \( x = k\tau > 1 \) on sub-horizon scales.

- resulting spectrum:

\[ \Rightarrow \Omega_{GW} = \frac{k^2}{3\pi^2 H_0^2 a_0^2} \left( \frac{v_{B-L}}{M_P} \right)^4 \int_{x_i}^{x_0} \frac{a^2(x/k) a_0^2 x}{\tilde{C}(x)} \tilde{C}(x) \, dx \]

\[ \to \text{const., dominated by lower boundary } x_i = \mathcal{O}(1) \]

- for radiation dom.: \( a \propto k^{-1} \to \Omega_{GW} \propto k^0 \)
- for matter dom.: \( a \propto k^{-2} \to \Omega_{GW} \propto k^{-2} \)

Spectrum dominated by horizon-sized cosmic strings
GWs from cosmic strings

\[ k [\text{Mpc}^{-1}] \]

\[ \Omega_{GW} h^2 \]

- cosmic strings (AH model)
- inflation

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GWs from cosmic strings

'\( f \)' @ Hz

\( k [\text{Mpc}^{-1}] \)

\( f_{\text{eq}} \)

\( f_{\text{RH}} \)

\( \sim v_{B-L}^4 f^0 \)

\( f^{-2} \)

same spectral shape as for inflation, potentially very different amplitude
GWs from cosmic strings

large uncertainties from loop size and decay mode
GWs from cosmic strings

\[ f_{\text{eq}} \sim v_B^4 f^L f_0 \]

\[ \alpha = 0.1 \]

[Blanco-Pillado et al. '11]

large uncertainties from loop size and decay mode
GWs from preheating

- high frequency peaks, determined by $m_S$, $m_V$, $H_{PH}$, $a_{PH}/a_{RH}$
Parameter dependencies / observational prospects

(1) millisecond pulsar timing, (2) EPTA, (3) LIGO, (4) SKA, (5) ET, (6) advanced LIGO, (7) eLISA, (8) BBO/DECIGO
Conclusion and Outlook

- early universe model based on spontaneous breaking of $U(1)_{B-L}$: GW spectrum fully* determined by Lagrangian parameters → GWs can be a powerful tool to discriminate models

- inflation: GW spectrum is sensitive to the entire cosmological history

- cosmic strings: can enhance inflation-type spectrum by many orders of magnitudes. But large uncertainties.

- GW have the potential to rule out or detect GUT-scale cosmic strings, measurement of $T_{RH}$, extra degrees of freedom,..
early universe model based on spontaneous breaking of $U(1)_{B-L}$: GW spectrum fully* determined by Lagrangian parameters\n$\rightarrow$ GWs can be a powerful tool to discriminate models

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GW have the potential to rule our or detect GUT-scale cosmic strings, measurement of $T_{RH}$, extra degrees of freedom,..

Thank you!
backup slides
GWs from inflation

Shape of the spectrum governed by transfer function:

$$\Omega_{GW}(k, \tau) = \frac{A_t}{12} \frac{k^2}{a_0^2 H_0^2} T_k^2(\tau), \quad T_k(\tau) = \frac{a(\tau_k)}{a(\tau)} \text{ with } k = a(\tau_k) H(\tau_k)$$

Consider frequency intervals $[k_0, k_{eq})$, $[k_{eq}, k_{RH})$, $[k_{RH}, k_{PH})$:

$$f_{eq} = 1.57 \times 10^{-17} \text{ Hz} \left( \frac{\Omega_m h^2}{0.14} \right), \quad f_{RH} = 4.25 \times 10^{-1} \text{ Hz} \left( \frac{T_\ast}{10^7 \text{ GeV}} \right)$$

$$f_{PH} = 1.93 \times 10^4 \text{ Hz} \left( \frac{\lambda}{10^{-4}} \right)^{1/6} \left( \frac{10^{-15} v_{B-L}}{5 \text{ GeV}} \right)^{2/3} \left( \frac{T_\ast}{10^7 \text{ GeV}} \right)^{1/3}$$

$$\Rightarrow T_k \simeq \Omega_r^{1/2} \left( \frac{g^k_*}{g^0_*} \right)^{1/2} \left( \frac{g^0_*,s}{g^k_*,s} \right)^{2/3} \frac{k_0}{k} \times \begin{cases} \frac{1}{\sqrt{2}} \frac{k_{eq}}{k}, & k_0 \ll k \ll k_{eq} \\ 1, & k_{eq} \ll k \ll k_{RH} \\ \sqrt{2} R^{1/2} C_{RH}^3 k_{RH}/k, & k_{RH} \ll k \ll k_{PH} \end{cases}$$
GWs from tachyonic preheating

- $f_{PH}$: typical scale of reheating, red-shifted
- $\Omega_{GW}^{(max)}$: redshift of $\Omega_{GW}^{PH}(k_{PH}) \simeq c_{PH} (d_{PH} H_{PH})^2$
- $(d^{(s)}_{PH})^{-1} = (\lambda v_{B-L} \dot{\phi}_c)^{1/3}$, \quad $(d^{(v)}_{PH})^{-1} \sim m_G$

\[
\begin{align*}
  f^{(s)}_{PH} &\simeq 6.3 \times 10^6 \text{ Hz} \left( \frac{M_1}{10^{11} \text{ GeV}} \right)^{1/3} \left( \frac{5 \times 10^{15} \text{ GeV}}{v_{B-L}} \right)^2 \left( \frac{m_S}{3 \times 10^{13} \text{ GeV}} \right)^{7/6} \\
  \Omega_{GW}^{(s,\text{max})} h^2 &\simeq 3.6 \times 10^{-16} \frac{c_{PH}}{0.05} \left( \frac{M_1}{10^{11} \text{ GeV}} \right)^{4/3} \left( \frac{5 \times 10^{15} \text{ GeV}}{v_{B-L}} \right)^{-2} \left( \frac{m_S}{3 \times 10^{13} \text{ GeV}} \right)^{-4/3} \\
  f^{(v)}_{PH} &\simeq 7.5 \times 10^{10} \text{ Hz} g \left( \frac{M_1}{10^{11} \text{ GeV}} \right)^{1/3} \left( \frac{m_S}{3 \times 10^{13} \text{ GeV}} \right)^{-1/2} \\
  \Omega_{GW}^{(v,\text{max})} h^2 &\simeq 2.6 \times 10^{-24} \frac{1}{g^2} \frac{c_{PH}}{0.05} \left( \frac{M_1}{10^{11} \text{ GeV}} \right)^{4/3} \left( \frac{5 \times 10^{15} \text{ GeV}}{v_{B-L}} \right)^2 \left( \frac{m_S}{3 \times 10^{13} \text{ GeV}} \right)^2
\end{align*}
\]
GWs from NG cosmic strings

Integrate over all redshifts and loop sizes \( (\rightarrow h) \)

\[
\Omega_{GW}(f) = \frac{2\pi^2 f^3}{3H_0^2} \int_0^{h_*} dh \int_0^{z_{PH}} dz h^2 \frac{d^2 R}{dzdh}
\]

\(\rightarrow\) resulting spectrum:
evolution of the phase space density $f_X(t, p)$:

$$\hat{L} f_X(t, p) = \left( \frac{\partial}{\partial t} - \frac{\dot{a}}{a} p \frac{\partial}{\partial p} \right) f_X(t, p) = \sum C_X$$

collision operator: $C_X(Xab.. \leftrightarrow ij..) = $

$$\frac{1}{2g_X E_X} \int \Pi(X | a, b, ..; i, j, ..)(2\pi)^4 \delta^4(P_{out} - P_{in})$$

$$\times [f_i f_j .. | M(ij.. \rightarrow Xab..)|^2 - f_X f_a f_b .. | M(Xab.. \rightarrow ij..)|^2]$$

Friedmann equation: $3M_P^2 \left( \frac{\dot{a}}{a} \right)^2 = \rho_{tot}$

Calculating the time evolution of phase space densities
An Example: Nonthermal $N_1$ Neutrinos

- Boltzmann equation:
  \[
  \hat{L} f_{N_1} = 2 C_{N_1} (\phi_S \rightarrow N_1 N_1) + C_{N_1} (\psi_S \rightarrow \tilde{N}_1^* N_1) + C_{N_1} (N_1 \leftrightarrow \text{MSSM})
  \]
  + initial conditions: tachyonic preheating, $B-L$ gauge boson decay

- solution: comoving number density of nonthermal neutrinos

\[
N_{N_1}^{nt} (t) = N_{N_1}^{PH} (t) + N_{N_1}^{G} (t) + N_{N_1}^{S} (t)
\]

\[
= N_{N_1}^{PH} (t_{PH}) e^{-\Gamma_{N_1}^0 (t-t_{PH})} + N_{N_1}^{G} (t_G) \exp \left[ - \int_{t_G}^{t} dt' \frac{M_1 \Gamma_{N_1}^0}{\mathcal{E}_{N_1} (m_G/2; t_G, t')} \right] \\
+ \int_{t_{PH}}^{t} dt' a^3 (t') \gamma_{S,N_1} (t') \exp \left[ - \int_{t'}^{t} dt'' \frac{M_1 \Gamma_{N_1}^0}{\mathcal{E}_{N_1} (m_S/2; t', t'')} \right]
\]

with

\[
\gamma_{S,N_1} (t) := 2 \frac{N_{\phi_S} (t)}{a(t)^3} \Gamma_{\phi_S \rightarrow N_1 N_1}^0 + \frac{N_{\psi_S} (t)}{a(t)^3} \Gamma_{\psi_S N_1}^0
\]

\[
\mathcal{E}_{N_1} (E_0; t', t) := E_0 \frac{a(t')}{a(t)} \left[ 1 + \left( \frac{a(t)}{a(t')} \right)^2 - 1 \right] \left( \frac{M_1}{E_0} \right)^2 \right]^{1/2}
\]
Boltzmann equation:
\[
\hat{L}f_{N_1} = 2 C_{N_1} (\phi_S \rightarrow N_1 N_1) + C_{N_1} (\psi_S \rightarrow \tilde{N}_1^* N_1) + C_{N_1} (N_1 \leftrightarrow \text{MSSM})
\]
+ initial conditions: tachyonic preheating, $B-L$ gauge boson decay

solution: comoving number density of nonthermal neutrinos

\[
N_{N_1}^{nt}(t) = N_{N_1}^{PH}(t) + N_{N_1}^{G}(t) + N_{N_1}^{S}(t)
\]
\[
= N_{N_1}^{PH}(t_{PH}) e^{-\Gamma_{N_1}^0(t-t_{PH})} + N_{N_1}^{G}(t_G) \exp \left[ - \int_{t_G}^{t} dt' \frac{M_1 \Gamma_{N_1}^0}{\mathcal{E}_{N_1}(m_G/2; t_G, t')} \right]
\]
\[
+ \int_{t_{PH}}^{t} dt' a^3(t') \gamma_{S,N_1}(t') \exp \left[ - \int_{t'}^{t} dt'' \frac{M_1 \Gamma_{N_1}^0}{\mathcal{E}_{N_1}(m_S/2; t', t'')} \right]
\]

Boltzmann equation for $N_1$ solved semi-analytically
Solving the Boltzmann Equations

Spontaneous $B - L$ Breaking

Tracking the evolution of the number densities of all species

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Schematic view

Gauge

Higgs + Inflaton $(S')$

Right-handed Neutrinos $(N_i, \bar{N}_i)$

Radiation $(R)$ + B-L asymmetry $(B-L)$

Gravitinos $(\tilde{G})$

tachyonic preheating

fast process

slow process
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Tracking the evolution of the number densities of all species
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Scale factor $a / a_{PH}$

Inverse temperature $M_1 / T$

$a_{PH}$

abs $N(a)$

$N_1^{\text{th}}$

$N_1^{\text{nt}}$

$B - L$

$\tilde{G}$

$R$

$S$

$10^{-2}$ $10^{-1}$ $10^0$ $10^1$ $10^2$ $10^3$

$10^0$ $10^1$ $10^2$ $10^3$

$10^4$ $10^5$ $10^6$ $10^7$ $10^8$

$10^{-2}$ $10^{-1}$ $10^0$ $10^1$ $10^2$

$10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$

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\[ W = \frac{\sqrt{\lambda}}{2} \Phi (v_{B-L}^2 - 2 S_1 S_2) + \frac{1}{\sqrt{2}} h_i^c n_i^c n_i c S_1 + h_{ij}^\nu n_i^c 5^*_j H_u + W_{MSSM} \]

- parameters of the superpotential: \( \lambda, h_{ij}, v_{B-L} \)
- re-parametrize assuming hierarchical right-handed neutrinos

\[ \Rightarrow v_{B-L}, \ M_1, \ \tilde{m}_1 \]

with \( v_{B-L} = 5 \times 10^{15} \) GeV fixed by hybrid inflation + cosmic strings

- plus sparticle masses \( m_{\tilde{g}} \equiv 1 \) TeV, \( m_{\tilde{G}} \)

Model parameters: \( v_{B-L}, M_1, \tilde{m}_1, m_{\tilde{G}} \)
Reheating Temperature

$T_{RH}(\tilde{m}_1, M_1)$ [GeV]

Inverse temperature $M_1/T$

- plateau in temperature evolution
- controlled by neutrino physics parameters

$T_{RH}$ plays a key role for both DM production and leptogenesis
requiring \( \Omega_{\text{DM}} = 0.11 \) eliminates \( M_1 \).

insert maximal \( CP \)-asymmetry

\[ \Rightarrow \eta_B > \eta_B^{\text{obs}} \]

Consistency of inflation, \( \tilde{G} \)-DM and leptogenesis for \( m_{\tilde{G}} \gtrsim 10 \text{ GeV} \)
\[ \Omega_{\text{LSP}}^h h^2 + \Omega_{\text{LSP}}^G h^2 \approx 0.11 \]

Consistency between inflation, leptogenesis, BBN and DM for e.g.  
\[ m_1 = 0.05 \, \text{eV}, \quad m_{\tilde{h}} < 900 \, \text{GeV}, \quad m_{\tilde{G}} > 10 \, \text{TeV} \]