Spontaneous $B-L$ breaking as the origin of the hot early universe.

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Based on a collaboration with W. Buchmüller and K. Schmitz

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Motivation and Outline

- Inflation
- Reheating
- Dark Matter
- Baryogenesis

$U(1)_{B-L}$ SSB
Qualitative Picture

Quantitative Description

Conclusion
A phase transition in the early universe

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

> ‘accidental’ global symmetry $\rightarrow$ gauge symmetry
> byproduct of other SM extensions, e.g. GUTs
> add right-handed neutrinos for anomaly cancellation
> Spontaneous symmetry breaking via Abelian Higgs mechanism

Supersymmetric framework:

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

Superpotential describing spontaneous breaking of $B-L$
Hybrid inflation and cosmic strings

> Slowly rolling homogeneous scalar field → exponential expansion of the universe.

> 'Stretched' quantum fluctuations → CMB inhomogeneities.

> Hybrid inflation: end of inflation = phase transition

⇒ \( U(1)_{B-L} \) SSB

> Formation of cosmic strings

⇒ \( v_{B-L} \approx 5 \times 10^{15} \) GeV

Hybrid inflation ends in \( U(1)_{B-L} \) phase transition
Tachyonic preheating

- triggered at phase transition ending inflation
- non-perturbative process

$B-L$ Higgs boson

$> \text{long wavelength modes grow exponentially, }$

$s_k(t) = s_k(0)e^{iEt} = s_k(0)e^{\sqrt{m^2-k^2}}$

$> \text{very effective particle production}$

$> \text{can be treated as classical background field}$

Particles coupled to the Higgs boson

$> \text{particle production due to dynamical background field, e.g.}$

$n_X^{(B)} \simeq 10^{-3} g_* m_S^3 f(\alpha, 1.3)/\alpha$  

with $f(\alpha, \gamma) = \sqrt{\alpha^2 + \gamma^2} - \gamma$, $\alpha = m_X/m_S$.

Tachyonic preheating sets the initial conditions for reheating

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- Decay and scattering processes, formation of thermal bath
- Transition to radiation dominated epoch

> Higgs bosons decay into radiation via $N_1, \tilde{N}_1$
> Track reheating process by solving Boltzmann equations
> plateau in temperature evolution $\rightarrow T_{RH}$

Reheating produces an epoch of constant temperature
Leptogenesis:

- Generate matter asymmetry dynamically in lepton sector
- Typically via decay of heavy neutrino
- Transfer to baryon sector via SM processes (Sphalerons)

Here,

- Asymmetry produced during reheating process
- Neutrinos generated thermally and non-thermally

\[
\frac{n_B}{n_\gamma} = (6.19 \pm 0.15) \cdot 10^{-10}
\]

[Komatsu et al. '10]

Thermal and non-thermal contribution to matter asymmetry
Dark matter

- 23% of the energy budget of our universe
- Well motivated candidates in (local) SUSY: neutralino, gravitino

Here, two possibilities:

**Gravitino LSP**

> produced thermally during reheating
> gravitino problem $\rightarrow$ virtue
> relates $m_{\tilde{G}}, m_{\tilde{g}} \overset{T_{RH}}{\leftrightarrow} \tilde{m}_1, M_1$

**Neutralino LSP**

> motivated by hints for Higgs at LHC
> from gravitino decay and thermal production
> bounds on neutralino and gravitino mass

Two viable DM candidates: gravitino and neutralino
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Qualitative Picture
Quantitative Description
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Model parameters

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

> Parameters of the superpotential: \( \lambda, h_{ij}, v_{B-L} \)

> Froggatt-Nielsen parametrization: [Froggatt, Nielsen '79]

\[ Y_{ijk} \sim \eta Q_i + Q_j + Q_k, \quad \eta \approx \frac{1}{\sqrt{300}} \]

+ SM mass hierarchies, hierarchical right-handed neutrinos

⇒ Froggatt - Nielsen charge assignments.

| \( \psi_i \) | 10_3 | 10_2 | 10_1 | 5_3^* | 5_2^* | 5_1^* | n_3^c | n_2^c | n_1^c | \Phi |
|-------------|------|------|------|-------|-------|-------|-------|-------|-------|-----|
| Q_i         | 0    | 1    | 2    | a     | a     | a + 1 | d - 1 | d - 1 | d     | 2(d - 1) |
$W = \frac{\sqrt{\lambda}}{2} \Phi (v_{B-L}^2 - 2 S_1 S_2) + \frac{1}{\sqrt{2}} h_i^c n_i S_1 + h_{ij}^c n_i L_j H_u + W_{MSSM}$

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> Physical parameters:

\[ v_{B-L} \sim \eta^{2a} \frac{v_{EW}^2}{m_\nu}, \quad M_1 \sim \eta^{2d} v_{B-L}, \quad \tilde{m}_1 \equiv \frac{(m_D^\dagger m_D)_{11}}{M_1} \sim \eta^{2a} \frac{v_{EW}^2}{v_{B-L}} \]

> plus sparticle masses $m_{\tilde{G}}, m_{\tilde{g}}$

---

Model parameters: $v_{B-L}, M_1, \tilde{m}_1, m_{\tilde{G}}, m_{\tilde{g}}$
A useful tool: Boltzmann equations

Evolution of the phase space density $f_X(t, p)$

$$\hat{L} f_X(t, p) = \sum C_X$$

Liouville operator:

$$\hat{L} f_\psi(t, p) = \frac{d}{dt} f_\psi(t, p)$$

Collision operator:

$$C_X(Xab.. \leftrightarrow ij..) =$$

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

$$\times [f_if_j..|\mathcal{M}(ij.. \rightarrow Xab..)|^2 - f_X f_a f_b..|\mathcal{M}(Xab.. \rightarrow ij..)|^2],$$

Calculating the time evolution of phase space densities
Solving the Boltzmann equations

Tracking the evolution of the number densities of all species
Reheating temperature

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

\[ T_{RH} \simeq 1.3 \times 10^{10} \text{ GeV} \left( \frac{\tilde{m}_1}{0.04 \text{ eV}} \right)^{1/4} \left( \frac{M_1}{10^{11} \text{ GeV}} \right)^{5/4} \]

\( T_{RH} \) is controlled by neutrino physics parameters

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Baryon asymmetry

\[
\eta_B(\tilde{m}_1, M_1) \quad \text{with} \quad \nu_{B-L} = 5.0 \times 10^{15} \text{GeV}
\]

Consistency of inflation and leptogenesis for
\[0.2 < \frac{M_1}{10^{11} \text{GeV}} < 30\]

\[
\eta_B^{nt} \simeq 6.7 \times 10^{-9} \left( \frac{M_1}{10^{11} \text{GeV}} \right)^{3/2}, \quad \eta_B^{th} \simeq 7.0 \times 10^{-10} \left( \frac{0.1 \text{eV}}{\tilde{m}_1} \right)^{1.1} \left( \frac{M_1}{10^{12} \text{GeV}} \right)
\]

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Consistency of inflation, leptogenesis and dark matter

\[ \Omega_{\tilde{G}} h^2 \approx 0.31 \left( \frac{10^{-3} \text{eV}}{\tilde{m}_1} \right)^c \left( \frac{T_{RH}}{10^{10} \text{GeV}} \right) \left[ 0.13 \left( \frac{m_{\tilde{G}}}{100 \text{GeV}} \right) + \left( \frac{100 \text{GeV}}{m_{\tilde{G}}} \right) \left( \frac{m_{\tilde{g}}}{1 \text{TeV}} \right)^2 \right] \]

with \( c \approx \begin{cases} 0.21 & \text{for } m_1 > 10^{-3} \text{eV} \\ -0.01 & \text{for } \tilde{m}_1 < 10^{-3} \text{eV} \end{cases} \)
Conclusion

Inflation
- hybrid inflation
- large vacuum energy from false vacuum in unbroken B-L phase

Reheating
- tachyonic preheating
- reheating via neutrino decay
- temperature plateau

U(1)$_{B-L}$ SSB
- in broken B-L phase

Dark Matter
- gravitino LSP
  > thermal production
- neutralino LSP
  > th. & non-th. prod.

Leptogenesis
- decay of th. and non-th. right-handed (s)neutrinos

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backup slides
Neutralino production

Setup:

> \( m_{\text{LSP}} \ll m_{\text{squark, slepton}} \ll m_{\tilde{G}} \)
> \( \text{LSP} = '\text{pure}' \text{ wino or higgsino} \)

Thermal production (\( m_{\text{LSP}} \gtrsim 1 \text{ TeV} \)):

\[
\Omega_{\text{LSP}}^{\text{th}} h^2 = c_{\tilde{w}, \tilde{h}} \left( \frac{m_{\text{LSP}}}{1 \text{ TeV}} \right)^2, \quad c_{\tilde{w}} = 0.014, \quad c_{\tilde{h}} = 0.10
\]

Production from heavy gravitino decay:

\[
\Omega_{\text{LSP}}^{\tilde{G}} h^2 = \frac{m_{\text{LSP}}}{m_{\tilde{G}}} \Omega_{\tilde{G}} h^2 \approx 2.7 \times 10^{-2} \left( \frac{m_{\text{LSP}}}{100 \text{ GeV}} \right) \left( \frac{T_{\text{RH}}(M_1, \tilde{m}_1)}{10^{10} \text{ GeV}} \right)
\]
Leptogenesis, BBN

[Matsumoto et al. '05] & observed DM abundance: bounds on $T_{RH}$ as function of $m_{\tilde{G}}$ and $\tilde{m}_1$

$T_{RH}$ as a link between Leptogenesis, BBN and DM
Bounds on neutralino mass

\[ \Omega_{\text{LSP}}^\text{th} h^2 + \Omega_{\tilde{G}}\tilde{G} h^2 = 0.11 \]

Consistency between inflation, leptogenesis, BBN and DM for e.g. \( m_1 = 0.05 \text{ eV}, \ m_{\tilde{h}} < 900 \text{ GeV}, \ m_{\tilde{G}} > 10 \text{ TeV} \)
B-L breaking

Unitary gauge:

\[ S_{1,2} = \frac{1}{\sqrt{2}} S' \exp(\pm iT), \quad V = Z + \frac{i}{2gq_S} (T - T^*) \, . \]

> Supermultiplet $T$ drops out of $W$ and $K$ ('eaten up')
> Gauge supermultiplet becomes massive

Time dependent mass spectrum:

\[ m_{\sigma}^2 = \frac{1}{2} \lambda (3v^2(t) - v_{B-L}^2), \quad m_{\tau}^2 = \frac{1}{2} \lambda (v_{B-L}^2 + v^2(t)), \]
\[ m_{\phi}^2 = \lambda v^2(t), \quad m_{\psi}^2 = \lambda v^2(t), \]
\[ m_{Z}^2 = 8g^2 v^2(t), \]
\[ M_{i}^2 = (h_i^n)^2 v^2(t). \]
Hybrid inflation

Bounds from successful supersymmetric hybrid inflation and cosmic string production:

$$\kappa \sim \sqrt{\lambda}, \quad M \sim v_{B-L}$$

[Hybrid Inflation](#)
Tachyonic preheating

Higgs boson

> acquires tachyonic mass term at end of hybrid inflation
> long wavelength modes grow exponentially
> very effective particle production
> can be treated as classical background field

Particles coupled to the Higgs boson

> particle production due to dynamical background field:

\[
\begin{align*}
    n_B(\alpha) &\simeq 1 \times 10^{-3} g_S m_S^3 f(\alpha, 1.3)/\alpha \\
    n_F(\alpha) &\simeq 3.6 \times 10^{-4} g_S m_S^3 f(\alpha, 0.8)/\alpha
\end{align*}
\]

with \( f(\alpha, \gamma) = \sqrt{\alpha^2 + \gamma^2} - \gamma \)

[Garcia-Bellido, Morales '02]
Thermal gravitino production

\[ \gamma_{\tilde{G}}(T) = \left( 1 + \frac{m_{\tilde{g}}^2(T)}{3m_{\tilde{G}}^2} \right) \frac{54 \zeta(3) g_s^2(T)}{\pi^2 M_P^2} T^6 \left[ \ln \left( \frac{T^2}{m_{\tilde{g}}^2(T)} \right) + 0.8846 \right] \]

[Bolz, Brandenburg, Buchmüller '01]
A representative parameter point

Input parameters:

\[ M_1 = 1.0 \times 10^{11} \text{ GeV} , \quad \tilde{m}_1 = 4.0 \times 10^{-2} \text{ eV} , \quad m_{\tilde{G}} = 135 \text{ GeV} , \quad m_{\tilde{g}} = 1 \text{ TeV} . \]

Resulting parameter values:

\[ m_S = 3.0 \times 10^{13} \text{ GeV} , \quad M_{2,3} = 3.0 \times 10^{13} \text{ GeV} , \]
\[ \Gamma^0_S = 1.2 \times 10^2 \text{ GeV} , \quad \Gamma^0_{N_{2,3}} = 7.1 \times 10^{10} \text{ GeV} , \quad \Gamma^0_{N_1} = 1.1 \times 10^6 \text{ GeV} , \quad \lambda = 3.6 \times 10^{-5} , \quad \epsilon_{2,3} = -3.0 \times 10^{-3} , \quad \epsilon_1 = 9.9 \times 10^{-6} . \]
Scan of the parameter space (III)

$T_{RH} [\text{GeV}]$ such that $\Omega_G h^2 = 0.11$

$\bar{m}_1 [\text{eV}]$ | $m_{\tilde{g}} = 1 \text{ TeV}$

- $3 \times 10^9$
- $2 \times 10^9$
- $1 \times 10^9$
- $5 \times 10^8$
- $3 \times 10^8$

$\nu_{B-L} = 5 \times 10^5 \text{ GeV}$

$\eta_B < \eta_B^{\text{obs}}$

$\eta_B^{\text{nt}} > \eta_B^{\text{obs}}$

$T_{RH} [\text{GeV}]$
Successful leptogenesis: lower bounds on $M_1$ and $T_{RH}$, as function of effective neutrino mass $\tilde{m}_1$

Leptogenesis, BBN [Matsumoto et al. ’05] & observed DM abundance: bounds on $T_{RH}$ as function of $m_{\tilde{G}}$

$T_{RH}$ as a link between Leptogenesis, BBN and DM
$m_{LSP} - m_{\tilde{G}}$ bounds

Higgsino LSP

Wino LSP