Matter and Dark Matter from False Vacuum Decay

PLB 693 (2010) 421
In Collaboration with W. Buchmuller and K. Schmitz
Motivation

**Obs:** ∃ B Asymmetry of the Universe

\[ \eta_B^{\text{obs}} \equiv \frac{n_B}{n_\gamma} \simeq 6 \times 10^{-10} \quad \Rightarrow \quad \eta_B^{\text{sym}} \simeq 10^{-18} \]

**Q?** How to generate B dynamically?
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**Prop:** Use the seesaw $N_R$: (Baryogenesis through leptogenesis) \cite{Fukugida, Yanagida 97}: 

- decay to LH pairs: generation of $L$ asymmetry
- no SM gauge interaction: out-of-equilibrium
- generation of CP asymmetry
- $L$ asymmetry converted to $B$ through sphalerons

Baryon Asymmetry: 

\[ \eta_B = \frac{n_B - n_{\bar{B}}}{n_{\gamma}} = n_{N}^{\text{eq}} \epsilon_{CP} + \epsilon_{sph} \]
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Hierarchical \( N_R \) → \( M_1 \gtrsim 10^{10} \text{ GeV} \)  Thermal \( N_R \) production → \( T_L \gtrsim 10^{10} \text{ GeV} \)
**Leptogenesis vs. SUSY**

**Tension:** unstable gravitinos: BBN constraint [Kawasaki, Kohri, Moroi 05]

\[ T_R \leq 10^5 \text{ GeV} \]
**Leptogenesis vs. SUSY**

**Virtue:** stable gravitinos as DM: Thermal production [Bolz et al. 01; Pradler & Steffen 06]:

\[
\Omega_G h^2 = 0.27 \left( \frac{T_R}{10^{10} \, \text{GeV}} \right) \left( \frac{100 \, \text{GeV}}{m_G} \right) \left( \frac{m_{\tilde{\tau}}}{1 \, \text{TeV}} \right)^2
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Q? Why \(T_L\) and \(T_R\) have the same order of magnitude?
**Thermal leptogenesis:** typical parameters

- Heavy Majorana neutrino mass: $M_1 \sim 10^{10} \text{ GeV}$
- Effective neutrino mass: $\tilde{m}_1 \equiv \frac{(m_D^\dagger m_D)_{11}}{M_1} \sim 10^{-2} \text{ eV}$

→ Heavy Majorana neutrino has a width of: $\Gamma_{N_1}^0 = \frac{\tilde{m}_1}{8\pi} \left( \frac{M_1}{v_{EW}} \right)^2 \sim 10^3 \text{ GeV}$
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**Q?** Could B asymmetry and \( \tilde{\zeta} \) Dark Matter be both generated out of the thermal bath produced by \( N_1 \) decays?
Flavour Model

Superpotential: \[ W_M = h_{i j}^{u} 10_i 10_j H_u + h_{i j}^{d} 5^* 10_j H_d + h_{i j}^{\nu} 5_i^* n_j^c H_u + h_i^{n} n_i^c n_i^c S \]

Symmetry breaking fields \[ \langle H_u \rangle = v_u , \quad \langle H_d \rangle = v_d , \quad \langle S \rangle = v_{B-L} \]
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**Yukawa couplings:** Froggatt-Nielsen U(1) flavour symmetry \([\text{Buchmuller & Yanagida 97}]\)

Yukawas from non-renorm. U(1)\(_{\text{FN}}\) -inv. higher-dim. operators

\[ h_{ij} \propto \eta^{Q_i + Q_j} \quad \eta \equiv v_{\text{FN}} / \Lambda \approx 1 / \sqrt{300} \]

with \( Q_i \) charges and \( \eta \) determined by quark & lepton mass hierarchies
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| \( \psi_i \) | 10_3 | 10_2 | 10_1 | 5_3^* | 5_2^* | 5_1^* | n_3^c | n_2^c | n_1^c |
|---|---|---|---|---|---|---|---|---|---|
| \( Q_i \) | 0 | 1 | 2 | a | a | a+1 | b | c | d |
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|---|---|---|---|---|---|---|---|---|---|
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Specific Example: \( a=1, d=1 \)

- Requirement: \( M_1 \ll M_{2,3} = m_S \) \( \rightarrow \) \( b = c = d-1 = 0 \)
- \( v_{B-L} \sim 3 \times 10^{12} \text{ GeV} \quad M_1 \sim 10^{10} \text{ GeV} \quad M_{2,3} = m_S \sim v_{B-L} \)
Cosmological Scenario

False vacuum decay after Hybrid inflation:
If $B-L$ symmetry breaking field couple to the inflaton, Then
1. responsible for SSB and generation of Neutrino masses
2. responsible for the sudden end of the inflationary era

$V(\phi, S)$

$\phi$

$s$
**Cosmological Scenario**

**False vacuum decay after Hybrid inflation:**
If $B$-$L$ symmetry breaking field couple to the inflaton, Then
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**Dynamics of symmetry breaking:**
Tachyonic instability in the S potential for $\phi < \phi_{\text{crit.}}$ causes spinodial growth of long-wavelength S modes: **Tachyonic preheating** [Felder et al. 2001]
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False vacuum energy \( \rho_0 = \frac{1}{4} \lambda v_{B-L}^4 \)
- nonrelativistic gas of S bosons
- heavy neutrinos \( N_i \)

For the considered flavor model:
\( \rho_{N_1}/\rho_0 = \mathcal{O}(\eta^4) \), \( \rho_{N_{2,3}}/\rho_0 \approx 10^{-3} \)

\[
\rho_s \approx \rho_0 \\
\rho_{N_i}/\rho_0 \approx 1.5 \times 10^{-3} g_N f(h_i^n/\sqrt{\lambda}, 0.8)
\]

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Cosmological Scenario: Initial State

False vacuum decay

- B-L breaking
- Tachyonic preheating

Higgs bosons $S$

Neutrinos $N_{2,3}$

\[ N_{2,3} \rightarrow LH, \overline{LH} \]

Radiation $R$

B-L asymmetry

Initial State

- Neutrinos $N_{2,3}$
- Radiation $R$

- Higgs bosons $S$

Non-perturbative

Out of kinetic equil.

In kinetic equil.

Non-relativistic

Relativistic
**Cosmological Scenario: Non Thermal N₁**

- False vaccum decay
  - B-L breaking
  - Tachyonic preheating

  **Higgs bosons S**
  \[ S \rightarrow N₁ N₁ \]

  **Neutrinos N₂₃**
  \[ N₂₃ \rightarrow LH, \overline{LH} \]

  **Non-thermal neutrinos N₁**
  \[ N₁ \leftrightarrow LH, \overline{LH} \]

  **B-L asymmetry**

- Radiation R
  \[ N₁ \leftrightarrow LH, \overline{LH} \]

- Gravitinos \( \tilde{G} \)
  \[ SUSY\text{ QCD }2 \rightarrow 2 \]
Cosmological Scenario: Thermal $N_1$

- False vacumm decay
  - $B$-$L$ breaking
  - Tachyonic preheating
- Higgs bosons $S$
  - $S \rightarrow N_1 N_1$
- Neutrinos $N_{2,3}$
  - $N_{2,3} \rightarrow LH, \bar{LH}$
  - $N_{2,3} \rightarrow LH, \bar{LH}$
- Non-thermal neutrinos $N_1$
  - $N_1 \leftrightarrow LH, \bar{LH}$
- Thermal neutrinos $N_1$
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- Radiation $R$
  - SUSY QCD $2 \rightarrow 2$
- Gravitinos $\tilde{G}$

- Non-perturbative
- Out of kinetic equil.
- In kinetic equil.
- Non-relativistic
- Relativistic
Cosmological Evolution

Evolution of the comobile densities $N_i \equiv a^3 n_i$ with the scale factor $a$

- $M_1 = 10^{10}$ GeV
- $M_{2,3} = 3 \times 10^{12}$ GeV
- $\tilde{m}_1 = 10^{-3}$ eV
- $\epsilon_1 = 10^{-6}$
- $\epsilon_{2,3} = -3 \times 10^{-4}$
- $M_{\tilde{G}} = 100$ GeV
- $M_{\tilde{g}} = 800$ GeV

![Graph showing cosmological evolution with scale factor $a$ on the x-axis and $\log_{10} \text{abs} N_i(a)$ on the y-axis.]
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$\eta_B = 1.6 \times 10^{-7} > \eta_B^{\text{obs}} = 6.2 \times 10^{-10}$

$\Omega_{\tilde{G}} h^2 = 0.11 = \Omega_{\text{DM}} h^2$
**Cosmological Evolution**

Reheating temperature:

\[ T_R \simeq 5 \times 10^9 \text{GeV} \]

in agreement with the estimate

\[ T_R = \left( \frac{90}{8\pi^3 g_*} \right)^{1/4} \sqrt{\Gamma_M} \approx 8 \times 10^9 \text{GeV} \]
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Extreme cases:

\[ \eta_B = 1.6 \times 10^{-7} \]

- thermal leptogenesis:

\[ \eta_{\text{thermal}} = \frac{3}{4} \frac{g_*^0}{g_*} c_{\text{sph}} \epsilon_1 \kappa_f (\tilde{m}_1) \simeq 5 \times 10^{-10} \]

- rapid nonrelativistic \( N_1 \) conversion

\[ \eta_{\text{rapid}} = 7 \frac{3}{4} c_{\text{sph}} \epsilon_1 \frac{T_L}{M_1} \simeq 9 \times 10^{-7} \]

\[ (M_1, \tilde{m}_1) \] drives the interpolation between thermal and nonthermal leptogenesis.
## Summary

### Ingredient: Seesaw extension of the SM
- Heavy Majorana neutrinos $N_i$
- $B$-$L$ symmetry breaking field $S$

### Recipe: Reheating of universe through $N_1$ decays
- Non-thermal $N_1$ production from $S$ decays after false vacuum decay
- Tachyonic preheating after hybrid inflation

### In the end: A common origin of Matter and Dark Matter
- Combination of thermal and non-thermal leptogenesis
- Thermal production of gravitinos
- Link between SUGRA and neutrino mass: $\tilde{m}_1 \leftrightarrow m_{\tilde{G}}$
Backup
Matter & DM Backup

- Boltzmann equations
- SUSY Dependance
- Baryon Asymmetry
- Reheating Temperature
\[ \hat{L}[f_S(t,p)] = - \frac{m_S}{E_S} \Gamma^0_S f_S(t,p) \]

\[ \hat{L}[f^S_{N_1}(t,p)] = - \frac{M_1}{E_{N_1}} \Gamma^0_{N_1} f^S_{N_1}(t,p) + \frac{2\pi^2 n_S \Gamma^0_S}{E^2_{N_1}} \left[ 1 - \left(\frac{2M_1}{m_S}\right)^2 \right]^{-1/2} \delta (E_{N_1} - m_S/2) \]

\[ aH \frac{d}{da} N^T_{N_1} = - \Gamma_{N_1} (N^T_{N_1} - N^{eq}_{N_1}) \]

\[ aH \frac{d}{da} N_{B-L} = \epsilon_1 \Gamma_{N_1} (N^T_{N_1} - N^{eq}_{N_1}) - \frac{N^{eq}_{N_1}}{2N^L_{eq}} \Gamma_{N_1} N_{B-L} + \epsilon_1 \Gamma^0_{N_1} \tilde{N}^S_{N_1} \]

\[ aH \frac{d}{da} N_{\tilde{G}} = a^3 C_{\tilde{G}}(T) \]

\[ 0 = \frac{d}{dt} (\rho_R + \rho^T_{N_1} + \rho_S + \rho^S_{N_1}) + 3H (\rho_R + \rho^T_{N_1} + \rho_S + \rho^S_{N_1} + p_R + p^T_{N_1} + p^S_{N_1}) \]

with

\[ N_X(t) = a^3 \frac{g_X}{(2\pi)^3} \int d^3 p \, f_X(t,p) \]

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

$\eta_B(\bar{m}_1, M_1)$

$\nu_{B-L} = 5.8 \times 10^{13} \text{ GeV}$

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

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

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

$\eta_B^S = \eta_B^T$

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Matter & DM from False Vacuum Decay

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SUSY Dependance

$M_1$ [GeV] s.t. $\Omega_C h^2 = 0.11$ and $\eta_B(\tilde{m}_1, M_1)$

$\eta_B(\tilde{m}_1, M_1)$

10^{-6.5}
10^{-7}
10^{-7.5}
10^{-8}
10^{-8.5}
10^{-9}

$\nu_{B-L} = 5.8 \times 10^{13}$ GeV ; $m_{\tilde{g}} = 800$ GeV

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Reheating Temperature

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

$\tilde{m}_1$ [eV]

$M_1$ [GeV]

$\nu_{\tilde{R}, i} = 5.8 \times 10^{13}$ GeV

Legend:
- Naive estimate
- Time dilatation included
- Assumption $\rho_{\text{tot}} \approx \rho_R$ dropped
- Exact result from the BEqns.