Reconciling Supersymmetry and Thermal Leptogenesis by Entropy Production

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Based on Jasper Hasenkamp, JK, PRD 82, arXiv:1008.1740 [hep-ph]

Leptogenesis

- See-saw mechanism
  Heavy neutrinos ν_R with Majorana masses M_R
  $\rightsquigarrow$ very light observed neutrinos

- Leptogenesis
  ν_R decays in early universe $\rightsquigarrow$ C, CP violation

$$|\epsilon| = \frac{|\Gamma(\nu_\mathrm{R} \to \ell H) - \Gamma(\nu_\mathrm{R} \to \bar{\ell}\,\overline{H})|}{\Gamma(\nu_\mathrm{R} \to \ell H) + \Gamma(\nu_\mathrm{R} \to \bar{\ell}\,\overline{H})} < \frac{3}{16\pi} \frac{M_\mathrm{R}\sqrt{\Delta m^2_\mathrm{atm}}}{v^2}$$

  $\rightsquigarrow$ baryon asymmetry $\eta_\mathrm{B} = \frac{n_B}{n_\gamma} \propto |\epsilon| < M_\mathrm{R} \cdot \ldots$

- Observed $\eta_\mathrm{B} \sim 6 \cdot 10^{-10} \rightsquigarrow M_\mathrm{R} \gtrsim 2 \cdot 10^9$ GeV

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- Observed $\eta_B \sim 6 \cdot 10^{-10} \rightsquigarrow M_R \gtrsim 2 \cdot 10^9$ GeV
- Thermal leptogenesis: ν_R produced thermally at $T > M_R$

Reheating temperature $T_R \gtrsim 2 \cdot 10^9$ GeV

By-Product: Gravitinos

- Superpartner of graviton in supergravity
- Thermal production at high temperature

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$$\Omega^{\text{tp}}_{3/2} h^2 \simeq 0.11 \left(\frac{T_\text{R}}{2 \cdot 10^9\,\text{GeV}} \right) \left(\frac{67\,\text{GeV}}{m_{3/2}} \right) \left(\frac{M_{\widetilde{g}}}{10^3\,\text{GeV}} \right)^2$$

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- Observed dark matter abundance: $\Omega_{\mathrm{DM}} h^2 \simeq 0.11$

$\rightsquigarrow$ Compatible with thermal leptogenesis:

- Gravitino LSP with mass $\gtrsim 60$ GeV
- Heavier non-LSP gravitino

Gravitino Problem

- Gravitino interacts via gravity $\leadsto$ extremely weakly
  $\leadsto$ lifetime for decays gravitino $\to \widetilde{X}$ and $\widetilde{X} \to$ gravitino
  $\sim 10^{-2}$ s ... years

Gravitino Problem

- Gravitino interacts via gravity $\rightsquigarrow$ extremely weakly
  - $\rightsquigarrow$ lifetime for decays gravitino $\to \widetilde{X}$ and $\widetilde{X} \to$ gravitino $\sim 10^{-2}$ s ... years
- Energetic decay products destroy nuclei produced in Big Bang Nucleosynthesis (BBN)
- Unstable gravitino: $T_\mathrm{R} \lesssim 10^7$ GeV or $m_{3/2} \gg 1$ TeV
  - $\rightsquigarrow$ Conflict with thermal leptogenesis, or unnatural spectrum
- Gravitino LSP: Next-to-LSP (NLSP) long-lived
  - $\rightsquigarrow$ Ruled out for standard cosmology (exception: sneutrino)

Solutions

- Abandon SUSY
- Abandon thermal leptogenesis
- Fine-tune to exploit loopholes
- Very heavy gravitino
- Gravitino LSP $+$ harmless NLSP
  - New interactions $\rightsquigarrow$ faster decay
  - Very light gravitino $\rightsquigarrow$ faster decay, $\Omega_{3/2} \not\propto T_\mathrm{R}$
  - Harmless decay products
  - Abundance smaller than thermal relic abundance
- Arbitrary combinations

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1. The Gravitino Problem
2. Entropy Production
3. Candidates for Entropy Producers

NLSP Dilution by Entropy Production

- BBN bounds depend on $\Omega_{\text{NLSP}} \propto \frac{n_{\text{NLSP}}}{n_\gamma} \propto \frac{\text{number density}}{\text{entropy density}}$
- Increase of entropy by factor Δ (after freeze-out)

  $\rightsquigarrow$ dilution of NLSP density: $\Omega_{\text{NLSP}} \to \frac{\Omega_{\text{NLSP}}}{\Delta}$

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- Entropy from decay of non-relativistic particle ϕ

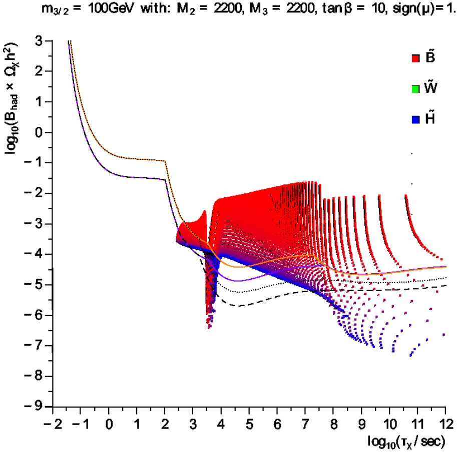
$$\frac{\rho_\phi}{\rho_{\text{rad}}} \propto \frac{R^{-3}}{R^{-4}} = R$$

  $\rightsquigarrow$ ϕ dominates energy density eventually
- Maximal dilution:

$$\Delta \lesssim 10^3$$

Neutralino NLSP with Entropy Production

- Gravitino LSP, $m_{3/2} = 100$ GeV
- Neutralino NLSP, $100 \text{ GeV} < m_{\text{NLSP}} < 2 \text{ TeV}$
- $\Delta = 10^3$



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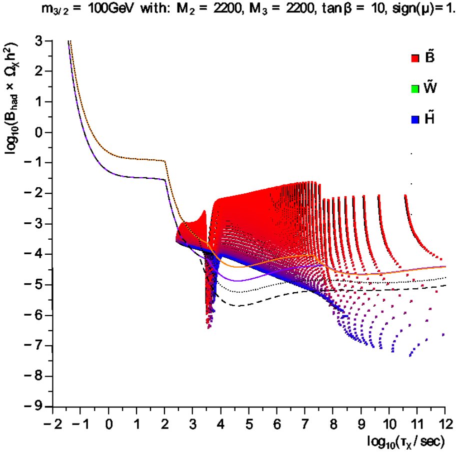

- Light neutralinos allowed for significant higgsino or wino content
- Pure binos remain excluded

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General Requirements

1. $T_{\rm dec} < T_{\rm fo}$ $\rightsquigarrow$ dilute $\Omega_{\rm NLSP}$
2. $T_{\rm dec} \gtrsim 4$ MeV $\rightsquigarrow$ BBN ok
3. $\frac{\rho_\phi}{\rho_{\rm rad}}(T_{\rm dec}) > 1$ $\rightsquigarrow$ $\Delta \gg 1$
4. $\frac{\rho_\phi}{\rho_{\rm rad}}(T_{\rm fo}) < 1$ $\rightsquigarrow$ standard NLSP freeze-out
5. $\mathrm{Br}(\phi \to \mathrm{NLSP}) \simeq 0$ $\rightsquigarrow$ solution of NLSP decay problem
6. $\mathrm{Br}(\phi \to \mathrm{Gravitino}) \simeq 0$ $\rightsquigarrow$ correct $\Omega^{\rm tp}_{3/2} = \Omega_{\rm DM}$
7. Compatibility with gravitino DM (e.g., gravitino remains stable)
8. Well-behaved superpartners

Generic or necessary for long-lived particles even without demanding entropy production

Entropy from Saxion Decays

- Strong CP problem $\rightsquigarrow$ Peccei-Quinn mechanism $\rightsquigarrow$ axion
- SUSY: axion supermultiplet (axion, saxion ϕ, axino)
- Interactions suppressed by characteristic scale $f_a \gtrsim 10^9$ GeV

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- Saxion produced in thermal equilibrium:

$$\Delta \lesssim 55 \left(\frac{f_a}{10^{12}\,\text{GeV}} \right)^{\frac{2}{3}} \ll 10^3 \quad ☹$$

- Failure due to conflicting requirements:
  - Sufficient production $\rightsquigarrow$ strong coupling (small f_a)
  - Late decay $\rightsquigarrow$ weak coupling (large f_a)
- Generic if same coupling responsible for production and decay

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- Further problem with axino

Non-Thermally Produced Saxion

- Saxion field displaced from potential minimum during inflation
- Oscillations around minimum $\rightsquigarrow$ non-relativistic particles
- Production and decay decoupled $\rightsquigarrow$ consistent scenario

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- Oscillations around minimum $\rightsquigarrow$ non-relativistic particles
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- Example with maximal dilution factor:

$$\begin{aligned}
\Delta &\sim 10^3 \\
\text{Saxion mass} &\sim 10\ \text{GeV} \\
\text{Axino mass} &\sim 1\ \text{TeV} \\
f_a &\sim 10^{10}\ \text{GeV} \\
\text{Initial amplitude} &\sim 10^4\, f_a \\
m_{\text{NLSP}} &\simeq 200\ \text{GeV} \\
m_{3/2} &\simeq 100\ \text{GeV}
\end{aligned}$$

Conclusions

- Gravitino problem in SUSY scenarios with thermal leptogenesis
- Solution: gravitino LSP, dilution of NLSP by entropy
- Neutralino NLSP with large higgsino or wino component ok
- Constraints on entropy-producing particle
- Thermally produced particles fail
- Saxion produced in oscillations works

Other Effects of Entropy

- ☺ $\Omega_{\text{NLSP}} \longrightarrow \frac{\Omega_{\text{NLSP}}}{\Delta}$
- ☺ Gravitino density: $\Omega_{3/2} \longrightarrow \frac{\Omega_{3/2}}{\Delta}$
- ☹ Baryon asymmetry: $\eta_{\text{B}} \longrightarrow \frac{\eta_{\text{B}}}{\Delta}$

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$\leadsto$ To keep observed η_{B}:
$M_{\text{R}} \to M_{\text{R}}\Delta$ and $T_{\text{R}} \to T_{\text{R}}\Delta$

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Without Δ	With Δ
η_B	η_B
T_R	$T_\text{R}\,\Delta$
$\Omega_{3/2}$	$\Omega_{3/2}$
Ω_NLSP	$\frac{\Omega_\text{NLSP}}{\Delta}$