Reconciling Supersymmetry and Thermal Leptogenesis

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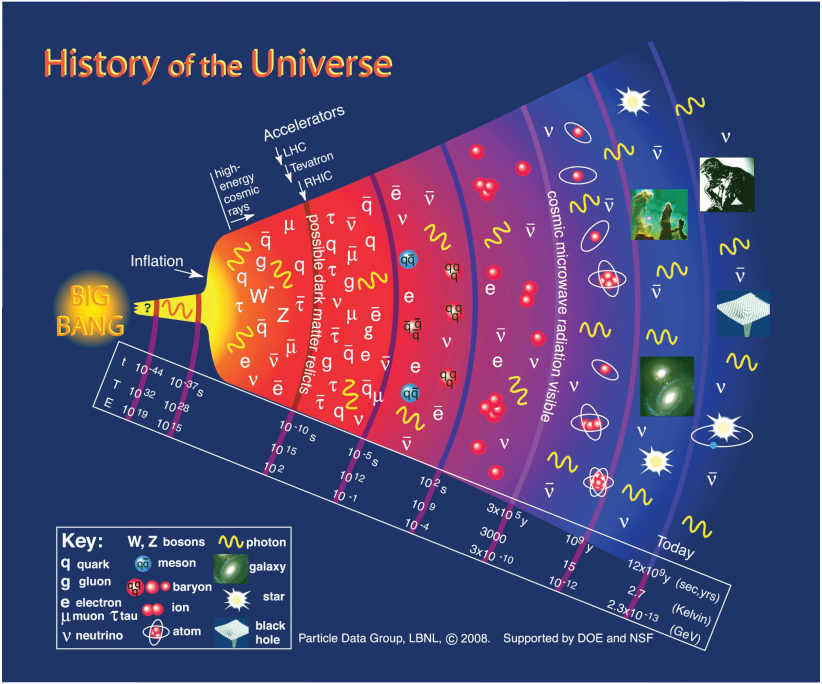
Based on Jasper Hasenkamp, JK, Phys. Rev. **D82** (2010) and Phys. Lett. **B701** (2011)

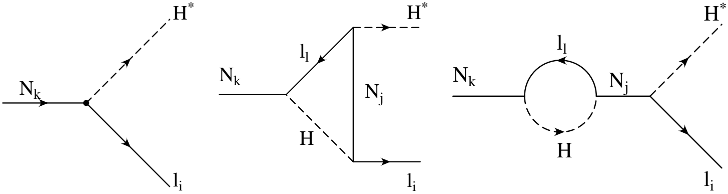
Outline

1. The Gravitino Problem
2. Entropy Production
3. Candidates for Entropy Producers
4. R-Parity Violation


History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
µ muon τ tau
atom
black hole
ν neutrino
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Leptogenesis

- Gauge singlet neutrinos N
- Large Majorana masses $M_\mathrm{R} \gtrsim 10^9$ GeV
- Related to light neutrino masses: see-saw mechanism
- C, CP violation in decays



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

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- Sphalerons (non-perturbative processes)
  $\rightsquigarrow$ baryon asymmetry $\eta_\mathrm{B} = \frac{n_B}{n_\gamma} \propto |\epsilon| < M_\mathrm{R} \cdot \ldots$
- Observed $\eta_\mathrm{B} \simeq 6 \cdot 10^{-10} \rightsquigarrow M_\mathrm{R} \gtrsim 2 \cdot 10^9$ GeV

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- Thermal leptogenesis: N produced thermally at $T > M_\mathrm{R}$

$$T_\mathrm{R} \gtrsim 2 \cdot 10^9 \text{ GeV}$$

Gravitino Production

- Thermal production at high temperature

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

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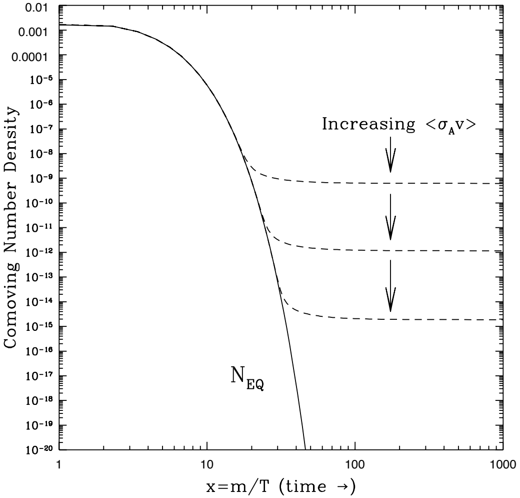
- Observed dark matter abundance: $\Omega_{\mathrm{DM}} h^2 \simeq 0.11$

$\rightsquigarrow$ Compatible with thermal leptogenesis:

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

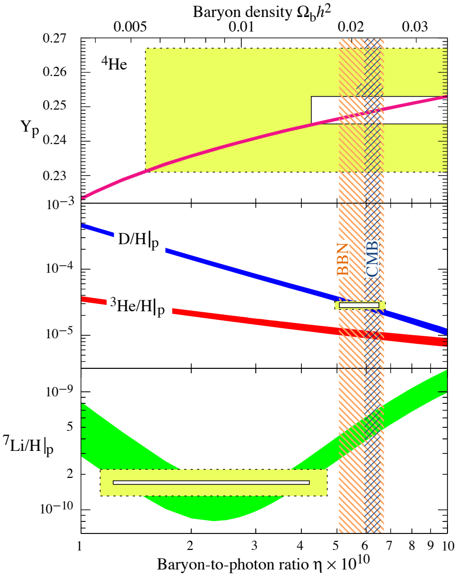
WIMP Freeze-Out



- Weakly interacting stable particle χ
- Thermal equilibrium: $N_\chi \propto e^{-T/m_\chi}$
- Annihilation rate $\Gamma(\chi\bar{\chi} \to xy) < H$
  $\rightsquigarrow$ freeze-out: $N_\chi = \text{const.}$
  $\rightsquigarrow$ relic density Ω_χ determined
- $T_{\text{fo}} \sim \dfrac{m_\chi}{25}$

Big Bang Nucleosynthesis

- $T \sim 1$ MeV or $t \sim 1$ s:
  freeze-out of $n \leftrightarrow p$
  $\rightsquigarrow n/p$ ratio fixed
- $T \sim 0.1$ MeV: $p + n \to \mathrm{D}$
- Afterwards formation of
  ^{3}He, ^{4}He, ^{7}Li
- Abundances depend on
  baryon density (Ω_B or η_B)
- Agree with observations for
  standard cosmology



Gravitino Problem

- Gravitino interacts via gravity
  $\rightsquigarrow$ extremely weakly
  $\rightsquigarrow$ lifetime $\sim 10^{-2}$ s ... years
- Energetic decay products destroy nuclei produced in Big Bang Nucleosynthesis
- Distortions of the Cosmic Microwave Background (less constraining)

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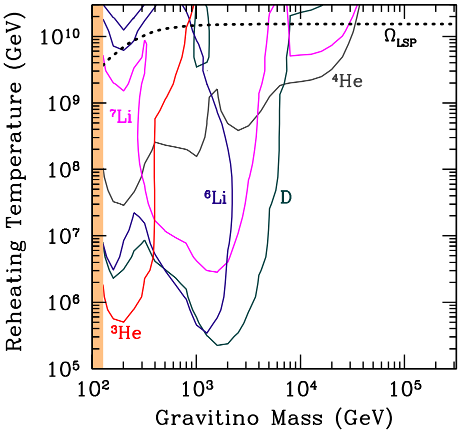

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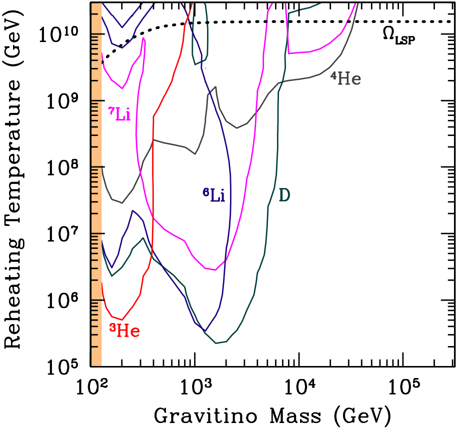


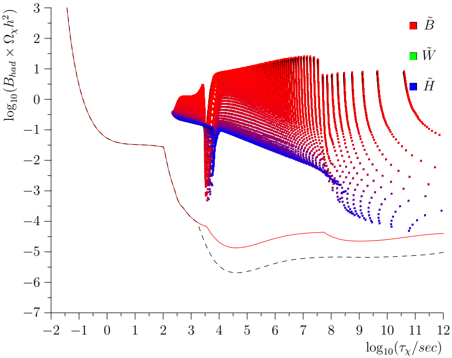
$\rightsquigarrow$ $T_R \lesssim 10^7$ GeV or $m_{3/2} \gg 1$ TeV

$\rightsquigarrow$ Conflict with thermal leptogenesis, or unnatural spectrum

Big Bang Nucleosynthesis with Gravitino LSP

- Gravitino LSP: Next-to-LSP (NLSP) long-lived
- BBN bounds depend on kind of NLSP
- Assume Ω_{NLSP} to be given by thermal relic density
- Neutralino ruled out unless very heavy

$m_{3/2} = 100GeV$ with: $M_2 = 2200$, $M_3 = 2200$, $\tan\beta = 10$, sign(μ)=1.



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- Stau decays can be ok, but bound states with nuclei change BBN reaction rates $\rightsquigarrow$ overproduction of ^{6}Li
- Sneutrino mostly harmless

$\rightsquigarrow$ Gravitino problem remains as NLSP decay problem

Solutions

- Abandon SUSY
- Abandon thermal leptogenesis
- R-symmetry restoration $\rightsquigarrow$ suppression of gravitino production?
- 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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NLSP Dilution by Entropy Production

- BBN bounds depend on $\Omega_{\text{NLSP}} \propto \dfrac{N}{S}$

  $S =$ comoving entropy density
- Increase of entropy after freeze-out: $S \to S\,\Delta$

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

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- Entropy from decay of non-relativistic particle ϕ

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

  $\rightsquigarrow$ ϕ dominates energy density at some time $t_=$, temperature $T_=$
- Candidates: later

Constraints

- Radiation domination at NLSP freeze-out:

$$T_{=} < T_{\text{fo}} \sim \frac{m_{\text{NLSP}}}{25}$$

$\rightsquigarrow$ standard calculation of Ω_{NLSP} applies (ϕ can be ignored)

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$$T_{\rm dec} = T(\tau_\phi) \gtrsim (0.7\ \ldots\ 4)\ \text{MeV}$$

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$\rightsquigarrow$ Maximal dilution factor:

$$\Delta \simeq 0.75\,\frac{T_=}{T_{\mathrm{dec}}} \lesssim 750\left(\frac{m_{\mathrm{NLSP}}}{100\ \mathrm{GeV}}\right) \sim 10^3$$

Other Effects of Entropy

- ☺ $\Omega_{\text{NLSP}} \longrightarrow \frac{\Omega_{\text{NLSP}}}{\Delta}$
- ☺ Gravitino density: $\Omega_{3/2} \longrightarrow \frac{\Omega_{3/2}}{\Delta}$
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$M_{\mathrm{R}} \rightarrow M_{\mathrm{R}}\Delta$ and $T_{\mathrm{R}} \rightarrow T_{\mathrm{R}}\Delta$

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Without Δ	With Δ
η_{B}	η_{B}
T_{R}	$T_{\mathrm{R}}\,\Delta$
$\Omega_{3/2}$	$\Omega_{3/2}$
Ω_{NLSP}	$\frac{\Omega_{\mathrm{NLSP}}}{\Delta}$

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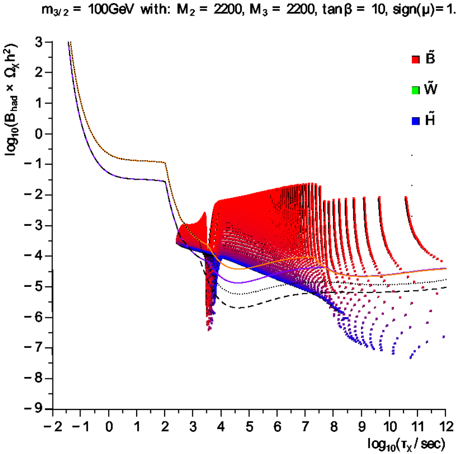
T_{R}	$T_{\text{R}}\,\Delta$
$\Omega_{3/2}$	$\Omega_{3/2}$
Ω_{NLSP}	$\frac{\Omega_{\text{NLSP}}}{\Delta}$

Strong washout of η_{B} for $M_{\text{R}} \gtrsim 10^{13}$ GeV $\leadsto$ slower increase
$\leadsto$ observed η_{B} can only be reached for $\Delta \lesssim 10^3 \ldots 10^4$

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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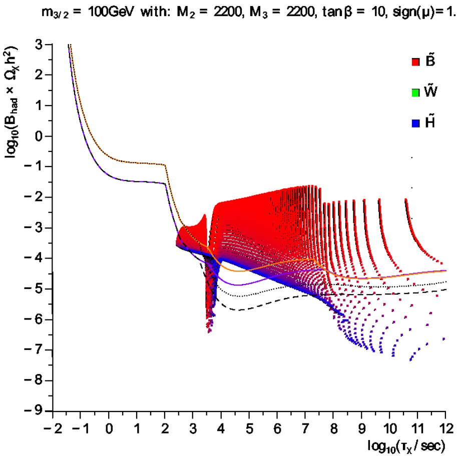

- Light neutralinos allowed for significant higgsino or wino content
- Pure binos remain excluded

$\rightsquigarrow$ Thermal leptogenesis possible

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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 $\widetilde{a}$)
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- Dominant decay $\phi \to gg \rightsquigarrow$ dilution factor:

$$\Delta \gtrsim 55 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{\frac{2}{3}} \ll 10^3 \;\; ☹$$

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- Further problem with axino

Non-Thermally Produced Saxion

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- Example with maximal dilution factor:

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

Axino-Saxion Mass Splitting

- Generically $m_{\tilde{a}} \sim m_{\rm sax} \sim m_{3/2} \rightsquigarrow$ large mass splitting not ideal
- Reason for large $m_{\tilde{a}}$:

$$\Omega_{\tilde{a}} h^2 \simeq 8 \cdot 10^{10} \left(\frac{m_{\tilde{a}}}{1\ \mathrm{TeV}} \right) \left(\frac{T_{\rm R}}{10^9\ \mathrm{GeV}} \right) \left(\frac{10^{10}\ \mathrm{GeV}}{f_a} \right)^2$$

Axinos decay into NLSPs
$\rightsquigarrow$ NLSP decay problem resurrected
$\rightsquigarrow$ axino must decay before NLSP freeze-out
$\rightsquigarrow$ $m_{\tilde{a}} \gtrsim 1$ TeV

R-Parity Breaking

$$W_{\mathrm{RPV}} = \lambda_{ijk} l_i e_j^c l_k + \lambda'_{ijk} d_i^c q_j l_k$$

- R-parity broken only in lepton sector $\rightsquigarrow$ no proton decay
- Preserve baryon asymmetry $\rightsquigarrow \lambda, \lambda' \lesssim 10^{-7}$
- Gravitino lifetime $\sim \frac{M_{\mathrm{Pl}}^2}{\lambda^2 m_{3/2}^2} \gg$ age of universe

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- Gravitino lifetime $\sim \frac{M_{\mathrm{Pl}}^2}{\lambda^2 m_{3/2}^2} \gg$ age of universe
- $\lambda, \lambda' \gtrsim 10^{-14} \leadsto$ NLSP decays to SM particles before BBN $\leadsto$ no decay problem
- Production and decay of axion multiplet unchanged $\leadsto$ axino NLSP remains forbidden

Softened Constraints on Axion Multiplet

- Fast NLSP decay $\rightsquigarrow$ axino may decay just before BBN
- Allowed spectra depend on axion model
  - $m_{\widetilde{g},\widetilde{\tau}} > m_{\widetilde{a}} > m_{\chi_1^0}$ allowed for KSVZ and DFSZ
  - $m_{\widetilde{g},\chi_1^0} > m_{\widetilde{a}} > m_{\widetilde{\tau}}$ allowed only for DFSZ

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- Axion density $< \Omega_{\mathrm{DM}} \rightsquigarrow f_a \lesssim 10^{10}$ GeV
- Larger f_a possible with entropy production

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
- R-parity violation also works
- Relaxes constraints on axion multiplet
  $\rightsquigarrow$ helps to solve strong CP problem