Reconciling Supersymmetry and Thermal Leptogenesis

Jörn Kersten

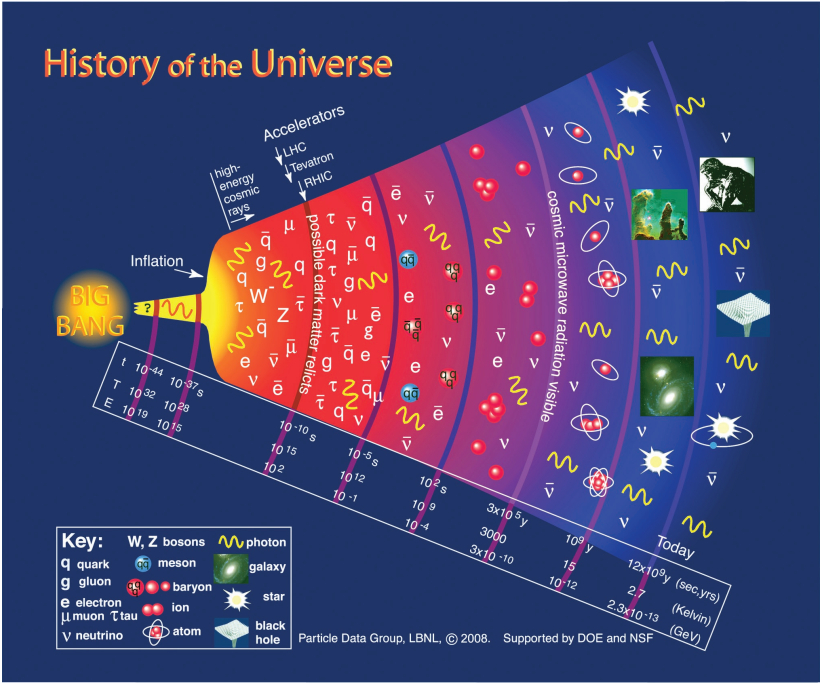
University of Hamburg

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

Outline

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

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


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 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Supersymmetry

- Symmetry between fermions and bosons
- Superpartner for each Standard Model particle:
  different spin, other properties equal

Supersymmetry

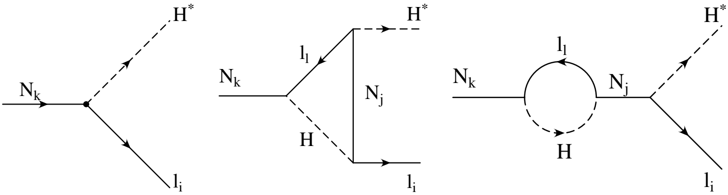
- Symmetry between fermions and bosons
- Superpartner for each Standard Model particle: different spin, other properties equal
    - Bino
Neutral Wino
2 Higgsinos $\Bigg\} \longrightarrow$  $\longrightarrow$ 4 neutralinos
    - Gravitino (in supergravity)

Supersymmetry

- Symmetry between fermions and bosons
- Superpartner for each Standard Model particle: different spin, other properties equal
  - Bino
Neutral Wino
2 Higgsinos } $\longrightarrow$  $\longrightarrow$ 4 neutralinos
  - Gravitino (in supergravity)
- Lightest superpartner (LSP) stable $\rightsquigarrow$ dark matter candidate

Leptogenesis

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



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

$\rightsquigarrow$ lepton asymmetry $\propto |\epsilon|$

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

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

$\rightsquigarrow$ lepton asymmetry $\propto |\epsilon|$

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

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

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

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

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

Gravitino Production

- Thermal production at high temperature

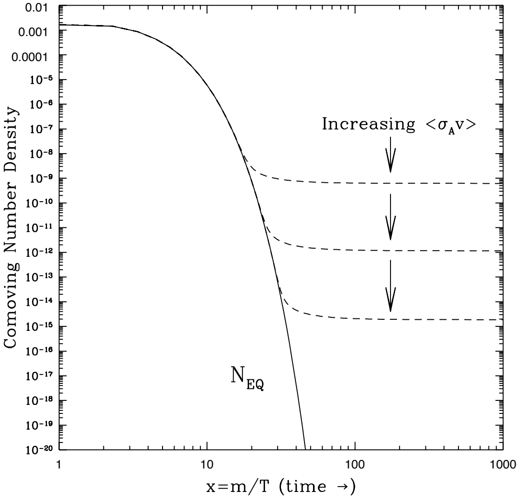
$$\Omega_{3/2}^{\mathrm{tp}} h^2 \simeq 0.11 \left(\frac{T_{\mathrm{R}}}{2 \cdot 10^9\ \mathrm{GeV}} \right) \left(\frac{M_{\tilde{g}}}{10^3\ \mathrm{GeV}} \right)^2 \left(\frac{67\ \mathrm{GeV}}{m_{3/2}} \right)$$

- 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



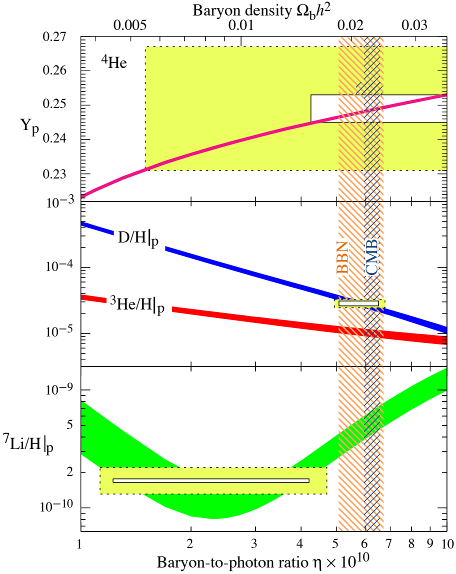
- Weakly interacting stable particle χ
- Thermal equilibrium: $N_\chi \propto e^{-T/m_\chi}$
- Annihilation rate $\Gamma(\chi\overline{\chi} \to xy) < H$
  $\rightsquigarrow$ freeze-out: $N_\chi = \text{const.}$
  $\rightsquigarrow$ relic density Ω_χ determined
- $T_{\text{fo}} \sim \dfrac{m_\chi}{25}$

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: $p + n \rightarrow \mathrm{D}$
- Afterwards formation of $^3\mathrm{He}, {}^4\mathrm{He}, {}^7\mathrm{Li}$
- Abundances depend on baryon density (Ω_B or η_B)
- Agree with observations for standard cosmology

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: $p + n \to \text{D}$
- Afterwards formation of $^3\text{He}, ^4\text{He}, ^7\text{Li}$
- Abundances depend on baryon density (Ω_B or η_B)
- Agree with observations for standard cosmology

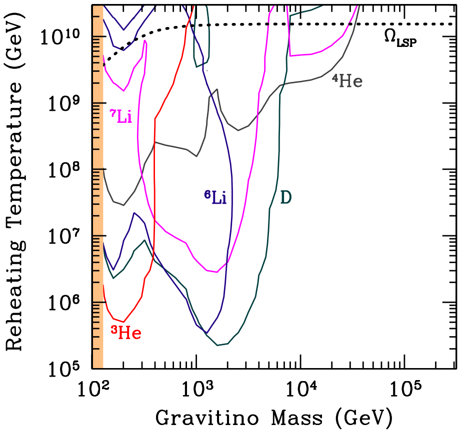


Gravitino Problem

- 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)

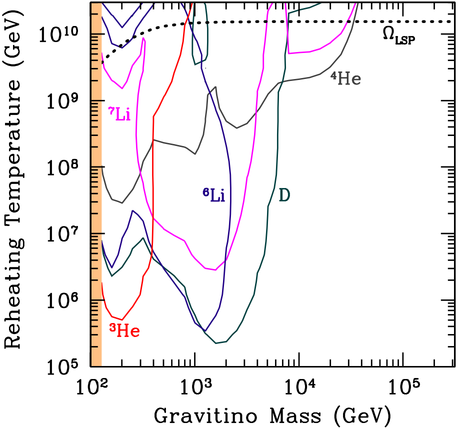
Gravitino Problem

- 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)



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)



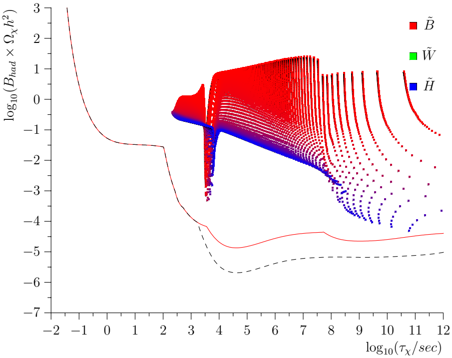
$\rightsquigarrow$ $T_R \lesssim 10^7$ GeV or $m_{3/2} \gg 1$ TeV

$\rightsquigarrow$ 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.



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

Solutions

- Abandon SUSY (heresy)
- 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

Solutions

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

NLSP Dilution by Entropy Production

- BBN bounds depend on $\Omega_{\mathrm{NLSP}} \propto \dfrac{N}{S}$
  $S =$ comoving entropy density
- Increase of entropy after freeze-out: $S \to S\,\Delta$
  $\rightsquigarrow$ dilution of NLSP density: $\Omega_{\mathrm{NLSP}} \to \dfrac{\Omega_{\mathrm{NLSP}}}{\Delta}$
  $\rightsquigarrow$ reduction of impact on BBN

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: $S \to S\,\Delta$

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

  $\leadsto$ reduction of impact on BBN
- Entropy from decay of non-relativistic particle ϕ

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

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

Constraints

- Radiation domination at NLSP freeze-out:

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

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

Constraints

- Radiation domination at NLSP freeze-out:

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

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

- Decay before BBN:

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

Constraints

- Radiation domination at NLSP freeze-out:

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

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

- Decay before BBN:

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

$\rightsquigarrow$ 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

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

Other Effects of Entropy

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

Remember $\eta_{\text{B}} \propto M_{\text{R}}$ and $T_{\text{R}} \gtrsim M_{\text{R}}$

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

$\leadsto$ $\Omega_{3/2} \propto T_{\text{R}}$ unchanged

Other Effects of Entropy

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

Remember $\eta_{\mathrm{B}} \propto M_{\mathrm{R}}$ and $T_{\mathrm{R}} \gtrsim M_{\mathrm{R}}$

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

$\rightsquigarrow$ $\Omega_{3/2} \propto T_{\mathrm{R}}$ unchanged

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

Other Effects of Entropy

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

Remember $\eta_{\mathrm{B}} \propto M_{\mathrm{R}}$ and $T_{\mathrm{R}} \gtrsim M_{\mathrm{R}}$

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

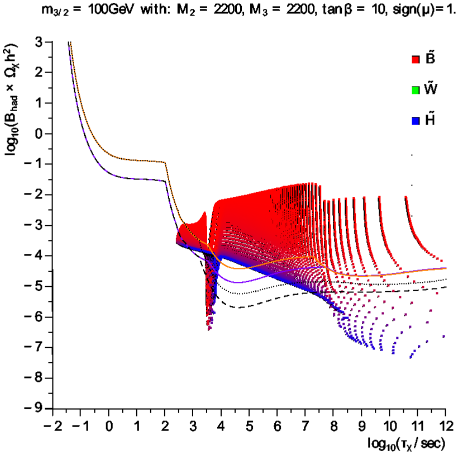
$\rightsquigarrow$ $\Omega_{3/2} \propto T_{\mathrm{R}}$ unchanged

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

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

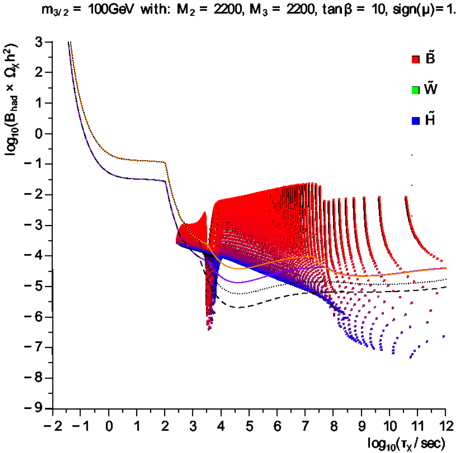
Neutralino NLSP with Entropy Production

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



Neutralino NLSP with Entropy Production

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



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

$\rightsquigarrow$ Thermal leptogenesis possible

General Requirements

1. $T_{\text{dec}} < T_{\text{fo}}$ $\rightsquigarrow$ dilute Ω_{NLSP}

General Requirements

1. $T_{\text{dec}} < T_{\text{fo}}$ $\rightsquigarrow$ dilute Ω_{NLSP}
2. $T_{\text{dec}} \gtrsim 4$ MeV $\rightsquigarrow$ BBN ok

General Requirements

1. $T_{\text{dec}} < T_{\text{fo}}$ $\rightsquigarrow$ dilute Ω_{NLSP}
2. $T_{\text{dec}} \gtrsim 4$ MeV $\rightsquigarrow$ BBN ok
3. $\frac{\rho_\phi}{\rho_{\text{rad}}}(T_{\text{dec}}) > 1$ $\rightsquigarrow$ $\Delta \gg 1$

General Requirements

1. $T_{\text{dec}} < T_{\text{fo}}$ $\quad\rightsquigarrow$ dilute Ω_{NLSP}
2. $T_{\text{dec}} \gtrsim 4$ MeV $\quad\rightsquigarrow$ BBN ok
3. $\frac{\rho_\phi}{\rho_{\text{rad}}}(T_{\text{dec}}) > 1$ $\quad\rightsquigarrow$ $\Delta \gg 1$
4. $\frac{\rho_\phi}{\rho_{\text{rad}}}(T_{\text{fo}}) < 1$ $\quad\rightsquigarrow$ standard NLSP freeze-out

General Requirements

1. $T_{\text{dec}} < T_{\text{fo}}$ $\leadsto$ dilute Ω_{NLSP}
2. $T_{\text{dec}} \gtrsim 4$ MeV $\leadsto$ BBN ok
3. $\frac{\rho_\phi}{\rho_{\text{rad}}}(T_{\text{dec}}) > 1$ $\leadsto$ $\Delta \gg 1$
4. $\frac{\rho_\phi}{\rho_{\text{rad}}}(T_{\text{fo}}) < 1$ $\leadsto$ standard NLSP freeze-out
5. $\text{Br}(\phi \to \text{NLSP}) \simeq 0$ $\leadsto$ solution of NLSP decay problem

General Requirements

1. $T_{\text{dec}} < T_{\text{fo}}$ $\rightsquigarrow$ dilute Ω_{NLSP}
2. $T_{\text{dec}} \gtrsim 4$ MeV $\rightsquigarrow$ BBN ok
3. $\frac{\rho_\phi}{\rho_{\text{rad}}}(T_{\text{dec}}) > 1$ $\rightsquigarrow$ $\Delta \gg 1$
4. $\frac{\rho_\phi}{\rho_{\text{rad}}}(T_{\text{fo}}) < 1$ $\rightsquigarrow$ standard NLSP freeze-out
5. $\text{Br}(\phi \rightarrow \text{NLSP}) \simeq 0$ $\rightsquigarrow$ solution of NLSP decay problem
6. $\text{Br}(\phi \rightarrow \text{Gravitino}) \simeq 0$ $\rightsquigarrow$ correct $\Omega^{\text{tp}}_{3/2} = \Omega_{\text{DM}}$

General Requirements

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

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 $\Omega_{3/2}^{\rm tp} = \Omega_{\rm DM}$
7. Compatibility with gravitino DM (e.g., gravitino remains stable)
8. Well-behaved superpartners

General Requirements

1. $T_{\text{dec}} < T_{\text{fo}}$ $\rightsquigarrow$ dilute Ω_{NLSP}
2. $T_{\text{dec}} \gtrsim 4$ MeV $\rightsquigarrow$ BBN ok
3. $\frac{\rho_\phi}{\rho_{\text{rad}}}(T_{\text{dec}}) > 1$ $\rightsquigarrow$ $\Delta \gg 1$
4. $\frac{\rho_\phi}{\rho_{\text{rad}}}(T_{\text{fo}}) < 1$ $\rightsquigarrow$ standard NLSP freeze-out
5. $\text{Br}(\phi \to \text{NLSP}) \simeq 0$ $\rightsquigarrow$ solution of NLSP decay problem
6. $\text{Br}(\phi \to \text{Gravitino}) \simeq 0$ $\rightsquigarrow$ correct $\Omega_{3/2}^{\text{tp}} = \Omega_{\text{DM}}$
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

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
- Saxion produced in thermal equilibrium for

$$T_{\mathrm{R}} \gtrsim 10^{12}\,\mathrm{GeV}\left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^2$$

- Correct $\Omega^{\mathrm{tp}}_{3/2} \rightsquigarrow$ need $\Delta \sim 10^3$ for $f_a = 10^{12}$ GeV

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
- Saxion produced in thermal equilibrium for

$$T_\mathrm{R} \gtrsim 10^{12}\,\mathrm{GeV}\left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^2$$

- Correct $\Omega^{\mathrm{tp}}_{3/2} \rightsquigarrow$ need $\Delta \sim 10^3$ for $f_a = 10^{12}$ GeV
- Dominant decay $\phi \to gg \rightsquigarrow$ dilution factor:

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

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
- Saxion produced in thermal equilibrium for

$$T_{\mathrm{R}} \gtrsim 10^{12}\,\mathrm{GeV}\left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^2$$

- Correct $\Omega^{\mathrm{tp}}_{3/2} \rightsquigarrow$ need $\Delta \sim 10^3$ for $f_a = 10^{12}$ GeV
- Dominant decay $\phi \rightarrow gg \rightsquigarrow$ dilution factor:

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

- 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

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
- Saxion produced in thermal equilibrium for

$$T_{\rm R} \gtrsim 10^{12}\,\text{GeV}\left(\frac{f_a}{10^{12}\,\text{GeV}}\right)^2$$

- Correct $\Omega_{3/2}^{\rm tp} \rightsquigarrow$ need $\Delta \sim 10^3$ for $f_a = 10^{12}$ GeV
- Dominant decay $\phi \to gg \rightsquigarrow$ dilution factor:

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

- 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
- 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

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
- 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