Dark and visible matter with broken R-parity and the axion multiplet

Jasper Hasenkamp (Hamburg U.)

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University of Hamburg

Universität Hamburg

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Towards consistent cosmology

1) Thermal leptogenesis: origin of **matter**$^{\checkmark}$ $\rightarrow$ no additional ingredients beyond see-saw mechanism.
2) Gravitino **dark matter**$^{\checkmark}$: $\Psi_{3/2}$ inevitable prediction of any local supersymmetric theory $\rightarrow \Omega_{3/2} = \Omega_{\rm DM}$ turns gravitino decay problem into a virtue $\rightarrow \tau_{\rm nlsp}{}^{\dagger} \gg 1$ s $\sim t_{\rm BBN}$ ↯

1+2) $\not{R}$: can solve NLSP decay problem, such that 1) and 2) still work $\rightarrow$ nontrivial observation!* (does not work for $\widetilde{a}$ LSP)

Consistent cosmology should enable solution of strong CP problem

3) Peccei-Quinn mechanism: standard **solution of strong CP problem**? $\rightarrow$ introduces axion $a \xrightarrow{susy} \{a, \phi_{\rm sax}, \widetilde{a}\}$

Solution of the strong CP problem possible? $\rightarrow$ motivation for $\not{R}$

† $\tau_{\rm nlsp} \propto M_{\rm Pl}^2 m_{3/2}^3 / m_{\rm nlsp}^5$ see, e.g., [Covi,JH,Pokorski,Roberts, 09]

* [Buchmüller,Covi,Hamaguchi,Ibarra,Yanagida, 07]

Axion multiplet poses cosmological problems itself

$\mathcal{L}_{\text{PQ}} \propto 1/f_a$, where $f_a \gtrsim 6 \times 10^8$ GeV and $m_{\tilde{a}}, m_{\text{sax}} \sim m_{3/2} \sim m_{\text{susy}}, m_a \ll$ eV

- $\tilde{a}$, ϕ_{sax} produced thermally and decay late $\rightarrow$ may not produce (N)LSPs after freeze-out $\rightarrow$ bounds on $f_a, m_{\tilde{a}}, m_{\text{sax}}$ and/or T_{R}
- ϕ_{sax} also produced in coherent oscillations $\rightarrow$ upper bound on initial amplitude $\phi^{\text{i}}_{\text{sax}}$
- Ω_a^{ntp} from vacuum misalignment and topological defects $\rightarrow$ upper bound on f_a (often quoted $f_a < 10^{12}$ GeV)
- $\phi_{\text{sax}} \rightarrow aa$ gives radiation energy $\rightarrow$ constraints on self-coupling x

1) Thermal leptogenesis $\Rightarrow T_{\text{R}} > T_{\text{L}} \sim \mathcal{O}\left(10^{10}\text{ GeV}\right) \Rightarrow$ axion multiplet likely enters thermal equilibrium $\rightarrow$ maximal thermal abundance $\lightning$
2) Gravitino dark matter $\Rightarrow$ no additional matter allowed $\lightning$

Easy to adapt our work to other situations: without gravitino, leptogenesis,...

Worst case study for the axion multiplet

Impact of broken R-parity

$\looparrowright$ additional $\not{R}$ couplings

i) nonthermal production mechanisms ($\Omega_a^{\text{ntp}}, \phi_{\text{sax}}^{\text{i}}$) not affected

ii) $\not{R}$ interactions of axion multiplet suppressed by:
f_a and **additionally** by $\not{R}$ coupling

$\Rightarrow$ axion multiplet is produced and decays as if R-parity were conserved!
(exception $\widetilde{a}$ NLSP)

iii) NLSP decays cosmologically fast ($\tau_{\text{nlsp}} \ll t_{\text{BBN}} \sim 1$ s)

$\Rightarrow \widetilde{a}$, ϕ_{sax} may decay right before nucleosynthesis $\rightarrow T_{\text{nlsp}}^{\text{fo}}/T_{\text{BBN}} \sim 10^3$

Absence of NLSP decay problem $\Rightarrow$ later decay allowed

What have we done?

- Thermal and nonthermal production mechanisms
- All possible decay channels depending on the axion model and (possibly) the mass spectrum
- DFSZ and KSVZ axion models explicitly $\rightarrow$ applicable to general axion
- Analytical computations, such that analytical formulae are provided
- Comprise everything in one table for comparison

Results I

[GeV]	standard	$\not{R}$
f_a	$\lesssim \mathbf{10^{10}}$ $(\lesssim 10^{11})_{\text{DFSZ}}$	$\lesssim 10^{10}$
$m_{\widetilde{a}}$	$> m_{\widetilde{g}}$ $(> m_{\widetilde{H}} + m_h)_{\text{DFSZ}}$	$> m_{\text{“nlsp”}}$
m_{sax}	$> 760 \left(\frac{f_a}{10^{10}\,\text{GeV}}\right)^{\frac{2}{3}}$ $(> 2m_h)_{\text{DFSZ}}$ or $\in [5 \left(\frac{f_a}{10^{10}\,\text{GeV}}\right)^{\frac{2}{3}}, 2m_{\text{nlsp}}]$	$\gtrsim 5 \left(\frac{f_a}{10^{10}\,\text{GeV}}\right)^{\frac{2}{3}}$
$\phi^{\text{i}}_{\text{sax}}$	$\lesssim 10^{13}$–10^{15}	$\lesssim 10^{13}$–10^{15}

i) bounds on f_a from particle decay superseded by those from Ω_a^{ntp}

ii) m_{sax} practically unconstrained

iii) $\widetilde{a}$ NLSP stays excluded, but anywhere else in the spectrum

iv) x unconstrained for $f_a < 10^{10}$ GeV and $m_{\text{sax}} > 100$ GeV

Naturally expected spectra become allowed

Results II

[GeV]	...	$\not{R}$	$\not{R} \wedge \Delta\|_{T<\Lambda_{\rm QCD}} = \Delta^{\rm max} = 10^4$
f_a	...	$\lesssim 10^{10}$	$\lesssim 4 \times 10^{12}$
$m_{\tilde{a}}$	...	$> m_{\text{“nlsp”}}$	$\gtrsim \max[m_{\text{“nlsp”}}, 300 \left(\frac{f_a}{10^{11}\,\rm GeV}\right)^{\frac{2}{3}}]$
$\rm m_{sax}$	...	$\gtrsim 5 \left(\frac{f_a}{10^{10}\,\rm GeV}\right)^{\frac{2}{3}}$	$\gtrsim 5 \left(\frac{f_a}{10^{10}\,\rm GeV}\right)^{\frac{2}{3}}$
$\phi^{\rm i}_{\rm sax}$	...	$\lesssim 10^{13}$–10^{15}	$\lesssim 5 \times (10^{14}$–$10^{16})$

v) entropy production very restricted possibility*

vi) bounds from “standard” $\Omega_a^{\rm ntp}$ still severe

Nonthermal production: Matter of axion model building

*Entropy may stem from saxion itself [JH,Kersten, 10].

Conclusions and Outlook

- ☺ naturally expected spectra become allowed
  $\longrightarrow$ when MSSM spectrum known, axion models disfavourable
  $\longrightarrow$ DFSZ vs. KSVZ?
- ☺ constraints from particle decay are superseded by those from Ω_a^{ntp}
  $\longrightarrow$ How solid are they?
- ☺ (here) no constraint on saxion-axion-axion-coupling $\longrightarrow$ opportunity to obtain any desired amount of additional radiation energy in the Universe

$\Rightarrow$ Motivation for (supersymmetric) axion model building

- ☺ $R\!\!\!/$ does not only solve the NLSP decay problem, but also makes it easier to solve the strong CP problem $\longrightarrow$ additional motivation for the scenario

$\Rightarrow$ Do other scenarios enable a solution to the strong CP problem? $\longrightarrow$ blueprint

Strong CP problem serves as an additional motivation for broken *R*-parity.

Thank you for your attention!

Hopefully, there are comments/questions?