Gravitino Dark Matter
and General Neutralino NLSP

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Conflict between SUGRA and BBN

- supergravity* (SUGRA) = supersymmetry (SUSY) + general relativity
  - minimal particle content is MSSM + graviton + gravitino $\Psi_{3/2}$
  - $\Psi_{3/2}$ is unique and inevitable prediction of any supersymmetric theory containing gravity!
  - $\Psi_{3/2}$ can be produced in the early universe and has typically long lifetimes $\tau_{3/2} \gg 1$ s (i.e. $\tau_{3/2} \propto M_{pl}^2/m_{3/2}^3$)

- Big Bang Nucleosynthesis (BBN) predicts successfully the light element abundances in the universe
  - Maintaining this success reveals bounds on energy (had/em) emitted by particle decays during or after BBN (i.e. for $t \gtrsim t_{BBN} \approx 1$ s)

Decaying gravitinos may spoil the success of BBN

*We assume that SUGRA is an appropriate low-energy approximation of a more fundamental theory.

‡[Pagels & Primack, 1982 and Ellis, Kim & Nanopoulos, 1984]
Gravitino Dark Matter

1) $\Psi_{3/2}$ is superweakly interacting massive particle (sWIMP)
   ⇒ if $\Psi_{3/2}$ is the lightest supersymmetric particle (LSP), it can be dark matter (DM)

2) If R-parity is conserved, it is stable ⇒ no dangerous $\Psi_{3/2}$ decays

3) **But** next-to-LSP (NLSP) becomes long-lived $\tau_{NLSP} \propto M_{pl}^2 m_{3/2}^2/m_{NLSP}^5$
   ⇒ may in turn spoil BBN

4) large $m_{3/2} \gtrsim 100$ GeV preferable to allow high reheating temperature $T_{RH}$, while $\Omega_{3/2} \lesssim \Omega_{DM} \sim$ high $T_{RH}$ needed for thermal leptogenesis to produce baryon asymmetry

[Fukugita & Yanagida, 1986 and Buchmüller, Bari, Plumacher, 2005]

⇒ Problem is softened*, but investigation is needed to determine lower bounds on $m_{NLSP}$ and upper bounds on $m_{3/2}$

**Bounds on $m_{NLSP}$ and $m_{3/2}$**

* $\tau_{NLSP}/\tau_{3/2} \propto m_{3/2}^5/m_{NLSP}^5 \ll 1$, if $\Psi_{3/2}$ is LSP.
Neutralino NLSP

1) neutralino $\chi$ is one of the lightest particles within MSSM and thus good NLSP candidate (often $\chi$ NLSP $\sim \tilde{B}$)

2) $\chi$ is superposition of bino $\tilde{B}$, wino $\tilde{W}$ and Higgsinos $\tilde{H}_u, \tilde{H}_d$

3) compute relic density $\Omega_\chi h^2 = \frac{\rho_\chi}{\rho_\text{cr}} h^2$ after freeze-out with micrOMEGAs

4) compute all neutralino decay channels $\chi \rightarrow \Psi_{3/2} + \text{SM particles}$
   to determine $\tau_\chi$ and branching ratios $B_{\text{had/em}}$

5) $m_{\text{NLSP}}$ in TeV range preferred

$\implies$ Find mass bounds and in particular how these are relaxed for different compositions

**Bounds on $m_\chi$ and $m_{3/2}$ depend on the $\chi$ composition**

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earlier work: [Feng, Su & Takayama, 2004], (cmssm) [Ellis, Olive, Santoso & Spanos, 2004 and Bailly, Choi, Jedamzik & Roszkowski, 2009], (charged slepton) [Steffen, 2006] and many more...
Example branching ratios

left: branching ratio of $\tilde{B} \rightarrow \Psi_{3/2} q\bar{q}$

right: $B_{had}$ for $\tilde{B}, \tilde{W}$, the maximally mixed case and $\tilde{\gamma}$

- below Z threshold decay dominated by off-shell $\gamma$ and light quarks preferred due to IR logarithmic enhancement
- $B_{had}$ after Z threshold increased for any state except $\tilde{\gamma}$
1) \( \tilde{W} \) and \( \tilde{H} \) with lower number densities \( \Rightarrow \) larger allowed \( m_{3/2} \)

2) at \( m_\chi \sim 100 \) GeV low \( B_{had} \) for \( \tilde{W} \) and \( \tilde{H} \) could allow \( m_{3/2} \sim \) few GeV

BBN bounds taken from [Jedamzik, 2006]
Results

3) resonant Higgs annihilation $(m_{3/2})_{\text{max, res}} \sim 70 \text{ GeV} \left( \frac{m_\chi}{1.15 \text{ TeV}} \right)^{5/2}$

4) $\chi = \tilde{\gamma}$ does not relax the hadronic constraints

5) sfermion coannihilation is order of magnitude effect for $\tilde{B}$ and small effect for $\tilde{W}, \tilde{H}$

6) changing $\tan \beta$ has small effect

**general $\chi$ NLSP extends allowed $m_{3/2}$ by about one order of magnitude**
**substantial hierarchy remains necessary**
thermal leptogenesis and $\Psi_{3/2}$ DM stay hardly reconcilable Higgs resonance region with lowered $m_\tilde{g} \sim m_\chi$, $m_{3/2} \sim 70$ GeV $\tilde{W}$ NLSP just above LEP bound with small $m_\tilde{g}$, $m_{3/2}$ of a few GeV

possibilty of producing $\Omega_{3/2}$ by $\chi$ NLSP decays* is excluded for LHC region

light $\chi$ (except $\tilde{W}$ with degenerate chargino) would be difficult to reconcile with $\Psi_{3/2}$ DM and thermal leptogenesis with conserved R-parity

* [Feng, Rajarama & Takayama, 2003]
**Motivation**

Gravitino Dark Matter and Neutralino NLSP

and LHC?

- gluino mass parameter should be smaller than 2 TeV
  -> main observable $E_{\text{miss}}$ in cascade decays as with $\chi_{\text{DM}}$
- resonant annihilation region needs precise measurements of $m_A$ and $m_{\chi}$
- $\tilde{W}, \tilde{H}$ NLSP easier to identify due to nearly degenerate charginos
  -> difficult to proof $\Omega_{\chi} \ll \Omega_{\text{DM}}$ with LHC alone

$\Rightarrow$ hard to disentangle $\chi_{\text{LSP}}$ and DM from $\Psi_{3/2}$ DM with $\chi$ NLSP

**Results and LHC**

large $m_{\chi}$ and enhanced NLSP annihilation (like Higgs resonance) may be first phenomenological signal for $\Psi_{3/2}$ DM at colliders