Gravitino Dark Matter
with broken R-parity

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# Introduction

“Standard” thermal history of the Universe

| Temperature   | time       | Events                                    |
|---------------|------------|-------------------------------------------|
| $1\text{eV}$  | $10^{13}\text{s}$ | decoupling of photons/CMB                 |
| $1\text{MeV}$ | $1\text{s}$            | decoupling of neutrinos                   |
| 0.1MeV-10MeV  | $10^2 - 10^{-2}\text{s}$| BBN                                      |
| 100MeV        | $10^{-4}\text{s}$     | QCD phase transition                      |
| 100GeV        | $10^{-10}\text{s}$    | EW phase transition                       |
| $10^9 - 10^{10}\text{GeV}$ | $10^{-24} - 10^{-26}\text{s}$ | leptogenesis?                            |
| $?\text{GeV}$ | $?$        | reheating                                 |
| $?$            | $?$        | inflation                                 |
| $?$            | $0$        | Big Bang                                  |

Alejandro Ibarra (DESY)
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- Dark matter
- Dark energy

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Goal for this talk: construct a consistent thermal history of a Universe with supersymmetric dark matter (neutralino/gravitino)

Constraints:

- Leptogenesis \( T \gtrsim 10^9\text{GeV}, t \lesssim 10^{-24}\text{s} \)
- BBN \( (T \sim 0.1 - 10\text{MeV}, t \sim 10^2 - 10^{-2}\text{s}) \)
- CMB \( (T \sim 1\text{eV}, t \sim 10^{13}\text{s}) \)

And of course, the relic dark matter abundance should be the observed one \( \Omega_{DM} \sim 0.23 \).
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**Neutralino dark matter**

★ If the gravitino is **NOT** the lightest supersymmetric particle (i.e. the neutralino is the LSP), it decays into the lightest neutralino and a photon: $\psi_{3/2} \to \chi_1^0 \gamma$. The photons can dissociate the light-elements if the photon energy is above a certain threshold. For example $D + \gamma \to n + p$, $E_{th} = 2.225\text{MeV}$. Very problematic for BBN!

★ Even worst, if $m_{3/2} > m_{\tilde{g}}$ the gravitino could decay into gluon and gluino, that hadronize producing energetic hadrons $\to$ hadro-dissociation of the primordial elements. Other hadronic channels are also dangerous.
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Difficult to reconcile with the leptogenesis requirement $T_R \gtrsim 10^9\text{GeV}$
Gravitino dark matter

Very interesting candidate for dark matter. The relic abundance is:

\[ \Omega_{3/2} h^2 \simeq 0.1 \left( \frac{T_R}{10^9 \text{GeV}} \right) \left( \frac{5 \text{ GeV}}{m_{3/2}} \right) \left( \frac{m_{\tilde{g}}}{500 \text{ GeV}} \right)^2 \]

Nicely compatible with leptogenesis! It requires \( m_{3/2} \gtrsim 5 \text{ GeV} \)

But this is not the end of the story. What is the impact of the next-to-LSP on the thermal history of the Universe?

If the gravitino is the LSP and \( R \)-parity is conserved, the NLSP can only decay gravitationally into gravitinos and SM particles, with a decay rate suppressed by \( M_P \):

\[ \Gamma_{\tilde{\tau}} \simeq \frac{m_{\tilde{\tau}}^5}{48\pi m_{3/2}^2 M_P^2} \implies \text{very long lifetimes.} \]

- RH stau: \( \tilde{\tau}_R \to \tau \psi_{3/2}, \quad \tau_{\tilde{\tau}} \simeq 9 \text{ days} \left( \frac{m_{3/2}}{10 \text{ GeV}} \right)^2 \left( \frac{150 \text{ GeV}}{m_{\tilde{\tau}}} \right)^5 \)

- Neutralino: \( \chi_1^0 \to \gamma \psi_{3/2}, \quad \tau_{\chi_1^0} \simeq 9 \text{ days} \left( \frac{m_{3/2}}{10 \text{ GeV}} \right)^2 \left( \frac{150 \text{ GeV}}{m_{\chi_1^0}} \right)^5 \) (for \( \chi_1^0 = \tilde{\gamma} \)).

The NLSP is present during and after BBN. Their decays could jeopardize the abundances of primordial elements.
Neutralino NLSP

The photons from $\chi_1^0 \rightarrow \gamma \psi_{3/2}$ can dissociate primordial elements. More importantly, $\chi_1^0 \rightarrow Z \psi_{3/2}$ could be kinematically allowed, and the hadronic decays of the $Z$ could be disastrous.

For $\chi_1^0 = \tilde{B}$,

Incompatible with leptogenesis ($m_{3/2} \sim 5 - 100$ GeV).
Right-handed stau NLSP

The decay $\tilde{\tau}_R \rightarrow \tau \psi_{32}$ only releases electromagnetic energy $\rightarrow$ not particularly dangerous.

However, recently another effect of stau NLSP during BBN has been realized: stau catalysis of lithium 6. Pospelov

\[ ^4\text{He} + D \rightarrow ^6\text{Li} + \gamma \]

The cross section for the catalyzed channel is around eight orders of magnitude larger than the standard channel! This leads to an overproduction of $^6\text{Li}$ of a factor 300-600.
Summary of the implications of a high reheat temperature \( (T_R \gtrsim 10^9 \text{ GeV}) \) for SUSY dark matter:

- **Neutralino LSP**
  - \( \psi_{3/2} \rightarrow \chi_1^0 \) hadrons
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BBN is the Achilles’ heel of SUSY dark matter

Root of all the problems: the NLSP is very long lived.

Simple solution: get rid of the NLSP before BBN $\rightarrow$ R-parity violation
Gravitino DM with broken R-parity

The superpotential now reads:

\[ W = W_{MSSM} + \mu_i (H_u L_i) + \frac{1}{2} \lambda_{ijk} (L_i L_j) e^c_k + \lambda'_{ijk} (Q_i L_j) d^c_k + \lambda''_{ijk} (u^c_i d^c_j d^c_k) \]

The coupling \( \lambda_{ijk} \) induces the decay of the right-handed stau. For example, \( \tilde{\tau}_R \rightarrow \mu \nu_\tau \), with lifetime:

\[ \tau_{\tilde{\tau}} \simeq 10^3 \text{s} \left( \frac{\lambda}{10^{-14}} \right)^{-2} \left( \frac{m_{\tilde{\tau}}}{100 \text{ GeV}} \right)^{-1} \]

With more generality, the lightest stau also contains a left-handed stau component, and will (partially) decay hadronically through \( \lambda' \).

Even with a tiny amount of R-parity violation, the stau will decay well before the time of BBN.
Many questions arise:

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The lepton/baryon number violating couplings $\lambda$, $\lambda'$, $\lambda''$ can erase the lepton/baryon asymmetry. The requirement that an existing baryon asymmetry is not erased before the electroweak transition implies:

$$\lambda, \lambda' \lesssim 10^{-7}$$

Plenty of room! $10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}$. In this range leptogenesis is unaffected.
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$$\tau_{3/2} \sim 10^{26} \text{s} \left( \frac{\lambda}{10^{-10}} \right)^{-2} \left( \frac{m_{3/2}}{10 \text{ GeV}} \right)^{-3}$$

(Remember: age of the Universe $\sim 10^{17} \text{s}$)

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**In summary:** The existence of a gravitino LSP with a mass in the range 5-100 GeV, and a small amount of $R$-parity violation $10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}$, is consistent with the “standard” thermal history of the Universe + SUSY dark matter (allows leptogenesis, and does not spoil BBN or CMB observations).
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**Question 1:** is $10^{-14} \lesssim \lambda$, $\lambda' \lesssim 10^{-7}$ reasonable?

**Question 2:** which are the experimental signatures for this scenario?
A model for small (and peculiar) $R$-parity breaking

We want to construct a model with small lepton number violation $(10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7})$ and tiny baryon number violation $(\lambda'\lambda'' \lesssim 10^{-27})$

Some insights to construct such a model:

- For convenience, we use $SO(10)$ notation (but no GUT in our model!). Quarks and leptons in $16_i$, Higgses in $10_H$.

- To give Majorana masses to neutrinos, $B - L$ has to be broken, either by a $\overline{16}$, $16$ (with $B - L = \pm 1$), or by $126$ (with $B - L = 2$). To have just small representations, we use $16$ and $\overline{16} \rightarrow R$-parity is necessarily broken when $\langle 16 \rangle \simeq \langle \overline{16} \rangle = v_{B-L}$. 

There are two types of terms in the superpotential:

16\(i\) 16\(j\) 10\(_H\). "Good term". Produces Dirac masses.

16\(i\) 16\(j\) 16. "Good term". Produces right-handed neutrino masses.

16\(i\) 1610\(_H\). "Bad term". Produces \(v_{B-L} LH_u\). Too large neutrino masses.

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We will forbid the bad terms by means of a $U(1)_R$ symmetry:

|       | $16_i$ | $10_H$ | $\overline{16}$ | $16$ | $1$ |
|-------|--------|--------|-----------------|------|-----|
| $R$   | 1      | 0      | 0               | -2   | -1  |

(the $SO(10)$ singlet has been introduced to break the $R$-symmetry).
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Key point 2: the Kähler potential is not protected by holomorphicity. Terms line $1 \overline{16} 16_i 10_H$, $1^\dagger \overline{16} 16_i 10_H$ can appear in the Kähler potential, producing eventually bilinear $R$-parity violation.
The model

Particle content:

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Particle content:

|     | $Q$, $u^c$, $e^c$, $d^c$, $L$, $\nu^c$ | $H_u$, $H_d$ | $N$ | $N^c$ | $\Phi$ | $X$ | $Z$ |
|-----|-----------------------------------|-------------|-----|-------|-------|-----|-----|
| $B - L$ | $\pm 1/3, \pm 1$ | 0 | 1 | -1 | 0 | 0 | 0 |
| $R$ | 1 | 0 | 0 | -2 | -1 | 4 | 0 |

$\Phi$ and $Z$ are spectator fields, $\langle \Phi \rangle = v_{B-L}$ and $\langle Z \rangle = F_Z\theta\theta$.

The effective theory is described by $W \simeq W_{\text{MSSM}} + W_{\nu^c} + W_{R_P}$:

- $W_{\text{MSSM}} = h^e L H_d e^c + h^d Q H_d d^c + h^u Q H_u u^c + \mu H_u H_d$
- $W_{\nu^c} = h^\nu L H_u \nu^c + M\nu^c\nu^c$, with $M_3 \sim \frac{v^2_{B-L}}{M_P}$
- $W_{R_P} = \frac{1}{2}\lambda\ LLe^c + \lambda'QLd^c + \lambda''u^cd^cd^c$

\[
\lambda \sim C\frac{v^2_{B-L}}{M_P^2}h^e \sim C\frac{M_3}{M_P}h^e
\]
\[
\lambda' \sim C\frac{v^2_{B-L}}{M_P^2}h^d \sim C\frac{M_3}{M_P}h^d
\]
\[
\lambda'' \sim m_3/2\frac{v^4_{B-L}}{M_P^5} \sim \frac{m_3/2}{M_P} \left(\frac{M_3}{M_P}\right)^2
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- $W_{R_p} = \frac{1}{2} \lambda \ L L e^c + \lambda' Q L d^c + \lambda'' u^c d^c d^c$

In a particular flavour model

- $\lambda \sim C \frac{v_{B-L}^2}{M_P^2} h^e \sim C \frac{M_3}{M_P} h^e \quad \lambda \sim 10^{-7} h^e$
- $\lambda' \sim C \frac{v_{B-L}^2}{M_P^2} h^d \sim C \frac{M_3}{M_P} h^d \quad \lambda' \sim 10^{-7} h^d$
- $\lambda'' \sim m_{3/2} \frac{v_{B-L}^4}{M_P^4} \sim \frac{m_{3/2}}{M_P} \left( \frac{M_3}{M_P} \right)^2 \quad \lambda'' \sim 10^{-28}$

Then, $\lambda_{3ij}, \lambda'_{3ij} \sim 10^{-8}$, within $10^{-14} \lesssim \lambda, \lambda' \lesssim 10^{-7}$
Signatures for gravitino DM with broken R-parity

I- Signatures at gamma ray observatories

The gravitino decays into photon and neutrino with a decay rate:

$$\Gamma(\psi_{3/2} \rightarrow \gamma \nu) = \frac{1}{32\pi} |U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{M_P^2}$$

with $|U_{\tilde{\gamma}\nu}|$ the photino-neutrino mixing. One gets approximately:

$$\tau_{3/2} \simeq 4 \times 10^{27} \text{s} \left( \frac{\epsilon_3}{10^{-7}} \right)^{-2} \left( \frac{\tilde{m}}{200 \text{ GeV}} \right)^2 \left( \frac{m_{3/2}}{10 \text{ GeV}} \right)^{-3}$$

where $\epsilon_3 \equiv C \frac{\nu B - L}{M_P^2} \sim C \frac{M_3}{M_P}$ parametrizes the size of the R-parity breaking.

The lifetime is much longer than the age of the Universe, but a few decays are happening NOW.

The measurement of the extraterrestrial neutrino flux with an energy between 5-50 GeV is very difficult (same energy range as atmospheric neutrinos).

On the other hand, the photon flux could be observable as an extragalactic diffuse gamma-ray flux with a characteristic spectrum.

**Shining dark matter**
First analysis of Sreekumar et al. from the EGRET data gave an extragalactic flux described by the power law:

$$E^2 \frac{dJ}{dE} = 1.37 \times 10^{-6} \left( \frac{E}{1 \text{ GeV}} \right)^{-0.1} \text{(cm}^2 \text{str s)}^{-1} \text{GeV}, \text{ for } 50 \text{ MeV} \lesssim E \lesssim 10 \text{ GeV}$$

This implies $\tau_{3/2} \gtrsim 4 \times 10^{27} \text{ s}$. Very close to the prediction of our model:

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The more recent analysis by Strong, Moskalenko and Reimer ('04) shows a power law behaviour between 50 MeV and 2 GeV, but a clear excess between 2 GeV and 50 GeV!!
II- Signatures for colliders

The signatures depend on the nature of the NLSP (stau/neutralino)

- If the NLSP is a (mainly right-handed) stau
  - Main decay: $\tilde{\tau}_R \rightarrow \tau \nu_\mu, \mu \nu_\tau$ (through $\lambda L Le^c$)

$$cT_{\tilde{\tau}}^{lep} \sim 30 \text{ cm} \left( \frac{m_{\tilde{\tau}}}{200 \text{ GeV}} \right)^{-1} \left( \frac{\epsilon_2}{10^{-7}} \right)^{-2} \left( \frac{\tan \beta}{10} \right)^{-2}$$

Long heavily ionizing charged track followed by a muon track or a jet.
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    Long heavily ionizing charged track followed by a muon track or a jet.
  - Also, the small left-handed component induces $\tilde{\tau}_L \rightarrow b^c t$ (through $\lambda' Q L d^c$)
    $$cT^\text{had}_\tilde{\tau} \sim 1.4 \text{ m} \left( \frac{m_{\tilde{\tau}}}{200 \text{GeV}} \right)^{-1} \left( \frac{\epsilon_3}{10^{-7}} \right)^{-2}$$
    Long heavily ionizing charged track, followed by three jets.
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    cT_{\tilde{\tau}}^{\text{lep}} \sim 30 \text{ cm} \left( \frac{m_{\tilde{\tau}}}{200 \text{ GeV}} \right)^{-1} \left( \frac{\epsilon_2}{10^{-7}} \right)^{-2} \left( \frac{\tan \beta}{10} \right)^{-2}
    \]
    Long heavily ionizing charged track followed by a muon track or a jet.
  - Also, the small left-handed component induces \( \tilde{\tau}_L \rightarrow b^c t \) (through \( \lambda' Q_{Ld}^c \))
    \[
    cT_{\tilde{\tau}}^{\text{had}} \sim 1.4 \text{ m} \left( \frac{m_{\tilde{\tau}}}{200 \text{ GeV}} \right)^{-1} \left( \frac{\epsilon_3}{10^{-7}} \right)^{-2}
    \]
    Long heavily ionizing charged track, followed by three jets.

- If the NLSP is a neutralino
  - Main decays: \( \chi_1^0 \rightarrow \tau^\pm W^\mp \), or \( \chi_1^0 \rightarrow b_b^c \nu \)
    \[
    cT_{\chi_1^0}^{2-\text{body}} \sim 20 \text{ cm} \left( \frac{m_{\chi_1^0}}{200 \text{ GeV}} \right)^{-3} \left( \frac{\epsilon_3}{10^{-7}} \right)^{-2} \left( \frac{\tan \beta}{10} \right)^2
    \]
    \[
    cT_{\chi_1^0}^{3-\text{body}} \sim 600 \text{ m} \left( \frac{m_{\tilde{\nu}_L}}{300 \text{ GeV}} \right)^4 \left( \frac{m_{\chi_1^0}}{200 \text{ GeV}} \right)^{-5} \left( \frac{\epsilon_3}{10^{-7}} \right)^{-2} \left( \frac{\tan \beta}{10} \right)^{-2}
    \]
    If the neutralino decays inside the detector, jets will be observed.
Conclusions

During the 20th century, a consistent thermal history of the Universe was outlined. The recent discoveries of dark matter and dark energy require a revision of the thermal history.

We have concentrated on incorporating the supersymmetric dark matter into the thermal history of the Universe.

The requirements of successful leptogenesis, Big Bang Nucleosynthesis and a thermal CMB spectrum lead to a scenario with gravitino dark matter and tiny $R$-parity violation.

The photons from the gravitino decay contribute to the diffuse gamma background. They may have already been observed by EGRET. Unequivocal evidence for decaying dark matter would come from GLAST.

This scenario predicts striking signatures at the LHC, in particular a vertex of the NLSP significantly displaced from the beam axis.