Indirect Searches for Gravitino Dark Matter

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Based on work in progress in collaboration with Laura Covi and Gilles Vertongen.
Motivation for Unstable Gravitino Dark Matter

Why Are We Interested in Unstable Gravitino Dark Matter?

- Supergravity predicts the gravitino as the spin-3/2 superpartner of the graviton
- Gravitinos are produced thermally after inflation:

\[
\Omega_{3/2} h^2 \simeq 0.27 \left( \frac{T_R}{10^{10} \text{GeV}} \right) \left( \frac{100 \text{ GeV}}{m_{3/2}} \right) \left( \frac{m_{\tilde{g}}}{1 \text{ TeV}} \right)^2
\]

[Bolz et al. (2001)]

- Problem in scenarios with neutralino dark matter:
  - Thermal leptogenesis requires high reheating temperature: \( T_R \gtrsim 10^9 \text{ GeV} \) [Davidson et al. (2002)]
  - Late gravitino decays are in conflict with BBN \( \Rightarrow \) Cosmological gravitino problem

Still problematic:
- Late NLSP decays are in conflict with BBN \( \Rightarrow \) Cosmological gravitino problem
  Possible solution: \( R \) parity is not exactly conserved!
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Possible solution: Gravitino is the LSP and thus stable!

- Correct relic density for \( m_{3/2} > \mathcal{O}(10) \text{ GeV} \) ⇒ Gravitino dark matter
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Gravitino Dark Matter with Bilinear $R$-Parity Violation

- **Bilinear $R$-Parity Violation:** 
  \[ W_{R_p} = \mu_i H_u L_i, \quad -\mathcal{L}^{\text{soft}}_R = B_i H_u \tilde{\ell}_i + m^2_{H_d} \ell_i H^*_d \tilde{\ell}_i + \text{h.c.} \]

  - Only lepton number violated \(\Rightarrow\) Proton remains stable!

- **Cosmological bounds on $R$-violating couplings**
  - Lower bound: The NLSP must decay fast enough to evade BBN constraints
  - Upper bound: The lepton/baryon asymmetry must not be washed out

- **Gravitino decay suppressed by Planck scale and small $R$-parity violation**
  - The gravitino lifetime exceeds the age of the universe by many orders of magnitude

  The unstable gravitino is a well-motivated and viable dark matter candidate!
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► Rich phenomenology instead of elusive gravitinos
- A long-lived NLSP could be observed at the LHC
- Gravitino decays lead to possibly observable signals at indirect detection experiments

Gravitinos could be indirectly observed at colliders and in the spectra of cosmic rays!
Gravitino Decay Channels

Several contributing decay channels: \( \psi_{3/2} \rightarrow \gamma \nu_i, \ Z^* \nu_i, \ h^* \nu_i, \ W^* \ell_i \)

- For \( m_{3/2} < m_W \) three-body decays can play an important role
- Ratio between \( \gamma \nu_i \) and other channels is model-dependent

![Graph showing branching ratios and spectra](image)

Gravitino decays produce spectra of stable cosmic rays: \( \gamma, \ e, \ p, \ \nu_e/\mu/\tau, \ d \)

- Two-body decay spectra generated with PYTHIA
- Deuteron coalescence treated on event-by-event basis

[Choi et al. (2010)]
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Basis for phenomenology of indirect gravitino dark matter searches!
Gravitino Decay Signals in Cosmic-Ray Spectra: \( \frac{e^+}{e^++e^-} \) and \( e^- \)

- Gravitino decay could explain the rise in the PAMELA positron fraction data
  - Explanation requires a gravitino lifetime of \( \mathcal{O}(10^{26}) \) s and a mass \( \gtrsim 200 \) GeV
- Also contribution to absolute electron flux expected
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  - Associated $\bar{p}$ from $W, Z$ and $h$ fragmentation in conflict with data ($\rightarrow$ gravitino not leptophilic)
  - Associated gamma-ray flux in conflict with Fermi LAT data for isotropic diffuse flux
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Astrophysical sources like pulsars required to explain cosmic-ray excesses!
Antideuteron Signals from Gravitino Decays

- In particular sensitive to low gravitino masses due to small astrophysical background
- AMS-02 and GAPS will be able to put strong constraints on light gravitinos
Indirect Detection of Gravitino Dark Matter

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Antideuterons are a valuable channel for light gravitino searches!
Neutrino Signals from Gravitino Decays

- Neutrinos provide directional information like gamma rays
- Gravitino signal features monoenergetic neutrino line at the end of the spectrum
- Atmospheric neutrinos are dominant background for gravitino signals
  - Measurement of other neutrino flavors would allow to reduce the background
  - Signal-to-background ratio best at the end of the spectrum and for large gravitino masses

![Graph showing $E^2 \times$ Neutrino Flux vs. Energy (GeV) with data points and lines indicating different neutrino species including $\nu_\mu$, $\nu_\tau$, and $\nu_e$.]

\[ \tau_{3/2} = 10^{26} \text{ s} \]

\[ m_{3/2} = 100 \text{ GeV} \]

\[ 1 \text{ TeV} \]

\[ 10 \text{ TeV} \]
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![Graph showing neutrino flux and energy](image)

**Neutrinos are a valuable channel for heavy gravitino searches!**
Neutrino Detection with Upward Through-Going Muons

- Muon tracks from charged current DIS of muon neutrinos off nuclei outside the detector

**Advantages**
- Muon track reconstruction is well-understood at neutrino telescopes

**Disadvantages**
- Neutrino–nucleon DIS and propagation energy losses shift muon spectrum to lower energies
- Bad energy resolution \( (0.3 \text{ in } \log_{10} E) \) smears out cutoff energy

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![Diagram of neutrino interaction](image)

**Statistical Significance**

![Graph showing muon flux and statistical significance](image)

Michael Grefe (DESY)

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Neutrino Detection – Improvements Using Showers

- Hadronic and electromagnetic showers from charged current DIS of electron and tau neutrinos and neutral current interactions of all neutrino flavors inside the detector

Disadvantages
- TeV-scale shower reconstruction is not yet well understood

Advantages
- $3 \times$ larger signal and $3 \times$ lower background compared to other channels
- Better energy resolution ($0.18 \text{ in } \log_{10} E$) helps to distinguish spectral features
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Shower Events

<table>
<thead>
<tr>
<th>Energy ($\text{GeV}$)</th>
<th>Atmospheric Background</th>
<th>Shower Events</th>
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<tr>
<td>$1$</td>
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<td>$10^0$</td>
</tr>
<tr>
<td>$10$</td>
<td>$10^1$</td>
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<td>$10^2$</td>
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<td>$1\text{ TeV}$</td>
<td>$10^3$</td>
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Statistical Significance

Shower Events

Showers are potentially the best channel for dark matter searches in neutrinos!
Cosmic-ray data give bounds on gravitino lifetime

- Photon line bounds very strong for low gravitino masses
- Uncertainties from charged cosmic-ray propagation
- Background subtraction could improve bounds
- Antideuterons can be complementary to photon line searches for low gravitino masses (→ future work)
- Neutrino bounds are competitive for heavy gravitinos
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**Strong bounds from multi-messenger approach!**
Conclusions and Outlook

- Gravitino dark matter with broken $R$ parity is well motivated from cosmology
- The Gravitino lifetime is naturally in the range of indirect detection experiments
- Cannot explain the PAMELA excess due to constraints from gamma rays and antiprotons
- Forthcoming antideuteron searches will probe light gravitino dark matter
- Neutrino experiments like IceCube can probe heavy gravitino dark matter
- New detection strategies will improve the sensitivity of neutrino experiments to dark matter
- Multi-messenger approach strongly constrains gravitino lifetime and strength of $R$-parity violation
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Thanks for your attention!