Neutrino Signals from Unstable Gravitino Dark Matter \(^1\)

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\(^1\)Based upon JCAP 0901 (2009) 029 and work in progress.
Outline

1. Gravitino Dark Matter
2. Gravitino Decays
3. Neutrino Detection Prospects
4. Conclusions
Gravitino Dark Matter

- Gravitino is spin-3/2 superpartner of graviton in supergravity theories.
- Thermally produced during reheating phase in the early universe:

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

[Bolz, Brandenburg, Buchmüller (2001)]

- Thermal leptogenesis requires reheating temperature \( T_R \gtrsim 10^9 \text{ GeV} \).
- High \( T_R \) together with low gravitino mass leads to overproduction! \( \Rightarrow \ m_{3/2} \gtrsim \mathcal{O}(10) \text{ GeV} \) favored.
- If gravitino not LSP, late decays can spoil BBN predictions.
- If gravitino LSP, natural candidate for Cold Dark Matter.
- With conserved \( R \)-parity, late NLSP decays into gravitinos and SM particles may spoil BBN predictions!

Possible solution: \( R \)-parity not exactly conserved!
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- Parity Violation and Indirect Detection

- $R$-parity violating terms in superpotential:

\[ W_{R_p} = \mu_i L_i H_u + \lambda LLE^c + \lambda' LQD^c + \lambda'' U^c D^c D^c. \]

- Even very small $R_p$ couplings make NLSP decay into SM particles before BBN.

- Proton stable if $\lambda''$ forbidden.

- Lower bound on $R_p$ couplings from BBN, upper bound from Leptogenesis.

  $\implies$ Gravitino unstable but very long-lived: $\tau_{3/2} \approx \mathcal{O}(10^{23} - 10^{37})$ s.

- Couplings suppressed by Planck mass and small $R$-parity violation.

Gravitino remains viable Dark Matter candidate!

- Even for gravitino lifetimes much larger than the age of the universe decay products may be observable.

- Look for signatures in cosmic-ray species with low background and spectra of particles that propagate freely:
  
  $\Rightarrow$ Gamma rays, Positrons, Antiprotons and Neutrinos.

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**WIMP Annihilation**

- Flux $\propto \rho^2 \rightarrow$ Dominant signal from dense regions.
- WIMPs accumulate inside stars and planets due to capturing via weak interactions.
  $\Rightarrow$ Look for cosmic rays from galactic center or at neutrinos from center of the Sun or the Earth!

**Gravitino Decay**

- Flux $\propto \rho \rightarrow$ Almost isotropic signal.
- Gravitinos do not accumulate inside stars or planets.
- Gravitino distribution follows DM halo density profile.
  $\Rightarrow$ Look for diffuse flux of cosmic rays.

Neutrino signals from galactic center and Sun not favored because of additional backgrounds from these directions.

Fluxes from decays are much less sensitive to density fluctuations.
$\Rightarrow$ No boost factors for decaying DM!

Annihilating and decaying DM require different strategies for observation!
Annihilating WIMP DM vs Decaying Gravitino DM

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![Graph showing annihilation and decay fluxes](image-url)
1 Gravitino Dark Matter

2 Gravitino Decays

3 Neutrino Detection Prospects

4 Conclusions
Gravitino Decay Channels

Tree level gravitino decay channels in models with bilinear $R$-parity breaking:

- $\psi_{3/2} \rightarrow \gamma \nu_l$
- $\psi_{3/2} \rightarrow W^\pm l^\mp$
- $\psi_{3/2} \rightarrow Z^0 \nu_l$
- $\psi_{3/2} \rightarrow h \nu_l$

Assumption: Gravitino decays through neutralino–neutrino and chargino–charged lepton mixing via sneutrino VEV.

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Neutrino Signals from Unstable Gravitino Dark Matter
Motivated by PAMELA and ATIC/PPB-BETS data we study the case of electron sneutrino VEV and the parameters

\[ m_{3/2} \simeq 250 \text{ GeV, } 500 \text{ GeV, } 1.2 \text{ TeV } \quad \text{and} \quad \tau_{3/2} \simeq \mathcal{O}(10^{26}) \text{ s.} \]

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Neutrino Spectra

Neutrino spectrum from gravitino decay:

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\frac{dN_\nu}{dE} = BR(\gamma \nu_e) \delta \left(E - \frac{m_{3/2}}{2}\right) + BR(We) \frac{dN_W^\nu}{dE} + BR(Z^0 \nu_e) \frac{dN_Z^\nu}{dE} + BR(h \nu_e) \frac{dN_h^\nu}{dE}
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- Branching ratios depend dominantly on gravitino mass.
- Spectra from fragmentation of $W$ and $Z^0$ and $h$ bosons generated with PYTHIA.
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Flux from Galactic and Extragalactic Decays

**Galactic Flux**

\[
\frac{dJ_{\text{halo}}}{dE} = \frac{1}{4\pi \tau_{3/2} m_{3/2}^2} \int \rho_{\text{halo}}(\vec{l}) \, d\vec{l} \cdot \frac{dN_{\nu}}{dE}
\]

- Exclude galactic disk to avoid galactic neutrino background.
- No strong angular dependence. \(\Rightarrow\) Use averaged galactic flux.
- No significant dependence on used halo profile.

**Extragalactic Flux**

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\frac{dJ_{\text{eg}}}{dE} = \frac{\Omega_{3/2} \rho_c}{4\pi \tau_{3/2} m_{3/2}^2 H_0 \Omega_M^{1/2}} \int_1^\infty \frac{y^{-3/2} \, dy}{\sqrt{1+\Omega_\Lambda/\Omega_M} y^{-3}} \, d(yE)
\]

- Redshifted spectrum from decays at extragalactic distances.
- Extragalactic contribution subdominant.

Include neutrino propagation: Oscillations redistribute flux into all flavors.

\(\Rightarrow\) Signals for \(\nu_\mu\) and \(\nu_\tau\) are equivalent, \(\nu_e\) is slightly different!

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**Neutrino Background**

- Main background are atmospheric electron and muon neutrinos.
- Tau neutrino background from conversion of muon into tau neutrinos.
- Neutrino signal from gravitino decay below the atmospheric background except for tau neutrinos!
- **Signal-to-background ratio increases for larger gravitino masses!**

**Strategy to reduce background and/or high statistics and spectral information needed!**

![Graph showing neutrino signals from unstable gravitino dark matter](image)
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• Tau neutrino background can be reduced substantially, if only down-going neutrinos are considered.

• Prompt tau neutrinos from atmospheric charmed particle decay become important at higher energies!

Very good signal-to-background ratio if cuts on the energy can be applied!

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Experimental Situation for Tau Neutrinos

Problems

- Only (partially) contained events for tau neutrinos.
  \[ \Rightarrow \] Small event rates: Only $\mathcal{O}(1)$ tau neutrinos per century in Super-Kamiokande.
- No detailed spectral information!
- Super-K can identify tau neutrinos, but only on a statistical basis.
- No event-by-event identification for tau neutrinos!

More statistics and better flavor identification needed to extract signal from background!

Future possibilities

- Hyper-Kamiokande will have mass of $\mathcal{O}(1)$ Mton.
  \[ \Rightarrow \] Factor of $\sim 20$ improvement in statistics compared to Super-K.
- IceCube could improve the statistics by several orders of magnitude.
- However, no strategy to identify tau neutrinos below many TeV!

Tau neutrinos offer the most promising signal but are also most difficult to detect in neutrino experiments!
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- Through-going muon events provide much better statistics due to larger effective detector volume!

IceCube (completed detector)

- Signal: $\mathcal{O}(10^3)$, $\mathcal{O}(10^2)$, $\mathcal{O}(10)$ events/yr for $m_{3/2} = 1.2$ TeV, 500 GeV, 250 GeV
- Atmospheric background: $\mathcal{O}(10^5)$ events/yr
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![Graph showing muon events vs. energy](image)

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Bound on Gravitino Lifetime

- Non-observation of neutrino signal can be used to constrain gravitino parameters!
- Compare signal from $\gamma\nu_e$ and $Z^0\nu_e$ lines to atmospheric background.
- Taking only down-going tau neutrinos can improve the bound significantly!

\[
\begin{align*}
\tau_{3/2} (s) & \quad m_{3/2} (GeV) \\
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Bound from down-going tau neutrinos may be competitive at higher masses!
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![Graph showing bounds on $\tau_{3/2}$ vs. $m_{3/2}$](graph.png)

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- Future neutrino experiments can improve sensitivity for low flux signals, but also have to provide tau flavor identification (ideally event by event).

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