# Neutrino Signals from Gravitino Dark Matter with broken *R*-parity [1]

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# Outline

# Gravitino Dark Matter

- Gravitino is spin-3/2 superpartner of graviton in supergravity theories.

- Thermally production after reheating phase in the early universe with relic density

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

<div align="right">[Bolz, Brandenburg, Buchmüller]<br>[Pradler, Steffen]</div>

- Can constitute DM: $\Omega_{\text{CDM}} h^2 \simeq 0.1$

- Thermal leptogenesis requires reheating temperature $T_R \gtrsim 10^9$ GeV.

- High $T_R$ together with low gravitino mass leads to overclosure!

$\Rightarrow$ $m_{3/2} \gtrsim 10$ GeV favored.

- If gravitino is not the lightest supersymmetric particle, it decays with

$$\tau_{3/2} \sim 3\,years \left( \frac{100\,\text{GeV}}{m_{3/2}} \right)^3.$$

$\Rightarrow$ Late gravitino decays can spoil BBN predictions.

- If gravitino is the LSP, it is natural candidate for CDM.

- With conserved $R$-parity, NLSP decays into gravitinos and SM particles suppressed by the Planck scale:

$$\tau_{\text{NLSP}} \simeq 9\,days \left( \frac{m_{3/2}}{10\,\text{GeV}} \right)^2 \left( \frac{150\,\text{GeV}}{m_{\text{NLSP}}} \right)^5$$

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Solution: $R$-parity not exactly conserved!

# R-Parity Violation and Indirect Detection

- $R$-parity violating terms in superpotential:

  $$W_{\not{R}} = \lambda LLE^c + \lambda' LQD^c + \lambda'' U^c D^c D^c + \mu_i L_i H_2$$

- Even very small $R$-parity violating couplings make NLSP decay into SM particles before BBN.

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

- Gravitino unstable but very long-lived: Couplings suppressed by Planck mass and small $R$-parity violation.

  $$\tau_{3/2} \simeq 10^{23} \,\text{s} \left( \frac{\lambda^{(\prime)}}{10^{-7}} \right)^2 \left( \frac{m_{3/2}}{100\,\text{GeV}} \right)^3$$

- Bounds on Yukawa couplings:
  - Leptogenesis: $\lambda, \lambda' \lesssim 10^{-7}$
  - BBN: $\lambda, \lambda' \gtrsim 10^{-14}$

$\Rightarrow$ $10^{23}$ s $\lesssim \tau_{3/2} \lesssim 10^{37}$ s for $m_{3/2} \sim 100$ GeV
(Age of the universe: $T \sim 10^{17}$ s)

$\Rightarrow$ Gravitino remains viable DM 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:

  - Neutrinos
  - Gamma-rays
  - Positrons     } Talk by David Tran
  - Antiprotons

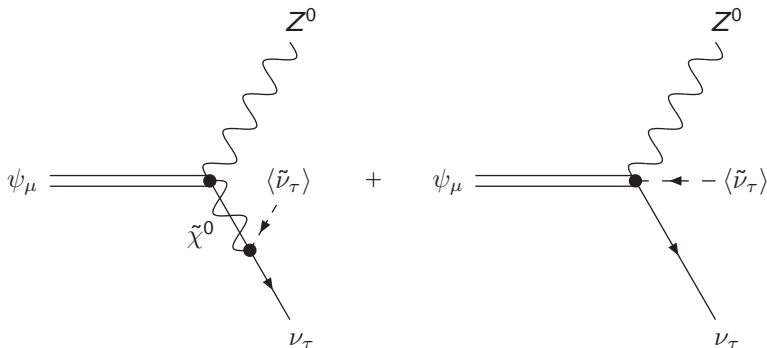*R*-parity violation makes gravitino accessible to indirect detection!

# Gravitino Decay Channels

Primary gravitino decay channels in models with bilinear R-parity breaking:

- $\psi_{3/2} \to \gamma \, \nu_\tau$
- $\psi_{3/2} \to W^\pm \tau^\mp$
- $\psi_{3/2} \to Z^0 \nu_\tau$
- $\psi_{3/2} \to h \nu_\tau$

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

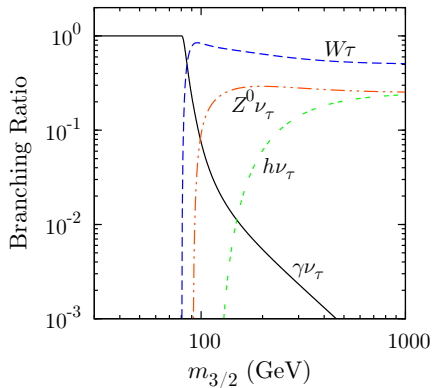Use large $\mu$ parameter limit (decoupling of heavy Higgs bosons).

$\Rightarrow$ Lightest Higgs Standard Model-like ($m_h = 115\,\text{GeV}$ used).

In addition, use $\tan\beta = 10$ and unification of gaugino masses.

Decay into heavy gauge bosons dominates above the threshold!



Branching ratios depend dominantly on gravitino mass.
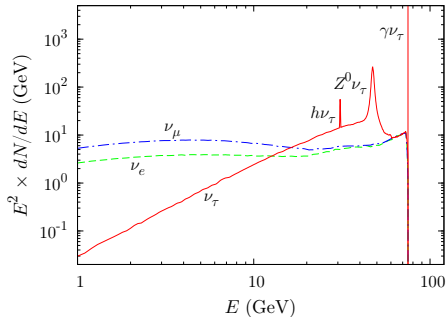
# Neutrino Spectra

Motivated by possible explanation of anomalies in gamma ray and positron channels, we use

$$m_{3/2} \simeq 150 \, \text{GeV} \qquad \text{and} \qquad \tau_{3/2} \simeq 10^{26} \, \text{s}.$$

Neutrino spectrum from gravitino decay:

$$\frac{dN_\nu}{dE} = \text{BR}(\gamma\nu_\tau)\, \delta\left(E - \frac{m_{3/2}}{2}\right) + \text{BR}(W\tau)\frac{dN_\nu^W}{dE} + \text{BR}(Z^0\nu_\tau)\frac{dN_\nu^Z}{dE} + \text{BR}(h\nu_\tau)\frac{dN_\nu^h}{dE}$$
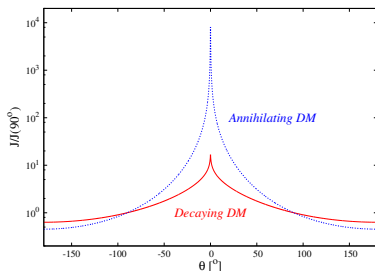
Spectra from fragmentation of $W$ and $Z^0$ and $h$ bosons generated with PYTHIA.

## Annihilation

- WIMPs accumulate inside the Sun and the Earth due to capturing via weak interactions.
- Flux $\propto \varrho^2 \rightarrow$ Signal only from dense regions.
- $\Rightarrow$ Look for annihilations in center of Milky Way or at neutrinos from annihilations in the center of Sun or Earth!



[Bertone, Buchmüller, Covi & Ibarra (2007)]

## Decay

- Gravitinos interact only gravitationally and do not accumulate inside stars or planets.
- Flux $\propto \varrho \rightarrow$ 'Almost isotropic' signal.
- $\Rightarrow$ Look for diffuse flux of neutrinos or other decay products.

Neutrino signals from the galactic center and the Sun are not favored because of not well understood large backgrounds.

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

Totally different strategies to observe the different scenarios!

# Flux from Galactic and Extragalactic Gravitino Decays

### Galactic Flux

$$\frac{dJ_{halo}}{dE} = \frac{1}{4\pi\tau_{3/2}m_{3/2}} \int_{l.o.s.} \varrho_{halo}(\vec{l})d\vec{l} \cdot \frac{dN_\nu}{dE}$$

- Navarro-Frenk-White halo density profile.
- Exclude galactic disk to avoid galactic neutrino background.
- Average over galactic flux.

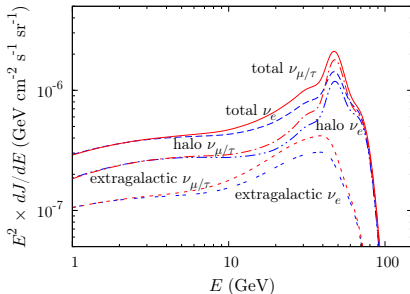No strong dependence on used halo profile.

Include neutrino propagation: Oscillations redistribute flux into all flavors.

$\Rightarrow$ Signals for $\nu_\mu$ and $\nu_\tau$ are equivalent!

### Extragalactic Flux

$$\frac{dJ_{eg}}{dE} = \frac{\Omega_{3/2}\varrho c}{4\pi\tau_{3/2}H_0\Omega_M^{1/2}} \int_1^\infty \frac{y^{-3/2}dy}{\sqrt{1 + \Omega_\Lambda/\Omega_M y^{-3}}} \frac{dN_\nu}{d(yE)}$$

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



Neutrino signal does not crucially depend on dominant decay to third lepton generation!

# Outline

# Neutrino Background

- Main neutrino background are atmospheric electron and muon neutrinos.

- Tau neutrino background from conversion of muon into tau neutrinos.

- Neutrino signal from gravitino decays far below the atmospheric background for all neutrino flavors!
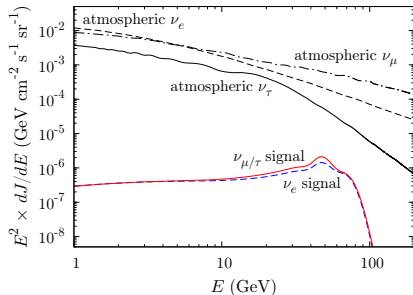
- Tau neutrino background can be reduced substantially, if only down-going neutrinos are considered.

- Then, also intrinsic atmospheric tau neutrino background from atmospheric charmed particle decay important!
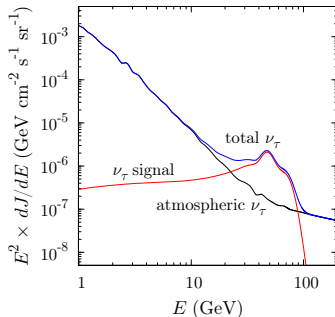




Tau neutrino signal from decaying gravitino dark matter is in principle observable!

# Present Experimental Situation

- Super-Kamiokande can identify tau neutrinos, but only on a statistical basis.

  [Super-K Collaboration]

- Event-by-event identification not possible so far!

- Expected fluxes very small: Only $\mathcal{O}(1)$ tau neutrinos per century in Super-K.

- In addition, spectral information cannot be reconstructed!
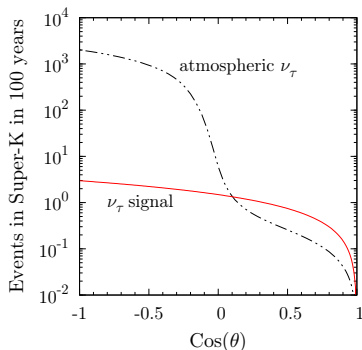


- OPERA can identify tau neutrinos event by event. However, fiducial mass $\sim 10$ times smaller than Super-K.

$\Rightarrow$ More statistics, better energy resolution and better flavor identification needed to disentangle signal from background!

Detection of signal from gravitino decay hindered by present technological limitations!

# Future Possibilities

- Hyper-Kamiokande will provide better statistics due to the larger fiducial mass ($\mathcal{O}(1)$ Mton).

$\Rightarrow$ Factor of $\sim 20$ improvement in statistics compared to Super-K.

- Km$^3$ detectors like IceCube could greatly improve the statistics.

$\Rightarrow$ We expect $\mathcal{O}(10\text{–}100)$ events per year.

Problem:

- IceCube looks in the opposite direction!

Other problems:

- Energy threshold for IceCube will be about $100\,\text{GeV}$.
  With Amanda reduction to $30\,\text{GeV}$ possible.

- No strategy to identify tau neutrinos below several TeV!

Future experiments might devise techniques to detect the signal, if the gravitino mass is fixed by observations in other channels!

# Bound on Gravitino Lifetime

Non-observation of neutrino signal can be used to contrain gravitino parameters!

- Compare signal from $\gamma$ and $Z^0$ lines to atmospheric background in all flavors.
- Taking only down-going tau neutrinos can improve the bound substantially!
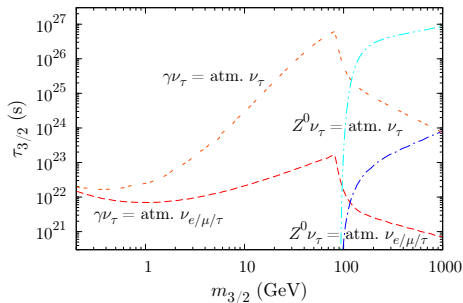


- Gamma ray channel sets bound on the order of $10^{27}$ s below $M_W$!

Neutrino channel imposes usually weaker bounds on the model than other channels.
Bound from down-going tau neutrinos may be competetive at higher energies!

# Outline

# Conclusions and Outlook

- Gravitino with broken *R*-parity is theoretically well motivated dark matter candidate, since it is compatible with baryogenesis via leptogenesis and with BBN predictions.

- Neutrinos from decaying gravitino dark matter are most likely observable in the tau sector, due to effective background reduction for downward-going neutrinos at high energies!

- Present neutrino experiments have low statistics and cannot identify tau neutrinos on an event-by-event basis.

⇒ Currently, detection prospects limited by technological feasibility.

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

If detected, neutrino signals might bring considerable support to the scenario of unstable gravitino dark matter!