Neutrino Signals from Gravitino Dark Matter with broken *R*-parity

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3. Kosmologietag

Bielefeld - 8th May 2008

Outline

Gravitino Dark Matter

- Gravitino is spin-3/2 superpartner of graviton in supergravity theories.
- If gravitino is not the lightest supersymmetric particle it decays with

$$\tau_{3/2} = 6 \times 10^7 \text{ s} \left(\frac{m_{3/2}}{100 \text{ GeV}} \right)^{-3} .$$

⇒ Late gravitino decays jeopardize BBN predictions.

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

⇒ BBN safe from gravitino decays!

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

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

[Bolz, Brandenburg, Buchmüller (2001)]

- WMAP: $\Omega_{\mathrm{CDM}}h^2 \simeq 0.1$

- Baryogenesis via leptogenesis requires reheating temperature $T_R \gtrsim 10^9$ GeV.
- High T_R together with low gravitino mass leads to overclosure!

⇒ $m_{3/2} \gtrsim 10$ GeV favored.

- Next-to-lightest supersymmetric particle is a neutralino or stau in most scenarios.
- With conserved R-parity, NLSP can only decay into gravitinos and SM particles suppressed by the Planck scale.

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

⇒ NLSP present during BBN and spoiling BBN predictions!

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Solution:

R-parity not exactly conserved!

R-parity Violation and indirect Detection

- R-parity violating terms in superpotential:

$$W_{\not R} = \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c + \mu_i L_i H_2$$

- Even very small R-parity violating couplings make NLSP decay into SM particles before BBN.
- Proton stable if λ'' forbidden.
- Gravitino unstable but very long-lived: Couplings suppressed by Planck mass and small R-parity violation.

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

- Bounds on couplings:
  - Leptogenesis: $\lambda^{(\prime)} \lesssim 10^{-7}$
  - BBN: $\lambda^{(\prime)} \gtrsim 10^{-14}$

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

$\Rightarrow$ 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
  - Antiprotons

  } Talk by David Tran (Gamma-rays, Positrons, Antiprotons)

R-parity violation makes gravitino accessible to indirect detection!

Outline

Gravitino Decay Channels

Primary gravitino decay channels in the considered model of bilinear R-parity breaking are:

- $\psi_{3/2} \rightarrow \gamma + \nu_\tau$
- $\psi_{3/2} \rightarrow W^\pm + \tau^\mp$
- $\psi_{3/2} \rightarrow Z^0 + \nu_\tau$

Latter two channels only available if $m_{3/2} > m_W$ or $m_{3/2} > m_Z$ respectively.

Assumption:

- Gravitino decays dominantly into third lepton generation.

Branching ratios depend only on gravitino mass.
Normalization of decay rates determined by gravitino lifetime.

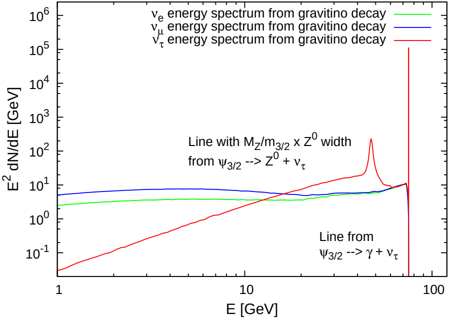
Here we use

$$m_{3/2} = 150\,\text{GeV} \;\;\text{and}\;\; \tau_{3/2} = 1.3 \times 10^{26}\,\text{s}.$$

Neutrino spectrum from gravitino decay:

$$\frac{dN_\nu}{dE} = \text{BR}(\gamma + \nu_\tau)\delta\left(E - \frac{m_{3/2}}{2}\right) + \text{BR}(W + \tau)\frac{dN_\nu^W}{dE} + \text{BR}(Z^0 + \nu_\tau)\frac{dN_\nu^Z}{dE}$$

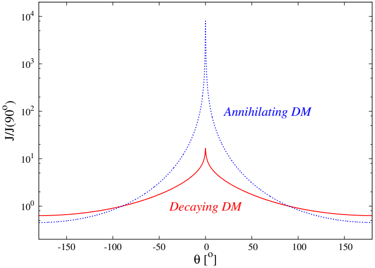
Spectra from W and Z channels generated with `PYTHIA`.



Annihilation

- Neutralinos accumulate inside the sun and the earth due to capturing via weak interactions.
- Flux $\propto \varrho^2$ $\longrightarrow$ Signal from 'point-like sources'.

$\Rightarrow$ Look at particles from annihilations in the center of the Milky-Way or other galaxies or at neutrinos from annihilations in the center of the sun or the earth!



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

Decay

- Gravitinos interact only gravitationally and do not accumulate inside stars or planets.
- Flux $\propto \varrho$ $\longrightarrow$ 'Almost isotropic' signal.

$\Rightarrow$ Look for diffuse flux of neutrinos or other decay products.

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.

Extragalactic Flux

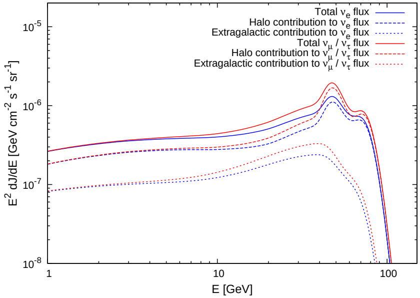
$$\frac{dJ_{eg}}{dE} = \frac{\Omega_{3/2}\varrho_c}{8\pi\tau_{3/2}H_0\Omega_M^{1/2}}\int_1^\infty dy\,\frac{dN_\nu}{d(yE)}\frac{y^{-3/2}}{\sqrt{1+\Omega_\Lambda/\Omega_M y^{-3}}}$$

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

No strong dependence on used halo profile.

Include neutrino propagation and average over neutrino oscillations.

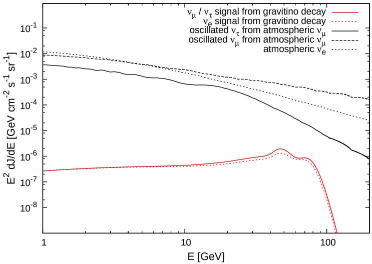
$\Rightarrow$ Signals for ν_μ and ν_τ are equivalent!



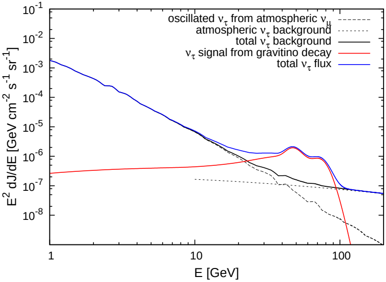
Neutrino signal does not crucially depend on dominant decay to third lepton generation!

Outline

- Main neutrino background comes from atmospheric electron and muon neutrinos.
- Use FLUKA fluxes. [Battistoni et al. (2001)]
- Intrinsic atmospheric tau neutrino flux negligible.
- Main contribution to tau neutrino background comes from oscillations between muon and tau neutrinos.
- Diffuse neutrino signal from gravitino decays lies far below the atmospheric background for all neutrino flavors!



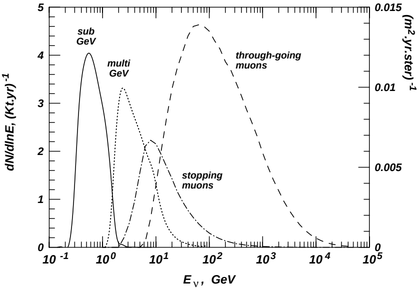
- Tau neutrino background can be reduced drastically if only down-going neutrinos are considered.
- Then also intrinsic atmospheric tau neutrino background is important.
- Use tau neutrino flux from atmospheric charmed particle production and decay calculated with PYTHIA. [Pasquali & Reno (1998)]



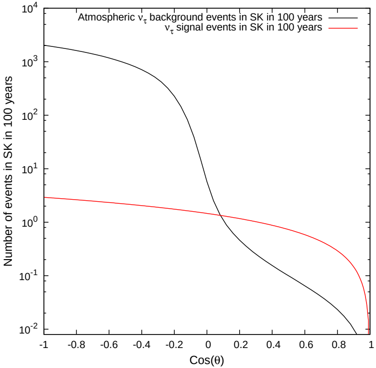
Tau neutrino signal from decaying gravitino dark matter could in principle be observable!

Present experimental Situation

- Present experiments like Super-Kamiokande can identify tau neutrinos, but on a statistical basis. [SK Collaboration (2007)]
- Event-by-event identification is not possible so far!
- Electrons and taus: Only contained events.
- Muons penetrate rock. $\longrightarrow$ Also through-going events.



[Gonzalez-Garcia & Nir (2002)]



- Neutrino energy cannot be reconstructed from through-going muons.

$\Rightarrow$ No spectral information on the neutrinos!

- Expected fluxes are very small: Only $\mathcal{O}(1)$ tau neutrinos in CC-interactions inside the fiducial volume in 100 years.

Future Possibilities

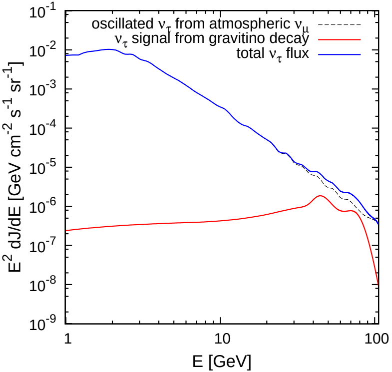
- Hyper-Kamiokande can provide better statistics due to the larger fiducial volume of ~ 0.5 Mton. That is a factor of ~ 20 improvement in statistics compared to SK.
- Higher energetic leptons can be contained in the larger detector.
- Km^3 detectors like IceCube could greatly improve the statistics. Then tau neutrino signal from gravitino decay would result in several hundred events per year.

Problem:

- IceCube looks downward!
  - Look for signal near the horizon! For example in the region $-0.1 < \cos\theta < 0$ the signal is comparable to the averaged background.

Caution:

- The ratio of signal to background is strongly dependent on the observed solid angle!



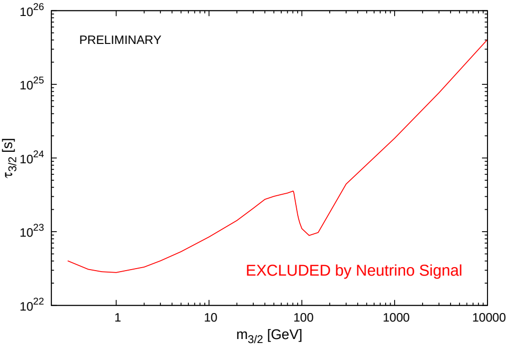
Other problems:

- Energy threshold for IceCube will be about 100 GeV.
- With Amanda reduction to 30 GeV possible.
- Up to now no strategy known to identify tau neutrinos below several TeV.

Bound on Gravitino Lifetime

It is possible to exclude regions of the gravitino mass/lifetime parameter space using the neutrino signal!

- Compare up-going muon neutrino signal with atmospheric background.
- Integration over energy range centered around the line from decay $\psi_{3/2} \to \gamma + \nu$.



- Dip comes from branching ratio into W and Z bosons. Fragmentation shifts part of the spectrum to lower energies.

Neutrino signal imposes much weaker bounds on the model than other channels!

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 the low background for downward-going neutrinos at high energies!
- Present neutrino experiments have low statistics and cannot identify tau neutrinos on an event-by-event basis.

$\Rightarrow$ At present not possible to see the neutrino signal!

- Future neutrino experiments like Hyper-Kamiokande or km^3 detectors can improve the sensitivity for low flux signals.
- Detailed searches for this signal should be made if specific gravitino parameters are favored or fixed by observations in other channels. These will be presented in the following talk by David Tran.