Neutrino Signals from Unstable Gravitino Dark Matter [1]

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LMU München – 9th March 2009

[1] Based upon JCAP **0901** (2009) 029 and work in progress.

Outline

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 $T_R \gtrsim 10^9$ GeV.
- High T_R together with low gravitino mass leads to overproduction!
  $\Rightarrow \quad m_{3/2} \gtrsim \mathcal{O}(10)$ 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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R-Parity Violation and Indirect Detection

- R-parity violating terms in superpotential:

$$W_{\not R_p} = \mu_i L_i H_u + \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c \, .$$

- Even very small $\not R_p$ couplings make NLSP decay into SM particles before BBN.
- Proton stable if λ'' forbidden.
- Lower bound on $\not R_p$ couplings from BBN, upper bound from Leptogenesis.
  $\Rightarrow$ 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:
  $\longrightarrow$ Gamma rays, Positrons, Antiprotons and Neutrinos.

R-parity violation makes gravitino accessible to indirect detection!

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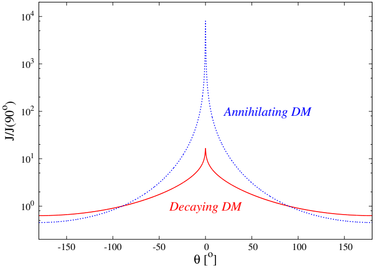
Annihilating WIMP DM vs Decaying Gravitino DM

WIMP Annihilation

- Flux $\propto \varrho^2 \rightarrow$ 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!



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

Gravitino Decay

- Flux $\propto \varrho \rightarrow$ 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!

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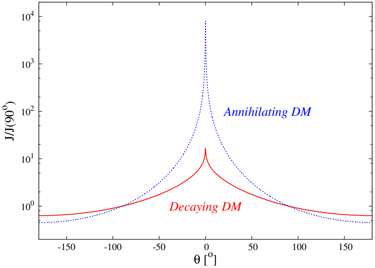

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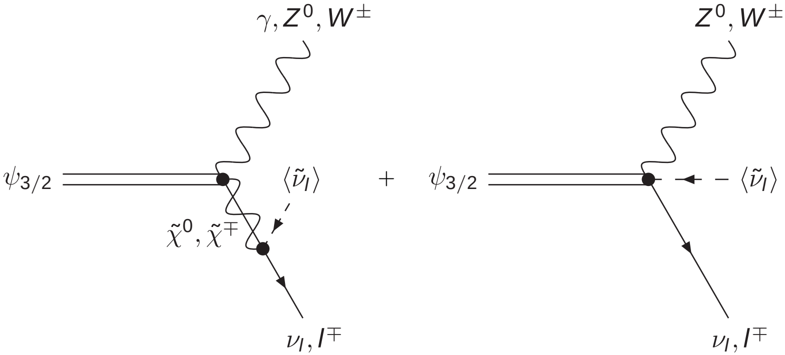
Gravitino Decay Channels

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

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

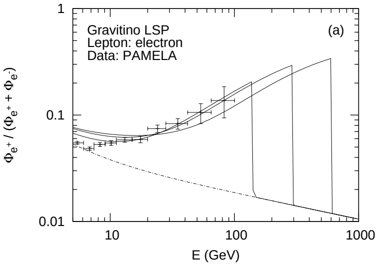
Assumption: Gravitino decays through neutralino–neutrino and chargino–charged lepton mixing via sneutrino VEV.



Signal in Positrons

- Motivated by PAMELA and ATIC/PPB-BETS data we study the case of electron sneutrino VEV and the parameters

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



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Is there also an observable signal in neutrinos?

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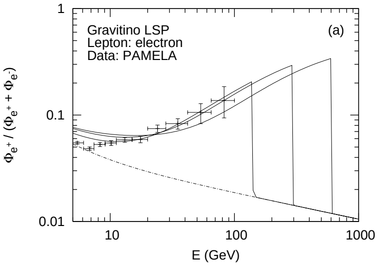

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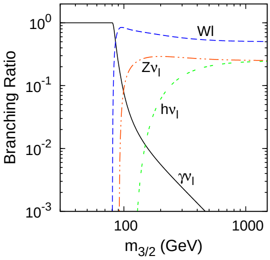
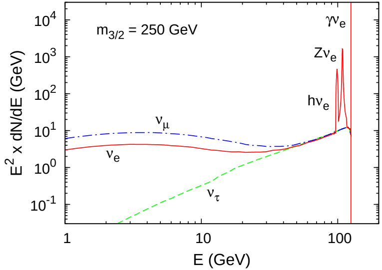
Neutrino Spectra

Neutrino spectrum from gravitino decay:

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

- 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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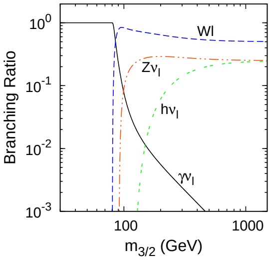

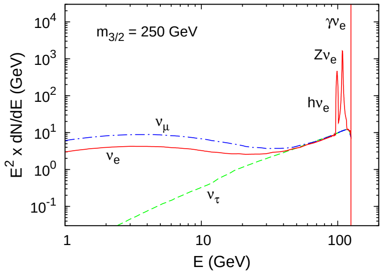

Flux from Galactic and Extragalactic Decays

Galactic Flux

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

- 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

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

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

Include neutrino propagation: Oscillations redistribute flux into all flavors.

$\Rightarrow$ Signals for ν_μ and ν_τ are equivalent, ν_e is slightly different!

Neutrino signal does not significantly depend on flavor of sneutrino VEV!

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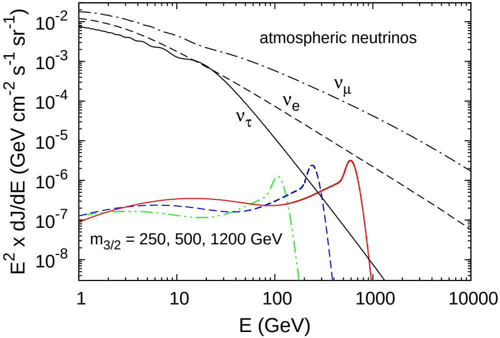
Neutrino Background

- 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!

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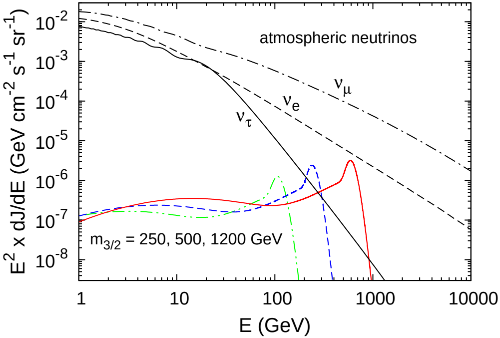

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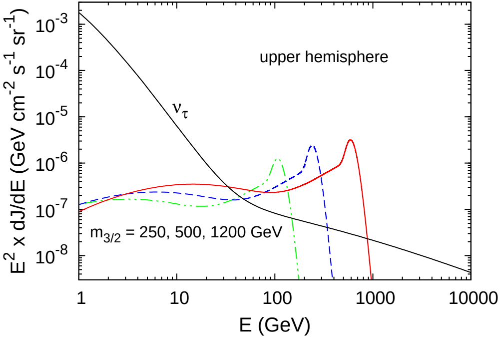
Background Reduction for Tau Neutrinos

- 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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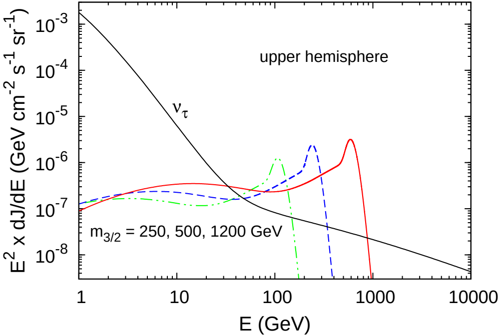

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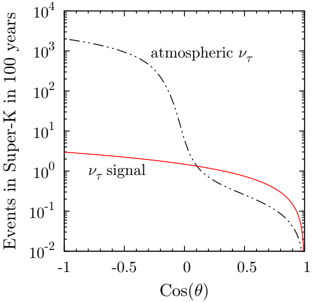
Experimental Situation for Tau Neutrinos

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 ~ 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
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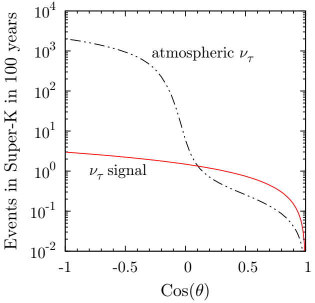

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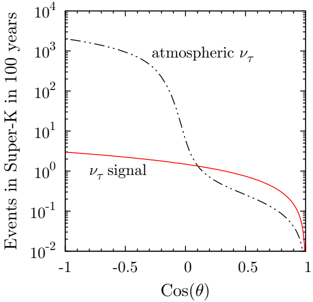

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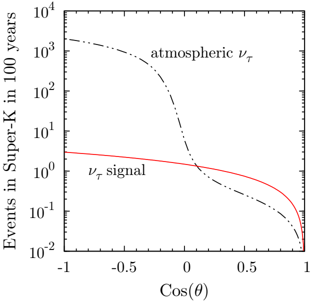

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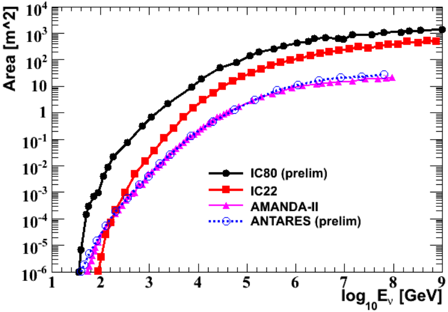

[Montaruli (2009)]

IceCube (completed detector)

- Signal: $\mathcal{O}(10^3)$, $\mathcal{O}(10^2)$, $\mathcal{O}(10)$ events/yr for $m_{3/2} = 1.2\,\text{TeV}, 500\,\text{GeV}, 250\,\text{GeV}$
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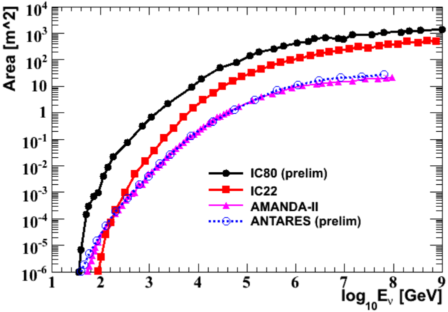

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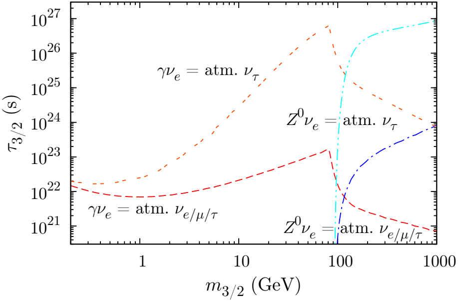
Bound on Gravitino Lifetime

- 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!



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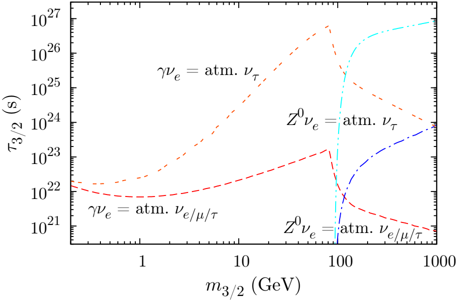

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Conclusions

- Gravitino with broken R-parity is theoretically well motivated Dark Matter candidate, compatible with thermal leptogenesis and BBN predictions.
- Neutrinos from decaying gravitino dark matter are most likely observable in the tau sector, due to a large signal-to-background ratio!
- Present neutrino experiments provide low statistics and cannot identify tau neutrinos on an event-by-event basis.
- Future neutrino experiments can improve sensitivity for low flux signals, but also have to provide tau flavor identification (ideally event by event).
- Muon neutrinos have larger statistics but low signal-to-background ratio.
- A dedicated analysis might extract the signal using spectral information!

Neutrino signals can make important contributions
to unveil the nature of the Dark Matter in the universe!

Conclusions

- Gravitino with broken R-parity is theoretically well motivated Dark Matter candidate, compatible with thermal leptogenesis and BBN predictions.
- Neutrinos from decaying gravitino dark matter are most likely observable in the tau sector, due to a large signal-to-background ratio!
- Present neutrino experiments provide low statistics and cannot identify tau neutrinos on an event-by-event basis.
- Future neutrino experiments can improve sensitivity for low flux signals, but also have to provide tau flavor identification (ideally event by event).
- Muon neutrinos have larger statistics but low signal-to-background ratio.
- A dedicated analysis might extract the signal using spectral information!

Neutrino signals can make important contributions
to unveil the nature of the Dark Matter in the universe!