Indirect Searches for Gravitino Dark Matter

Michael Grefe

Deutsches Elektronen-Synchrotron
DESY, Hamburg, Germany

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Based on work in progress in collaboration with Laura Covi and Gilles Vertongen.

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:

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

[Bolz *et al.* (2001)]

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

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Possible solution: Gravitino is the LSP and thus stable!

- Correct relic density for $m_{3/2} > \mathcal{O}(10)\,\mathrm{GeV}$ $\Rightarrow$ Gravitino dark matter
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Possible solution: *R* parity is not exactly conserved!

Gravitino Dark Matter with Bilinear R-Parity Violation

- Bilinear R-Parity Violation: $W_{\not{R}_p} = \mu_i H_u L_i, \qquad -\mathcal{L}^{\text{soft}}_{\not{R}_p} = B_i H_u \tilde{\ell}_i + m^2_{H_d \ell_i} H_d^* \tilde{\ell}_i + \text{h.c.}$
  - 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

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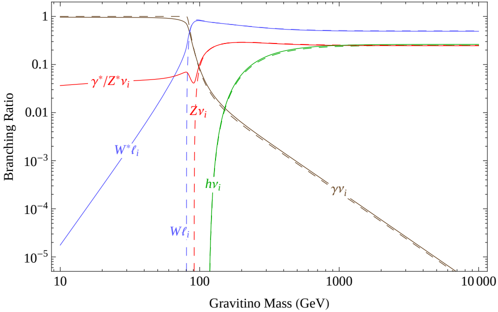
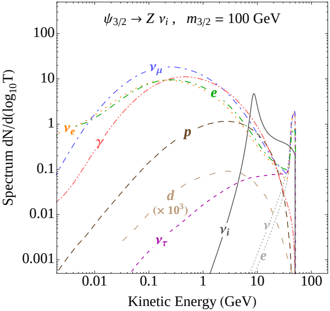
- Rich phenomenology instead of elusive gravitinos
  - A long-lived NLSP could be observed at the LHC
  - Gravitino decays lead to possibly observable signals at indirect detection experiments

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

Gravitino Decay Channels

- Several contributing decay channels: $\psi_{3/2} \to \gamma\,\nu_i,\ Z^*\nu_i,\ h^*\nu_i,\ W^*\ell_i$
  - For $m_{3/2} < m_W$ three-body decays can play an important role [Choi *et al.* (2010)]
  - Ratio between $\gamma\,\nu_i$ and other channels is model-dependent





- 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

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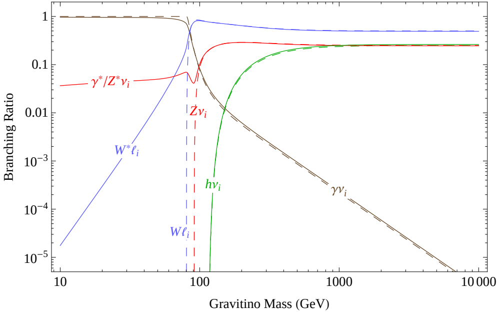

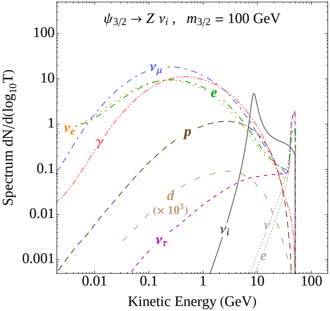

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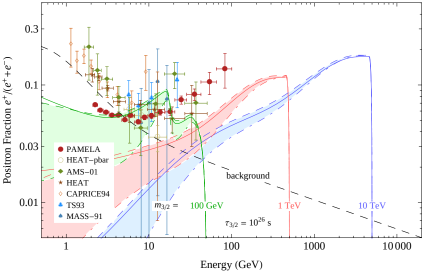
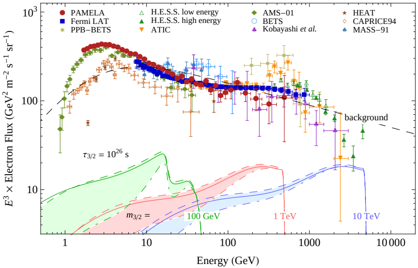
Basis for phenomenology of indirect gravitino dark matter searches!

Gravitino Decay Signals in Cosmic-Ray Spectra: $\frac{e^+}{e^+ + e^-}$ and e^-

positron fraction



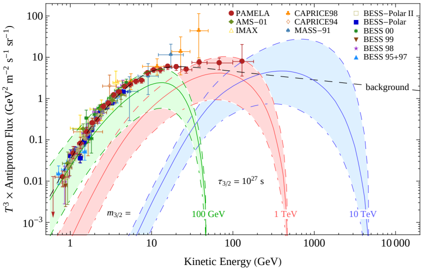
electron flux



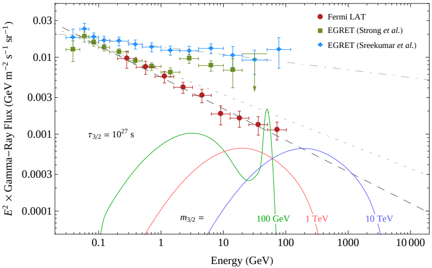
- Gravitino decay could explain the rise in the PAMELA positron fraction data
  - Explanation requires a gravitino lifetime of $\mathcal{O}(10^{26})$ s and a mass $\gtrsim 200$ GeV
- Also contribution to absolute electron flux expected

Gravitino Decay Signals in Cosmic-Ray Spectra: $\bar{p}$ and γ

antiproton flux



isotropic diffuse gamma-ray flux



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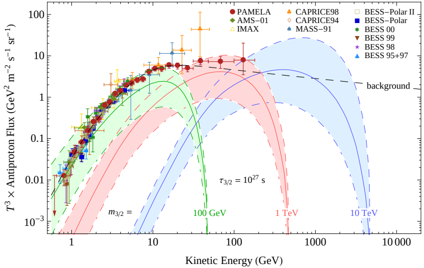

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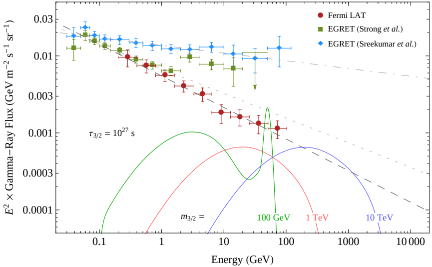

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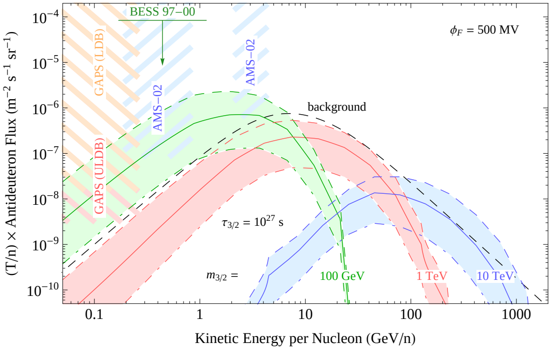
Astrophysical sources like pulsars required to explain cosmic-ray excesses!

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



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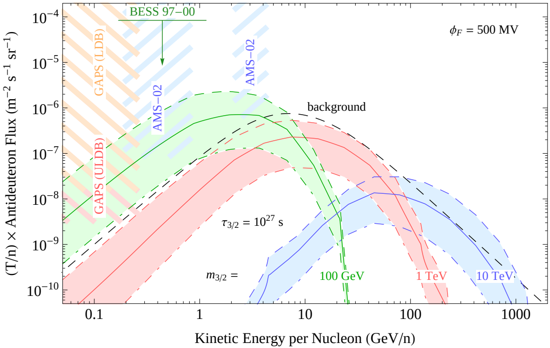
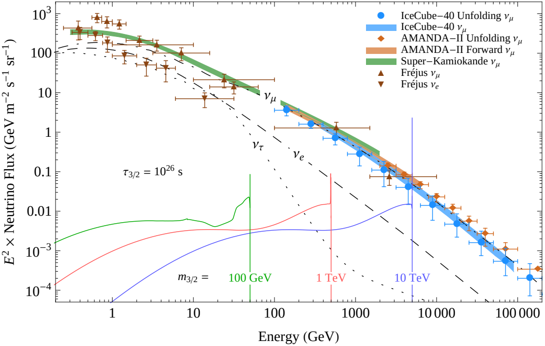


Antideuterons are a valuable channel for light gravitino searches!

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



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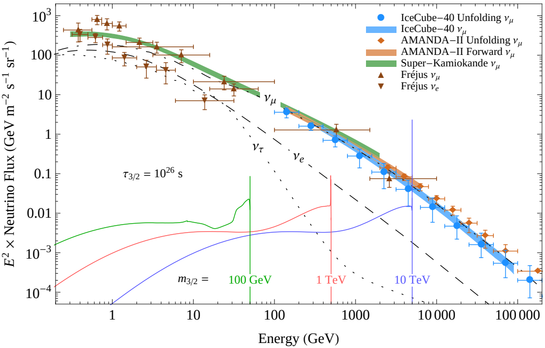


Neutrinos are a valuable channel for heavy gravitino searches!

Neutrino Detection with Upward Through-Going Muons

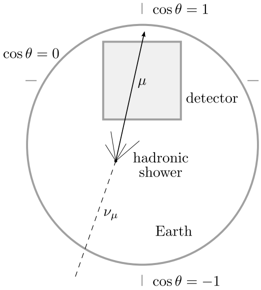
- Muon tracks from charged current DIS of muon neutrinos off nuclei outside the detector

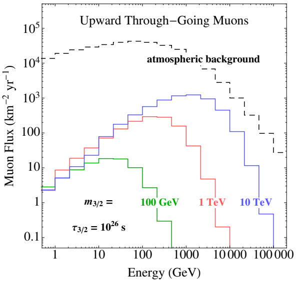
Advantages

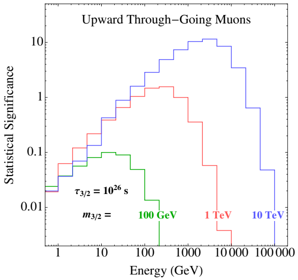
- Muon track reconstruction is well-understood at neutrino telescopes

Disadvantages

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







Neutrino Detection – Improvements Using Showers

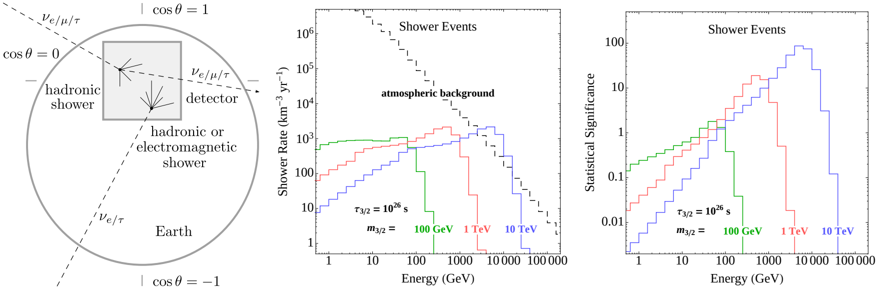
- Hadronic and electromagnetic showers from charged current DIS of electron and tau neutrinos and neutral current interactions of all neutrino flavors inside the detector

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 in $\log_{10} E$) helps to distinguish spectral features



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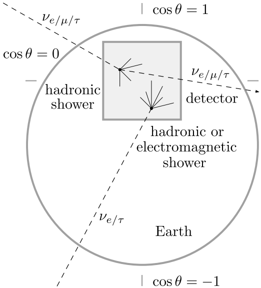
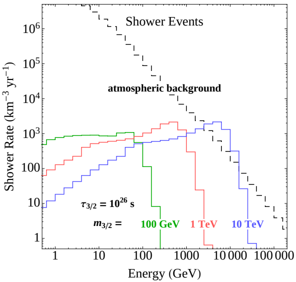
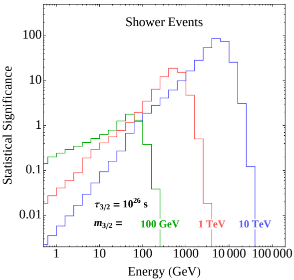
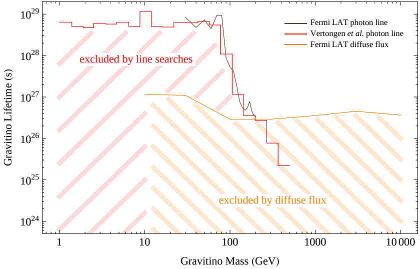


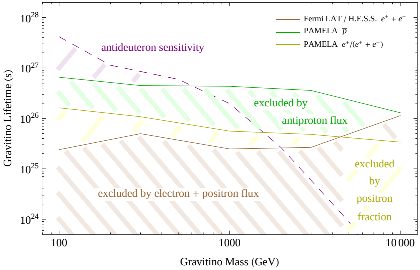




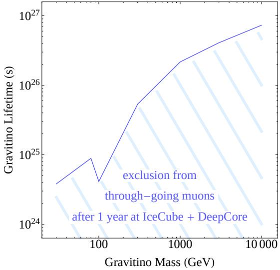
Showers are potentially the best channel for dark matter searches in neutrinos!

Limits on the Gravitino Dark Matter Parameter Space





- 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 ($\rightarrow$ future work)
  - Neutrino bounds are competitive for heavy gravitinos



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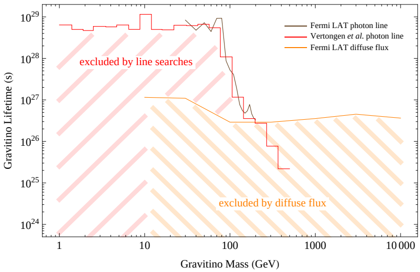

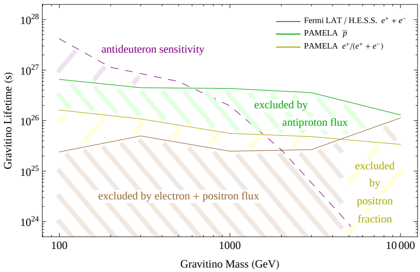

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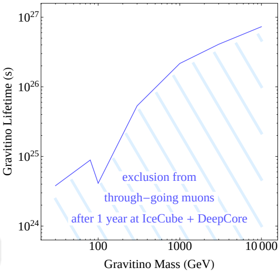
Strong bounds from multi-messenger approach!



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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