Indirect Searches for Gravitino Dark Matter

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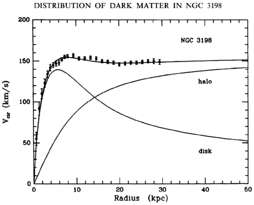
What Do We Know about Dark Matter?

- Dark matter is observed on various scales through its gravitational interaction
- Dark matter contributes significantly to the energy density of the universe



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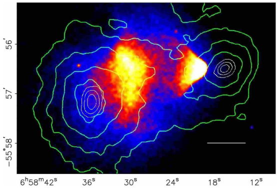

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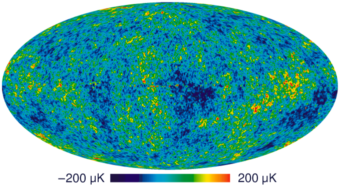
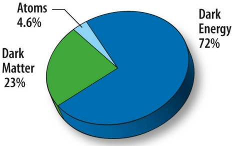


[NASA / WMAP Science Team]

- Dark matter properties known from observations:
  - No electromagnetic and strong interactions
  - At least gravitational and at most weak-scale interactions
  - Non-baryonic
  - Cold (maybe warm)
  - Long-lived on cosmological time scales but not necessarily stable!



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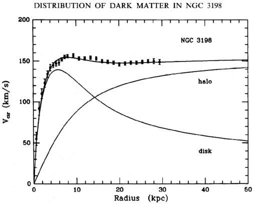

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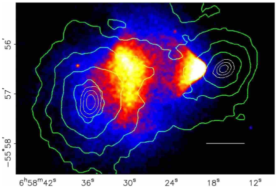

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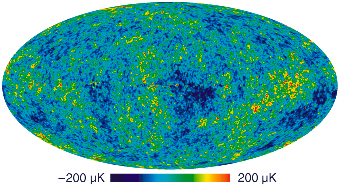

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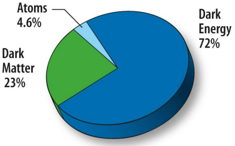

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Particle dark matter could be a (super)WIMP with lifetime $\gg$ age of the universe!

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:

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

[Bolz *et al.* (2001)]

- Problem in scenarios with neutralino dark matter:
  - Thermal leptogenesis requires high reheating temperature: $T_R \gtrsim 10^9\,\text{GeV}$ [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!

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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 (parametrized by ξ)
  - Lower bound: The NLSP must decay fast enough to evade BBN constraints: $\xi \gtrsim 10^{-11}$
  - Upper bound: The lepton/baryon asymmetry must not be washed out: $\xi \lesssim 10^{-7}$
- Gravitino decay suppressed by Planck scale and small R-parity violation
  - Gravitino decay width: $\Gamma_{3/2} \propto \frac{\xi^2 \, m_{3/2}^3}{M_{\text{Pl}}^2}$
  - The gravitino lifetime exceeds the age of the universe by many orders of magnitude

The unstable gravitino is a well-motivated and viable dark matter candidate!

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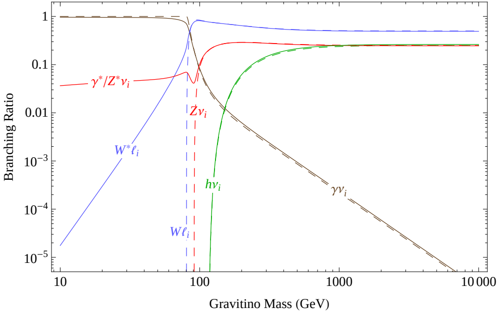
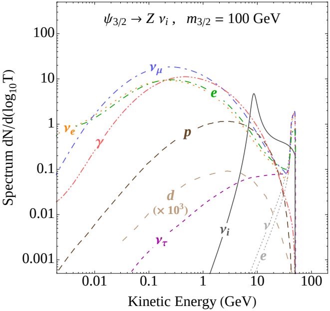
- Rich phenomenology instead of elusive gravitinos
  - A long-lived NLSP could be observed at the LHC [Bobrovskyi *et al.* (2010, 2011)]
  - Gravitino decays lead to possibly observable signals at indirect detection experiments

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 in PYTHIA [Kadastik *et al.* (2009)]

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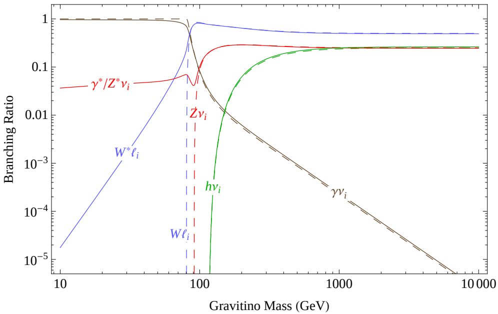

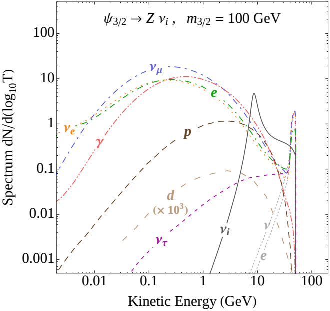

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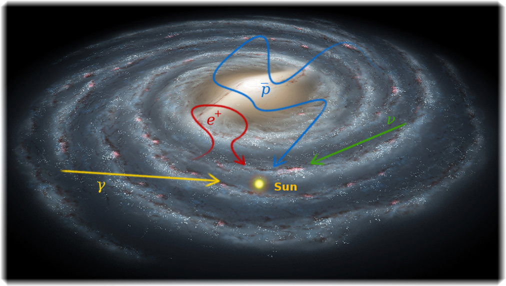
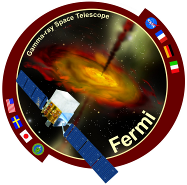
Basis for phenomenology of indirect gravitino dark matter searches!

Cosmic-Ray Propagation

- Cosmic rays from gravitino decays propagate through the Milky Way

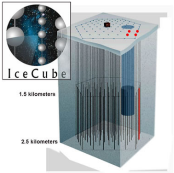


- Experiments observe spectra of gamma rays, charged cosmic rays and neutrinos



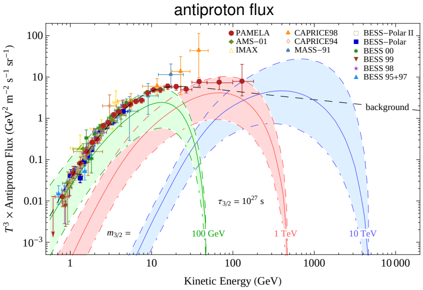
[NASA E/PO, SSU, Aurore Simonnet]

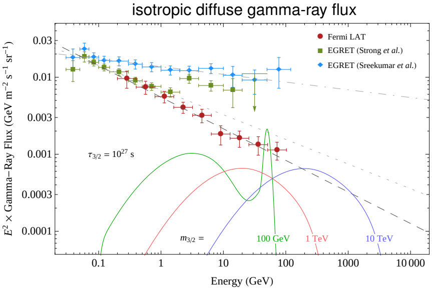
[AMS-02 Collaboration]



[IceCube Collaboration]

Gravitino Decay Signals in Cosmic-Ray Spectra





- Observed antiproton spectrum well described by astrophysical background
  - No need for contribution from dark matter
- Isotropic diffuse gamma-ray spectrum exhibits power-law behaviour
  - Source not completely understood, but no sign of spectral features of a particle decay
- Even without astrophysical backgrounds lifetimes below $\mathcal{O}(10^{26}$–$10^{27})$ s excluded
  - Gravitino decay cannot be the origin of the PAMELA and Fermi LAT cosmic-ray anomalies

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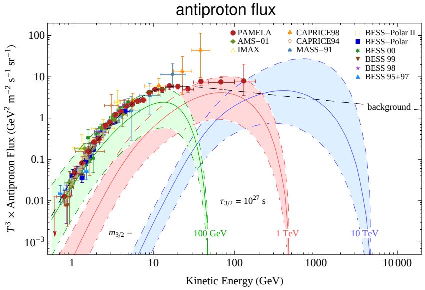

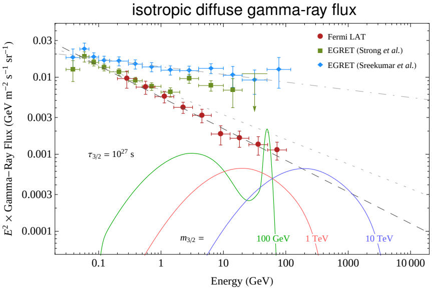

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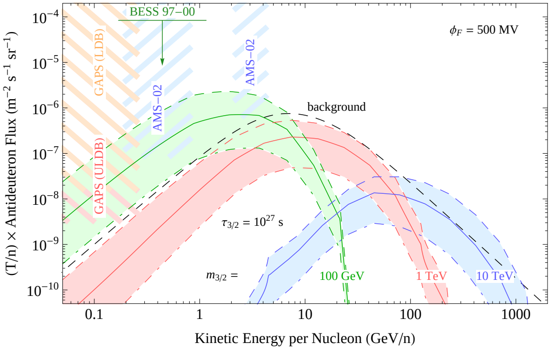
Astrophysical sources like pulsars required to explain cosmic-ray excesses!

Antideuteron Signals from Gravitino Decays

- In particular sensitive at low energies due to small astrophysical background
- AMS-02 and GAPS will be able to put strong constraints on light gravitinos



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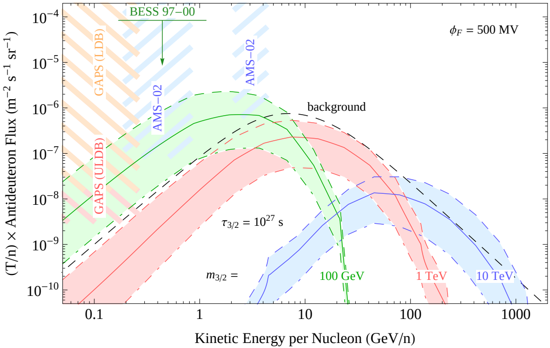
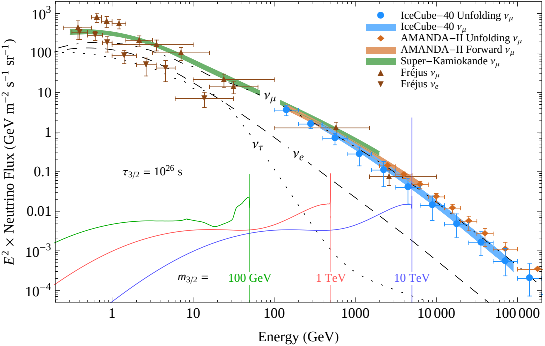


Antideuterons are a valuable channel for light gravitino searches!

Neutrino Signals from Gravitino Decays

- Neutrinos provide directional information like gamma rays
- Gravitino signal features neutrino line at the end of the spectrum
- Atmospheric neutrinos are the dominant background for the gravitino signal
  - Discrimination of neutrino flavours 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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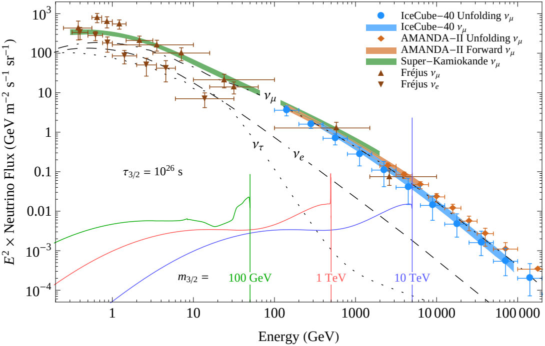


Neutrinos are a valuable channel for heavy gravitino searches!

Neutrino Detection with Upward Through-Going Muons

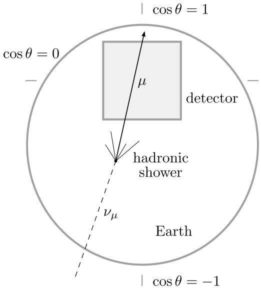
- Muon tracks from charged current DIS of muon neutrinos off nuclei outside the detector

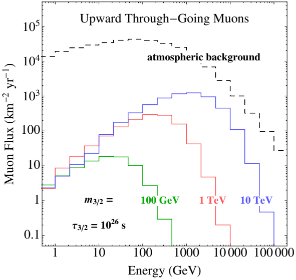
Advantages

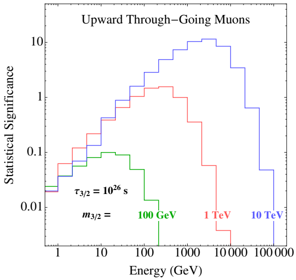
- Muon track reconstruction is well-understood at neutrino telescopes

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 cut-off energy







Neutrino Detection – Improvements Using Showers

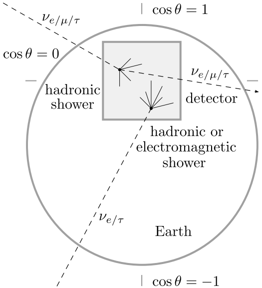
- Hadronic and electromagnetic showers from charged current DIS of electron and tau neutrinos and neutral current interactions of all neutrino flavours inside the detector

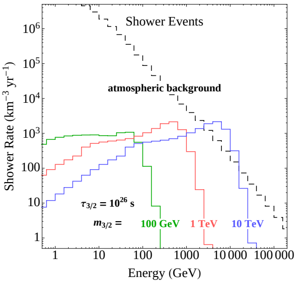
Disadvantages

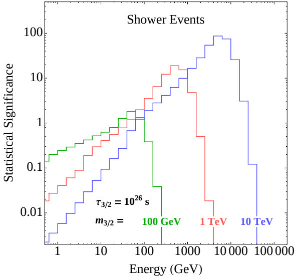
- TeV-scale showers are difficult to discriminate from short muon tracks

Advantages

- 3× larger signal and 3× lower background compared to other channels
- Better energy resolution (0.18 in $\log_{10} E$) helps to distinguish spectral features







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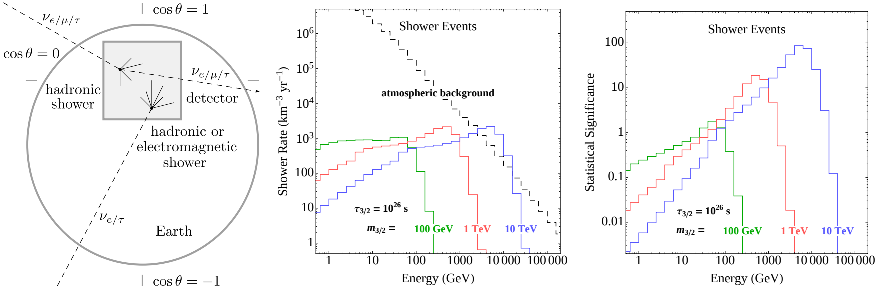
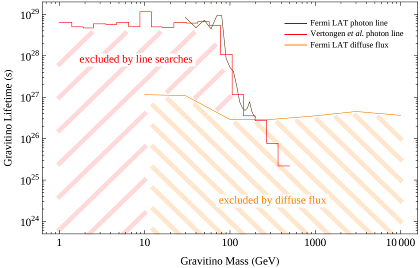
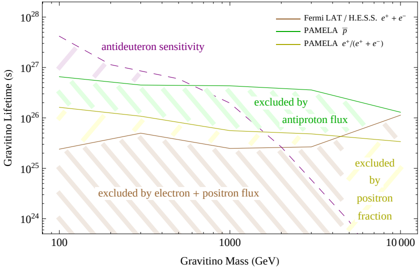


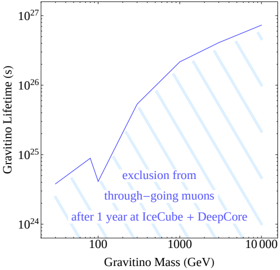
Showers are potentially the best channel for dark matter searches in neutrinos!

Limits on the Gravitino Lifetime





- 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 will improve bounds
  - Antideuterons can be complementary to photon line searches for low gravitino masses
  - Neutrino bounds are competitive for heavy gravitinos



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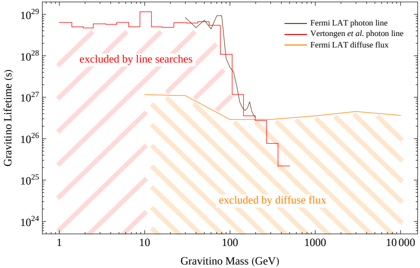

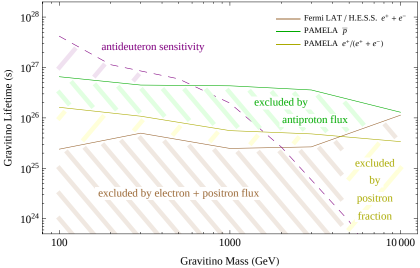

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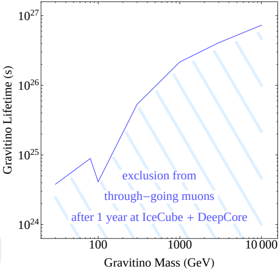
Wide range of bounds from multi-messenger approach!



Limits on the Amount of *R*-Parity Violation

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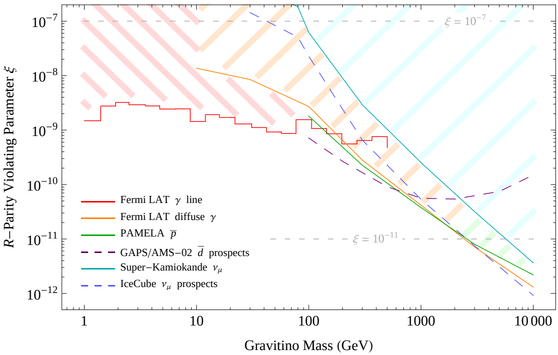

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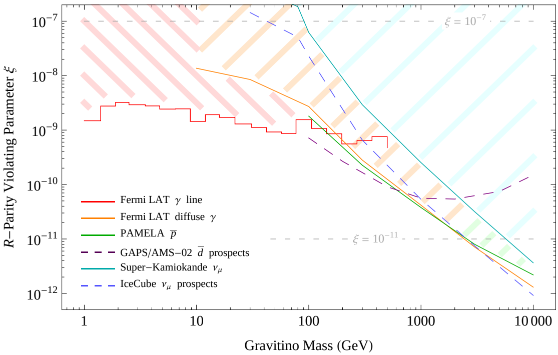

Indirect searches reach the cosmologically favoured range of *R*-parity violation!

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 and Fermi LAT anomalies 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 allows to constrain gravitino lifetime and strength of R-parity violation over a wide range of gravitino masses

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