Unstable Gravitino Dark Matter

Prospects for Indirect and Direct Detection

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Disputationsvortrag

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Based on JCAP **1004** (2010) 017 and ongoing projects.

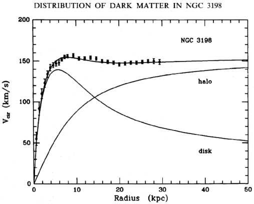
Outline

- Motivation for Unstable Gravitino Dark Matter
- Gravitino Dark Matter with Broken R Parity
  - Gravitino decay channels, branching ratios and spectra of final state particles
- Indirect Detection of Gravitino Dark Matter
  - Cosmic-ray signals and limits on the gravitino lifetime
- Direct Detection of Gravitino Dark Matter
  - Does R-parity violation lead to observable gravitino–nucleon scatterings?
- Conclusions and Outlook

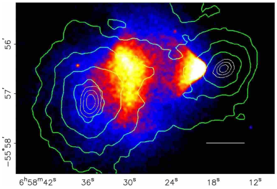
Motivation for Unstable Gravitino Dark Matter

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



[van Albada *et al.* (1985)]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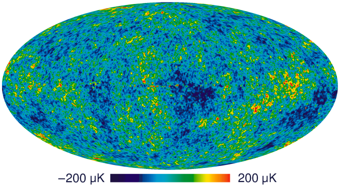
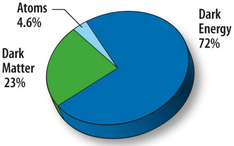


[NASA / WMAP Science Team]

- 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 timescales but not necessarily stable!



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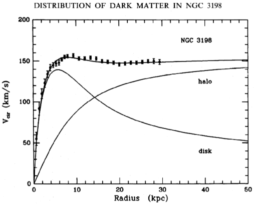

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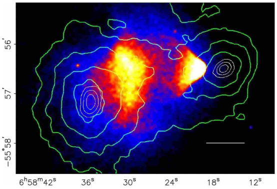
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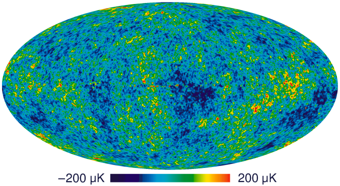

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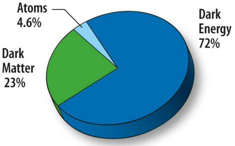

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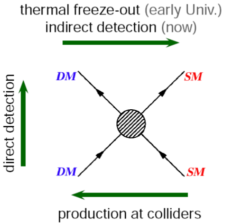
Particle dark matter could be a (super)WIMP with lifetime $\gg$ age of the universe!

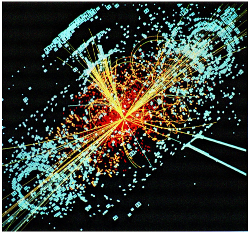
How Can We Unveil the Nature of Dark Matter?

► There are three main strategies for detecting dark matter based on non-gravitational interactions:

- Production of dark matter particles at colliders
- Direct detection of dark matter in the scattering off matter nuclei
- Indirect detection of dark matter in cosmic ray signatures



[Max-Planck-Institut für Kernphysik]



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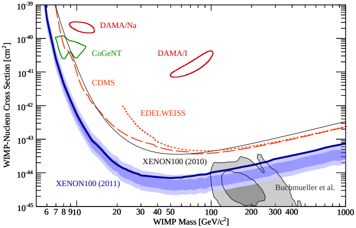

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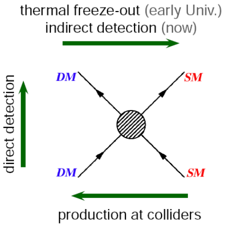

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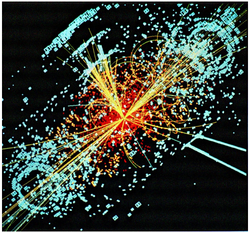
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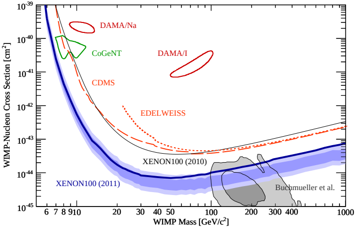

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A combination of these search strategies is necessary to reliably identify the particle nature of the dark matter in the universe!

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:

$$\Omega_{3/2}h^2 \simeq 0.27 \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2$$ [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)]
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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
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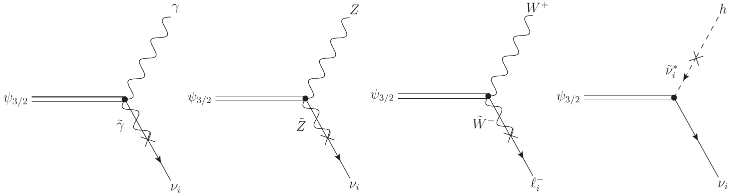
- Rich phenomenology instead of elusive gravitinos
  - A long-lived NLSP could be observed at the LHC
  - Gravitino decays lead to possibly observable signals at indirect detection experiments
  - Maybe even a direct detection of gravitino dark matter is conceivable

Gravitinos could be indirectly observed at colliders and in the spectra of cosmic rays or maybe even via scatterings in underground detectors!

Gravitino Dark Matter with Broken R Parity

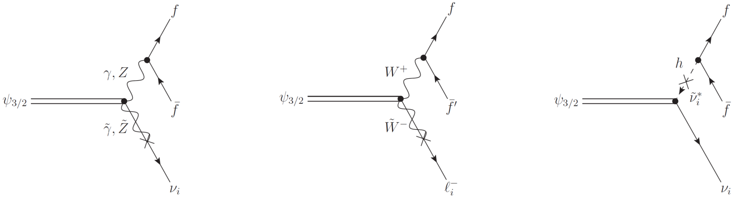
Gravitino Decay Channels

- Gravitino decays via *R*-parity breaking interactions: $\Gamma_{3/2} \propto \frac{\xi^2 \, m_{3/2}^3}{M_{\text{Pl}}^2}$
- Several two-body decay channels: $\psi_{3/2} \to \gamma\,\nu,\ Z\,\nu,\ W\,\ell,\ h\,\nu$



+ six additional diagrams

- For $m_{3/2} < m_W$ also three-body decays can play an important role



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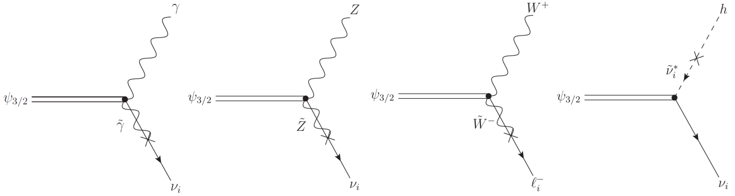

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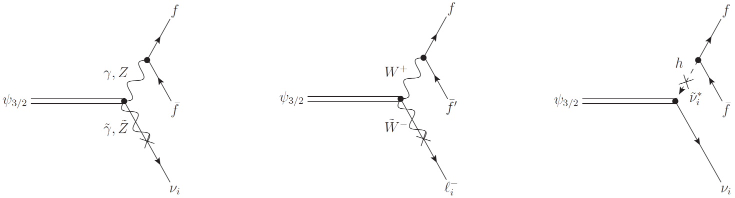

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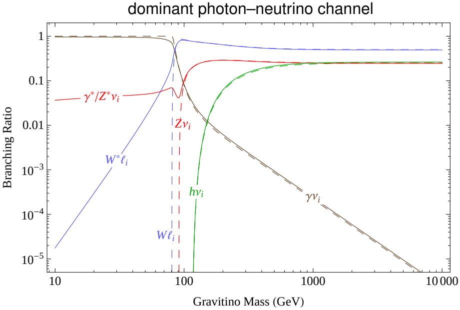
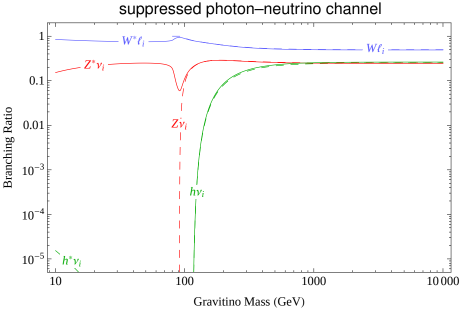
Calculation of decay widths crucial for gravitino phenomenology!

Gravitino Branching Ratios

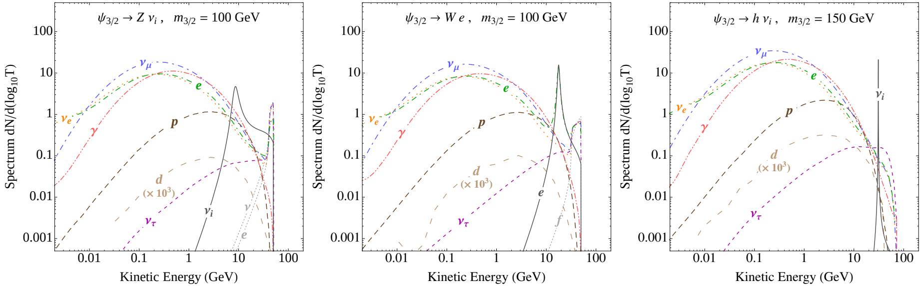
- Branching ratios are independent of strength of *R*-parity violation
- Two-body and three-body decay calculations agree above on-shell thresholds
- Three-body decays via off-shell propagators are important below m_W
- Ratio between $\psi_{3/2} \to \gamma\,\nu$ and other channels is model-dependent
  - $\psi_{3/2} \to \gamma\,\nu$ is the only two-body decay channel below m_W
  - Depending on the gaugino masses $\psi_{3/2} \to \gamma\,\nu$ can also be strongly suppressed





Final State Particle Spectra in Gravitino Decays

- Gravitino decays produce spectra of stable cosmic rays
  - Photons, electrons, neutrinos, protons, deuterons + antiparticles
- Two-body decay spectra generated with PYTHIA
  - Good agreement with spectra from analytical calculation
  - Large particle multiplicities from hadronization processes
  - Deuteron coalescence treated on event-by-event basis



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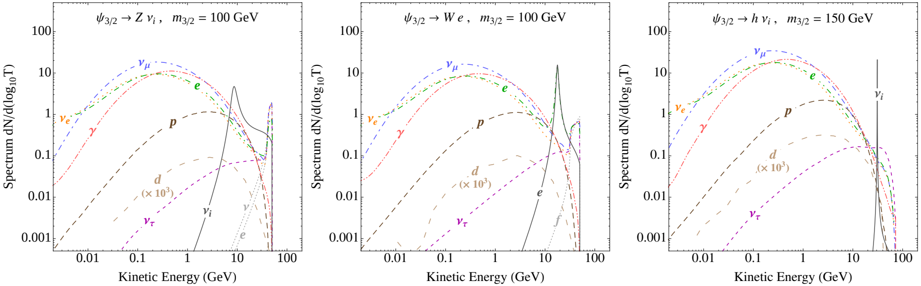

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Basis for phenomenology of indirect gravitino dark matter searches!

Indirect Detection of Gravitino Dark Matter

What Is the Difference of Dark Matter Annihilations and Decays?

- Different angular distribution of the gamma-ray/neutrino flux from the galactic halo:

Dark Matter Annihilation

$$\frac{dJ_{\text{halo}}}{dE} = \frac{\langle \sigma v \rangle_{\text{DM}}}{8\pi\, m_{\text{DM}}^2} \frac{dN}{dE} \int_{\text{l.o.s.}} \rho_{\text{halo}}^2(\vec{l})\, d\vec{l}$$

particle physics — astrophysics

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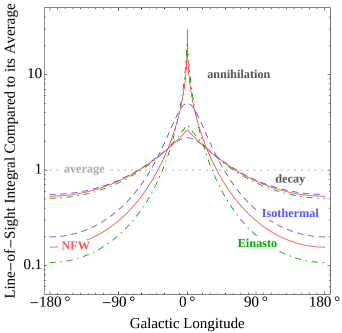

Annihilation (*e.g.* WIMP dark matter)

- Annihilation cross section related to relic density
- Strong signal from peaked structures
- Uncertainties from choice of halo profile

Decay (*e.g.* unstable gravitino dark matter)

- Lifetime unrelated to production in the early universe
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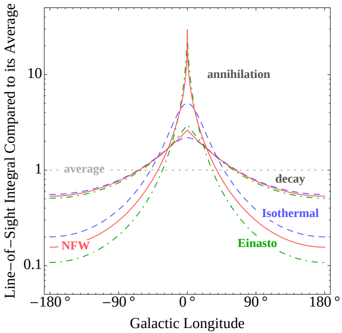

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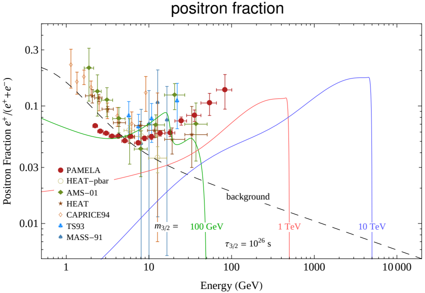
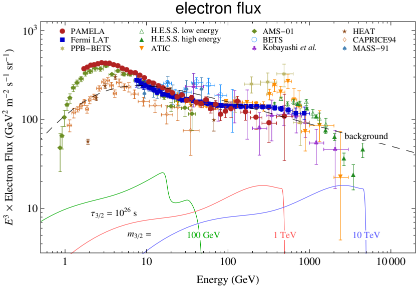
Directional detection can distinguish unstable gravitino from standard WIMPs!

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





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  - Explanation requires a gravitino lifetime of $\mathcal{O}(10^{26})$ s and a mass $\gtrsim 200$ GeV
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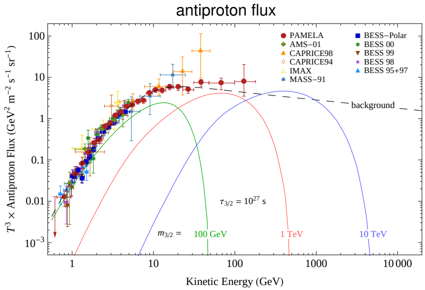

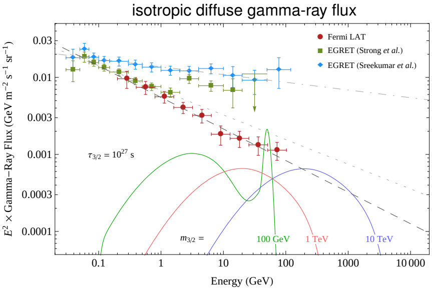

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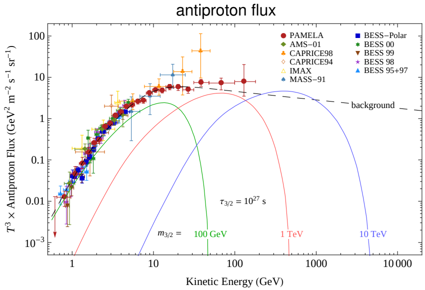

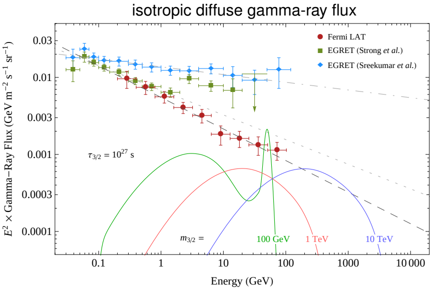

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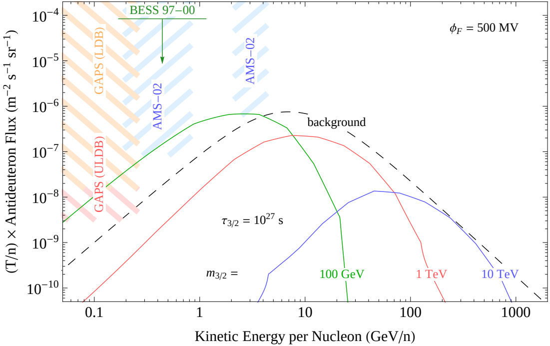
Astrophysical sources like pulsars required to explain cosmic-ray excesses!

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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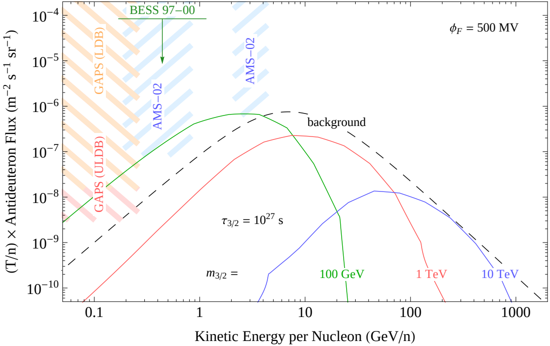
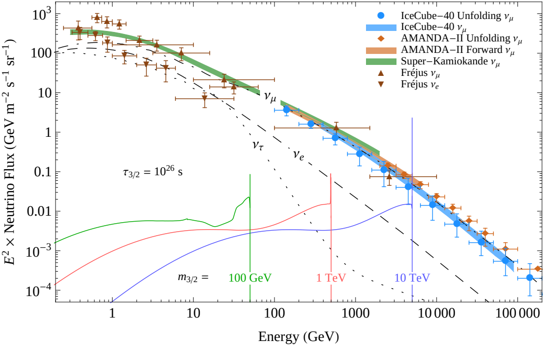


Antideuterons are a valuable channel for light gravitino searches!

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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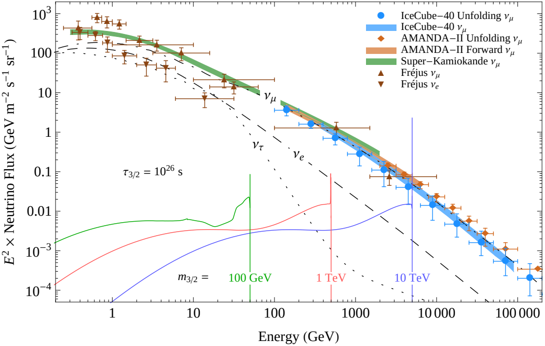


Neutrinos are a valuable channel for heavy gravitino searches!

Neutrino Detection with Upward Through-Going Muons

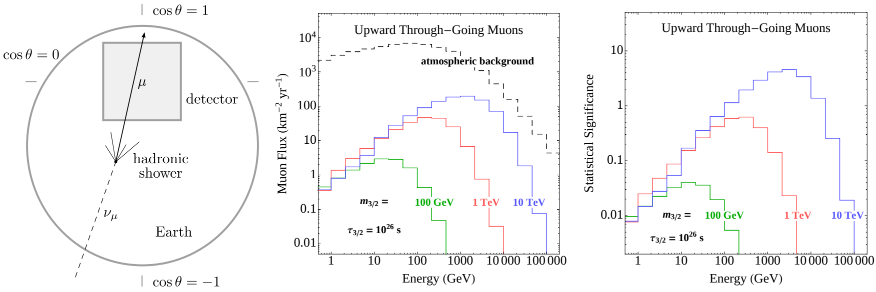
- Muon tracks from charged current DIS of muon neutrinos off nuclei outside the detector

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

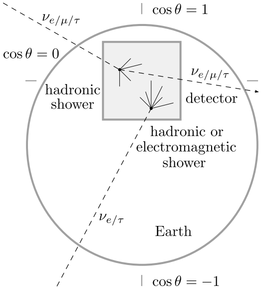
▶ Hadronic and electromagnetic showers from charged current DIS of electron and tau neutrinos and neutral current interactions of all neutrino flavors inside the detector

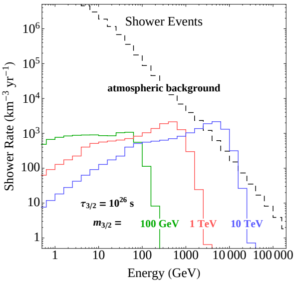
Disadvantages

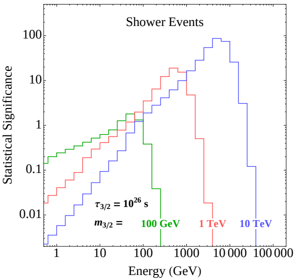
- TeV-scale shower reconstruction is not yet well understood

Advantages

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







Neutrino Detection – Improvements Using Showers

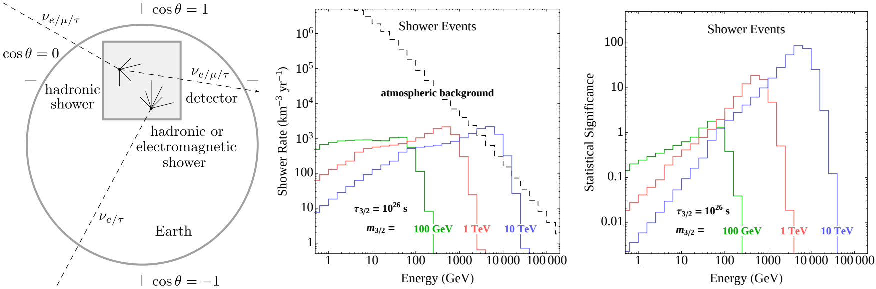
► Hadronic and electromagnetic showers from charged current DIS of electron and tau neutrinos and neutral current interactions of all neutrino flavors inside the detector

Disadvantages

- TeV-scale shower reconstruction is not yet well understood

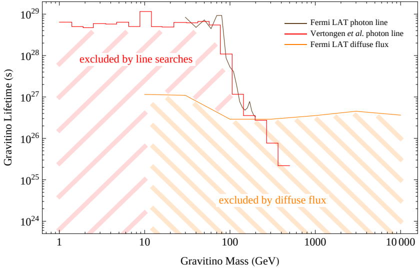
Advantages

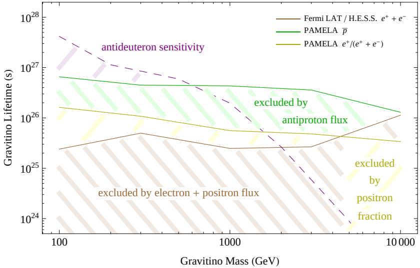
- 3× larger signal and 3× lower background compared to other channels
- Better energy resolution (0.18 in $\log_{10} E$) helps to distinguish spectral features



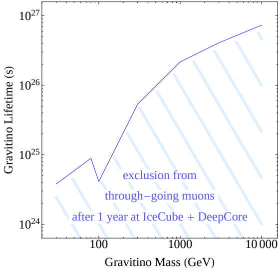
Showers are potentially the best channel for dark matter searches in neutrinos!

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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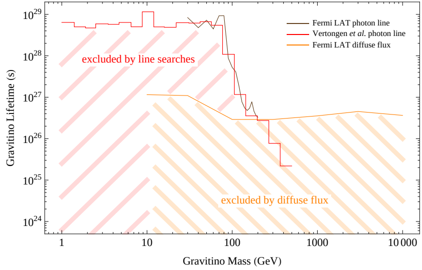

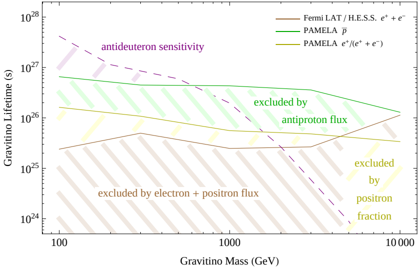

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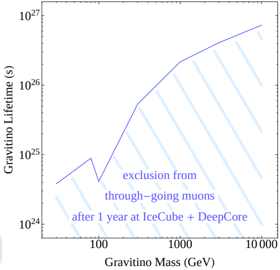
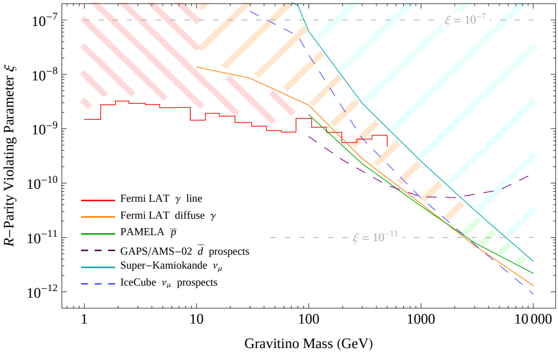
Strong bounds from multi-messenger approach!



Limits on the Amount of *R*-Parity Violation

- Limits on cosmic-ray fluxes place bounds on the strength of *R*-parity violation
  - Gamma-ray bounds are important for all gravitino masses
  - Bounds from all cosmic-ray channels are comparable in strength
  - Neutrino bounds competitive especially for large masses



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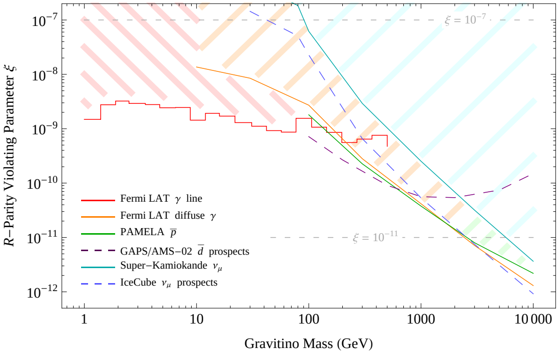
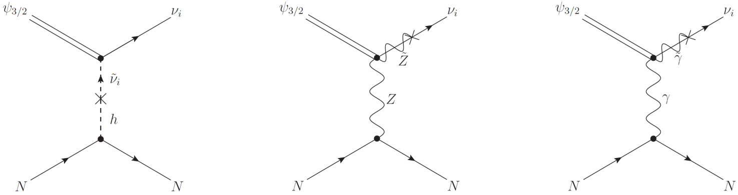


Indirect gravitino searches efficiently probe the cosmologically favored range of *R*-parity violation!

Direct Detection of Gravitino Dark Matter

Gravitino–Nucleon Scattering

- Elastic gravitino scattering suppressed by M_{Pl}^4 $\longrightarrow$ No observable signal!
- *R*-parity violation allows for inelastic scattering: $\sigma_N \propto \frac{\xi^2}{M_{\text{Pl}}^2}$ $\longrightarrow$ Less suppressed!



+ four additional diagrams

- Gravitino can scatter via photon exchange
  - No photon exchange for other dark matter candidates (no electromagnetic interactions)
  - Massless photon propagator leads to sizable enhancement compared to *Z* and Higgs exchange channels
- Cross section on protons still very small: $\sigma_p \sim 10^{-43}\text{pb}\left(\frac{\xi}{10^{-7}}\right)^2$
- Way below the reach of current underground detectors: $\sigma_N \gtrsim 10^{-8}\text{pb}$

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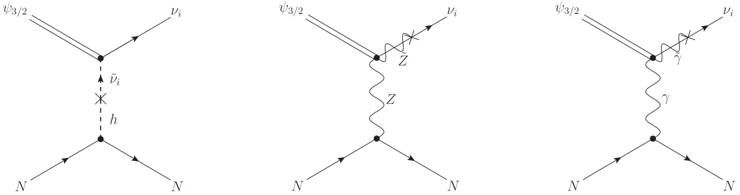

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Even with broken *R* parity direct gravitino detection appears to be hopeless!

Conclusions and Outlook

Conclusions

- 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
- Neutrino experiments like IceCube can probe heavy gravitino dark matter
- Multi-messenger approach strongly constrains gravitino lifetime and strength of *R*-parity violation
- Direct detection of unstable gravitino is hopeless

Outlook

- Forthcoming experiments like AMS-02 will greatly improve cosmic-ray data
- Antideuteron searches will probe light gravitino dark matter
- New detection strategies will improve the sensitivity of neutrino experiments to dark matter
- Colliders and direct detection experiments provide complementary dark matter searches
- The nature of dark matter will hopefully be unveiled within the next decade!

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Thanks for your attention!

Backup Slides

Neutralino–Neutrino Mixing

- Bilinear *R*-parity violation extends neutralino mass matrix to include neutrinos
- 7×7 matrix with basis $\psi_i^0 = (-i\tilde{\gamma},\, -i\tilde{Z},\, \tilde{H}_u^0,\, \tilde{H}_d^0,\, \nu_i)^T$

$$M_N^7 = \begin{pmatrix} M_1 c_W^2 + M_2 s_W^2 & (M_2 - M_1)\, s_W c_W & 0 & 0 & 0 \\ (M_2 - M_1)\, s_W c_W & M_1 s_W^2 + M_2 c_W^2 & m_Z s_\beta & -m_Z c_\beta & -m_Z \xi_j \\ 0 & m_Z s_\beta & 0 & -\mu & 0 \\ 0 & -m_Z c_\beta & -\mu & 0 & 0 \\ 0 & -m_Z \xi_i & 0 & 0 & 0 \end{pmatrix}$$

- Diagonalized by unitary matrix N^7
- Mixing to neutrinos via neutrino–zino coupling: $N^7_{\nu_i X} \simeq -\xi_i\, U_{X\tilde{Z}}$
- Analytical approximations show dependence on SUSY parameters
  - $U_{\tilde{\gamma}\tilde{Z}} \simeq m_Z \sin\theta_W \cos\theta_W \frac{M_2 - M_1}{M_1 M_2}$
  - $U_{\tilde{Z}\tilde{Z}} \simeq -m_Z \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2} \right)$
  - $U_{\tilde{H}_u^0\tilde{Z}} \simeq m_Z^2 \cos\beta \frac{M_1 \cos^2\theta_W + M_2 \sin^2\theta_W}{M_1 M_2 \mu}$
  - $U_{\tilde{H}_d^0\tilde{Z}} \simeq -m_Z^2 \sin\beta \frac{M_1 \cos^2\theta_W + M_2 \sin^2\theta_W}{M_1 M_2 \mu}$

Chargino–Charged Lepton Mixing

- Bilinear R-parity violation extends chargino mass matrix to include charged leptons
- 5×5 matrix with basis vectors $\psi^- = (\tilde{W}^-, \tilde{H}_d^-, \ell_i^-)^T$ and $\psi^+ = (\tilde{W}^+, \tilde{H}_u^+, e_i^{c\,+})^T$

$$M_C^5 = \begin{pmatrix} M_2 & \sqrt{2}\, m_W\, s_\beta & 0 \\ \sqrt{2}\, m_W\, c_\beta & \mu & -m_{\ell_{ij}}\, \xi_i\, c_\beta \\ \sqrt{2}\, m_W\, \xi_i & 0 & m_{\ell_{ij}} \end{pmatrix}$$

- Diagonalized by unitary matrices U^5 and V^5
- Mixing to left-handed leptons via lepton–wino coupling: $U^5_{\ell_i X} \simeq -\sqrt{2}\, \xi_i\, U_{X\tilde{W}}$
- Mixing to right-handed leptons suppressed and negligible
- Analytical approximations show dependence on SUSY parameters
  - $U_{\tilde{W}\tilde{W}} \simeq \frac{m_W}{M_2}$
  - $U_{\tilde{H}_d^-\,\tilde{W}} \simeq -\frac{\sqrt{2}\, m_W^2 \sin\beta}{M_2\, \mu}$

Higgs–Sneutrino Mixing

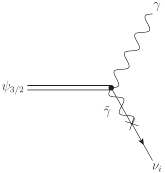
- Bilinear *R*-parity induces mass mixing in the scalar sector

$$\mathcal{L}_{h\tilde{\nu}_i} = -\,(h\ \tilde{\nu}_i^*) \begin{pmatrix} m_h^2 & \frac{1}{\sqrt{2}}\left(B_j\, s_\beta - m_{H_d \ell_i}^2\, c_\beta\right) \\ \frac{1}{\sqrt{2}}\left(B_i^*\, s_\beta - m_{H_d \ell_i}^{*2}\, c_\beta\right) & m_{\tilde{\ell}_{ij}}^2 + \frac{1}{2}\, m_Z^2\, \xi_i^2 \end{pmatrix} \begin{pmatrix} h \\ \tilde{\nu}_j \end{pmatrix}$$

- Mixing between standard model-like Higgs and sneutrino proportional to sneutrino vacuum expectation value

Gravitino Decay Widths

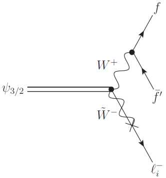
- Two-body decay to photon and neutrino

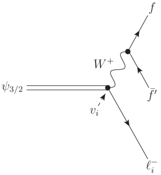


$$\Gamma = \frac{\xi^2\, m_{3/2}^3}{64\,\pi\, M_{\rm Pl}^2} |U_{\tilde{\gamma}\tilde{Z}}|^2 \propto \frac{\xi^2\, m_{3/2}^3}{M_{\rm Pl}^2} \left(\frac{M_2 - M_1}{M_1\, M_2}\right)^2$$

  - Decay width depends on R-parity breaking parameter ξ
  - Also depends on photino–zino mass mixing $U_{\tilde{\gamma}\tilde{Z}}$ $\rightarrow$ dependence on gaugino masses

- Three-body decay to fermions and charged lepton via virtual W boson

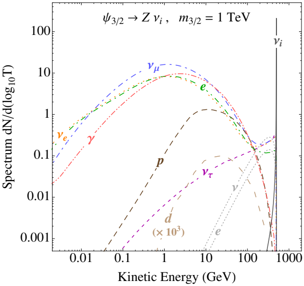


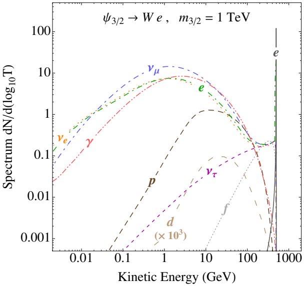


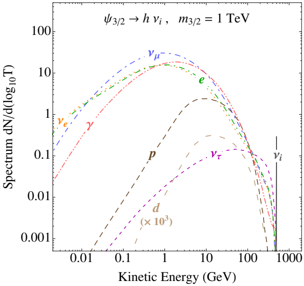
$$\frac{d\Gamma}{ds} \propto \frac{\xi^2\, m_{3/2}^3\, \beta_s^2}{M_{\rm Pl}^2\left((s - m_W^2)^2 + m_W^2\Gamma_W^2\right)} \times \left(s\, U_{\tilde{W}\tilde{W}}^2\, f_s - \frac{8}{3}\,\frac{m_W}{m_{3/2}}\, s\, U_{\tilde{W}\tilde{W}} j_s + \frac{1}{6}\, m_W^2 h_s\right)$$

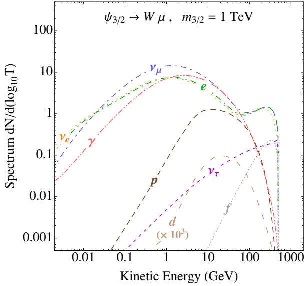
  - β_s, f_s, j_s and h_s are functions of the W invariant mass s and $m_{3/2}$
  - Second diagram independent of gaugino masses $\rightarrow$ dominates for heavy gravitinos

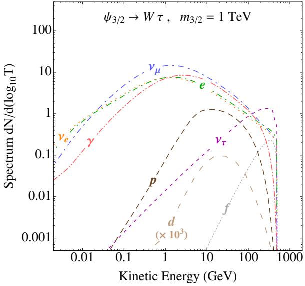
Other Two-Body Decay Final State Particle Spectra



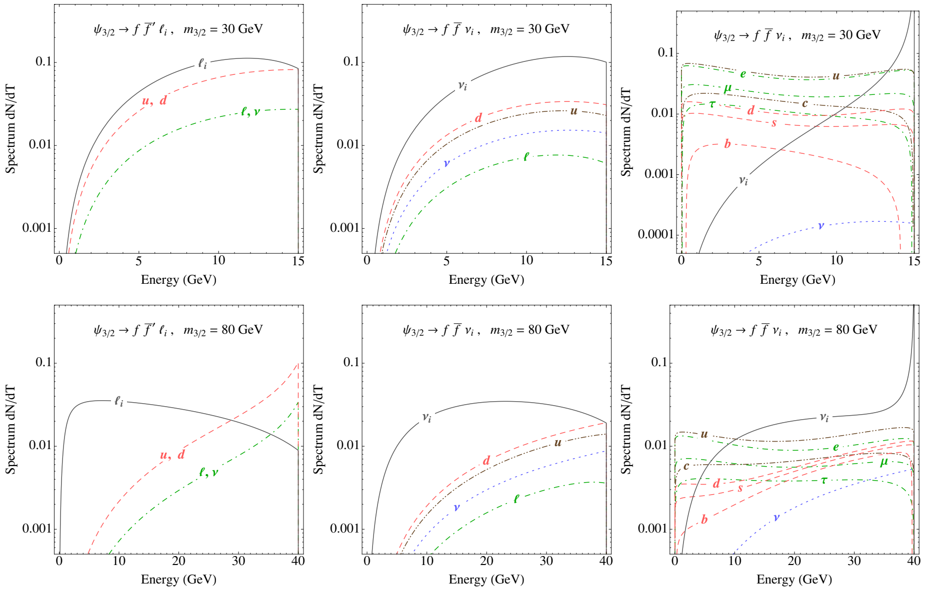




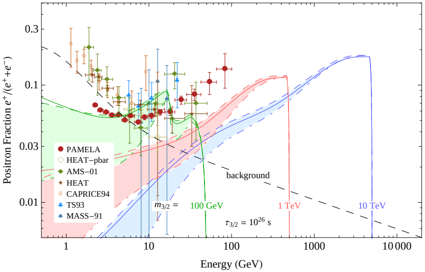


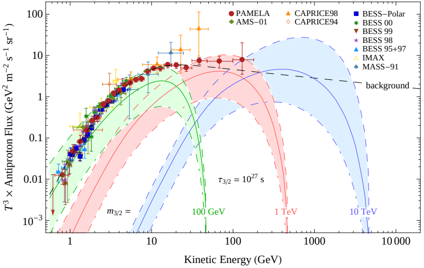


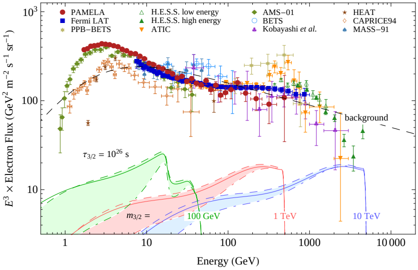
Three-Body Decay Particle Spectra

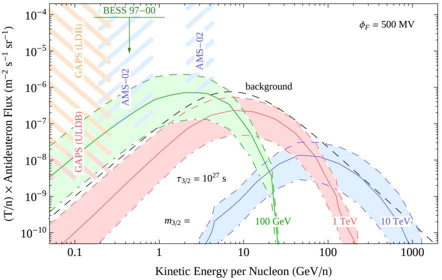


Charged Cosmic Ray Propagation Uncertainties

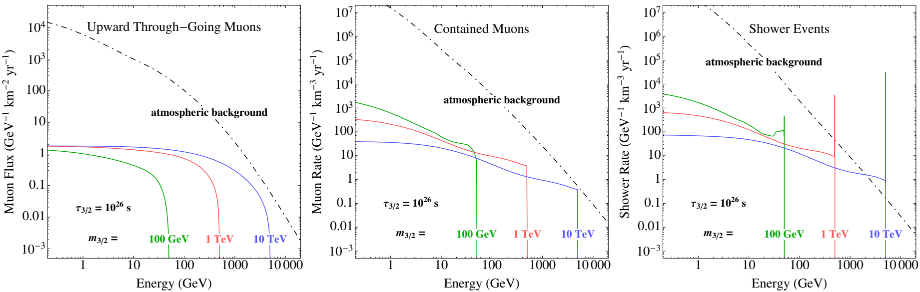








Neutrino Signals without Energy Resolution



Current Lifetime Limits from Neutrino Experiments