Gravitino Dark Matter with Broken R-Parity

Michael Grefe

Departamento de Física Teórica
Instituto de Física Teórica UAM/CSIC
Universidad Autónoma de Madrid

Instituto de Física Teórica UAM/CSIC

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Based on JCAP 0901 (2009) 029, JCAP 1004 (2010) 017, arXiv:1111.6779 [hep-ph] and ongoing work.

Collaborators: L. Covi, T. Delahaye, A. Ibarra, D. Tran, G. Vertongen

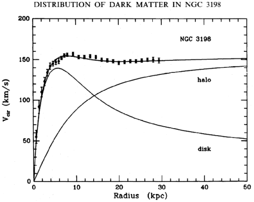
Outline

- Motivation for Unstable Gravitino Dark Matter
- Gravitino Dark Matter with Broken *R* Parity
- Indirect Detection of Gravitino Dark Matter
- Implications for the LHC
- Limits on the Amount of *R*-Parity Violation
- Conclusions and Outlook

Motivation for Unstable Gravitino Dark Matter

What Do We Know about Dark Matter?

- Observed on various scales through its gravitational interaction
- Contributes significantly to the energy density of the universe



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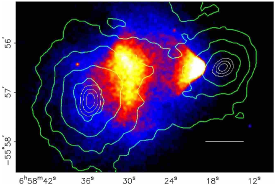

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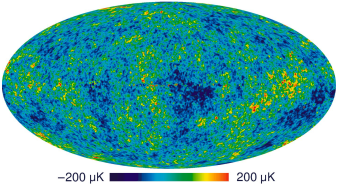
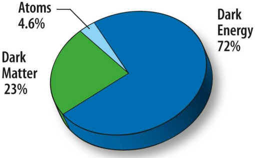


[NASA / WMAP Science Team]

- 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)
  - Extremely long-lived but can be unstable!



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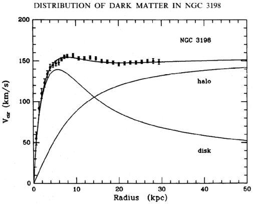

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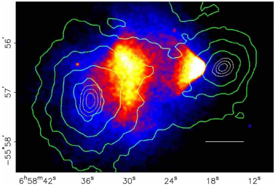

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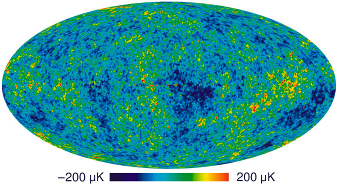

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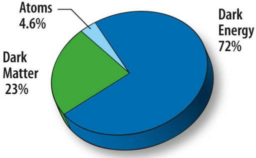
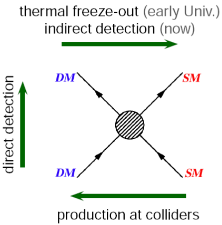


[NASA / WMAP Science Team]

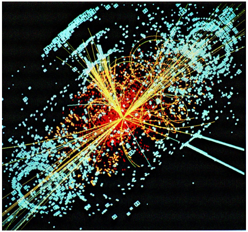
Dark matter could be (super)WIMP with lifetime $\gg$ age of the universe!

How Can We Unveil the Nature of Dark Matter?

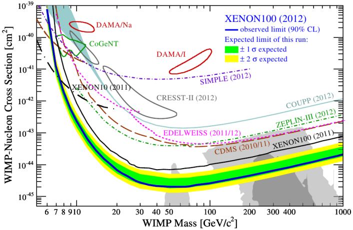
- Three search strategies for dark matter:
  - Direct detection in the scattering off matter nuclei
  - Production of dark matter particles at colliders
  - Indirect detection in cosmic ray signatures



[Max-Planck-Institut für Kernphysik]



[CERN]



[Aprile *et al.* (2012)]

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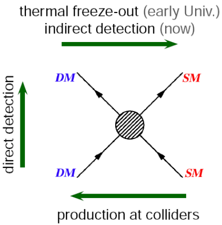

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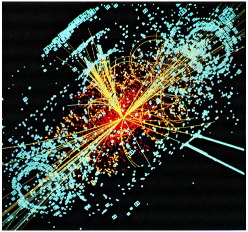

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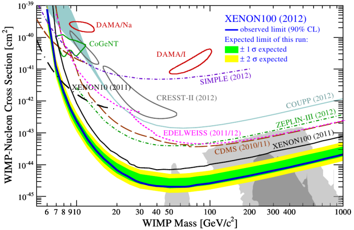

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A combination will be necessary to identify the nature of particle dark matter!

Why Unstable Gravitino Dark Matter?

- Smallness of observed neutrino masses motivates seesaw mechanism
- Explains baryon asymmetry via thermal leptogenesis [Fukugita, Yanagida (1986)]
  - Needs high reheating temperature: $T_R \gtrsim 10^9$ GeV [Davidson, Ibarra (2002)]
- Supergravity predicts gravitino as spin-3/2 superpartner of the graviton
- Gravitinos are thermally produced after inflation in the early universe:

$$\Omega_{3/2}^{\mathrm{TP}} h^2 \simeq \sum_{i=1}^{3} \omega_i \, g_i^2 \left(1 + \frac{M_i^2}{3\, m_{3/2}^2}\right) \ln\left(\frac{k_i}{g_i}\right) \left(\frac{m_{3/2}}{100\,\mathrm{GeV}}\right) \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)$$

[Pradler, Steffen (2006)]

- Problem in scenarios with neutralino dark matter:
  - Gravitino decays suppressed by Planck scale:

$$\tau_{3/2} \sim \frac{M_{\mathrm{Pl}}^2}{m_{3/2}^3} \approx 3\,\text{years} \left(\frac{100\,\mathrm{GeV}}{m_{3/2}}\right)^3$$

  - Decays with $\tau \gtrsim \mathcal{O}(1\text{–}1000\,\mathrm{s})$ spoil BBN $\Rightarrow$ Cosmological gravitino problem

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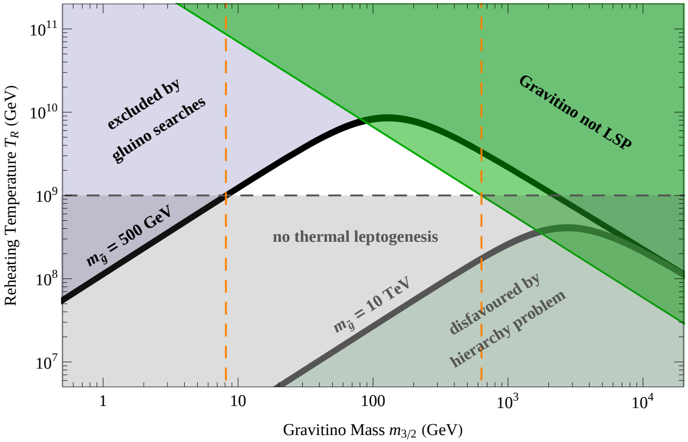
Possible solution: Gravitino is the LSP and thus stable!

Why Unstable Gravitino Dark Matter?

- Relation between gravitino mass and reheating temperature:



- With thermal leptogenesis correct relic density possible for $\mathcal{O}(10)\,\text{GeV} < m_{3/2} < \mathcal{O}(500)\,\text{GeV} \;\; \Rightarrow$ Gravitino dark matter

[Buchmüller *et al.* (2008))]

Why Unstable Gravitino Dark Matter?

- Still problematic:
  - NLSP can only decay to gravitino LSP:

$$\tau_{\mathrm{NLSP}} \simeq \frac{48\pi M_{\mathrm{Pl}}^2 m_{3/2}^2}{m_{\mathrm{NLSP}}^5} \approx 9\,\mathrm{days} \left(\frac{m_{3/2}}{10\,\mathrm{GeV}}\right)^2 \left(\frac{150\,\mathrm{GeV}}{m_{\mathrm{NLSP}}}\right)^5$$

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  - Late NLSP decays are in conflict with BBN $\Rightarrow$ Cosmological gravitino problem

Possible solution: *R*-parity is not exactly conserved!

- Other options:
  - Choose harmless NLSP like sneutrino [Covi, Kraml (2007)]
  - Dilute NLSP density by late entropy production [Buchmüller *et al.* (2006)]

Gravitino Dark Matter with Broken *R*-Parity

Models with Gravitino DM and *R*-Parity Violation

- Bilinear *R*-parity violation from *B*–*L* breaking [Buchmüller *et al.* (2007)]
  - Consistent gravitino cosmology with thermal leptogenesis and BBN
  - $\mathcal{O}(10)$ GeV $< m_{3/2} < \mathcal{O}(500)$ GeV, gluino mass below a few TeV
- Bilinear *R*-parity violation (BRpV) [Valle *et al.* (1990s), Takayama *et al.* (2000)]
  - *R*-parity violation is source of neutrino masses and mixings
  - Predictive model: gravitino mass constrained to be below few GeV
- "μ from ν" Supersymmetric SM ($\mu\nu$SSM) [López-Fogliani, Muñoz (2005)]
  - Electroweak see-saw mechanism for neutrino masses
  - Solves the μ-problem similar to the NMSSM
  - Predictive model: gravitino mass constrained to be below few GeV
- Trilinear *R*-parity violation [Moreau *et al.* (2001), Lola *et al.* (2007)]
  - Phenemenological study, trilinear terms generically expected without *R*-parity

Gravitino Dark Matter with Bilinear R-Parity Violation

- Bilinear R-parity violation: $W_{\not{R}_p} = \mu_i H_u L_i$, $-\mathcal{L}^{\text{soft}}_{\not{R}_p} = B_i H_u \tilde{\ell}_i + m^2_{H_d \ell_i} H_d^* \tilde{\ell}_i + \text{h.c.}$
  - Only lepton number violated $\Rightarrow$ Proton remains stable!
- R-parity violation can be parametrized by sneutrino VEV: $\xi = \dfrac{\langle \tilde{\nu} \rangle}{v}$
- Cosmological bounds on R-violating couplings
  - Lower bound: The NLSP must decay before the time of BBN: $\xi \gtrsim \mathcal{O}(10^{-11})$
  - Upper bound: No washout of lepton/baryon asymmetry: $\xi \lesssim \mathcal{O}(10^{-7})$
- Tiny bilinear R-parity violation can be related to $U(1)_{B-L}$ breaking
  [Buchmüller *et al.* (2007)]
- Gravitino decay suppressed by Planck scale and small R-parity violation
  - Gravitino decay width: $\Gamma_{3/2} \propto \dfrac{\xi^2\, m^3_{3/2}}{M^2_{\text{Pl}}} = 2.6 \times 10^{-24}\,\text{s}^{-1} \left(\dfrac{m^3_{3/2}}{10\,\text{GeV}}\right)^3 \left(\dfrac{\xi}{10^{-7}}\right)^2$
    [Takayama, Yamaguchi (2000)]
  - The gravitino lifetime by far exceeds the age of the universe ($\tau_{3/2} \gg 10^{17}$ s)

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

Phenomenology of Unstable Gravitino Dark Matter

- Rich phenomenology instead of elusive gravitinos:
  - A long-lived NLSP could be observed at the LHC
    [Buchmüller *et al.* (2007), Bobrovskyi *et al.* (2010)]
  - Gravitino decays can possibly be observed at indirect detection experiments
    [Takayama *et al.* (2000), Buchmüller *et al.* (2007), Ibarra, Tran (2008), Ishiwata *et al.* (2008) etc.]

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

Neutralino–Neutrino Mixing

- Bilinear *R*-parity violation extends neutralino mass matrix with 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 approximation shows dependence on SUSY parameters
  - $U_{\tilde{\gamma}\tilde{Z}} \simeq m_Z \sin\theta_W \cos\theta_W \frac{M_2 - M_1}{M_1 M_2}$
  - $U_{\tilde{Z}\tilde{Z}} \simeq -m_Z \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2} \right)$

Chargino–Charged Lepton Mixing

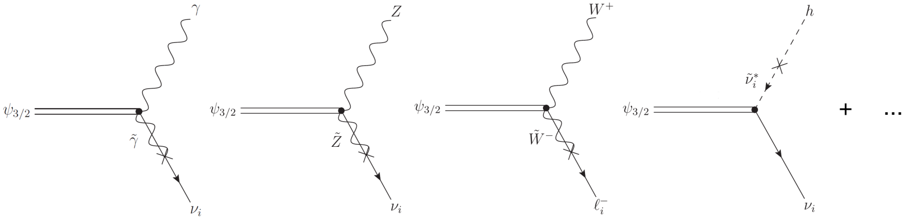
- Bilinear R-parity violation extends chargino mass matrix with leptons
- 5 × 5 matrix with basis $\psi^- = (-i\tilde{W}^-, \tilde{H}_d^-, \ell_i^-)^T$, $\psi^+ = (-i\tilde{W}^+, \tilde{H}_u^+, e_i^{c\,+})^T$

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

- Diagonalized by unitary matrices U^5 and V^5
- Mixing to 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 approximation shows dependence on SUSY parameters
  - $U_{\tilde{W}\tilde{W}} \simeq \frac{m_W}{M_2}$
- Bilinear R-parity also induces mass mixing in the scalar sector
  - Mixing between SM-like Higgs and sneutrino proportional to sneutrino VEV

Gravitino Decay Channels

- Several two-body decay channels: $\psi_{3/2} \to \gamma\,\nu_i,\ Z\,\nu_i,\ W\,\ell_i,\ h\,\nu_i$

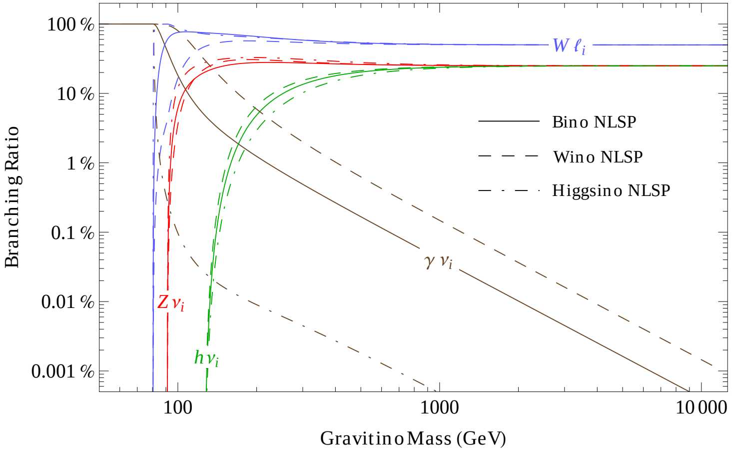


  - $\Gamma_{\gamma\nu_i} \simeq \frac{\xi_i^2\, m_{3/2}^3}{32\,\pi\, M_{\text{Pl}}^2} |U_{\tilde{\gamma}\tilde{Z}}|^2 \propto \frac{\xi_i^2\, m_{3/2}^3}{M_{\text{Pl}}^2} \left(\frac{M_2 - M_1}{M_1\, M_2}\right)^2$
  - $\Gamma_{Z\nu_i} \simeq \frac{\xi_i^2\, m_{3/2}^3}{32\,\pi\, M_{\text{Pl}}^2} \left(1 - \frac{m_Z^2}{m_{3/2}^2}\right)^2 \left\{ U_{\tilde{Z}\tilde{Z}}^2\, f\!\left(\frac{m_Z^2}{m_{3/2}^2}\right) + \ldots \right\}$
  - $\Gamma_{W^+\ell_i^-} \simeq \frac{\xi_i^2\, m_{3/2}^3}{32\,\pi\, M_{\text{Pl}}^2} \left(1 - \frac{m_W^2}{m_{3/2}^2}\right)^2 \left\{ U_{\tilde{W}\tilde{W}}^2\, f\!\left(\frac{m_W^2}{m_{3/2}^2}\right) + \ldots \right\}$
  - $\Gamma_{h\nu_i} \simeq \frac{\xi_i^2\, m_{3/2}^3}{196\,\pi\, M_{\text{Pl}}^2} \left(1 - \frac{m_h^2}{m_{3/2}^2}\right)^4$

- Dependence on mass mixings $\to$ dependence on gaugino masses

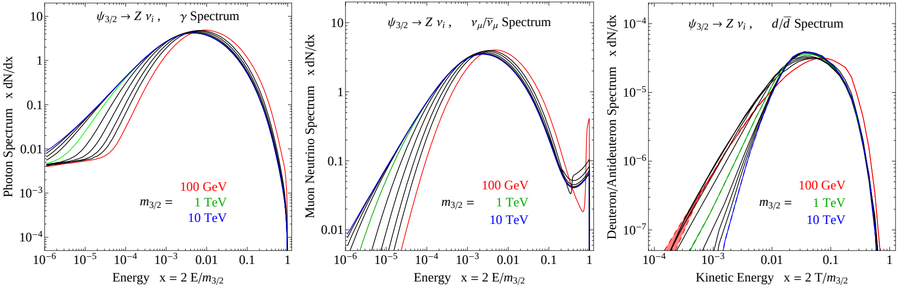
Gravitino Branching Ratios

- Branching ratios are independent of strength of *R*-parity violation
- Exact ratio between channels is model-dependent, in particular $\gamma\,\nu_i$



Final State Particle Spectra

- Gravitino decays produce stable cosmic rays: γ, e, p, $\nu_{e/\mu/\tau}$, d
  - Two-body decay spectra generated with PYTHIA
  - Deuteron coalescence treated on event-by-event basis [Kadastik *et al.* (2009)]
  - Deuteron formation in event generators not tested against data [Dal *et al.* (2012)]



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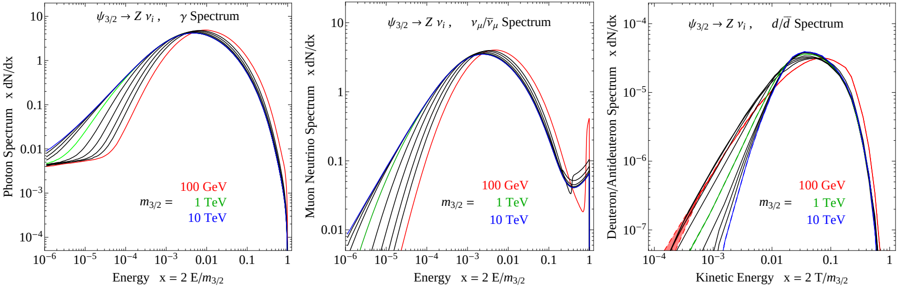
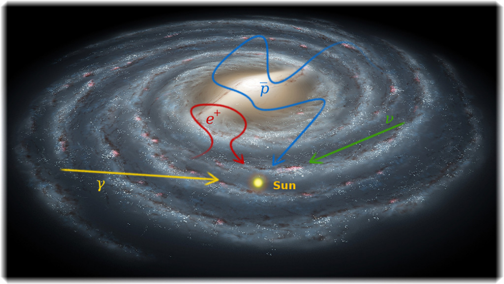


Basis for phenomenology of indirect gravitino dark matter searches!

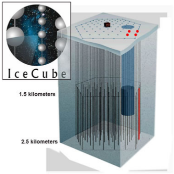
Indirect Detection of Gravitino Dark Matter

Cosmic-Ray Propagation

- Cosmic rays from gravitino decays propagate through the Milky Way



- Experiments observe spectra of cosmic rays at Earth



[NASA E/PO, SSU, Aurore Simonnet] [AMS-02 Collaboration] [IceCube Collaboration]

Difference of Dark Matter Annihilations and Decays

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

Dark Matter Annihilation

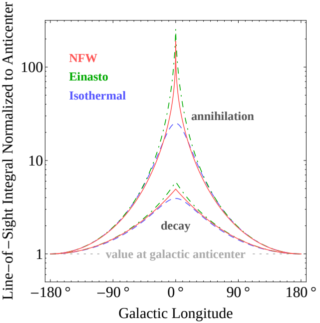
$$\frac{dJ_{\text{halo}}}{dE} = \frac{\langle \sigma v \rangle_{\text{DM}}}{8\pi\, m_{\text{DM}}^2} \frac{dN}{dE} \int_{\text{l.o.s.}} \rho_{\text{halo}}^2(\vec{l})\, d\vec{l}$$

particle physics — astrophysics

Dark Matter Decay

$$\frac{dJ_{\text{halo}}}{dE} = \frac{1}{4\pi\, \tau_{\text{DM}}\, m_{\text{DM}}} \frac{dN}{dE} \int_{\text{l.o.s.}} \rho_{\text{halo}}(\vec{l})\, d\vec{l}$$

particle physics — astrophysics



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 early universe
- Less anisotropic signal
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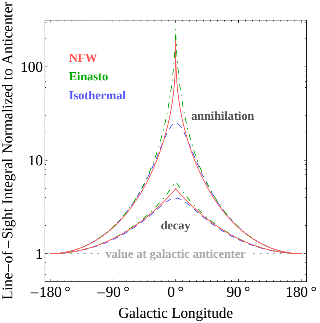

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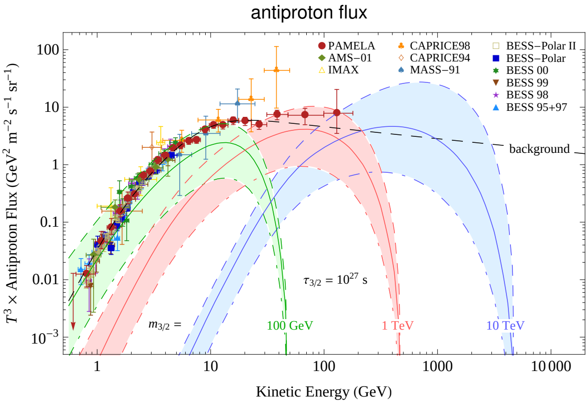
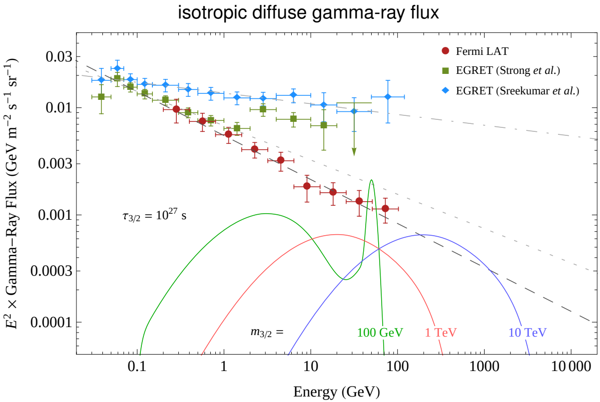
Directional detection can distinguish unstable gravitino from standard WIMPs!

Gravitino Decay Signals in Cosmic-Ray Spectra



- Observed antiproton spectrum well described by astrophysical background
  - No need for contribution from dark matter
- Lifetimes below $\mathcal{O}(10^{26}\text{–}10^{28})$ s excluded
  - Gravitino decay cannot explain PAMELA and Fermi LAT cosmic-ray anomalies

Gravitino Decay Signals in Cosmic-Ray Spectra



- Isotropic diffuse gamma-ray spectrum exhibits power-law behaviour
  - Source not understood, but no sign of spectral features of a particle decay
  - Similar constraints on gravitino lifetime as from antiprotons

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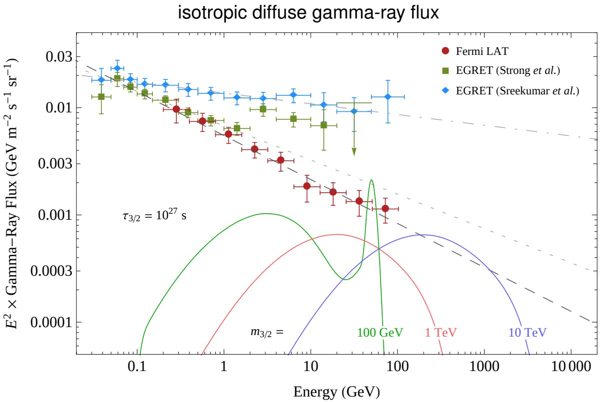

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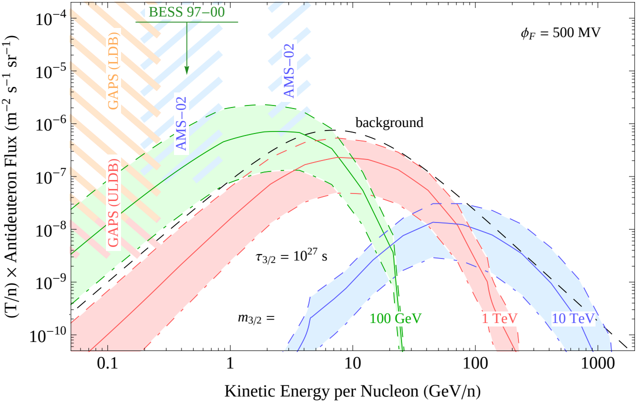
Astrophysical sources like pulsars required to explain cosmic-ray excesses!

Antideuteron Signals from Gravitino Decays

- Sensitive at low energies due to small astrophysical background
- AMS-02 and GAPS will put constraints on light gravitinos
- Probably not much more sensitive than antiprotons

[Ibarra *et al.* (2012)]



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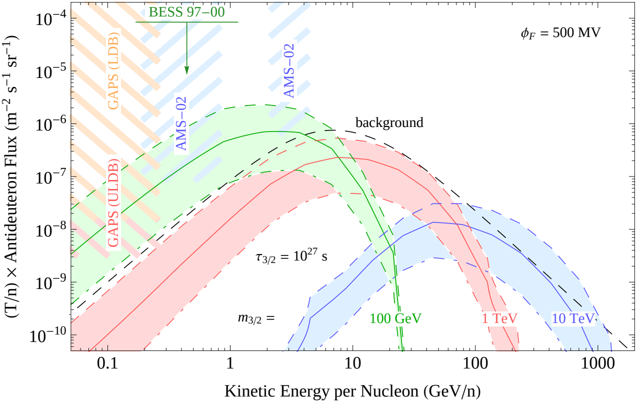
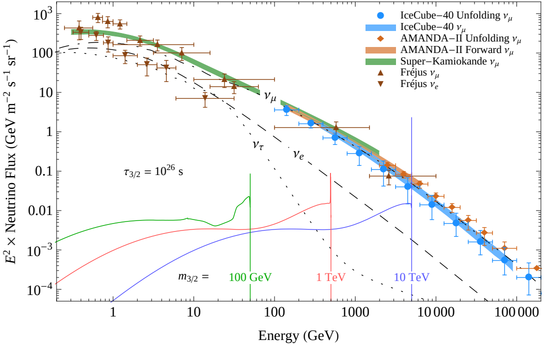


Antideuterons could be a valuable channel for light gravitino searches!

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 dominant background for gravitino decay signal
  - Discrimination of neutrino flavours would allow to reduce the background
  - Signal-to-background ratio best for large gravitino masses



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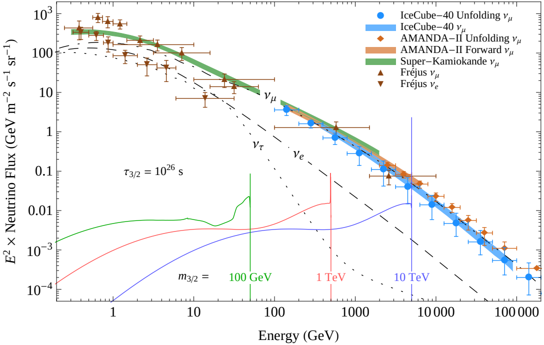
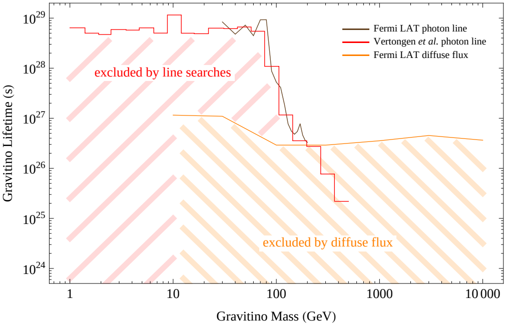
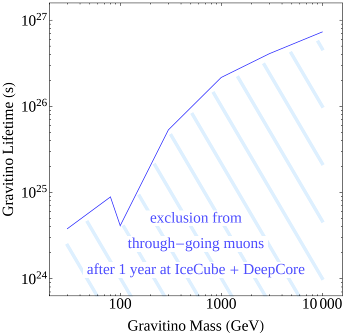


Neutrinos are a valuable channel for heavy gravitino searches!

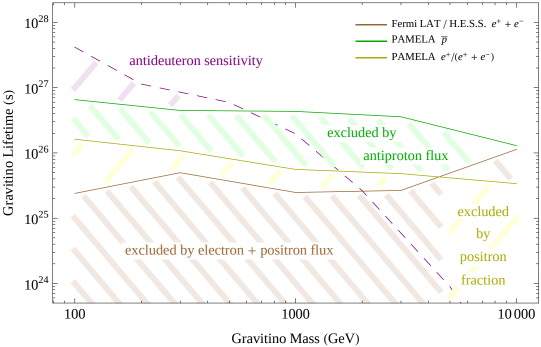
Limits on the Gravitino Lifetime





- Cosmic-ray data give bounds on gravitino lifetime
  - Photon line bounds very strong for low gravitino masses
  - Bounds from isotropic diffuse flux for larger masses
  - Neutrino bounds are competitive for heavy gravitinos

Limits on the Gravitino Lifetime



- Cosmic-ray data give bounds on gravitino lifetime
  - Uncertainties from charged cosmic-ray propagation
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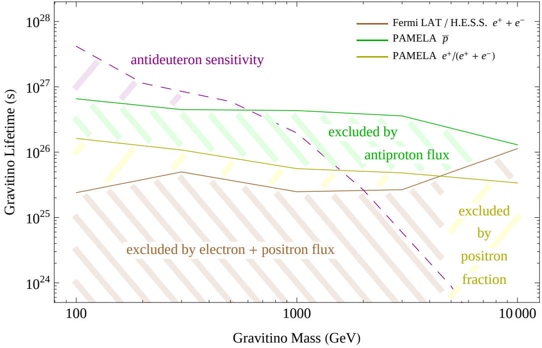

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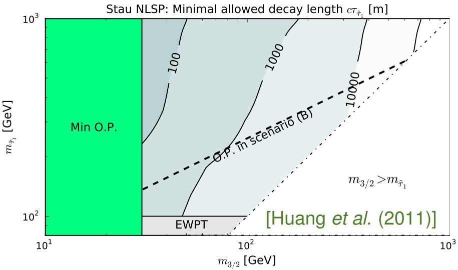
Wide range of bounds from multi-messenger approach!

Implications for the LHC

Implications for the LHC: Stau NLSP

- NLSP decays before BBN but may be metastable on collider scales
- Stau decay channels: $\tilde{\tau}_R \rightarrow \tau\,\nu_\mu, \mu\,\nu_\tau$ and $\tilde{\tau}_L \rightarrow \bar{t}_R\, b_L$
- Characteristic signatures:
  - Slow particle with long ionising charged track
  - Displaced vertex with missing energy and muon track or jet
- Minimal decay length from washout limit: 4 mm

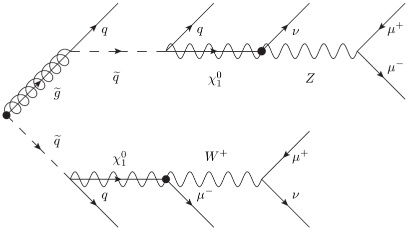


- Gamma-ray limits constrain minimal decay length [Huang *et al.* (2011)]
- Minimal decay lengths from current limits: $\mathcal{O}(100)$ m – $\mathcal{O}(10)$ km

Implications for the LHC: Neutralino NLSP

- Neutralino decay channels: $\tilde{\chi}_1^0 \to Z\,\nu_i, W^+\ell_i^-, h\,\nu_i$
- Bino decay length is directly related to gravitino decay width
- Characteristic signatures:
  - Displaced vertices far from the interaction point
  - For too small *R*-parity violation indistinguishable from stable neutralino

decay chain with secondary vertices



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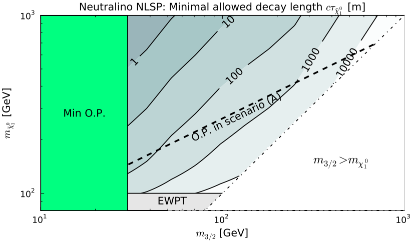

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Limits on the Amount of *R*-Parity Violation

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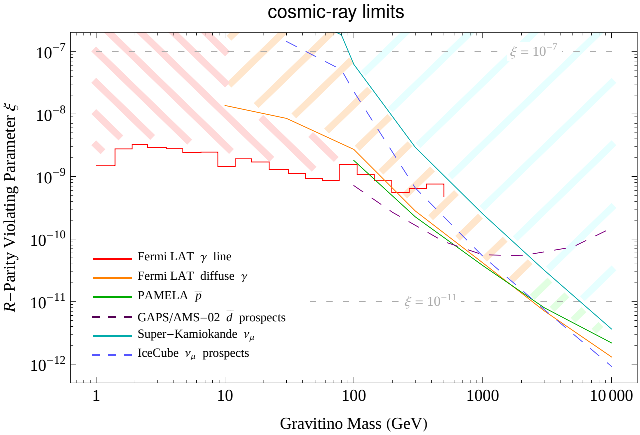
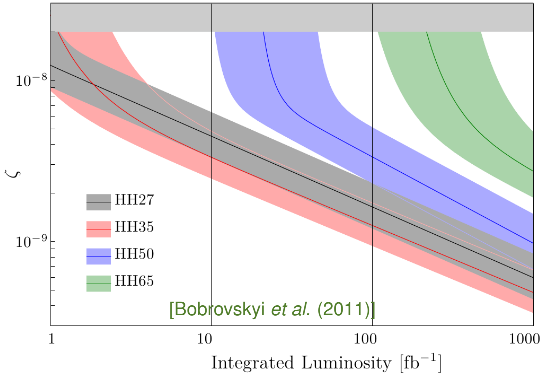
- Gravitino lifetime limits constrain *R*-parity violation: $\tau_{3/2} \propto \frac{M_{\rm Pl}^2}{\xi^2\, m_{3/2}^3}$
  - Limits from photon line searches dominate for small gravitino masses
  - For heavier gravitino bounds from all cosmic-ray channels are comparable



Limits on the Amount of *R*-Parity Violation

- The LHC could detect NLSP decays beyond cosmic-ray constraints
  - Good sensitivity with clean decay chain: $\tilde{\chi}_1^0 \to Z\,\nu_i$ and $Z \to \mu^+\mu^-$
  - Taking all channels could improve sensitivity by a factor $\sim$10 [Bobrovskyi *et al.* (2011)]

LHC sensitivity for bino-like NLSP decays



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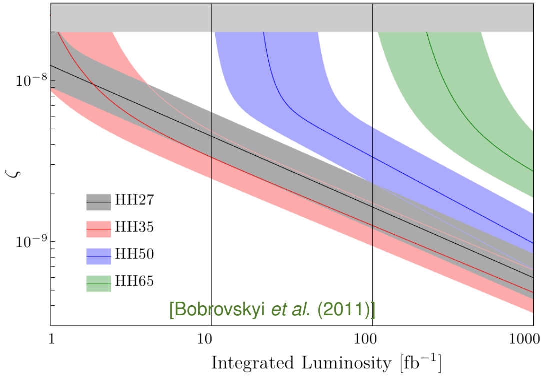

Indirect and collider searches probe interesting range of *R*-parity violation!

Conclusions and Outlook

Conclusions

- Gravitino dark matter models with broken *R*-parity are well motivated
- Consistent cosmology with thermal leptogenesis and BBN
- The Gravitino lifetime is naturally in the range of indirect detection experiments
- Cannot explain the PAMELA and Fermi LAT excesses due to constraints from gamma rays and antiprotons
- Multi-messenger approach constrains gravitino lifetime and strength of *R*-parity violation

Outlook

- Forthcoming experiments like AMS-02 will greatly improve cosmic-ray data
- Antideuteron searches will probe light gravitino dark matter
- Neutrino experiments like IceCube will probe heavy gravitino dark matter
- LHC may discover decays of metastable NLSPs beyond cosmic-ray constraints on R-parity violation
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Thanks for your attention!