Antiproton Limits on Decaying Gravitino Dark Matter

Michael Grefe

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

Departamentos de Física Teórica I y II
Universidad Complutense de Madrid

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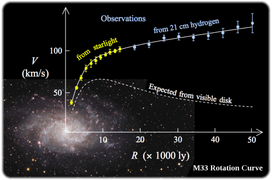
Outline

- Motivation for Decaying Gravitino Dark Matter
- Gravitino Dark Matter with Broken *R* Parity
- Indirect Detection of Gravitino Dark Matter
- Antiproton Limits on the Lifetime and the Amount of *R*-Parity Violation
- Conclusions

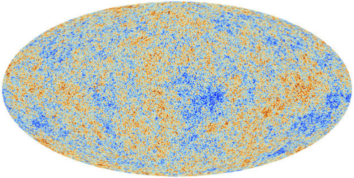
Motivation for Decaying Gravitino Dark Matter

What Do We Know about Dark Matter?

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



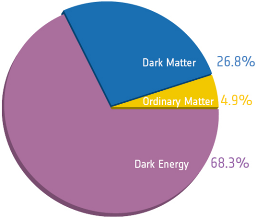
[M. Whittle]



[ESA / Planck Collaboration]

[NASA / Clowe *et al.*]

- 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!

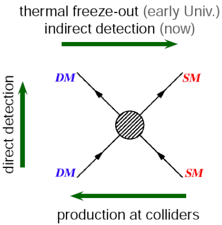


[ESA / Planck Collaboration]

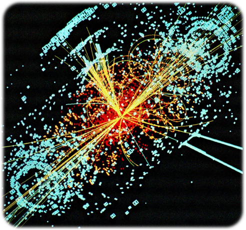
How Can We Unveil the Nature of Dark Matter?

▶ Three search strategies for dark matter

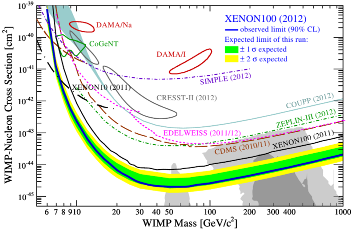
- Direct detection in the scattering off matter nuclei
- Production of dark matter particles at colliders
- Indirect detection in cosmic ray signatures



[Max-Planck-Institut für Kernphysik]



[CERN]



[Aprile *et al.* (2012)]

[AMS Collaboration]

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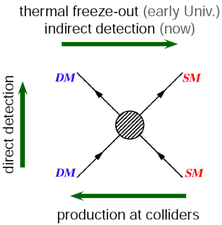

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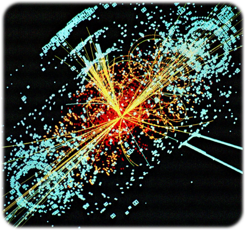

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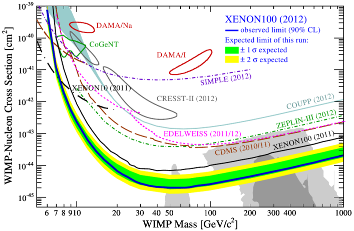

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[AMS Collaboration]

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

Gravitino Dark Matter: Stable or Unstable?

▶ Stable Gravitino Dark Matter

- Typical in gauge mediation with conserved *R*-parity
- No direct detection signal expected: $\sigma_N \sim M_{\rm Pl}^{-4}$
- No annihilation signal expected: $\sigma_{ann} \sim M_{\rm Pl}^{-4}$
- Collider signals from long-lived NLSP expected
- Long-lived NLSP can be in conflict with BBN

[The Particle Zoo]

▶ Unstable Gravitino Dark Matter

- Typical candidate in models with *R*-parity violation
- Lifetime larger than the age of the universe
- No direct detection signal expected: $\sigma_N \sim M_{\rm Pl}^{-4}$
- Decays could lead to observable cosmic-ray signals
- Collider signals from long-lived NLSP expected

Models with Gravitino DM and *R*-Parity Violation

- **Bilinear *R*-parity violation (BRpV)** [Takayama, Yamaguchi (2000), Restrepo *et al.* (2011)]
  - *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
- **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
- **Trilinear *R*-parity violation** [Moreau *et al.* (2001), Lola *et al.* (2007)]
  - Phenemenological study, trilinear terms generically expected without *R*-parity

Why Decaying 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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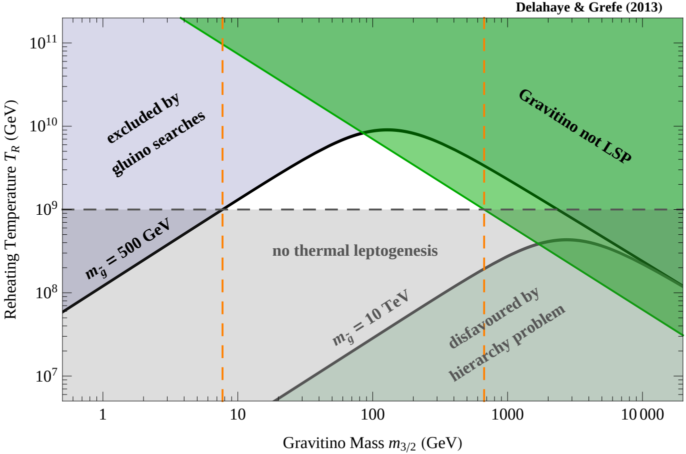
Possible solution: Gravitino is the LSP and thus stable!

Why Decaying 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 Decaying 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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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

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: $\xi = \frac{\langle \tilde{\nu} \rangle}{v}$
- Bound from contribution to neutrino masses
  - Upper bound: Below limit on sum of neutrino masses: $\xi \lesssim \mathcal{O}(10^{-4\text{–}6})$
- Cosmological bounds on *R*-violating couplings
  - Lower bound: The NLSP must decay before the time of BBN: $\xi \gtrsim \mathcal{O}(10^{-11\text{–}14})$
  - Upper bound: No washout of lepton/baryon asymmetry: $\xi \lesssim \mathcal{O}(10^{-6})$
- Tiny bilinear *R*-parity violation can be related to $U(1)_{B\text{–}L}$ breaking

[Buchmüller *et al.* (2007)]

Gravitino Dark Matter with Bilinear R-Parity Violation

- Gravitino decay suppressed by Planck scale and small R-parity violation
  - Gravitino decay width: $\Gamma_{3/2} \propto \frac{\xi^2\, m_{3/2}^3}{M_{\text{Pl}}^2} = 2.6 \times 10^{-24}\,\text{s}^{-1} \left(\frac{m_{3/2}^3}{10\,\text{GeV}}\right)^3 \left(\frac{\xi}{10^{-7}}\right)^2$

    [Takayama, Yamaguchi (2000)]
  - The gravitino lifetime by far exceeds the age of the universe ($\tau_{3/2} \gg 10^{17}$ s)

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

    [Buchmüller *et al.* (2007), Bobrovskyi *et al.* (2010, 2011, 2012)]
  - 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 $\psi^- = (-i\tilde{W}^-,\, \tilde{H}_d^-,\, \ell_i^-)^T$, $\psi^+ = (-i\tilde{W}^+,\, \tilde{H}_u^+,\, e_i^{c\,+})^T$

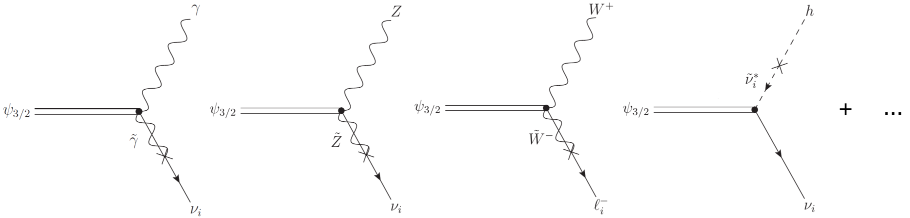
$$M_C^5 = \begin{pmatrix} M_2 & \sqrt{2}\, m_W\, s_\beta & 0 \\ \sqrt{2}\, m_W\, c_\beta & \mu & -m_{\ell_{ij}}\, \xi_i\, c_\beta \\ \sqrt{2}\, m_W\, \xi_i & 0 & m_{\ell_{ij}} \end{pmatrix}$$

- 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: $\psi_{3/2} \to \gamma\,\nu_i,\ Z\,\nu_i,\ W\,\ell_i,\ h\,\nu_i$

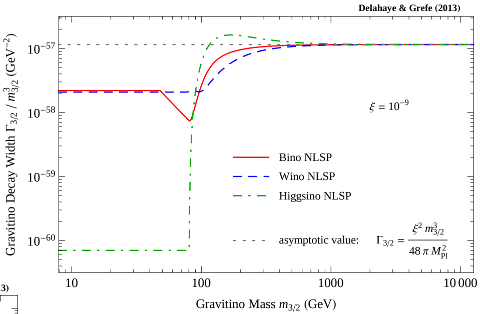


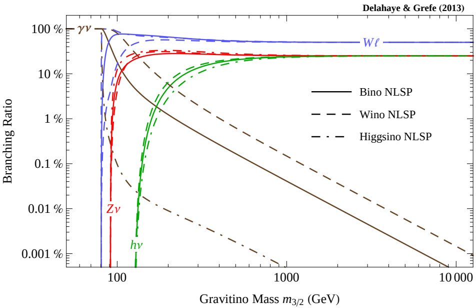
- $\Gamma_{\gamma\nu_i} \simeq \frac{\xi_i^2\, m_{3/2}^3}{32\,\pi\, M_{\mathrm{Pl}}^2} |U_{\tilde{\gamma}\tilde{Z}}|^2 \propto \frac{\xi_i^2\, m_{3/2}^3}{M_{\mathrm{Pl}}^2} \left(\frac{M_2 - M_1}{M_1\, M_2}\right)^2$
- $\Gamma_{Z\nu_i} \simeq \frac{\xi_i^2\, m_{3/2}^3}{32\,\pi\, M_{\mathrm{Pl}}^2} \left(1 - \frac{m_Z^2}{m_{3/2}^2}\right)^2 \left\{ U_{\tilde{Z}\tilde{Z}}^2\, f\!\left(\frac{m_Z^2}{m_{3/2}^2}\right) + \ldots \right\}$
- $\Gamma_{W^+\ell_i^-} \simeq \frac{\xi_i^2\, m_{3/2}^3}{16\,\pi\, M_{\mathrm{Pl}}^2} \left(1 - \frac{m_W^2}{m_{3/2}^2}\right)^2 \left\{ U_{\tilde{W}\tilde{W}}^2\, f\!\left(\frac{m_W^2}{m_{3/2}^2}\right) + \ldots \right\}$
- $\Gamma_{h\nu_i} \simeq \frac{\xi_i^2\, m_{3/2}^3}{192\,\pi\, M_{\mathrm{Pl}}^2} \left(1 - \frac{m_h^2}{m_{3/2}^2}\right)^4$

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

Gravitino Decay Width and Branching Ratios

- Three benchmark models
  - Bino-like NLSP: $M_1 = 1.1\, m_{3/2}$
  - Wino-like NLSP: $M_2 = 1.1\, m_{3/2}$
  - Higgsino-like NLSP: $\mu = 1.1\, m_{3/2}$
- Common asymptotic decay width

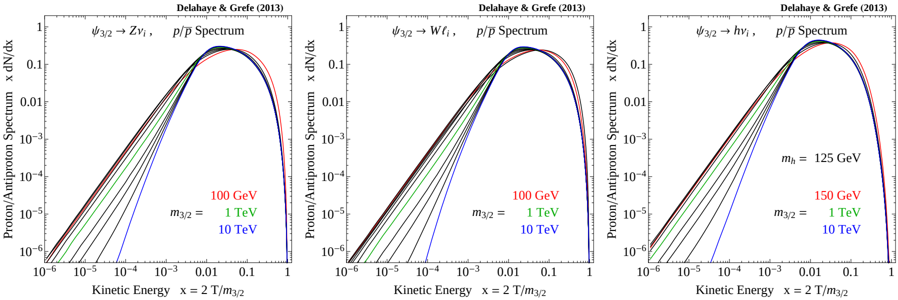




- Branching ratios are independent of strength of R-parity violation
- Exact ratio between channels is model-dependent, in particular $\gamma\nu$

Final State Particle Spectra

- Gravitino decays produce stable cosmic rays: γ, e, p, d, $\nu_{e/\mu/\tau}$
  - Proton/antiproton spectra from gravitino decay generated with PYTHIA
  - No protons from $\gamma\nu$; $Z\nu$ and $W\ell$ very similar; a bit more protons from $h\nu$



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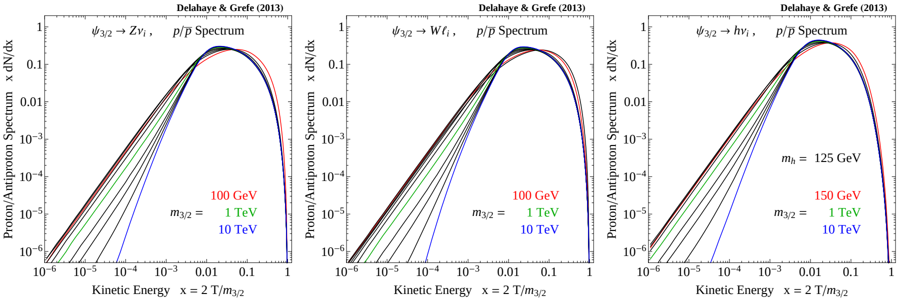
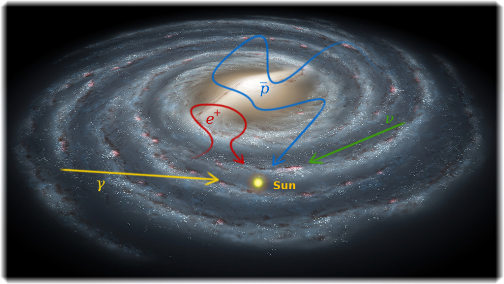


Basis for phenomenology of indirect gravitino dark matter searches!

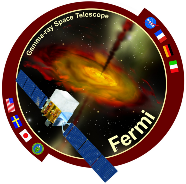
Indirect Detection of Gravitino Dark Matter

Cosmic-Ray Propagation

- Cosmic rays from gravitino decays propagate through the Milky Way

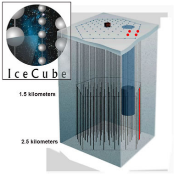


- Experiments observe spectra of cosmic rays at Earth



[NASA E/PO, SSU, Aurore Simonnet]

[PAMELA Collaboration]



[IceCube Collaboration]

Cosmic-Ray Propagation

- Diffusion equation for cosmic-ray density ψ:

$$\vec{\nabla} \cdot (\vec{V}_c \, \psi - K_0 \, \beta \, p^\delta \, \vec{\nabla}\psi) + 2\, h \, \delta(z) \, \partial_E \, (b_{\text{loss}} \, \psi - D_{EE} \, \partial_E \psi) = Q^{\text{prim}} + 2\, h \, \delta(z) \left(Q^{\text{sec}} + Q^{\text{ter}}\right) - 2\, h \, \delta(z) \, \Gamma^{\text{ann}} \, \psi$$

+ boundary conditions

  - $\vec{V}_c$: velocity of the convective wind from stars in the Galactic plane
  - $K_0 \, \beta \, p^\delta$: spatial diffusion from irregularities of the Galactic magnetic field
  - b_{loss}: energy losses from interaction with interstellar gas
  - D_{EE}: coefficient for diffusion in energy
  - Q^{sec}: antiprotons from collisions of cosmic-ray protons or α with interstellar gas
  - Q^{ter}: antiprotons from inelastic collisions of antiprotons with interstellar gas
  - Γ^{ann}: annihilation of antiprotons with cosmic-ray protons

- Gravitino decays are a primary antiproton source in the Galactic halo:

$$Q^{\text{prim}}(T, r) = \frac{\rho_{\text{halo}}(r)}{m_{3/2} \, \tau_{3/2}} \frac{dN}{dT}$$

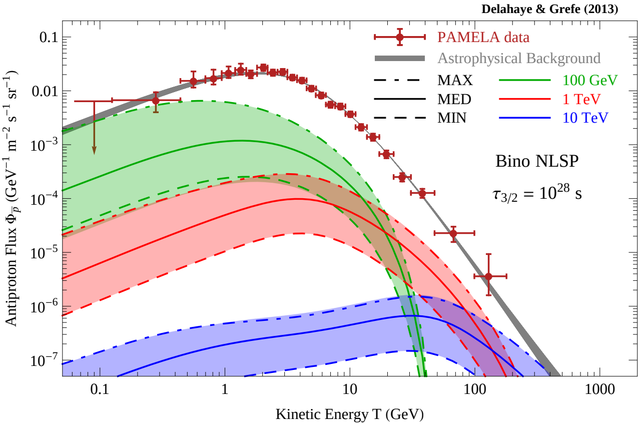
Cosmic-Ray Propagation

- Two approaches to solve diffusion equation:
  - Numerical: GALPROP, DRAGON
  - Semi-analytical: Two-zone diffusion model for the Milky Way (USINE)
- Propagation parameters constrained by secondary-to-primary ratios
- Typical approach: 3 parameter sets to estimate uncertainty

	L (kpc)	K_0 (kpc^2/Myr)	δ	$\|\vec{V}_c\|$ (km/s)	V_a (km/s)
MIN	1	0.0016	0.85	13.5	22.4
MED	4	0.0112	0.70	12	52.9
MAX	15	0.0765	0.46	5	117.6

- Our approach: Scan over all allowed propagation parameters
  - Roughly 1600 parameter sets [Maurin *et al.* (2001))]
  - Allows to reliably estimate the uncertainty from cosmic-ray propagation

Gravitino Decay Signals in Antiproton Spectra



- Observed antiproton spectrum well described by astrophysical background
  - No need for contribution from dark matter
- Propagation uncertainty roughly one order of magnitude
  - Expected to be improved by forthcoming AMS-02 cosmic-ray data

Antiproton Limits on the Lifetime and the Amount of *R*-Parity Violation

Limits on the Gravitino Lifetime

- Lifetime limits derived using chi-squared statistics

$$\chi^2 = \sum_i \frac{(\mathcal{O}_i - \mathcal{E}_i)^2}{\sigma_i^2}$$

  - $\mathcal{O}_i$: Observed flux in energy bin i
  - $\mathcal{E}_i$: Expected flux in energy bin i (DM signal + astrophysical background)
  - σ_i: Data error bar in energy bin i

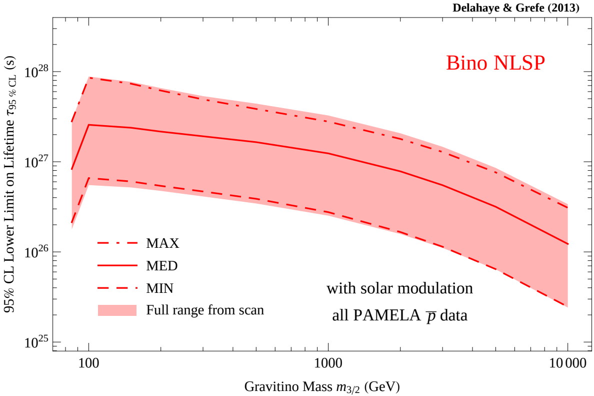
- Limits at 95 % CL derived from deviation from best fit

$$\chi^2(\tau_{95\,\%\,\mathrm{CL}}) = \chi^2(\tau_{\mathrm{best\,fit}}) + \Delta\chi^2_\nu$$

  - $\chi^2(\tau_{\mathrm{best\,fit}})/\mathrm{dof} \sim 0.7$ (in general no DM contribution)
  - $\Delta\chi^2_{22}/\mathrm{dof} = 1.54$ (23 PAMELA data bins − 1 fit parameter)

Limits on the Gravitino Lifetime

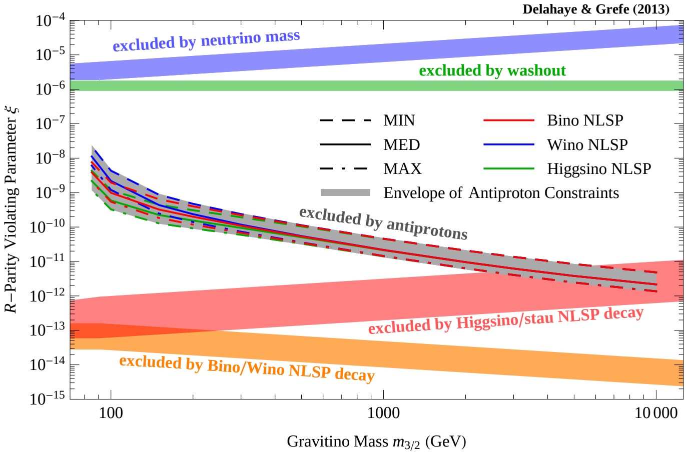
- Bounds on gravitino lifetime derived from PAMELA antiproton data



- Gravitino lifetimes below $\mathcal{O}(10^{28}\text{–}10^{25})$ s excluded
  - Scan over propagation parameters changes highest/lowest limits by $\sim 15\,\%$
  - Gravitino decay cannot explain rise in positron fraction (PAMELA, AMS-02)

Limits on the Amount of *R*-Parity Violation

- Gravitino lifetime limits constrain *R*-parity violation: $\tau_{3/2} \propto \frac{M_{\mathrm{Pl}}^2}{\xi^2\, m_{3/2}^3}$



Limits on the Amount of *R*-Parity Violation

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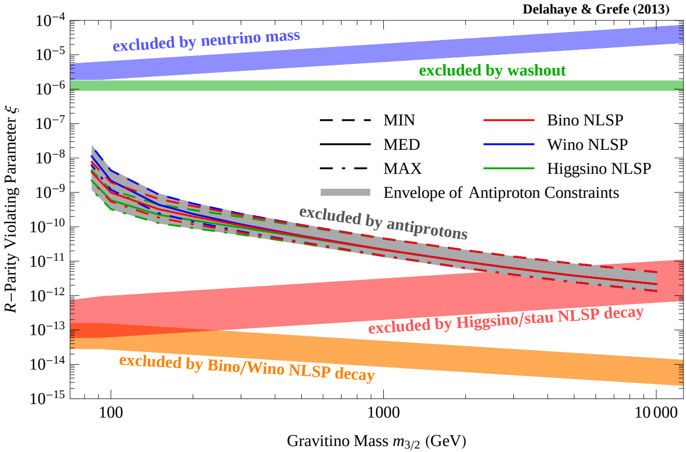

Indirect searches set strong limits on *R*-parity violation!

Conclusions

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- Both, stable and unstable gravitinos, are viable dark matter candidates
- Gravitino DM models with broken *R*-parity are well motivated: could explain neutrino masses / solve cosmological gravitino problem
- Decaying gravitino DM can be probed in colliders and cosmic rays
- Strong constraints on the lifetime from PAMELA antiproton data
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Thanks for your attention!