Antiproton Limits on Decaying Gravitino Dark Matter

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Outline

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

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)]

- Gravitino dark matter with small R-parity violation is consistent with thermal leptogenesis and BBN contraints on late-decaying particles

[Buchmüller et al. 2007)]

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No cosmological gravitino problems!

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: $\xi \lesssim \mathcal{O}(10^{-6})$
- Gravitino decay suppressed by Planck scale and small R-parity violation
  - The gravitino lifetime by far exceeds the age of the universe ($\tau_{3/2} \gg 10^{17}$ s)

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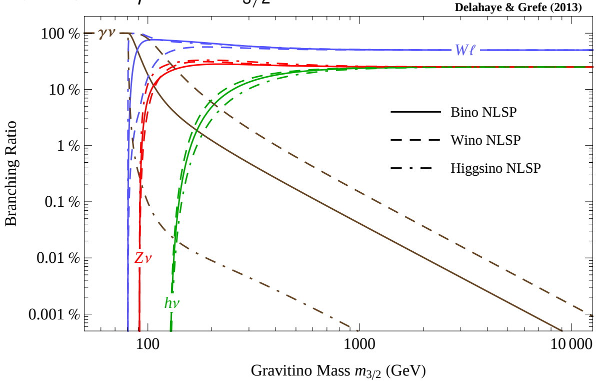
The unstable gravitino is a well-motivated and viable dark matter candidate!

Gravitino Branching Ratios

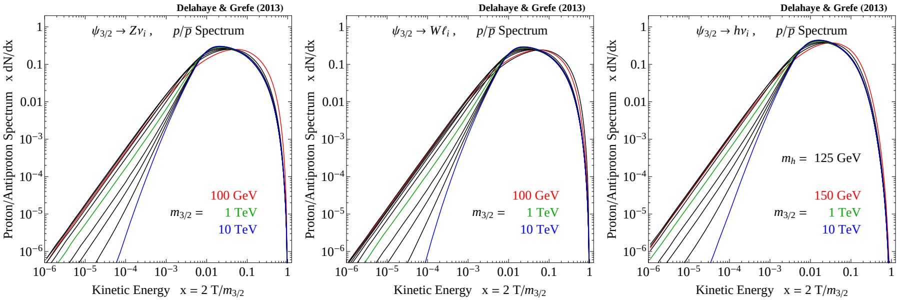
- Three benchmark models
  - Bino-like NLSP: $M_1 = 1.1\, m_{3/2}$
  - Wino-like NLSP: $M_2 = 1.1\, m_{3/2}$
  - Higgsino-like NLSP: $\mu = 1.1\, m_{3/2}$



- 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 6.4
  - No protons from $\gamma\nu$; $Z\nu$ and $W\ell$ very similar; a bit more protons from $h\nu$



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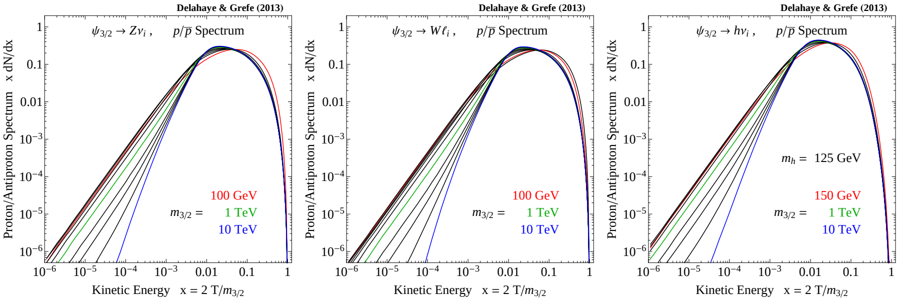
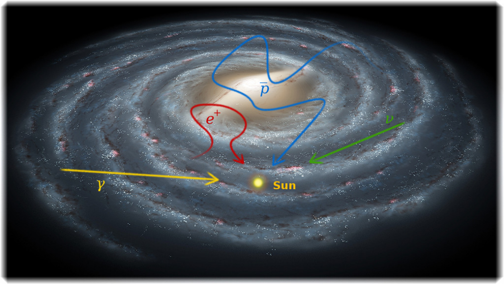


Basis for phenomenology of indirect gravitino dark matter searches!

Cosmic-Ray Propagation

- Cosmic rays from gravitino decays propagate through the Milky Way halo



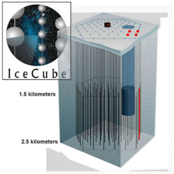
see talk by F. Donato

- Experiments observe spectra of cosmic rays at Earth

[Fermi Collaboration]

[PAMELA Collaboration]

[AMS 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 interstellar hydrogen

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

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

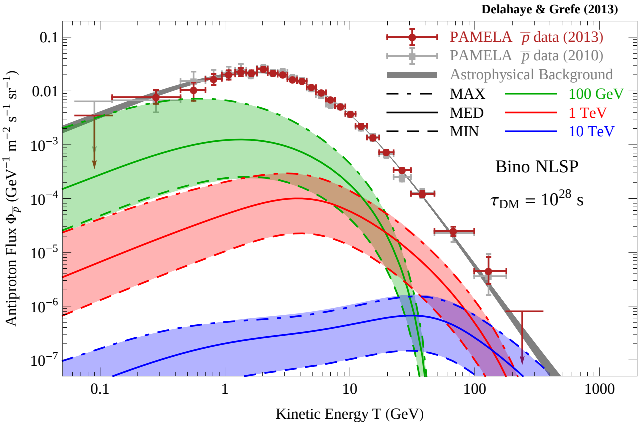
Cosmic-Ray Propagation

- 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



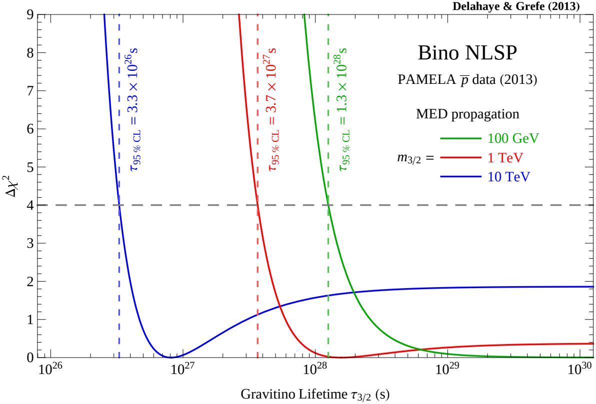
- Observed antiproton spectrum well described by astrophysical background
  - No need for contribution from dark matter — see talk by F. Donato
- Propagation uncertainty roughly one order of magnitude for DM signal
  - Expected to be improved by AMS-02 cosmic-ray data — see talk by R. Battiston

Limits on the Gravitino Lifetime

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

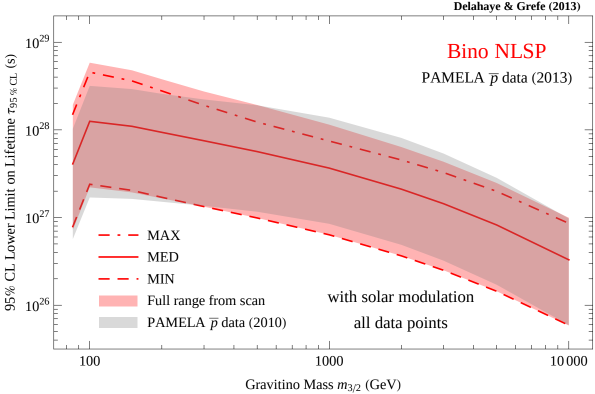
$$\chi^2(\tau_{95\,\%\,\mathrm{CL}}) = \chi^2(\tau_{\mathrm{best\ fit}}) + \Delta\chi^2$$

  - $\chi^2(\tau_{\mathrm{best\ fit}})/\mathrm{dof} \sim 0.4$ (DM contribution not statistically significant)
  - $\Delta\chi^2 = 4$ (corresponding to 2σ exclusion for 1 fit parameter)



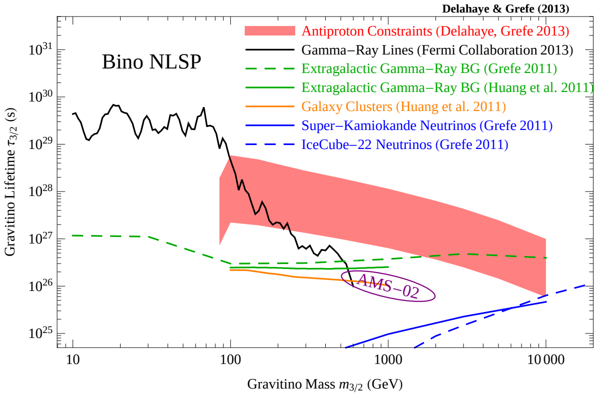
Limits on the Gravitino Lifetime

- Bounds on gravitino lifetime derived from recent PAMELA antiproton data



- Gravitino lifetimes below a few times 10^{28} s to 10^{26} s excluded
  - Scan over propagation parameters can change highest/lowest limits by up to 60 %
  - PAMELA 2013 data lead to slightly different limits compared to 2010 data

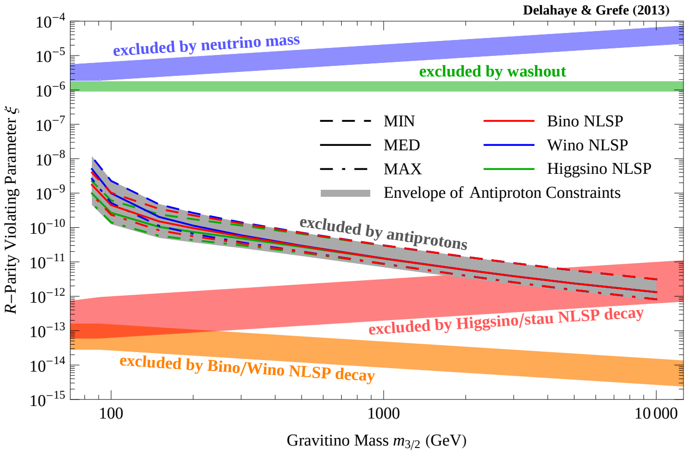
Comparison with other Cosmic-Ray Limits



- Antiproton constraints dominate in the 100 GeV to 10 TeV mass range
  - Gamma line searches dominate for low masses; above m_W branching ratio drops
  - EGB limits could improve with subtraction of astrophysical contributions
  - Neutrinos become relevant around 10 TeV; will improve with full IceCube data
  - Antiprotons exclude gravitino explanation of AMS-02 positrons [Ibe *et al.* (2013)]

Limits on the Amount of *R*-Parity Violation

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



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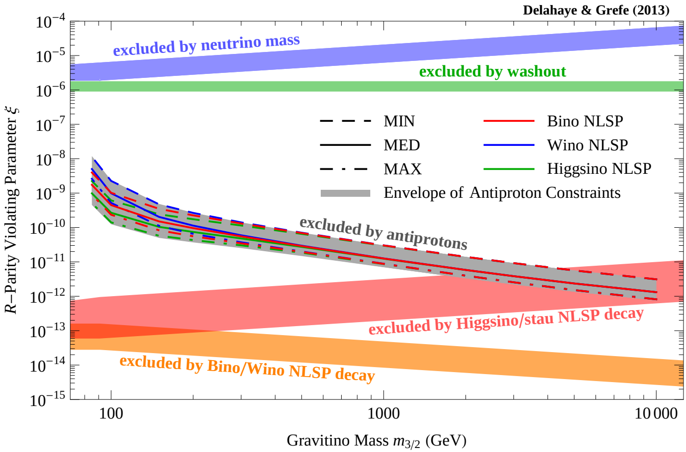

Indirect searches set strong limits on *R*-parity violation!

Conclusions

- Gravitino DM with broken *R*-parity is well motivated from cosmology
- Decaying gravitino dark matter can be probed with cosmic rays
- Strong constraints on the lifetime from PAMELA antiproton data
- Other cosmic-ray channels provide complementary constraints
- Antiproton limits constrain the strength of *R*-parity violation

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Thanks for your attention!