

Gravitino Dark Matter with Broken R -Parity



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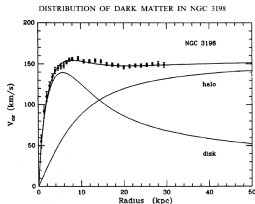
Based on JCAP 0901 (2009) 029, JCAP 1004 (2010) 017,
arXiv:1111.6779 [hep-ph] and ongoing work.

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

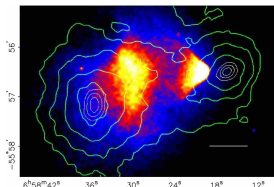


What Do We Know about Dark Matter?

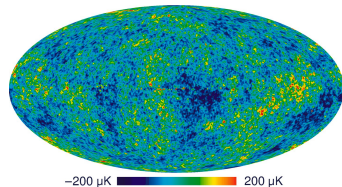
- ▶ Observed on various scales through its gravitational interaction
- ▶ Contributes significantly to the energy density of the universe



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

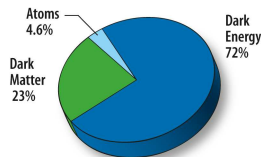


[Clowe *et al.* (2006)]



[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!**

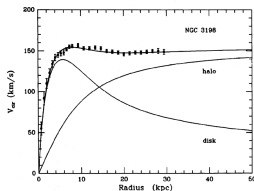
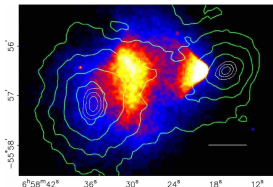
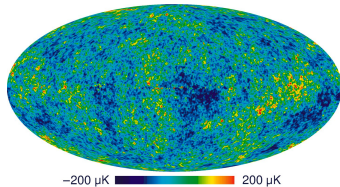


[NASA / WMAP Science Team]

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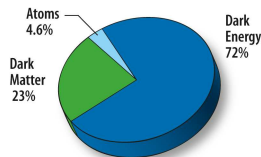
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DISTRIBUTION OF DARK MATTER IN NGC 3198

[van Albada *et al.* (1985)][Clowe *et al.* (2006)]

[NASA / WMAP Science Team]

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[NASA / WMAP Science Team]

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

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: $T_R \gtrsim 10^9 \text{ GeV}$ [Davidson, Ibarra (2002)]
- ▶ **Supergravity** predicts **gravitino** as spin-3/2 superpartner of the graviton
- ▶ Gravitinos are thermally produced after inflation in the early universe:

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

[Pradler, Steffen (2006)]

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

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

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

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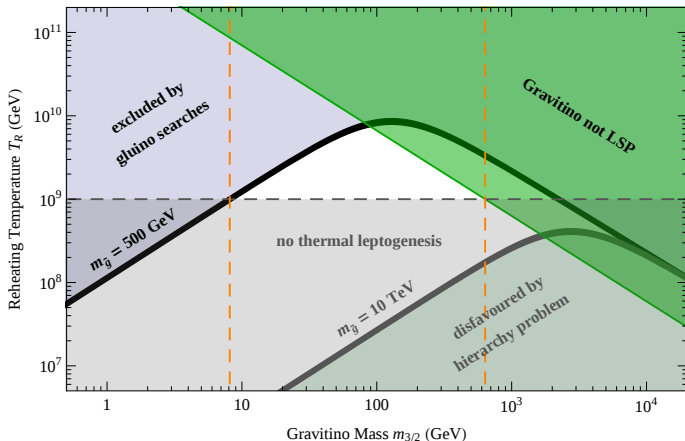
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Possible solution: Gravitino is the LSP and thus stable!

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:

- Next-to-LSP can only decay to gravitino LSP:

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

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Possible solution: R -parity is not exactly conserved!

► Other options:

- Choose harmless NLSP like sneutrino
- Dilute NLSP density by late entropy production

[Covi, Kraml (2007)]

[Buchmüller *et al.* (2006)]

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
 - $\mathcal{O}(10) \text{ GeV} < m_{3/2} < \mathcal{O}(500) \text{ GeV}$, 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)]
 - Phenomenological study, trilinear terms generically expected without R -parity

Gravitino Dark Matter with Bilinear R -Parity Violation

- ▶ **Bilinear** R -parity violation: $W_{\mathcal{R}_p} = \mu_i H_u L_i$, $-\mathcal{L}_{\mathcal{R}_p}^{\text{soft}} = B_i H_u \tilde{\ell}_i + m_{H_d \ell_i}^2 H_d^* \tilde{\ell}_i + \text{h.c.}$
 - Only lepton number violated $\Rightarrow$ **Proton remains stable!**
- ▶ R -parity violation can be parametrized by sneutrino VEV: $\xi = \frac{\langle \tilde{\nu} \rangle}{v}$
- ▶ 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: $\Gamma_{3/2} \propto \frac{\xi^2 m_{3/2}^3}{M_{\text{Pl}}^2} = 2.6 \times 10^{-24} \text{ s}^{-1} \left(\frac{m_{3/2}}{10 \text{ GeV}} \right)^3 \left(\frac{\xi}{10^{-7}} \right)^2$
[Takayama, Yamaguchi (2000)]
 - The gravitino lifetime by far exceeds the age of the universe ($\tau_{3/2} \gg 10^{17} \text{ s}$)

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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), Bobrovskiy *et al.* (2010)]

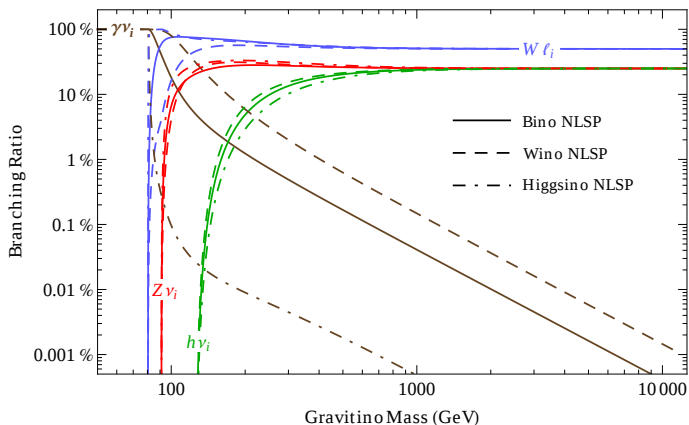
- Gravitino decays can possibly be observed at indirect detection experiments

[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!

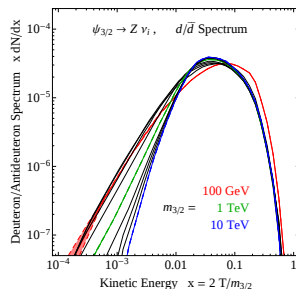
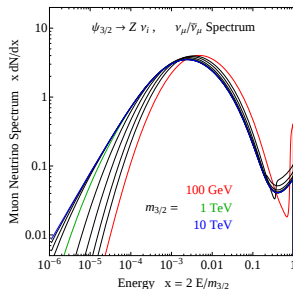
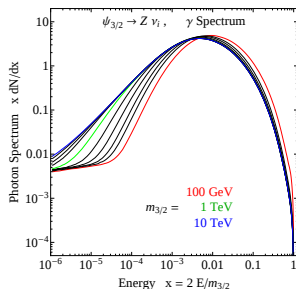
Gravitino Decay Channels

- Several two-body decay channels: $\psi_{3/2} \rightarrow \gamma \nu_i, Z \nu_i, W \ell_i, h \nu_i$
 - Branching ratios are independent of strength of R -parity violation
 - Exact ratio between channels is model-dependent, in particular $\gamma \nu_i$



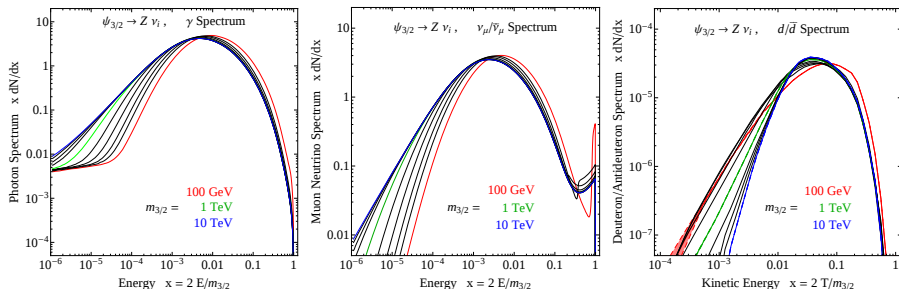
Final State Particle Spectra

- ▶ 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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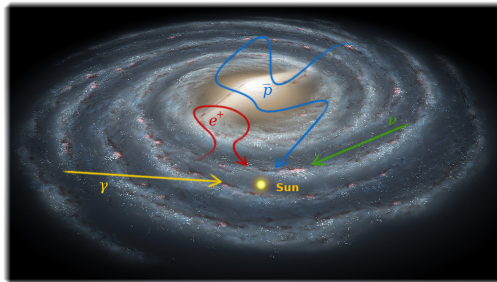
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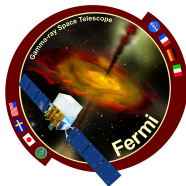
Basis for phenomenology of indirect gravitino dark matter searches!

Cosmic-Ray Propagation

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



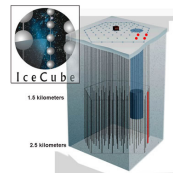
- ▶ Experiments observe spectra of cosmic rays at Earth



[NASA E/PO, SSU, Aurore Simonnet]

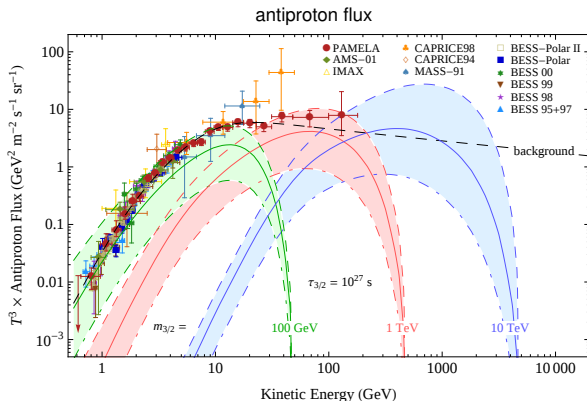


[AMS-02 Collaboration]



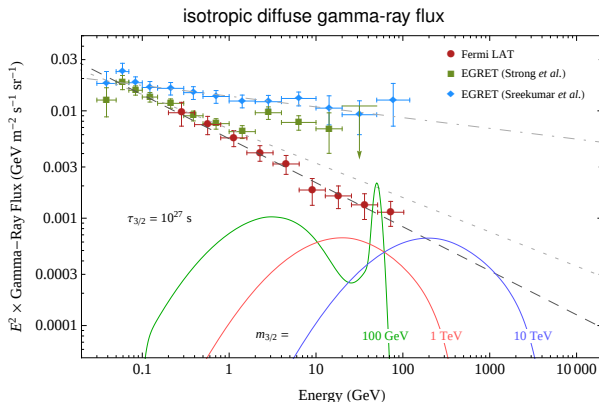
[IceCube Collaboration]

Gravitino Decay Signals in Cosmic-Ray Spectra



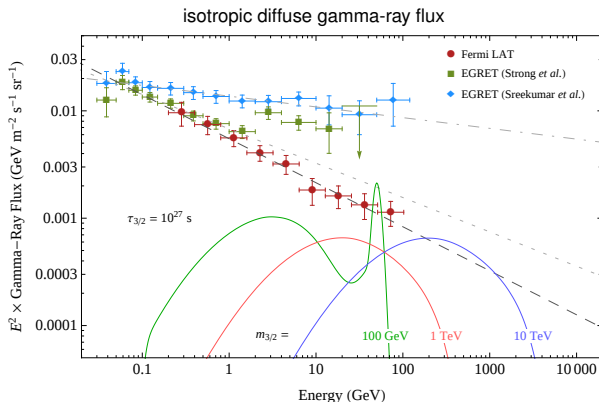
- ▶ Observed antiproton spectrum well described by astrophysical background
 - No need for contribution from dark matter
- ▶ Lifetimes below $\mathcal{O}(10^{26}-10^{28})$ s excluded
 - Gravitino decay cannot explain PAMELA and Fermi LAT cosmic-ray anomalies

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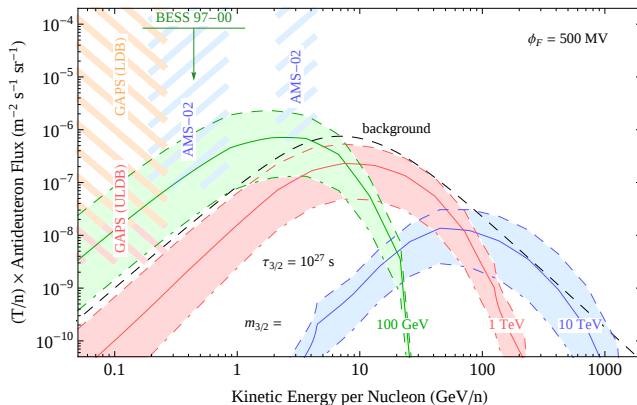
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Astrophysical sources like pulsars required to explain cosmic-ray excesses!

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

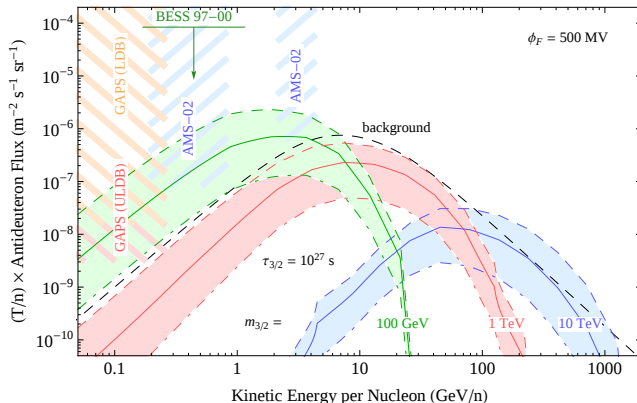
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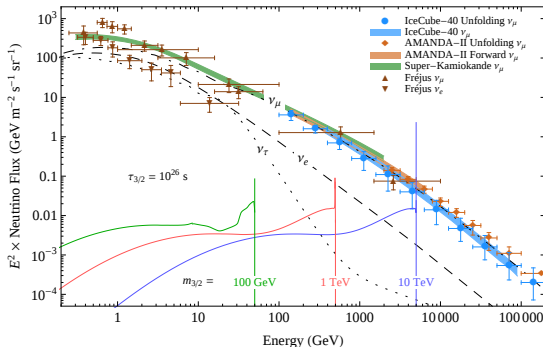
[Ibarra *et al.* (2012)]



Antideuterons could be a valuable channel for light gravitino searches!

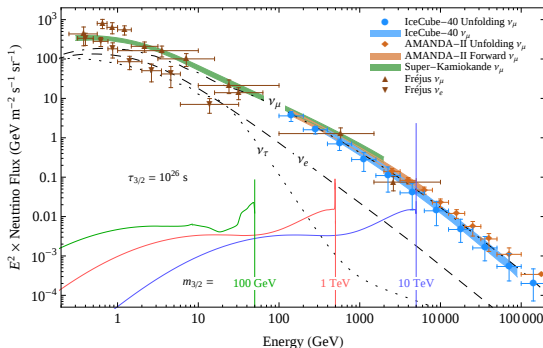
Neutrino Signals from Gravitino Decays

- ▶ 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



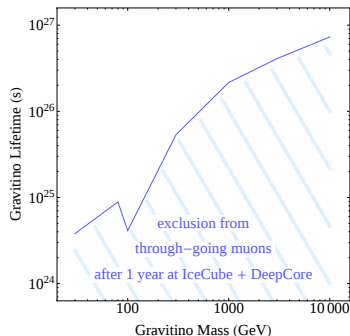
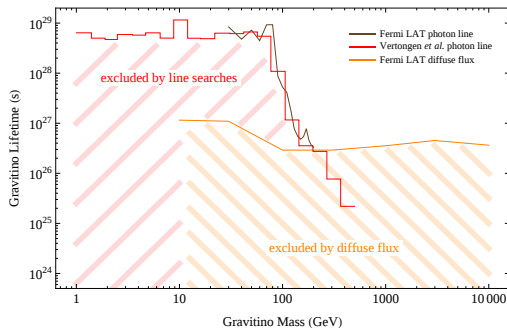
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Neutrinos are a valuable channel for heavy gravitino searches!

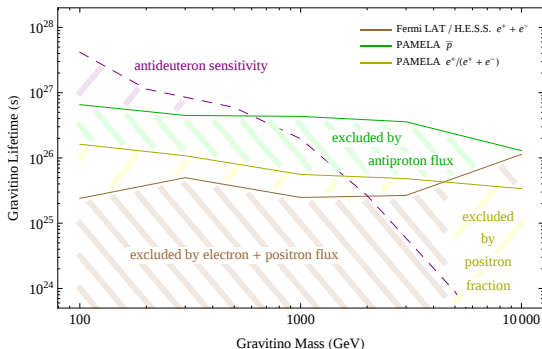
Limits on the Gravitino Lifetime



► 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

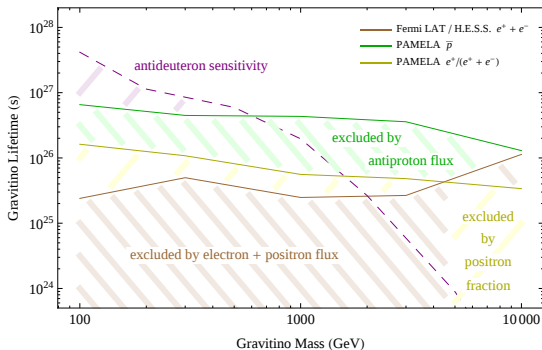
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- Antideuterons might be complementary to photon line searches for low masses

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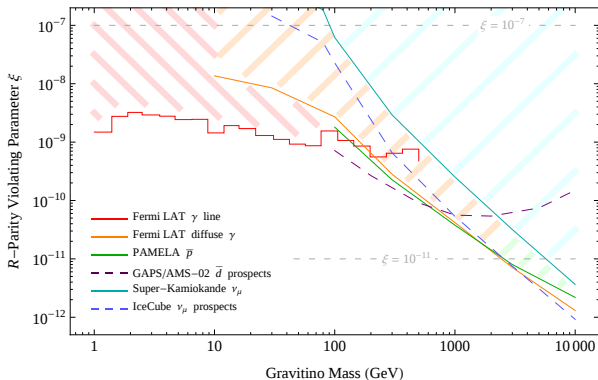


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Wide range of bounds from multi-messenger approach!

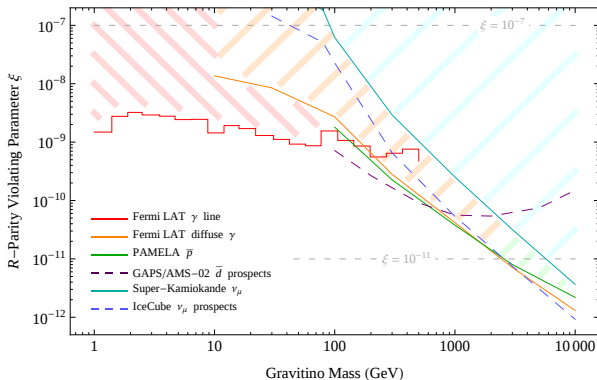
Limits on the Amount of R -Parity Violation

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



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Indirect searches probe interesting range of R -parity violation!

Conclusions and Outlook

- Gravitino dark matter models with broken R -parity are well motivated
- The Gravitino lifetime can be probed in indirect detection experiments
- Cannot explain the PAMELA and Fermi LAT excesses due to constraints from gamma rays and antiprotons
- Antideuteron searches could probe light gravitino dark matter
- Neutrino experiments like IceCube can probe heavy gravitino dark matter
- Multi-messenger approach constrains gravitino lifetime and strength of R -parity violation

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Thanks for your attention!