Cosmic-Ray Constraints on Unstable Gravitino Dark Matter

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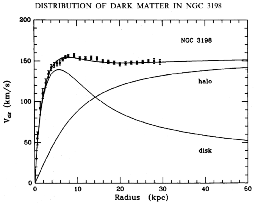
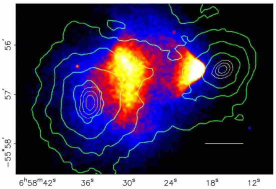
Collaborators: L. Covi, **T. Delahaye**, A. Ibarra, D. Tran, G. Vertongen

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)]



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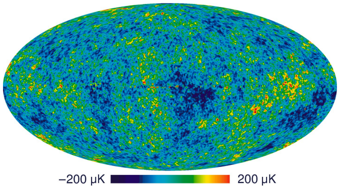
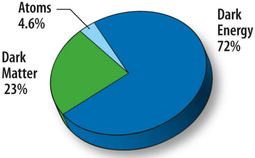


[NASA / WMAP Science Team]

- 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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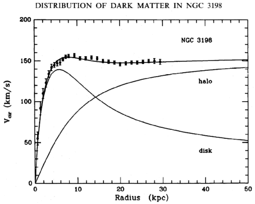

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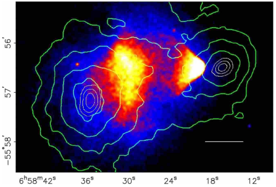

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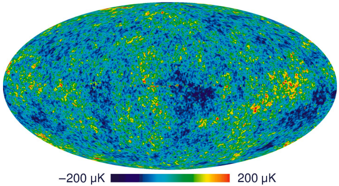

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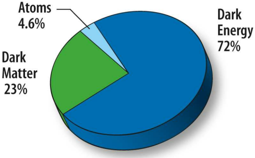

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Dark matter could be (super)WIMP with lifetime $\gg$ age of the universe!

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: $T_R \gtrsim 10^9$ 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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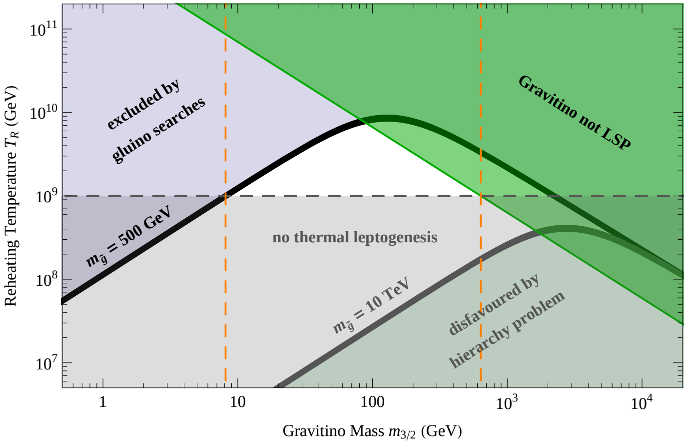
Possible solution: Gravitino is the LSP and thus stable!

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:
  - 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 [Covi, Kraml (2007)]
  - Dilute NLSP density by late entropy production [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
  - $\mathcal{O}(10)$ 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: $\Gamma_{3/2} \propto \frac{\xi^2 \, m_{3/2}^3}{M_{\text{Pl}}^2} = 2.6 \times 10^{-24}\,\text{s}^{-1} \left(\frac{m_{3/2}^3}{10\,\text{GeV}} \right)^3 \left(\frac{\xi}{10^{-7}} \right)^2$
    [Takayama, Yamaguchi (2000)]
  - The gravitino lifetime by far exceeds the age of the universe ($\tau_{3/2} \gg 10^{17}\,\text{s}$)

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

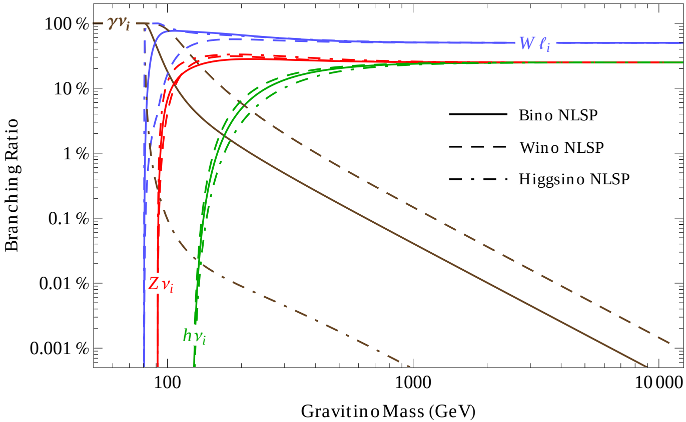
Phenomenology of Unstable Gravitino Dark Matter

- Rich phenomenology instead of elusive gravitinos:
  - A long-lived NLSP could be observed at the LHC
    [Buchmüller *et al.* (2007), Bobrovskyi *et al.* (2010, 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!

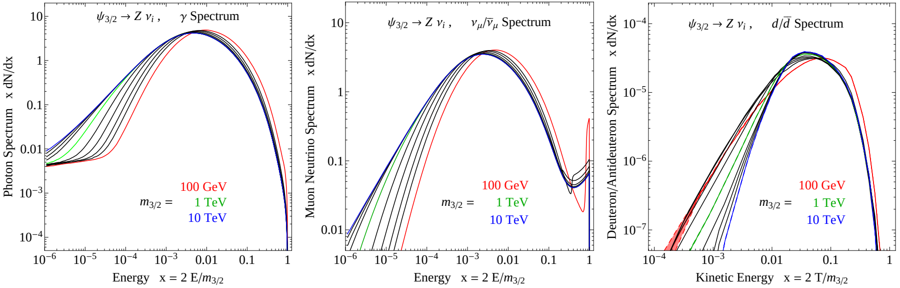
Gravitino Decay Channels

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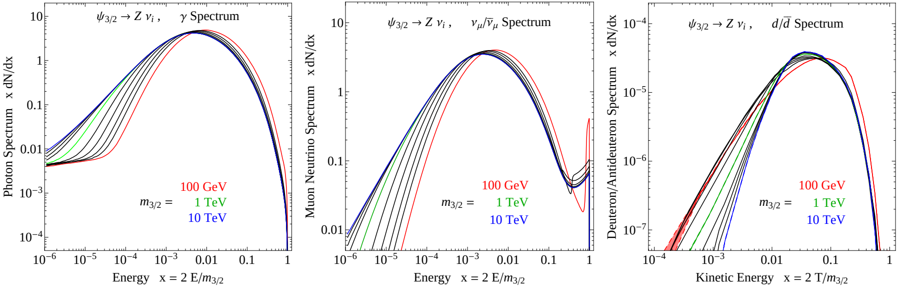
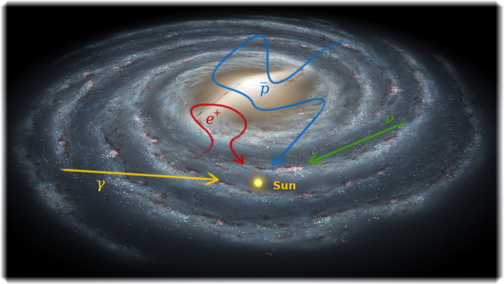


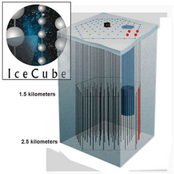
Basis for phenomenology of indirect gravitino dark matter searches!

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]

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

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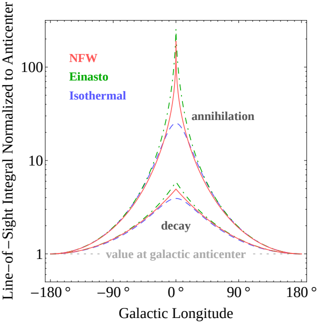

Annihilation (*e.g.* WIMP dark matter)

- 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 early universe
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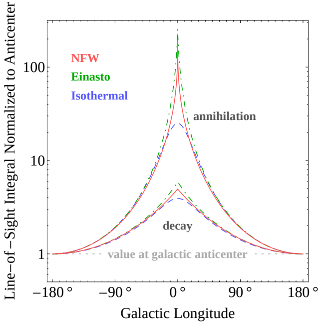

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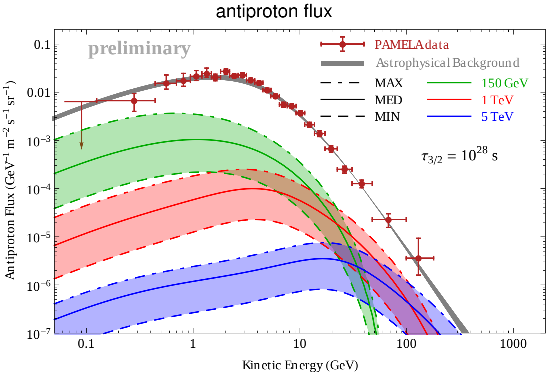
Directional detection can distinguish unstable gravitino from standard WIMPs!

Gravitino Decay Signals in Cosmic-Ray Spectra



- 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

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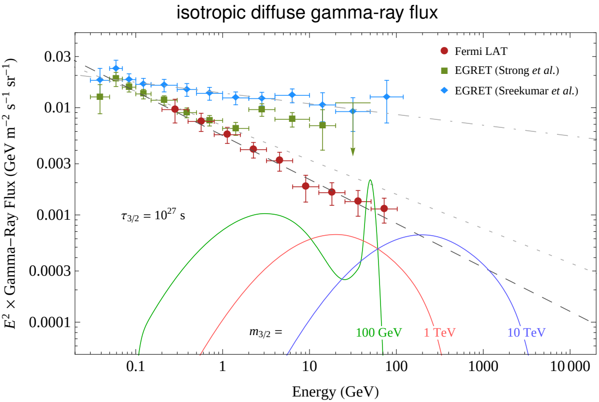

- Isotropic diffuse gamma-ray spectrum exhibits power-law behaviour
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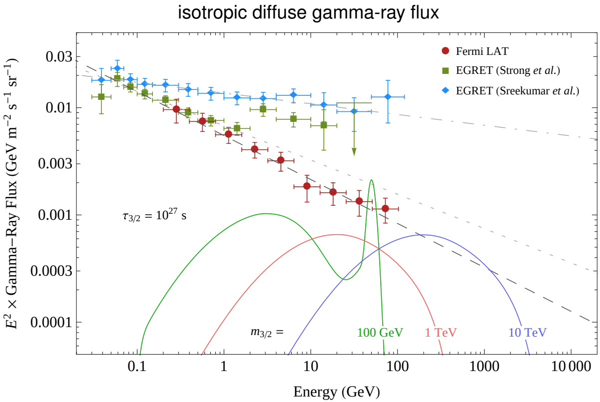

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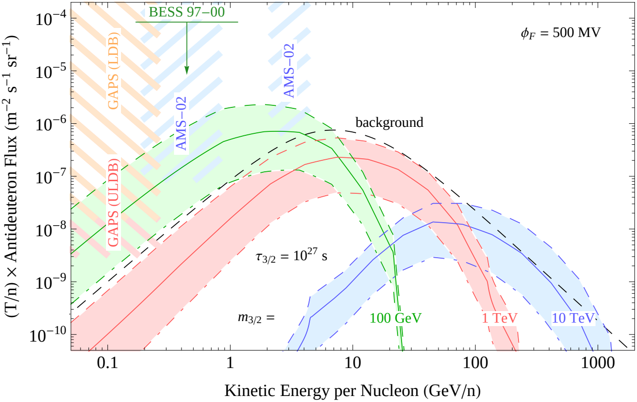
Astrophysical sources like pulsars required to explain cosmic-ray excesses!

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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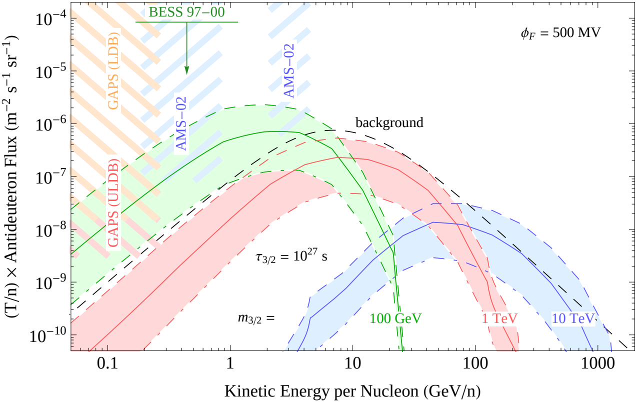
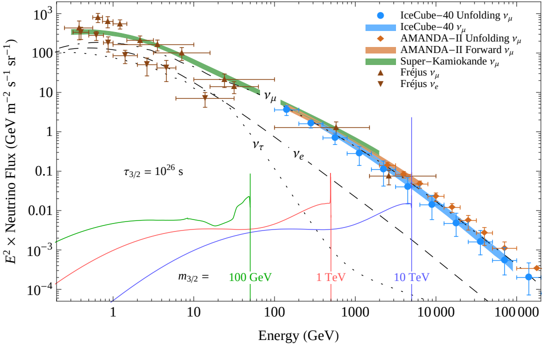


Antideuterons could be a valuable channel for light gravitino searches!

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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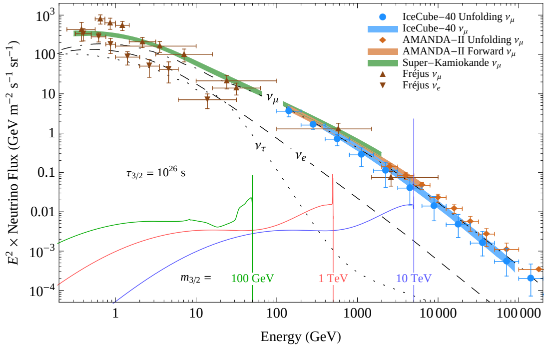
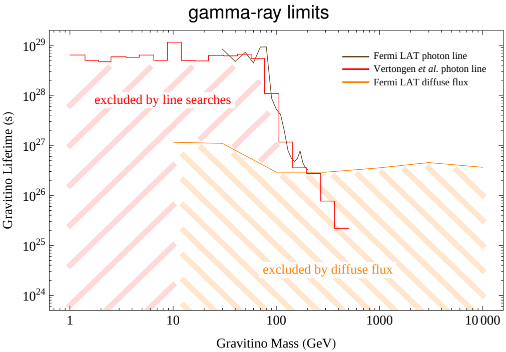
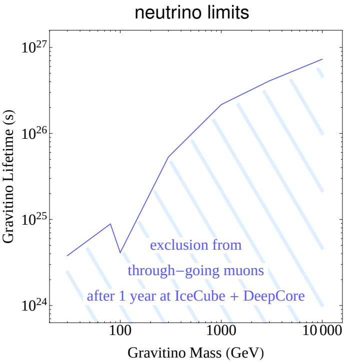


Neutrinos are a valuable channel for heavy gravitino searches!

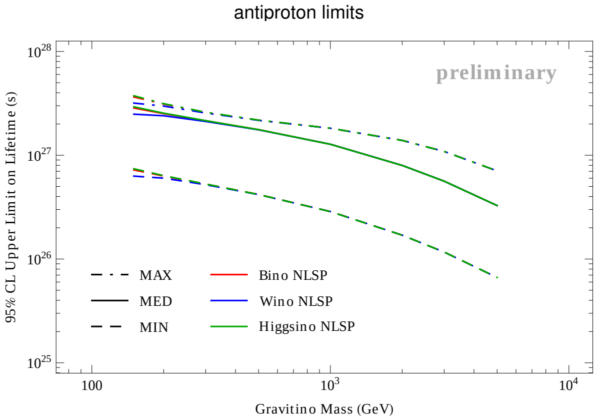
Limits on the Gravitino Lifetime





- 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



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  - No strong dependence on SUSY model parameters

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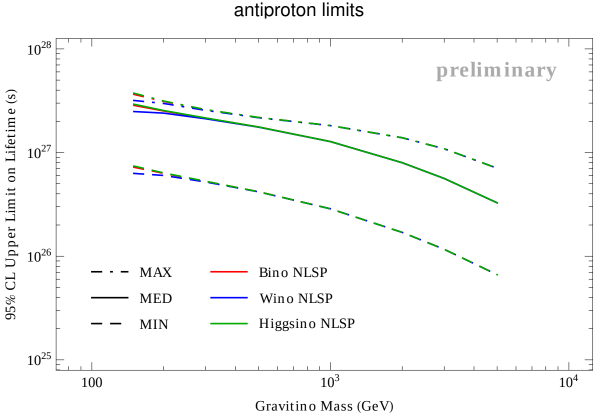

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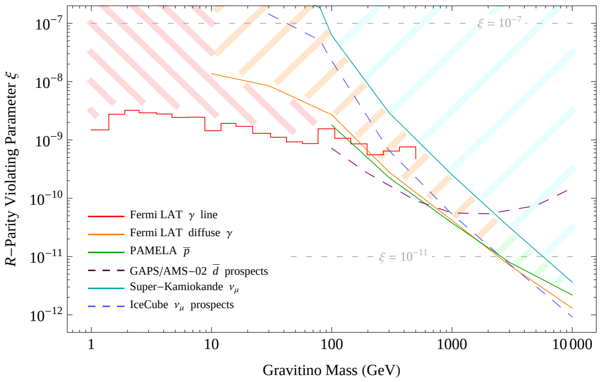
Wide range of bounds from multi-messenger approach!

Limits on the Amount of *R*-Parity Violation

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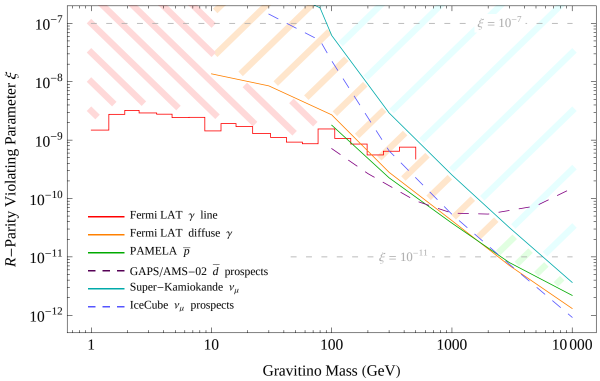

Indirect searches probe interesting range of *R*-parity violation!

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

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

Thanks for your attention!