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

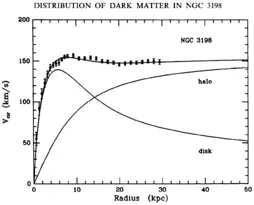
Outline

- 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?

- Dark matter is observed on various scales through its gravitational interaction
- Dark matter contributes significantly to the energy density of the universe



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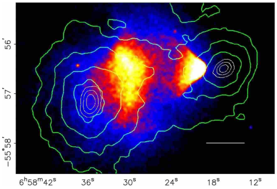

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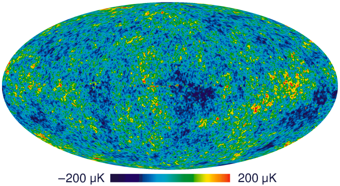
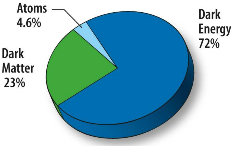


[NASA / WMAP Science Team]

- 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)
  - Long-lived on cosmological time scales but not necessarily stable!



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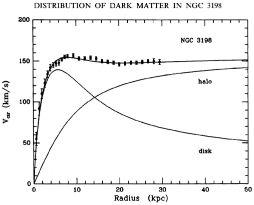

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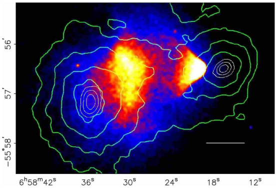

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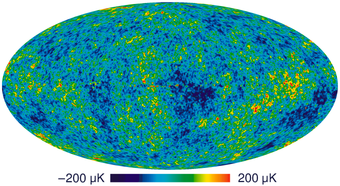

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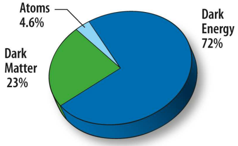
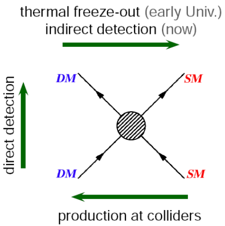


[NASA / WMAP Science Team]

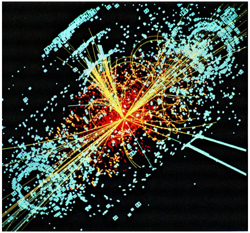
Particle dark matter could be a (super)WIMP with lifetime $\gg$ age of the universe!

How Can We Unveil the Nature of Dark Matter?

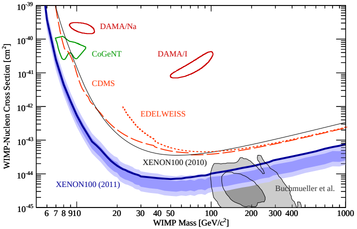
- There are three main search strategies for dark matter:
  - Direct detection of dark matter in the scattering off matter nuclei
  - Production of dark matter particles at colliders
  - Indirect detection of dark matter in cosmic ray signatures



[Max-Planck-Institut für Kernphysik]



[CERN]



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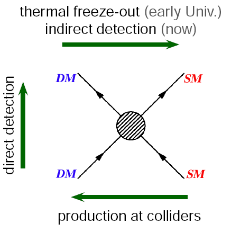

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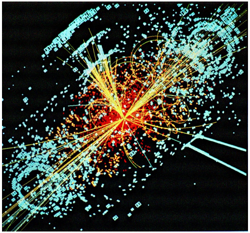

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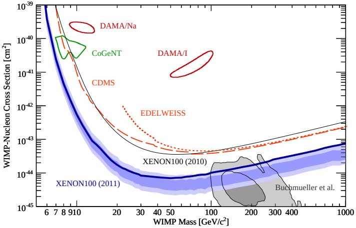

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A combination will be necessary to identify the nature of particle dark matter!

Why Are We Interested in Unstable Gravitino Dark Matter?

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

$$\Omega_{3/2}h^2 \simeq 0.27 \left(\frac{T_R}{10^{10}\,\text{GeV}}\right)\left(\frac{100\,\text{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\,\text{TeV}}\right)^2$$

[Bolz *et al.* (2001)]

- Problem in scenarios with neutralino dark matter:
  - Gravitino decays suppressed by Planck scale: $\tau_{3/2} \sim \frac{M_{\text{Pl}}^2}{m_{3/2}^3} \approx 3\,\text{years}\left(\frac{100\,\text{GeV}}{m_{3/2}}\right)^3$
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Possible solution: Gravitino is the LSP and thus stable!

Why Are We Interested in Unstable Gravitino Dark Matter?

- Gravitino relic density:

$$\Omega_{3/2}h^2 \simeq 0.27 \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2$$

- Correct relic density possible for $m_{3/2} > \mathcal{O}(10)\,\mathrm{GeV} \Rightarrow$ Gravitino dark matter
- Still problematic:
  - NLSP can only decay to gravitino LSP:

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

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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: $W_{\not R_p} = \mu_i H_u L_i, \qquad -\mathcal{L}^{\text{soft}}_{\not R_p} = B_i H_u \tilde{\ell}_i + m^2_{H_d \ell_i} H_d^* \tilde{\ell}_i + \text{h.c.}$
  - Only lepton number violated $\Rightarrow$ Proton remains stable!
- R-parity violation parametrized by non-vanishing sneutrino VEV: $\xi = \frac{\langle \tilde{\nu} \rangle}{v}$
- Cosmological bounds on R-violating couplings
  - Lower bound: The NLSP must decay fast enough to evade BBN constraints: $\xi \gtrsim \mathcal{O}(10^{-11})$
  - Upper bound: No washout of the 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: $\Gamma_{3/2} \propto \frac{\xi^2 \, m^3_{3/2}}{M^2_{\text{Pl}}}$ [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, 2011)]
  - Gravitino decays lead to possibly observable signals at indirect detection experiments [Takayama, Yamaguchi (2000), Buchmüller *et al.* (2007), Bertone *et al.* (2007), Ibarra, Tran (2008), Ishiwata *et al.* (2008) etc.]

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

Bilinear R-Parity Violation: Neutralino–Neutrino Mixing

- Bilinear R-parity violation extends neutralino mass matrix to include 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
  - $U_{\tilde{\gamma}\tilde{Z}} \simeq m_Z \sin\theta_W \cos\theta_W \frac{M_2 - M_1}{M_1\, M_2}$
  - $U_{\tilde{Z}\tilde{Z}} \simeq -m_Z \left(\frac{\sin^2\theta_W}{M_1} + \frac{\cos^2\theta_W}{M_2} \right)$

Bilinear R-Parity Violation: Chargino–Charged Lepton Mixing

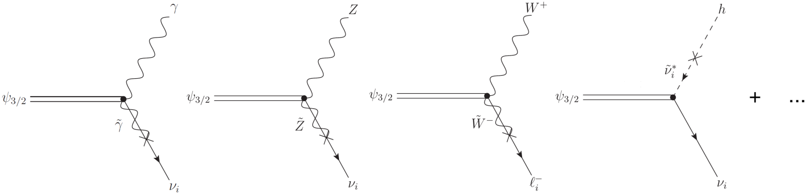
- Bilinear R-parity violation extends chargino mass matrix to include charged leptons
- 5×5 matrix with basis vectors $\psi^- = (-i\tilde{W}^-, \tilde{H}_d^-, \ell_i^-)^T$ and $\psi^+ = (-i\tilde{W}^+, \tilde{H}_u^+, e_i^{c\,+})^T$

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

- Diagonalized by unitary matrices U^5 and V^5
- Mixing to left-handed 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: 2-body Decays

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

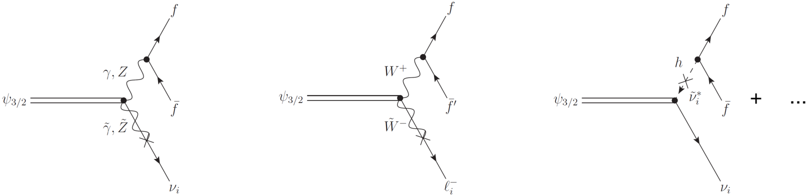


- $\Gamma_{\gamma\nu_i} \simeq \dfrac{\xi_i^2\, m_{3/2}^3}{32\,\pi\, M_{\rm Pl}^2} |U_{\tilde{\gamma}\tilde{Z}}|^2 \propto \dfrac{\xi_i^2\, m_{3/2}^3}{M_{\rm Pl}^2} \left(\dfrac{M_2 - M_1}{M_1\, M_2}\right)^2$
- $\Gamma_{Z\nu_i} \simeq \dfrac{\xi_i^2\, m_{3/2}^3}{32\,\pi\, M_{\rm Pl}^2} \left(1 - \dfrac{m_Z^2}{m_{3/2}^2}\right)^2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

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

Gravitino Decay Channels: 3-body Decays

- For $m_{3/2} < m_W$ also three-body decays can play an important role [Choi *et al.* (2010)]



  - $\frac{d\Gamma_{Z^*\nu_i}}{ds} \propto \frac{\xi_i^2\, m_{3/2}^3}{M_{\text{Pl}}^2\left((s-m_Z^2)^2+m_Z^2\Gamma_Z^2\right)}\left(1-\frac{s}{m_{3/2}^2}\right)^2\left\{s\, U_{\tilde{Z}\tilde{Z}}^2\, f\left(\frac{s}{m_{3/2}^2}\right)+\ldots\right\}$
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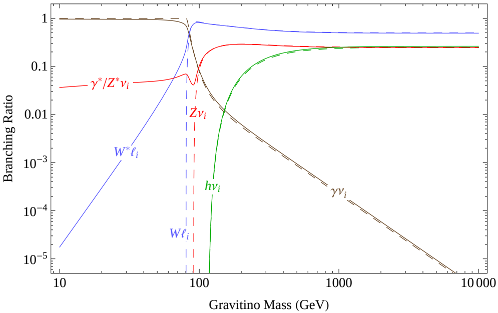
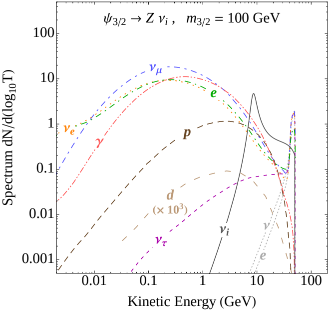
  - $\frac{d\Gamma_{h^*\nu_i}}{ds} \propto \frac{\xi_i^2\, m_{3/2}^3\, m_f^2\, s}{M_{\text{Pl}}^2\, v^2\left((s-m_h^2)^2+m_h^2\Gamma_h^2\right)}\left(1-\frac{s}{m_{3/2}^2}\right)^4$

- I will concentrate on 2-body dacays in this talk

Gravitino Branching Ratios and Final State Particle Spectra

- Branching ratios are independent of strength of *R*-parity violation
- Ratio between $\gamma\,\nu_i$ and other channels is model-dependent





- Gravitino decays produce spectra of 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 in PYTHIA [Kadastik *et al.* (2009)]

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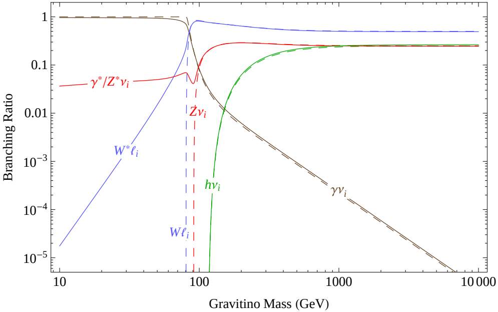

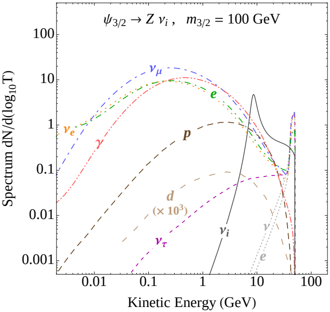

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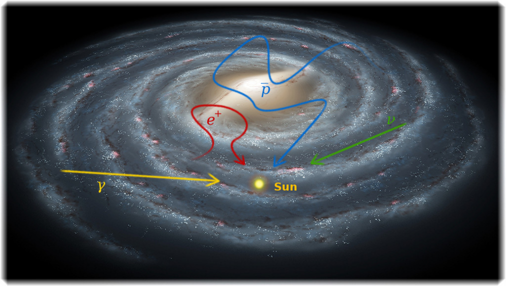
Basis for phenomenology of indirect gravitino dark matter searches!

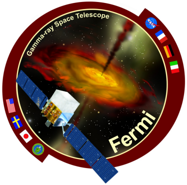
Indirect Detection of Gravitino Dark Matter

Cosmic-Ray Propagation

- Cosmic rays from gravitino decays propagate through the Milky Way

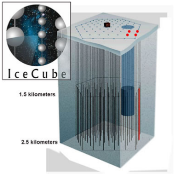


- Experiments observe spectra of gamma rays, charged cosmic rays and neutrinos



[NASA E/PO, SSU, Aurore Simonnet]

[AMS-02 Collaboration]



[IceCube Collaboration]

What Is the Difference of Dark Matter Annihilations and Decays?

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

Dark Matter Annihilation

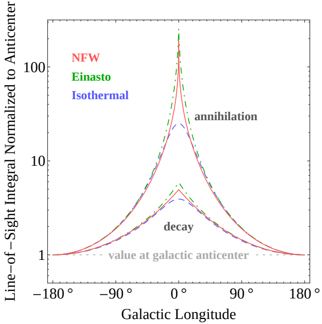
$$\frac{dJ_{\text{halo}}}{dE} = \frac{\langle \sigma v \rangle_{\text{DM}}}{8\pi\, m_{\text{DM}}^2} \frac{dN}{dE} \int_{\text{l.o.s.}} \rho_{\text{halo}}^2(\vec{l})\, d\vec{l}$$

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 the early universe
- Less anisotropic signal
- Less sensitive to the halo model

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Dark Matter Annihilation

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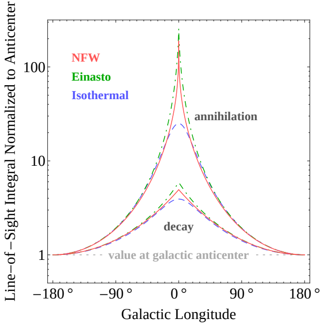
Dark Matter Decay

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



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

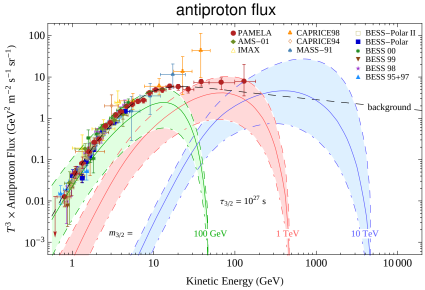
- Annihilation cross section related to relic density
- Strong signal from peaked structures
- Uncertainties from choice of halo profile

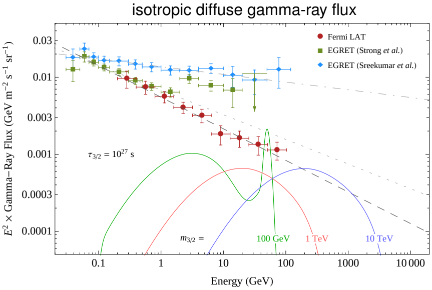
Decay (*e.g.* unstable gravitino dark matter)

- Lifetime unrelated to production in the early universe
- Less anisotropic signal
- Less sensitive to the halo model

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
- Isotropic diffuse gamma-ray spectrum exhibits power-law behaviour
  - Source not completely understood, but no sign of spectral features of a particle decay
- Even without astrophysical backgrounds lifetimes below $\mathcal{O}(10^{26}–10^{27})$ s excluded
  - Gravitino decay cannot be the origin of the PAMELA and Fermi LAT cosmic-ray anomalies

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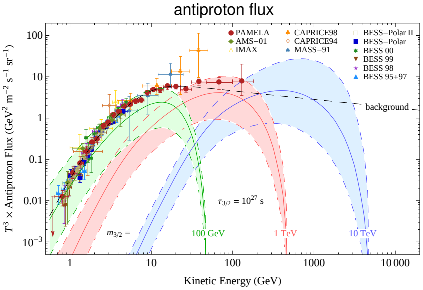

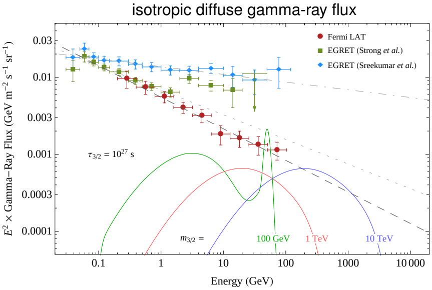

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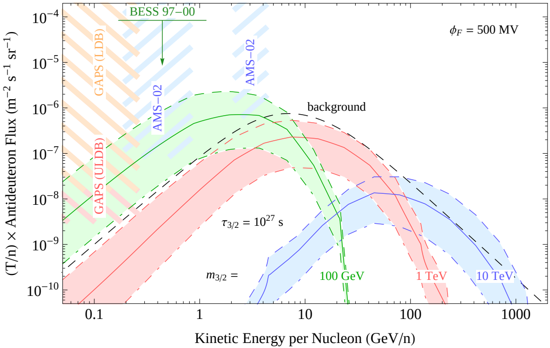
Astrophysical sources like pulsars required to explain cosmic-ray excesses!

Antideuteron Signals from Gravitino Decays

- In particular sensitive at low energies due to small astrophysical background
- AMS-02 and GAPS will be able to put strong constraints on light gravitinos



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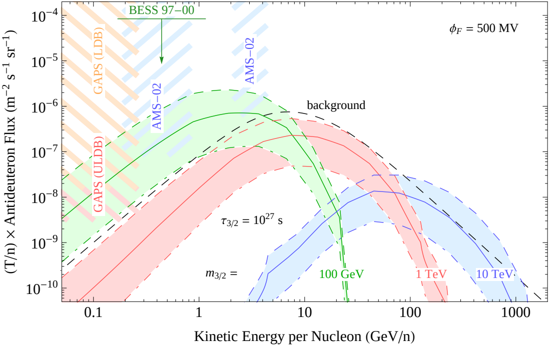
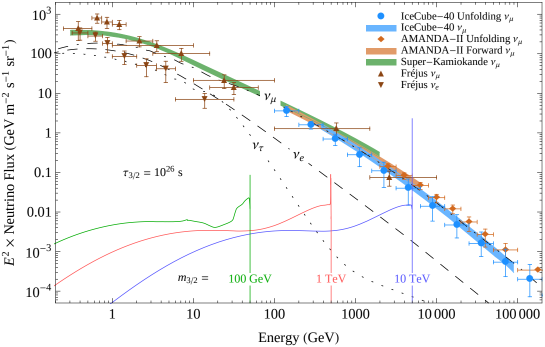


Antideuterons are a valuable channel for light gravitino searches!

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



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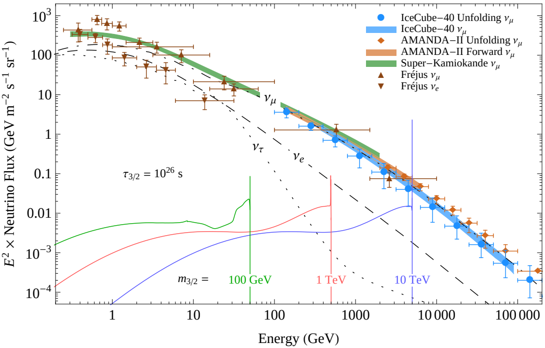


Neutrinos are a valuable channel for heavy gravitino searches!

Neutrino Detection with Upward Through-Going Muons

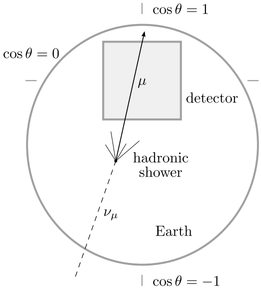
- Muon tracks from charged current DIS of muon neutrinos off nuclei outside the detector

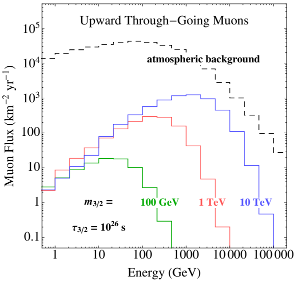
Advantages

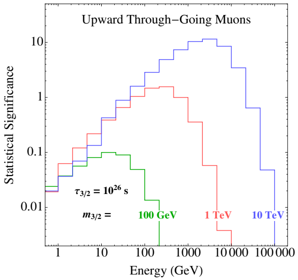
- Muon track reconstruction is well-understood at neutrino telescopes

Disadvantages

- Neutrino–nucleon DIS and propagation energy losses shift muon spectrum to lower energies
- Bad energy resolution (0.3 in $\log_{10} E$) smears out cut-off energy







Neutrino Detection – Improvements Using Showers

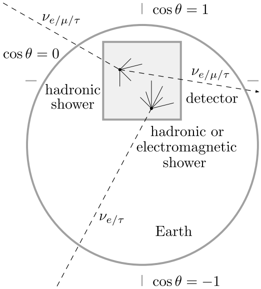
► Hadronic and electromagnetic showers from charged current DIS of electron and tau neutrinos and neutral current interactions of all neutrino flavours inside the detector

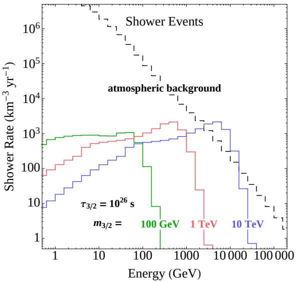
Disadvantages

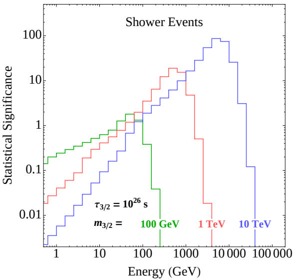
- TeV-scale showers are difficult to discriminate from short muon tracks

Advantages

- 3× larger signal and 3× lower background compared to other channels
- Better energy resolution (0.18 in $\log_{10} E$) helps to distinguish spectral features







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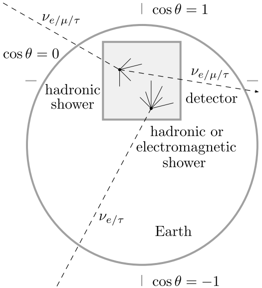
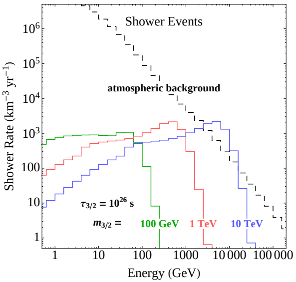
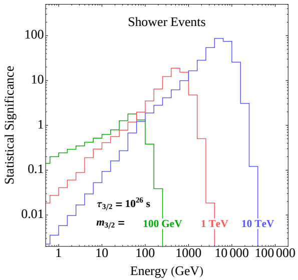
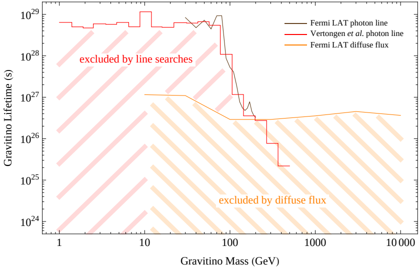


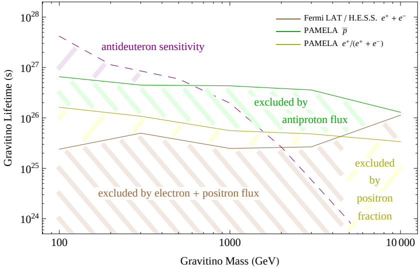




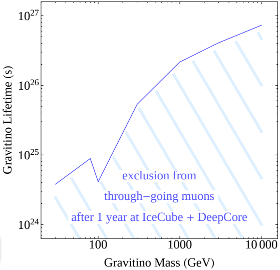
Showers are potentially the best channel for dark matter searches in neutrinos!

Limits on the Gravitino Lifetime





- Cosmic-ray data give bounds on gravitino lifetime
  - Photon line bounds very strong for low gravitino masses
  - Uncertainties from charged cosmic-ray propagation
  - Background subtraction will improve bounds
  - Antideuterons can be complementary to photon line searches for low gravitino masses
  - Neutrino bounds are competitive for heavy gravitinos

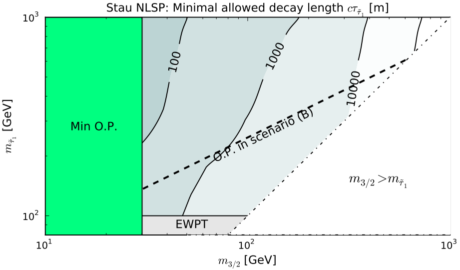


Wide range of bounds from multi-messenger approach!

Implications for the LHC

Implications for the LHC: Stau NLSP

- NLSP decays before BBN but may be metastable on collider scales
- Stau decay channels: $\tilde{\tau}_R \to \tau\,\nu_\mu, \mu\,\nu_\tau$ and $\tilde{\tau}_L \to \bar{t}_R\, b_L$
- 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



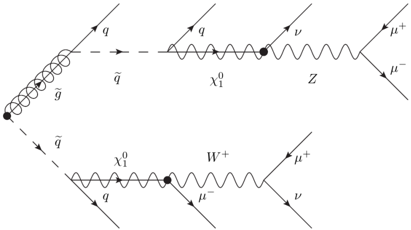
[Huang *et al.* (2011)]

- Gamma-ray limits from galaxy clusters constrain 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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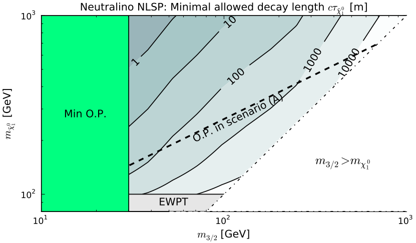

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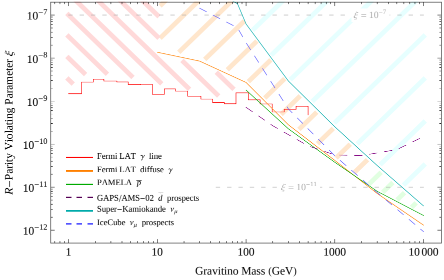
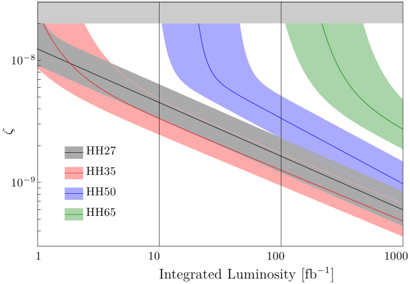
- Limits on gravitino lifetime constrain the strength of *R*-parity violation: $\tau_{3/2} \propto \frac{M_{\mathrm{Pl}}^2}{\xi^2\, m_{3/2}^3}$
  - Limits from photon line searches dominate for small gravitino masses
  - For heavier gravitino bounds from all cosmic-ray channels are comparable

cosmic-ray limits



LHC sensitivity for bino-like NLSP decays



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- The LHC has the potential to detect NLSP decays beyond cosmic-ray constraints
  - Good sensitivity with clean decay chain: $\tilde{\chi}_1^0 \to Z\,\nu_i$ and $Z \to \mu^+\mu^-$
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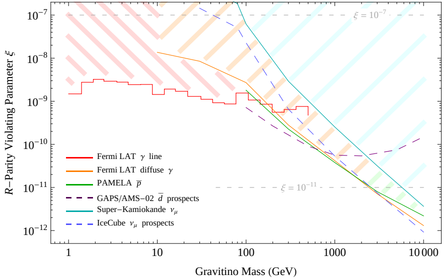

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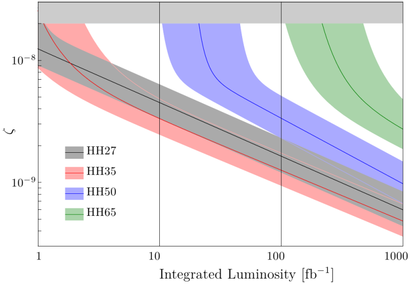

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Indirect and collider searches probe interesting range of *R*-parity violation!

Conclusions and Outlook

Conclusions

- Gravitino dark matter with broken *R*-parity is well motivated from cosmology
- Consistent with thermal leptogenesis and big bang nucleosynthesis
- 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!