Gravitino Dark Matter

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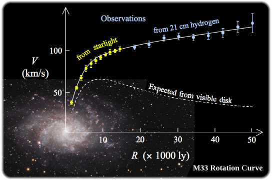
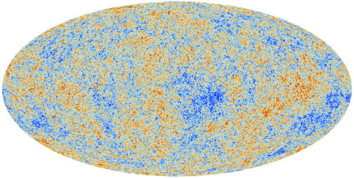
What Do We Know about Dark Matter?

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



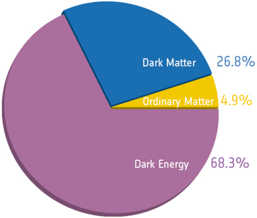
[M. Whittle]



[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]

Gravitino Dark Matter: Stable or Unstable?

Stable Gravitino Dark Matter

- Typical in gauge mediation with conserved *R*-parity
- No direct detection signal expected: $\sigma_N \sim M_{\mathrm{Pl}}^{-4}$
- No annihilation signal expected: $\sigma_{ann} \sim M_{\mathrm{Pl}}^{-4}$
- 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: $\sigma_N \sim M_{\mathrm{Pl}}^{-4}$
- Decays could lead to observable cosmic-ray signals
- Collider signals from long-lived NLSP expected

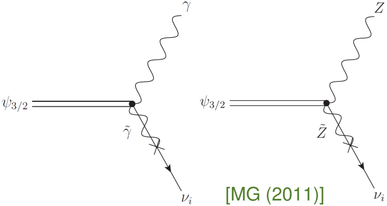
Models with Gravitino DM and *R*-Parity Violation

- 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
  - $\mathcal{O}(10)\,\mathrm{GeV} < m_{3/2} < \mathcal{O}(500)\,\mathrm{GeV}$, 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
- PeV neutrino events from gravitino decay? [Feldstein *et al.* (2013)]
  - Gravitino mass and lifetime: 2.4 PeV, 10^{28} s. Continuum neutrinos observable?

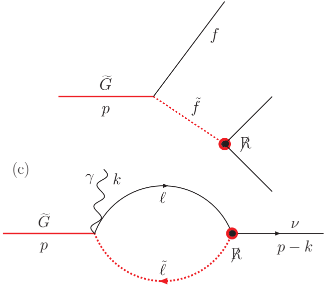
Gravitino Decay Channels

Bilinear *R*-parity violation

- Several two-body decay channels:
  $$\psi_{3/2} \to \gamma\,\nu_i,\ Z\,\nu_i,\ W\,\ell_i,\ h\,\nu_i$$
- Neutrino line + continuous spectrum
- Flavour of the monochromatic neutrino depends on the flavour structure of RpV



[MG (2011)]



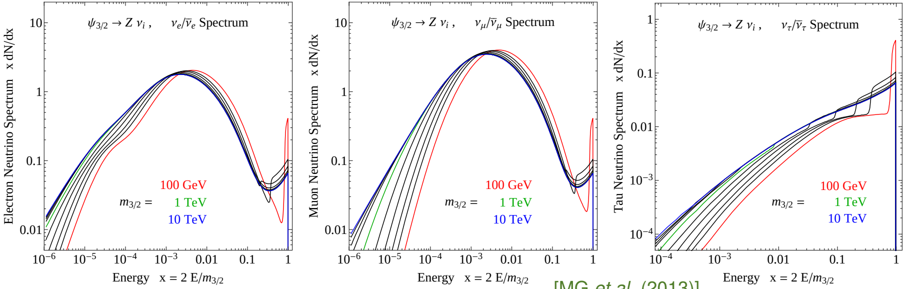
[Lola *et al.* (2007)]

Trilinear *R*-parity violation

- Several three-body decay channels:
  $$\psi_{3/2} \to \nu_i\,\ell_j\,\bar{\ell}_k,\ \nu_i\,d_j\,\bar{d}_k,\ \ell_i\,u_j\,\bar{d}_k,\ u_i\,d_j\,d_k$$
- Depends on flavour structure of RpV
- Continuous neutrino spectrum
- Two-body decay only possible via loops:
  $$\psi_{3/2} \to \gamma\,\nu_i$$

Final State Particle Spectra

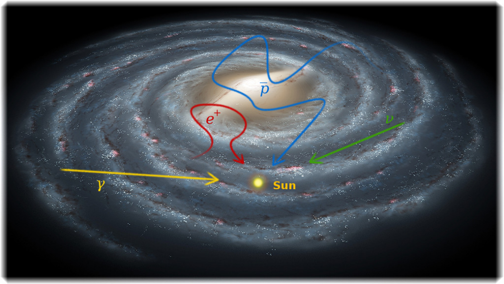
- Gravitino decays produce stable cosmic rays: γ, e, p, d, $\nu_{e/\mu/\tau}$
  - Spectra can be simulated with PYTHIA
  - Soft part dominated by pion decay: $\nu_\mu \sim 2 \times \nu_e$, ν_τ much lower
  - Spectral features close to high-energy cut-off from Z, W, h decay
  - In addition neutrino line at $E \sim m_{3/2}/2$



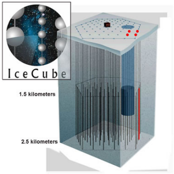
[MG *et al.* (2013)]

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

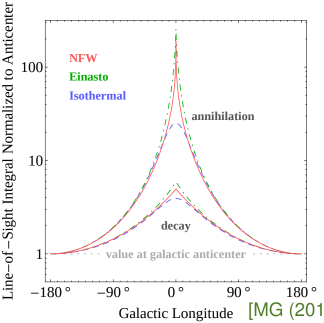
- Angular distribution of the gamma-ray/neutrino flux from the galactic halo:

Dark Matter Annihilation

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

Dark Matter Decay

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



[MG (2011)]

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
- Less anisotropic signal
- Less sensitive to the halo model

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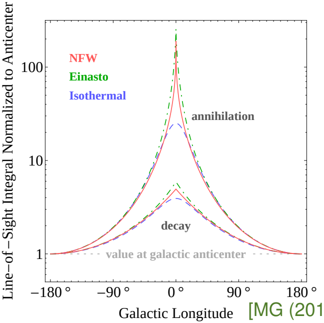

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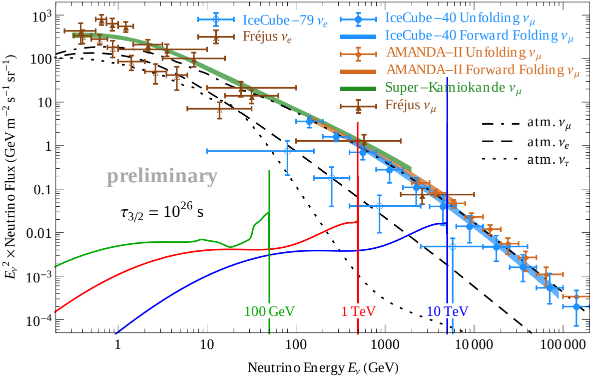
Directional detection can distinguish unstable gravitino from WIMPs!

Neutrino Signals from Gravitino Decays

- Atmospheric neutrinos are dominant background for gravitino decay signal
  - Discrimination of neutrino flavours allows to reduce the background
  - Sensitivity best for large gravitino masses



[MG *et al.* (2013)]

- Neutrinos from models like BRpV and $\mu\nu$SSM most likely not observable
  - Sensitivity to lifetimes beyond 10^{28} s needed at energies around 1 GeV

Neutrino Detection – Upward Through-Going Muons

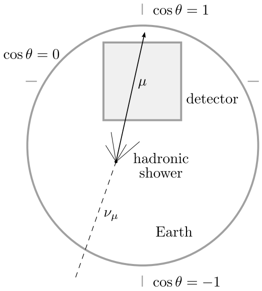
- Muon tracks from charged current DIS of muon neutrinos off nuclei

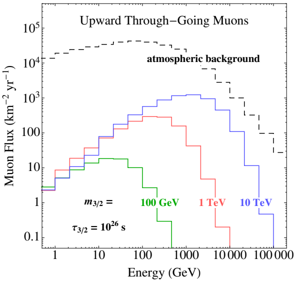
Advantages

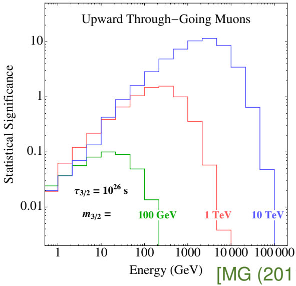
- Muon track reconstruction is well-understood at neutrino telescopes

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







[MG (2011)]

Neutrino Detection – Improvements With Cascades

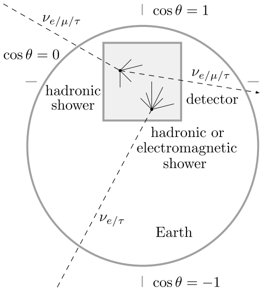
- Hadronic and electromagnetic cascades from charged current DIS of electron and tau neutrinos and neutral current interactions of all neutrino flavours

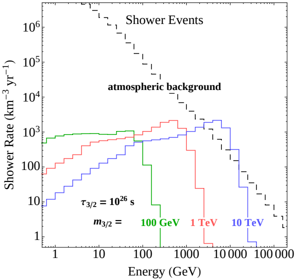
Disadvantages

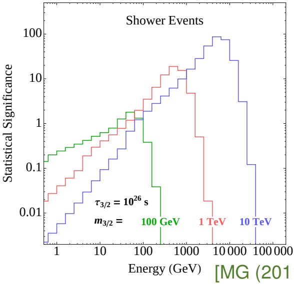
- TeV-scale cascades are difficult to discriminate from short muon tracks

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

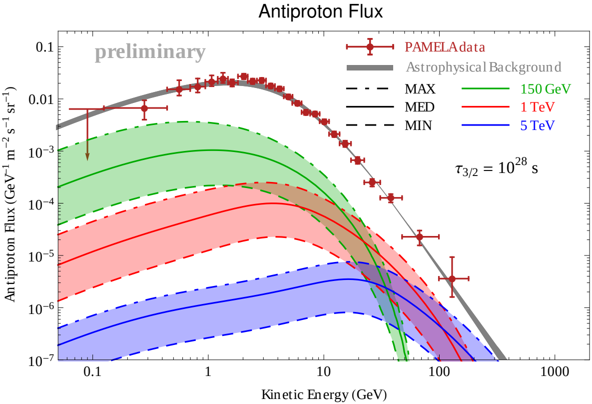






[MG (2011)]

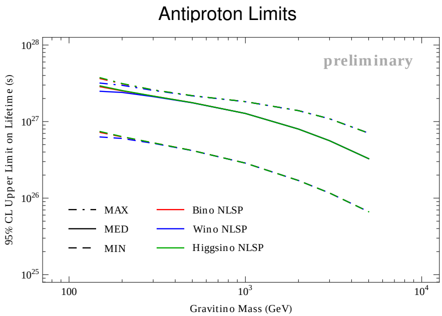
Gravitino Decay Signals in Cosmic-Ray Spectra

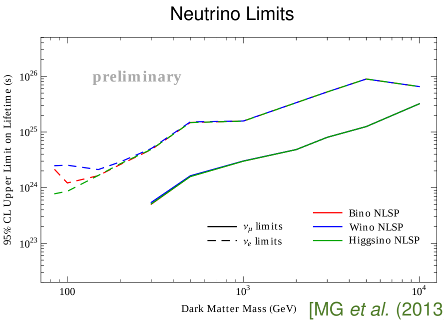


[MG *et al.* (2013)]

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

Limits on the Gravitino Lifetime


Antiproton Limits


Neutrino Limits

[MG *et al.* (2013)]

- Cosmic-ray data give bounds on gravitino lifetime
  - Uncertainties from charged cosmic-ray propagation through the Milky Way
- Estimated bounds on gravitino lifetime from atmospheric neutrino data
  - Neutrino sensitivity could be competitive for heavy gravitinos
  - Bounds from cascade events are already stronger than bounds from track events
  - Improvement with a dedicated analysis using angular and spectral information?

Summary

- 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
- Gravitino decays from bilinear RpV produce neutrino line
- Neutrino telescopes have best sensitivity for heavy gravitino DM
- Cascade events appear to be the most valuable channel
- A dedicated search for gravitino signals could improve the sensitivity

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Thanks for your attention!

Further Reading ...

Models with decaying gravitino dark matter

- Takayama *et al.*, Phys. Lett. B **485** (2000) 388 [hep-ph/0005214]
- López-Fogliani *et al.*, Phys. Rev. Lett. **97** (2006) 041801 [hep-ph/0508297]
- Buchmüller *et al.*, JHEP **0703** (2007) 037 [hep-ph/0702184]
- Lola *et al.*, Phys. Lett. B **656** (2007) 83 [arXiv:0707.2510 [hep-ph]]
- Bajc *et al.*, JHEP **1005** (2010) 048 [arXiv:1002.3631 [hep-ph]]
- Díaz *et al.*, Phys. Rev. D **84** (2011) 055007 [arXiv:1106.0308 [hep-ph]]
- Restrepo *et al.*, Phys. Rev. D **85** (2012) 023523 [arXiv:1109.0512 [hep-ph]]
- ...

Neutrino signals from gravitino decays

- Covi *et al.*, JCAP **0901** (2009) 029 [arXiv:0809.5030 [hep-ph]]
- Bomark *et al.*, Phys. Lett. B **686** (2010) 152 [arXiv:0911.3376 [hep-ph]]
- Erkoca *et al.*, Phys. Rev. D **82** (2010) 113006 [arXiv:1009.2068 [hep-ph]]
- MG, DESY-THESIS-2011-039 [arXiv:1111.6779 [hep-ph]]
- Feldstein *et al.*, arXiv:1303.7320 [hep-ph]
- ...