# Indirect Detection of Gravitino Dark Matter with Broken $R$-Parity

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# Outline

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# Gravitino Dark Matter

- Gravitino: spin-3/2 superpartner of the graviton in the supergravity multiplet
- Natural candidate for cold dark matter if the gravitino is the lightest supersymmetric particle
- Gravitinos were thermally produced in the early universe.
  Relic density:

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

  [M. Bolz, A. Brandenburg, W. Buchmüller 2001,
  J. Pradler, F.D. Steffen 2006]

- Cold dark matter density from WMAP: $\Omega_{\text{CDM}}h^2 \simeq 0.1$
- Leptogenesis requires a high reheating temperature: $T_R \gtrsim 10^9$ GeV which favors $m_{3/2} \gtrsim 5$ GeV.

# Problems with the NLSP

- Next-to-lightest supersymmetric particle is either a neutralino or a scalar $\tau$ in most scenarios
  $\longrightarrow$ Problems with Big Bang nucleosynthesis
- With conserved $R$-parity, the NLSP can only decay into gravitinos and Standard Model particles with a decay rate suppressed by the Planck scale
- This leads to the NLSP being present during BBN and potentially disturbing the BBN processes
- Neutralinos: photo-dissociation of primordial elements
- Scalar $\tau$s: Form bound states with $^4$He, catalyzing the production of $^6$Li
- Successful BBN predictions are spoiled! $\longrightarrow$ Talk by Frank Steffen

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**Solution:**

$R$-parity is not exactly conserved

# $R$-parity Violation

- Even a very small amout of $R$-parity violation makes the NLSP decay into Standard Model particles before the onset of BBN
- $R$-parity violation makes the gravitino unstable, or rather metastable – it remains a viable dark matter candidate due to the extremely long lifetime [F. Takayama, M. Yamaguchi 2000]
- $10^{23}$ s $\lesssim \tau_{3/2} \lesssim 10^{37}$ s for $m_{3/2} \sim 100$ GeV and $R$-parity violating Yukawa couplings in the range required by compatibility with BBN and leptogenesis
  (Age of the universe: $T \sim 10^{17}$ s)

$R$-parity violation also makes the gravitino accessible to indirect detection!

# Indirect Detection

- Even for gravitino lifetimes far in excess of the age of the universe, the decay products may be observable
- Look for signatures in rare, low background cosmic-ray species and spectra of particles that propagate freely:
  - Gamma-rays
  - Positrons
  - Antiprotons
  - Neutrinos → Talk by Michael Grefe

# Outline

# The Gamma-Ray Spectrum

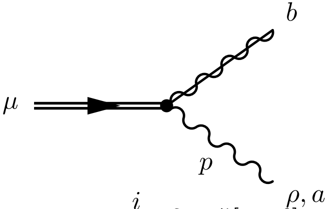
- The gamma-ray spectrum was measured by EGRET
- A first analysis of the extragalactic spectrum gave a power law spectrum [P. Sreekumar et al. 1998]
- A more recent re-analysis revealed a clear excess over the power law behavior at energies above $\sim 1$ GeV [A.W. Strong, I.V. Moskalenko, O. Reimer 2004]
- Interpretation of this excess in terms of dark matter annihilation or decay?

# The Gamma-Ray Spectrum

- Two contributions to the gamma-ray spectrum from gravitino decay
  - The signal from gravitino decays in the Milky Way halo
  - A redshifted signal from extragalactic sources
- The halo contribution has an angular dependence on the line of sight
- The extragalactic contribution gives an isotropic signal
- Together with the assumed power law background, the angular dependence of the predicted spectrum is mild enough to be easily compatible with the EGRET results

# The Gamma-Ray Spectrum

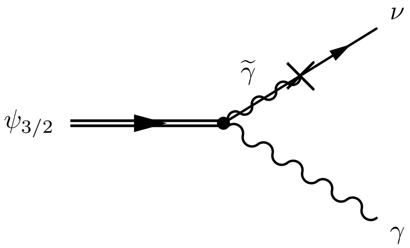
- Calculate decay rates from supergravity Lagrangian
- The model is highly constrained: gravitino interactions are fixed by symmetries




$$= -\frac{i}{4M_P}\delta_{ab}\gamma^\mu[\not{p}, \gamma^\rho]$$

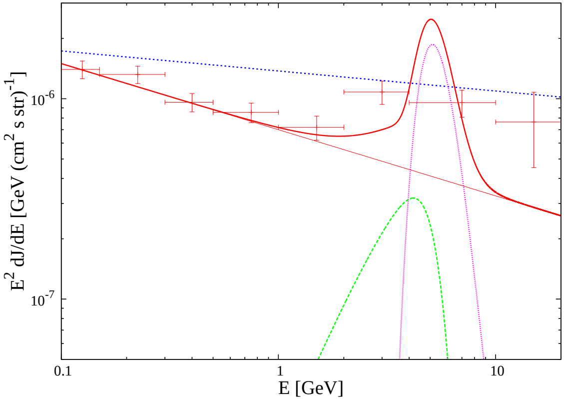
# The Gamma-Ray Spectrum

- Only two free parameters: $m_{3/2}$, $\tau_{3/2}$ (under assumption of gaugino mass universality at the GUT scale).
- Light gravitino: $m_{3/2} < m_W$
  Injection spectrum is a monochromatic line from $\psi_{3/2} \rightarrow \gamma\nu$ at $E = \frac{1}{2} m_{3/2}$



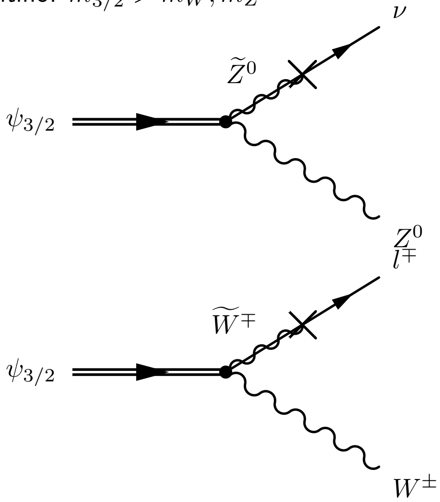
# The Gamma-Ray Spectrum

- Spectrum for light gravitino:




[G. Bertone, W. Buchmüller, L. Covi, A. Ibarra 2007]

- Heavier gravitino: $m_{3/2} > m_W, m_Z$

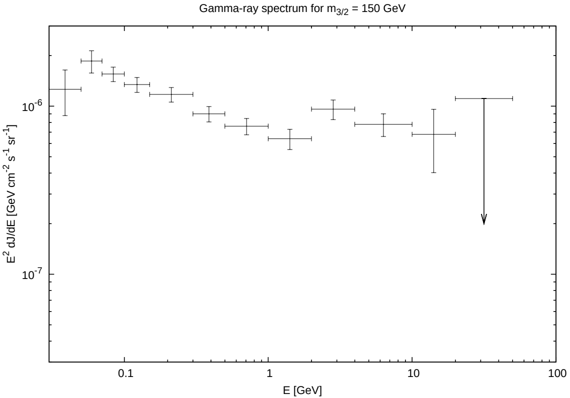


- Heavier gravitino: $m_{3/2} > m_W, m_Z$

  $$\psi_{3/2} \to Z^0 \nu$$
  $$\psi_{3/2} \to W^{\pm} l^{\mp}$$

  are kinematically allowed
- Fragmentation of the gauge bosons produces photons in the gamma-ray energy range
- Use Monte Carlo simulation to compute energy spectrum

- Spectrum for heavier gravitino:



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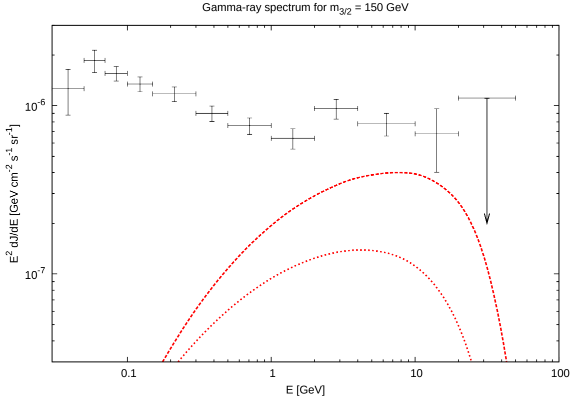


[A. Ibarra, DT 2007]

- $m_{3/2} = 150$ GeV, $\tau_{3/2} = 1.6 \times 10^{26}$ s.

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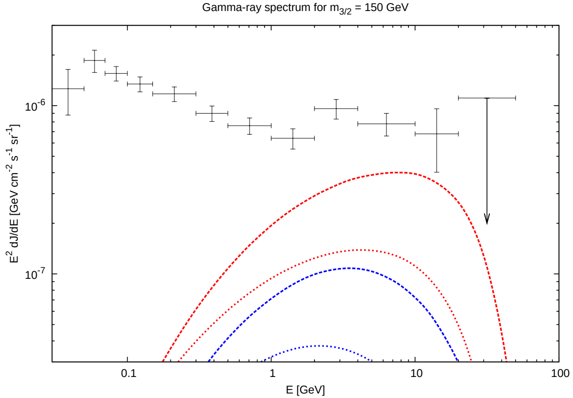


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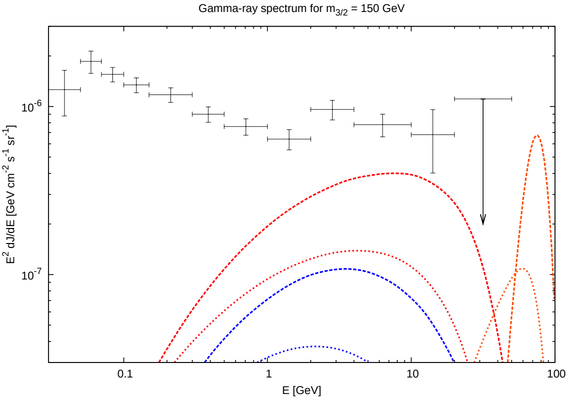


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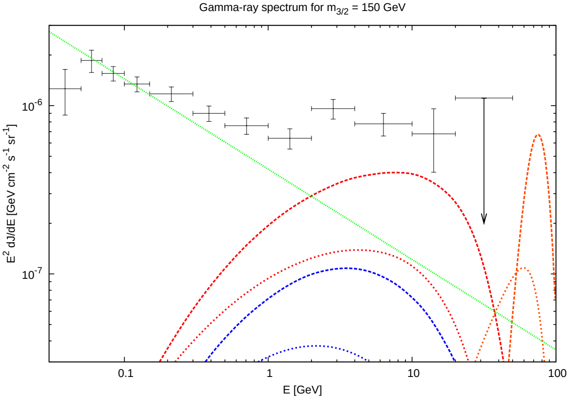


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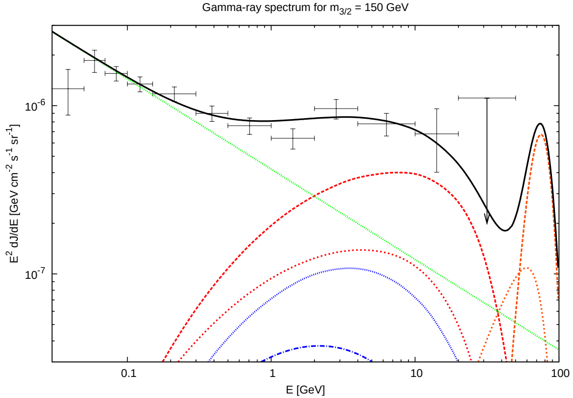


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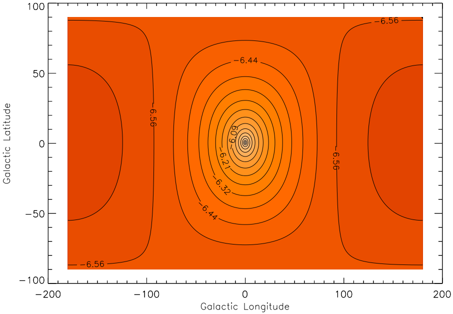
- $m_{3/2} = 150$ GeV, $\tau_{3/2} = 1.6 \times 10^{26}$ s.

# The Gamma-Ray Spectrum

- The monochromatic line is very characteristic and strongly suppressed in the case of neutralino dark matter
- The predicted anisotropy and the presence of the line may be tested by GLAST




- The line may also be visible by Cerenkov telescopes in galaxies such as M31

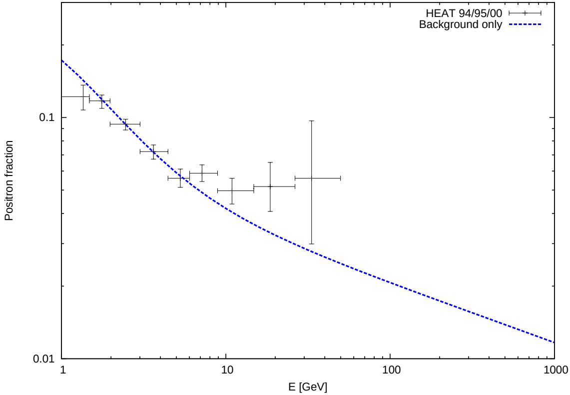
# Outline

# The Positron Fraction

- Fragmentation of the gauge bosons also produces positrons
- Complicated propagation due to energy loss and diffusion $\longrightarrow$ no directional information
- Astrophysics involves many uncertainties
- Propagation is modeled using a cylindrical diffusion zone
- Diffusion-loss equation can be solved numerically

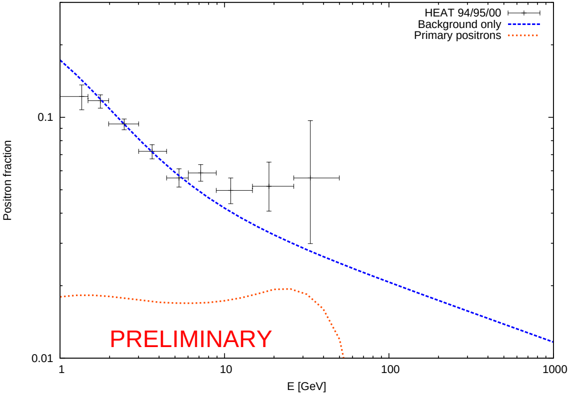
# The Positron Fraction

- Experiments measure the positron fraction because of solar modulation
- HEAT measured an excess in the positron fraction that cannot be explained by standard production and propagation models



# The Positron Fraction

- Using the EGRET excess to fix $m_{3/2}, \ \tau_{3/2}$ predicts an excess in the right energy range!

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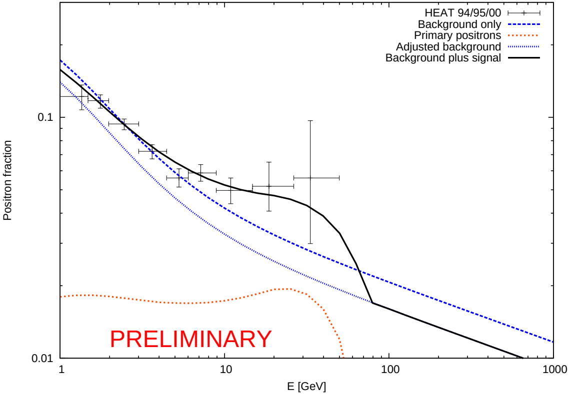


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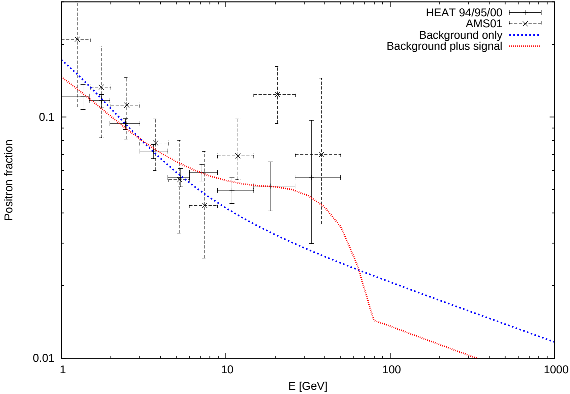
- $m_{3/2} = 150$ GeV, $\tau_{3/2} = 1.6 \times 10^{26}$ s.

# The Positron Fraction

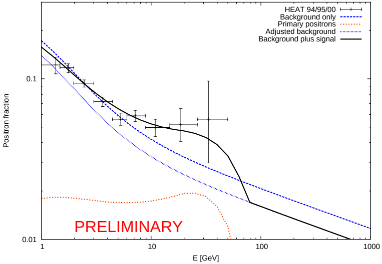
- Agreement with the HEAT data can be slightly improved

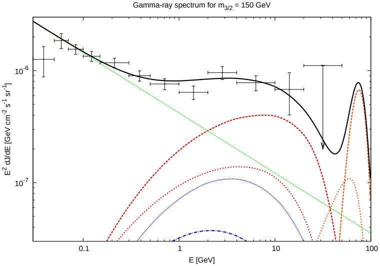



[A. Ibarra, DT]

- $m_{3/2} = 150$ GeV, $\tau_{3/2} = 1.0 \times 10^{26}$ s.
- Very close to the number obtained from the EGRET excess ($\tau_{3/2} = 1.6 \times 10^{26}$ s)!

- The coincidence of the parameters is very intriguing
- The anomalies in gamma-rays and positrons are related in this model – interpreting one of
  them in terms of decaying gravitinos automatically produces the other



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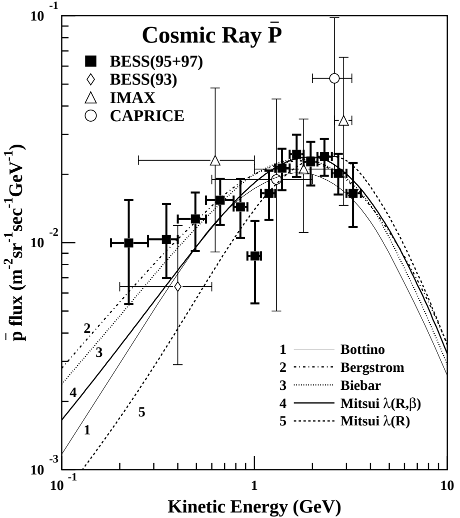
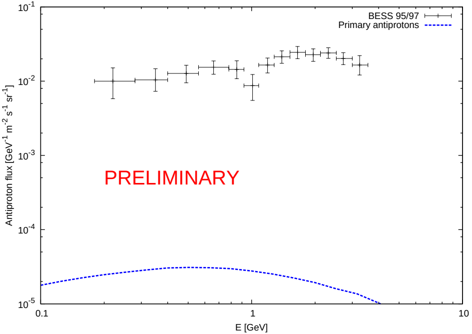
# The Antiproton Spectrum

- No need for new physics in the antiproton spectrum



# The Antiproton Spectrum

- Similar propagation mechanisms as in the case of positrons
- Model uses a two-layer diffusion zone




[A. Ibarra, DT]

- $m_{3/2} = 150$ GeV, $\tau_{3/2} = 1.6 \times 10^{26}$ s, maximal signal flux parameters.
- Primary antiproton flux is well below the background

# Outline

# Nice Features of Decaying Gravitino Dark Matter

- The gravitino is theoretically very well motivated
- Gravitino dark matter with broken $R$-parity is fully compatible with leptogenesis and primordial nucleosynthesis
- Very few free parameters $\longrightarrow$ predictive scenario that can "easily" be falsified experimentally
- May explain two anomalies simultaneously while remaining consistent with all existing experimental constraints

# Conclusions

- Gravitino dark matter with broken $R$-parity is very attractive
- GLAST and PAMELA (AMS-02?) will soon provide clarification on the existence of the excesses and their interpretation in terms of new physics
- Collider searches at the LHC for low energy supersymmetry and direct detection experiments will provide complementary information

We will soon be able to conclusively test this scenario!