Decaying Gravitino Dark Matter

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Outline

References

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1 Gravitino Cosmology

- If gravitinos are in thermal equilibrium in the early universe depending on the gravitino mass their relic density might overclose the universe.

  ⇒ An inflationary phase that dilutes any primordial gravitino density is needed!

- Thermal gravitino production during the reheating phase of the universe can lead to the correct relic density for dark matter [3]:

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

- Thermal leptogenesis requires a reheating temperature $T_R \gtrsim 10^9\,\mathrm{GeV}$.

  ⇒ A gravitino mass $m_{3/2} \gtrsim \mathcal{O}(10)\,\mathrm{GeV}$ is reasonable.

- If the gravitino is not the lightest supersymmetric particle (LSP) it is very long-lived due to its M_{Pl} suppressed couplings and can spoil the successful predictions of big bang nucleosynthesis (BBN).

  ⇒ If the gravitino is the LSP it is a natural candidate for cold dark matter. Then the next-to-lightest supersymmetric particle (NLSP) is long-lived and can spoil the BBN predictions.

- One possible solution is the introduction of a tiny R-parity violation. It must be large enough to make the NLSP decay into standard model particles before BBN and small enough to guarantee that the baryon asymmetry is not washed out by sphaleron processes before the electroweak phase transition.

  ⇒ These conditions lead to a gravitino lifetime exceeding the age of the universe by many orders of magnitude.

2 Bilinear R-parity Breaking

- The most general MSSM superpotential contains renormalizable lepton and baryon number violating terms that are usually removed by the introduction of R-parity to avoid rapid proton decay [4]:

$$W_{\mathrm{MSSM}}^{\not R_p} = \mu_i H_u L_i + \underbrace{\frac{1}{2}\lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk} U_i^c D_j^c D_k^c}_{\text{set to zero in the case of bilinear } \not R_p} .$$

- R-parity breaking introduces a mixing between the H_d and L_i fields. Thus there is an ambiguity in the choice of the basis for these fields:

$$L_\alpha = \begin{pmatrix} H_d \\ L_i \end{pmatrix} \quad \rightarrow \quad \begin{pmatrix} H'_d \\ L'_i \end{pmatrix} = U \begin{pmatrix} H_d \\ L_i \end{pmatrix}.$$

- We choose the basis where the bilinear R-parity breaking term vanishes:

$$H_d = H'_d - \frac{\mu_i}{\mu} L'_i \quad \text{and} \quad L_i = L'_i + \frac{\mu_i}{\mu} H'_d\,.$$

- In this case trilinear lepton number violating couplings are generated from the MSSM superpotential:

$$\begin{aligned} W &= \mu H_u H_d + \mu_i H_u L_i + \lambda^e_{jk} H_d L_j E^c_k + \lambda^d_{jk} H_d Q_j D^c_k + \ldots \\ \rightarrow \quad W' &= \mu H_u H'_d - \frac{\mu_i}{\mu} \lambda^e_{jk} L'_i L'_j E^c_k - \frac{\mu_i}{\mu} \lambda^d_{jk} L'_i Q_j D^c_k + \ldots\,. \end{aligned}$$

- No baryon number violating term is generated in this way. Therefore the proton stability is maintained.

- There are also R-parity violating terms in the soft scalar potential:

$$V^{\not R_p}_{\text{soft}} = B_i H_u \tilde{L}_i + \tilde{m}^2_{di} H^\dagger_d \tilde{L}_i + h.c. + \ldots\,.$$

- The bilinear R-parity breaking term in the superpotential and those in the soft scalar potential cannot be rotated away simultaneously.

- One can easily see that there arises a VEV for the sneutrino fields from the soft R-parity breaking bilinear terms:

$$\begin{aligned} V &= m^2_{\tilde{L}_i} |\tilde{L}_i|^2 + \Big(B_i H_u \tilde{L}_i + \tilde{m}^2_{di} H^\dagger_d \tilde{L}_i + h.c. \Big) + \ldots \\ &= m^2_{\tilde{\nu}_i} |\tilde{\nu}_i|^2 + \big(-B_i H^0_u \tilde{\nu}_i + \tilde{m}^2_{di} (H^0_d)^* \tilde{\nu}_i + h.c. \big) + \ldots \\ 0 &= \frac{\partial V_{\min}}{\partial \tilde{\nu}^*_i} = m^2_{\tilde{\nu}_i} \langle \tilde{\nu}_i \rangle - B_i v_u + \tilde{m}^2_{di} v_d \\ \Rightarrow \qquad \langle \tilde{\nu}_i \rangle &= v\, \frac{B_i \sin\beta - \tilde{m}^2_{di} \cos\beta}{m^2_{\tilde{\nu}_i}}\,. \end{aligned}$$

- In fact one has to perform the minimization of the complete scalar potential for the Higgs and the sneutrino fields. Then one finds for the sneutrino VEV:

$$\langle \tilde{\nu}_i \rangle = v\, \frac{B_i \sin\beta - \tilde{m}^2_{di} \cos\beta}{m^2_{\tilde{\nu}_i} + \frac{1}{2} m^2_Z \cos 2\beta}\,.$$

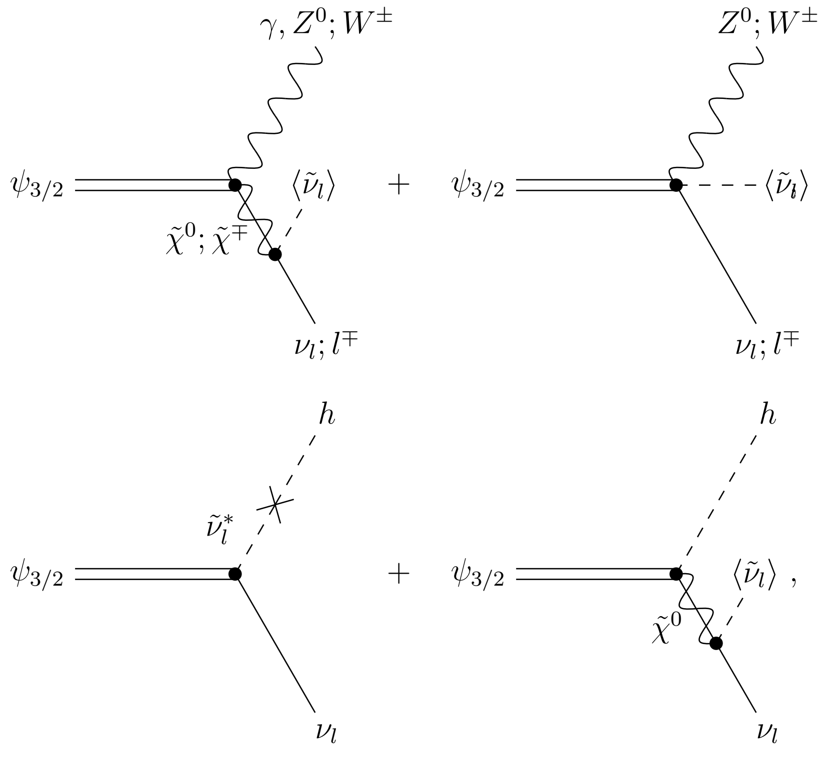
- With bilinear R-parity breaking we have Higgs–slepton mixing terms that appear in the soft scalar potential and gaugino–lepton mixing terms that arise from MSSM gauge vertices in the presence of a sneutrino VEV.

3 Gravitino Decay Channels

- The gravitino decay channels are determined by the gravitino interaction Lagrangian and the MSSM gauge Lagrangian:

$$\begin{aligned}\mathcal{L}_{\text{int}} &= -\frac{i}{\sqrt{2}\,M_{\text{Pl}}}\left[\left(D_\mu^*\phi^{*i}\right)\bar{\psi}_\nu\gamma^\mu\gamma^\nu P_L\chi^i - \left(D_\mu\phi^i\right)\bar{\chi}^i P_R\gamma^\nu\gamma^\mu\psi_\nu\right] \\ &\quad -\frac{i}{8M_{\text{Pl}}}\bar{\psi}_\mu\left[\gamma^\nu,\,\gamma^\rho\right]\gamma^\mu\lambda^{(\alpha)\,a}F_{\nu\rho}^{(\alpha)\,a} + \mathcal{O}(M_{\text{Pl}}^{-2})\,, \\ \mathcal{L}_{\text{gauge}} &= -\sqrt{2}g_\alpha\bar{\lambda}^{(\alpha)\,a}\phi^{*i}T_{a,\,ij}^{(\alpha)}P_L\chi^j - \sqrt{2}g_\alpha\bar{\chi}^i P_R T_{a,\,ij}^{(\alpha)}\phi^j\lambda^{(\alpha)\,a} + \ldots\,.\end{aligned}$$

- In the presence of bilinear R-parity breaking we find the following tree level diagrams for gravitino two-body decays:



- The three-body decays from trilinear R-parity breaking terms are neglected in the calculation.

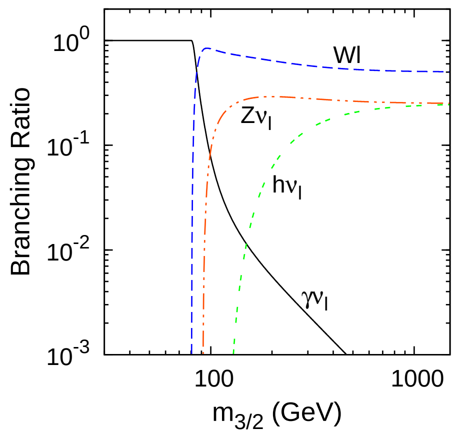


Figure 1: Gravitino branching ratios for the two-body decays.

- Then, for instance, the gravitino decay width into Z^0 and ν_l is given by:

$$\Gamma\left(\psi_{3/2} \to Z^0 \nu_l\right) \simeq \frac{\xi_l^2}{64\pi} \frac{m_{3/2}^3}{M_{\text{Pl}}^2} \beta_Z^2 \left\{ U_{\tilde{Z}\tilde{Z}}^2 f_Z - \frac{8}{3} \frac{m_Z}{m_{3/2}} U_{\tilde{Z}\tilde{Z}} j_Z + \frac{1}{6} h_Z \right\},$$

$$\xi_l = \frac{\langle \tilde{\nu}_l \rangle}{v}, \; \beta_Z = 1 - \frac{m_Z^2}{m_{3/2}^2}, \; U_{\tilde{Z}\tilde{Z}} = m_Z \sum_{\alpha=1}^{4} \frac{S_{\tilde{Z}\alpha}^* S_{\alpha\tilde{Z}}}{m_{\tilde{\chi}_\alpha^0}},$$

$$f_Z = 1 + \frac{2}{3} \frac{m_Z^2}{m_{3/2}^2} + \frac{1}{3} \frac{m_Z^4}{m_{3/2}^4}, \; j_Z = 1 + \frac{1}{2} \frac{m_Z^2}{m_{3/2}^2}, \; h_Z = 1 + 10 \frac{m_Z^2}{m_{3/2}^2} + \frac{m_Z^4}{m_{3/2}^4}.$$

- The branching ratios are independent of the sneutrino VEV in contrast to the total decay width.

- In the phenomenological studies the lifetime ($\tau_{3/2} = 1/\Gamma_{3/2}$) and the mass are unknown parameters.

- Most of the two-body decay products are unstable. The lepton l subsequently decays (if $l = \mu$, τ) and the Z^0, $W^\pm$ and h bosons fragment into stable particles:

$$\gamma, \quad \nu_i, \quad e^-, \quad e^+, \quad p, \quad \bar{p}.$$

- The spectra of γ, ν_i and $e^\mp$ (if $l = e$) contain a peak from the two-body decay and all spectra have a continuum contribution from fragmentation.

4 Fluxes from Gravitino Dark Matter Decay

- If the gravitino accounts for the dark matter, its decays produce an astrophysical flux of decay products.

$$\frac{dJ}{dE} \equiv \frac{dN}{dE\, dA\, dt\, d\Omega}$$

- The differential flux from a volume element in the galactic halo is given by ($\vec{l} = (s, b, l)$ are galactic coordinates):

$$\frac{dJ(\vec{l})}{dE} = \frac{n_{3/2}(\vec{l})}{4\pi\, s^2\, \tau_{3/2}} \frac{dN}{dE}\, s^2 \cos b\, ds\, db\, dl\, .$$

- In contrast to charged particles (see Christoph's talk) gamma rays and neutrinos propagate freely over cosmic distances (neutrino oscillations distribute the signal equally into all flavors). Thus the differential flux is simply given by the line-of-sight integral

$$\frac{dJ_{\text{halo}}(b,l)}{dE} = \frac{1}{4\pi\, \tau_{3/2}\, m_{3/2}} \frac{dN}{dE} \int_{\text{line of sight}} \varrho_{\text{halo}}(\vec{l})\, ds\, .$$

- There is a second, subdominant contribution from the cosmic dark matter density:

$$\frac{dJ_{\text{eg}}}{dE} = \frac{\Omega_{3/2}\, \varrho_c}{4\pi\, \tau_{3/2}\, m_{3/2} H_0 \Omega_m^{1/2}} \int_0^\infty \frac{dN}{d(E\,(1+z))} \frac{(1+z)^{-3/2} dz}{\sqrt{1 + \Omega_\Lambda/\Omega_m\,(1+z)^{-3}}}\, .$$

- In the case of WIMP annihilation the halo flux reads

$$\frac{dJ_{\text{halo}}(b,l)}{dE} = \frac{\langle \sigma v \rangle}{8\pi\, m_{DM}^2} \frac{dN}{dE} \int_{\text{line of sight}} \varrho_{\text{halo}}^2(\vec{l})\, ds\, .$$

- Due to the n_{DM}^2 dependence the signal from annihilating dark matter is much more sensitive to the dark matter distribution in the halo and in particular to the inner slope of the halo profile.

- In that case one expects a dominant signal from the galactic center and also neutrino signals from the annihilation of WIMPs that accumulate inside the Sun and the Earth.

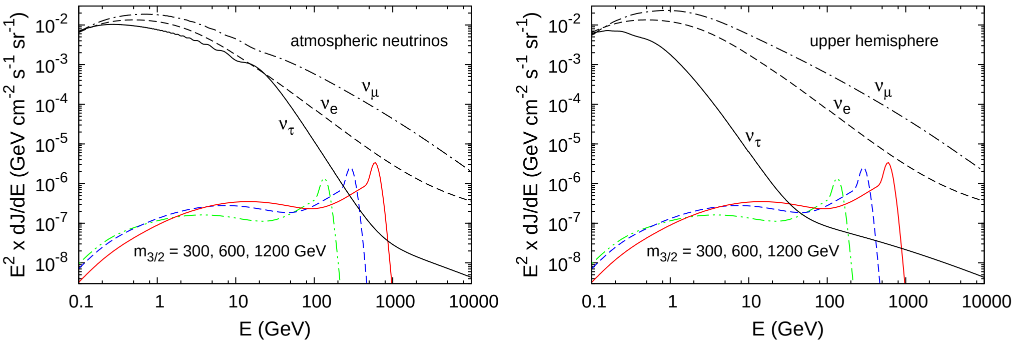


Figure 2: Neutrino flux from gravitino decay compared to the atmospheric background for the complete sky (left) and for the upper hemisphere (right).

- For decaying gravitinos on the other hand the best strategy is to look for a diffuse signal in gamma rays and neutrinos.
- Therefore in the following we use the averaged halo flux:

$$\frac{dJ_{\text{halo}}}{dE} = \frac{1}{4\pi} \int_0^{2\pi} dl \int_{-\pi/2}^{\pi/2} \frac{dJ_{\text{halo}}(b,l)}{dE} \cos b \, db \, .$$

5 Neutrino Observation

- There are three important questions:
  - How large is the neutrino flux from gravitino decay compared to background fluxes?
  - How large are the expected neutrino event rates?
  - What is the detection efficiency of neutrino experiments?
- We choose the gravitino mass and lifetime to account for the rise of the positron flux in the PAMELA data:

$$m_{3/2} = 300\,,\ 600\,,\ 1200\,\text{GeV} \qquad \text{and} \qquad \tau_{3/2} = \mathcal{O}(10^{26})\,\text{s}\,.$$

- The main background in the GeV to TeV range are atmospheric neutrinos. Interactions of cosmic rays with the atmosphere produce mainly pions and kaons which subsequently decay into muon and electron neutrinos besides other particles.

- ∘ The dominant tau neutrino background comes from the conversion of atmospheric muon neutrinos due to neutrino oscillations.
- ∘ This tau neutrino background can be reduced significantly if only the upper hemisphere is considered.
- ∘ Generally the signal-to-background ratio increases for increasing gravitino mass. However, only in the tau flavor the signal from gravitino decay exceeds the background.
- ∘ It might be possible to extract the muon and electron neutrino signals if large statistics is available.

- ∘ Since the fluxes are very small km^3 detectors are necessary in order to obtain considerable event rates.
- ∘ The νN cross section is proportional to the neutrino energy. This effect compensates the $1/m_{3/2}$ behavior of the neutrino flux from gravitino decay.

- ∘ Cherenkov detectors like IceCube have virtually no efficiency to detect shower events (i.e. ν_e and ν_τ) at sub-TeV energies.
- ∘ By contrast charged current interactions of ν_μ produce a muon that leaves a clear signal in the detector.
- ∘ The effective detector volume for muon neutrinos increases by the fact that the muon can penetrate several kilometers of surrounding material before it reaches the detector. This muon range increases with the muon energy.
- ∘ The neutrino event rate is given by the convolution of the flux with the neutrino effective area:

$$\frac{dN}{dt} \sim \Delta\Omega \int \frac{dJ}{dE} \, A_{\text{eff}}(E) \, dE \, .$$

- ∘ The neutrino effective area encodes all effects of neutrino attenuation from the passage through Earth, the νN cross section, the muon range and the detection and selection efficiencies.
- ∘ Using the effective area of the completed IceCube experiment, we expect $\mathcal{O}(10 - 1000)$ events from gravitino decay per year.

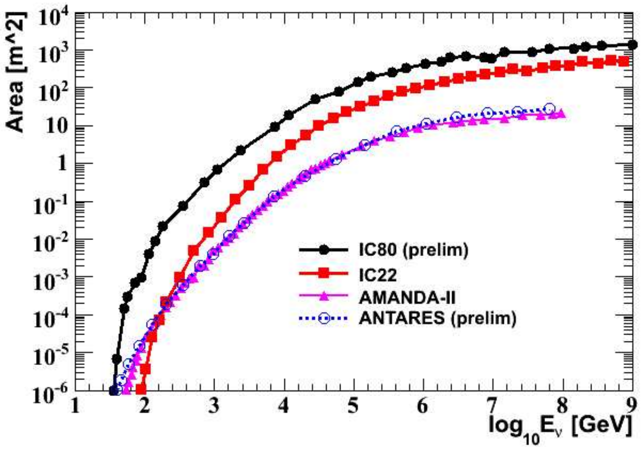


Figure 3: Neutrino effective areas of present neutrino telescopes. Figure taken from [5].

- ◦ This number has to be compared to an expected atmospheric muon neutrino background of $\mathcal{O}(10^5)$ events per year.
- ◦ Still it seems possible to achieve a statistic significance of $S/\sqrt{B} \sim \mathcal{O}(1)$ in one year depending on the gravitino mass and lifetime.

6 Signals from Gamma Rays and Antimatter

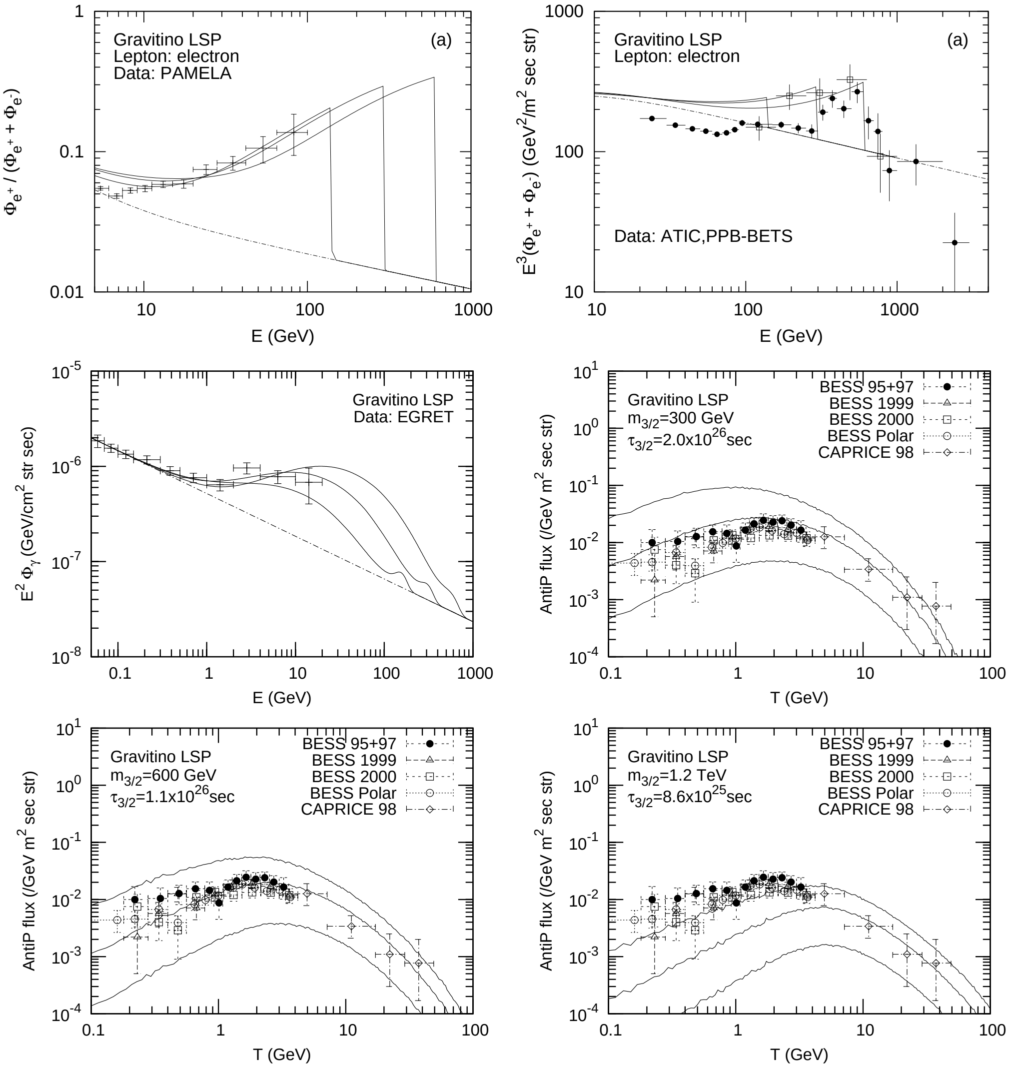


Figure 4: Signals in other particle species from gravitino dark matter decay. From top left to bottom right: Positron fraction (MED propagation parameters), electron + positron flux (MED propagation parameters), gamma ray flux, antiproton flux (300, 600, 1200 GeV). Figures taken from [6].