MSSM and Gravitino Dark Matter in view of PAMELA and Fermi-LAT

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Based on arXiv:1002.3631,
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Outline

- Experiments and Motivations
- MSSM as a complete theory for

    i. Gravitino Dark Matter,

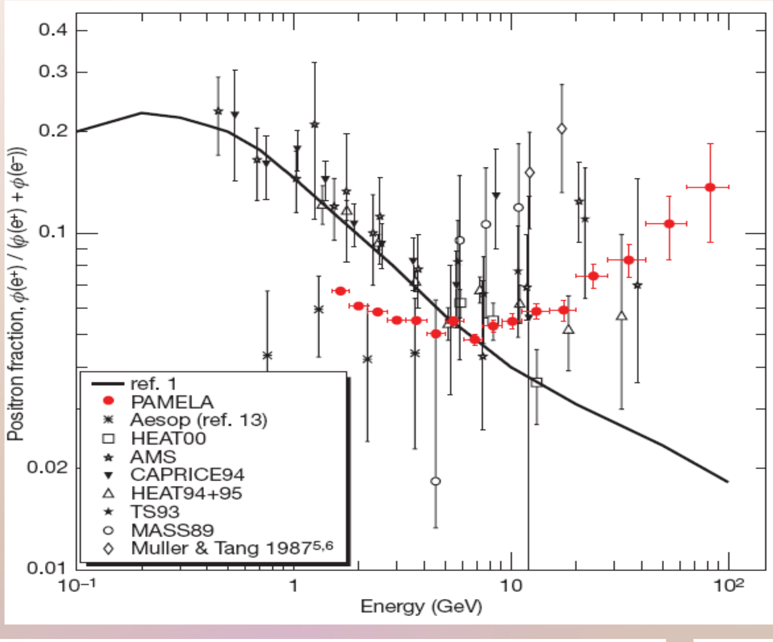
    ii. Neutrino Mass,

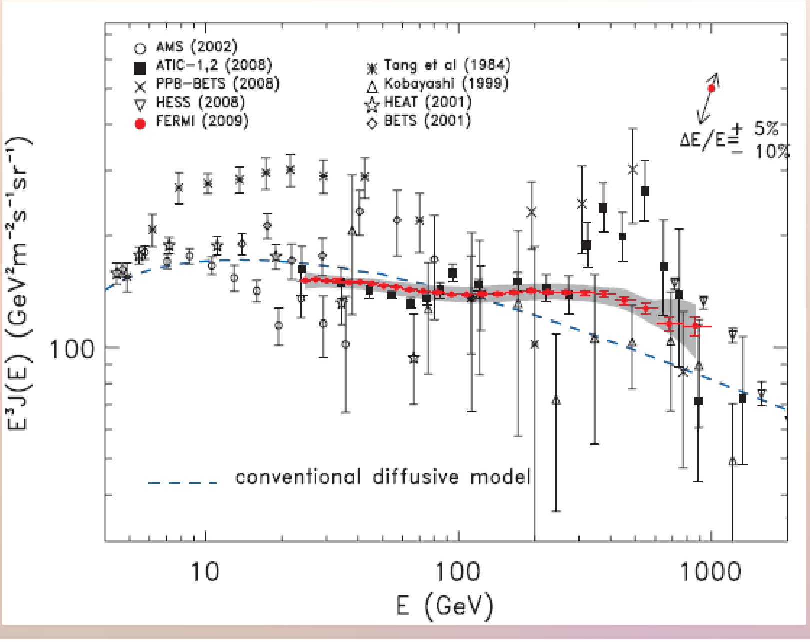
    iii. consequences:
- The fate of slepton/squark masses.
- Sketch of possible LHC signatures, comment on flavor violations, baryogenesis.
- Conclusion and Outlook

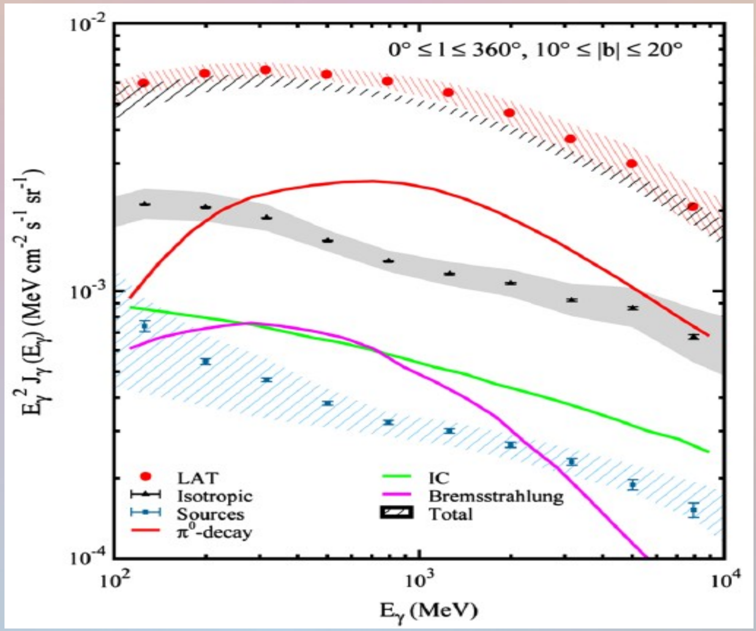
Indirect Detections of Dark Matter

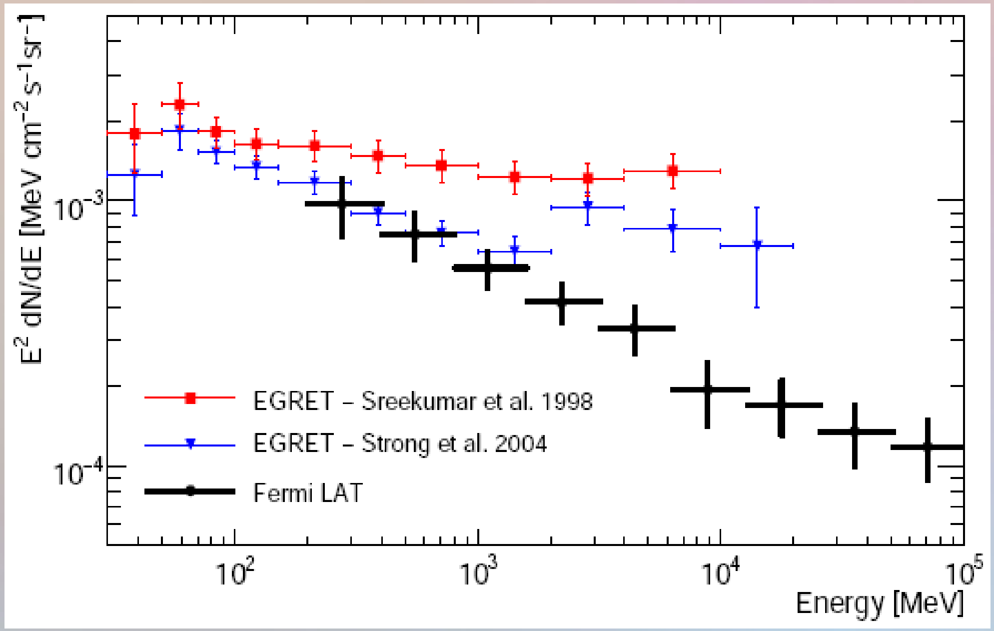
- Cosmic ray e^+ Excess without $\bar{p}$
  - PAMELA, ATIC, Fermi, HESS, HEAT, etc
- Possible astrophysical origins: pulsars, supernovae remnants, etc
- The existence of dark matter is well established by WMAP.
- It is extremely interesting if due to dark matter oringins.
- More correlated observations:
- Cosmic gamma-ray observations
  - γ from bremsstralung, prompt decay (π^0), inverse-Compton scattering, etc
- High-energy neutrino flux
  - dark matter annihilate/decay in the galaxy
  - from the core of the sun

Some Recent Experiments









The Nature of Dark Matter Candidates

- Long-lived, weakly interacting, non-baryonic, cold.
- Leptophilic (dynamics or kinematics)
- Annihilating DM: thermal freeze out (pb), need boost to PAMELA (nb); light force carrier or non-thermal produced
- Decaying DM: e.g. gravitino: produced via R-parity con-serving process, decay via RPV;
- Longevity ($\tau \sim 10^{26}$ s equivalent to $n\sigma v \sim$ nb)
  - Gravitino decays via supergravity and RPV interactions $\Gamma \sim \lambda^2 m^7/(8\pi M_{pl}^2 M_{susy}^4)$
  - Also possible via GUT interaction, dimension 6 operator $\Gamma \sim m^5/(8\pi M_{gut}^4)$

The Dark Matter Candidate in MSSM

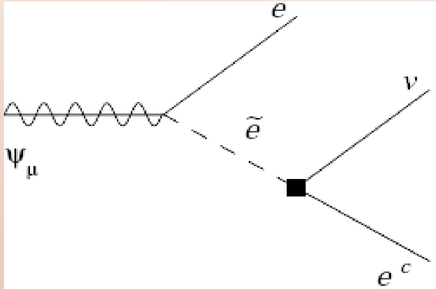
- Take MSSM as a complete theory for dark matter and neutrino mass, then R-parity must be violated.
- Neutralino will simply decays too fast, cannot be DM.
- Gravitino decays slowly, is the only candidate.
- Production: from other sparticle decays after inflation
- $$\Omega_{3/2}h^2 \approx 0.27 \left(\frac{T_R}{10^{10}\ \mathrm{GeV}}\right)\left(\frac{100\ \mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\ \mathrm{TeV}}\right)^2$$
- NLSP late decay problem, cured by R-parity violation. Decay to SM: can leave distinct signatures visible at LHC
- Source of RPV: λ" break baryon number, μ' leads gravitino to decay to gauge bosons, need to be suppressed.

$$W_{\not R} = \frac{1}{2}\lambda L L e^c + \lambda' Q L d^c + \frac{1}{2}\lambda'' u^c d^c d^c + \mu' L H_u$$

Gravitino Decays I

- Tree-level three-body decay:

$$\Gamma_3(\psi_\mu \to \ell^+\ell^-\nu) = \frac{\lambda^2}{18432\pi^3}\frac{m_{3/2}^4}{m_{\tilde{\ell}}^4}\frac{m_{3/2}^3}{M_{\rm Pl}^2}$$



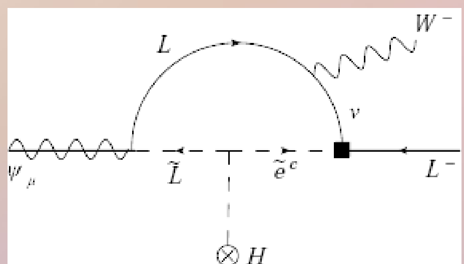
- Generally, to fit PAMELA&Fermi, need $10^{-51} < \Gamma_3 < 10^{-49}$ gives an upper bound on slepton mass

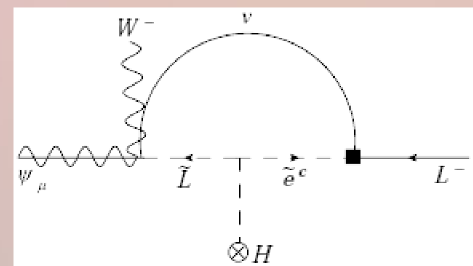
$$m_{\tilde{\ell}} \lesssim 10^4\,\mathrm{TeV}\left(\frac{\lambda_{\rm max}^2}{4\pi}\right)^{1/4}\left(\frac{m_{3/2}}{400\,\mathrm{GeV}}\right)^{7/4}\left(\frac{\Gamma_3}{10^{-51}\mathrm{GeV}}\right)^{-1/4}$$

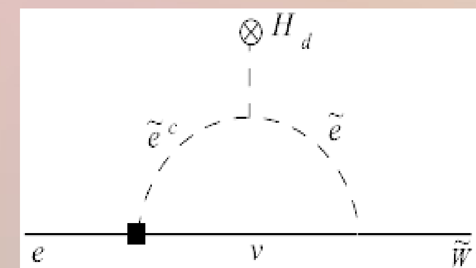
- Two-body decay, absence of μ' forbids tree level decay
  - Effective operator analysis:
  - Dimension 5 operator: $\overline{\psi}_\mu\gamma^\nu\gamma^\mu(D_\nu L)H$ (supercurrent-like)
  - Dimension 6 operator: $\overline{\psi}_\mu\sigma^{\mu\nu}LW_{\mu\nu}H$, gauge invariance need the Higgs field.

Gravitino Decays II

- In SUSY limit, Kahler and supercurrent are diagonalized simultaneously, eliminate the d=5 operator, hold when SUSY breaking are included by using spurion argument.
- Finite contribute to d=6 operators







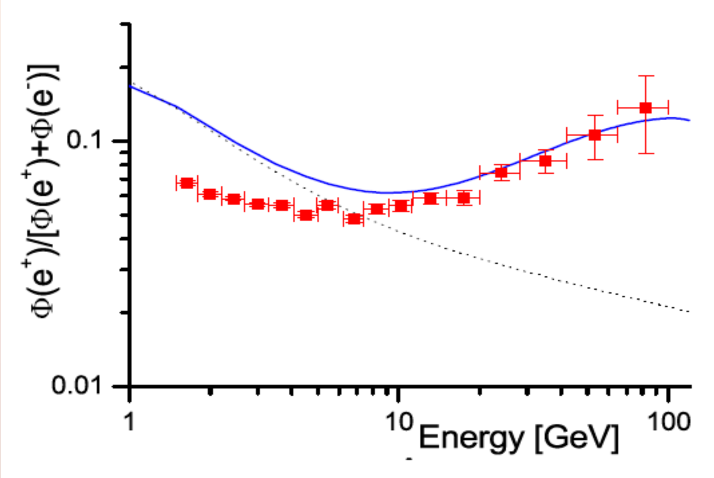
- Two-body decay Rate: $\Gamma_2(\psi_\mu \to W^\pm \ell^\mp) \simeq \frac{g^2\lambda^2}{18432\pi^5}\frac{(m^2_{\tilde{\ell}})^2_{LR}}{m^4_{\tilde{\ell}}}\frac{m^3_{3/2}}{M^2_{\rm Pl}}$
- Gauge boson will lead to antiprotons, suppress 2-body decay compared with 3-body by an order of magnitude.
- This leads to $(m^2_{\tilde{\ell}})_{LR} \lesssim m^2_{3/2}$

Fitting the Positron Excesses

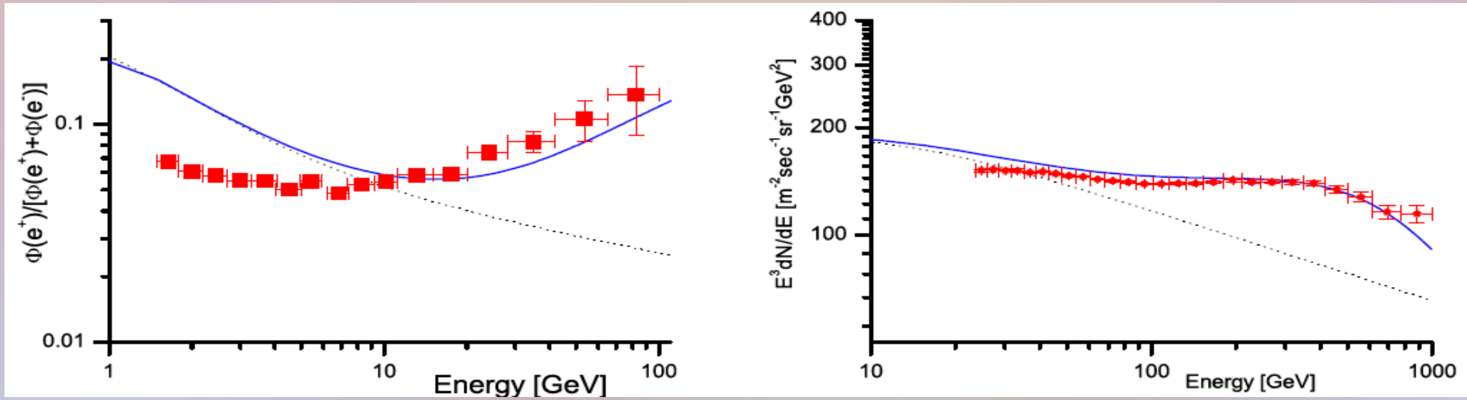
- Fitting PAMELA only, take gravitino mass 400 GeV, only fix the ratio

  $$m^2_{\tilde{\ell}}/\lambda \simeq 1.3 \times 10^7\ \mathrm{TeV}^2$$

  get lifetime: $\tau_{3/2} = 2.3 \times 10^{26}\ \mathrm{sec}$



- To Fit both PAMELA and Fermi, heavier gravitino 3.3 TeV, and $m^2_{\tilde{\ell}}/\lambda \simeq 10^{10}\ \mathrm{TeV}^2$, get $\tau_{3/2} = 5 \times 10^{25}\mathrm{sec}$

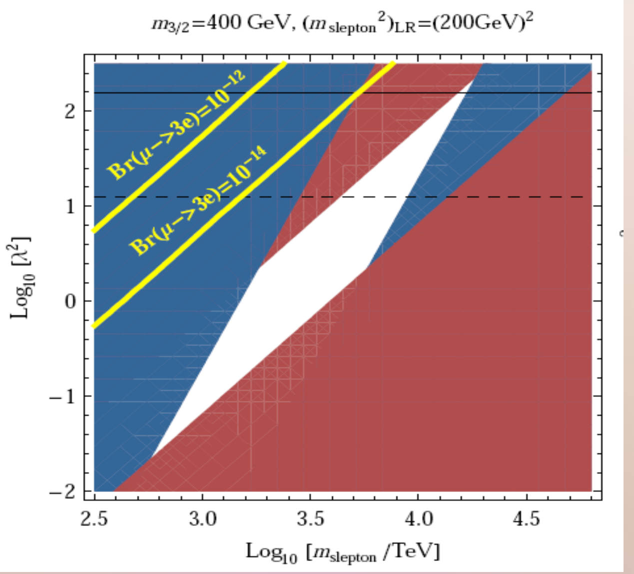


- Up to here, has no prediction on the spectrum yet.

Both PAMELA and Neutrino Mass

- If neutrino mass (0.1eV) is generated by the same λ element

$$m_\nu \simeq \frac{\lambda^2 (m^2_{\tilde{\ell}})_{LR} m_\tau}{16\pi^2 m^2_{\tilde{\ell}}}$$



- A *Huge* lower bound on the slepton mass

$$m_{\tilde{\ell}} \gtrsim 500\ \text{TeV} \left(\frac{m_{3/2}}{400\ \text{GeV}}\right)^{5/2} \left(\frac{M_\nu}{0.1\text{eV}}\right)^{1/2} \left(\frac{\Gamma_3}{10^{-49}\text{GeV}}\right)^{-1/2}$$

(Bajc, Enkhbat, Ghosh, Senjanovic, YZ, 2010)

- To explain Fermi, need heavier gravitino, larger lower bound.
- λ can be large as long as sleptons are heavy, do not upset low-energy constraints
- Also and upper bound on gravitino mass

$$\left(\frac{m_{3/2}}{3\,\text{TeV}}\right) \left[0.5 + 0.5\left(\frac{m_{3/2}}{3\,\text{TeV}}\right)^2\right]^{1/4} \lesssim \left(\frac{\lambda^2}{4\pi}\right)^{1/3} \left(\frac{\Gamma_3}{10^{-49}\text{GeV}}\right)^{1/3} \left(\frac{m_\nu}{0.1\text{eV}}\right)^{-2/3}$$

Towards the general case

- Need heavy slepton to explain PAMEA and neutrino mass:

  (i) not overproduce e+ or p: $\Gamma_3 \sim \lambda^2/m^4$,

  (ii) large enough contribution to $m_\nu \sim \lambda^2/m^2$.
- Assumptions made so far:

  (i) $M_L^2 = M_R^2$: if not, same bound for the lighter guy.

  (ii) Single λ/slepton contribution,
- For 3 famlies, if tune down all λ_{ijk} for given i, then slepton i can be < TeV, if the ratio λ/m^2 is not enhanced;
- This is fine-tuning since slepton mass and λ are not related.
- All sleptons are heavy barring fine-tunings.
- Squarks can be light: depends on contribution to m_ν via λ'.

Sketch of NLSP signatures at LHC

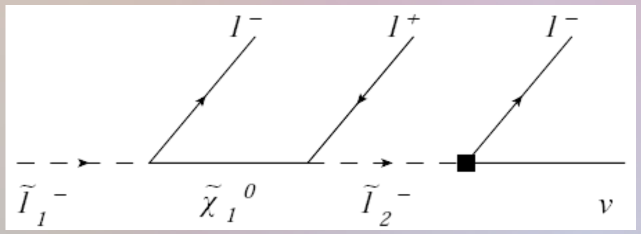
- To discover SUSY at LHC, take $m_{3/2}$ <500 GeV, enough for PAMELA; leave Fermi to other origins, e.g. astrophysical.
- Gaugino as NLSP: $\tilde{\chi}_1^0 \to \ell^+ \ell^- \nu$ $\tau_{\rm NLSP}^{\tilde{\chi}_1^0} \simeq 10^{-7}{\rm sec} \left(\frac{m_{\rm NLSP}}{600\ {\rm GeV}}\right)^{-5}$

  (*decay in the detector,* T. Moroi et al, 2008)
- Slepton as NLSP: depending on λ (*displaced vertex*)

$$\Gamma_{\rm NLSP}(\tilde{\ell}_1 \to \ell_j \ell_k) = \frac{\lambda_1^2 m_{\rm NLSP}}{8\pi} \lesssim 6 \times 10^{-13}\,{\rm GeV} \left(\frac{m_{\rm NLSP}}{600\ {\rm GeV}}\right)^5 \left(\frac{m_{3/2}}{400\ {\rm GeV}}\right)^{-7}$$

- If λ_1=0, four-body decay (*outside the detector*)

$$\tau_{\rm NLSP}^{\tilde{\ell}_1} \simeq 10^{-3}{\rm sec} \left(\frac{m_{\rm NLSP}}{600\ {\rm GeV}}\right)^{-7} \left(\frac{m_{\tilde{\chi}_1}}{1\ {\rm TeV}}\right)^2$$



- Gluino LSP, decay very slowly (*missing energy*)
  Lifetime even as long as the BBN time scale $\lambda' > 10^{-11}$

Flavor violation and Baryogenesis

- LFV has two contributions
  - RPV contribution, proportional to m_ν^2, always supressed even if one slepton is tuned to TeV scale.
  - Usual SUSY loop contribution cannot be supressed if a slepton is light (fine-tuned case).
- Squark mass not necessarily heavy, so QFV is not solved.
- If unification, all sfermions in a family as heavy–split SUSY
- Baryogenesis: Heavy gravitino mass rules out electroweak baryogenesis; Lage λ washes any primordial lepton number,
  - Afflect-Dine baryogenesis is one viable candidate. (Enqvist and McDonald, 1998)

Conclusion and Outlook

- We take MSSM seriously, as a complete theory for dark matter, neutrino mass, without ad hoc extensions.
- PAMELA and Fermi e^+ Excess can be explained by gravitino dark matter (the only candidate) decay.
- The main conclusion: Slepton has to be heavy to explain both PAMELA and neutrino mass. RPV coupling λ can be order 1. Heavy sleptons delay the NLSP decay.
- Distinct NLSP singatures at LHC,
- Fermi-LAT gamma-ray: able to reveal RPV structure:
  - Constraining from γ-rays on different flavor structures in $l_i^+ l_j^- \nu$ final state.

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Thanks!