MSSM AFTER PAMELA AND FERMI/LAT

Borut Bajc

J. Stefan Institute, Ljubljana, Slovenia

BB, Enkhbat, Ghosh, Senjanović, Zhang, 10

Outline

- Introduction
- Dark matter in MSSM (the old paradigm)
- Dark matter after PAMELA and Fermi/LAT
- Neutrino mass in MSSM
- Who is the dark matter in MSSM?
- Constraints for MSSM parameters
- Tests/consequences of gravitino DM
- Conclusion

Introduction

The SM very successful, except for two things (right now)

- dark matter (DM)
- neutrino masses

Some physics beyond the SM thus needed

A very appealing candidate is the Minimal Supersymmetric Standard Model (MSSM):

- resolves (or better, stabilizes) the hierarchy problem

$$m_H^2 \approx m_{H,0}^2 + \frac{\alpha}{4\pi} m_{SUSY}^2$$

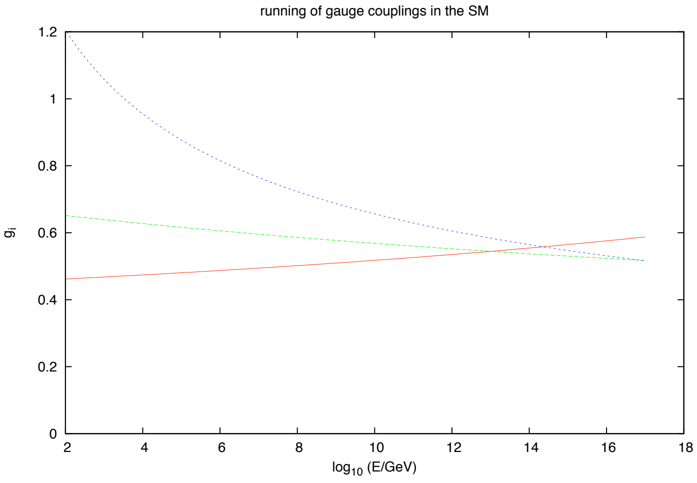
SUSY does not automatically give (the doublet-triplet problem)

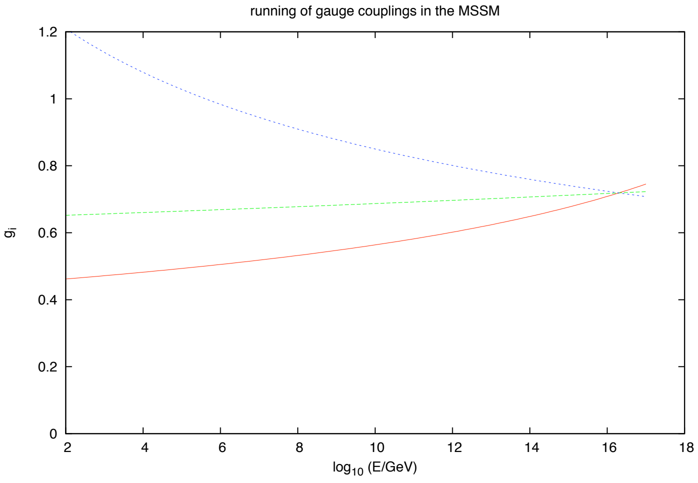
$$m_{H,0}^2 \approx m_H^2$$

but once this is done the correction is small providing

$$m_{SUSY}^2 \approx m_{H,0}^2$$

- it improves the running of the gauge couplings to reach a one-step unification





- in many of its versions it has a DM candidate

  (to be considered soon)

- in some of its versions it can accomodate nonzero neutrino masses

  (to be considered soon)

Dark matter in MSSM (the old paradigm)

Dark matter must

- live enough to be seen today as almost stable

$$\tau_{DM} > \text{life of the universe}$$

- have the right density for

$$m_{DM} n_{DM} \approx 5\ \rho_{visible}$$

In the MSSM that means that

- have a relatively good approximate R-parity $\Longrightarrow$ the lightest supersymmetric partner (LSP) relatively long-lived
- two candidates: neutralino (mixture of neutral higgsinos and neutral wino and bino) and gravitino

Dark matter after PAMELA and Fermi/LAT

What is PAMELA?

- it is a satellite based experiment, measuring and distinguishing electrons, positrons, protons, antiprotons
- it was believed we knew and understood the abundance of these particles in cosmic rays
- it was a surprise to find out an increase of the measured positron to electron fluxes ratio: it started at $\approx$ 10 GeV and became 10× bigger than the expected theoretical background at $\approx$ 100 GeV
- NO such increase was found in the antiproton vs proton fluxes

What is Fermi/LAT?

- Fermi is recently launched Gamma-Ray Space Telescope
- LAT stands for its main detector, the Large Area Telescope
- It was originally designed to measure gamma rays, but it can probe also electrons/positrons up to 1 TeV.
- it was found that the electron + positron flux is larger than the theoretical expectations in the region

  50 GeV $\lesssim E \lesssim$ 1 TeV (with a factor up to ≈ 2)

There are some candidates for describing these discrepancies with astrophysics (for example pulsars), but nothing conclusive

Let us assume that it is particle physics that explains the DM and its decay explains PAMELA and/or Fermi/LAT

Two main consequences follow from here

- the DM candidate should be heavy enough:

$$m_{DM} \gtrsim \text{ few hundred GeV} \qquad \text{(from PAMELA)}$$

$$m_{DM} \gtrsim \text{ few TeV} \qquad \text{(from Fermi/LAT)}$$

- the interaction that makes the DM candidate decay must be leptophilic
-

$$\Gamma_{DM} \approx 10^{-50} \text{ GeV} \qquad (\tau_{DM} \approx 10^{26} \ s)$$

Neutrino mass in MSSM

There is no way to describe neutrino mass using only the d.o.f. of the renormalizable standard model.

Always possible to write down the $d = 5$ Weinberg operator

$$\mathcal{L} = Y_{ij} \frac{L_i H H L_j}{M}$$

After $\langle H \rangle = v$ one gets the mass

$$m_\nu = Y \frac{v^2}{M}$$

This not very useful: it tells us that new degrees if freedom at the scale M have been integrated out. This term is a remnant of the UV completion.

Can we describe the neutrino mass in MSSM without any new physics in the UV?

Yes, enough to break the lepton number (i.e. R-parity). In general R-parity violating couplings are

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

λ, λ', μ' break lepton number

λ'' break baryon number

Experimental constraints:

- proton decay

$$\lambda'\lambda'' \lesssim 10^{-27} \left(\frac{m_{\tilde{d}}}{300\mathrm{GeV}}\right)^2$$

Smirnov, Vissani, 96

- neutron-antineutron oscillation

$$\lambda'' \lesssim (10^{-7} - 10^{-8}) \left(\frac{m_{\tilde{d}}}{100\mathrm{GeV}}\right)^2 \left(\frac{m_{\tilde{\chi}^0}}{100\mathrm{GeV}}\right)^{1/2}$$

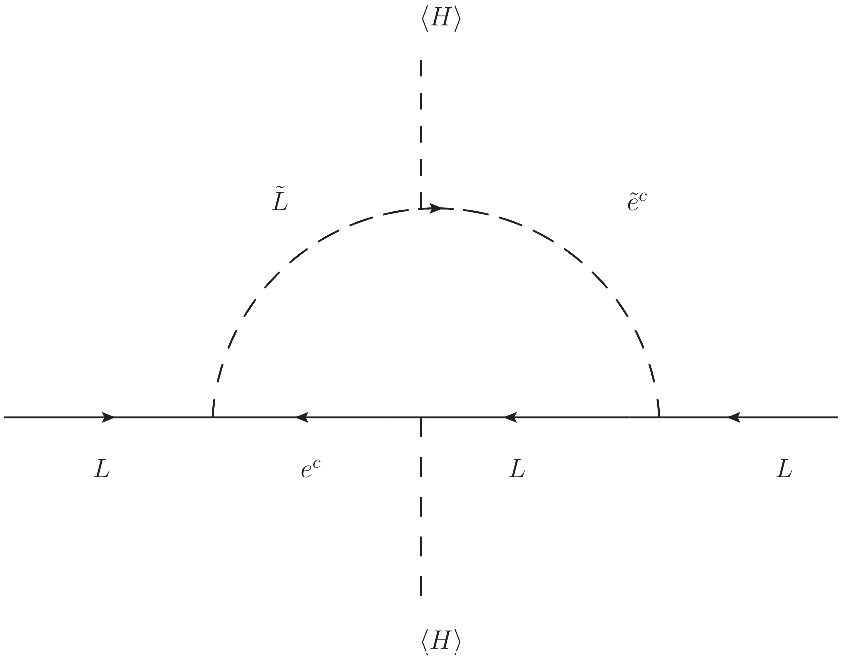
Zwirner, 83

Dimopoulos, Hall, 87

Hinchliffe, Kaeding, 93

Babu Mohapatra, 01

All we need is a small enough λ''. Assuming for example $\lambda \neq 0$:

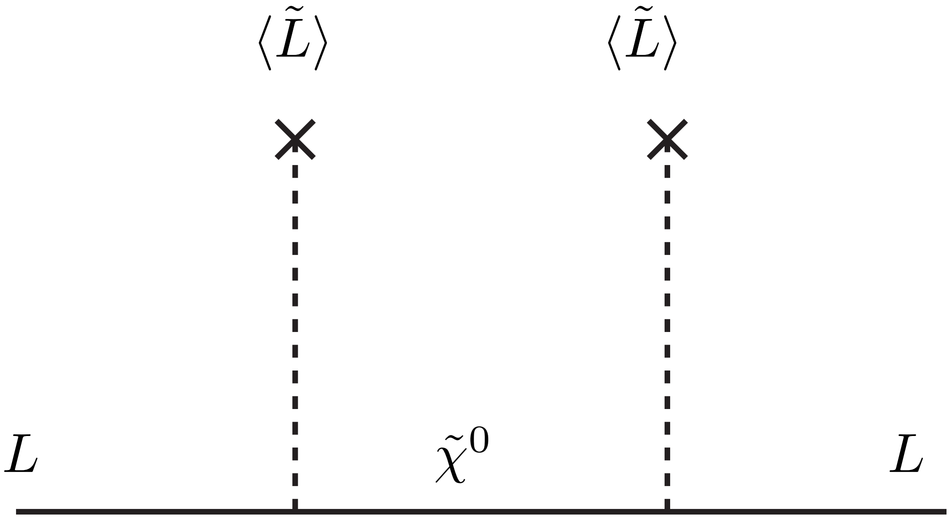


$$m_\nu \simeq \frac{\lambda^2 (m^2_{\tilde{\ell}})_{LR} m_\tau}{16\pi^2 m^2_{\tilde{\ell}}} \qquad (m^2_{\tilde{\ell}})_{LR} = A_\ell v_d - \mu^* y_\tau v_u$$

Similar result for internal quarks and squarks with

- $\lambda \to \lambda'$
- extra factor 3 $(= N_C)$

Last possibility is the tree order contribution due to $\langle\tilde{\nu}\rangle \neq 0$ vev:



$$m_\nu \simeq \frac{g^2\langle\tilde{\nu}\rangle^2}{m_{\tilde{\chi}_0}}$$

Notice that $\langle\tilde{\nu}\rangle \propto \mu'$

Who is the dark matter in MSSM?

$\cancel{R}$ couplings $\neq 0$

$\Longrightarrow$ neutralinos decay too fast

$\Longrightarrow$ gravitino the only DM candidate (decay suppressed by $1/M_{Pl}$)

$$\mathcal{L} \quad = \quad -\frac{1}{\sqrt{2}M_{\rm Pl}}\left[\bar{\chi}_L\gamma^\mu\gamma^\nu D_\nu\phi - \frac{i}{4\sqrt{2}}\bar{\lambda}^a\gamma^\mu\sigma^{\nu\rho}F^a_{\nu\rho}\right]\psi_\mu + \text{h.c.}$$

$\psi_\mu \ldots$ gravitino

$(\chi_L, \phi) \ldots$ chiral multiplet

$(\lambda^a, F^a_{\mu\nu}) \ldots$ vector multiplet

Which are the gravitino decay modes? Depending on its mass

- 2-body decay modes:

$$\psi_\mu \to W\ell$$
$$\psi_\mu \to Z\nu$$
$$\psi_\mu \to \gamma\nu$$
$$\psi_\mu \to H^0\nu$$
$$\ldots$$

- 3-body decay modes

$$\psi_\mu \to \ell^+\ell'^-\nu \qquad \Longleftarrow \text{ MUST DOMINATE!}$$
$$\psi_\mu \to q\bar{q}'\ell/\nu$$
$$\ldots$$

Constraints for MSSM parameters

Nothing original in considering gravitino DM candidate to explain PAMELA and/or Fermi/LAT. Many different works so far:

Takayama , Yamaguchi, 00

Covi, Grefe, Ibarra, Tran, 09

Hamaguchi, Takahashi, Yanagida, 09

Chen, Mohapatra, Nussinov, Zhang, 09

Ishiwata, Matsumoto, Moroi, 09

Buchmuller, Ibarra, Shindou, Takayama, Tran, 09

Bomark, Lola, Osland, Raklev, 09

What is new here is describing at the same time neutrino mass and DM data.

$\psi_\mu \to \ell^+ \ell'^- \nu$ main decay mode

- $\Gamma_2(\psi_\mu) \ll \Gamma_3(\psi_\mu)$ (2-body less than 3-body)
- $\lambda' \ll \lambda$ (3-body with quarks less than 3-body with leptons)

Since $\Gamma_2(\psi_\mu \to \nu\gamma) \propto \mu'^2$, among $\not{R}$ parameters λ, λ', μ'

$\Longrightarrow$ only λ important

Constraints we will take:

$$\begin{aligned}
0.03\,\mathrm{eV} \lesssim m_\nu \lesssim 0.3\,\mathrm{eV} &\qquad (\nu\,\mathrm{mass})\\
10^{-51}\,\mathrm{GeV} \lesssim \Gamma_3 \lesssim 10^{-49}\,\mathrm{GeV} &\qquad (\mathrm{PAMELA/Fermi\text{-}LAT})\\
\Gamma_2 \lesssim \Gamma_3/10 &\qquad (\mathrm{leptophilic\,DM})\\
\lambda^2 \lesssim 4\pi &\qquad (\mathrm{perturbativity\,bound})
\end{aligned}$$

What do they mean for the MSSM parameters?

$$
\begin{aligned}
m_\nu &\simeq 10^{-2}\lambda^2\frac{(m^2_{\tilde{\ell}})_{LR}m_\tau}{m^2_{\tilde{\ell}}} \\
\Gamma_2 &\simeq 10^{-7}\lambda^2\frac{(m^2_{\tilde{\ell}})^2_{LR}}{m^4_{\tilde{\ell}}}\frac{m^3_{3/2}}{M^2_{\mathrm{Pl}}} \\
\Gamma_3 &\simeq 10^{-6}\lambda^2\frac{m^4_{3/2}}{m^4_{\tilde{\ell}}}\frac{m^3_{3/2}}{M^2_{\mathrm{Pl}}}
\end{aligned}
$$

From these tree level (Γ_3) and 1-loop (Γ_2, m_ν) expressions and previous constraints some inequalities follow

From m_ν, Γ_2, Γ_3 and $\Gamma_2 < \Gamma_3/10$ $\Longrightarrow$lower bound on slepton mass:

$$m_{\tilde\ell} \gtrsim 600\,\mathrm{TeV}\left(\frac{m_{3/2}}{400\,\mathrm{GeV}}\right)^{5/2}\left(\frac{m_\nu}{0.1\mathrm{eV}}\right)^{1/2}\left(\frac{\Gamma_3}{10^{-49}\mathrm{GeV}}\right)^{-1/2}$$

From Γ_3 and $\lambda^2 < 4\pi$ $\Longrightarrow$ upper bound on slepton mass:

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

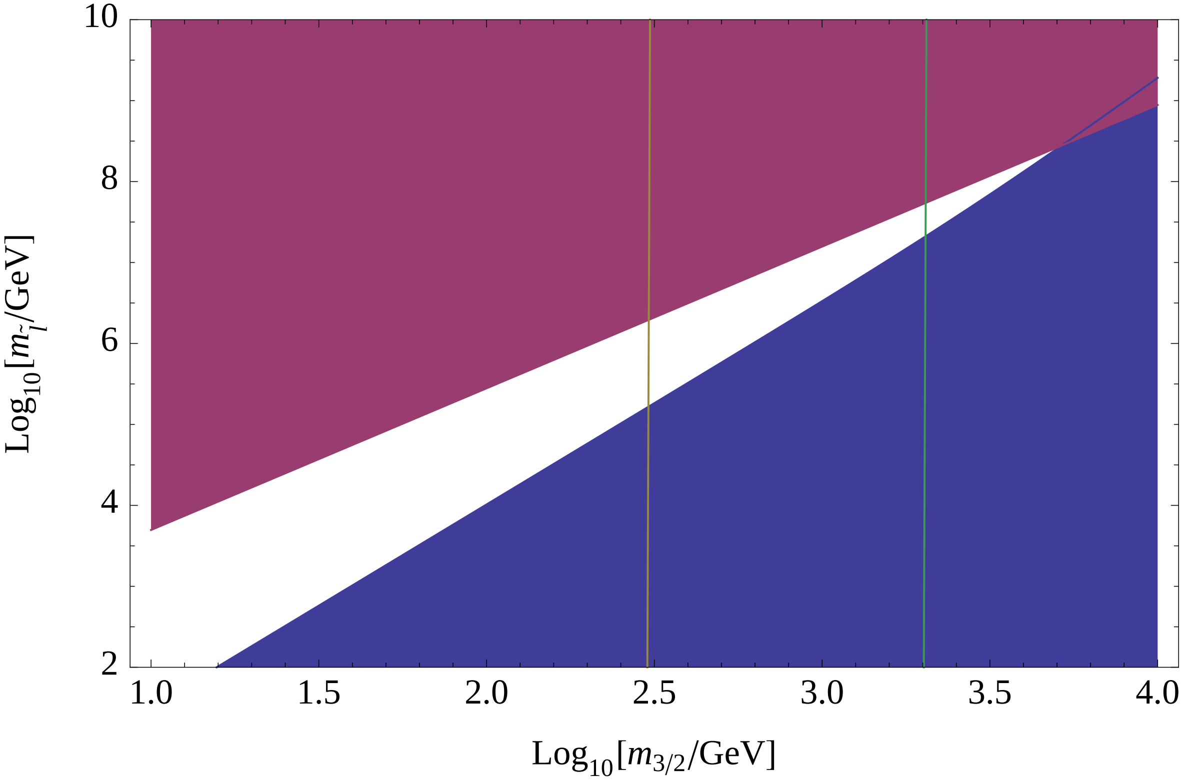
From m_ν, Γ_2 and $(\Gamma_2 < \Gamma_3/10)$ + $(\lambda^2 < 4\pi)$ + $(m_\nu > 0.03\ \mathrm{eV}) \Longrightarrow$ upper bound on gravitino mass:

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

For $\lambda^2 = 4\pi$, $\Gamma_3 = 10^{-49}$ GeV, $m_\nu = 0.03$ eV:

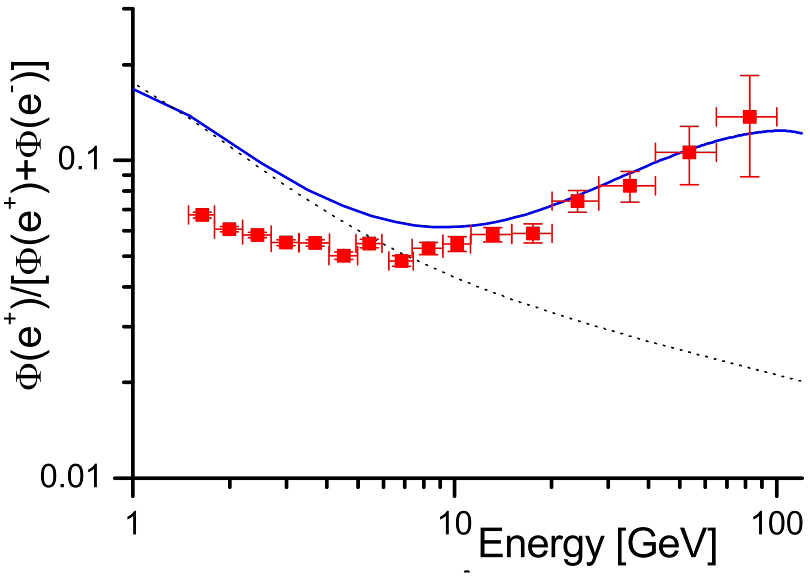
$$m_{3/2} \lesssim 5\mathrm{TeV}$$

(PAMELA: $m_{3/2} \gtrsim 300$ GeV Fermi/LAT: $m_{3/2} \gtrsim 2$ TeV)

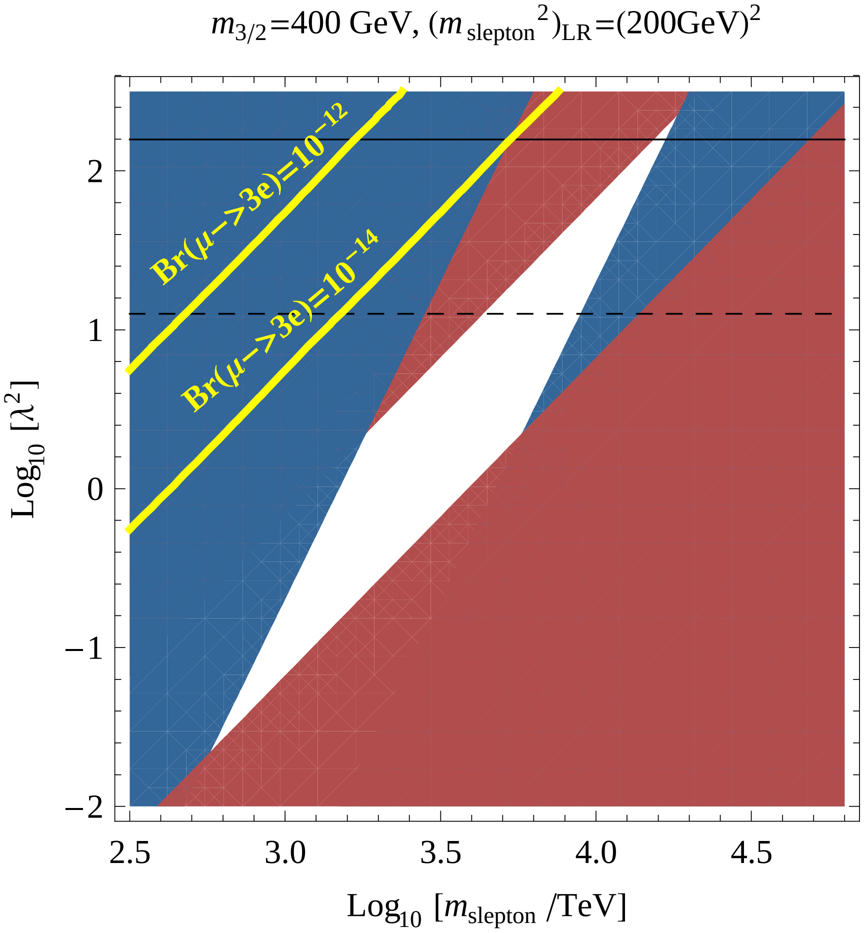


Fit only PAMELA positron excess ($m_{3/2} \gtrsim$ few hundred GeV)

- $m_{3/2} = 400$ GeV
- $\tau_{3/2} = 2.3 \times 10^{26}\,\text{sec}$ ($\Gamma_{3/2} = 0.3 \times 10^{-50}\,\text{GeV}$)
- $m_\nu = 0.2$ eV
- $m^2_{\tilde{\ell}}/\lambda \simeq 1.3 \times 10^7\,\text{TeV}^2$ (best fit)



This fit is valid for different values of $(m^2_{\tilde{\ell}})_{LR}$ and λ providing we are in the white region below (for example):



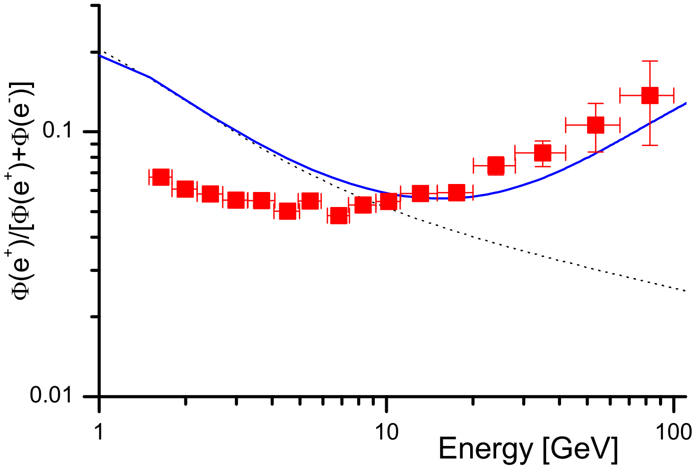
$m_{3/2}$=400 GeV, $(m_{\mathrm{slepton}}{}^2)_{\mathrm{LR}}=(200\mathrm{GeV})^2$

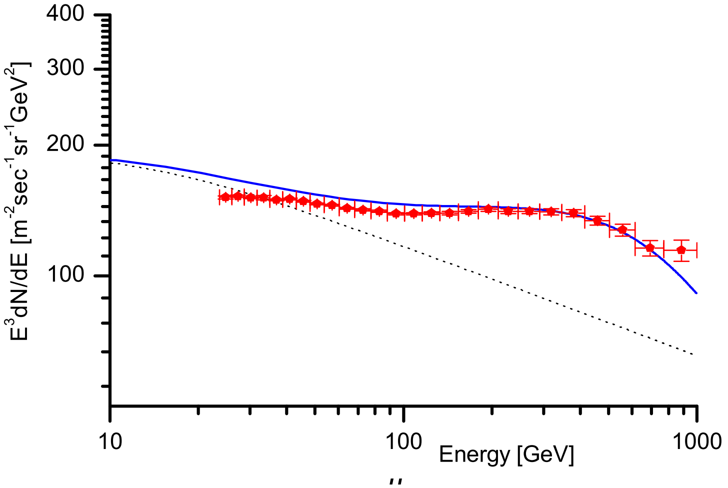
So explanation of PAMELA in MSSM requires:

- $m_{3/2} \approx 400$ GeV (or more)
- $m_{\tilde{\ell}} \approx 500$ TeV (or more)
- $m_{\tilde{q}} \approx \mathcal{O}(\text{TeV})$ if λ' small (or bigger if λ' large)

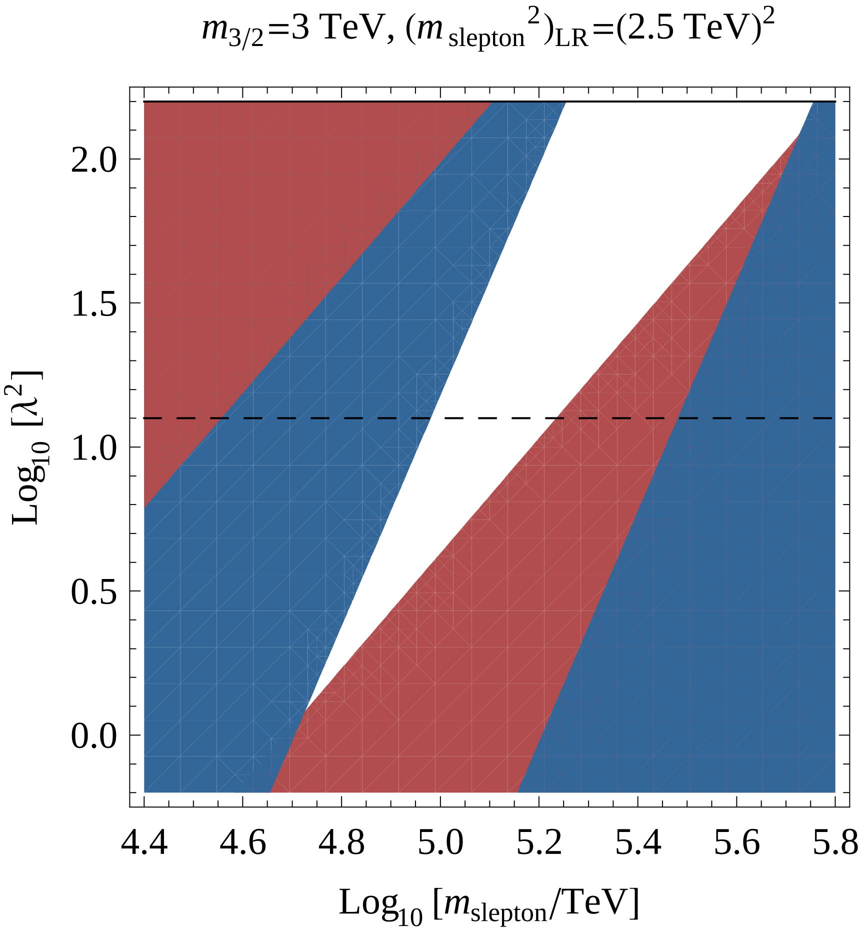
Fit now both PAMELA and FERMI ($m_{3/2} \gtrsim$ few TeV)

- $m_{3/2} = 3.3$ TeV
- $\tau_{3/2} = 5 \times 10^{25}$ sec ($\Gamma_{3/2} = 1.4 \times 10^{-50}$ GeV)
- $m_\nu = 0.03$ eV
- $m^2_{\tilde{\ell}}/\lambda \simeq 10^{10}$ TeV^2 (best fit)





This fit is valid for different values of $(m^2_{\tilde{\ell}})_{LR}$ and λ providing we are in the white region below (for example):



So explanation of PAMELA and FERMI in MSSM requires:

- $m_{3/2} \approx 3$ TeV (or a bit more)
- $m_{\tilde{\ell}} \approx 10^5$ TeV (or a bit more)
- $m_{\tilde{q}} \approx \mathcal{O}(\mathrm{TeV})$ if λ' small (or bigger if λ' large)

Tests/consequences of gravitino DM

- no sleptons at LHC if only PAMELA is described:

$$m_{\tilde{\ell}} \gtrsim \text{ few hundreds TeV}$$

- nothing except the Higgs if also Fermi/LAT is explained

$$m_{\text{superpartners}} > m_{LSP} = m_{3/2} = \text{ few TeV}$$

- in this last case excess of antiprotons will have to be seen with a 1 order of magnitude improvement in precision

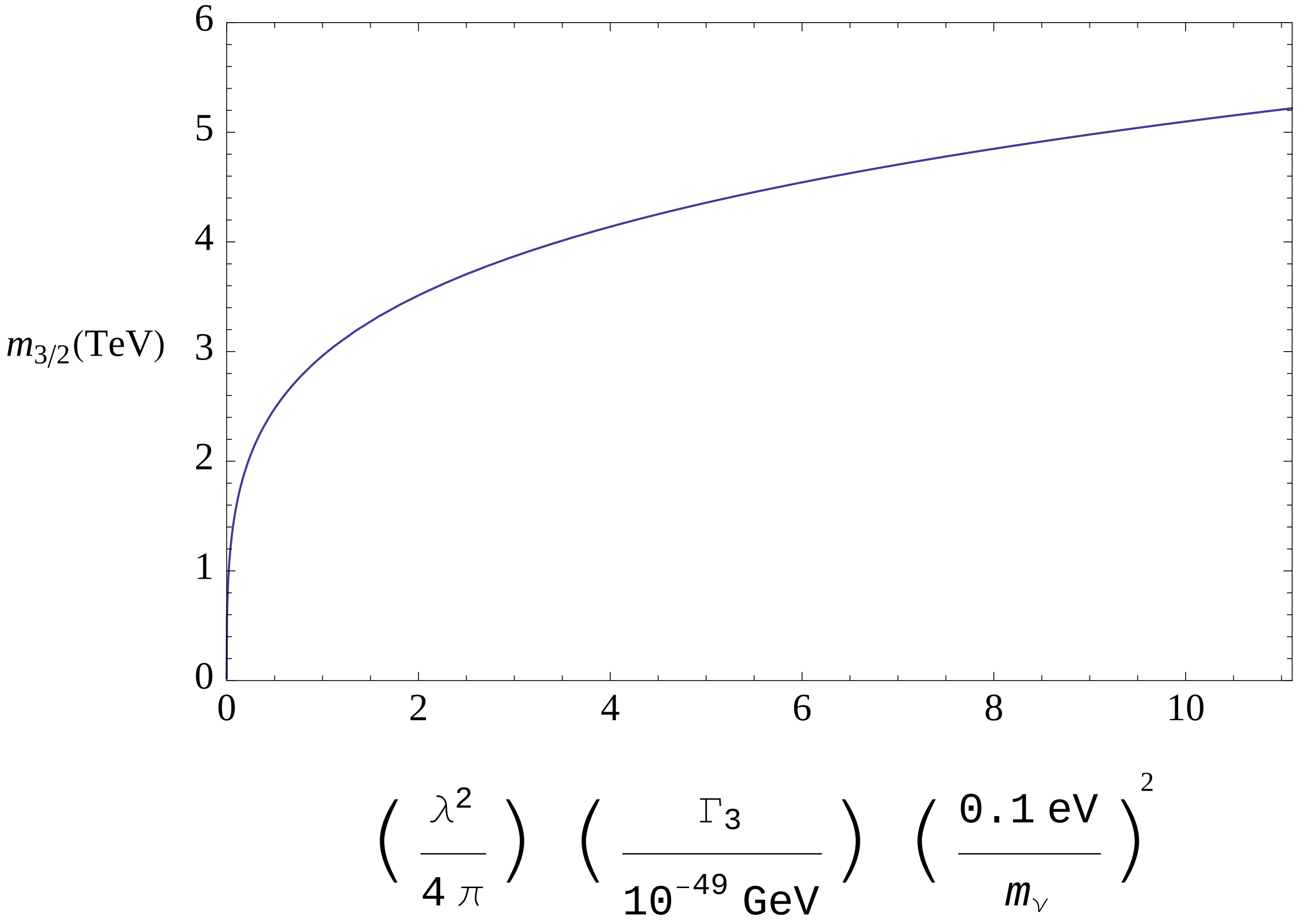
$$\Gamma_2 = \Gamma_3/10 \text{ saturated here}$$

- in this same case (PAMELA + Fermi/LAT) gravitino mass large and close to upper limit. Due to perturbativity requirements hierarchical neutrino pattern preferred.

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

For $m_{3/2} = 3.3$ TeV, $\lambda^2 = 4\pi$, $\Gamma_3 = 10^{-49}$ GeV

$\Longrightarrow m_\nu \lesssim 0.08$ eV


$m_{3/2}$(TeV)
0
1
2
3
4
5
6
0
2
4
6
8
10
$\left(\frac{\lambda^2}{4\pi}\right)\left(\frac{\Gamma_3}{10^{-49}\,\text{GeV}}\right)\left(\frac{0.1\,\text{eV}}{m_\nu}\right)^2$

- Flavor lepton violation small and should not be see in the near future

$$B(\mu \to 3e) \simeq \left(\frac{\lambda}{g}\right)^4 \left(\frac{M_W}{m_{\tilde{\ell}}}\right)^4$$

$\mu \to e\gamma$, $\mu \to e$ conversion, etc even smaller, further loop suppression

Conclusion

- It is natural to try with the MSSM when something cannot be explained in the SM
- From nonzero neutrino mass only gravitino with $\not{R}$ couplings remains a DM candidate
- Here an analysis of both neutrino masses and Fermi/LAT and/or PAMELA data done.
- It is possible to descibe PAMELA (and Fermi/LAT) providing sleptons are much too heavy to be seen at LHC
- No restrictions on squarks, neutralino, chargino masses, but for heavy gravitino (from Fermi/LAT) they seem also out of reach
- Some tests possible, in spite of massive sleptons and/or other superpartners.