GRAVITINO DARK MATTER

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Why Gravitino Dark Matter?

Supergravity predicts the gravitino, analog of W and Z bosons in electroweak theory; may be LSP, natural DM candidate:

- $m_{3/2} < 1\mathrm{keV}$, hot DM, (Pagels, Primack '81)
- $1\mathrm{keV} \lesssim m_{3/2} \lesssim 15\mathrm{keV}$, warm DM, (Gorbunov, Khmelnitsky, Rubakov '08)
- $100\mathrm{keV} \lesssim m_{3/2} \lesssim 10\mathrm{MeV}$, cold DM, gauge mediation and thermal leptogenesis (Fuji, Ibe, Yanagida '03); recently proven to be correct by F-theory (Heckman, Tavanfar, Vafa '08)
- $10\mathrm{GeV} \lesssim m_{3/2} \lesssim 1\mathrm{TeV}$, cold DM, gaugino/gravity mediation and thermal leptogenesis (Bolz, WB, Plümacher '98)

Baryogenesis, (gravitino) DM and primordial nucleosynthesis (BBN) strongly correlated in cosmological history.

Gravitino Problem

Thermally produced gravitino number density grows with reheating temperature after inflation (Khlopov, Linde '83; Ellis, Kim, Nanopoulos '84;...),

$$\frac{n_{3/2}}{n_\gamma} \propto \frac{\alpha_3}{M_{\rm p}^2} T_R.$$

For unstable gravitinos, nucleosynthesis implies stringent upper bound on reheating temperature T_R (Kawasaki, Kohri, Moroi '05; ...),

$$T_R < \mathcal{O}(1) \times 10^5 \text{ GeV},$$

hence standard mSUGRA with neutralino LSP incompatible with baryogenesis via thermal leptogenesis where $T_R \sim 10^{10}$ GeV !!

Possible way out: Gravitino LSP, explains dark matter!

Gravitino Virtue

Can one understand the amount of dark matter, $\Omega_{DM} \simeq 0.23$, with $\Omega_{DM} = \rho_{DM}/\rho_c$, if gravitinos are dominant component, i.e. $\Omega_{DM} \simeq \Omega_{3/2}$?

Production mechanisms: (i) WIMP decays, i.e., 'Super-WIMPs' (Covi, Kim, Roszkowski '99; Feng, Rajaraman, Takayama '03),

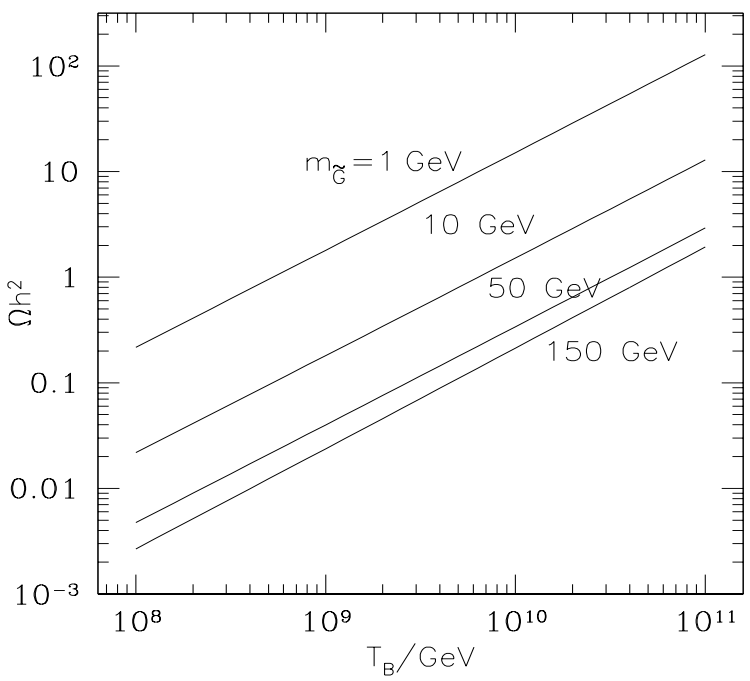
$$\Omega_{3/2} = \frac{m_{3/2}}{m_{\rm NLSP}} \Omega_{\rm NLSP} \ ,$$

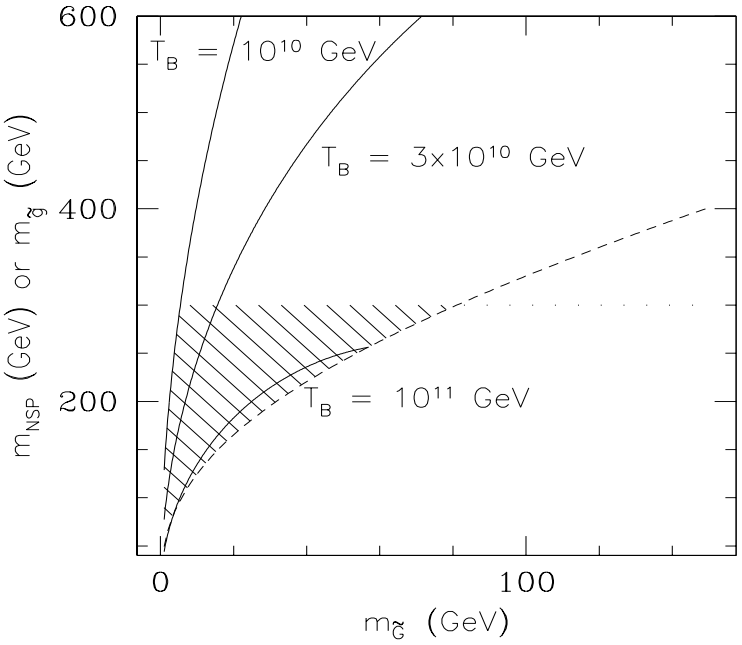
independent of initial temperature T_R (!), but inconsistent with BBN constraints; (ii) Thermal production, from $2 \to 2$ QCD processes,

$$\Omega_{3/2} h^2 \simeq 0.5 \left(\frac{T_R}{10^{10}{\rm GeV}} \right) \left(\frac{100{\rm GeV}}{m_{3/2}} \right) \left(\frac{m_{\tilde{g}}(\mu)}{1{\rm TeV}} \right) \ .$$

$\to \Omega_{DM} h^2$ for typical parameters of supergravity and leptogenesis!

Leptogenesis, GDM and BBN (Bolz, WB, Plümacher '98)



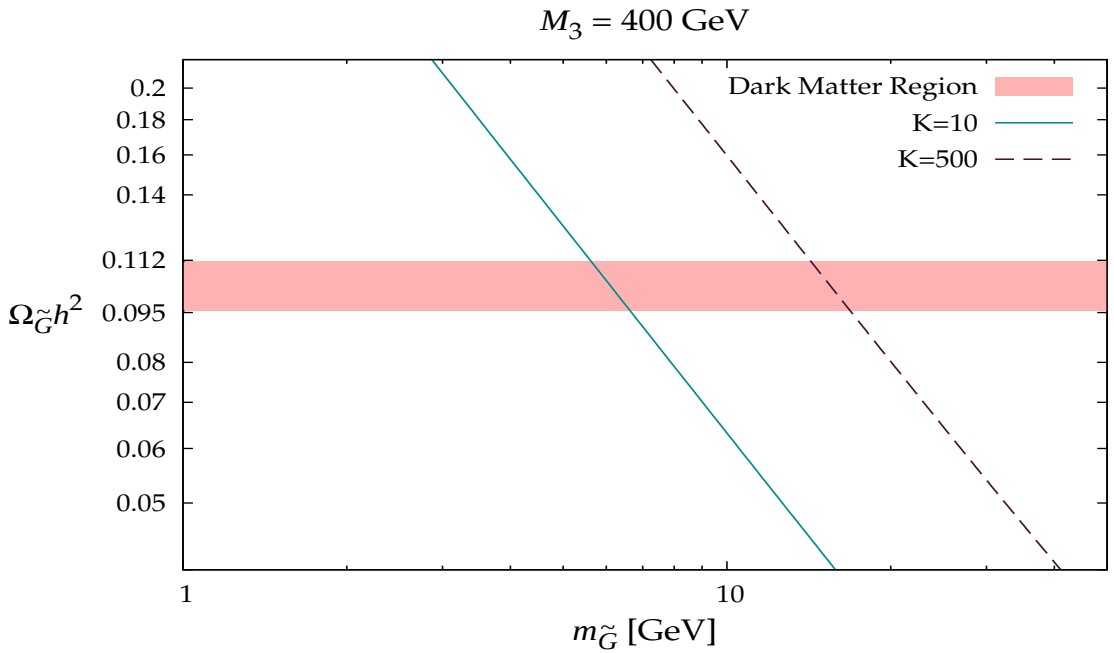


Left: Gravitino abundance as function of reheating temperature. *Right:* Upper bound on gluino mass, lower bound on higgsino NLSP; shaded area: BBN ok. Note: gaugino mass unification not possible. Improved BBN constraints $\longrightarrow \tilde{\tau}$ NLSP ... $\longrightarrow$... Pospelov '06 ... review Steffen '08

Reheating: initial RH-neutrino dominance

(...Asaka et al '99; Hahn-Woernle, Plümacher '08; Erbe '09)

Reheating process from inflaton decay: $\phi \to N_1 N_1 \to (lH)(lH) \to \ldots$; combined system of Boltzmann eqs connects LG and gravitino production



parameters: $M_1 = 10^9$ GeV $\sim T_R$, $m_{\tilde{g}} = 1$ TeV; for $K = 10$ (strong washout): $m_{3/2} \simeq 6$ GeV (cf. thermal LG: $\Omega h^2 \sim 1$).

Decaying GDM (WB, Covi, Hamaguchi, Ibarra, Yanagida '07)

BBN, leptogenesis and gravitino dark matter are all consistent in case of a small 'R-parity' breaking, which leads to processes $\widetilde{\tau}_R \to \tau\ \nu_\mu, \mu\ \nu_\tau$, $\widetilde{\tau}_L \to b^c t$, ... and also $\psi_{3/2} \to \gamma\nu$. Small R-parity breaking can occur together with B-L breaking,

$$\lambda \sim h^{(e,d)}\Theta \lesssim 10^{-7}\ , \quad \Theta \sim \frac{v_{B-L}^2}{{M_{\rm P}}^2}\ .$$

The NLSP lifetime becomes sufficiently short (decay before BBN),

$$c\tau_{\tilde{\tau}}^{lep} \sim 30\ {\rm cm} \left(\frac{m_{\tilde{\tau}}}{200{\rm GeV}}\right)^{-1} \left(\frac{\lambda}{10^{-7}}\right)^{-2}\ .$$

BBN, thermal leptogenesis and gravitino dark matter are consistent for $10^{-14} < \lambda, \lambda' < 10^{-7}$ (B, L washout) and $m_{3/2} \gtrsim 5$ GeV.

At LHC one should see characteristic signal with strongly ionising macroscopic charged tracks, followed by a muon track or a jet and missing energy, corresponding to $\widetilde{\tau} \to \mu\nu_\tau$ or $\widetilde{\tau} \to \tau\nu_\mu$.

The gravitino decay $\psi_{3/2} \to \gamma\nu$ is suppressed both by the Planck mass and the small R-parity breaking couplings, so the lifetime is much longer than the age of the universe (Takayama, Yamaguchi '00),

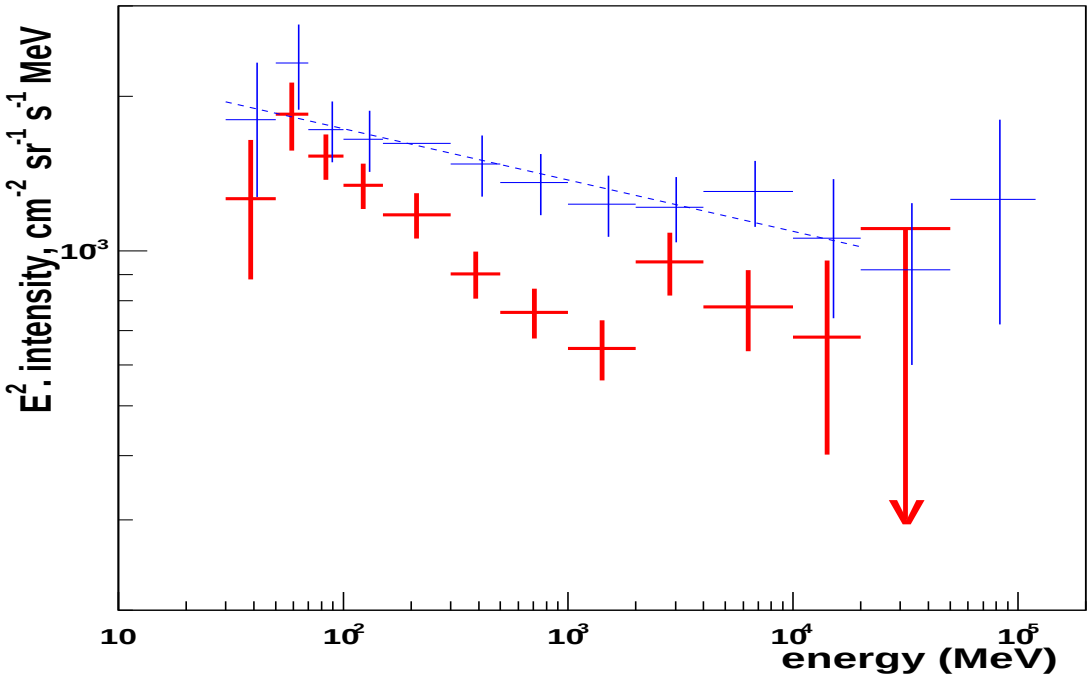
$$\tau_{3/2} \sim 10^{26}\mathrm{s} \left(\frac{\lambda}{10^{-7}}\right)^{-2} \left(\frac{m_{3/2}}{10\ \mathrm{GeV}}\right)^{-3} ;$$

(Note that this lifetime became very popular after PAMELA). What are the cosmic ray signatures? Gamma-ray flux of the order of EGRET excess !!

Several other mechanisms to generate small R-parity breaking have been proposed (Mohapatra et al '08; Endo, Shindou '09, ...)

LAUNCH07, March 2007, MPK Heidelberg:

Extragalactic diffuse gamma-ray flux obtained from EGRET data (1998)



analysis of Strong, Moskalenko and Reimer, astro-ph/0406254 (2004), astro-ph/0506359 (2005); subtraction of galactic component difficult astro-ph/0609768; extragalactic gravitino signal consistent with data for $m_{3/2} \sim 10$ GeV; halo component may partly be hidden in anisotropic galactic gamma-ray flux $\rightarrow$ wait for GLAST !!

Superparticle Mass Window (WB, Endo, Shindou '08)

What are the constraints from leptogenesis and GDM on superparticle masses for unstable gravitinos, i.e. without BBN? GDM: upper bound on gluino mass for given reheating temperature; low energy observables: lower bound on NLSP.

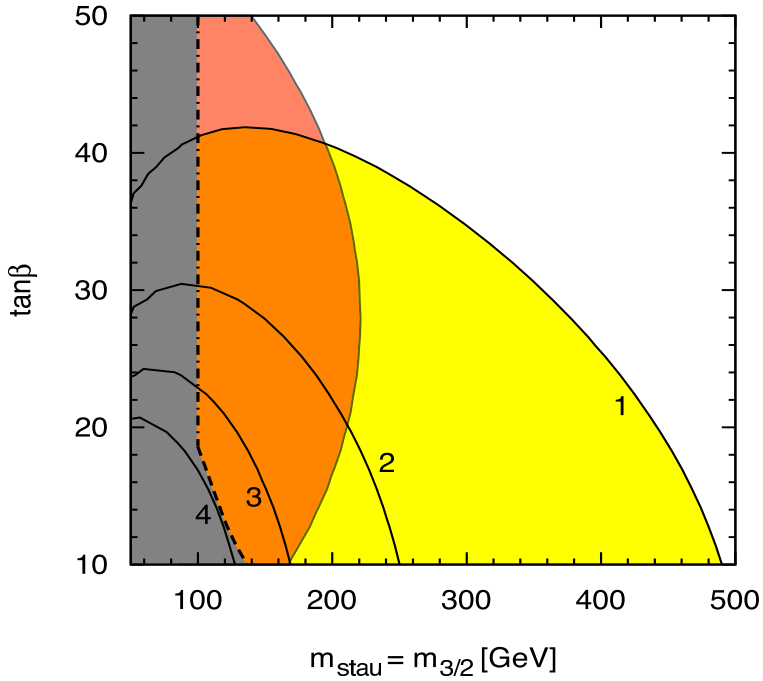
Connection is model dependent; assume gaugino mass unification ($m_{\rm gluino} \simeq 6 m_{\rm bino}$). Two typical examples (different ratios $m_{\rm NLSP}/m_{\rm gluino}$),

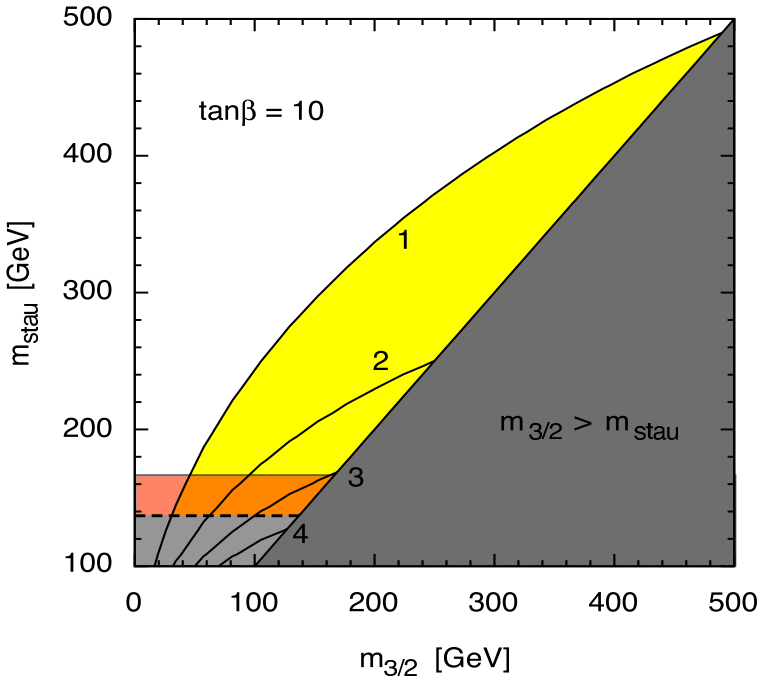
$$(A) \quad \tilde{\chi}\ \text{NLSP}: \quad m_0 = m_{1/2}\ , \quad a_0 = 0\ , \quad \tan\beta\ ;$$
$$(B) \quad \tilde{\tau}\ \text{NLSP}: \quad m_0 = 0\ , \quad m_{1/2}\ , \quad a_0 = 0\ , \quad \tan\beta\ .$$

Low energy observables: $m_h > 114$ GeV, $\text{BR}(B_d \to B_s\gamma)$, $m_{\rm charged} > 100$ GeV. Possible hint for supersymmetry (Marciano, Sirlin '08),

$$a_\mu(\text{exp}) - a_\mu(\text{SM}) = 302(88) \times 10^{-11}\ .$$

Stau and gravitino masses





Left: (A) gravitino: $m_{3/2} < 490$ GeV. *Right:* (B) stau: 100 GeV $< m_{\rm stau} < 490$ GeV. *Red:* mass range favoured by a_μ.

Cosmic-Ray Signatures from Decaying Gravitinos

(WB, Ibarra, Shindou, Takayama, Tran '09)

Gravitino decays: $\psi_{3/2} \to \gamma\nu; h\nu, Z\nu, W^{\pm}l^{\mp}$, leads to continuous gamma-ray and antimatter spectrum: $\psi_{3/2} \to \gamma X, \bar{p}X, e^{\pm}X$; qualitative features from operator analysis (hierarchy: $m_{SM} \ll m_{3/2} \ll m_{\rm soft}$):

$$\mathcal{L}_{\rm eff} = \frac{i\kappa}{\sqrt{2}M_{\rm P}} \left\{ \bar{l}\gamma^{\lambda}\gamma^{\nu} D_{\nu}\phi\psi_{\lambda} + \frac{i}{2}\bar{l}\gamma^{\lambda} \left(\xi_1 g' Y B_{\mu\nu} + \xi_2 g W_{\mu\nu}\right) \sigma^{\mu\nu}\phi\psi_{\lambda} \right\} + \text{h.c.}$$

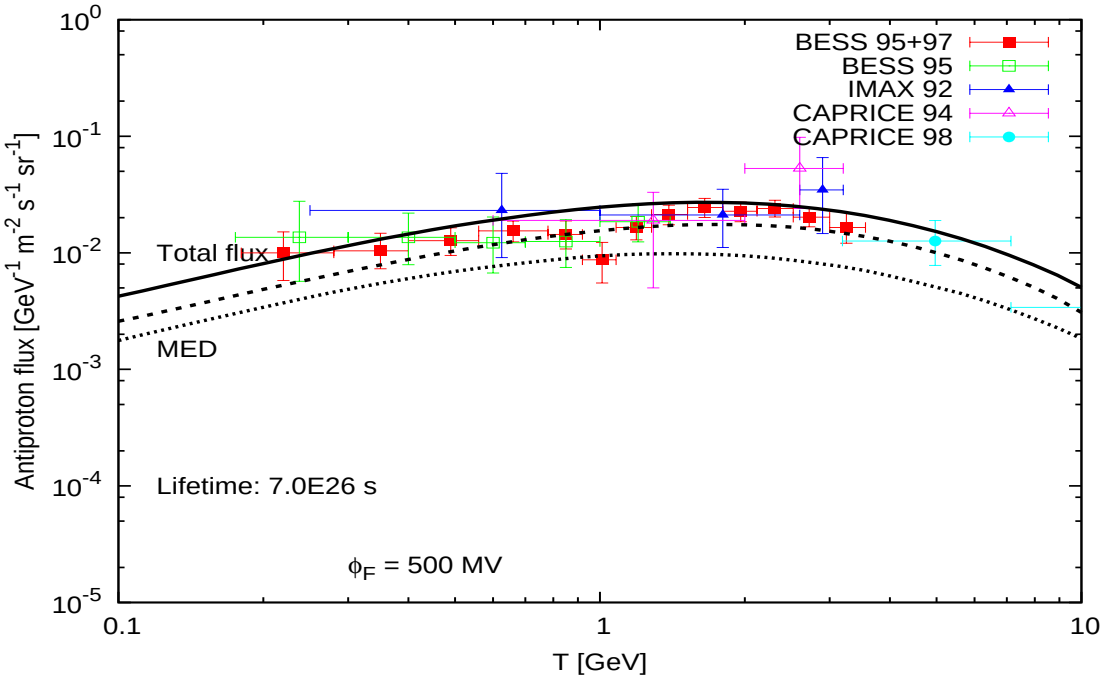
R-parity breaking: κ; further suppression: $\xi_{1.2} = \mathcal{O}(1/m_{3/2})$

$$\text{dim } 5: \ \psi_{3/2} \to h\nu, Z\nu, W^{\pm}l^{\mp}; \text{ continuous spectrum ,}$$

i.e., single term correlates antiproton flux, PAMELA and Fermi!

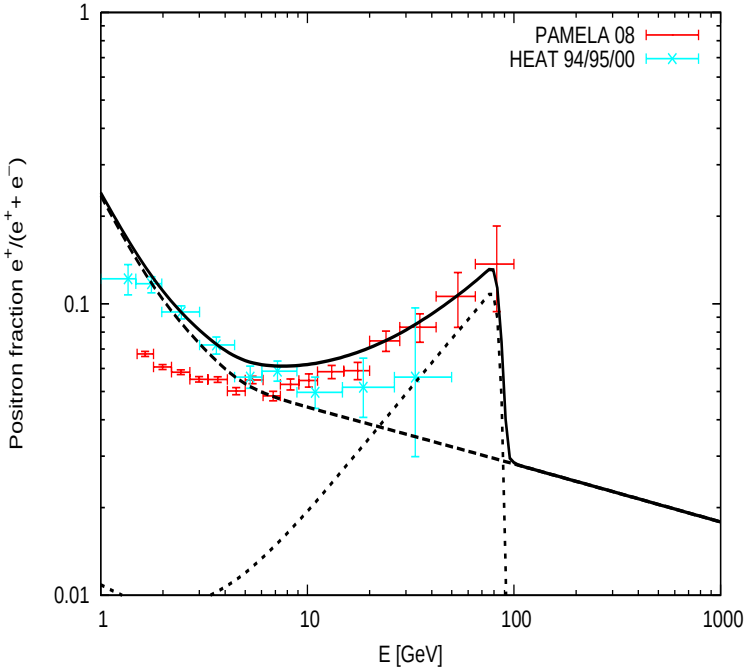
$$\text{dim } 6: \ \psi_{3/2} \to \gamma\nu; \text{ gamma line}$$

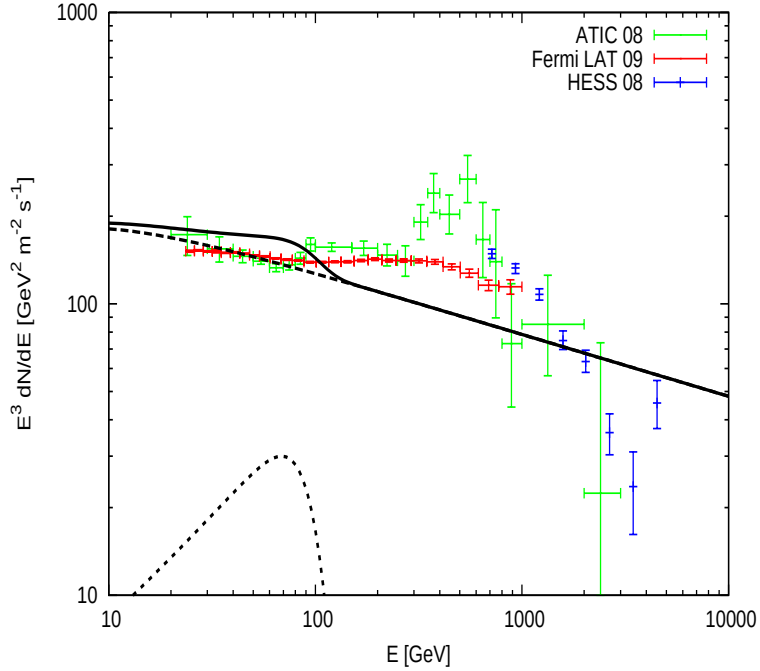
Minimal gravitino lifetime from antiproton flux



conservative propagation model (B/C ratio): MED model; require that total antiproton flux (including gravitino decays) lies below maximal flux from spallation (including astrophysical uncertainties) $\longrightarrow$ minimal lifetime; for $m_{3/2} = 200$ GeV one finds $\tau_{3/2}^{\rm min}(200) = 7 \times 10^{26}$ s.

PAMELA & Fermi vs 'electron dominance'



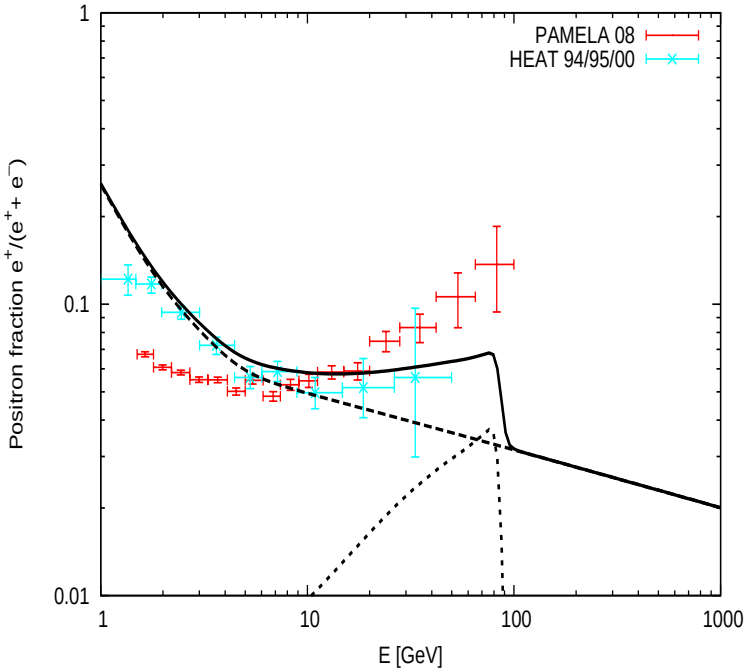


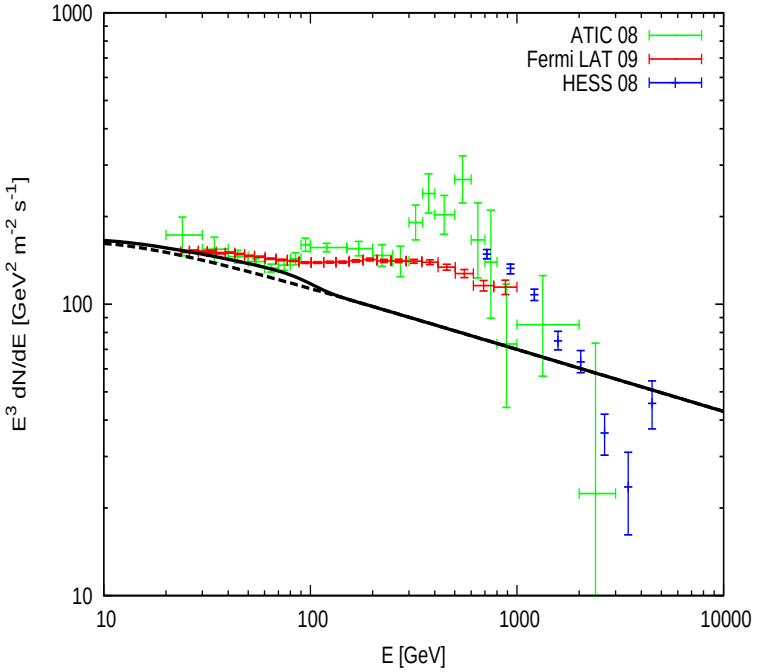
Input: $m_{3/2} = 200$ GeV, $\tau_{3/2} = 3.2 \times 10^{26}$ s, $\mathrm{BR}(\psi \to \mu^{\pm} W^{\mp}, \tau^{\pm} W^{\mp}) \ll \mathrm{BR}(\psi \to e^{\pm} W^{\mp})$ (why?); background: "Model 0" (Grasso et al, Fermi LAT '09)

Conclusion: GALPROP & gravitino incompatible with PAMELA & Fermi !!

[PAMELA & Fermi make CR signature for dark matter UNLIKELY !!]

PAMELA & Fermi vs 'flavour democracy'

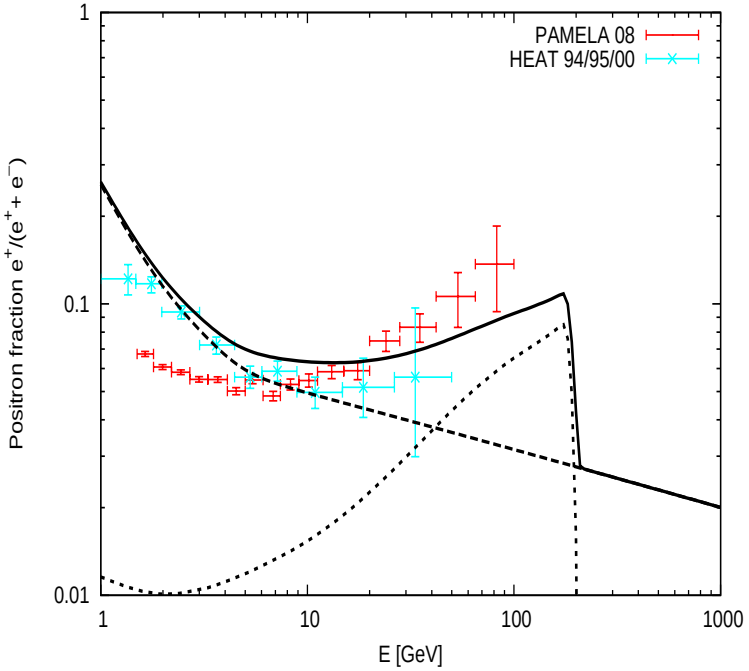


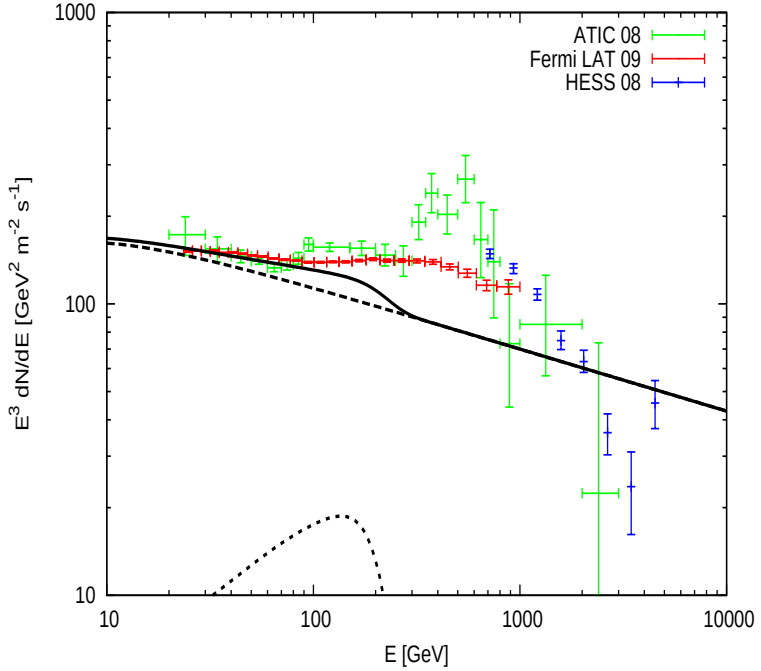


Input: $m_{3/2} = 200$ GeV, $\tau_{3/2} = 7 \times 10^{26}$ s, $\mathrm{BR}(\psi \to l_i^{\pm} W^{\mp})$ universal for $i = e, \mu, \tau$ (theoretical model exists), background: "Model 0".

Conclusion: astrophysical sources needed to explain PAMELA & FERMI!!

Contribution from gravitino decays to positron fraction increases with increasing gravitino mass:

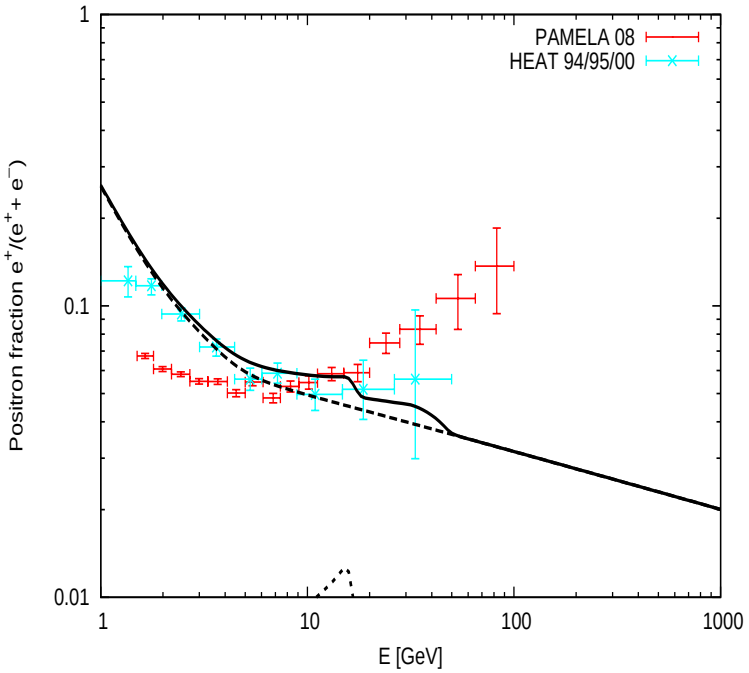


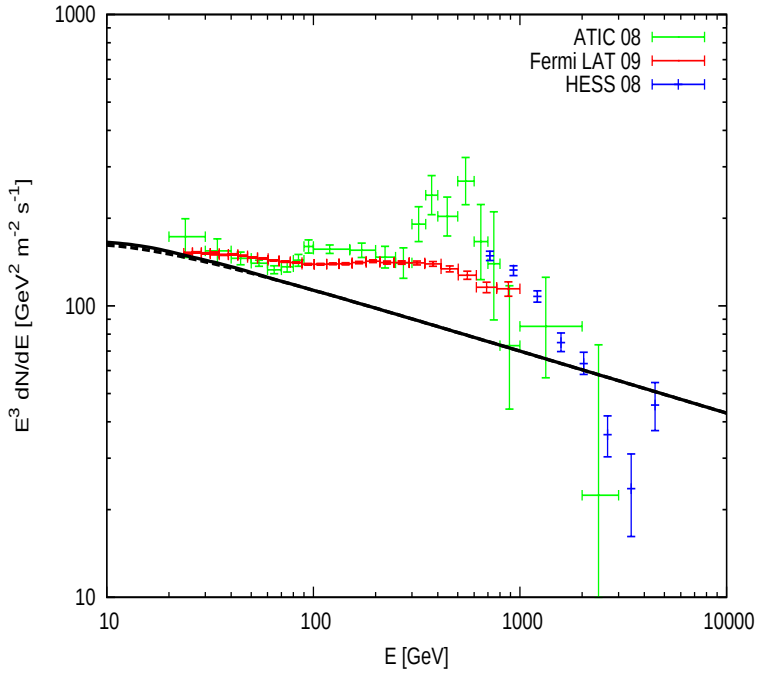


Input: $m_{3/2} = 400$ GeV, $\tau_{3/2} = 3 \times 10^{26}$ s, $\mathrm{BR}(\psi \to l_i^{\pm} W^{\mp})$ universal for $i = e, \mu, \tau$, background: "Model 0".

Conclusion: gravitino contribution to electron/positron fluxes may be sizable, has to be complemented by astrophysical sources!

Contribution from gravitino decays to positron fraction decreases rapidly for gravitino masses below 200 GeV:





Input: $m_{3/2} = 100$ GeV, $\tau_{3/2} = 1 \times 10^{27}$ s, $\mathrm{BR}(\psi \to l_i^{\pm} W^{\mp})$ universal for $i = e, \mu, \tau$, background: "Model 0".

Conclusion: gravitino contribution to electron/positron fluxes may be negligable, as for antiproton flux!

Predictions for the Gamma-Ray Spectrum

Important contributions form extragalactic DM and DM in the Milky Way halo; typical branching ratio for gamma line (cf. operator analysis):

$$\mathrm{BR}(\psi_{3/2} \to \nu\gamma) \sim 0.02 \left(\frac{200\ \mathrm{GeV}}{m_{3/2}}\right)^2 \ ;$$

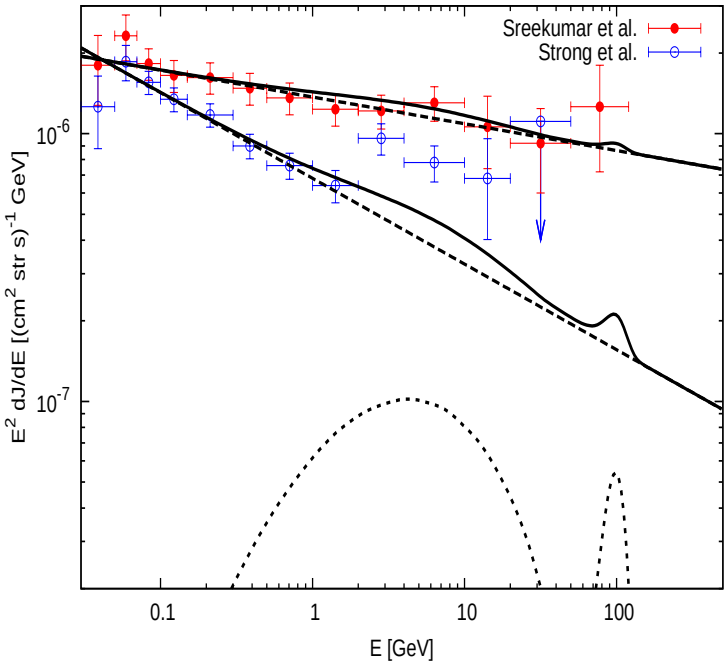
Gamma-ray background presently uncertain, two analyses of EGRET data; Sreekumar et al:

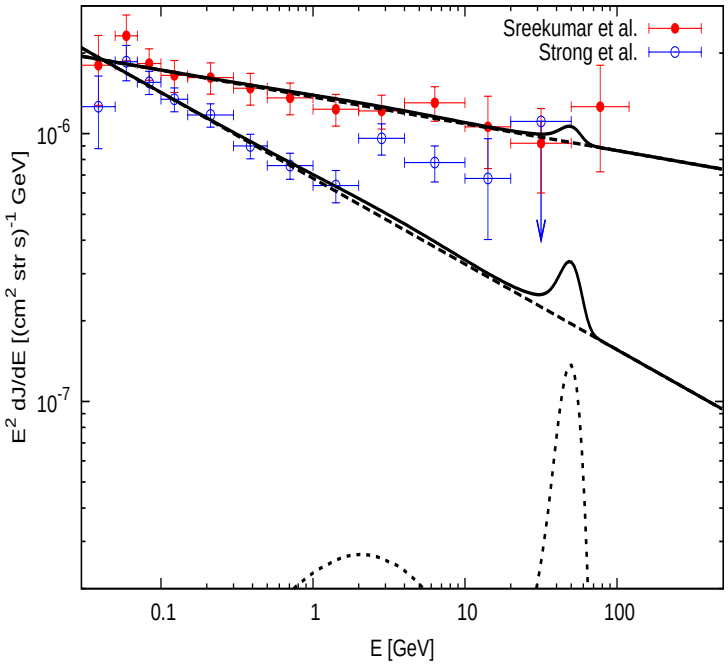
$$\left[E^2 \frac{dJ}{dE}\right]_{\mathrm{bg}} = 1.37 \times 10^{-6} \left(\frac{E}{\mathrm{GeV}}\right)^{-0.1} (\mathrm{cm}^2\ \mathrm{str}\ \mathrm{s})^{-1}\ \mathrm{GeV}\ ,$$

and Moskalenko et al:

$$\left[E^2 \frac{dJ}{dE}\right]_{\mathrm{bg}} = 6.8 \times 10^{-7} \left(\frac{E}{\mathrm{GeV}}\right)^{-0.32} (\mathrm{cm}^2\ \mathrm{str}\ \mathrm{s})^{-1}\ \mathrm{GeV}.$$

Height of gamma line depends on energy resolution (assumed: $\sigma(E)/E = 15\%$) and background; 'minimal' lifetime from antiproton flux constraint give maximal gamma-ray flux:

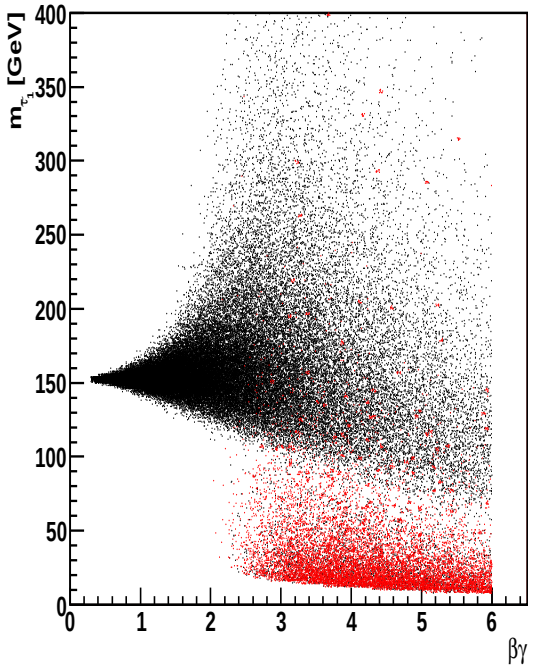


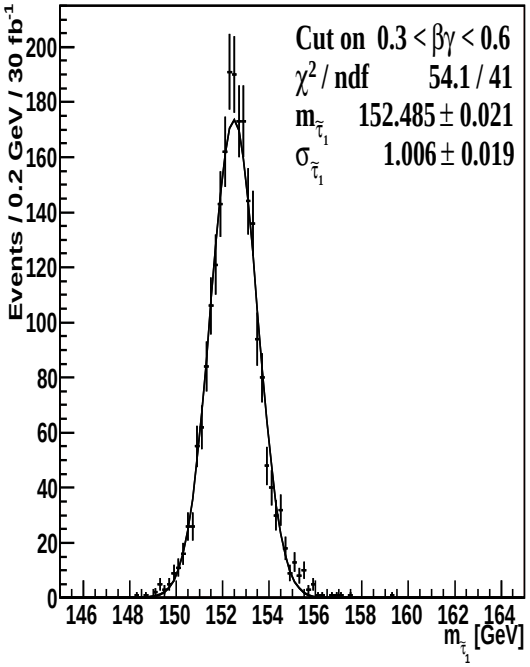


left: $m_{3/2} = 200$ GeV, $\tau_{3/2} = 7 \times 10^{26}$ s; *right:* $m_{3/2} = 100$ GeV, $\tau_{3/2} = 1 \times 10^{27}$ s; improvement of energy resolution?

Hope for the LHC: $\tilde{\tau}$-mass measurement (Ellis, Raklev, Oye '06)

$\tilde{\tau}$-mass can be measured from $m_{\tilde{\tau}} = p_{\mathrm{meas}}/\beta\gamma_{\mathrm{meas}}$, slow $\tilde{\tau}$'s important! Background from muon tracks, accurate measurement of $\tilde{\tau}$-mass possible





analysis relevant for sufficiently long lifetimes, such that the $\tilde{\tau}$-lepton leaves the detector; more work in progress ...

SUMMARY

- Gravitino DM is viable possibility
- Gravitino DM is theoretically motivated: leptogenesis and/or gauge mediation ...
- Decaying gravitino DM consistent with leptogenesis and BBN
- GALPROP & gravitino DM incompatible with PAMELA & Fermi, astrophysical sources needed !!
- Sizable excess in gamma-ray spectrum possible, in particular line at $E_\gamma \simeq m_{3/2}/2$. Gravitino DM can be discovered with Fermi LAT and/or falsified at the LHC !!