GRAVITINO DARK MATTER AT LHC AND GLAST

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OUTLINE

1. Gravitino Cosmology
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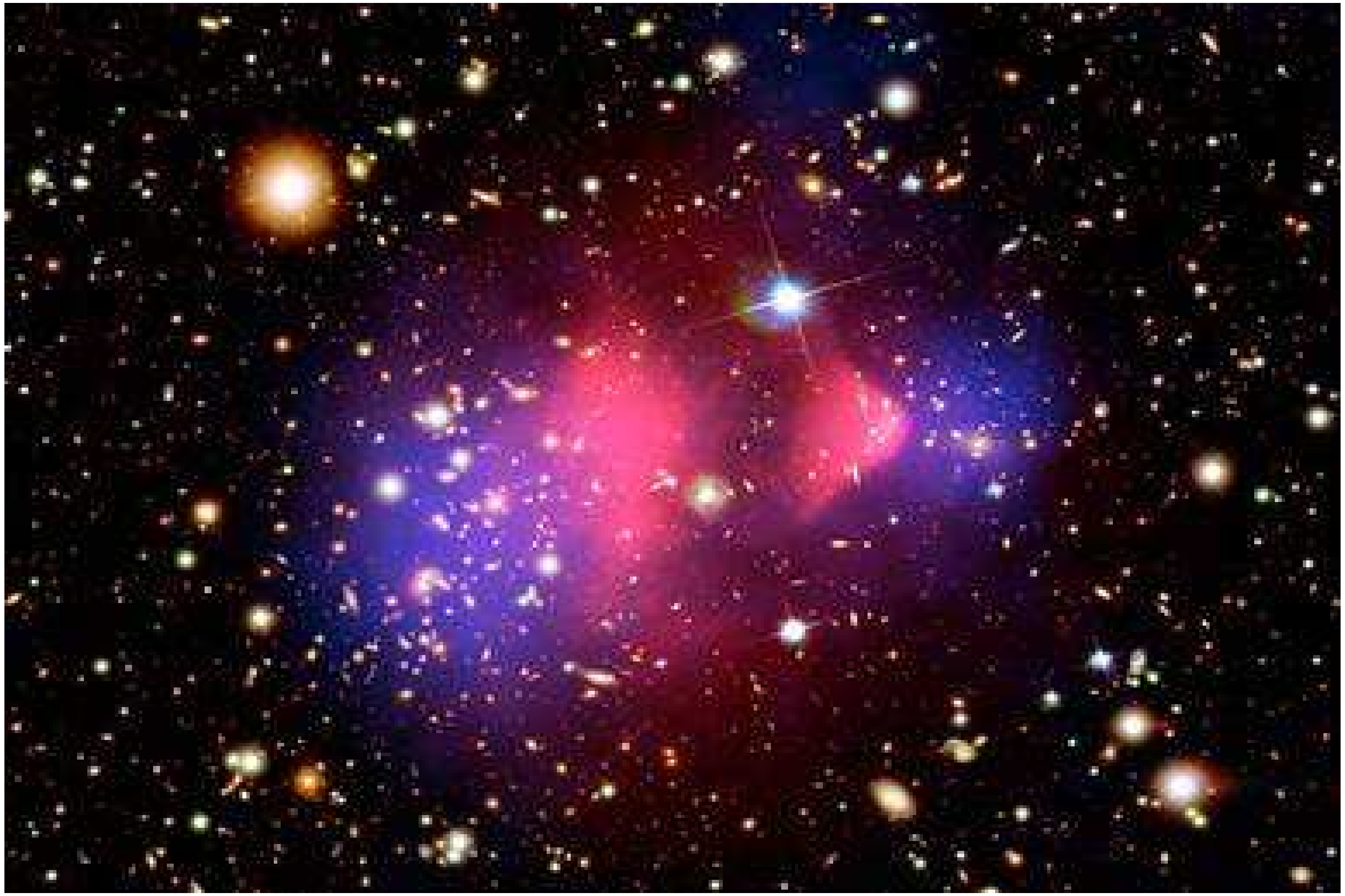


“Direct” evidence for dark matter: “Photo” from NASA of two colliding clusters of galaxies (Bullet Cluster), with baryonic matter (red) and dark matter (blue) seperated (cf. D. Clowe et al., astro-ph/0608407)

(1) Gravitino Cosmology

What are the constituents of the dark matter? Attractive candidates are suggested by supergravity theories (elegant, unavoidable (?) extensions of the standard model and Einstein gravity):

- the neutralino (WIMP), the superpartner of photon, Z and Higgs boson (in some linear combination), most popular, many search experiments !!

- the gravitino, the superpartner of the graviton, gauge fermion of local supersymmetry (analog of W-boson for weak interactions), theoretically most attractive, all interactions fixed via symmetry !! First proposed dark matter candidate (Pagels and Primack '81), with $m_{3/2} \sim 1\ \mathrm{keV}$ (for negligable neutrino masses).

- Other candidates: axion (axino), heavy 'sterile' neutrinos, ...

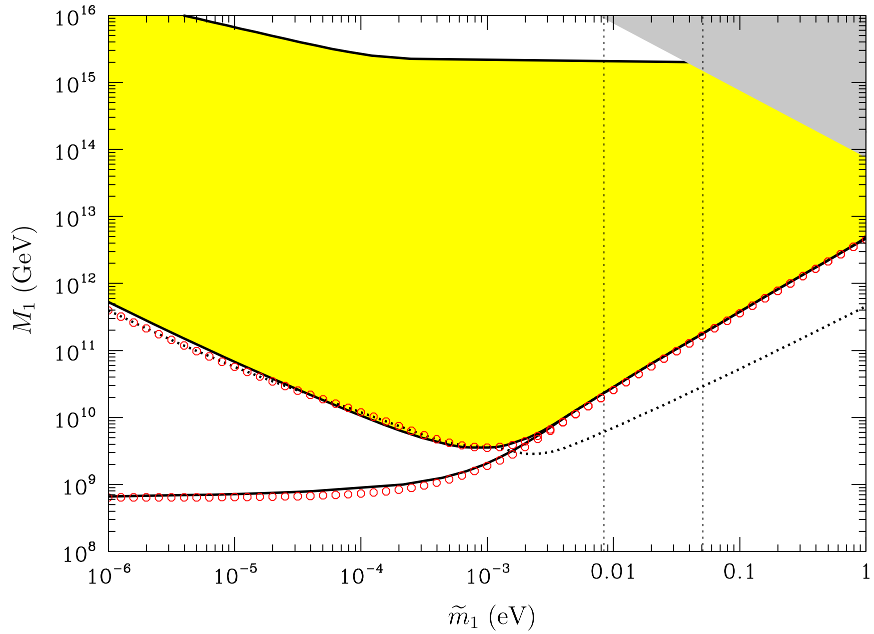
Strong constraints on allowed dark matter candidates follow from the 'reheating' temperature T_R in the hot phase of the early universe; relevant temperature scales are determined by microscopic physics:

- $0.1\ \mathrm{eV}$ $[10^{13}\ \mathrm{s}]$: decoupling of photons, CMB
- $0.1 \ldots 10\ \mathrm{MeV}$ $[10^{2} \ldots 10^{-2}\ \mathrm{s}]$: primordial nucleosynthesis (BBN)
- $\sim 10\ \mathrm{GeV}$ $[10^{-8}\ \mathrm{s}]$: WIMP decoupling, standard SUSY dark matter
- $100\ \mathrm{GeV}$ $[10^{-10}\ \mathrm{s}]$: electroweak transition, sphaleron processes
- $10^{6} \ldots 10^{10}\ \mathrm{GeV}$ $[10^{-18} \ldots 10^{-26}\ \mathrm{s}]$: leptogenesis, gravitino DM
- $\sim 10^{12}\ \mathrm{GeV}$ $[10^{-30}\ \mathrm{s}]$: 'maximal' temperature ?

Constraints from leptogenesis

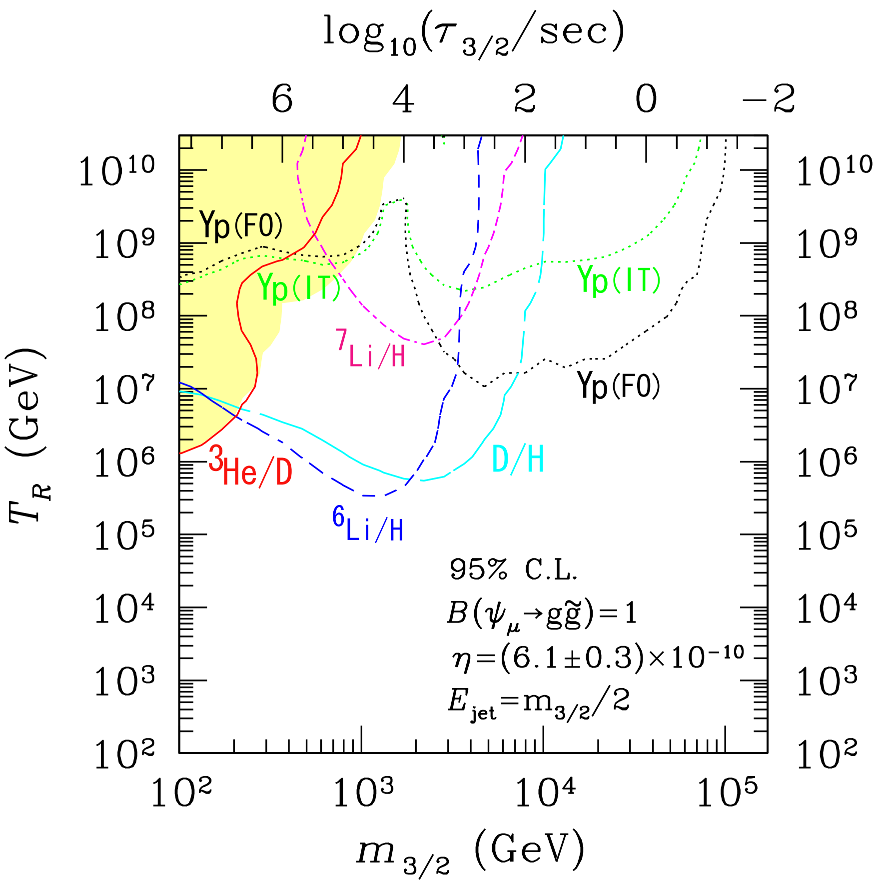
Leptogenesis (Fukugita, Yanagida '86) is attractive theory for origin of matter. Non-equilibrium process yields quantitative relation between neutrino masses and baryon asymmetry; in the simple case of 'N_1-dominance' crucial quantities CP asymmetry ε_1 and efficiency factor κ_f in terms of neutrino mass parameters M_1, $\widetilde{m}_1$,...

$$\eta_B = \frac{n_B}{n_\gamma} \simeq 0.01\,\varepsilon_1\,\kappa_f\,.$$



Implications: light neutrino mass window (current discussion: flavour dependence!); lower bound on heavy neutrino mass and baryogenesis temperature $T_B \sim M_1 > 10^9$ GeV (WB, Di Bari, Plümacher,'05) $\longrightarrow$ strong constraints on superparticle mass spectrum.

Constraints from nucleosynthesis (BBN)



Gravitino problem: production dominated by QCD processes; gravitino number density grows with reheating temperature after inflation,

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

Most stringent upper bound on T_R (Kawasaki, Kohri, Moroi '05):

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

incompatible with thermal leptogenesis !!

Possible way out: Gravitino LSP, with special signatures but also potential problems depending on NLSP... (Bolz, WB, Plümacher '98) $\longrightarrow$ non-thermal or resonant leptogenesis ?

(3) R-Parity Breaking and B-L Breaking

Most supersymmetric extensions of the standard model impose R-parity as an exact symmetry (Fayet '78) for phenomenological reasons. On theoretical grounds, however, theories with and without R-parity are on the same footing. Also in string compactifications R-parity plays no preferred role.

Models without R-parity have been constructed (reviews: Allanach et al. '04; Barbier et al. '05). Without R-parity conservation, the lightest superparticle (LSP) is no longer stable and, in general, it does not contribute to dark matter.

Stringent constraints on the lepton number and R-parity violating interactions

$$W_{\Delta L=1} = \lambda_{ikj} l_i e_j^c l_k + \lambda'_{kji} d_i^c q_j l_k$$

are imposed by baryogenesis. Together with sphaleron processes, both operators influence the baryon asymmetry at high temperature in the early universe. The requirement that an existing baryon asymmetry is not erased before the electroweak transition typically implies

(Campbell et al., Fischler et al., '91)

$$\lambda\ , \lambda' < 10^{-7}\ .$$

Note: For such a small breaking of R-parity a gravitino LSP has a lifetime much longer than the age of the universe (Takayama, Yamaguchi '00). Reason: the double suppression by the inverse Planck mass and the R-parity breaking coupling, $\Gamma_{3/2} \propto \lambda^2 m_{3/2}^3 / {M_{\rm P}}^2$. The gravitino lifetime is

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

consistent with gravitino dark matter.

For a gravitino LSP, the properties of the next-to-lightest superparticle (NLSP) are strongly constrained by primordial nucleosynthesis (BBN). In the interesting case of a charged NLSP, like a scalar τ-lepton, its lifetime has to be rather short, $\tau_{\rm NLSP} \lesssim 10^3 - 10^4\ {\rm s}$ (Pospelov; Kohri, Takayama '06), which typically requires $m_{3/2} < 1\ {\rm GeV}$. For neutral particles, BBN excludes a neutralino NLSP for lifetimes longer than $10^2\ {\rm s}$ due to the strong constraints from hadronic showers.

Standard thermal leptogenesis needs a large reheating temperature in the early universe, $T_R \gtrsim 10^9$ GeV. This reheating temperature implies $m_{3/2} \gtrsim 5$ GeV for a gluino mass of $m_{\tilde{g}} = 500$ GeV in order to avoid overclosure of the universe due to thermal gravitino production. The lower bound on the gravitino mass scales as $m_{3/2}^{\min} \sim T_R m_{\tilde{g}}^2$.

All these cosmological problems are automatically solved without any fine tuning of parameters in the case of a small breaking of R-parity, with a gravitino LSP. The NLSP lifetime becomes sufficiently short for $\lambda, \lambda' > 10^{-14}$,

$$\tau_{\mathrm{NLSP}} \simeq 10^3 \mathrm{s} \left(\frac{\lambda}{10^{-14}}\right)^{-2} \left(\frac{m_{\mathrm{NLSP}}}{100\ \mathrm{GeV}}\right)^{-1} .$$

Therefore, primordial nucleosynthesis, thermal leptogenesis and gravitino dark matter are naturally consistent for $10^{-14} < \lambda, \lambda' < 10^{-7}$ and $m_{3/2} \gtrsim 5$ GeV.

Can such small R-parity violating couplings occur in theoretically well motivated extensions of the standard model? What are the constraints from neutrino physics, collider searches, EGRET data etc?

A Model for R-parity Breaking

Consider supersymmetric extension of the standard model with symmetry group G, including $U(1)_{B-L}$ and R-invariance,

$$G = SU(3) \times SU(2) \times U(1)_Y \times U(1)_{B-L} \times U(1)_R \ .$$

Field content: 3 quark-lepton generations grouped into the $SU(5)$ representations $\mathbf{10}_i = (q, u^c, e^c)_i$, $\bar{\mathbf{5}}_i = (d^c, l)_i$, $\mathbf{1} = \nu_i^c$, together 16-plets of $SO(10)$; two Higgs doublets H_u and H_d, 2 SM singlets N^c and N, and 3 $SO(10)$ singlets X, Φ and Z. The two Higgs doublets are contained in $\mathbf{5}$- and $\bar{\mathbf{5}}$-plets of $SU(5)$, H_u and H_d; N^c and N are contained in $\mathbf{16}$ and $\bar{\mathbf{16}}$ of $SO(10)$, which fixes their B-L charge as $+1$ and -1; X, Φ and Z have B-L charge zero. The field content is familiar from $SO(10)$ orbifold GUTs (cf. Asaka, WB, Covi): matter fields form complete $SO(10)$ representations, fields which break $SU(2) \times U(1)_Y$ and $U(1)_{B-L}$ appear as 'split' multiplets.

The superpotential of the matter sector has the usual form

$$W_M = h_{ij}^{(u)} \mathbf{10}_i \mathbf{10}_j H_u + h_{ij}^{(d)} \bar{\mathbf{5}}_i \mathbf{10}_j H_d + h_{ij}^{(\nu)} \bar{\mathbf{5}}_i \mathbf{1}_j H_d + \frac{1}{M_{\mathrm{P}}} h_{ij}^{(n)} \mathbf{1}_i \mathbf{1}_j N^2 \ ,$$

with $M_{\mathrm{P}} = 2.4 \times 10^{18}$ GeV as Planck mass. The expectation values of H_u and H_d generate Dirac masses of quarks and leptons, the expectation value of the singlet field N generates the Majorana mass matrix of the right-handed neutrinos $\mathbf{1}_i$.

The superpotential responsible for B-L breaking is chosen as

$$W_{B-L} = X(NN^c - \Phi^2) \ .$$

Φ plays the role of a spectator field, with $\langle\Phi\rangle = v_{B-L}$. Also Z is a spectator field which breaks supersymmetry and $U(1)_R$, $\langle Z\rangle = F_Z\theta\theta$. The total superpotential is the most general one consistent with the R-charges listed in Table 1, up to higher order terms.

	$\mathbf{10}_i$	$\mathbf{5}^*_i$	$\mathbf{1}_i$	H_u	H_d	N	N^c	Φ	X	Z
R	1	1	1	0	0	0	-2	-1	4	0

Table 1: *R-charges of matter fields, Higgs fields and $SO(10)$ singlets.*

The expectation value of Φ leads to the breaking of B-L,

$$\langle N \rangle = \langle N^c \rangle = \langle \Phi \rangle = v_{B-L} \ ,$$

where the first equality is a consequence of the $U(1)_{B-L}$ D-term. This generates Majorana mass matrix M for the right-handed neutrinos with 3 large eigenvalues, with $M_1 < M_2 < M_3$. If the largest eigenvalue of $h^{(n)}$ is $\mathcal{O}(1)$, one has $M_3 \simeq v_{B-L}^2/M_{\mathrm{P}}$. The heavy Majorana neutrinos can be integrated out yielding for the matter part of the superpotential

$$W_M = h_{ij}^{(u)} \ \mathbf{10}_i \mathbf{10}_j H_u + h_{ij}^{(d)} \ \bar{\mathbf{5}}_i \mathbf{10}_j H_d - \frac{1}{2} (h^{(\nu)} \frac{1}{M} h^{(\nu)T})_{ij} (\bar{\mathbf{5}}_i H_u)(\bar{\mathbf{5}}_j H_u) \ ,$$

with the familiar dimension-5 seesaw operator for light neutrino masses.

Since the field Φ carries R-charge -1, the VEV $\langle \Phi \rangle$ breaks R-parity, which is conserved by the VEV $\langle Z \rangle$. Thus, the breaking of B-L is tied to the breaking of R-parity!.

The breaking of R-parity is transmitted to the low-energy degrees of freedom via higher-dimensional operators in the superpotential and the Kähler potential. The leading correction to the Kähler potential is

$$\delta K_1 = \frac{1}{{M_{\rm P}}^3}(a_i Z^\dagger + a_i' Z)\Phi^\dagger N^c \bar{\mathbf{5}}_i H_u + \frac{1}{{M_{\rm P}}^3}(c_i Z^\dagger + c_i' Z)\Phi N^\dagger \bar{\mathbf{5}}_i H_u + h.c. \ .$$

Replacing the spectator fields Z and Φ, as well as N^c by their VEVs (breaking of B-L and R-parity !!), one obtains the correction to the superpotential

$$\delta W_1 = \mu_i \Theta \bar{\mathbf{5}}_i H_u \ , \quad \mu_i = \mathcal{O}(m_{3/2}) \ , \quad \Theta = \frac{v_{B-L}^2}{{M_{\rm P}}^2} \simeq \frac{M_3}{M_{\rm P}} \ ,$$

where $m_{3/2} = F_Z/(\sqrt{3}M_{\rm P})$ is the gravitino mass (bilinear R-parity breaking). The correction to the Kähler potential

$$\delta K_0 = \frac{k}{M_{\rm P}} Z^\dagger H_d H_u + h.c.$$

yields the corresponding R-parity conserving term (Giudice, Masiero '88)

$$\delta W_0 = \mu H_d H_u \ , \quad \mu = \mathcal{O}(m_{3/2}) \ .$$

The convenient change of basis,

$$H_d = H'_d - \epsilon_i l'_i \ , \quad l_i = l'_i + \epsilon_i H'_d \ , \quad \epsilon_i = \Theta \frac{\mu_i}{\mu} \ ,$$

leads to the superpotential

$$\begin{aligned} W &= W_M + \delta W_0 + \delta W_1 \\ &= \mu H'_d H_u + h^{(u)}_{ij} q_i u^c_j H_u + h^{(d)}_{ij} d^c_i q_j H'_d + h^{(e)}_{ij} l'_i e^c_j H'_d \\ &\quad -\epsilon_k h^{(d)}_{ij} d^c_i q_j l'_k - \epsilon_k h^{(e)}_{ij} \ l'_i e^c_j l'_k - \frac{1}{2}(h^{(\nu)} \frac{1}{M} h^{(\nu)T})_{ij} (l'_i H_u)(l'_j H_u) + \ldots \ . \end{aligned}$$

The mixing of Higgs and lepton superfields has induced trilinear R-parity breaking terms $\mathcal{O}(\epsilon)$. These mixing terms induce vacuum expectation values for the scalar neutrinos, mixing terms $\mathcal{O}(\epsilon)$ of neutrinos with neutralinos, and (negligable) neutrino masses $\mathcal{O}(\epsilon^2)$,

$$m_\nu^{R\!\!\!/ p} \sim 10^{-4}\mathrm{eV} \left(\frac{\epsilon_3}{10^{-7}}\right)^2 \left(\frac{\widetilde{m}_1}{200\mathrm{GeV}}\right)^{-1} \ .$$

Scale of B-L Breaking and Thermal Leptogenesis

The phenomenological viability of the model depends on the size of R-parity breaking mixings ϵ_i and therefore on the scale v_{B-L} of R-parity breaking. The potential washout of a baryon asymmetry before the electroweak phase transition is avoided if the R-parity violating Yukawa couplings satisfy $\lambda_{ijk}, \lambda'_{ijk} \lesssim 10^{-7}$, which implies

$$\left(\frac{\epsilon_i}{10^{-6}}\right)\left(\frac{\tan\beta}{10}\right) \lesssim 1 \ .$$

The possible scales of B-L breaking can be illustrated by a model for quark and lepton mass hierarchies (WB, Yanagida '99) based on a Froggatt-Nielsen $U(1)$ flavour symmetry. The mass hierarchies are generated by the expectation value of a singlet field ϕ with charge $Q_\phi = -1$ via nonrenormalizable interactions with a scale $\Lambda = \langle\phi\rangle/\eta > \Lambda_{GUT}$, $\eta \simeq 0.06$. Yukawa couplings and bilinear terms for $SU(5)$ multiplets ψ_i with charge Q_i scale like

$$h_{ij} \propto \eta^{Q_i+Q_j} \ , \quad \mu_i \propto \eta^{Q_i} \ .$$

ψ_i	$\mathbf{10}_3$	$\mathbf{10}_2$	$\mathbf{10}_1$	$\mathbf{5}^*_3$	$\mathbf{5}^*_2$	$\mathbf{5}^*_1$	$\mathbf{1}_3$	$\mathbf{1}_2$	$\mathbf{1}_1$	H_u	H_d	Φ	X	Z
Q_i	0	1	2	a	a	a+1	b	c	d	0	0	0	0	0

Table 2: *Chiral charges.* $a = 0$ *or* 1, *and* $0 \leq b \leq c \leq d$.

Charges Q_i describing the observed quark and lepton masses and mixings are listed in Table 2. The model also predicts the observed baryon asymmetry via leptogenesis for the cases where $a + d = 2$. There are two, at low energies indistinguishable, consistent scales of B-L breaking:

$$M_3 \sim 10^{15}\ \mathrm{GeV} \quad (a = b = 0, c = 1, d = 2)\ ,$$
$$M_3 \sim 10^{12}\ \mathrm{GeV} \quad (b = c = 0, a = d = 1).$$

For $\mu_i/\mu = 1.0 \ldots 0.01$ these two cases lead to the R-parity breaking mixing parameters

$$\text{(I)} \quad \frac{\epsilon_i}{\eta^{Q_i}} = 10^{-3} \ldots 10^{-5}\ , \qquad \text{(II)} \quad \frac{\epsilon_i}{\eta^{Q_i}} = 10^{-6} \ldots 10^{-8}\ .$$

In the extreme case $M_3 \sim M_2 \sim M_1 \sim 10^{10}$ GeV without Froggatt-Nielsen symmetry, where leptogenesis may still work for an appropriate enhancement of the CP asymmetry, one has

$$\text{(III)} \quad \epsilon_i = 10^{-8} \ldots 10^{-10} \, .$$

In the flavour models (I) and (II) the RPV mixings ϵ_i are suppressed by η^{Q_i}; model (I) is inconsistent with the constraints from neutrino masses and baryogenesis washout; the models (II) and (III) are consistent with both constraints.

The expected mass scale of right-handed neutrinos depends on the mechanism which breaks B-L. The expectation value of a field with lepton number $L = 2$ generates heavy Majorana masses via renormalizable Yukawa couplings. With B-L broken at the GUT scale, and for Yukawa coupling $\mathcal{O}(1)$ for the third family, one then obtains the canonical result $M_3 \sim v_{B-L} \sim 10^{15}$ GeV. If right-handed neutrino masses are generated via a nonrenormalizable dimension-5 operator and the expectation value of a field with $L = 1$, one has instead $M_3 \sim v_{B-L}^2/M_{\rm P} \sim 10^{12}$ GeV. This illustrates how the two mass scales for M_3, which correspond to the two cases (I) and (II), respectively, might be obtained.

(4) Signatures at LHC and GLAST

Since R-parity is broken, the gravitino is no more stable. But its decay is suppressed both by the Planck mass and the small R-parity breaking parameters, so the lifetime is much longer than the age of the universe (Takayama, Yamaguchi '00),

$$\Gamma(\psi_{3/2} \to \gamma\nu) = \frac{1}{32\pi} |U_{\tilde{\gamma}\nu}|^2 \frac{m_{3/2}^3}{M_{\mathrm{P}}{}^2} \; .$$

Here the photino-neutrino mixing is

$$|U_{\tilde{\gamma}\nu}| \simeq g_z \left| \sum_{\alpha=1}^{4} c_{\tilde{\gamma}\alpha} c_{\tilde{z}\alpha}^* \frac{v_\nu}{m_{\chi_\alpha^0}} \right| \sim 10^{-8} \left(\frac{\epsilon_3}{10^{-7}} \right) \left(\frac{\widetilde{m}_1}{200 \text{ GeV}} \right)^{-1} \; ,$$

for $\epsilon_1, \epsilon_2 \leq \epsilon_3$, with the rough estimate $0.1/\widetilde{m}_1$ for the weighted sum of neutralino masses and the coupling. Using $M_{\mathrm{P}} = 2.4 \times 10^{18}$ GeV, the gravitino lifetime becomes

$$\tau_{3/2}^{2-\mathrm{body}} \simeq 4 \times 10^{27} \mathrm{s} \left(\frac{\epsilon_3}{10^{-7}} \right)^{-2} \left(\frac{\widetilde{m}_1}{200 \text{ GeV}} \right)^{2} \left(\frac{m_{3/2}}{10 \text{ GeV}} \right)^{-3} \; .$$

Extragalactic Diffuse Gamma-Ray Emission

Decaying gravitino dark matter leads to an extragalactic diffuse gamma-ray flux with a characteristic energy spectrum, corresponding to a red shifted monochromatic line. A photon with measured energy $E = m_{3/2}/(2(1+z))$ has been emitted at the comoving distance $\chi(z)$, with $d\chi/dz = (1+z)^{-3/2}/(a_0 H_0 \sqrt{\Omega_M(1+\kappa(1+z)^{-3})})$ (a_0: scale factor, H_0: Hubble parameter, $\kappa = \Omega_\Lambda/\Omega_M \simeq 3$, $\Omega_\Lambda + \Omega_M = 1$, assuming a flat universe). This yields the photon flux ($\tau_{3/2} \gg H_0^{-1}$)

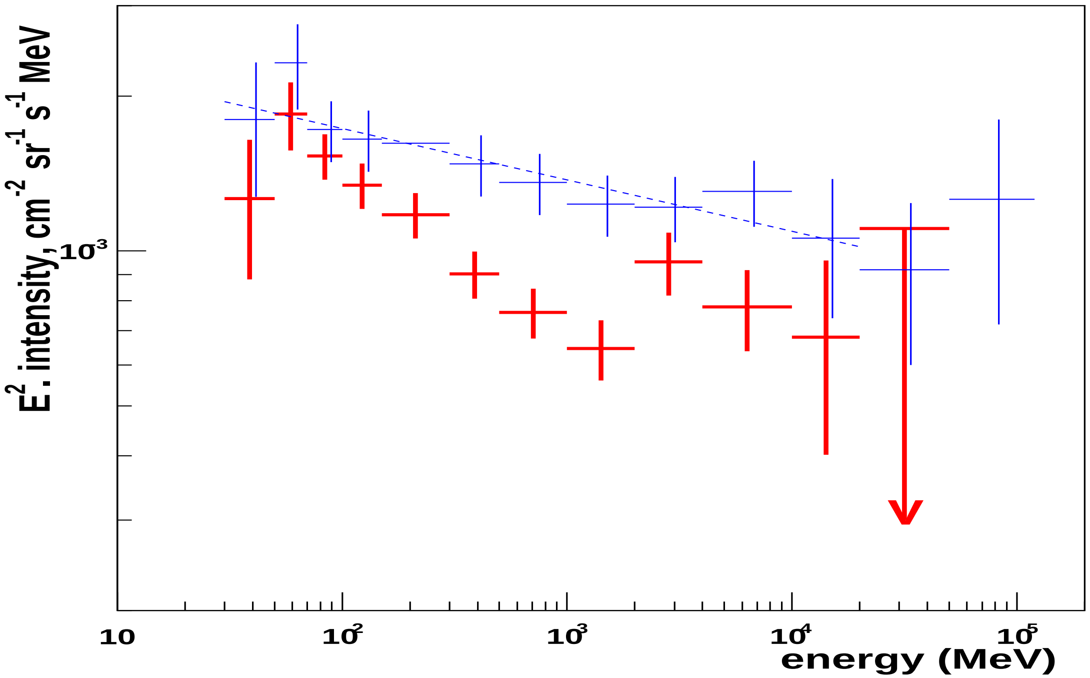
$$E^2 \frac{dJ_{eg}}{dE} = C_\gamma \left(1 + \kappa \left(\frac{2E}{m_{3/2}}\right)^3\right)^{-1/2} \left(\frac{2E}{m_{3/2}}\right)^{5/2} \theta\left(1 - \frac{2E}{m_{3/2}}\right) ,$$

with

$$C_\gamma = \frac{\Omega_{3/2}\rho_c}{8\pi\tau_{3/2}H_0\Omega_M^{1/2}} = 10^{-6}\ (\mathrm{cm}^2\mathrm{str\ s})^{-1}\mathrm{GeV}\left(\frac{\tau_{3/2}}{10^{28}\mathrm{s}}\right)^{-1} ;$$

here the gravitino density is taken equal to the Cold Dark Matter density: $\Omega_{3/2}h^2 = 0.1$, $\rho_c = 1.05\ h^2 \times 10^{-5}\mathrm{GeVcm}^{-3}$, $\Omega_M = 0.25$, $H_0 = h\ 100\ \mathrm{km\ s}^{-1}\ \mathrm{Mpc}^{-1}$, $h = 0.73$; flux is normalized to expectation from theoretical model. In addition there is an anisotropic halo contribution of comparable magnitude.

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 $m_{3/2} \sim 10\ \mathrm{GeV}$; halo component may partly be hidden in anisotropic galactic gamma-ray flux $\longrightarrow$ wait for GLAST !!

Signatures at Colliders

The collider signatures depend on the nature of the NLSP. Most important cases: the lightest stau (assume mostly $\widetilde{\tau}_R$) or the lightest neutralino.

The lightest stau decays through $\widetilde{\tau}_R \longrightarrow \tau\ \nu_\mu, \mu\ \nu_\tau$. Further, the small left-handed component of the stau mass eigenstate can trigger a decay into two jets through $\widetilde{\tau}_L \longrightarrow b^c t$, if the process is kinematically open. The hadronic decays are enhanced compared to the leptonic decays by the larger bottom Yukawa coupling and by the colour factor, but are usually suppressed by the small left-right mixing.

If the leptonic decay channel is dominant, the decay length is

$$c\tau_{\tilde{\tau}}^{lep} \sim 30\ \mathrm{cm} \left(\frac{m_{\tilde{\tau}}}{200\mathrm{GeV}}\right)^{-1} \left(\frac{\epsilon_2}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{-2} .$$

Note: the sufficient condition to avoid the erasure of the baryon asymmetry, $\epsilon_2 < 10^{-6}$, implies the observation of a displaced stau vertex at future colliders, more than 3mm away from the beam axis. For the FN flavour model (II), with $\epsilon_2 \sim 6 \times 10^{-8}$, one has a spectacular signal with heavily ionising charged track of length ~ 0.8 m, followed by a muon track or a jet and missing energy, corresponding to $\widetilde{\tau} \longrightarrow \mu\nu_\tau$ or $\widetilde{\tau} \longrightarrow \tau\nu_\mu$.

If the hadronic channel $\widetilde{\tau}_L \longrightarrow b^c t$ is dominant, the decay length is given by

$$c\tau_{\tilde{\tau}}^{had} \sim 1.4 \text{ m} \left(\frac{m_{\tilde{\tau}}}{200\text{GeV}}\right)^{-1} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{-2} \left(\frac{\cos\theta_\tau}{0.1}\right)^{-2} ,$$

where θ_τ is the mixing angle of the staus. Again one has a unique signature: a heavily ionising charged track followed by two jets.

If the lightest neutralino is the NLSP, it decays through $\chi_1^0 \longrightarrow \tau^\pm W^\mp$, if kinematically possible, otherwise through $\chi_1^0 \longrightarrow b\, b^c\, \nu$. The corresponding decay lengths are

$$c\tau_{\chi_1^0}^{2-\text{body}} \sim 20 \text{ cm} \left(\frac{m_{\chi_1^0}}{200\text{ GeV}}\right)^{-3} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{2} ,$$

$$c\tau_{\chi_1^0}^{3-\text{body}} \sim 600 \text{ m} \left(\frac{m_{\widetilde{\nu}_L}}{300\text{ GeV}}\right)^{4} \left(\frac{m_{\chi_1^0}}{200\text{ GeV}}\right)^{-5} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{-2} ,$$

yielding again displaced vertices with characteristic decays. In general, the models with very small R-parity violation are characterized by macroscopic NLSP decay lengths, which can clearly be distinguished from the case of conserved R-parity.

SUMMARY

- Gravitino is viable dark matter candidate, favoured by the simplest version of thermal leptogenesis
- For small R-parity breaking, gravitino dark matter is consistent with BBN constraints; the photon flux from gravitino decays may have already been observed by EGRET
- Long lived NLSPs, scalar tau or neutralino, lead to spectacular signatures at LHC/ILC.