GRAVITINO DARK MATTER IN TREE LEVEL GAUGE MEDIATION

based on:

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JHEP 1112:040,2011

Invisibles Pre-Meeting Madrid March 29th 2012

Plan of the talk

1. Tree Level Gauge Mediation

2. Gravitino DM with R-parity conserved

3. Gravitino DM with R-parity violated

4. An R-parity violating SO(10) model

5. Cosmological analysis

MSSM DM CANDIDATES

WIMP DM (ONLY RPC) → Lightest neutralino

Pro:

- "Wimp miracle", a very elegant mechanism for generation of the DM relic density only dependent on IR physics;
- Higly testable scenario, (direct/indirect detection, colliders)

Con:

- Very difficult to achieve the correct relic density

NON WIMP DM (BOTH RPC AND RPV) → Gravitino

RPC case

Pro:

- Sensitivity of the relic density to the DM mass, itself connected to the SUSY breaking mechanism;

Con:

- Relic density may depend on UV physics (related to the reheating temperature)
- More difficult detection
- Tension with BBN for high gravitino masses.

GRAVITINO DM WITH RPV

Why RPV:

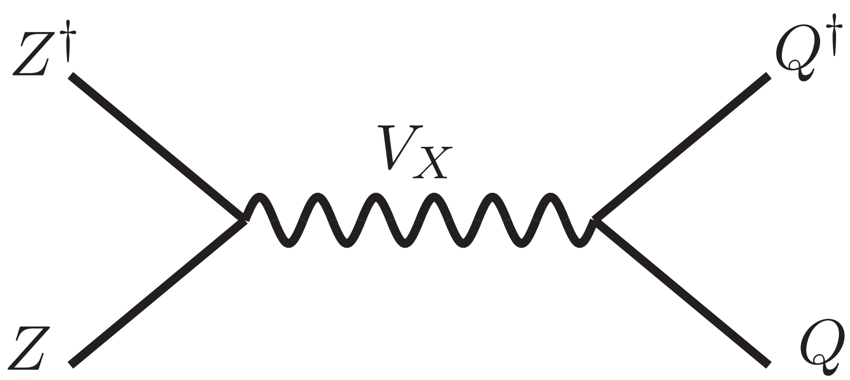
- RPV not forbidden a priory from theoretical/phenomenological point of view
- Possible explanation for negative LHC searches
- Other interesting features, e.g. generation of neutrino masses

Gravitino DM with RPV:

- BBN bounds evaded for higher gravitino masses
- Connection with thermal leptogenesis
- Possibility of DM detection through its decays
- Additional constraints: proton decay, several astrophysical and cosmological bounds.

Tree Level Gauge Mediation

Susy is spontaneously broken by the F-term v.e.v of a SM singlet chiral superfield Z.
Susy breaking is directly communicated at tree level by gauge interactions associated to an extra U(1) symmetry.



$$\int d^4\theta \frac{Z^\dagger Z Q^\dagger Q}{M_X^2} \to (\tilde{m}_Q^2)_{\text{tree}} \tilde{Q}^\dagger \tilde{Q} \quad \langle Z \rangle = F\theta^2$$

$$(\tilde{m}_Q^2)_{\text{tree}} = g_X^2 X_Q X_Z \frac{F^2}{M_X^2}$$

$$m_{3/2} \sim m_{\text{soft}} \frac{M_X}{M_P}$$

Natural embedding into a rank-5 Grand Unified theory.

The sfermion mass terms are flavor Universal also for mediation scale coinciding with GUT scale.

Ratios among sfermion masses, up to radiative corrections, fixed by charges under the additional gauge symmetries.

References:
M. Nardecchia, A. Romanino, R. Ziegler; **JHEP 0911:112,2009**
M. Nardecchia, A. Romanino, R. Ziegler; **JHEP 1003:024,2010**
M. Monaco, M. Nardecchia, A. Romanino, R. Ziegler; **JHEP 1110:022,2011**

SO(10) theory

The (usual) embedding of chiral MSSM superfields in the 16 does not work. 10 and 16 representations are needed.

$$16_F = (D^c \oplus L)_{\bar{5}_{-3}} \oplus (u^c \oplus q \oplus e^c)_{10_{+1}} \oplus (\nu^c)_{1_{+5}}$$

$$10_F = (D \oplus L^c)_{5_{-2}} \oplus (d^c \oplus \ell)_{\bar{5}_{+2}}$$

"Pure embedding"

Heavy additional states

$$16_H = (T_d^{16} \oplus h_d^{16})_{\bar{5}_{-3}} \oplus (\ldots)_{10_{+1}} \oplus (\ldots)_{1_{+5}}$$

$$\overline{16}_H = (T_u^{\overline{16}} \oplus h_u^{\overline{16}})_{5_{+3}} \oplus (\ldots)_{\overline{10}_{-1}} \oplus (\ldots)_{1_{-5}}$$

$$10_H = (T_u^{10} \oplus h_u^{10})_{5_{-2}} \oplus (T_d^{10} \oplus h_d^{10})_{\bar{5}_{+2}}$$

The fields in the same representation have the same charge under U(1)

$$W = \frac{y_{ij}}{2} 16_i 16_j 10 + h_{ij} 16_i 10_j 16 + h'_{ij} 16_i 10_j 16' + W_{\text{vev}} + W_{\text{NR}}$$

Nardecchia, Romanino, Ziegler; JHEP(2009)

Tree level contribution to sfermion masses

$$(\tilde{m}_Q^2)_{\text{tree}} = \begin{cases} 2\,\tilde{m}_{10}^2 & Q = d^c, \ell \\ \tilde{m}_{10}^2 & Q = q, u^c, e^c \\ -2\,\tilde{m}_{10}^2 < (\tilde{m}_{h_u}^2)_{\text{tree}} < 3\,\tilde{m}_{10}^2 \\ -3\,\tilde{m}_{10}^2 < (\tilde{m}_{h_d}^2)_{\text{tree}} < 2\,\tilde{m}_{10}^2 \end{cases}$$

Gaugino masses generated at one-loop

$$M_a = \frac{\alpha}{4\pi} \operatorname{Tr}(h' h^{-1})\, m \equiv M_{1/2}$$

$$\left.\frac{M_2}{\tilde{m}_t}\right|_{M_{\text{GUT}}} = \frac{3\sqrt{10}}{(4\pi)^2} \lambda, \quad \lambda = \frac{g^2 \operatorname{Tr}(h' h^{-1})}{3}$$

In principle Susy breaking is mediated both and tree and at the loop level.

$$\tilde{m}_Q^2 = (\tilde{m}_Q^2)_{\rm tree} + 2\,\eta\, C_Q M_{1/2}^2 \qquad\qquad \eta = \frac{\sum (h_i'/h_i)^2}{(\sum_i h_i'/h_i)^2} \geq \frac{1}{3}$$

Q	q	u^c	d^c	ℓ	e^c	h_u	h_d
C_Q	21/10	8/5	7/5	9/10	3/5	9/10	9/10

TGM dominates if: $\tilde{m}_{10} \gtrsim (5.2 + 4.2\,\eta)^{1/2}\, M_{1/2}$ ⟶ The NLSP is the lightest gaugino

⟶ $\tilde{m}_t \gtrsim 1.2 \text{ TeV} \left(\frac{m_{\tilde{g}}}{700 \text{ GeV}}\right)$

The gravitino mass is always related to the tree level contribution. $m_{3/2} \approx 15\,\text{GeV} \left(\frac{\tilde{m}_{10}}{1 \text{ TeV}}\right)$

RPC Cosmology

$$\Omega^T_{DM} h^2 = \left(\frac{m_{3/2}}{10\ \text{GeV}}\right)\left(\frac{T_{RH}}{10^9\ \text{GeV}}\right)\sum_r y'_r\, g_r^2(T_{RH})\,(1+\delta_r)\left(1+\frac{M_r^2(T_{RH})}{2m_{3/2}^2}\right)\ln\left(\frac{k_r}{g_r(T_{RH})}\right)$$

J. Pradler and F. D. Steffen; PRD (2007)

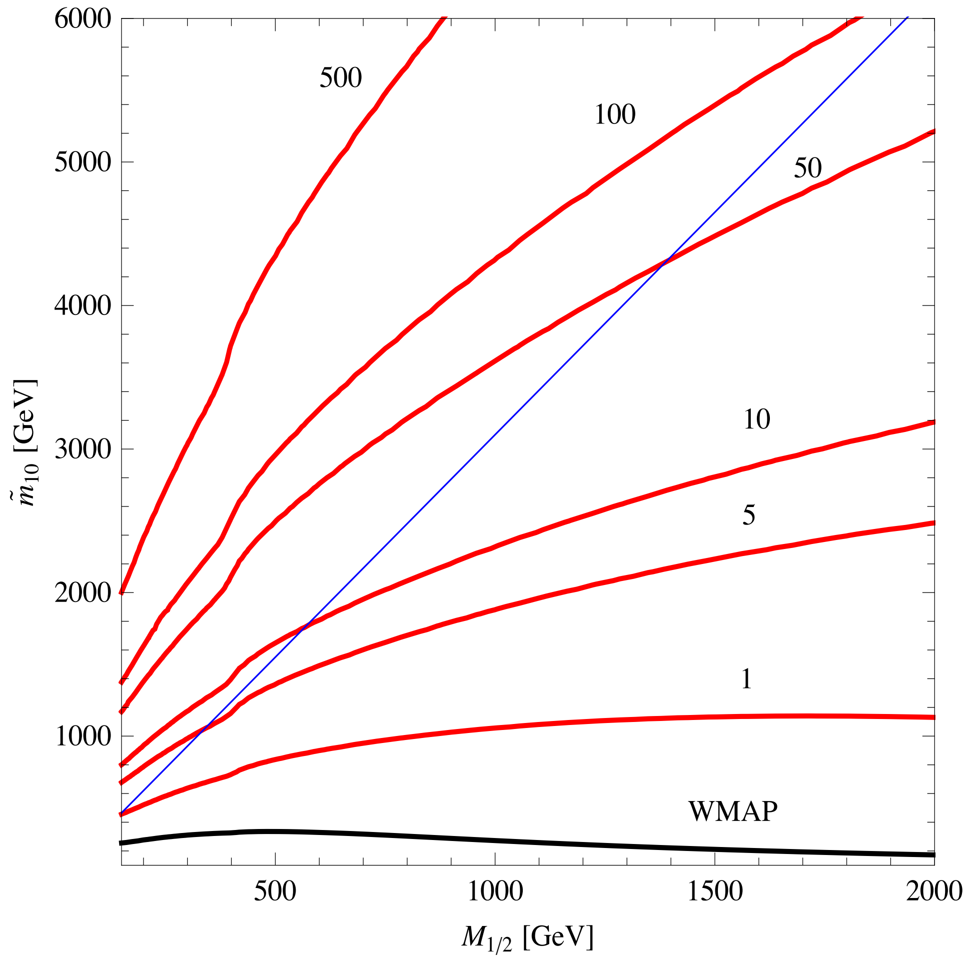
$$\Omega^{NT}_{3/2} h^2 = \frac{m_{3/2}}{m_{NLSP}}\Omega_{NLSP}\, h^2 \simeq 3\times 10^{-2}\frac{\tilde{m}_{10}}{M_{1/2}}\Omega_{NLSP}\, h^2$$

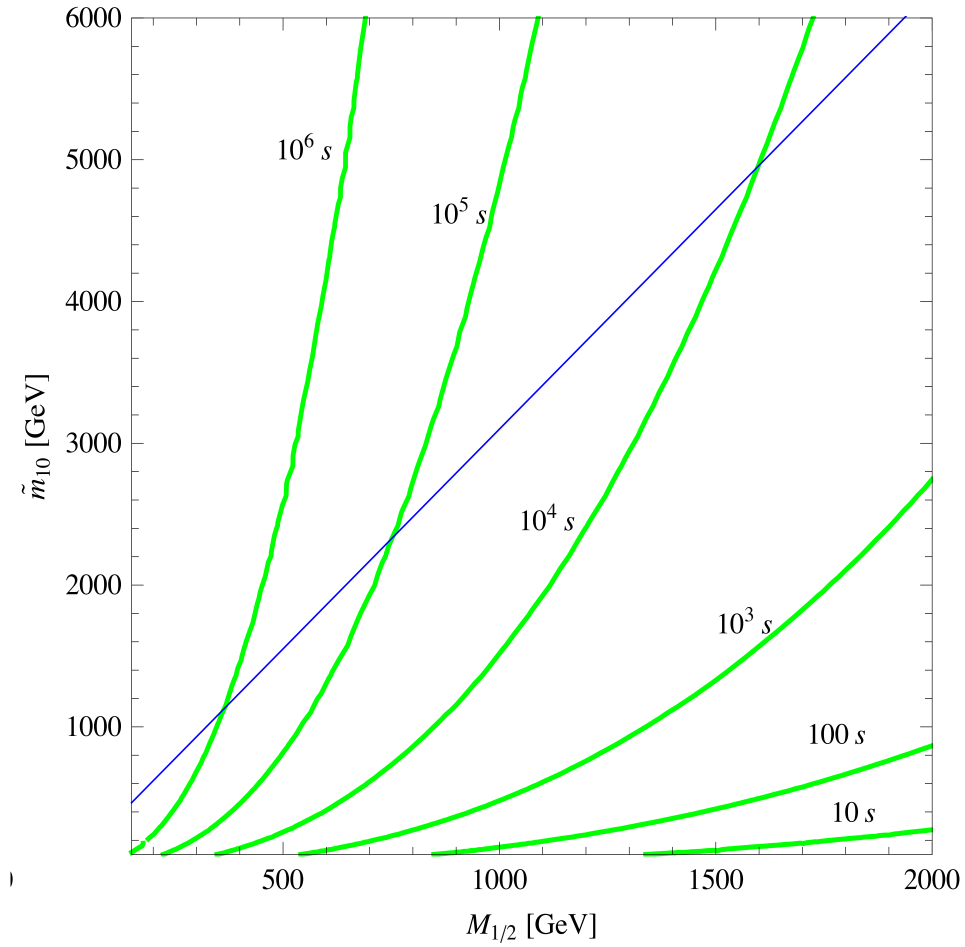
Sizable contribution from gravitinos produced by NLSP decays.

Late time decays, because of the high gravitino mass should not affect BBN:

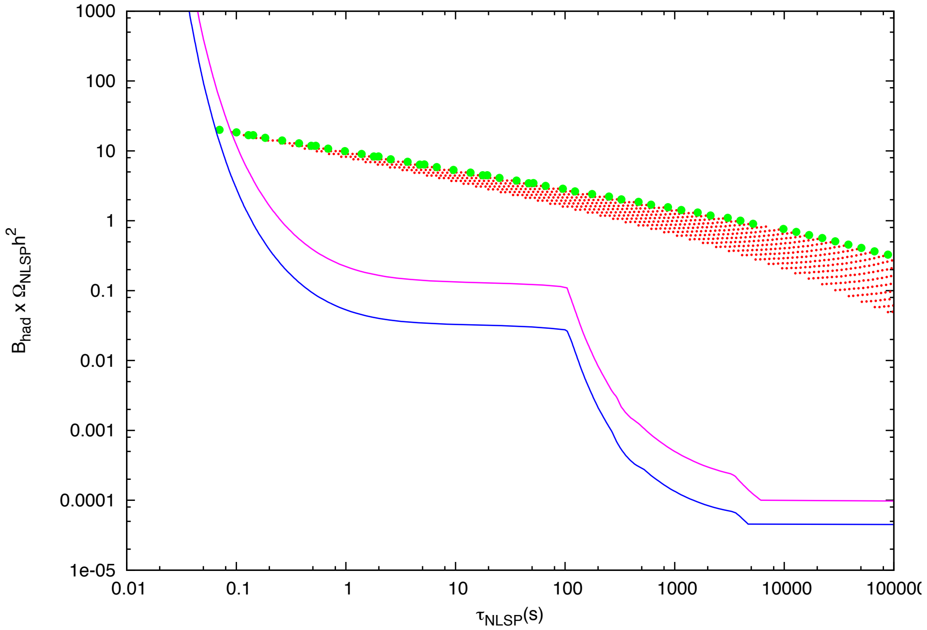
$$\Gamma(\chi^0_1 \to Z\tilde{G}) = \frac{\sin^2\theta_W}{48\pi M_P^2}\frac{m^5_{\chi^0_1}}{m^2_{3/2}}$$

$$\Gamma(\chi^0_1 \to \gamma\,\tilde{G}) = \frac{\cos^2\theta_W}{48\pi M_P^2}\frac{m^5_{\chi^0_1}}{m^2_{3/2}}$$



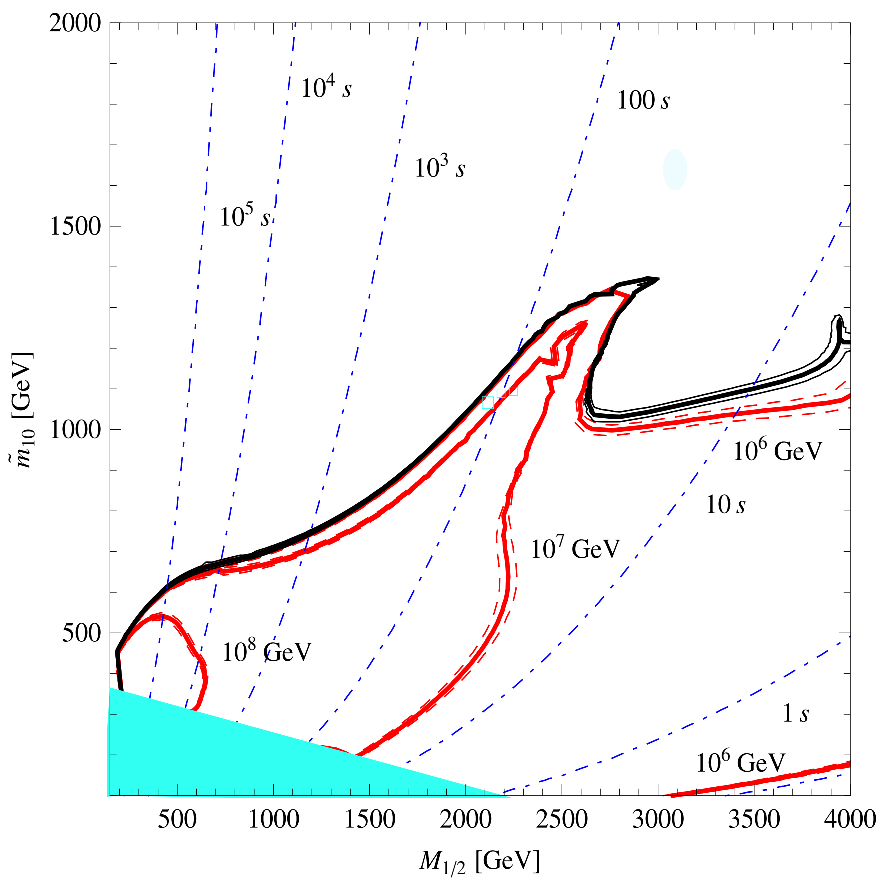


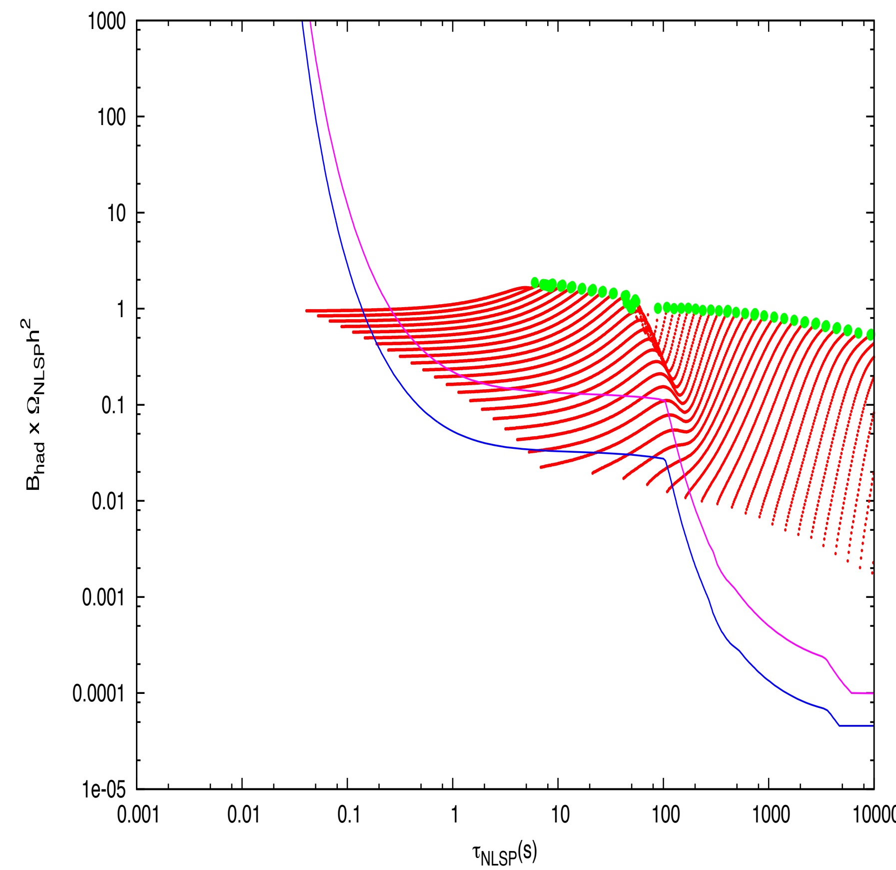
Severe tension with cosmological constraints.



SO(10) model ruled out by BBN where TGM is the main origin of sfermion masses.

Cosmological viability can be achieved where Tree-level mediation is subdominant respect to loop-level one.





(we thank J. Hasenkamp and J. Roberts for providing BBN bounds, see also, L. Covi, J. Hasenkamp, S. Pokorski, and J. Roberts, JHEP (2009) and referencees therein)

Summary of RPC case:

NLSP (and hence gravitinos) are typically over produced and are too-much long-lived

Cosmological viability only in small regions in the parameter space where the NLSP abundance can be suppressed.

In none of this regions TGM is the dominant mechanism for sfermion mass generation.

Elegant solution in RPV:

NLSP lifetime can be shorter respect to the onset of BBN thanks to new decay channels allowed.

NLSP mainly decays into only SM particles, no overproduction of gravitinos.

"Explicit" SO(10) RPV theory

SO(10) broken at the renormalizable level by: $54_H \oplus 45_H \oplus 16_H \oplus \overline{16}_H \oplus 10_H$

$$\delta W_{RPV} = \left(\tilde{\mu}^i_{10} + \tilde{\eta}^i_{10} 45_H + \tilde{\lambda}^i_{10} 54_H\right) 10^i_F 10_H + \left(\tilde{\mu}^i_{16} + \tilde{\lambda}^i_{16} 45_H\right) 16^i_F \overline{16}_H$$
$$+ \tilde{\rho}^i 16^i_F 16_H 10_H + \tilde{\sigma}^i 10^i_F 16_H 16_H + \tilde{\overline{\sigma}}^i 10^i_F \overline{16}_H \overline{16}_H + \tilde{\Lambda}^{ijk} 16^i_F 16^j_F 10^k_F$$

+ Non-renormalizable term

$$\frac{\tilde{\Lambda}^{NR}_{ijk}}{M_P} 10^i_F 10^j_F 16^k_F \langle \overline{16}_H \rangle \supset \lambda^{NR}_{ijk} \ell_i \ell_j e^c_k + \lambda'^{NR}_{ijk} d^c_i \ell_j q_k + \lambda''^{NR}_{ijk} d^c_i d^c_j u^c_k$$

SO(10) RPV Theory

Contrary to the usual embedding SO(10) does not protect from RPV.

Most general theory within the chosen set of representations.

$$
\begin{aligned}
16_F &= (D^c \oplus L)_{\overline{5}_{-3}} \oplus (u^c \oplus q \oplus e^c)_{10_{+1}} \oplus (\nu^c)_{1_{+5}} \\
10_F &= (D \oplus L^c)_{5_{-2}} \oplus (d^c \oplus \ell)_{\overline{5}_{+2}} \\
16_H &= (T_d^{16} \oplus h_d^{16})_{\overline{5}_{-3}} \oplus (\ldots)_{10_{+1}} \oplus (\ldots)_{1_{+5}} \\
\overline{16}_H &= (T_u^{\overline{16}} \oplus h_u^{\overline{16}})_{5_{+3}} \oplus (\ldots)_{\overline{10}_{-1}} \oplus (\ldots)_{1_{-5}} \\
10_H &= (T_u^{10} \oplus h_u^{10})_{5_{-2}} \oplus (T_d^{10} \oplus h_d^{10})_{\overline{5}_{+2}}
\end{aligned}
$$

→ SO(10) broken at the renormalizable level by:

$$54_H \oplus 45_H \oplus 16_H \oplus \overline{16}_H \oplus 10_H$$

Renormalizable Superpotential

$$
\begin{aligned}
W_H &= (\mu_{54} + \eta_{54} 45_H + \lambda_{54} 54_H)\, 54_H^2 + \mu_{45} 45_H^2 + (\mu_{10} + \lambda_{10} 54_H)\, 10_H^2 \\
&\quad + (\mu_{16} + \lambda_{16} 45_H)\, 16_H \overline{16}_H + \lambda_{16-10} 16_H^2 10_H + \overline{\lambda}_{16-10} \overline{16}_H^2 10_H \,, \\
W_Y &= Y_{10}^{ij} 16_F^i 16_F^j 10_H + Y_{16}^{ij} 16_F^i 10_F^j 16_H + \left(M_{10}^{ij} + \eta^{ij} 45_H + \lambda^{ij} 54_H \right) 10_F^i 10_F^j \,,
\end{aligned}
$$

$$
\begin{aligned}
\delta W_{RPV} &= \left(\tilde{\mu}_{10}^i + \tilde{\eta}_{10}^i 45_H + \tilde{\lambda}_{10}^i 54_H \right) 10_F^i 10_H + \left(\tilde{\mu}_{16}^i + \tilde{\lambda}_{16}^i 45_H \right) 16_F^i \overline{16}_H \\
&\quad + \tilde{\rho}^i 16_F^i 16_H 10_H + \tilde{\sigma}^i 10_F^i 16_H 16_H + \tilde{\overline{\sigma}}^i 10_F^i \overline{16}_H \overline{16}_H + \tilde{\Lambda}^{ijk} 16_F^i 16_F^j 10_F^k
\end{aligned}
$$

+ Non-renormalizable term

$$\frac{\tilde{\Lambda}_{ijk}^{NR}}{M_P} 10_F^i 10_F^j 16_F^k \langle \overline{16}_H \rangle \supset \lambda_{ijk}^{NR}\, \ell_i \ell_j e_k^c + \lambda_{ijk}^{\prime NR}\, d_i^c \ell_j q_k + \lambda_{ijk}^{\prime\prime NR}\, d_i^c d_j^c u_k^c$$

Effective RPV theory

$$W_{RPV}^{eff} = \mu_i \, \ell_i h_u + \lambda_{ijk} \, \ell_i \ell_j e_k^c + \lambda'_{ijk} \, d_i^c \ell_j q_k + \lambda''_{ijk} \, d_i^c d_j^c u_k^c \longleftarrow \mu^i = \cos\theta_u \left(\tilde{\mu}_{10}^i - \tilde{\eta}_{10}^i V_R^{45} + \frac{1}{2}\sqrt{\frac{3}{5}} \tilde{\lambda}_{10}^i V^{54} \right) + \sin\theta_u \tilde{\overline{\sigma}}^i V^{16}$$

$$\uparrow$$

$$\frac{\tilde{\Lambda}_{NR}^{ijk}}{M_P} 10_F^i 10_F^j 16_F^k \langle \overline{16}_H \rangle \supset \frac{\tilde{\Lambda}_{NR}^{ijk}}{M_P} \overline{5}_{10_F}^i \overline{5}_{10_F}^j 10_{16_F}^k \langle 1_{\overline{16}_H} \rangle = \frac{\tilde{\Lambda}_{NR}^{ijk} V^{16}}{M_P} \left(\ell_i \ell_j e_k^c + 2 \, d_i^c \ell_j q_k + d_i^c d_j^c u_k^c \right)$$

Bounds from proton decay passed if:

$$\Lambda \lesssim 10^{-10} \left(\frac{\tilde{m}}{1 \text{ TeV}} \right)^2$$

A.Y. Smirnov and F. Vissani; Nucl. Phys. B460, 37 (1996)

Combination of bounds from proton decay and GUT relations points towards strong suppression of trilinear couplings.

Relevant phenomenology can be traced through an effective Bilinear R-parity violating theory.

For reference see e.g. Suzuki and Hall Nucl. Phys. B (1984),
Hirsch et al. PRD (2000)

Bilinear RPV theory

$$W^{eff}_{RPV} = \mu_i \, \ell_i h_u$$

$$V^{\rm soft}_{RPV} = B_i \, \tilde{\ell}_i h_u + \tilde{m}^2_{h_d \ell_i} h^\dagger_d \tilde{\ell}_i + {\rm h.c.}$$

$\longrightarrow$ $\epsilon_i = \mu_i/\mu$

$$h_d \to \hat{h}_d = h_d + \epsilon_i \ell_i$$

$$\ell_i \to \hat{\ell}_i = \ell_i - \epsilon_i h_d$$

$\downarrow$ Sneutrinos get v.e.v at EWSB

$$v_i \equiv -\xi_i \langle h_d \rangle = -\frac{\hat{B}_i \tan\beta + \hat{\tilde{m}}^2_{h_d \ell_i}}{\hat{\tilde{m}}^2_{\ell_i} + \frac{1}{2} M_Z^2 \cos 2\beta} \langle h_d \rangle$$

$$\xi_i \approx \frac{(B_i - \epsilon_i B)\tan\beta + \tilde{m}^2_{h_d \ell_i} + \epsilon_i (\tilde{m}^2_{\ell_i} - \tilde{m}^2_{h_d})}{\tilde{m}^2_{\ell_i} + \frac{1}{2} M_Z^2 \cos 2\beta}$$

$\downarrow$

$$\hat{\lambda}_{ijk} = -(Y_e)_{ik} \epsilon_j + (Y_e)_{jk} \epsilon_i$$

$$\hat{\lambda}'_{ijk} = -(Y_d)_{ik} \epsilon_j$$

see e.g. W. Buchmuller, L. Covi, K. Hamaguchi, A. Ibarra, and T. Yanagida; JHEP (2007),
S. Bobrovskyi, W. Buchmuller, J. Hajer, and J. Schmidt; JHEP (2010)

Relevant phenomenology and constraints:

- NLSP lifetime and BBN;
- Gravitino lifetime and cosmic rays;
- Neutrino masses through RPV;
- Gravitino relic density and thermal leptogenesis.

NLSP Lifetime and BBN

2-body decays:

$$\Gamma\left(\chi_1^0 \to Z\,\nu\right) = \frac{G_F\, m_{\chi_1^0}^3}{4\pi\sqrt{2}} \frac{\sin^2\theta_W \cos^2\beta}{M_1^2}\xi^2$$

$$\Gamma\left(\chi_1^0 \to W^{\pm} l^{\mp}\right) = \frac{G_F\, m_{\chi_1^0}^3}{2\pi\sqrt{2}} \frac{\sin^2\theta_W \cos^2\beta}{M_1^2}\xi^2$$

see e.g. S. Bobrovskyi, W. Buchmuller, J. Hajer, and J. Schmidt, JHEP (2010)

3-body decays:

$$\Gamma_{3-\text{body}} = \frac{g^2 |\hat{\lambda}'|^2}{1024\,\pi^3} \frac{m_{\chi_1^0}^5}{\tilde{m}_Q^4}$$

$$BR(3-\text{body}/2-\text{body}) \approx 1.3\times 10^{-5} \left(\frac{\epsilon}{\xi}\right)^2 \left(\frac{\tan\beta}{10}\right)^4 \left(\frac{\tilde{m}_Q}{1\ \text{TeV}}\right)^{-4} \left(\frac{m_{\chi_1^0}}{150\ \text{GeV}}\right)^4$$

$$\tau_{\text{NLSP},\,2-\text{body}} \approx 0.02\ \text{s} \left(\frac{m_{\chi_1^0}}{150\ \text{GeV}}\right)^{-1} \left(\frac{\tan\beta}{10}\right)^2 \left(\frac{\xi}{10^{-10}}\right)^{-2}$$

Requiring that the NLSP decays before BBN we get the conservative lower bound:

$$\tau_{\text{NLSP}} \gtrsim 10^{-2} \longrightarrow \xi \gtrsim 10^{-(10\div 11)}$$

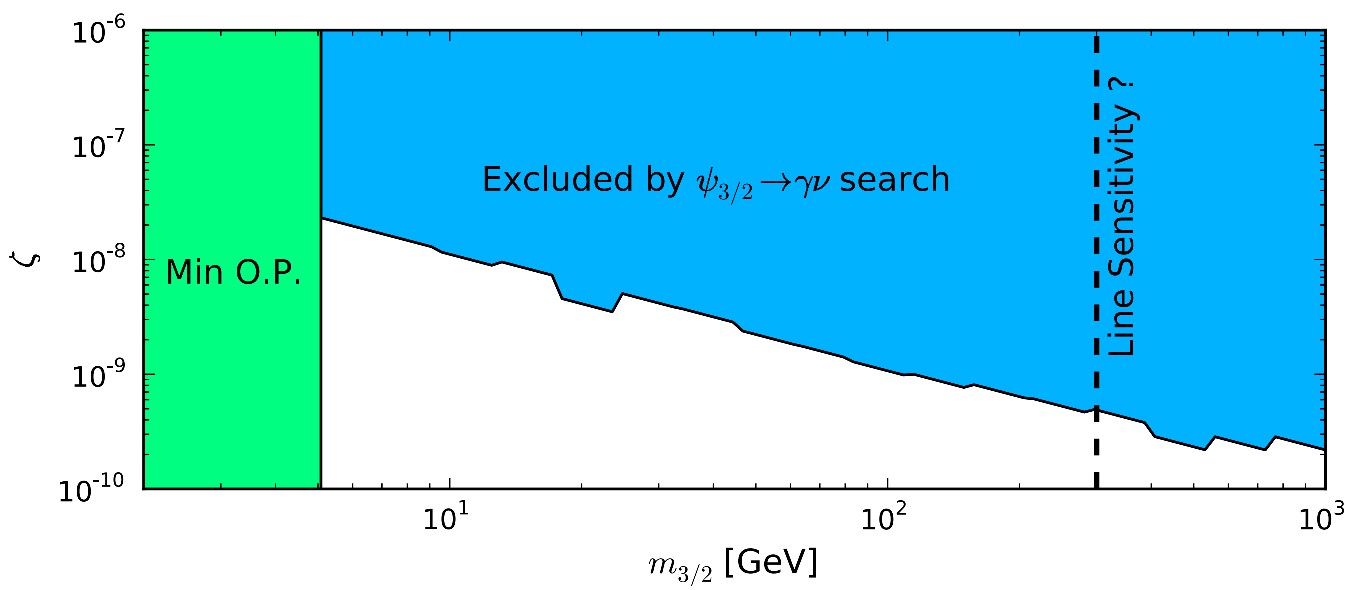
Gravitino lifetime and cosmic rays

Gravitino is a cosmologically viable DM canditate also with RPV. Small amount of decay is however detectable in cosmic rays.

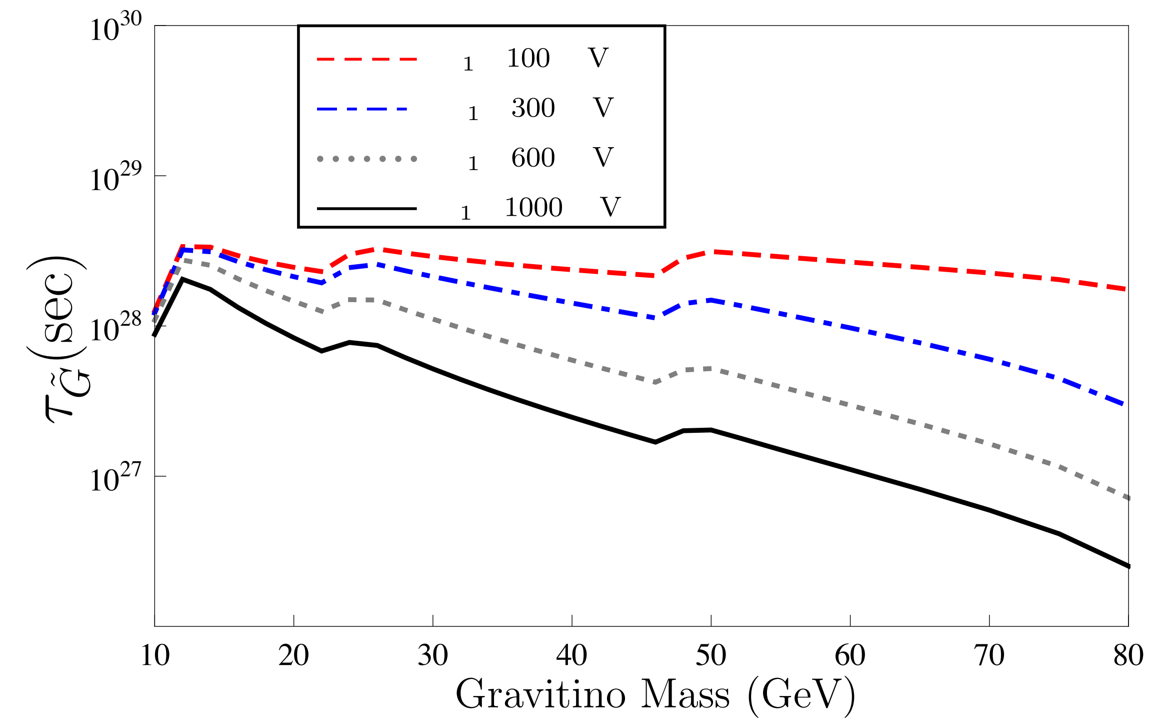
Main signature in our scenario are gamma rays.

$$\Gamma(\tilde{G} \to \gamma\,\nu) = \frac{1}{32\pi}\frac{(M_2 - M_1)^2}{M_1^2 M_2^2} M_Z^2 \sin^2\theta_W \cos^2\theta_W \cos^2\beta\,\xi^2 \frac{m_{3/2}^3}{M_P^2} \qquad \tau \simeq 7.3\times 10^{28}\ \mathrm{s}\left(\frac{\tan\beta}{10}\right)^2\left(\frac{M_{1/2}}{300\ \mathrm{GeV}}\right)^2\left(\frac{m_{3/2}}{15\ \mathrm{GeV}}\right)^{-3}\left(\frac{\xi}{10^{-7}}\right)^{-2}$$

Constraints from Fermi-Lat



Vertongen and Weniger 2011, **JCAP 1105:027,2011**



Choi et al. 2010, **JCAP 1010:033,2010**

From negative Fermi searches we get the upper bound:

$$\xi < 10^{-(6\div 8)}$$

Neutrino masses through RPV

see for review e.g., Barbier et al. (2004);
D. Restrepo, M. Taoso, J. Valle, and O. Zapata; PRD (2012)

$$M_N = \begin{pmatrix} m_\nu^{ss} & m_{RPV} \\ m_{RPV}^T & M_N^{MSSM} \end{pmatrix}$$

$$m_{RPV} = \begin{pmatrix} M_Z s_W \xi_1 cos\beta & -M_Z c_W \xi_1 cos\beta & 0 & 0 \\ M_Z s_W \xi_2 cos\beta & -M_Z c_W \xi_2 cos\beta & 0 & 0 \\ M_Z s_W \xi_3 cos\beta & -M_Z c_W \xi_3 cos\beta & 0 & 0 \end{pmatrix}$$

$$m_{\nu,ij}^{\text{eff}} = m_{ij}^{1-loop} - \left(m_{RPV} M_N^{-1} m_{RPV}^T\right)_{ij}$$

$$\left(m_{\alpha\beta}^\nu\right)_{1-loop} \simeq \frac{3\lambda'_{\alpha ij}\lambda'_{\beta lk}}{8\pi^2}\frac{m_{ik}^d \left(\tilde{m}_{jl}^d\right)_{LR}^2}{\tilde{m}^2} + \frac{3\lambda_{\alpha\gamma j}\lambda_{\beta\sigma k}}{8\pi^2}\frac{m_{\gamma k}^l \left(\tilde{m}_{j\sigma}^l\right)_{LR}^2}{\tilde{m}^2}$$

$$m_{\nu_3} = M_Z^2\,\xi^2 \cos^2\beta \left(\frac{M_1 M_2}{M_1 c_W^2 + M_2 s_W^2} - \frac{M_Z^2}{\mu}\sin 2\beta\right)^{-1}$$

$$\xi \simeq 1.5 \times 10^{-5} \left(\frac{\sqrt{\Delta m_{\text{atm}}^2}}{0.05 \text{ eV}}\right)^{1/2} \left(\frac{\tan\beta}{10}\right) \left(\frac{M_{1/2}}{300 \text{ GeV}}\right)^{1/2}$$

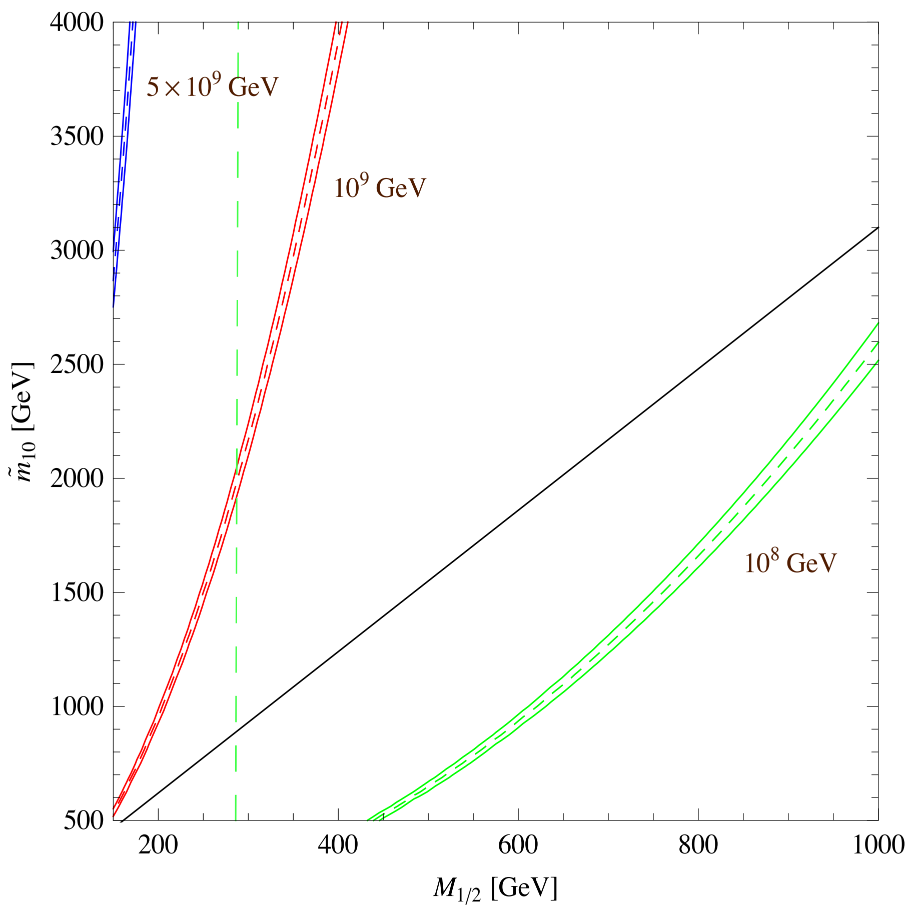
RPV cannot account for neutrino masses compatibly with astrophysical and cosmological bounds

DM relic density and thermal leptogenesis

$$BR(RPC/RPV) \approx 10^{-8} \left(\frac{m_{\chi_1^0}}{150\ \text{GeV}}\right)^4 \left(\frac{m_{3/2}}{15\ \text{GeV}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^2 \left(\frac{\xi}{10^{-10}}\right)^{-2}$$

No contribution to DM relic density from NLSP decays

$$\Omega_{DM}^T h^2 \approx 0.12 \left(\frac{T_{RH}}{10^9\ \text{GeV}}\right) \left(\frac{30\ \text{GeV}}{m_{3/2}}\right) \left(\frac{M_{1/2}}{300\ \text{GeV}}\right)^2$$



Thanks to the natural prediction of a gravitino mass of at least 10 GeV the correct relic density is achieved in agreement with the constraints from thermal leptogenesis

$$\Omega_{DM}^T h^2 \approx 0.12 \left(\frac{T_{RH}}{10^9\ \text{GeV}}\right) \left(\frac{2\ \text{TeV}}{\tilde{m}_{10}}\right) \left(\frac{M_3}{700\ \text{GeV}}\right)^2$$

Thermal leptogenesis requires multi-TeV sfermions.

Conclusions

TGM is a simple SUSY breaking scenario which guarantees flavor universality and a rather high gravitino mass.

The model is naturally feasible in presence of a small amount of R-parity violation.

The presence of RPV opens new possibilities of detection of the gravitino DM.

BACK UP SLIDES

GRAVITINO AND SUSY BREAKING

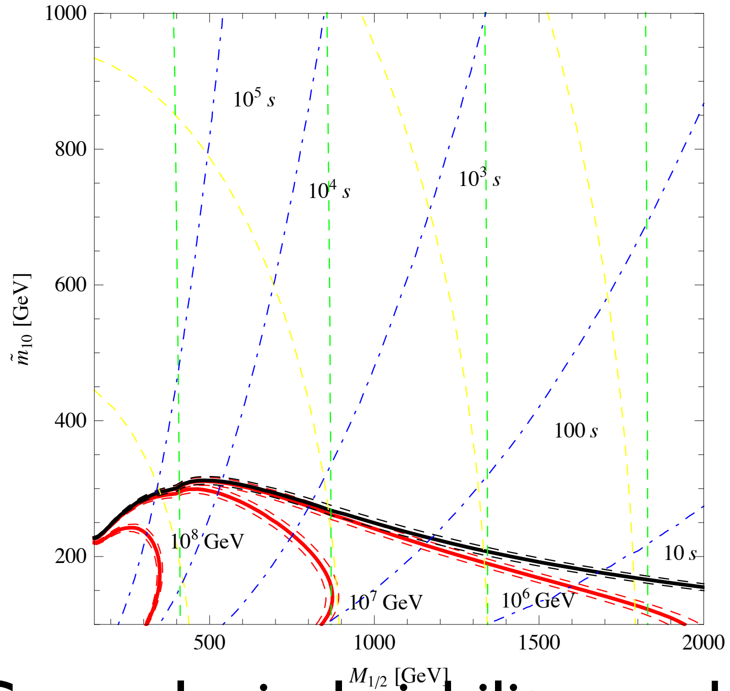
In a large class of theories SUSY is broken by the F-term of a chiral superfield and the breaking is communicated to the SM fields a scale M.

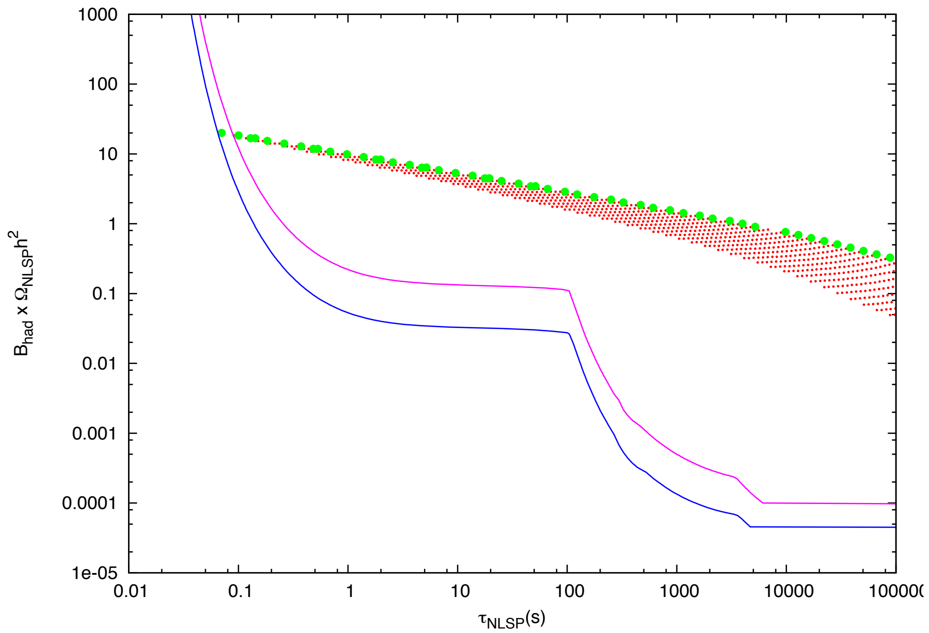
Gravity Mediation → $m_{\rm soft} \sim \frac{F}{M_{\rm Pl}}$

Gauge Mediation → $m_{\rm soft} \sim \frac{\alpha}{4\pi}\frac{F}{M}$

Gravitino mass → $m_{3/2} = \frac{F}{\sqrt{3}M_{\rm Pl}}$

Depending on the mechanism of SUSY breaking the gravitino mass ranges from very low values (typical of gauge mediation) to orders of 10-100 GeV (gravity mediation) or even much higher values (like in anomaly mediation).





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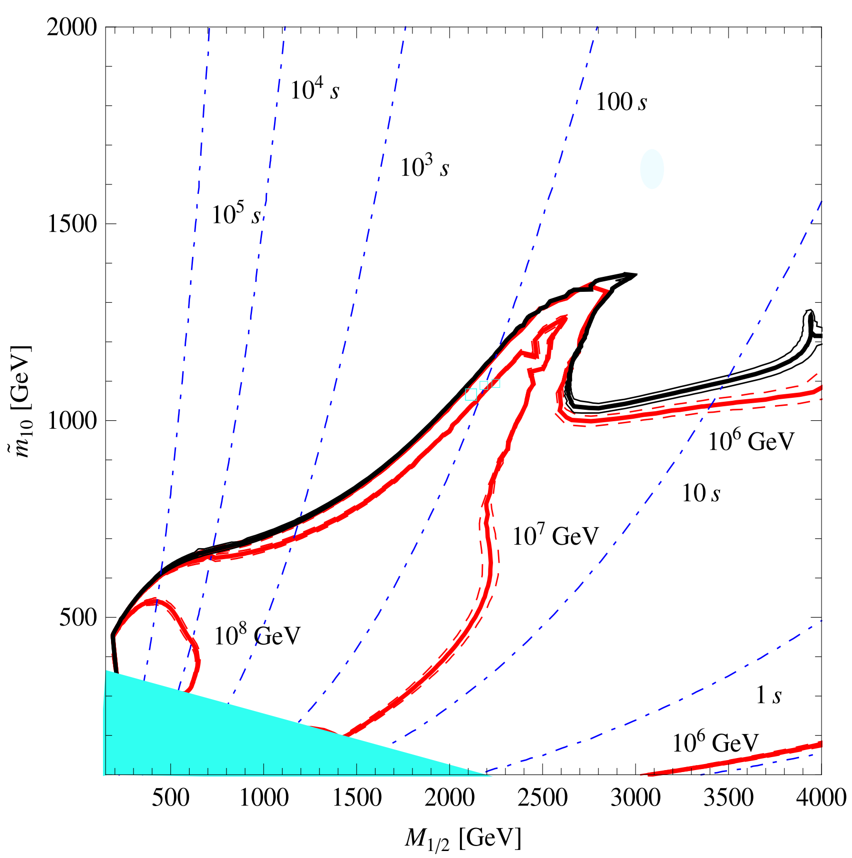
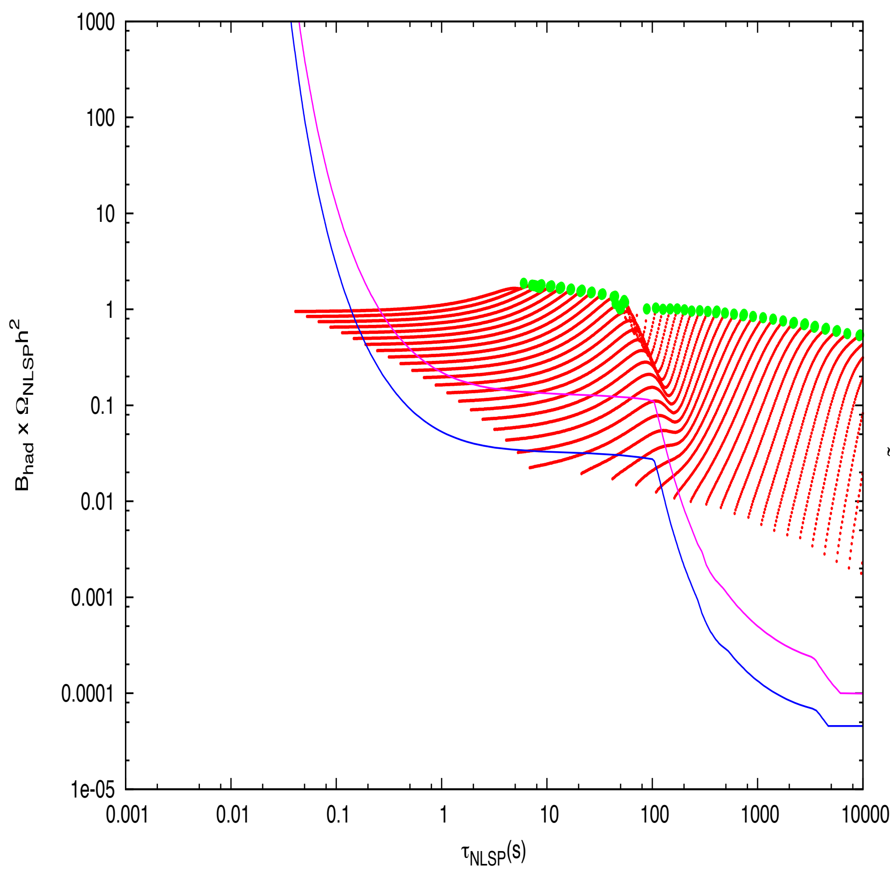
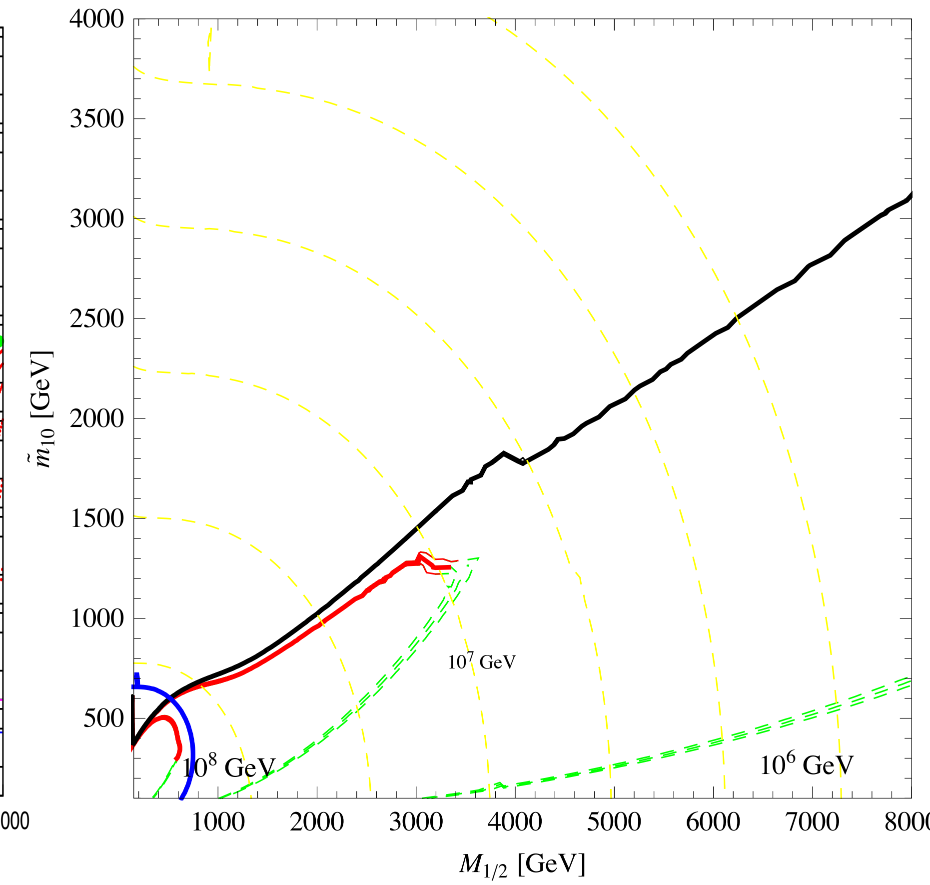
Cosmological viability can be achieved by CP-odd higgs resonances and stau NLSP where Tree-level mediation is subdominant respect to loop-level one.







(we thank J. Hasenkamp and J. Roberts for providing BBN bounds)

SO(10) RPV Theory

$$16_F = (D^c \oplus L)_{\overline{5}_{-3}} \oplus (u^c \oplus q \oplus e^c)_{10_{+1}} \oplus (\nu^c)_{1_{+5}}$$
$$10_F = (D \oplus L^c)_{5_{-2}} \oplus (d^c \oplus \ell)_{\overline{5}_{+2}}$$
$$16_H = (T_d^{16} \oplus h_d^{16})_{\overline{5}_{-3}} \oplus (\ldots)_{10_{+1}} \oplus (\ldots)_{1_{+5}}$$
$$\overline{16}_H = (T_u^{\overline{16}} \oplus h_u^{\overline{16}})_{5_{+3}} \oplus (\ldots)_{\overline{10}_{-1}} \oplus (\ldots)_{1_{-5}}$$
$$10_H = (T_u^{10} \oplus h_u^{10})_{5_{-2}} \oplus (T_d^{10} \oplus h_d^{10})_{\overline{5}_{+2}}$$

→ SO(10) broken at the renormalizable level by:

$$54_H \oplus 45_H \oplus 16_H \oplus \overline{16}_H \oplus 10_H$$

Renormalizable Superpotential

$$W_H = (\mu_{54} + \eta_{54} 45_H + \lambda_{54} 54_H)\, 54_H^2 + \mu_{45} 45_H^2 + (\mu_{10} + \lambda_{10} 54_H)\, 10_H^2$$
$$+ (\mu_{16} + \lambda_{16} 45_H)\, 16_H \overline{16}_H + \lambda_{16-10} 16_H^2 10_H + \overline{\lambda}_{16-10} \overline{16}_H^2 10_H\,,$$
$$W_Y = Y_{10}^{ij} 16_F^i 16_F^j 10_H + Y_{16}^{ij} 16_F^i 10_F^j 16_H + \left(M_{10}^{ij} + \eta^{ij} 45_H + \lambda^{ij} 54_H\right) 10_F^i 10_F^j\,,$$

$$\delta W_{RPV} = \left(\tilde{\mu}_{10}^i + \tilde{\eta}_{10}^i 45_H + \tilde{\lambda}_{10}^i 54_H\right) 10_F^i 10_H + \left(\tilde{\mu}_{16}^i + \tilde{\lambda}_{16}^i 45_H\right) 16_F^i \overline{16}_H$$
$$+ \tilde{\rho}^i 16_F^i 16_H 10_H + \tilde{\sigma}^i 10_F^i 16_H 16_H + \tilde{\overline{\sigma}}^i 10_F^i \overline{16}_H \overline{16}_H + \tilde{\Lambda}^{ijk} 16_F^i 16_F^j 10_F^k$$

+ Non-renormalizable term

$$\frac{\tilde{\Lambda}_{ijk}^{NR}}{M_P} 10_F^i 10_F^j 16_F^k \langle \overline{16}_H \rangle \supset \lambda_{ijk}^{NR}\, \ell_i \ell_j e_k^c + \lambda_{ijk}^{\prime NR}\, d_i^c \ell_j q_k + \lambda_{ijk}^{\prime\prime NR}\, d_i^c d_j^c u_k^c$$