Neutralino dark matter in $U(1)_R$ mediation

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based on

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SUSY breaking from Gravity mediation

- 4D Planck-scale mediation leads to a direct coupling between hidden and visible sectors, $\int d^4\theta \frac{c_{ij}}{M_P^2} Q_h^\dagger Q_h Q_i^\dagger Q_j$. For $\langle Q_h \rangle = \theta^2 F_{Q_h}$ with $|F_{Q_h}| \simeq (10^{11}\mathrm{GeV})^2$, weak-scale soft masses are obtained naturally as $m_{ij}^2 = c_{ij}\frac{|F_{Q_h}|^2}{M_P^2}$. However, SUSY flavor problem arises for generic c_{ij}.
- In higher dimensions, the hidden sector can be sequestered from the visible sector at a different place in extra dimensions. In 5D, anomaly mediation can be a dominant source for soft masses but sleptons would be tachyonic. [Randall,Sundrum(1998)]
- In $D > 5$, the 4D effective supergravity is not of sequestered form and sequestering depends on modulus stabilization.

[Anisimov,Dine,Graesser,Thomas(2001,2002); Falkowski,Lee,Lüdeling(2005);

Kachru,McAllister,Sundrum(2007)].

$U(1)'$ mediation

- When both hidden and visible sector are charged under a gauged $U(1)'$, it is possible to transmit SUSY breaking by the $U(1)'$ vector multiplet.
- There are two possibilities of the $U(1)'$ mediation:
  - loop-induced soft masses due to massive $U(1)'$ gaugino running in loops, [e.g. Langacker et al(2008); Grimm et al(2008)]
  - tree-level soft masses in the presence of nonzero $U(1)'$ D-term.

  In both cases, if $U(1)'$ charges of matter fields are family universal, the $U(1)'$ mediation does not lead to flavor problems.
- We consider the $U(1)_R$ mediation with nonzero D-term in the MSSM with gauged $U(1)_R$, derived from flux compactifications in a 6D chiral gauged supergravity.

$U(1)_R$ symmetry

- $U(1)_R$ is the global symmetry of $\mathcal{N}=1$ SUSY algebra: for a chiral superfield $\Phi = \phi + \theta\psi + \theta^2 F_\phi$, the R transformation with R-character r is

$$\Phi(\theta) \to e^{ir\alpha}\Phi(e^{-i\alpha}\theta).$$

- $U(1)_R$ or its discrete subgroup can be used to forbid unwanted terms, e.g. μ term, dimension-4 and -5 B/L violating operators.
- However, a spontaneous breaking of the global $U(1)_R$ symmetry would lead to a dangerous R-axion and any global symmetry must be gauged in quantum gravity or string theory.
- The gauged $U(1)_R$ symmetry is possible only in local supersymmetry.

$U(1)_R$ symmetry in 4D supergravity

[Freedman(1977); Barbieri et al(1982); Ferrara et al(1983); Binetruy et al(2004)]

- In Weyl compensator formalism, the 4D supergravity action is

$$S = \int d^4x \Big[d^4\theta \mathbf{E}(-3C^\dagger e^{4g_R V_R/3} C\, e^{-K/3}) + \int d^2\theta \mathcal{E} C^3 W + \text{h.c.} \Big]$$

where $\mathbf{E}$ is the full superspace measure, $\mathcal{E}$ is the chiral superspace measure, C is the chiral compensator superfield and V_R is the $U(1)_R$ vector superfield. Here $K = K(\Phi_i^\dagger e^{-2r_i g_R V_R}\Phi_i)$ and $W = W(\Phi_i)$.

- The action has super-Weyl invariance:

$$\mathbf{E} \to e^{2\tau+2\tau}\mathbf{E}, \quad \mathcal{E} \to e^{6\tau}\mathcal{E}, \quad C \to e^{-2\tau}C, \quad W \to W;$$

$U(1)_R$ invariance: $V_R \to V_R + \frac{i}{2}(\Lambda_R - \Lambda_R^\dagger),\, C \to e^{-i\frac{2}{3}g_R\Lambda_R}C,$

$$\Phi_i \to e^{ir_i g_R\Lambda_R}\Phi_i, \qquad W \to e^{2ig_R\Lambda_R}W.$$

- In super-Weyl gauge $C = 1 + \theta^2 F_C$, combined $U(1)_R$ transform and super-Weyl transform with $\tau = -i\frac{2}{3}g_R\Lambda_R$ makes the action invariant.
- The 4D scalar potential is given by

$$V = M_P^2 K_{i\bar{j}} F^i F^{\bar{j}} - 3M_P^4 e^K |W|^2 + \frac{1}{2}\mathrm{Re}(f_a) D^a D^a$$

with $F^i = -M_P e^{K/2} K^{i\bar{j}} (D_j W)^\dagger$ with $D_i W = \frac{\partial W}{\partial \Phi_i} + \frac{\partial K}{\partial \Phi_i} W$ and $D^a = \frac{M_P^2}{\mathrm{Re}(f_a)}(-i\eta_a^i \partial_i K + 3ir_a)$ with $\delta\Phi_i = \eta_a^i(\Phi)$ and $\delta_a W = -3r_a W$.
- The $U(1)_R$ D-term is

$$D_R = \frac{2g_R M_P^2}{\mathrm{Re}(f_R)}\left(1 + \frac{1}{2} r_i \Phi_i^\dagger \partial_i K\right).$$

- There appears a constant Fayet-Iliopoulos term, which is cancelled by a scalar VEV for D-flat condition.

6D chiral gauged supergravity

[Nishino,Sezgin(1984); Salam,Sezgin(1984)]

- 6D chiral gauged supergravity is composed of

$$\begin{aligned} \text{gravity} &: \quad e_M^A, \quad \psi_M, \quad B^+_{MN}, \\ \text{tensor} &: \quad \phi, \quad \chi, \quad B^-_{MN}, \\ \text{vector} &: \quad A_M, \quad \lambda. \end{aligned}$$

- The bulk vector multiplet gauges the $U(1)_R$ symmetry.
- 6D anomalies are cancelled by adding hyper multiplets and/or non-abelian vector multiplets satisfying $n_H = 245 + n_V$.
- The bosonic part of the 6D bulk supergravity Lagrangian is

$$\frac{\mathcal{L}}{\sqrt{-g}} = \Big(R - \frac{1}{4}(\partial_M \phi)^2 - 8g^2 e^{-\frac{1}{2}\phi} - \frac{1}{4} e^{\frac{1}{2}\phi} F^2_{MN} - \frac{1}{12} e^{\phi} G^2_{MNP} \Big)$$

with $G_{MNP} = 3\partial_{[M} B_{NP]} + \frac{3}{2} F_{[MN} A_{P]}$.

Supersymmetric codimension-two branes

[HML,Papazoglou(2007); HML(2008)]

- The brane tension action, $\mathcal{L}_{\rm brane} = -e_4 \delta^2(y) T_0$, is supersymmetrized by modifying the field strength tensors with singular terms as

$$\hat{G}_{\mu mn} = G_{\mu mn} - \xi_0 A_\mu \epsilon_{mn} \frac{\delta^2(y)}{e_2},$$

$$\hat{F}_{mn} = F_{mn} - \xi_0 \epsilon_{mn} \frac{\delta^2(y)}{e_2},$$

  where $\xi_0 = \eta \frac{T_0}{4g}$ with $\eta = \pm 1$ is the localized FI term.
- Half the bulk SUSY is broken on the brane by Z_2-parity.
- Brane matter couplings are also introduced.

General warped solutions

[Gibbons et al(2003); Aghababaie et al(2003); Papazoglou,HML(2007)]

- The general warped solution with axial symmetry is

$$\begin{aligned} ds^2 &= W^2\eta_{\mu\nu}dx^\mu dx^\nu + \frac{W^2}{(1+r^2/r_0^2)^2}\left(dr^2 + \lambda^2\frac{r^2}{W^4}d\theta^2\right), \\ \hat{F}_{mn} &= qW^{-6}\epsilon_{mn}, \quad \phi = 4\ln W, \end{aligned}$$

where $W^4(r) = \frac{1+r^2/r_1^2}{1+r^2/r_0^2}$ with $r_0^2 = \frac{1}{2g^2}$ and $r_1^2 = \frac{8}{q^2}$.

- Two brane tensions are located at the conical singularities:

$$T_1 = 2\pi M_*^4(1-\lambda), \quad T_2 = 2\pi M_*^4\left(1-\lambda\frac{16g^2}{q^2}\right).$$

- For $q = 4g$, we obtain an $\mathcal{N}=1$ SUSY football solution with two equal brane tensions.
- Supersymmetric multi-brane solutions also exist. [HML, in progress]

4D effective supergravity

- Branes: chiral multiplets $Q_i(Q_h)$ on the visible(hidden) brane of the supersymmetric football.
- Bulk: matter multiplets X coming from singlet hyper multiplets.
- Making the KK reduction to 4D for the supersymmetric football,

$$\begin{aligned} ds^2 &= e^{-\psi(x)} g_{\mu\nu}(x) dx^\mu dx^\nu + e^{\psi(x)} ds_2^2, \\ \phi &= f(x), \quad \hat{F}_{mn} = 4g\epsilon_{mn}, \end{aligned}$$

we obtain the 4D Kähler potential as

$$K = -\ln\left(\frac{1}{2}(S+S^\dagger)\right) + X^\dagger e^{-2r_X g_R V_R} X$$

$$-\ln\left(\frac{1}{2}(T+T^\dagger - 8g_R V_R) - \sum_{a=i,h} Q_a^\dagger e^{-2r_a g_R V_R} Q_a\right).$$

- Bulk moduli, S and T, are the admixture of volume modulus and dilaton;

$$S = s + i\sigma, \qquad T = t + |Q_i|^2 + ib.$$

  with $s = e^{\psi+\frac{1}{2}f}$, $t = e^{\psi-\frac{1}{2}f}$, $e^f G_{\mu\nu\rho} = \epsilon_{\mu\nu\rho\tau}\partial^\tau\sigma$ and $b = -\frac{1}{2}\epsilon^{mn}B_{mn}$.
- Bulk and brane gauge kinetic functions are $f_R = S$ and $f_W = 1$, respectively.
- The effective superpotential coming from branes and bulk is

$$W = W_{\rm vis}(Q_i) + W_{\rm hid}(Q_h) + W_{\rm bulk}(S, T, X).$$

- $U(1)_R$ gauge boson gets mass $M_A = 2g_R M_P/(\sqrt{s}t)$ by a Chern-Simons term.

$U(1)_R$ anomaly-free MSSM

[Chamseddine, Dreiner(1995); Castano,Freedman,Manuel(1995)]

- With family-universal R-charges for the MSSM fields, the $U(1)_R$ anomaly coefficients involving the SM gauge group are

$$
\begin{aligned}
C_1 &= 3\Big(\frac{1}{2}l + e + \frac{1}{6}q + \frac{4}{3}u + \frac{1}{3}d\Big) + \frac{1}{2}(h_d + h_u), \\
C_1' &= 3(-l^2 + e^2 + q^2 - 2u^2 + d^2) - h_d^2 + h_u^2, \\
C_2 &= 3\Big(\frac{1}{2}l + \frac{3}{2}q\Big) + \frac{1}{2}(h_d + h_u) + 2, \\
C_3 &= 3\Big(q + \frac{1}{2}u + \frac{1}{2}d\Big) + 3.
\end{aligned}
$$

- We assume that pure $U(1)_R$ anomalies are cancelled by hidden SM-singlet fermions.
- For renormalizable Yukawa couplings($q + u + h_u = -1$,etc), there is no solution for $C_1 = C_1' = C_2 = C_3 = 0$.

- From $U(1)_R$ transformation $T \to T + 4ig_R\Lambda_R$, brane-localized Green-Schwarz(GS) terms are introduced to cancel the $U(1)_R$ anomalies:

$$\mathcal{L}_{GS} = -(\mathrm{Im}\,T)\sum_{a=1}^{3} k_a \frac{1}{2}\mathrm{tr}(F_a\tilde{F}_a)$$

  where k_a are the Kac-Moody levels with $\frac{C_a}{k_a} = 16\pi^2 g_R$.
- For unified gauge couplings and $\sin^2\theta_W = \frac{3}{8}$ at the GUT scale, the consistent anomalies are $C_1 = -15$ and $C_2 = C_3 = -9$.
- The R-charges of scalar partners are obtained as

$$\begin{aligned} \tilde{l} &= -3\tilde{q} - \frac{16}{3}, \quad \tilde{e} = -\frac{3}{7}\tilde{q} - \frac{26}{21}, \quad \tilde{u} = \frac{17}{7}\tilde{q} + \frac{18}{7}, \\ \tilde{d} &= -\frac{31}{7}\tilde{q} - \frac{46}{7}, \quad \tilde{h}_d = \frac{24}{7}\tilde{q} + \frac{60}{7}, \quad \tilde{h}_u = -\frac{24}{7}\tilde{q} - \frac{4}{7}. \end{aligned}$$

Moduli stabilization

- For $W=0$, the $U(1)_R$ D-term stabilizes only T-modulus from
$$V_0 = \frac{1}{2} s D_R^2 = \frac{2g_R^2 M_P^2}{s}\left[1-\frac{1}{t}(1-r_i|Q_i|^2)\right]^2.$$
- For a T-independent W, in the small scalar VEVs limit, the T-modulus stabilization condition is changed to
$$V_F - \frac{|F^{Q'}|^2}{t} + \frac{D^2}{t^2} - \frac{2g_R M_P^2 D_R}{t} \simeq 0$$
where $F^{Q'}, D$ are hidden brane F/D-terms.
- Visible sector soft masses are given only by the $U(1)_R$ D-term,
$$m_i^2 \simeq \frac{1}{M_P^2}V_F + \frac{D^2}{t^2 M_P^2} - \frac{|F^{Q'}|^2}{t} + \left(-\frac{2}{t}+r_i\right) g_R D_R \simeq r_i g_R D_R.$$

- For S-modulus stabilization, we consider a bulk-induced effective superpotential as

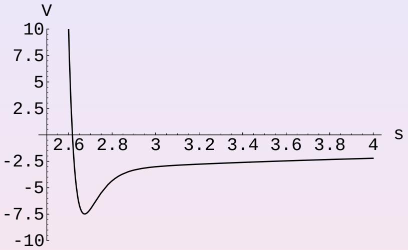
$$W_{\rm bulk} = W_0 + \frac{\lambda}{X^n} e^{-bS}$$

where W_0 comes from a $U(1)_R$ breaking bulk sector. Then, for a nonzero X scalar VEV, the S modulus becomes stabilized.

- With hidden-sector SUSY breaking and φ added in the hidden brane, the total superpotential is

$$W = fQ_h + W_0 + \left(\frac{\lambda}{X^n} e^{-bS} + \lambda' \varphi^p X^2 + \kappa \varphi^q\right).$$

- For $\frac{|W_0|}{2bs} \ll |\kappa| \ll |\lambda'|$, the scalar VEVs are $|X| \ll 1$ and $|\varphi| \ll 1$. Then, the S modulus is stabilized at $s = \mathcal{O}(1)$ for $b = \mathcal{O}(10)$ while the T modulus remains stabilized at $t \simeq 1$.



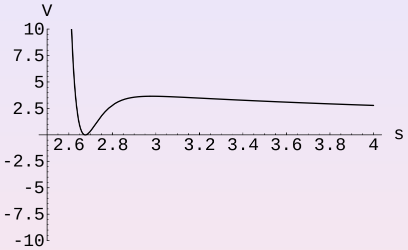


Figure: Plot of the scalar potential for $s = \mathrm{Re}S$ with non-zero W_0 with $f = 0$ (Left) and $f \neq 0$ (Right) to show the uplifting of the potential. Here we used $\lambda = 0.01$, $b = 15$, $\lambda' = 10^{-7}$, $p = 3$, $q = 1, n = 1$, $\kappa = -10^{-15}$, $W_0 = 10^{-16}$, with $f = 0$ (Left) and $f = 1.413 \times 10^{-16}$ (Right). The minimum values are approximately $t_0 \simeq 1.00095, s_0 \simeq 2.673, X_0 \simeq -0.03087, \varphi_0 \simeq -0.00187$.

Soft mass parameters

- The soft mass parameters at the GUT scale($M_{GUT} = M_A$) are

$$
\begin{aligned}
m_i^2 &\simeq -r_i m_{3/2}^2, \\
M_a &\simeq \frac{C_a g_a^2}{16\pi^2 g_R} F^T \simeq -\frac{9}{16\pi^2 g_R}, \text{ any } a \\
A_{ijk} &\simeq -2m_{3/2}, \text{ any } i,j,k.
\end{aligned}
$$

- At GUT scale, all squarks and leptons soft squared masses are positive for $-\frac{46}{31} < \tilde{q} < -\frac{18}{17}$; Higgs squared soft masses are negative.
- Gaugino masses come from $U(1)_R$ anomalies. For $gM_* < 1$(i.e. $g_R < 1/\sqrt{4\pi}$), we get $|M_a| > 0.2m_{3/2}$.
- There are 5 free parameters in $U(1)_R$ mediation: $m_{3/2}$, $M_{1/2}$, $\tilde{q}$, $\tan\beta$, and $\mathrm{sign}(\mu)$.

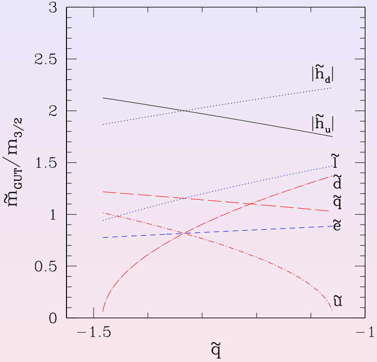


Figure: The soft masses $\tilde{m}_{\rm GUT}$ for sparticles at the GUT scale with a varying $\tilde{q}$. For the Higgs masses, we plot $\tilde{m}_{\rm GUT} = \sqrt{|m^2_{\tilde{h}_{u,d}}|}$.

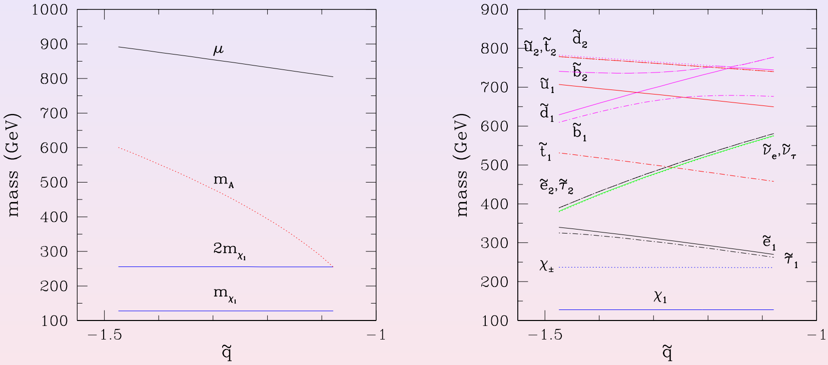


Figure: The particle masses versus $\tilde{q}$ at low energy in the model for $m_{3/2} = 360\,\mathrm{GeV}$, $M = 310\,\mathrm{GeV}$, $\tan\beta = 10$ with $\mu > 0$ and $m_t = 172.7\,\mathrm{GeV}$.

Neutralino dark matter

- For moderate to large values of $\tan\beta$ and $|m_{H_u}| \gg M_Z$, tree-level pseudoscalar Higgs mass is $m_A^2 = m_{H_u}^2 - m_{H_d}^2 + 2\mu^2 \simeq m_{H_d}^2 - m_{H_u}^2$.
- At the GUT scale, we get $m_A^2 = \left(\frac{48}{7}|\tilde{q}| - \frac{64}{7}\right) m_{3/2}^2$. Loop corrections with top Yukawa coupling drives $m_{H_u}^2$ more negative while $m_{H_d}^2$ unchanges for the moderate value of $\tan\beta$, so that EWSB occurs even for smaller $|\tilde{q}|$.
- For a smaller $|\tilde{q}|$, m_A gets closer to $2m_{\chi_1}$. Then, the relic density of neutralino dark matter can be obtained by A-Higgs resonances even for low $\tan\beta$ values.

- Unless $\tan\beta$ is large, (Bino-like) neutralino and lighter stau masses are $m_\chi \simeq 0.4 M_{1/2}$ and $m^2_{\tilde\tau_1} \simeq m^2_{\tilde\tau_R}(GUT) + 0.15 M^2_{1/2} + \Delta m^2_{\tilde\tau_R}$ where $m^2_{\tilde\tau_R}(GUT) = \left(\frac{3}{7}\tilde q + \frac{26}{21}\right) m^2_{3/2}$ and $\Delta m^2_{\tilde\tau_R}$ comes from non-vanishing $S = \mathrm{Tr}(Y_i m^2_{\phi_i}) = \left(\frac{168}{7}\tilde q + \frac{224}{7}\right) m^2_{3/2}$.
- In stau-neutralino coannihilation region, $m_{\tilde\tau} \sim m_{\chi_1} \sim 0.4 M_{1/2}$ for $m_{3/2} \sim \frac{1}{3} M_{1/2}$. Then, $m_{\chi_1} \sim 1.2 m_{3/2}$ so gravitino becomes LSP while stau or neutralino is NLSP.
- There are strong BBN constraints on neutralino/stau NLSP. The BBN problem with neutralino/stau NLSP can be evaded by making them heavier than $1-10$ TeV and/or by introducing a small breaking of R-parity. For stau NLSP, the annihilation into Higgs bosons reduces the thermal relic density of staus.

[Cerdeno et al(2005); Pospelov(2006); Pradler,Steffen(2007); Buchmuller et al(2007); Ratz et al(2008)]

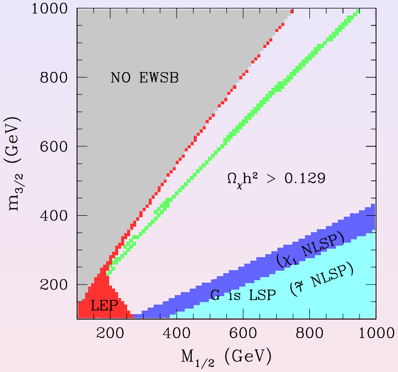


Figure: The scan on the plane of $(M_{1/2}, m_{3/2})$ with $\tilde{q} = -1.1$, $\tan\beta = 10$ and $\mu > 0$. The black region is excluded due to unsuccessful EWSB (upper left corner). The red region is disfavored by the LEP constraints on chargino and Higgs mass $m_{\chi^\pm} > 104\,\mathrm{GeV}$ and $m_{h^0} > 114.4\,\mathrm{GeV}$.

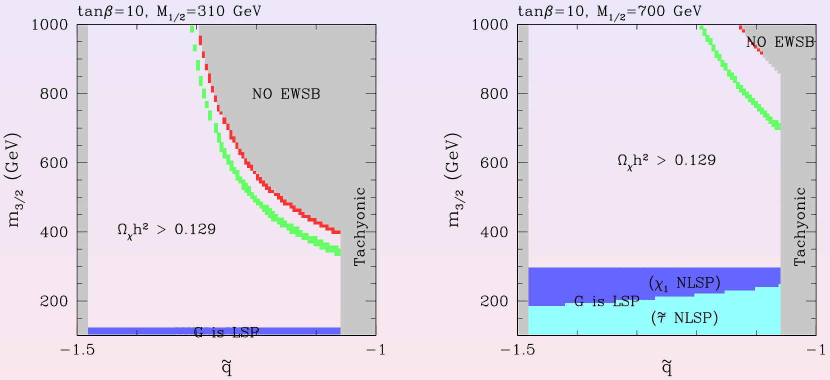


Figure: The gravitino mass vs $\tilde{q}$ with $\tan\beta = 10$ and $\mu > 0$ for $M_{1/2} = 310\,\mathrm{GeV}$ (Left) and $M_{1/2} = 700\,\mathrm{GeV}$ (Right).

	P1	P2	P3	P4
$m_{3/2}$	360	756	175	250
$M_{1/2}$	310	700	500	800
$\tilde{q}$	-1.1	-1.1	-1.1	-1.1
$\tan\beta$	10	10	10	10
μ	810	170	744	111
m_{h^0}	115	120	116	119
m_A	284	626	715	1100
m_{H^0}	284	626	715	1100
$m_{H^\pm}$	295	631	720	1103
m_{χ_1}	127	299	207	339
m_{χ_2}	246	572	393	641
m_{χ_3}	806	1690	747	1117
m_{χ_4}	811	1691	757	1124

$m_{\chi_1^\pm}$	246	572	393	641
$m_{\chi_2^\pm}$	811	1691	757	1124
$m_{\tilde{g}}$	754	1600	1148	1772
$m_{\tilde{u}_1}$	677	1420	1010	1549
$m_{\tilde{t}_1}$	492	1095	781	1228
$m_{\tilde{d}_1}$	768	1612	1027	1568
$m_{\tilde{b}_1}$	710	1495	975	1498
$m_{\tilde{e}_1}$	274	581	224	342
$m_{\tilde{\tau}_1}$	267	570	215	333
Ωh^2	0.1115	0.1099	χ_1 NLSP	$\tilde{\tau}$ NLSP
LSP	χ_1	χ_1	Gravitino	Gravitino

Table: All masses are in GeV. P1, P2: A-annihilation funnel. P3: Gravitino LSP with neutralino NLSP, P4: Gravitino LSP with stau NLSP. (SUSPECT + DarkSusy)

Conclusion

- Flux compactification can provide $U(1)_R$ as a new SUSY mediator.
- Scalar soft masses are family-independent but non-universal while gaugino masses are universal.
- Neutralino LSP can be a dark matter in the A-annihilation funnel. In this case, the pseudo-scalar Higgs can be light to be observed at LHC.
- In stau-coannihilation region, neutralino or stau is NLSP and gravitino is LSP. In this case, there are strong BBN constraints.
- The mechanism for generating neutrino masses and mu term consistently and its consequence for dark matter is under study. [K.-Y. Choi, E. J. Chun, HML, in progress]