Lightest $U$-parity Particle (LUP) dark matter

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HL, K. Matchev, T. Wang [0709.0763]; T. Hur, HL, S. Nasri [0710.2653];
HL, C. Luhn, K. Matchev [0712.3505]; HL [0802.0506].

SUSY 2008
Lightest $\mathcal{U}$-parity Particle (LUP) dark matter

in the $\mathcal{R}$-parity violating SUSY model

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SUSY 2008
Outline

• Companion symmetry of SUSY
  - $R$-parity
  - TeV scale $U(1)'$ gauge symmetry

• $R$-parity violating, $U(1)'$-extended SUSY model
  - Proton stability
  - Dark matter candidate
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Companion symmetry of SUSY
SUSY with $R$-parity

$$W_{R^p} = \mu H_u H_d$$

$$+ y_E H_d L E^c + y_D H_d Q D^c + y_U H_u Q U^c$$

$$+ (\lambda L L E^c + \lambda' L Q D^c + \mu' L H_u + \lambda'' U^c D^c D^c)$$

$$+ \frac{\eta_1}{M} Q Q Q Q L + \frac{\eta_2}{M} U^c U^c D^c E^c + \cdots$$

1. **$\mu$-problem**: $\mu \sim \mathcal{O}(\text{EW})$ to avoid fine-tuning in the EWSB.
   (Kim, Nilles [1984])

2. **over-constraining of the $R$-parity**: All renormalizable $\mathcal{L}$ violating and $\mathcal{B}$ violating terms are (unnecessarily) forbidden.

3. **under-constraining of the $R$-parity**: Dimension 5 $\mathcal{L}$&$\mathcal{B}$ violating terms still mediate too fast proton decay. (Weinberg [1982])
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Fast proton decay

$\begin{align*}
\begin{array}{c}
\text{[Dim 4 $L$ violation \& Dim 4 $B$ violation]} \\
R\text{-parity violating terms}
\end{array}
\end{align*}$

$\begin{align*}
\begin{array}{c}
\text{[Dim 5 $B$\&$L$ violation]} \\
R\text{-parity conserving terms}
\end{array}
\end{align*}$
Look for an additional or alternative explanation (symmetry).

→ We will consider a TeV scale Abelian gauge symmetry, $U(1)'$. 

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**TeV scale $U(1)'$ gauge symmetry**

Natural scale of $U(1)'$ in SUSY models is TeV (linked to sfermions scales).

→ provides a natural solution to the $\mu$-problem.

Two conditions to “**solve the $\mu$-problem**”. $(z[F]: U(1)'$ charge of $F')$

- $\mu H_u H_d$: forbidden $\quad z[H_u] + z[H_d] \neq 0$
- $h S H_u H_d$: allowed $\quad z[S] + z[H_u] + z[H_d] = 0$

$S$ is a Higgs singlet that breaks the $U(1)'$ spontaneously.

$\mu_{\text{eff}} = h \langle S \rangle \sim \mathcal{O}(\text{EW/TeV})$
**Goal**

Construct a stand-alone $R_p$ violating TeV scale SUSY model without

1. $\mu$-problem: $U(1)'$

2. proton decay problem

3. dark matter problem (non-LSP dark matter)

“$R$-parity violating $U(1)'$ model” as an alternative to the usual “$R$-parity conserving model”.

**Use residual discrete symmetry of the $U(1)'$ to address the issues.**
Conditions to have $U(1) \rightarrow Z_N$

$U(1)$ have a residual discrete symmetry $Z_N$ if their charges satisfy (after normalization to integers):

- $z[S] = N$
- $z[F_i] = q[F_i] + n_i N$

($z[F_i]$: $U(1)$ charge, $q[F_i]$: $Z_N$ charge) for each field $F_i$. 
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Discrete symmetry compatible with MSSM sector

Most general $Z_N$ of the MSSM sector (Ibanez, Ross [1992]) is

$$Z_N : B_N^b L_N^\ell$$

with family-universal cyclic symmetries ($\Phi_i \rightarrow e^{2\pi i \frac{q_i}{N}} \Phi_i$)

$$B_N = e^{2\pi i \frac{q_B}{N}}, \quad L_N = e^{2\pi i \frac{q_L}{N}}.$$
Residual discrete symmetry of the RPV $U(1)'$ model

: Proton stability without $R$-parity

HL, Luhn, Matchev [arXiv:0712.3505]
Discrete symmetries in presence of exotics

- There may be TeV scale exotic fields required to cancel chiral anomaly.
- The MSSM discrete symmetries still hold among the MSSM fields.

For a physics process which has only MSSM fields in its effective operators (such as proton decay), we can still discuss with $Z_{N}^{\text{MSSM}}$.

\[
\text{operator[p-decay]} = \left( \frac{1}{M} \right)^{m} \left[ F_{1} F_{2} F_{3} F_{4} F_{5} \cdots \right]
\]

MSSM fields only
Discrete symmetry in the $\mathcal{L}$ violating case

From the superpotential terms and $[SU(2)_L]^2-U(1)'$ anomaly condition, general $U(1)'$ charges for the MSSM sector in the $\mathcal{L}$ violating case:

$$
\begin{pmatrix}
  z[Q] \\
  z[U^c] \\
  z[D^c] \\
  z[L] \\
  z[N^c] \\
  z[E^c] \\
  z[H_d] \\
  z[H_u] \\
  z[S]
\end{pmatrix}
= \alpha' \begin{pmatrix}
  1 \\
  -4 \\
  2 \\
  -3 \\
  0 \\
  6 \\
  -3 \\
  3 \\
  0
\end{pmatrix}
+ \beta' \begin{pmatrix}
  0 \\
  3(1 + n) + 1 \\
  -3n - 1 \\
  1 \\
  3(1 - a + n) \\
  -3n - 2 \\
  3n + 1 \\
  -3(1 + n) - 1 \\
  3
\end{pmatrix}
\rightarrow
\begin{pmatrix}
  q[Q] \\
  q[U^c] \\
  q[D^c] \\
  q[L] \\
  q[N^c] \\
  q[E^c] \\
  q[H_d] \\
  q[H_u] \\
  q[S]
\end{pmatrix}
= - \begin{pmatrix}
  0 \\
  -1 \\
  1 \\
  -1 \\
  0 \\
  -1 \\
  -1 \\
  1 \\
  0
\end{pmatrix}
\mod 3.

Compare with charge table. $\rightarrow B_3$ (baryon triality) in the MSSM sector

<table>
<thead>
<tr>
<th></th>
<th>$Q$</th>
<th>$U^c$</th>
<th>$D^c$</th>
<th>$L$</th>
<th>$E^c$</th>
<th>$N^c$</th>
<th>$H_u$</th>
<th>$H_d$</th>
<th>meaning of $q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_3$</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>$-B + y/3$</td>
</tr>
</tbody>
</table>
Selection rule of $B_3$ and proton stability

The discrete charge of $B_3$ for arbitrary operator is $(-B + y/3) \mod 3$.

$$\Delta B = 3 \times \text{integer}$$

for any process. (Castano, Martin [1994])

(Baryon number can be violated by only $3 \times \text{integer}$ under the $B_3$.)

$\rightarrow$ Proton decay ($\Delta B = 1$): Forbidden
Ensuring proton stability in the $\mathcal{L}$ violating model ($B_3$)

1. Solve the $\mu$-problem with $U(1)'$ gauge symmetry.

2. Require $\mathcal{L}$ violating terms such as $\lambda' L Q D^c$. [$B_3$ is invoked]

3. Then proton is absolutely stable!
Recap of the goal

Construct a stand-alone $R_P$ violating TeV scale SUSY model without

1. $\mu$-problem: $U(1)'$

2. proton decay problem: $U(1)' \rightarrow B_3$

3. dark matter problem (non-LSP dark matter)

A dark matter candidate without introducing an independent symmetry?
Residual discrete symmetry extended to hidden sector

: LUP dark matter from hidden sector

Hur, HL, Nasri [arXiv:0710.2653]

HL [arXiv:0802.0506]
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**SM-singlet exotics** (hidden sector fields)

*SM-singlet exotics*: often required for anomaly cancellations with $U(1)'$

\[ ([\text{gravity}]^2 - U(1)', [U(1)']^3) \]

We consider Majorana fields for simplicity.

\[ W_{\text{hidden}} = \frac{\xi}{2} SXX \]

These hidden sector fields ($X$) are neutral and massive particles.

→ Potentially dark matter candidate if they are stable.
How to stabilize hidden sector field?

Introduce “$U$-parity”

\[ U_p[\text{MSSM}] = \text{even}, \quad U_p[X] = \text{odd} \]

- Lightest $U$-parity Particle (LUP): Lightest $X \rightarrow$ stable
  either fermion ($\psi_X$) or scalar ($\phi_X$) component

It can be invoked as a residual discrete symmetry of the $U(1)'$.

\[ Z_{hid}^N : U_2 \quad (U\text{-parity}) \]

\[ z[F_i] = q[F_i] + 2n_i \]

<table>
<thead>
<tr>
<th></th>
<th>$Q$</th>
<th>$U^c$</th>
<th>$D^c$</th>
<th>$L$</th>
<th>$E^c$</th>
<th>$N^c$</th>
<th>$H_u$</th>
<th>$H_d$</th>
<th>$X$</th>
<th>meaning of $q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_2$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$-U$ ($X$ number)</td>
</tr>
</tbody>
</table>

(Other exotics: assumed to be heavier than the lightest $X$.)
Discrete symmetries over the MSSM and the hidden sectors

Now consider $U(1)' \rightarrow Z^\text{tot}_6$, which is

$$Z^\text{tot}_6 = B_3 \times U_2$$

with $q = 2q_B + 3q_U \mod 6$.

<table>
<thead>
<tr>
<th>$Z_6 = B_3 \times U_2$</th>
<th>$Q$</th>
<th>$U^c$</th>
<th>$D^c$</th>
<th>$L$</th>
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<th>$H_d$</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>-2</td>
<td>2</td>
<td>-2</td>
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<td>0</td>
<td>2</td>
<td>-2</td>
<td>-3</td>
</tr>
</tbody>
</table>

(Other exotic fields: assumed to be heavier than proton and the LUP → not stable due to the discrete symmetry.)

More generally, it is $U(1)' \rightarrow Z^\text{tot}_N$, which is

$$Z^\text{tot}_N = Z^\text{obs}_N \times Z^\text{hid}_N$$

(where $N = N_1 N_2$; $N_1$ and $N_2$ are coprime).
A unified picture of the stabilities in the observable and hidden sectors

\[ U(1)' \rightarrow Z_{N_1}^{obs} \times Z_{N_2}^{hid} \]

MSSM sector

\[ Z_{N_1}^{obs} (B_3) \]

: stable proton

Hidden sector

\[ Z_{N_2}^{hid} (U_2) \]

: stable dark matter

A single $U(1)'$ gauge symmetry provides stabilities for proton (MSSM sector) and dark matter (hidden sector).
Lightest $U$-parity Particle (LUP) dark matter

Lightest $U$-parity Particle (LUP)

- It is a neutral, massive, and stable particle from hidden sector.
- It can be either a fermion or a scalar.
- It is neither the RH neutrino nor RH sneutrino ($H_u LN^c$).
- It naturally arises when an extra $U(1)$ gauge symmetry is present.

To be a viable dark matter candidate, it should satisfy the *relic density* and *direct detection* constraints, too.
Annihilation channels for the LUP dark matter

For $\psi_X$ (fermionic) LUP,

1. $\psi_X\psi_X \rightarrow f\bar{f}$ ($Z'$ mediated $s$-channel)

2. $\psi_X\psi_X \rightarrow \tilde{f}\tilde{f}^*$ ($S$ mediated $s$-channel, $Z'$ mediated $s$-channel)

3. $\psi_X\psi_X \rightarrow SS, Z'Z'$ ($S$ mediated $s$-channel, $\psi_X$ mediated $t$-channel)

4. $\psi_X\psi_X \rightarrow SZ'$ ($Z'$ mediated $s$-channel, $\psi_X$ mediated $t$-channel)

5. $\psi_X\psi_X \rightarrow \tilde{S}\tilde{S}$ ($Z'$ mediated $s$-channel, $\phi_X$ mediated $t$-channel)

6. $\psi_X\psi_X \rightarrow \tilde{Z}'\tilde{Z}'$ ($\phi_X$ mediated $t$-channel)

7. $\psi_X\psi_X \rightarrow \tilde{S}\tilde{Z}'$ ($S$ mediated $s$-channel, $\phi_X$ mediated $t$-channel)

and also similarly for $\phi_X$ (scalar) LUP.
Predictions of relic density and direct detection cross-section (for $\phi_X$)

[Simulated with micrOMEGAs + newly constructed UMSSM model file]

LUP dark matter can satisfy both the relic density and direct detection constraints.
Summary

$R$-parity conserving model vs. $R$-parity violating $U(1)'$ model

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Conclusion: TeV scale $U(1)'$ is an attractive alternative to $R$-parity.
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