The LSP in M-Theory

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Outline

Moduli Stabilization in the G_2 MSSM

- All Moduli are stabalized – in detail.
- G_2 moduli z_i are stabilized by hidden sector Gaugino Condensation

$$W = A_1 \Phi^{a_1} e^{ib_1 f_1(z)} + A_2 \Phi^{a_2} e^{ib_2 f_2(z)} + \dots$$

- SUSY breaking is dominated by the hidden sector meson fields.
- MSSM scalar masses $\sim m_{3/2} \gtrsim 10$ TeV
- Meson fields (to leading order) do not appear in the gauge kinetic function
- Gaugino Masses are suppressed – Wino LSP

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Non-Thermal LSP Acharya, Kumar, Bobkov, Kane, Shao, Watson arXiv:0804.0863

- Moduli dominate the early universe and Decay to LPSs
- The gravitino mass and Moduli masses need to be $\gtrsim 10$ TeV for succesful BBN
- Gives the correct relic abundance !

Note: Probably generic in String Theory - SUGRA Lagrangian suggests at least one Moduli Mass $\sim$ Gravitino Mass

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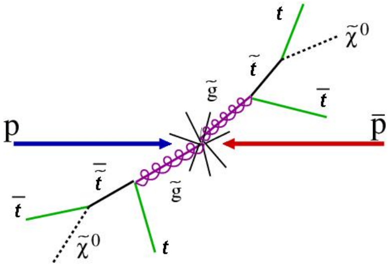
- Gluinos are produced in pairs
- $\sigma \approx$ pb
- Gluinos decay to 4 tops and Missing Energy
- Can be discovered early and easily at the LHC



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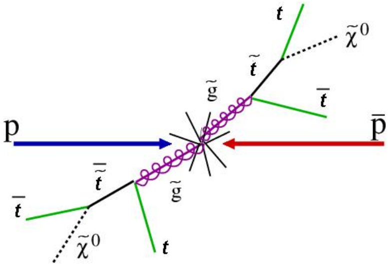

Wino LSP

Question:
How robust is the prediction that the LSP is Wino?

Wino LSP

- The LSP is a combination of Bino, Wino and Higgsino Components

$$\chi = \epsilon_{\tilde{B}} \tilde{B} + \epsilon_{\tilde{W}} \tilde{W} + \epsilon_{\tilde{h}_u} \tilde{h}_u + \epsilon_{\tilde{h}_d} \tilde{h}_d$$

- Even small Higgsino components can have large effects on direct detection of dark matter.
- We need a theory of the μ term
- Why is the LSP stable?

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Discrete Symmetries in M-Theory

- Witten (hep-ph/0201018) constructed a geometric discrete symmetry that can
  - forbid μ term $H_u H_d$ while allowing the Higgs triplet mass DD^c – Solved $D - T$ splitting.
  - forbid Dimension 4 and 5 proton decay
  - forbids R-parity violating operators
- This symmetry must be broken since μ cannot be zero
  - Moduli may be charged under this symmetry, but get vevs

$$\langle z \rangle \approx m_p + \theta^2 m_{1/2} m_p$$

  - Will reintroduce dangerous couplings.

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Moduli Induced R-Parity Problem

- Axionic shift symmetries

$$z_i \to z_i + a_i$$

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- But the μ term and R-parity violating couplings are allowed in the Kahler potential
  - $K \supset (Im\, z_j + i\ Im\, z_k) H_u H_d \to W \supset m_{1/2} H_u H_d$
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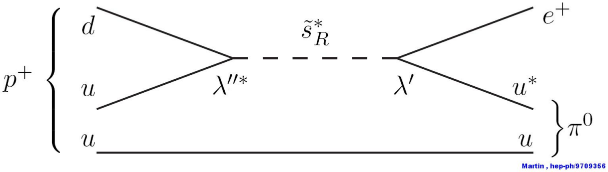
Proton Decay

- Baryon and lepton number are violated

$$W_{\not R} = \lambda' LQd^c + \lambda'' u^c d^c d^c + \lambda''' LLe^c$$

$$\lambda' \sim \lambda'' \sim \lambda''' \sim \frac{m_{1/2}}{m_p}$$

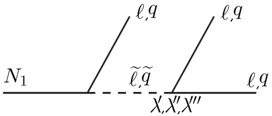
- Dimension-4 proton decay is really Dimension-6



$$\approx \left(\frac{m_{1/2}}{m_p}\right)^2 \frac{1}{m_{3/2}^2}$$ Experimentally Allowed

LSP Lifetime

- The LSP will decay



$$\tau \approx \frac{10^{-17}\,\text{sec}}{\lambda^2} \left(\frac{m_{\tilde{q},\tilde{l}}}{\text{TeV}}\right)^4 \left(\frac{100\text{ GeV}}{m_{\tilde{N}_1}}\right)^5$$

- For $m_{\tilde{q},\tilde{l}} \sim 10$ TeV, $m_{\tilde{N}_1} \sim 100$ GeV, $\lambda \sim 10^{-15}$

$$\tau \sim 10^{17}\,\text{sec} \sim t_0$$ Age of the Universe

- Indirect detection requires

$$\tau \gtrsim 10^{26}\,\text{sec}$$

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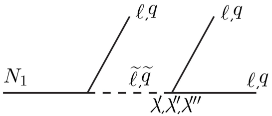

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R-Parity from GUTs

- Where is R-Parity?
- Try a local continous $U(1)$ – Moduli are uncharged.
- Which $U(1)$s?
  - Simple GUT Groups - Additional $U(1)$s are difficult to understand in global embeddings
  - Chiral Theory
  - Anomaly free theory
  - E_6, $SO(10)$ and $SU(5)$
- It is well known that these contain R-Parity

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GUT Review Slansky

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$\mathbf{27}$	$\mathbf{16}_1$	$\mathbf{10}_{-1}$	Q	$(\mathbf{3},\mathbf{2})_1$	-1	1
			u^c	$(\overline{\mathbf{3}},\mathbf{1})_{-4}$	-1	1
			e^c	$(\mathbf{1},\mathbf{1})_6$	-1	1
		$\overline{\mathbf{5}}_3$	d^c	$(\overline{\mathbf{3}},\mathbf{1})_2$	3	1
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		$\mathbf{1}_{-5}$	ν^c	$(\mathbf{1},\mathbf{1})_0$	-5	1
	$\mathbf{10}_{-2}$	$\mathbf{5}_2$	D	$(\mathbf{3},\mathbf{1})_{-2}$	2	-2
			H_u	$(\mathbf{1},\mathbf{2})_3$	2	-2
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	$\mathbf{1}_4$	$\mathbf{1}_0$	S	$(\mathbf{1},\mathbf{1})_0$	0	4

Wilson Line Breaking

- How will the symmetries be broken?
  - By Wilson Lines
  - E_6, $SO(10) \to SM \times U(1)_\chi (\times U(1)_\eta)$
    $U(1)_\chi$ cannot be broken by Wilson lines – Witten 85
  - $E_6 \to SU(10) \times U(1)_\eta$
    $S0(10)$ broken by $16, \overline{16}$
  - E_6, $SO(10) \to SU(5) \times U(1)_\chi (\times U(1)_\eta)$
    $SU(5)$ broken by $10, \overline{10}$
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$$K \supset (Im\, z_j + i\ Im\, z_k)\nu^c L H_u$$

$$\rightarrow W \supset m_{1/2}\frac{m_{3/2}}{m_p} L H_u \rightarrow W \supset \frac{m_{3/2}}{m_p} L L e^c$$

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$\mathbf{27}$	$\mathbf{16}_1$	$\mathbf{10}_{-1}$	Q	$(\mathbf{3},\mathbf{2})_1$	-1	1
			u^c	$(\bar{\mathbf{3}},\mathbf{1})_{-4}$	-1	1
			e^c	$(\mathbf{1},\mathbf{1})_6$	-1	1
		$\bar{\mathbf{5}}_3$	d^c	$(\bar{\mathbf{3}},\mathbf{1})_2$	3	1
			L	$(\mathbf{1},\mathbf{2})_{-3}$	3	1
		$\mathbf{1}_{-5}$	ν^c	$(\mathbf{1},\mathbf{1})_0$	-5	1
	$\mathbf{10}_{-2}$	$\mathbf{5}_2$	D	$(\mathbf{3},\mathbf{1})_{-2}$	2	-2
			H_u	$(\mathbf{1},\mathbf{2})_3$	2	-2
		$\bar{\mathbf{5}}_{-2}$	D^c	$(\bar{\mathbf{3}},\mathbf{1})_2$	-2	-2
			H_d	$(\mathbf{1},\mathbf{2})_{-3}$	-2	-2
	$\mathbf{1}_4$	$\mathbf{1}_0$	S	$(\mathbf{1},\mathbf{1})_0$	0	4

$E_6, SO(10) \to SU(5) \times U(1)_\chi$- Flipped $SU(5)$

- $E_6, SO(10) \to SU(5) \times U(1)_\chi$
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- LSP decays faster than before

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E_8

$$E_8 \rightarrow E_6 \times SU(3)$$

$$\lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_8 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

E_6	$U(1)_3$	$U(1)_8$
27	1	1
27	-1	1
27	0	-2

$E_6 \rightarrow$	$SO(10)_\eta \rightarrow$	$SU(5)_\chi$		SM	$\times U(1)_\chi$	$\times U(1)_\eta$
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Discrete symmetry revisited

- Can a discrete symmetry be broken to allow the μ-term while preserving R-parity.
- Witten's construction

Field		$\mathcal{Z}_n$
M_{10}		$e^{i\sigma}$
$M_{\bar{5}}$		$e^{i\tau}$
H_5	D	$e^{i\alpha}$
	H_u	$e^{i\alpha}$
$H_{\bar{5}}$	D^c	$e^{i\gamma}$
	H_d	$e^{i\delta}$

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Discrete symmetry revisited

- Allow Yukawa couplings, Majorana neutrino masses, and the Higgs triplet masses

	Coupling	Constraint
Up Yukawa Coupling	$M_{10}M_{10}H_u$	$2\sigma + \alpha = 2\pi$
Down Yukawa Coupling	$M_{10}M_{\bar{5}}H_d$	$\sigma + \tau + \delta = 2\pi$
Majorana Neutrino Masses	$H_dH_dM_{\bar{5}}M_{\bar{5}}$	$2\alpha + 2\tau = 2\pi$
Triplet Masses	DD^c	$\alpha + \gamma = 2\pi.$

Discrete symmetry revisited

- Find the solution

$$\alpha = -2\sigma, \gamma = 2\sigma, \delta = -3\sigma + \pi, \tau = 2\sigma + \pi, \sigma = \sigma$$

- Then forbid μ-term and R-parity violation

	Coupling	Constraint
$\mu -$ term	$H_d H_u$	$-5\sigma + \pi \neq 2\pi$
R-Parity	$M_{10} M_{10} M_{\bar{5}}$	$5\sigma \neq 2\pi$
	$M_{\bar{5}} H_u$	$\pi \neq 2\pi$

Discrete symmetry revisited

- Can this symmetry be broken and preserve R-parity?
- Yes
- Example $N = 6, \sigma = 2\pi/6$

	Coupling	Charge	$\mathcal{Z}_6$
$\mu-$term	$H_d H_u$	$-5\sigma+\pi$	$e^{i2\pi\frac{4}{6}}$
R-Parity	$M_{10}M_{\bar{5}}M_{\bar{5}}$	5σ	$2e^{i2\pi\frac{5}{6}}$
	$M_{\bar{5}}H_u$	π	$e^{i2\pi\frac{3}{6}}$

- Vevs of moduli transforming as $z \to e^{i2\pi\frac{2}{6}} z$ preserve R-Parity
- Why do we live in this vacuum?

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Summary

- M-Theory is awesome.
- R-parity is non-generic.
- Geometric symmetries may or may not be enough.
- Simple GUT models in M-Theory will not provide R-parity.

- Outlook
    - Look for a stable LSP: Non-GUT $U(1)$s, moduli vacuum, Monodromies ...

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$E_6 \to SU(5) \times U(1)_\chi \times U(1)_\eta$

- $E_6 \to SU(5) \times U(1)_\chi \times U(1)_\eta$
- $U(1)_\eta$ Can be broken by $\langle S \rangle, \langle \bar{S} \rangle$
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$$\to W \supset \frac{m_{1/2} m_{GUT} \langle \bar{S} \rangle}{m_p^3} M_{10} M_{10} M_{\bar{5}}$$

LSP is stable enough for $\langle \bar{S} \rangle \sim \frac{m_{3/2}}{m_p}$

$E_6 \to$	$SO(10)_\eta \to$	$SU(5)_\chi$		$SM \times$	$U(1)_\chi \times$	$U(1)_\eta$
$\mathbf{27}$	$\mathbf{16}_1$	$\mathbf{10}_{-1}$	Q	$(\mathbf{3},\mathbf{2})_1$	-1	1
			u^c	$(\bar{\mathbf{3}},\mathbf{1})_{-4}$	-1	1
			e^c	$(\mathbf{1},\mathbf{1})_6$	-1	1
		$\bar{\mathbf{5}}_3$	d^c	$(\bar{\mathbf{3}},\mathbf{1})_2$	3	1
			L	$(\mathbf{1},\mathbf{2})_{-3}$	3	1
		$\mathbf{1}_{-5}$	ν^c	$(\mathbf{1},\mathbf{1})_0$	-5	1
	$\mathbf{10}_{-2}$	$\mathbf{5}_2$	D	$(\mathbf{3},\mathbf{1})_{-2}$	2	-2
			H_u	$(\mathbf{1},\mathbf{2})_3$	2	-2
		$\bar{\mathbf{5}}_{-2}$	D^c	$(\bar{\mathbf{3}},\mathbf{1})_2$	-2	-2
			H_d	$(\mathbf{1},\mathbf{2})_{-3}$	-2	-2
	$\mathbf{1}_4$	$\mathbf{1}_0$	S	$(\mathbf{1},\mathbf{1})_0$	0	4

$E_6 \to SU(5) \times U(1)_\chi \times U(1)_\eta$

- $E_6 \to SU(5) \times U(1)_\chi \times U(1)_\eta$
- $U(1)_\eta$ Can be broken by $\langle S \rangle, \langle \bar{S} \rangle$
- Will break R-Parity

$$K \supset (Im\, z_j + i\, Im\, z_k)(\langle \bar{S} \rangle H_{10} M_{10} M_{10} M_{\bar{5}})$$

$$\to W \supset \frac{m_{1/2} m_{GUT} \langle \bar{S} \rangle}{m_p^3} M_{10} M_{10} M_{\bar{5}}$$

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$E_6 \to$	$SO(10)_\eta \to$	$SU(5)_\chi$		SM	$\times U(1)_\chi$	$\times U(1)_\eta$
$\mathbf{27}$	$\mathbf{16}_1$	$\mathbf{10}_{-1}$	Q	$(\mathbf{3},\mathbf{2})_1$	-1	1
			u^c	$(\bar{\mathbf{3}},\mathbf{1})_{-4}$	-1	1
			e^c	$(\mathbf{1},\mathbf{1})_6$	-1	1
		$\bar{\mathbf{5}}_3$	d^c	$(\bar{\mathbf{3}},\mathbf{1})_2$	3	1
			L	$(\mathbf{1},\mathbf{2})_{-3}$	3	1
		$\mathbf{1}_{-5}$	ν^c	$(\mathbf{1},\mathbf{1})_0$	-5	1
	$\mathbf{10}_{-2}$	$\mathbf{5}_2$	D	$(\mathbf{3},\mathbf{1})_{-2}$	2	-2
			H_u	$(\mathbf{1},\mathbf{2})_3$	2	-2
		$\bar{\mathbf{5}}_{-2}$	D^c	$(\bar{\mathbf{3}},\mathbf{1})_2$	-2	-2
			H_d	$(\mathbf{1},\mathbf{2})_{-3}$	-2	-2
	$\mathbf{1}_4$	$\mathbf{1}_0$	S	$(\mathbf{1},\mathbf{1})_0$	0	4

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$E_6 \to$	$SO(10)_\eta \to$	$SU(5)_\chi$		SM	$\times U(1)_\chi$	$\times U(1)_\eta$
$\mathbf{27}$	$\mathbf{16}_1$	$\mathbf{10}_{-1}$	Q	$(\mathbf{3},\mathbf{2})_1$	-1	1
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		$\bar{\mathbf{5}}_3$	d^c	$(\bar{\mathbf{3}},\mathbf{1})_2$	3	1
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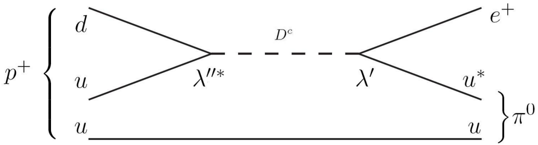
		$\mathbf{1}_{-5}$	ν^c	$(\mathbf{1},\mathbf{1})_0$	-5	1
	$\mathbf{10}_{-2}$	$\mathbf{5}_2$	D	$(\mathbf{3},\mathbf{1})_{-2}$	2	-2
			H_u	$(\mathbf{1},\mathbf{2})_3$	2	-2
		$\bar{\mathbf{5}}_{-2}$	D^c	$(\bar{\mathbf{3}},\mathbf{1})_2$	-2	-2
			H_d	$(\mathbf{1},\mathbf{2})_{-3}$	-2	-2
	$\mathbf{1}_4$	$\mathbf{1}_0$	S	$(\mathbf{1},\mathbf{1})_0$	0	4

$E_6, \to SU(5) \times U(1)_\chi \times U(1)_\eta$

- Doublet-Triplet Splitting and proton decay is spoiled
  $\bar{H}\bar{H}\bar{h}$ is forbidden
- Details are complicated – proton will decay



$$\approx Y^2 \frac{1}{m_{3/2}^2}$$

$E_6 \to$	$SO(10)_\eta \to$	$SU(5)_\chi$		SM	$\times U(1)_\chi$	$\times U(1)_\eta$
$\mathbf{27}$	$\mathbf{16}_1$	$\mathbf{10}_{-1}$	Q	$(\mathbf{3},\mathbf{2})_1$	-1	1
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		$\bar{\mathbf{5}}_{-2}$	D^c	$(\bar{\mathbf{3}},\mathbf{1})_2$	-2	-2
			H_d	$(\mathbf{1},\mathbf{2})_{-3}$	-2	-2
	$\mathbf{1}_4$	$\mathbf{1}_0$	S	$(\mathbf{1},\mathbf{1})_0$	0	4