## The LSP in M-Theory

## Eric Kuflik with Bobby Acharya and Gordon Kane

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May 5 / SVP

Eric Kuflik The LSP in M-Theory

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## Moduli Stabilization in the G<sub>2</sub> MSSM

- All Moduli are stabalized in detail.
- *G*<sub>2</sub> moduli *z<sub>j</sub>* 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

- $\bullet\,$  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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## LHC Phenomonology Acharya, Grajek, Kane, Kuflik, Suruliz, Wang arXiv:0901.3367

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



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



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## 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  $\mu$  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  $\mu$  term  $H_uH_d$  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  $\mu$  cannot be zero
  - Moduli may be charged under this symmetry, but get vevs

$$\langle z 
angle pprox m_p + heta^2 m_{1/2} m_p$$

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Moduli Induced R-Parity Problem

Axionic shift symmetries

$$z_i \rightarrow z_i + a_i$$

will forbid superpotential couplings.

- But the  $\mu$  term and R-parity violating couplings are allowed in the Kahler potential
  - $K \supset (Im z_j + i Im z_k)H_uH_d \rightarrow W \supset m_{1/2}H_uH_d$
  - $K \supset (Im z_j + i Im z_k)(M_{\bar{5}}h_5 + M_{10}M_{\bar{5}}M_{\bar{5}}) \rightarrow m_{1/2}M_{\bar{5}}h_5 + \frac{m_{1/2}}{m_p}M_{10}M_{\bar{5}}M_{\bar{5}}$

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### **Proton Decay**

Baryon and lepton number are violated

$$egin{aligned} \mathcal{W}_{p_{1}} &= \lambda' L Q d^{c} + \lambda'' u^{c} d^{c} d^{c} + \lambda''' L L e^{c} \ \lambda' &\sim \lambda'' \sim \lambda''' \sim rac{m_{1/2}}{m_{p}} \end{aligned}$$

Dimension-4 proton decay is really Dimension-6



### LSP Lifetime

• The LSP will decay

 $\begin{array}{c} \underbrace{\frac{N_1}{2}}{\frac{10^{-17} \sec}{\lambda^2} \left(\frac{m_{\tilde{q},\tilde{l}}}{1 \mathrm{eV}}\right)^4 \left(\frac{100 \ \mathrm{GeV}}{m_{\tilde{N}_1}}\right)^5 } \\ \tau \approx \frac{10^{-17} \sec}{\lambda^2} \left(\frac{m_{\tilde{q},\tilde{l}}}{1 \mathrm{eV}}\right)^4 \left(\frac{100 \ \mathrm{GeV}}{m_{\tilde{N}_1}}\right)^5 \end{array} \\ \bullet \ \mathrm{For} \ m_{\tilde{q},\tilde{l}} \sim 10 \ \mathrm{TeV}, \ m_{\tilde{N}_1} \sim 100 \ \mathrm{GeV}, \ \lambda \sim 10^{-15} \\ \tau \sim 10^{17} \sec \sim t_0 \qquad \mathrm{Age \ of \ the \ Universe} \end{array}$ 

Indirect detection requires

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Indirect detection requires

$$au\gtrsim$$
 10<sup>26</sup> sec

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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*<sub>6</sub>, *SO*(10) and *SU*(5)
- It is well known that these contain *R*-Parity

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## **GUT Review Slansky**

$$\frac{E_{6} \rightarrow SO(10)_{\eta} \rightarrow SU(5)_{\chi} \quad SM \times U(1)_{\chi} \times U(1)_{\eta}}{\left\{ \begin{array}{cccc} \mathbf{I0}_{-1} \left\{ \begin{array}{cccc} Q & (\mathbf{3}, \mathbf{2})_{1} & -1 & 1 \\ u^{c} & (\mathbf{\overline{3}}, \mathbf{1})_{-4} & -1 & 1 \\ e^{c} & (\mathbf{1}, \mathbf{1})_{6} & -1 & 1 \\ \mathbf{\overline{5}}_{3} & \left\{ \begin{array}{cccc} d^{c} & (\mathbf{\overline{3}}, \mathbf{1})_{2} & 3 & 1 \\ \mathbf{1}_{-5} & \nu^{c} & (\mathbf{1}, \mathbf{1})_{0} & -5 & 1 \\ \mathbf{10}_{-2} \left\{ \begin{array}{cccc} \mathbf{5}_{2} & \left\{ \begin{array}{cccc} D & (\mathbf{3}, \mathbf{1})_{-2} & 2 & -2 \\ H_{u} & (\mathbf{1}, \mathbf{2})_{-3} & 3 & 1 \\ \mathbf{1}_{-5} & \nu^{c} & (\mathbf{1}, \mathbf{1})_{0} & -5 & 1 \\ \mathbf{10}_{-2} \left\{ \begin{array}{cccc} \mathbf{5}_{2} & \left\{ \begin{array}{cccc} D & (\mathbf{3}, \mathbf{1})_{-2} & 2 & -2 \\ H_{u} & (\mathbf{1}, \mathbf{2})_{3} & 2 & -2 \\ \mathbf{5}_{-2} & \left\{ \begin{array}{cccc} D^{c} & (\mathbf{\overline{3}}, \mathbf{1})_{2} & -2 & -2 \\ H_{d} & (\mathbf{1}, \mathbf{2})_{-3} & -2 & -2 \\ H_{d} & (\mathbf{1}, \mathbf{2})_{-3} & -2 & -2 \\ \mathbf{1}_{4} & \mathbf{1}_{0} & S & (\mathbf{1}, \mathbf{1})_{0} & 0 & 4 \end{array} \right\} \right\}$$

Eric Kuflik

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## Wilson Line Breaking

#### • How will the symmetries be broken?

- By Wilson Lines
- $E_6$ ,  $SO(10) \rightarrow SM \times U(1)_{\chi} (\times U(1)_{\eta})$  $U(1)_{\chi}$  cannot be broken by Wilson lines – Witten 8
- $E_6 \rightarrow SU(10) \times U(1)_{\eta}$ S0(10) broken by 16, 16
- $E_6$ ,  $SO(10) \rightarrow SU(5) \times U(1)_{\chi}(\times U(1)_{\eta})$ SU(5) broken by 10,  $\overline{10}$
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## $E_6, SO(10) ightarrow SM imes U(1)_{\chi}^{-1}$

# • $E_6$ , $SO(10) \rightarrow SM \times U(1)_{\chi}$

- $U(1)_{\chi}$  Can be broken by  $\langle \bar{\nu}^c \rangle$
- Will break R-Parity
- How will a small vev be generated?
- Even if we could

$$K \supset (Im z_j + i Im z_k) \nu^c LH_u$$

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LSP decays as before

$E_6 \rightarrow S$	$SO(10)_{\eta}$	$\rightarrow SU(s)$	$(5)_{\chi}$	$SM\times U$	$(1)_{\chi}$	$\times U(1)_{\eta}$
		. (	Q	$\left( 3,2\right) _{1}$	-1	1
	ſ	$10_{-1}$	$u^c$	$({\bf \overline{3}},{\bf 1})_{-4}$	-1	1
		l	$e^{c}$	$(1, 1)_{6}$	-1	1
	$\begin{bmatrix} 16_1 \\ \end{bmatrix}$	<u>₹</u> .∫	$d^c$	$(\overline{3},1)_2$	3	1
	$\mathbf{J}_3$	L	$(1, 2)_{3}$	3	1	
	l	$1_{-5}$	$\nu^c$	$(1,1)_0$	-5	1
27 { 10.2	(	<b>5</b> ₂ ∫	D	$({\bf 3},{\bf 1})_{-2}$	2	-2
	10 .)	ົ ໂ	$H_u$	$(1, 2)_3$	2	-2
	$\overline{5}_{2} \int D^{c}$	$(\overline{3},1)_2$	-2	-2		
	$\int \int H_d$		$H_d$	$(1, 2)_{-3}$	-2	-2
	$1_4$	$1_0$	S	$(1, 1)_0$	0	4

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			$\left( Q \right)$	$(3,2)_1$	-1	1
	ſ	<b>10</b> <sub>-1</sub>	$\left\{ u^{c} \right\}$	$(\overline{3}, 1)_{\mathcal{A}}$	-1	1
			$\left  e^{c} \right $	$(1,1)_{6}$	-1	1
	$\begin{bmatrix} 16_1 \\ \end{bmatrix}$	F.	$\int d^c$	$(\overline{3},1)_{2}^{\circ}$	3	1
	03	L	$(1, 2)_{3}$	3	1	
	l	$1_{-5}$	$\nu^{c}$	$(1,1)_0$	-5	1
27	6	5.	∫ D	$({\bf 3},{\bf 1})_{-2}$	2	-2
	10.	02	$\left  H_u \right $	$(1, 2)_3$	2	-2
	10-2	5 .	$\int D^c$	$(\overline{3},1)_2$	-2	-2
	L L		$\left  H_d \right $	$(1, 2)_{-3}$	-2	-2
	$\begin{bmatrix} 1_4 \end{bmatrix}$	$1_0$	S	$(1, 1)_0$	0	4

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LSP decays as before

$E_6 \rightarrow S$	$SO(10)_{\eta}$	$\rightarrow SU$	$V(5)_{\chi}$	$SM \times U$	$(1)_{\chi}$	$\times U(1)_{\eta}$
			Q	$(3,2)_1$	-1	1
	ſ	<b>10</b> <sub>-1</sub>	$\left  u^{c} \right $	$(\overline{3}, 1)_{\mathcal{A}}$	-1	1
			$e^{c}$	$(1,1)_{6}$	-1	1
1	$\begin{bmatrix} 16_1 \\ \end{bmatrix}$	F	$\int d^c$	$(\overline{3},1)_{2}^{\circ}$	3	1
	$\mathbf{D}_3$	L	$(1, 2)_{-3}$	3	1	
	l	$1_{-5}$	$\nu^{c}$	$(1,1)_0$	-5	1
27	6	5.	f D	$({\bf 3},{\bf 1})_{-2}$	2	-2
10-2	10.	02	$H_u$	$(1, 2)_3$	<b>2</b>	-2
	10-2	<u>5</u> .	$\int D^c$	$(\overline{3},1)_2$	-2	-2
	l	0-2	$\left  H_d \right $	$(1, 2)_{-3}$	-2	-2
	$1_4$	$1_{0}$	S	$(1, 1)_0$	0	4

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## $E_6, SO(10) ightarrow SM imes U(1)_{\chi}$

- $E_6$ ,  $SO(10) \rightarrow SM \times U(1)_{\chi}$
- $U(1)_{\chi}$  Can be broken by  $\langle \bar{\nu}^c \rangle$
- Will break R-Parity
- How will a small vev be generated?
- Even if we could

$$K \supset (\operatorname{Im} z_j + i \operatorname{Im} z_k) \nu^{c} L H_u$$

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

LSP decays as before

$E_6 \rightarrow SO(10)_\eta \rightarrow SU(5)_\chi$	$SM \times U$	$(1)_{\chi}$	$\times U(1)_{\eta}$
(Q	$({\bf 3},{\bf 2})_1$	-1	1
$\begin{bmatrix} 10_{-1} \\ u^c \end{bmatrix}$	$(\overline{3}, 1)_{\mathcal{A}}$	-1	1
$e^{c}$	$(1,1)_{6}^{-1}$	-1	1
$\left( \begin{array}{c} 16_1 \\ \mathbf{\overline{F}} \end{array} \right) \left( \begin{array}{c} \mathbf{d}^c \end{array} \right)$	$({\bf \bar{3}},{\bf 1})_{2}^{\circ}$	3	1
$\mathbf{a}_3 \in L$	$(1,2)_{-3}$	3	1
$1_{-5}$ $\nu^{c}$	$(1,1)_0$	-5	1
$27$ $(5)$ $\int D$	$({\bf 3},{\bf 1})_{-2}$	2	-2
$10_{2}$	$(1, 2)_3$	2	-2
$\overline{5}_{2} \int \overline{5}_{2} \int D^{c}$	$(\overline{3},1)_2$	-2	-2
	$(1, 2)_{-3}$	-2	-2
$\begin{bmatrix} 1_4 & 1_0 & S \end{bmatrix}$	$(1, 1)_0$	0	4

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# $E_6$ , $SO(10) \rightarrow SU(5) \times U(1)_{\chi}$ - Flipped SU(5)

## • $E_6, SO(10) \rightarrow SU(5) \times U(1)_{\chi}$

- Can be broken by  $H = \langle 10_{-1} \rangle, \overline{H} = \langle \overline{10}_1 \rangle$
- $W \supset H_{10}H_{10}h_5 + \overline{H}_{\overline{10}}\overline{H}_{\overline{10}}\overline{h}_{\overline{5}}$  Solves D-T Splitting
- Will break R-Parity
- Will need GUT scale vev
- Even if we could

 $K \supset (\operatorname{Im} z_j + i \operatorname{Im} z_k)(H_{10}\overline{H}_{\overline{5}}M_{\overline{5}}) \rightarrow W \supset \frac{m_{1/2}m_{GUT}}{m_p} \frac{m_{3/2}}{m_p} LH_u$ 

Eric Kuflik

#### • LSP decays faster than before

$E_6 \rightarrow S$	$SO(10)_{\eta}$ -	$\rightarrow SU$	$(5)_{\chi}$	$SM \times U$	$(1)_{\chi}$ :	$\times U(1)_{\eta}$
			$\left[ \begin{array}{c} Q \end{array} \right]$	$({\bf 3},{\bf 2})_1$	-1	1
	ſ	10-1	$u^c$	$(\bar{\bf 3}, {\bf 1})_{4}$	-1	1
	. 10			$(1, 1)_6$	-1	1
	$\begin{bmatrix} 10_1 \\ 10_1 \end{bmatrix}$	<u>F</u> .	$\int d^c$	$(\overline{3},1)_2$	3	1
	<b>J</b> 3 (	$\lfloor L \rfloor$	$(1, 2)_{3}$	3	1 /	
	l	$1_{-5}$	$\nu^{c}$	$(1,1)_{0}$	-5	$_{1}/$
$\left  \begin{array}{c} 27 \\ 10_{-2} \end{array} \right  \\ \left  \begin{array}{c} 10_{-2} \end{array} \right  \\ \left  \left  \left  \begin{array}{c} 10_{-2} \end{array} \right  \\ \left  $	6	5.	$\int D$	$({\bf 3},{\bf 1})_{-2}$	2	-2
	92 (	$H_u$	$(1, 2)_3$	2	-2	
	10-2	$\overline{5}$ .	$\int D^c$	$(\overline{3},1)_2$	-2	-2
		0-2 .	$H_d$	$(1, 2)_{-3}$	-2	-2
	$1_4$	$1_0$	S	$(1, 1)_0$	0	4

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$E_6 \rightarrow S$	$SO(10)_{\eta}$	$\rightarrow SU(5)_{\chi}$	$SM \times U$	$(1)_{\chi}$	$\times U(1)_{\eta}$
		(Q	$({\bf 3},{\bf 2})_1$	-1	1
	ſ	$10_{-1}$ $u^{c}$	$(\bar{\bf 3}, {\bf 1})_{4}$	-1	1
		( e <sup>c</sup>	$(1,1)_{6}$	-1	1
	$\begin{bmatrix} 16_1 \\ \end{bmatrix}$	$\overline{\mathbf{E}}$ , $\int d^c$	$(\overline{3},1)_2$	3	1
		$\mathbf{J}_{3} \left\{ L \right\}$	$(1,2)_{-3}$	3	1 /
	ι	1.5 $\nu^{c}$	$(1,1)_0$	-5	1 /
27	6	$5_2 \int D$	$({\bf 3},{\bf 1})_{-2}$	2	-2
- 1	10	$\int H_u$	$(1, 2)_3$	2	-2
	$\overline{5} \circ \int D^c$	$(\overline{3},1)_2$	-2	-2	
	$\int H_d$	$(1,2)^{-3}$	-2	-2	
	14	10 S	(1 1)	0	1

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	ſ	<b>10</b> <sub>-1</sub>	$\left\{ u^{c} \right\}$	$(\bar{\bf 3}, {\bf 1})_{4}$	-1	1
			$e^{c}$	$(1,1)_{6}$	-1	1
1	$\begin{bmatrix} 16_1 \\ \end{bmatrix}$	Ē.	$\int d^{c}$	$(\overline{3},1)_2$	3	1
	03	L	$(1, 2)_{3}$	3	1 /	
	L L	$1_{-5}$	$\nu^{c}$	$(1, 1)_0$	-5	1 /
27	(	5.	$\int D$	$({\bf 3},{\bf 1})_{-2}$	2	-2
10.2	02	$H_u$	$(1, 2)_3$	2	-2	
	10-2	$\overline{5}$ .	$\int D^c$	$(\overline{3},1)_2$	-2	-2
	l (	0-2	$\left  H_d \right $	$(1, 2)_{-3}$	-2	-2
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			Q	$({\bf 3},{\bf 2})_1$	-1	1
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	. 10	l	$e^{c}$	$(1,1)_{6}$	-1	1
	$\begin{bmatrix} 16_1 \\ 1 \end{bmatrix}$	= J	$d^{c}$	$(\overline{3},1)_2$	3	1
0	<b>J</b> 3 1	$\lfloor L \rfloor$	$(1, 2)_{3}$	3	1 /	
	l	$1_{-5}$	$\nu^{c}$	$(1,1)_0$	-5	$_{1}/$
27	6	5. J	$\int D$	$({\bf 3},{\bf 1})_{-2}$	2	-2
10.2 (	10	້ ໂ	$H_u$	$(1, 2)_3$	2	-2
	10-2	5.1	$\int D^c$	$(\overline{3},1)_2$	-2	-2
	ן ני	5-2 }	$H_d$	$(1, 2)_{-3}$	-2	-2
	$1_4$	$1_0$	S	$(1, 1)_0$	0	4

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$$\begin{split} E_8 \to E_6 \times SU(3) \\ \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_8 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} 2^{27} \begin{cases} 16_1 \begin{cases} U(1)_3 & U(1)_3 \\ U(1)_3 & U(1)_8 \\ 10_2 \end{cases} \begin{array}{c} \frac{E_6 \to SO(10)_\eta \to SU(5)_X & SM \times U(1)_X \times U(1)_\eta}{\left(3,2\right)_4 & -1 & 1\right)} \\ 10_1 \begin{cases} Q & (3,2)_1 & -1 & 1 \\ Q & (3,1)_2 & 3 & 1 \\ 1 & 5 & \frac{V^2}{C^2} \\ (1,1)_0 & -5 & -1 \\ 10_2 \begin{cases} 5_2 \begin{cases} D & (3,1)_2 & 2 & -2 \\ H_u & (1,2)_3 & 2 & -2 \\ 10_2 \begin{cases} 5_2 \begin{cases} D & (3,1)_2 & 2 & -2 \\ H_u & (1,2)_3 & 2 & -2 \\ 5_2 \begin{cases} D^2 & (3,1)_2 & -2 & -2 \\ H_u & (1,2)_3 & 2 & -2 \\ 14 & 1_0 & S \\ (1,1)_0 & 0 & 4 \\ 14 & 1_0 & S \\ (1,1)_0 & 0 & 4 \\ 14 & 1_0 & S \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 1 & 1_0 \\ 16 & 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\ 16 & 1_0 \\$$

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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

$$\begin{array}{c|c} \mbox{Field} & \mathcal{Z}_n \\ \hline M_{10} & e^{i\sigma} \\ M_{\overline{5}} & e^{i\tau} \\ H_{\overline{5}} & D & e^{i\alpha} \\ H_{\overline{5}} & H_u & e^{i\alpha} \\ H_{\overline{5}} & H_d & e^{i\delta} \end{array}$$

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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	$H_d H_d M_{\overline{5}} M_{\overline{5}}$	$2\alpha + 2\tau = 2\pi$
Triplet Masses	DDc	$\alpha + \gamma = 2\pi.$

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## Discrete symmetry revisited

Find the solution

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

• Then forbid  $\mu$ -term and R-parity violation

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

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## Discrete symmetry revisited

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

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

- 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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## Discrete symmetry revisited

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

- 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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		(	Q	$(3,2)_1$	-1	1
27 <	ſ	$10_{-1}$	$u^c$	$(\bar{\bf 3}, {\bf 1})_{4}$	-1	1
	$\left( \begin{array}{c} 16_1 \end{array} \right)$	l	$e^{c}$	$(1,1)_6$	-1	1
		Ē.∫	$d^c$	$(\overline{3},1)_2$	3	1
		$^{3}$ $\left(\right)$	L	$(1, 2)_{3}$	3	1 /
	l	$1_{-5}$	$\nu^{c}$	$(1, 1)_0$	-5	1 /
	10-2	<b>5</b> ₂ ∫	D	$({\bf 3},{\bf 1})_{\!-\!2}$	2	-2
		ັ ໂ	$H_u$	$(1, 2)_3$	2	-2
		$\overline{5} \circ \int I$	$D^c$	$(\overline{3},1)_2$	-2	-2
	l	$I_d$		$(1, 2)_{-3}$	-2	-2
	$1_4$	$1_0$	S	$(1, 1)_0$	0	4

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 $\begin{array}{c} \underline{E_6 \rightarrow SO(10)_{\eta} \rightarrow SU(5)_{\chi} \quad SM \times U(1)_{\chi} \times U(1)_{\eta}} \\ & \left\{ \begin{array}{c} \mathbf{10}_{-1} \left\{ \begin{array}{ccc} Q & (\mathbf{3}, \mathbf{2})_{1} & -1 & 1 \\ u^c & (\mathbf{3}, \mathbf{1})_{-4} & -1 & 1 \\ \overline{c^c} & (\mathbf{1}, \mathbf{1})_{\mathbf{6}} & -1 & -1 \\ \overline{c^c} & (\mathbf{1}, \mathbf{1})_{\mathbf{6}} & -1 & -1 \\ \overline{c^c} & (\mathbf{1}, \mathbf{1})_{\mathbf{6}} & -1 & -1 \\ 1_{-5} & u^c & (\mathbf{1}, \mathbf{1})_{-3} & 3 & 1 \\ \mathbf{1}_{-5} & v^c & (\mathbf{1}, \mathbf{1})_{0} & -5 & 1 \end{array} \right\} \\ \mathbf{27} \left\{ \begin{array}{c} \mathbf{27} \left\{ \begin{array}{c} \mathbf{10}_{-2} \left\{ \begin{array}{c} \mathbf{5}_{2} & \left\{ \begin{array}{c} D \\ H_{u} \end{array} \right| & (\mathbf{1}, \mathbf{2})_{-3} & 2 & -2 \\ \mathbf{10}_{-2} \left\{ \begin{array}{c} \mathbf{5}_{2} & \left\{ \begin{array}{c} D \\ H_{u} \end{array} \right| & (\mathbf{1}, \mathbf{2})_{-3} & -2 & -2 \\ \overline{\mathbf{5}}_{-2} & \left\{ \begin{array}{c} D^e \\ H_{d} \end{array} \right| & (\mathbf{1}, \mathbf{2})_{-3} & -2 & -2 \\ \mathbf{14} & \mathbf{10} & S \end{array} \right\} \right. \end{array} \right. \end{array} \right. \end{array} \right.$ 

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 $K \supset (\operatorname{Im} z_j + i \operatorname{Im} z_k)(H_{10}M_{10}M_{10}M_{\overline{5}})$ 

 $ightarrow W \supset rac{m_{1/2} m_{GUT}}{m_p^2} M_{10} M_{10} M_{ar{5}}$ 

LSP decays as before

Eric Kuflik

## $E_6$ , $SO(10) \rightarrow SU(5) \times U(1)_{\chi}$ - Flipped SU(5)

- $E_6$ ,  $SO(10) \rightarrow SU(5) \times U(1)_{\chi}$ • Can be broken by
  - $H = \langle 10_{-1} \rangle, \bar{H} = \langle \bar{10}_1 \rangle$
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 $\begin{array}{c|c} \underline{E_{6} \rightarrow SO(10)_{\eta} \rightarrow SU(5)_{\chi}} & SM \times U(1)_{\chi} \times U(1)_{\eta} \\ \hline \\ E_{6} \rightarrow SO(10)_{\eta} \rightarrow SU(5)_{\chi} & SM \times U(1)_{\chi} \times U(1)_{\eta} \\ \hline \\ 10_{-1} \begin{cases} Q & (\mathbf{3}, \mathbf{2})_{1} & -1 & 1 \\ u^{c} & (\mathbf{3}, \mathbf{1})_{-4} & -1 & 1 \\ \hline \\ \overline{\mathbf{5}}_{3} & \left\{ \begin{array}{c} U^{c} & (\mathbf{3}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{3} & \left\{ \begin{array}{c} U^{c} & (\mathbf{3}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{3} & \left\{ \begin{array}{c} U^{c} & (\mathbf{1}, \mathbf{1})_{6} & -1 & -1 \\ 1 & \mathbf{5}_{3} & \left\{ \begin{array}{c} U^{c} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & \left\{ \begin{array}{c} U^{c} & (\mathbf{1}, \mathbf{1})_{-6} & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & \left\{ \begin{array}{c} U^{c} & (\mathbf{1}, \mathbf{1})_{-6} & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{1}, \mathbf{1})_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & (\mathbf{5}_{-6} & -1 & -1 \\ 1 & \mathbf{5}_{-6} & -1 & -1 \\ 1 & \mathbf{$ 

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 $K \supset (Im z_j + i Im z_k)(H_{10}M_{10}M_{10}M_{5})$ 

 $W \supset \frac{m_{1/2}m_{GUT}}{m_p^2} M_{10}M_{10}M_{\bar{5}}$ 

LSP decays as before

Eric Kuflik

## $E_6$ , $SO(10) \rightarrow SU(5) \times U(1)_{\chi}$ - Flipped SU(5)

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$$\rightarrow W \supset \frac{m_{1/2}m_{GUT}}{m_p^2} M_{10}M_{10}M_{\bar{5}} \qquad \text{LSP decays as before}$$

Eric Kuflik

$$\begin{array}{c} \underline{E_6 \rightarrow SO(10)_{\eta} \rightarrow SU(5)_{\chi}} & SM \times U(1)_{\chi} \times U(1)_{\eta} \\ & \left\{ \begin{array}{c} \mathbf{10}_{-1} \left\{ \begin{array}{c} Q \\ u^c \\ u^c \\ \overline{\mathbf{3}}, \mathbf{1}_{-4} & -1 & 1 \\ \frac{Q}{c^c} \\ (\mathbf{1}, \mathbf{1})_{\overline{\mathbf{6}}} & -4 & -1 \\ \overline{\mathbf{5}}_3 \\ \mathbf{1}_{-5} \\ \mathbf{10}_{-5} \\ \mathbf{10}_{-2} \\ \end{array} \right\} \\ \mathbf{27} \left\{ \begin{array}{c} \mathbf{16}_1 \\ \mathbf{16}_1 \\ \mathbf{16}_1 \\ \mathbf{16}_2 \\ \mathbf{10}_2 \\ \mathbf{10$$

 $E_6 
ightarrow SU(5) imes U(1)_\chi imes U(1)_\eta$ 

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

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

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

LSP is stable enough for  $\langle ar{S} 
angle \sim rac{m_{3/2}}{m_{
m p}}$ 

 $\begin{array}{c|c} \underline{E_{6} \rightarrow SO(10)_{\eta} \rightarrow SU(5)_{\chi}} & SM \times U(1)_{\chi} \times U(1)_{\eta} \\ \hline \\ E_{6} \rightarrow SO(10)_{\eta} \rightarrow SU(5)_{\chi} & SM \times U(1)_{\chi} \times U(1)_{\eta} \\ \hline \\ 10_{-1} \begin{cases} Q & (\mathbf{3}, \mathbf{2})_{1} & -1 & 1 \\ u^{c} & (\mathbf{3}, \mathbf{1})_{-4} & -1 & 1 \\ \hline \\ \mathbf{5}_{3} & \left\{ \begin{array}{c} U^{c} & (\mathbf{3}, \mathbf{1})_{-6} & -\mathbf{1} & -\mathbf{1} \\ \hline \\ \mathbf{5}_{3} & \left\{ \begin{array}{c} U^{c} & (\mathbf{3}, \mathbf{1})_{-6} & -\mathbf{1} & -\mathbf{1} \\ \hline \\ \mathbf{5}_{3} & \left\{ \begin{array}{c} U^{c} & (\mathbf{3}, \mathbf{1})_{-2} & 3 & -\mathbf{1} \\ \mathbf{1}_{-5} & \nu^{c} & (\mathbf{1}, \mathbf{1})_{0} & -\mathbf{5} & 1 \\ \hline \\ \mathbf{1}_{-5} & \nu^{c} & (\mathbf{1}, \mathbf{1})_{0} & -\mathbf{5} & 1 \\ \hline \\ \mathbf{10}_{-2} & \left\{ \begin{array}{c} \mathbf{5}_{2} & \left\{ \begin{array}{c} D & (\mathbf{3}, \mathbf{1})_{-2} & 2 & -2 \\ H_{u} & (\mathbf{1}, \mathbf{2})_{-3} & 2 & -2 \\ \hline \\ \mathbf{5}_{-2} & \left\{ \begin{array}{c} D^{c} & (\mathbf{3}, \mathbf{1})_{2} & -2 & -2 \\ H_{d} & (\mathbf{1}, \mathbf{2})_{-3} & -2 & -2 \\ H_{d} & (\mathbf{1}, \mathbf{2})_{-3} & -2 & -2 \\ \end{array} \right\} \end{cases} \end{cases} \end{cases} \end{array} \right.$ 

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 $\overline{E_6} \rightarrow SU(5) \times U(1)_{\gamma} \times U(1)_n$ 

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$$E_6 
ightarrow SU(5) imes U(1)_\chi imes U(1)_\eta$$

$$ightarrow W \supset rac{m_{1/2}m_{GUT}\left}{m_p^3}M_{10}M_{10}M_{ar{5}}$$

 $E_6 \rightarrow SO(10)_\eta \rightarrow SU(5)_\chi \quad SM \times U(1)_\chi \times U(1)_\eta$ 
$$\begin{split} & E_{6} \rightarrow SU(5) \times U(1)_{\chi} \times U(1)_{\eta} \\ & U(1)_{\eta} \text{ Can be broken by } \langle S \rangle, \langle \bar{S} \rangle \\ & \text{Will break R-Parity} \\ & \mathcal{K} \supset (Im \, z_{j} + i \, Im \, z_{k})(\langle \bar{S} \rangle \, H_{10} M_{10} M_{\bar{5}}) \\ & \rightarrow \mathcal{W} \supset \frac{m_{1/2} m_{GUT} \, \langle \bar{S} \rangle}{m_{3}^{2}} M_{10} M_{10} M_{\bar{5}} \end{split} 27 \begin{cases} \frac{16_{13}}{10_{13}} \frac{10_{13}}{10_{13}} \frac{10_$$

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 $\overline{E_6} 
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angle}{m_{
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m p}}$ 

 $\begin{array}{c|c} \underline{E_{6} \rightarrow SO(10)_{\eta} \rightarrow SU(5)_{\chi}} & SM \times U(1)_{\chi} \times U(1)_{\eta} \\ \hline \\ E_{6} \rightarrow SO(10)_{\eta} \rightarrow SU(5)_{\chi} & SM \times U(1)_{\chi} \times U(1)_{\eta} \\ \hline \\ 10_{-1} \begin{cases} Q & (\mathbf{3}, \mathbf{2})_{1} & -1 & 1 \\ u^{c} & (\mathbf{3}, \mathbf{1})_{-4} & -1 & 1 \\ \hline \\ \mathbf{5}_{3} & \left\{ \begin{array}{c} U^{c} & (\mathbf{3}, \mathbf{1})_{-2} & 3 & 1 \\ 1 & (\mathbf{1}, \mathbf{2})_{-3} & 3 & 1 \\ 1 & -5 & \nu^{c} & (\mathbf{1}, \mathbf{1})_{0} & -5 & 1 \end{array} \right. \\ \hline \\ \mathbf{27} \begin{cases} \mathbf{16}_{1} & \left\{ \begin{array}{c} \mathbf{5}_{2} & \left\{ \begin{array}{c} D & (\mathbf{3}, \mathbf{1})_{-2} & 2 & -2 \\ \mathbf{10}_{-2} & \left\{ \begin{array}{c} \mathbf{5}_{2} & \left\{ \begin{array}{c} D & (\mathbf{3}, \mathbf{1})_{-2} & 2 & -2 \\ H_{u} & (\mathbf{1}, \mathbf{2})_{3} & 2 & -2 \\ \hline \mathbf{5}_{-2} & \left\{ \begin{array}{c} D^{c} & (\mathbf{3}, \mathbf{1})_{-2} & -2 & -2 \\ H_{u} & (\mathbf{1}, \mathbf{2})_{-3} & -2 & -2 \\ H_{d} & (\mathbf{1}, \mathbf{2})_{-3} & -2 & -2 \\ \end{array} \right. \\ \hline \end{array} \end{cases}$ 

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ightarrow SU(5) imes U(1)_\chi imes U(1)_\eta$ 

