$SO(10)$ Grand Unification from M-theory on a G_2-manifold

Miguel Crispim Romão[1]

In collaboration with Bobby S. Acharya[2] Krzysztof Bożek[2] Stephen F. King[1] Chakrit Pongkitivanichkul[2]

[1]School of Physics and Astronomy
University of Southampton, Southampton, SO17 1BJ, UK

[2]Department of Physics
King's College London, London, WC2R 2LS, UK

Discrete 2014

Outline

Outline

Introduction and Motivation

- The LHC discovery of a Standard Model (SM) like Higgs stresses the need to understand the Electroweak Scale (EWS).

Introduction and Motivation

- The LHC discovery of a Standard Model (SM) like Higgs stresses the need to understand the Electroweak Scale (EWS).
- Supersymmetry (SUSY) provides an elegant solution for the EWS stability, but naturalness requires SUSY partners to be of order $\mathcal{O}(\text{TeV})$.

Introduction and Motivation

- The LHC discovery of a Standard Model (SM) like Higgs stresses the need to understand the Electroweak Scale (EWS).
- Supersymmetry (SUSY) provides an elegant solution for the EWS stability, but naturalness requires SUSY partners to be of order $\mathcal{O}(\text{TeV})$.
- These predictions and constraints are usually within the Minimal Supersymmetric Standard Model (MSSM) setup.

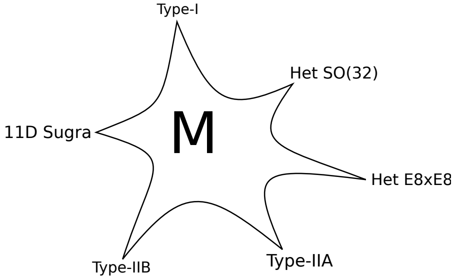
Introduction and Motivation

- The LHC discovery of a Standard Model (SM) like Higgs stresses the need to understand the Electroweak Scale (EWS).
- Supersymmetry (SUSY) provides an elegant solution for the EWS stability, but naturalness requires SUSY partners to be of order $\mathcal{O}(\text{TeV})$.
- These predictions and constraints are usually within the Minimal Supersymmetric Standard Model (MSSM) setup.
- One is led to search for more general SUSY models. A fruitful guideline for this has been given by String Theory phenomenology.

Introduction and Motivation

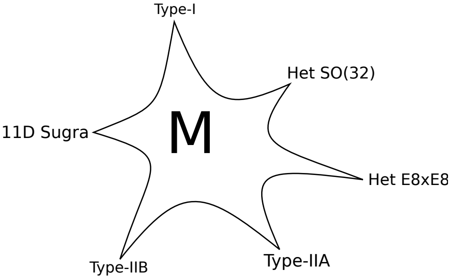
- The LHC discovery of a Standard Model (SM) like Higgs stresses the need to understand the Electroweak Scale (EWS).
- Supersymmetry (SUSY) provides an elegant solution for the EWS stability, but naturalness requires SUSY partners to be of order $\mathcal{O}(\text{TeV})$.
- These predictions and constraints are usually within the Minimal Supersymmetric Standard Model (MSSM) setup.
- One is led to search for more general SUSY models. A fruitful guideline for this has been given by String Theory phenomenology.
- Nowadays we understand different String Theories to be limits of an underlying 11 dimensional theory, M-Theory.

- A full formulation of M-Theory is still unknown, so we work with the $d = 11$ Supergravity (SUGRA) low energy limit.



Introduction and Motivation

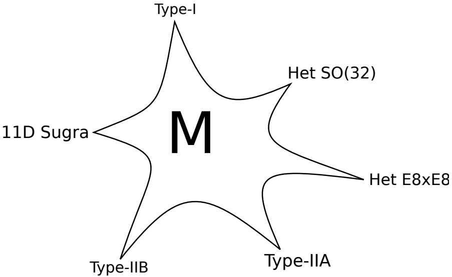
- A full formulation of M-Theory is still unknown, so we work with the $d = 11$ Supergravity (SUGRA) low energy limit.



- Recent developments in M-Theory compactified in G_2-manifolds have shown that SUSY breaking and moduli stabilisation provide hierarchal effective field theories.

Introduction and Motivation

- A full formulation of *M*-Theory is still unknown, so we work with the $d = 11$ Supergravity (SUGRA) low energy limit.



- Recent developments in *M*-Theory compactified in G_2-manifolds have shown that SUSY breaking and moduli stabilisation provide hierarchal effective field theories.
- In this case we also find all the realistic scenario ingredients: $N = 1$ SUSY, Chiral fermions, Non-abelian gauge theories, etc.

Outline

1. Introduction and Motivation
2. Model building in M-Theory
   - The framework
   - The G_2-MSSM
3. $SO(10)$ models from M-Theory
4. Conclusions and future work

Outline

Model Building: Framework

- The compactified manifold, K, plays a crucial role in defining the 4D QFT:

Model Building: Framework

- The compactified manifold, K, plays a crucial role in defining the 4D QFT:
    - ADE type singularities provide gauge irreps and interactions.

Model Building: Framework

- The compactified manifold, K, plays a crucial role in defining the 4D QFT:
  - ADE type singularities provide gauge irreps and interactions.
  - Symmetries of the geometry constrain resulting QFT.

Model Building: Framework

- The compactified manifold, K, plays a crucial role in defining the 4D QFT:
  - ADE type singularities provide gauge irreps and interactions.
  - Symmetries of the geometry constrain resulting QFT.
  - Wilson lines break the GUT group, G.

Model Building: Framework

- The compactified manifold, K, plays a crucial role in defining the 4D QFT:
  - ADE type singularities provide gauge irreps and interactions.
  - Symmetries of the geometry constrain resulting QFT.
  - Wilson lines break the GUT group, G.
- The allowed tree-level superpotential coefficients are functions of the distances in K

$$W \supset \lambda^{ijk}\Phi^i\Phi^j\Phi^k : \lambda^{ijk} \sim \exp(-\mathrm{vol}_{ijk}).$$

Model Building: Framework

- The compactified manifold, K, plays a crucial role in defining the 4D QFT:
  - *ADE* type singularities provide gauge irreps and interactions.
  - Symmetries of the geometry constrain resulting QFT.
  - Wilson lines break the GUT group, G.
- The allowed tree-level superpotential coefficients are functions of the distances in K

$$W \supset \lambda^{ijk}\Phi^i\Phi^j\Phi^k : \lambda^{ijk} \sim \exp(-\mathrm{vol}_{ijk}).$$

- The unified gauge coupling is a function of the volume of K

$$\alpha_U^{7/3} \sim \frac{1}{V_7}.$$

Model Building: Framework

- The compactified manifold, K, plays a crucial role in defining the 4D QFT:
  - ADE type singularities provide gauge irreps and interactions.
  - Symmetries of the geometry constrain resulting QFT.
  - Wilson lines break the GUT group, G.
- The allowed tree-level superpotential coefficients are functions of the distances in K

$$W \supset \lambda^{ijk}\Phi^i\Phi^j\Phi^k : \lambda^{ijk} \sim \exp(-\text{vol}_{ijk}).$$

- The unified gauge coupling is a function of the volume of K

$$\alpha_U^{7/3} \sim \frac{1}{V_7}.$$

- G_2 holonomy manifolds do not have continuous symmetries but admit discrete symmetries.

Model Building: Framework

- The compactified manifold, K, plays a crucial role in defining the 4D QFT:
  - ADE type singularities provide gauge irreps and interactions.
  - Symmetries of the geometry constrain resulting QFT.
  - Wilson lines break the GUT group, G.
- The allowed tree-level superpotential coefficients are functions of the distances in K

$$W \supset \lambda^{ijk}\Phi^i\Phi^j\Phi^k : \lambda^{ijk} \sim \exp(-\mathrm{vol}_{ijk}).$$

- The unified gauge coupling is a function of the volume of K

$$\alpha_U^{7/3} \sim \frac{1}{V_7}.$$

- G_2 holonomy manifolds do not have continuous symmetries but admit discrete symmetries.
- Witten (2001) showed that such symmetries provide a solution for the doublet-triplet splitting problem.

Model Building: Framework

- If K admits a non-trivial fundamental group, $\pi_1(K)$, then there are non-trivial quantities

$$\mathcal{W} = \exp \oint A \neq 1,$$

called Wilson lines, where A are the vector fields of G.

Model Building: Framework

- If K admits a non-trivial fundamental group, $\pi_1(K)$, then there are non-trivial quantities

$$\mathcal{W} = \exp \oint A \neq 1,$$

called Wilson lines, where A are the vector fields of G.

- These cannot be gauged away, but can be absorbed on a chiral supermultiplet, Ψ, living on K along the Wilson line

$$\Psi^w = (\mathcal{W}\Psi).$$

Model Building: Framework

- If K admits a non-trivial fundamental group, $\pi_1(K)$, then there are non-trivial quantities

$$\mathcal{W} = \exp \oint A \neq 1,$$

called Wilson lines, where A are the vector fields of G.

- These cannot be gauged away, but can be absorbed on a chiral supermultiplet, Ψ, living on K along the Wilson line

$$\Psi^w = (\mathcal{W}\Psi).$$

- This breaks the gauge group to $H = \{g \in G, \ [g, \mathcal{W}] = 0\}$ as Ψ^w transforms under the elements of G that commute with $\mathcal{W}$.

Model Building: Framework

- $\mathcal{W}$ has a topological meaning and furnishes a representation of $\pi_1(K)$.

Model Building: Framework

- $\mathcal{W}$ has a topological meaning and furnishes a representation of $\pi_1(K)$.
- If $\pi_1(K) = Z_n$ then $\mathcal{W}^n = 1$.

Model Building: Framework

- $\mathcal{W}$ has a topological meaning and furnishes a representation of $\pi_1(K)$.
- If $\pi_1(K) = Z_n$ then $\mathcal{W}^n = 1$.
- Witten noticed that if K admits a geometrical symmetry isomorphic to the fundamental group, Z_n, then the Wilson line phases of Ψ^w act as charges of the symmetry.

Model Building: Framework

- $\mathcal{W}$ has a topological meaning and furnishes a representation of $\pi_1(K)$.
- If $\pi_1(K) = Z_n$ then $\mathcal{W}^n = 1$.
- Witten noticed that if K admits a geometrical symmetry isomorphic to the fundamental group, Z_n, then the Wilson line phases of Ψ^w act as charges of the symmetry.
- As $\mathcal{W}$ does not commute with G then **we have a discrete symmetry that does not commute with the GUT group**.

Model Building: Framework

- $\mathcal{W}$ has a topological meaning and furnishes a representation of $\pi_1(K)$.
- If $\pi_1(K) = Z_n$ then $\mathcal{W}^n = 1$.
- Witten noticed that if K admits a geometrical symmetry isomorphic to the fundamental group, Z_n, then the Wilson line phases of Ψ^w act as charges of the symmetry.
- As $\mathcal{W}$ does not commute with G then **we have a discrete symmetry that does not commute with the GUT group**.
- This provides a mechanism with a solution for the doublet-triplet splitting problem.

Outline

[Acharya, Kane, Kuflik, Lu (2011)]

Consider the $SU(5)$ GUT with the MSSM spectrum, plus the geometric symmetry Z_n.
Let $\overline{\mathbf{5}}^w \supset \left(H_d, \overline{D}\right)$ be localised along the Wilson line. Under the discrete symmetry The GUT multiplets transform

$$\begin{aligned}
\overline{\mathbf{5}}^w &\to \eta^\omega \left(\eta^\delta H_d^w \oplus \eta^\gamma \overline{D}^w\right), \\
\mathbf{5}^h &\to \eta^\chi \mathbf{5}^h, \\
\overline{\mathbf{5}}^m &\to \eta^\tau \overline{\mathbf{5}}^m, \\
\mathbf{10}^m &\to \eta^\sigma \mathbf{10}^m,
\end{aligned}$$

where $\eta \equiv e^{2\pi i/n}$, $2\delta + 3\gamma = 0 \mod n$ (for simplicity we will set $\overline{\mathbf{5}}^w$ to $\omega = 0$).

The G_2-MSSM

Description	Coupling	Constraint
Down-type Yukawas	$H_u^h \mathbf{10}^m \mathbf{10}^m$	$2\sigma + \chi = 0 \bmod n$
Up-type Yukawas	$H_d^w \mathbf{10}^m \overline{\mathbf{5}}^m$	$\sigma + \tau + \delta = 0 \bmod n$
Neutrino Majorana-masses	$H_d^w H_d^w \overline{\mathbf{5}}^m \overline{\mathbf{5}}^m$	$2\chi + 2\tau = 0 \bmod n$
Colour-triplet mass	$\overline{D}^w D^h$	$\chi + \gamma = 0 \bmod n$

A solution exists while **forbidding a tree-level μ-term and dimension four and five proton decay operators.**
An effective μ-term is generated by moduli vev

$$K \supset \frac{s}{M_{Pl}} H_u H_d + \text{h.c.},$$

$$\mu = \langle m_{3/2} K_{H_u H_d} - F^k K_{H_u H_d k} \rangle \sim 0.1 m_{3/2} \sim \mathcal{O}(\text{TeV}).$$

Outline

$SO(10)$ models from M-Theory

- $\mathcal{W} \in SO(10)$ and commutes with the surviving group, H. As it commutes with itself : $\mathcal{W}$ is a diagonal element of H.

- $\mathcal{W} \in SO(10)$ and commutes with the surviving group, H. As it commutes with itself : $\mathcal{W}$ is a diagonal element of H.
- The Wilson phases are linear combination of $U(1)$ quantum numbers. For $\mathbf{10}^w$

$$\mathbf{10}^w \to \eta^{\omega} \left(\eta^{-\alpha} H_d^w \oplus \eta^{\beta} \overline{D}^w \oplus \eta^{\alpha} H_u^w \oplus \eta^{-\beta} D^w \right).$$

$SO(10)$ models from M-Theory

- $\mathcal{W} \in SO(10)$ and commutes with the surviving group, H. As it commutes with itself : $\mathcal{W}$ is a diagonal element of H.
- The Wilson phases are linear combination of $U(1)$ quantum numbers. For $\mathbf{10}^w$

$$\mathbf{10}^w \to \eta^{\omega}\left(\eta^{-\alpha} H_d^w \oplus \eta^{\beta} \overline{D}^w \oplus \eta^{\alpha} H_u^w \oplus \eta^{-\beta} D^w\right).$$

- In minimal $SO(10)$ the μ-term is contained in

$$W \supset \mathbf{10}^w \mathbf{10}^w = \mu H_u H_d + m_D D\overline{D},$$

but as $\mathcal{W} \in SO(10)$, both terms are invariant under its action.

$SO(10)$ models from M-Theory

- Consider an additional $\mathbf{10}^h$ multiplet, without Wilson line phases: $\mathbf{10}^h \to \eta^\xi \mathbf{10}^h$.

$SO(10)$ models from M-Theory

- Consider an additional $\mathbf{10}^h$ multiplet, without Wilson line phases: $\mathbf{10}^h \rightarrow \eta^{\xi}\mathbf{10}^h$.
- All the possible gauge invariant couplings between $\mathbf{10}^w$ and $\mathbf{10}^h$ are

$$W \supset \mathbf{H}_d^T \cdot \mu_H \cdot \mathbf{H}_u + \overline{\mathbf{D}}^T \cdot M_D \cdot \mathbf{D},$$

where μ_H and M_D are two 2×2 superpotential mass parameters matrices, $\mathbf{H}_{u,d}^T = \left(H_{u,d}^w, H_{u,d}^h\right)$, $\overline{\mathbf{D}}^T = \left(\overline{D}^w, \overline{D}^h\right)$, and $\mathbf{D}^T = \left(D^w, D^h\right)$.

- Consider an additional $\mathbf{10}^h$ multiplet, without Wilson line phases: $\mathbf{10}^h \to \eta^{\xi}\mathbf{10}^h$.
- All the possible gauge invariant couplings between $\mathbf{10}^w$ and $\mathbf{10}^h$ are

$$W \supset \mathbf{H}_d^T \cdot \mu_H \cdot \mathbf{H}_u + \overline{\mathbf{D}}^T \cdot M_D \cdot \mathbf{D},$$

  where μ_H and M_D are two 2×2 superpotential mass parameters matrices, $\mathbf{H}_{u,d}^T = \left(H_{u,d}^w, H_{u,d}^h\right)$, $\overline{\mathbf{D}}^T = \left(\overline{D}^w, \overline{D}^h\right)$, and $\mathbf{D}^T = \left(D^w, D^h\right)$.
- **There is no choice of vanishing constraints that leaves one eigenvalue of μ_H light while keeping both masses of M_D heavy.**

$SO(10)$ models from M-Theory

- We are led to a novel doublet-triplet problem solution: allow for light $D^w, \overline{D}^w$ while decoupled from matter.

$SO(10)$ models from M-Theory

- We are led to a novel doublet-triplet problem solution: allow for light $D^w, \overline{D}^w$ while decoupled from matter.
- We use the discrete symmetry to allow only for the Higgses couplings in

$$\mathbf{10}^w \mathbf{16}^m \mathbf{16}^m,$$

where matter irreps transform $\mathbf{16}^m \to \eta^m \mathbf{16}^m$.

$SO(10)$ models from M-Theory

- We are led to a novel doublet-triplet problem solution: allow for light $D^w, \overline{D}^w$ while decoupled from matter.
- We use the discrete symmetry to allow only for the Higgses couplings in

$$\mathbf{10}^w \mathbf{16}^m \mathbf{16}^m,$$

where matter irreps transform $\mathbf{16}^m \to \eta^m \mathbf{16}^m$.

- Phenomenological challenges with unified Yukawa scenarios, we restrict to the case with only the top-quark Yukawa.

$SO(10)$ models from M-Theory

- We are led to a novel doublet-triplet problem solution: allow for light $D^w, \overline{D}^w$ while decoupled from matter.
- We use the discrete symmetry to allow only for the Higgses couplings in

$$\mathbf{10}^w \mathbf{16}^m \mathbf{16}^m,$$

where matter irreps transform $\mathbf{16}^m \to \eta^m \mathbf{16}^m$.

- Phenomenological challenges with unified Yukawa scenarios, we restrict to the case with only the top-quark Yukawa.
- Allowing for light $D^w, \overline{D}^w$ has two immediate consequences.

$SO(10)$ models from M-Theory

- We are led to a novel doublet-triplet problem solution: allow for light $D^w, \overline{D}^w$ while decoupled from matter.
- We use the discrete symmetry to allow only for the Higgses couplings in

$$\mathbf{10}^w \mathbf{16}^m \mathbf{16}^m,$$

  where matter irreps transform $\mathbf{16}^m \to \eta^m \mathbf{16}^m$.
- Phenomenological challenges with unified Yukawa scenarios, we restrict to the case with only the top-quark Yukawa.
- Allowing for light $D^w, \overline{D}^w$ has two immediate consequences.
  - Moduli vevs break the discrete symmetry, leading to to proton-decay interactions.

$SO(10)$ models from M-Theory

- We are led to a novel doublet-triplet problem solution: allow for light $D^w, \overline{D}^w$ while decoupled from matter.
- We use the discrete symmetry to allow only for the Higgses couplings in
$$\mathbf{10}^w \mathbf{16}^m \mathbf{16}^m,$$
where matter irreps transform $\mathbf{16}^m \to \eta^m \mathbf{16}^m$.
- Phenomenological challenges with unified Yukawa scenarios, we restrict to the case with only the top-quark Yukawa.
- Allowing for light $D^w, \overline{D}^w$ has two immediate consequences.
    - Moduli vevs break the discrete symmetry, leading to to proton-decay interactions.
    - The presence of light coloured states will ruin unification.

$SO(10)$ models from M-Theory

- Consider the relevant Kahler potential operators

$$K \supset \frac{s}{M_{Pl}^2} DQQ + \frac{s}{M_{Pl}^2} De^c u^c + \frac{s}{M_{Pl}^2} DNd^c + \\ + \frac{s}{M_{Pl}^2} \overline{D} d^c u^c + \frac{s}{M_{Pl}^2} \overline{D} QL.$$

$SO(10)$ models from M-Theory

- Consider the relevant Kahler potential operators

$$K \supset \frac{s}{M_{Pl}^2} DQQ + \frac{s}{M_{Pl}^2} De^c u^c + \frac{s}{M_{Pl}^2} DNd^c + \\ + \frac{s}{M_{Pl}^2} \overline{D} d^c u^c + \frac{s}{M_{Pl}^2} \overline{D} QL.$$

- The effective potential may be calculated a la Giudice-Masiero to be

$$W_{eff} \supset \lambda DQQ + \lambda De^c u^c + \lambda DNd^c + \\ + \lambda \overline{D} d^c u^c + \lambda \overline{D} QL,$$

where

$$\lambda \approx \frac{1}{M_{Pl}^2} \left(\langle s \rangle m_{3/2} + \langle F_s \rangle \right) \sim 10^{-14}.$$

- The proton-decay rate can be estimated by

$$\Gamma_p \approx \frac{\left|\lambda^2\right|^2}{16\pi^2} \frac{m_p^5}{m_D^4}.$$

$SO(10)$ models from M-Theory

- The proton-decay rate can be estimated by

$$\Gamma_p \approx \frac{\left|\lambda^2\right|^2}{16\pi^2}\frac{m_p^5}{m_D^4}.$$

- $m_D \sim \mathcal{O}(10)$ TeV, so the proton lifetime is

$$\tau_p = \Gamma_p^{-1} \sim 10^{38} \text{ yrs}.$$

$SO(10)$ models from M-Theory

- The proton-decay rate can be estimated by

$$\Gamma_p \approx \frac{\left|\lambda^2\right|^2}{16\pi^2} \frac{m_p^5}{m_D^4}.$$

- $m_D \sim \mathcal{O}(10)$ TeV, so the proton lifetime is

$$\tau_p = \Gamma_p^{-1} \sim 10^{38} \text{ yrs.}$$

- The D triplet decay rate can also be estimated

$$\tau_D = \Gamma_D^{-1} \sim \left(\lambda^2 m_D\right)^{-1} \sim 0.1 \text{ sec},$$

which is consistent with BBN constraint.

$SO(10)$ models from M-Theory

- $D, \overline{D}$ also spoil unification.

$SO(10)$ models from M-Theory

- $D, \overline{D}$ also spoil unification.
- Workaround: adding new states such that $D, \overline{D}$ “complete” a GUT multiplet.

$SO(10)$ models from M-Theory

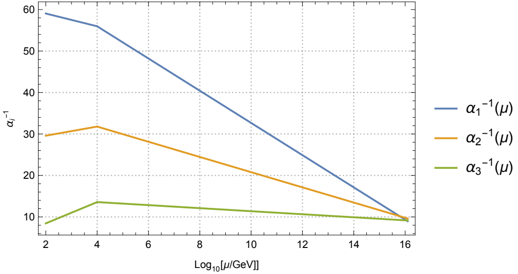
- $D, \overline{D}$ also spoil unification.
- Workaround: adding new states such that $D, \overline{D}$ “complete” a GUT multiplet.
- Consider an addition vector-like family $\mathbf{16}_X, \overline{\mathbf{16}}_X$.

$SO(10)$ models from M-Theory

- $D, \overline{D}$ also spoil unification.
- Workaround: adding new states such that $D, \overline{D}$ "complete" a GUT multiplet.
- Consider an addition vector-like family $\mathbf{16}_X, \overline{\mathbf{16}}_X$.
- Using the discrete symmetry, we find a solution where $d^c_X, \overline{d^c}_X$ are split from the rest of the family.

$SO(10)$ models from M-Theory

- $D, \overline{D}$ also spoil unification.
- Workaround: adding new states such that $D, \overline{D}$ "complete" a GUT multiplet.
- Consider an addition vector-like family $\mathbf{16}_X, \overline{\mathbf{16}}_X$.
- Using the discrete symmetry, we find a solution where $d^c_X, \overline{d^c}_X$ are split from the rest of the family.
- The resulting spectrum is effectively the same as the MSSM with additional vector-like family.



- Such solution exists if either $\mathbf{16}_X$ or $\overline{\mathbf{16}}_X$ absorb Wilson line phases. Considering

$$\mathbf{16}_X \rightarrow \eta^{x}\left(\eta^{-3\gamma}L \oplus \eta^{3\gamma+\delta}e^c \oplus \eta^{3\gamma-\delta}N \oplus \eta^{-\gamma-\delta}u^c \oplus \right.$$
$$\left. \oplus \eta^{-\gamma+\delta}d^c \oplus \eta^{\gamma}Q\right).$$

and $\overline{\mathbf{16}}_X \rightarrow \eta^{\overline{x}}\overline{\mathbf{16}}_X$, the splitting condition is given by

$$\overline{d^c}_X d^c_X : x - \gamma + \delta + \overline{x} = 0 \mod n,$$

while forbidding all the other self couplings from $\mathbf{16}_X\overline{\mathbf{16}}_X$.

$SO(10)$ models from M-Theory

- Such solution exists if either $\mathbf{16}_X$ or $\overline{\mathbf{16}}_X$ absorb Wilson line phases. Considering

$$\mathbf{16}_X \to \eta^{x} \left(\eta^{-3\gamma} L \oplus \eta^{3\gamma+\delta} e^c \oplus \eta^{3\gamma-\delta} N \oplus \eta^{-\gamma-\delta} u^c \oplus \right.$$
$$\left. \oplus \eta^{-\gamma+\delta} d^c \oplus \eta^{\gamma} Q \right).$$

  and $\overline{\mathbf{16}}_X \to \eta^{\overline{x}} \overline{\mathbf{16}}_X$, the splitting condition is given by

$$\overline{d^c}_X d^c_X : x - \gamma + \delta + \overline{x} = 0 \mod n,$$

  while forbidding all the other self couplings from $\mathbf{16}_X \overline{\mathbf{16}}_X$.

- The remaining states of $\mathbf{16}_X, \overline{\mathbf{16}}_X$ get a TeV scale μ-term from moduli vevs.

$SO(10)$ models from M-Theory

- Such solution exists if either $\mathbf{16}_X$ or $\overline{\mathbf{16}}_X$ absorb Wilson line phases. Considering

$$\mathbf{16}_X \rightarrow \eta^x \left(\eta^{-3\gamma} L \oplus \eta^{3\gamma+\delta} e^c \oplus \eta^{3\gamma-\delta} N \oplus \eta^{-\gamma-\delta} u^c \oplus \right.$$
$$\left. \oplus \eta^{-\gamma+\delta} d^c \oplus \eta^{\gamma} Q \right) .$$

  and $\overline{\mathbf{16}}_X \rightarrow \eta^{\overline{x}} \overline{\mathbf{16}}_X$, the splitting condition is given by

$$\overline{d^c}_X d^c_X : x - \gamma + \delta + \overline{x} = 0 \mod n,$$

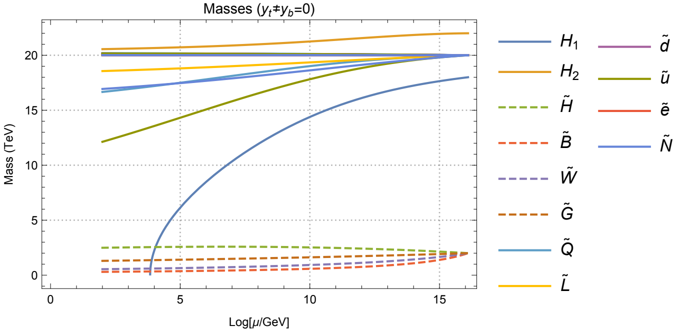
  while forbidding all the other self couplings from $\mathbf{16}_X \overline{\mathbf{16}}_X$.
- The remaining states of $\mathbf{16}_X, \overline{\mathbf{16}}_X$ get a TeV scale μ-term from moduli vevs.
- Unification scale is found to be $M_{\text{GUT}} \sim 10^{16}$ GeV, with $\alpha_u^{-1} \sim 9.6$.

$SO(10)$ models from M-Theory

- The tree-level superpotential of our model allowed by the discrete symmetry is
$$W = y_t H_u Q^3 t^c + M \overline{d^c}_X d^c_X$$

$SO(10)$ models from M-Theory

- The tree-level superpotential of our model allowed by the discrete symmetry is
$$W = y_t H_u Q^3 t^c + M\overline{d^c}_X d^c_X$$
- One can perform an RGE analysis of the spectrum assuming general values for the mass parameters at the GUT scale.



$SO(10)$ models from M-Theory

- The addition of an extra family has other benefits for model building: $N_X, \overline{N}_X$ vevs (v_x) **break the rank of the gauge group** and **generate Right-handed neutrinos Majorana masses**.

$$\frac{1}{M_{Pl}}\overline{N}_X\overline{N}_X\mathbf{N}^m\mathbf{N}^m : \; M_{\text{Majorana}} \sim \frac{{v_X}^2}{M_{Pl}}$$

$SO(10)$ models from M-Theory

- The addition of an extra family has other benefits for model building: $N_X, \overline{N}_X$ vevs (v_x) **break the rank of the gauge group** and **generate Right-handed neutrinos Majorana masses**.

$$\frac{1}{M_{Pl}}\overline{N}_X\overline{N}_X\mathbf{N}^m\mathbf{N}^m : \; M_{\text{Majorana}} \sim \frac{{v_X}^2}{M_{Pl}}$$

- There are other consequences one has to study.

- The addition of an extra family has other benefits for model building: $N_X, \overline{N}_X$ vevs (v_x) **break the rank of the gauge group** and **generate Right-handed neutrinos Majorana masses**.

$$\frac{1}{M_{Pl}}\overline{N}_X\overline{N}_X\mathbf{N}^m\mathbf{N}^m: \; M_{\text{Majorana}} \sim \frac{{v_X}^2}{M_{Pl}}$$

- There are other consequences one has to study.
  - Potential mixing with regular matter through the effective μ-terms

$$\mu\mathbf{16^m}\overline{\mathbf{16}}_\mathbf{X}.$$

$SO(10)$ models from M-Theory

- The addition of an extra family has other benefits for model building: $N_X, \overline{N}_X$ vevs (v_x) **break the rank of the gauge group** and **generate Right-handed neutrinos Majorana masses**.

$$\frac{1}{M_{Pl}}\overline{N}_X\overline{N}_X\mathbf{N}^m\mathbf{N}^m: \;\; M_{\text{Majorana}} \sim \frac{{v_X}^2}{M_{Pl}}$$

- There are other consequences one has to study.
  - Potential mixing with regular matter through the effective μ-terms

$$\mu \mathbf{16^m}\overline{\mathbf{16}}_\mathbf{X}.$$

  - R-Parity violating (RPV) interactions through the Kahler terms

$$K_{RPV} \supset \alpha\frac{s}{M_{Pl}^3}\mathbf{16}_X\mathbf{16}^m\mathbf{16}^m\mathbf{16}^m + \beta\frac{s}{M_{Pl}^2}\mathbf{10}^w\mathbf{16}_X\mathbf{16}^m.$$

Outline

Conclusions and future work

- We showed that it's possible to construct $SO(10)$ SUSY GUT models from M-Theory with interesting features

Conclusions and future work

- We showed that it's possible to construct $SO(10)$ SUSY GUT models from M-Theory with interesting features
  - Consistent unification scenario.

Conclusions and future work

- We showed that it's possible to construct $SO(10)$ SUSY GUT models from M-Theory with interesting features
  - Consistent unification scenario.
  - EWS dynamically originated by radiative symmetry breaking.

Conclusions and future work

- We showed that it's possible to construct $SO(10)$ SUSY GUT models from M-Theory with interesting features
  - Consistent unification scenario.
  - EWS dynamically originated by radiative symmetry breaking.
  - See-saw mechanism generated neutrino masses.

Conclusions and future work

- We showed that it's possible to construct $SO(10)$ SUSY GUT models from M-Theory with interesting features
  - Consistent unification scenario.
  - EWS dynamically originated by radiative symmetry breaking.
  - See-saw mechanism generated neutrino masses.
  - RPV is controlled given some assumptions from Kahler potential coefficients.

Conclusions and future work

- We showed that it's possible to construct $SO(10)$ SUSY GUT models from M-Theory with interesting features
  - Consistent unification scenario.
  - EWS dynamically originated by radiative symmetry breaking.
  - See-saw mechanism generated neutrino masses.
  - RPV is controlled given some assumptions from Kahler potential coefficients.
  - LHC reachable vector-like family and fermionic superpartners.

Conclusions and future work

- We showed that it's possible to construct $SO(10)$ SUSY GUT models from M-Theory with interesting features
  - Consistent unification scenario.
  - EWS dynamically originated by radiative symmetry breaking.
  - See-saw mechanism generated neutrino masses.
  - RPV is controlled given some assumptions from Kahler potential coefficients.
  - LHC reachable vector-like family and fermionic superpartners.
- Nonetheless there are some issues we still have to work on.

Conclusions and future work

- We showed that it's possible to construct $SO(10)$ SUSY GUT models from M-Theory with interesting features
  - Consistent unification scenario.
  - EWS dynamically originated by radiative symmetry breaking.
  - See-saw mechanism generated neutrino masses.
  - RPV is controlled given some assumptions from Kahler potential coefficients.
  - LHC reachable vector-like family and fermionic superpartners.
- Nonetheless there are some issues we still have to work on.
  - LSP too unstable to be Dark Matter candidate. Axions?

Conclusions and future work

- We showed that it's possible to construct $SO(10)$ SUSY GUT models from M-Theory with interesting features
  - Consistent unification scenario.
  - EWS dynamically originated by radiative symmetry breaking.
  - See-saw mechanism generated neutrino masses.
  - RPV is controlled given some assumptions from Kahler potential coefficients.
  - LHC reachable vector-like family and fermionic superpartners.
- Nonetheless there are some issues we still have to work on.
  - LSP too unstable to be Dark Matter candidate. Axions?
  - It's not clear what symmetry breaking mechanism can break the rank.

Conclusions and future work

- We showed that it's possible to construct $SO(10)$ SUSY GUT models from M-Theory with interesting features
  - Consistent unification scenario.
  - EWS dynamically originated by radiative symmetry breaking.
  - See-saw mechanism generated neutrino masses.
  - RPV is controlled given some assumptions from Kahler potential coefficients.
  - LHC reachable vector-like family and fermionic superpartners.
- Nonetheless there are some issues we still have to work on.
  - LSP too unstable to be Dark Matter candidate. Axions?
  - It's not clear what symmetry breaking mechanism can break the rank.
  - Detailed spectrum and Z boson mass prediction study has not been carried out yet.

Thank you!

MCR thanks the support from the FCT under the grant SFRH/BD/84234/2012.

Backup slides: The G_2-MSSM

- Tree-level terms in the superpotential are functions of distances between the supermultiplets in K.
- The superpotential mass parameters, the μ-terms, values are suppressed Planck masses.
- By considering $\overline{\mathbf{5}}^{w}$ and $\mathbf{5}^{\mathbf{h}}$ to be near in K then the $D^{h}\overline{D}^{w}$ mass can be GUT/Planck valued while the Higgses don't have a μ-term $\Rightarrow$ **we split the H and D masses**.
- On the other hand, direct gaugino searches tell us $\mu \geq 100$ GeV.
- Fortunately **there is a natural way of generating an effective μ-term of $\mathcal{O}$(TeV) in M-Theory**!
- Discrete symmetry is a geometric symmetry of the extra dimensions, therefore the moduli fields are naturally charged under it. As moduli acquire vevs they break the discrete symmetry.

Backup slides: The G_2-MSSM

- The moduli vev generate an effective μ-term a la Giudice-Masiero from Kahler potential operators of the form

$$K \supset \frac{s}{M_{Pl}} H_u H_d + \text{h.c.}.$$

- From standard supergravity calculations we know that

$$\mu = \langle m_{3/2} K_{H_u H_d} - F^k K_{H_u H_d k} \rangle,$$

which leads to

$$\mu \sim \frac{\langle s \rangle}{M_{Pl}} m_{3/2} + \frac{\langle F_s \rangle}{M_{Pl}}.$$

- Developments in M-Theory have shown that the moduli vevs are approximately $\langle s \rangle \sim 0.1 M_{Pl}$, $\langle F_s \rangle \sim m_{1/2} M_{Pl}$, $\mathbf{m_{3/2}} \sim \mathcal{O}(\mathbf{10}\ \text{TeV})$.
- In M-Theory the gaugino masses are suppressed, so the F-term is subleading and we conclude

$$\mu \sim 0.1 m_{3/2} \sim \mathcal{O}(\text{TeV}).$$

- To study the potential mixing we focus on the superpotential contributions to the up-type quarks mass matrix.
- Schematically, $W \supset \overline{U} \cdot M_U \cdot U$, where $U^T = \left(u_i, \overline{u^c}_X, u_X\right)$, $\overline{U}^T = (u_i^c, \overline{u}_X, u_X^c)$, with $i = 1, 2, 3$, and

$$M_U = \begin{pmatrix} y_u^{ij} H_u & \mu_{iX} & \lambda_{iX} \\ \mu_{Xj} & \lambda_{XX} & \mu_{XX} \\ \lambda_{Xj} & \mu_{XX} & \lambda_{XX} \end{pmatrix}$$

  where y_u are EWS Yukawas, μ-terms are of order TeV, and λ couplings are of order 10^{-14}.
- In the limit $\lambda_{iX}, \lambda_{Xj}, \lambda_{XX} \to 0$ one finds that the determinant of M_U is independent of μ_{iX}, μ_{Xj}, i.e. of the mixing masses.
- **To leading order in λ the mass eigenstates do not mix matter with $\overline{16}_X$.**

Backup slides: $SO(10)$ models from M-Theory

- RPV interactions arise from the Kahler potential terms and are effectively described by the superpotential

$$W_{RPV}^{eff} \supset \alpha\lambda \frac{v_X}{M_{Pl}} L L e^c + \alpha\lambda \frac{v_X}{M_{Pl}} Q L e^c + \alpha\lambda \frac{v_X}{M_{Pl}} u^c d^c d^c + \\ + \beta\lambda v_X L H_u.$$

- Due to the nature of $SO(10)$, neutrinos have the same Dirac mass as the up-type quarks. A realistic τ-neutrino physical mass requires

$$M_{\text{Majorana}} \gtrsim 10^{14}\ \text{GeV} \Rightarrow v_X \sim 10^{16}\ \text{GeV}.$$

- The effective strength of the first terms is $\lambda v_X / M_{Pl} \sim \mathcal{O}(10^{-16})$ (taking $\alpha \sim \mathcal{O}(1)$). The resulting LSP lifetime can be estimated as

$$\tau_{LSP} \simeq \frac{10^{-13}\,\text{sec}}{(v_X/M_{Pl})^2} \left(\frac{m_0}{10\ \text{TeV}}\right)^4 \left(\frac{100\ \text{GeV}}{m_{LSP}}\right)^5 \sim 10^{-13}\,\text{sec},$$

for $m_0 \sim 10$ TeV, $m_{LSP} \sim 100$ GeV.

- The last term in the effective superpotential

$$\beta\lambda v_x L H_u,$$

is constrained by neutrino mass limit exclusions.

- The bilinear contribution to the mixing to be at most of

$$\beta\lambda v_X \lesssim \mathcal{O}(10^{-3}\ \text{TeV}),$$

which means leads to the upper bound

$$v_X \lesssim 10^{14}/\beta\ \text{GeV},$$

and one has to consider there is some suppression by β of order $\mathcal{O}(10^{-2})$.