# Symmetry breaking and $\nu$ masses in $M$ Theory


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In collaboration with Bobby S. Acharya[2] Krzysztof Bożek[2]

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and other work in progress


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# Outline

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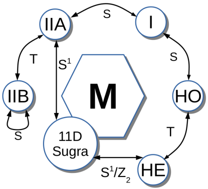
1. Introducing SO(10) models from M Theory
2. Extra $U(1)$ Symmetry Breaking
3. Neutrino masses
4. Conclusions

- **M Theory**, through its $11d$ low-energy limit, accounts for a **new and exciting corner of String Phenomenology**.



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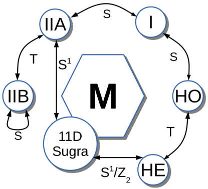


- When compatified on a $G_2$-holonomy manifold, we retrieve **all the required ingredients for model building**: Gauge interactions, charged chiral matter, spontaneously broken $\mathcal{N} = 1$ SUSY, etc (Acharya, Gukov hep-th/0409191; Acharya, Bobkov, Kane, Kumar, Vaman hep-th/0606262)

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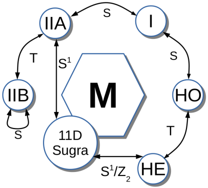


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- Further, as **moduli are stabilised** (in the absence of fluxes), all (GUT scale) **mass parameters can estimated**, and reasonable SUGRA approximations employed (Acharya, Bobkov, Kane, Shao, Kumar hep-ph/0801.0478)

- The **G2-MSSM** (Acharya, Kane, Kuflik, Lu hep-ph/1102.0556) – an $SU(5)$ SUSY GUT – was presented following a proposal by Witten (hep-ph/0201018) that provided us with a **natural $Z_n$ discrete symmetry**.

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- If the internal space is **not simply-connected** (it has holes or handles), there are **non-trivial quantities called Wilson lines**

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- This **provides a solution for the Doublet-Triplet problem** $\mathcal{W} = \mathrm{diag}(\eta^\delta, \eta^\delta, \eta^\delta, \eta^\gamma, \eta^\gamma)$, $\eta^n = 1$, $3\delta + 2\gamma = 0 \mod n$:

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- Generic $\mathcal{O}(10^3 \text{ GeV})$ $\mu$-parameters are generated by moduli vevs

$$K \supset \frac{s}{m_{Pl}} H_u H_d + \text{h.c.} \to \mu \simeq \frac{\langle s \rangle m_{3/2}}{m_{Pl}} \sim \mathcal{O}(10^3 \text{ GeV}),$$

- Recently (Acharya, Bozek, MCR, King, Pongkitivanichkul 1502.01727) we proposed an $SO(10)$ **model from M Theory on $G_2$-manifolds**. Unfortunately, **the same Doublet-Triplet problem solution does not work**

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

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- This vector-like family also**provides a Higgs to break the rank** through $N_X$, $\overline{N}_X$ vevs.

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- If this mass is to be generated by the symmetry breaking, we **need a high-scale breaking mechanism**.

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one can minimise the scalar potential, obtaining

$$\langle X \rangle \simeq \sqrt{\tilde{m}_X m_{Pl}}$$

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- More generally

$$W \supset \frac{1}{m_{Pl}^{2n-3}} \left(N_X \overline{N}_X\right)^{n-k} \left(N\overline{N}_X\right)^k, \quad n \geq 2, \; k < n$$

can lift $\langle X \rangle$ even more for larger $n$.

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- The minima above are obtained while keeping $F$ and $D$ flatness $\Rightarrow$ These vevs **do not generate extra SUSY breaking**.
- The high-scale nature of these vevs will impact the **neutrino masses physics**. Namely, the presence of matter vevs indicate the **emergence of RPV terms**.

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$$\begin{aligned} W_{non.ren.} \supset & \frac{c_{2,2}}{m_{Pl}} (NN) (\overline{N}_X \overline{N}_X) + \frac{c_{n,k}}{m_{Pl}^{2n-3}} \left(N_X \overline{N}_X\right)^{n-k} \left(N \overline{N}_X\right)^k \\ & + \frac{1}{m_{Pl}} \Big( b_1 H_d H_u L \overline{L}_X + b_2 L L \overline{L}_X \overline{L}_X + b_3 H_d H_u L_X \overline{L}_X + b_4 L L_X \overline{L}_X \overline{L}_X \\ & + b_5 L_X L_X \overline{L}_X \overline{L}_X + b_6 H_d H_u N \overline{N}_X + b_7 L \overline{L}_X N \overline{N}_X + b_8 L_X \overline{L}_X N \overline{N}_X \\ & + b_9 H_d H_u N_X \overline{N}_X + b_{10} L \overline{L}_X N_X \overline{N}_X + b_{11} L_X \overline{L}_X N_X \overline{N}_X \Big) \end{aligned}$$

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- of these, we are specially interested in allowing

$$\frac{b_{11}}{m_{Pl}} L_X \overline{L}_X N_X \overline{N}_X$$

while disallowing $b_6$, $b_7$, $b_9$, $b_{10}$.

- Disallowed terms can arise from Kähler potential as the moduli stabilise

$$K \supset \frac{s}{m_{Pl}}\overline{L}_X L_X + \frac{s}{m_{Pl}}\overline{L}_X L + \frac{s}{m_{Pl}}\overline{N}_X N_X + \frac{s}{m_{Pl}}\overline{N}_X N + \frac{s}{m_{Pl}}\overline{H}_u H_d$$
$$+ \frac{s}{m_{Pl}^2} N_X L_X H_u + \frac{s}{m_{Pl}^2} N L H_u + \frac{s}{m_{Pl}^2} N_X L H_u + \frac{s}{m_{Pl}^2} N L_X H_u + \frac{s}{M_{Pl}^2}\overline{N}_X \overline{L}_X H_d$$

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- We obtain effective superpotential terms

$$\begin{aligned} W_{eff} \supset & \mu^L_{XX}\overline{L}_X L_X + \mu^L_{Xm}\overline{L}_X L + \mu^N_{XX}\overline{N}_X N_X + \mu^N_{Xm}\overline{N}_X N + \mu H_u H_d \\ & + \lambda_{\overline{XX}} H_d \overline{L}_X \overline{N}_X + \lambda_\nu H_u L N + \lambda_{mX} H_u L N_X \\ & + \lambda_{Xm} H_u L_X N + \lambda_{XX} H_u L_X N_X \end{aligned}$$

where

$$\begin{aligned} \mu \simeq & m_{3/2}\frac{s}{m_{Pl}} \simeq \mathcal{O}(10^3)\ \text{GeV} \\ \lambda \simeq & m_{3/2}\frac{s}{m_{Pl}^2} \simeq \mathcal{O}(10^{-14}) \end{aligned}$$

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- The low-energy effective theory has the total superpotenial

$$W_{total} \supset W_{tree} + W_{non.ren.} + W_{eff}$$

- Matter $N$ vev $\Rightarrow$ emergence of B-RPV

$$\kappa_m H_u L + \kappa_X H_u L_X + \kappa_{\overline{X}} H_d \overline{L}_X$$

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- B-RPV can mediate LSP decay

$$\tau_{LSP} \simeq (3.9 \times 10^{-15}) \left(\frac{\mu}{g_w y_d \kappa_m}\right)^2 \left(\frac{m_0}{10 \text{ TeV}}\right)^4 \left(\frac{100 \text{ GeV}}{m_{LSP}}\right)^5 \text{sec},$$

which in order to be stable requires $\kappa_m < 10^{-14}$ GeV

- From kinetic terms we have matter-gaugino mixing. Both the $\nu$-type fermions

$$g'\widetilde{B}\langle\widetilde{\nu}_i\rangle\nu_i, \quad g\widetilde{W}^0\langle\widetilde{\nu}_i\rangle\nu_i, \quad g''\widetilde{B}_X\langle\widetilde{\nu}_i\rangle\nu_i$$

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- In the basis $(\widetilde{B}, \widetilde{W}^0, \widetilde{B}_X, \widetilde{H}_d^0, \widetilde{H}_u^0, \nu, \nu_X, \overline{\nu}_X, N, N_X, \overline{N}_X)$, the total mass matrix is then

$$\mathbf{M}_{\chi-\nu} = \begin{pmatrix} \mathbf{M}_{\chi^0}^{5\times5} & \mathbf{M}_{\chi\nu}^{5\times6} \\ (\mathbf{M}_{\chi\nu}^{5\times6})^T & \mathbf{M}_{\nu}^{6\times6} \end{pmatrix}$$

$\mathbf{M}_{\chi^0}^{5\times5}$: Gaugino-Higgsinos masses and mixing.
$\mathbf{M}_{\chi\nu}^{5\times6}$: Gaugino and Higgsino mixings with $\nu$-type and $N$-type states.
$\mathbf{M}_{\nu}^{6\times6}$: $\nu$-type and $N$-type masses and mixings.

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$\Rightarrow$ This can be accomplish by letting the discrete symmetry to allow

$$b_{11} \frac{\langle \overline{N}_X \rangle \langle N_X \rangle}{m_{Pl}}$$

while forbidding $b_7$,$b_{10}$.

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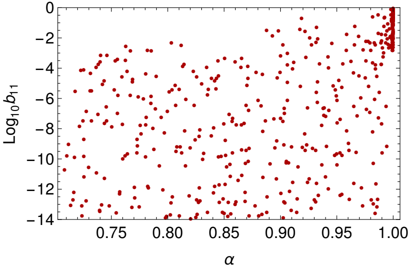
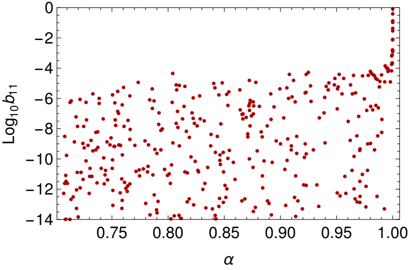
    where $\alpha$ is the biggest coefficient.
  - $$m_{2^{nd}\,lightest} > 100 \text{ GeV}$$

First we look into $b_{11}$ coupling effects on the lightest state composition




(a) $(2, 0)$

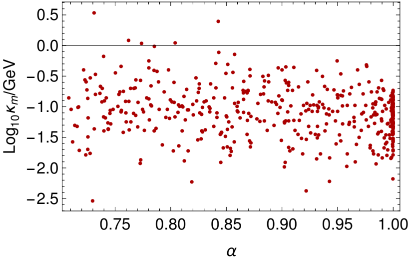



(b) $(3, 0)$

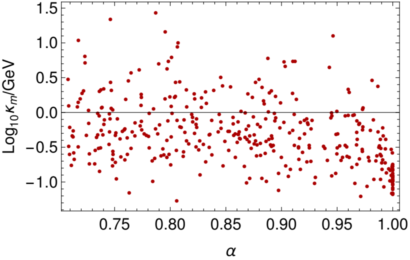
We find $b_{11} \simeq \mathcal{O}(1)$ – i.e. non-suppressed – returns desired physical neutrino states $\alpha \simeq 1$.

Furthermore, for $b_{11} \simeq 1$, the B-RPV coupling is bound

$$\kappa_m < 1 \text{ GeV}$$




(c) $(2, 0)$




(d) $(3, 0)$

This not only ensures us good Higgs physics, but is also in agreement with customary lore on B-RPV bounds from neutrino masses.

# Outline

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- Breaking mechanism scenario is intrinsically connected to neutrino masses through non-renormalisable terms and B-RPV terms
- Physical neutrinos with realistic masses are obtained
- In the regions of the parameter space that return good physical neutrinos, B-RPV is naturally suppressed in agreement with the usual lore $\kappa_m < 1$ GeV

Thank you!

# Backup slides

- The compactified $G_2$ manifold, $K$, is crucial for defining the 4D theory:
  - Gauge fields supported on 3-spaces with orbifold singularities.
  - Additional conical singularities on the 3-spaces $\Rightarrow$ localised chiral superfields in gauge irreps.
  - $G_2$ manifolds do not have continuous symmetries but admit discrete symmetries.
- In fluxless compactifications axions have an exact Peccei-Quinn symmetry $\Rightarrow$ no perturbative moduli superpotential.
- Tree-level superpotential coefficients are functions of volumes in $K$

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

- Unification coupling is given by the volume of $K$, $\alpha_U^{7/3} \sim 1/V_7$.

- In M Theory, moduli are stabilised and SUSY is broken by a confining hidden sector (hep-th/0701034).
- The hidden sector allows for a two chiral supermultiplets that originate a condensate,$\phi$, charged under two gauge groups $SU(P) \times SU(Q)$.
- Due to axionic PQ symmetry, the hidden sector superpotential is non-perturbative

$$W_{hidd} = c_1 \phi^{-2/P} e^{-\sum N_i s_i 2\pi/P} + c_2 e^{-\sum N_i s_i 2\pi/Q}$$

  $c_i$ are complex numbers with order 1 magnitude, $N_i$ are determined by the homologies of the hidden 3-cycles.
- The above construction *formally* fixes all moduli and, since

$$m_{3/2} = m_{Pl}^{-2} e^{K/2m_{Pl}^2} |W|,$$

  hierarchy for the visible sector.

- Numerical studies with reasonable, expectable, values for parameters return

$$m_{3/2} \simeq \mathcal{O}(10 - 100 \text{ TeV})$$

- $$K/m_p^2 = \hat{K}/m_p^2 + \tilde{K}_{\overline{\alpha}\beta}(s_i)\overline{\Phi}^{\overline{\alpha}}\Phi^\beta + \left(Z(s_i)_{\alpha\beta}\Phi^\alpha\Phi^\beta + \text{h.c.}\right) + \mathcal{O}(\Phi^3)$$
$$W = W_{hid} + Y'_{\alpha\beta\gamma}\Phi^\alpha\Phi^\beta\Phi^\gamma$$

  where $\Phi$ are visible chiral superfields, $Y'_{\alpha\beta\gamma}$.
- The un-normalised Yukawas, $Y'_{\alpha\beta\gamma}$ are given by non-perturbative effects from membrane instantons action on the 3-dimensional subspace where the superfields $\Phi^\alpha$, $\Phi^\beta$, $\Phi^\gamma$ are supported. More explicitly, the trilinear couplings take the form

$$Y'_{\alpha\beta\gamma} \simeq C_{\alpha\beta\gamma} e^{i2\pi \sum_i l_i^{\alpha\beta\gamma}(is_i + a_i)}$$

The soft-terms are all obtained by the usual SUGRA formulae (9707209)

$$m^2_{\overline{\alpha}\beta} \simeq m^2_{3/2}\delta_{\overline{\alpha}\beta}$$

$$A_{\alpha\beta\gamma} \simeq \mathcal{O}(1) m_{3/2} Y_{\alpha\beta\gamma}$$

The gaugino masses are suppressed in relation to the other soft-terms

$$m^a_{1/2} \simeq \mathcal{O}(100\ \text{GeV})$$

This happens as the leading contribution to the gravitino mass is the $F$-term of the hidden sector meson field, to which the gaugino mass is insensitve.

- $K$ admits a non-trivial fundamental group, $\pi_1(K)$: non-trivial quantities, Wilson lines, ($A$ GUT connection)

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

- Convenient representation for $\mathcal{W}$:

$$\mathcal{W} = \sum_m \frac{1}{m!} \left( \frac{i2\pi}{n} \sum_j a_j Q_j \right)^m ,$$

with $Q_i$ generators of the surviving $U(1)$ factors, $a_j$ s.t. $\mathcal{W}^n = 1$.
- $\mathcal{W}$ cannot be gauged away, but can be absorbed on a chiral supermultiplets $\Rightarrow$ GUT is broken.
- $\mathcal{W}$ are holonomies: have a topological meaning and furnishes a representation of $\pi_1(K)$: If $\pi_1(K) = Z_n \Rightarrow \mathcal{W}^n = 1$.
- All possible $\mathcal{W}$ commute between them $\Rightarrow$ each $\mathcal{W}$ is a diagonal element of the GUT group and the breaking pattern is rank preserving.
- Witten: if $K$ admits a geometrical (freely acting) symmetry isomorphic to $\pi_1(K) \Rightarrow \mathcal{W}$ act as charges of the symmetry.