F-theory and Neutrinos: Kaluza Klein Dilution of Flavor Hierarchy

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Outline

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Neutrinos

- Why are neutrinos interesting?
  - Defies Standard Model
  - Experimental data to come: predict vs postdict
- Why is it hard to put neutrinos into GUT?
  - We know little about neutrinos
  - Neutrinos are too different from other sectors

F-theory GUT models

- String theory can promote higher dimensional operator for neutrino seesaw mechanism

$$W_{\text{eff}} \supset \lambda_{ij}^{(\nu)} \frac{\left(H_u L^i\right)\left(H_u L^j\right)}{\Lambda_{\text{UV}}}$$

- F-theory model building is
  - Better than Heterotic String Theory model building in breaking GUT group $\to SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Better than Type IIB String Theory model building in allowing $\mathbf{5}_H \times \mathbf{10}_M \times \mathbf{10}_M$ up-type interaction

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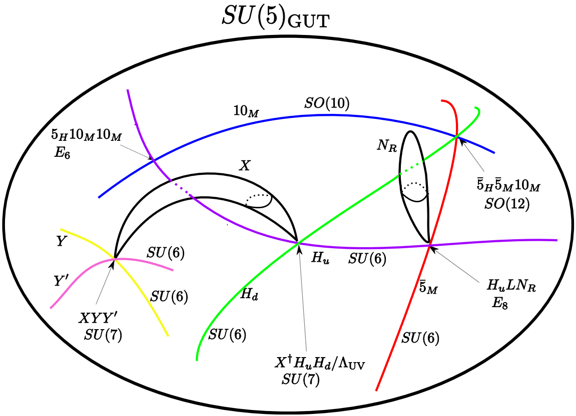
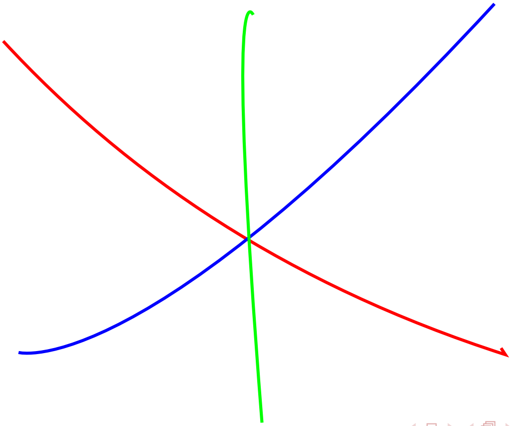
F-theory SU(5) GUT model

- Various matters live on the curve
- When the curves intersect, the matters interact



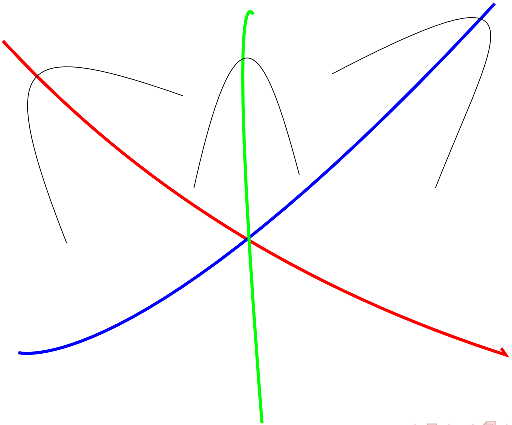
Yuwaka Coupling and Wavefunction

- Three matter curves intersect at a point to form a Yukawa interaction



Yuwaka Coupling and Wavefunction

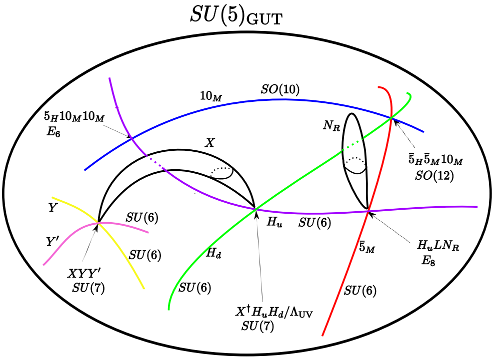
- The overlap between the wavefunctions will give the strength of Yukawa interaction



KK modes vs 0-modes

KK modes - excited state in internal (compactifaction) geometry

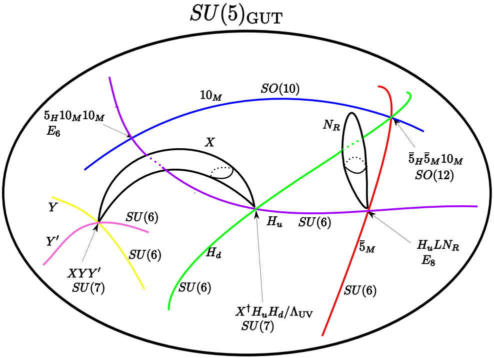
- N_R curve: KK-modes
- Other colored curves: 0-modes



KK modes vs 0-modes

Distinctive tastes of neutrinos

- Wavefunction for KK modes behave differently than 0-modes
- Yukawas involving N_R are very different from others



KK modes on N_R curve

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KK modes living on N_R curve

- provide heavy mass Λ_{UV} for seesaw mechanism

$$W_{\text{eff}} \supset \lambda_{ij}^{(\nu)} \frac{\left(H_u L^i\right)\left(H_u L^j\right)}{\Lambda_{\text{UV}}}$$

- dilute mass hierarchy of neutrinos
- dilute mixing matrix of neutrinos

Yukawa Coupling and Seesaw Mechanism

- Superpotential terms for neutrino interactions

$$\widetilde{W} \supset \widetilde{y}_{i,I} \widetilde{H}_u \widetilde{L}^i \widetilde{N}_I + \widetilde{y}'_{j,J} \widetilde{H}_u \widetilde{L}^j \widetilde{N}^c_J + \widetilde{M}_{IJ} \widetilde{N}^c_I \widetilde{N}_J$$

with Yukawa coupling from overlap $\widetilde{y}_{i,I} = \int \widetilde{\Psi}_{H_u} \widetilde{\Psi}^i_L \widetilde{\Psi}^{(I)}_N$

- After integrating out the heavy right-handed neutrinos, we get

$$W_{\text{eff}} \supset \lambda^{(\nu)}_{ij} \frac{\left(H_u L^i\right) \left(H_u L^j\right)}{\Lambda_{\text{UV}}}$$

with $\frac{\lambda^{(\nu)}}{\Lambda_{\text{UV}}} = \widetilde{y} \cdot \frac{1}{M} \cdot \widetilde{y}^T$

Neutrino Seesaw Mass

$$\frac{\lambda^{(\nu)}}{\Lambda_{\text{UV}}} = \widetilde{y} \cdot \frac{1}{M} \cdot \widetilde{y}^T$$

$$\sim \frac{1}{M_*} \begin{pmatrix} \varepsilon^2 & \varepsilon^{3/2} & \varepsilon \\ \varepsilon^{3/2} & \varepsilon & \varepsilon^{1/2} \\ \varepsilon & \varepsilon^{1/2} & 1 \end{pmatrix}$$

with $\varepsilon \sim \sqrt{\alpha_{GUT}}$

This matrix teaches us a lot about neutrinos

- eigenvalues → neutrino masses $m_1 : m_2 : m_3 \sim \varepsilon^2 : \varepsilon : 1$
- eigenvectors → neutrino mixing matrix (next slide)

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Hierarchical Mixing

Mild hierarchy and wild mixing

From the Yukawa coupling matrix, we get

$$U_{\mathrm{PMNS}}^{\mathrm{F-th}} = U_L^{(l)} \left(U_L^{(\nu)} \right)^\dagger \sim \begin{pmatrix} U_{e1} & \varepsilon^{1/2} & \varepsilon \\ \varepsilon^{1/2} & U_{\mu 2} & \varepsilon^{1/2} \\ \varepsilon & \varepsilon^{1/2} & U_{\tau 3} \end{pmatrix}$$

with $\varepsilon \sim \sqrt{\alpha_{GUT}} \sim 0.2$

Hierarchical Mixing

Comparison with experiments

- Our model gives

$$\left|U^{\mathrm{F-th}}_{\mathrm{PMNS}}\right| \sim \begin{pmatrix} 0.87 & 0.45 & 0.2 \\ 0.45 & 0.77 & 0.45 \\ 0.2 & 0.45 & 0.87 \end{pmatrix}$$

- The experimental result tells

$$\left|U^{3\sigma}_{\mathrm{PMNS}}\right| \sim \begin{pmatrix} 0.77-0.86 & 0.50-0.63 & 0.00-0.22 \\ 0.22-0.56 & 0.44-0.73 & 0.57-0.80 \\ 0.21-0.55 & 0.40-0.71 & 0.59-0.82 \end{pmatrix}$$

(from Gonzalez-Garcia and Maltoni's global fit)

Ratio of Neutrino Mass Eigenvalues

Much weaker hierarchy than charged leptons and quarks

- We predict mild "normal hierarchy"

$$m_1 : m_2 : m_3 \sim \varepsilon^2 : \varepsilon : 1$$

with $\varepsilon \sim \sqrt{\alpha_{GUT}} \sim 0.2$

- Experimental data (+normal hierarchy) automatically gives

$$m_3^{\text{observe}} \sim \sqrt{\Delta m_{31}^2} \sim 50 \pm 4 \text{ meV}$$
$$m_2^{\text{observe}} \sim \sqrt{\Delta m_{21}^2} \sim 8.7 \pm 0.4 \text{ meV}$$

- Our F-theory model predicts

$$m_1^{\text{F-th}} \sim 1 - 3 \text{ meV}$$

Our Prediction for Upcoming Experiments

How to falsify/challenge our model

- Double Beta Decay (EXO @4-40 meV, etc)

$$\left|m_{\beta\beta}\right|^2 = \left|\sum_{i=1}^{3} m_i \left(U_{ei}^{\mathrm{PMNS}}\right)^2\right|^2$$

$$m_{\beta\beta}^{\mathrm{max}} \sim 6 \text{ meV}$$

- Single Beta Decay (KATRIN @200 meV, etc)

$$\left|m_{\beta}\right|^2 = \sum_{i=1}^{3} m_i^2 \left|U_{ei}^{\mathrm{PMNS}}\right|^2$$

$$\left|m_{\beta}^{\mathrm{F-th}}\right| \sim 5 - 10 \text{ meV}$$

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Conclusion

- F-theory GUT model building made much progress in recent years, and it can now explain/accommodate neutrino physics as well
- KK modes on N_R curve provide heavy mass for seesaw mechanism to work - smaller mass scale
- These same KK modes makes neutrino sector distinctive from others - milder mass hierarchy and wilder mixing
- We predict θ_{13} near its current experimental upper bound
- We predict m_1 and other masses measurable in beta decay experiments