How Grand Unification is realized in string theory?

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Lessons from Unification

Since the Standard Model is gauge theory based on group $SU(3) \times SU(2) \times U(1)$, it is natural to think of a larger group for unification. [Georgi, Glashow] [Pati, Salam]

Indeed its nontrivial structure is well explained by symmetry breaking of Grand Unification.

group	matter			feature
SM	$q\vert u^c\vert e^c$	$d^c\vert l$	$h_d\vert h_u^c$	
$SU(5)$	$\mathbf{10}$	$\bar{\mathbf{5}}$	$\bar{\mathbf{5}}_H, \mathbf{5}_H$	minimal group
$SO(10)$	$\mathbf{16}$		$\mathbf{10}_H$	single matter rep., R-handed neutrino
E_6	$\mathbf{27}$			(SUSY) matter-Higgs unification
E_7	$\mathbf{56}$			
E_8	$\mathbf{248}$			one single rep.:matter-Higgs-gauge unif.

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Maybe everything originates from a pure Yang–Mills
or more lower-level theory, e.g. string theory

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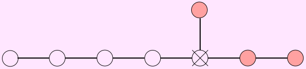
SM	
$SU(5)$	
$SO(10)$	ɔ
E_6	
E_7	
E_8	if.

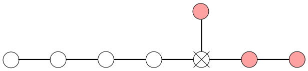
Identifying $SO(10) = E_5, SU(5) = E_4$,
the SM group is at the unique position of E_n unification chain [Ramond] [Olive] See also Nilles's talk.



$E_3 \times U(1)$

or more lower-level theory, e.g. string theory

Conclusion: SM from E_8



Under the maximal breaking incl. SM group
$E_8 \to SU(3) \times SU(2) \times \underbrace{S[U(1)_Y \times U(5)]}$,

$$\begin{aligned}\mathbf{248} \to \text{adjoints} &+ e^c(\mathbf{1},\mathbf{1},\mathbf{5})_1 + l(\mathbf{1},\mathbf{2},\mathbf{10})_{-1/2} \\ &+ q(\mathbf{3},\mathbf{2},\mathbf{5})_{1/6} + X(\mathbf{3},\mathbf{2},\mathbf{1})_{-5/6} \\ &+ d^c(\overline{\mathbf{3}},\mathbf{1},\mathbf{10})_{1/3} + u^c(\overline{\mathbf{3}},\mathbf{1},\mathbf{5})_{-2/3} + c.c.\end{aligned}$$

A desirable spectrum

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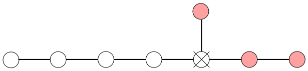

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A desirable spectrum

Different matter unification relation.

- Desirable if only chiral parts are kept.
- How to distinguish between l and h_d?
- What happens to X?
- Why three generations?

Generic feature: background flux

String predicts SYM in higher dim, where gauge fields decomposes [Kaluza] [Klein]

$$A_M = \underbrace{A_\mu}_{\text{4D gauge boson}} \oplus \underbrace{A_5 \oplus A_6 \oplus \cdots}_{\text{4D scalars}}.$$

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ex. From $U(5) \to U(3) \times U(2)$,

$$\mathbf{24} \to (\mathbf{8}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{3}, \mathbf{2}) + (\overline{\mathbf{3}}, \mathbf{2})$$

In the T-dual theory, it becomes the position of branes $A_5 \leftrightarrow 2\pi\alpha' X_5$.

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2. Choice of non-simply connected internal space e.g. torus

Position dependent vector $\langle A_5 \rangle = mx^6$ or flux $\langle F_{56} \rangle = m$ [Landau] [Nilson-Olessen] ['t Hooft]

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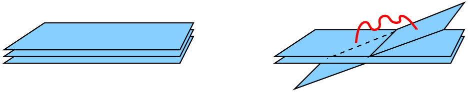

- Chiral: exclusively $(3, 2)$ or $(\bar{3}, 2)$ survives [Berkooz, Douglas, Leigh] [Cremades, Ibanez, Marchesano]
- Generalized and classified by Chern characters $F \wedge F$, $F \wedge F \wedge F \ldots$

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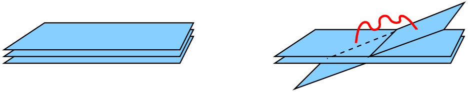

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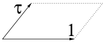
- Gener

Since open string has two ends,
only bifund representations under U, SO, Sp are possible.

F-theory can describe E_8

$SL(2,\mathbb{Z}) : \tau \to \frac{a\tau+b}{c\tau+d}$

- U-diality of type IIB string $\tau = C_0 + ie^{-\phi}$
- Symmetry of torus 

M-theory shows that they are well identified = F-theory on torus is IIB string. [Vafa]

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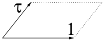
- Symmetry of torus 

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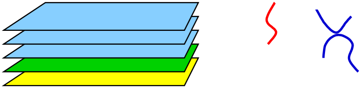
- Geometry of extra torus automatically takes into account nonperturbative effect.
- Connectedness of the singular torus = connectedness of Lie algebra
  We have codim 1 worldvolume theory with this gauge group.
- Exceptional group is described on equal footing. cf. [DeWolfe, Zwiebach]...



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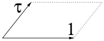
- Symmetry of torus 

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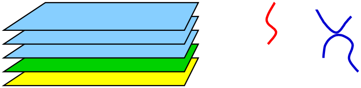


branes and strings have F,D charges

Using heterotic dual (CY4 admitting K3 fibration)

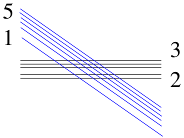
- We have $E_8 \times E_8$ as a starting point. [Morrison, Vafa] cf. Nilles's talk
- Chiral fermions from the same mechanism, including spinorial repr.
  eg. $E_6 \to SO(10)$, $\mathbf{78} \to \mathbf{45} + \mathbf{16} + \overline{\mathbf{16}} + \mathbf{1}$ [Katz, Vafa]

Spectral cover = flavor brane = broken symmetry

We can specify SM by the broken group $S[U(1)_Y \times U(5)]$.

The background instanton/Higgs bundle of, satisfying SUSY conditions, is described by spectral covers 'flavor branes.' [Freedman, Morgan, Witten]

We can extract everything from the equation having roots t_i as positions of branes.



$$0 = \underbrace{(a_0 s + a_1)}_{U(1)_Y}\underbrace{(b_0 s^5 + b_1 s^4 + b_2 s^3 + b_3 s^2 + b_4 s + b_5)}_{SU(5)_\perp}$$

$$= a_0 b_0 (s - t_Y)(s - t_1)(s - t_2)(s - t_3)(s - t_4)(s - t_5) \qquad \text{mod } S_5$$

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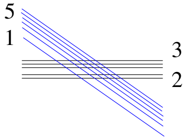

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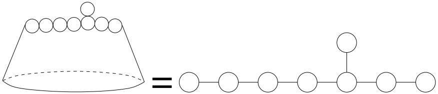
- We recycle well-known $SU(5)$ parameters b_i.
  $a_1 \to 0$: $SU(5)$ unification limit.
- The generator of $U(1)_Y$ = the trace part of $U(5)_\perp$: $b_1 = -a_1 b_0,\ a_1 \sim -c_1(S)$
- Reflects S_5 monodromy‘
  b_m/b_0 elementary symmetric polynomials of deg. m of $t_1, \ldots t_5$.

From the information on the broken part, we can describe unbroken part.

The $SU(3) \times SU(2) \times U(1)_Y$ singularity [KSC, Kobayashi] [KSC]

F-theory claims that on the vanishing discriminant of torus of G-singularity, we have $(7+1)$-dimensional SYM with gauge group G.



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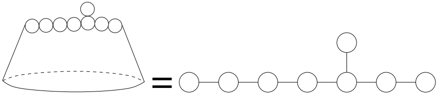

The torus fiber

$$y^2 = x^3 + (b_5 + b_4 a_1)xy + (b_4 + b_3 a_1)zx^2 + b_0(a_1 b_5 + z)^2 z^3$$
$$+ (b_3 + b_2 a_1)(a_1 b_5 + z)zy + (b_2 + b_1 a_1)(a_1 b_5 + z)z^2 x + \dots$$

describes the SM singularity on $z = 0$.

- Mainly simple groups have been classified: semisimple groups were not.
- The discriminant is not factorized, being embedded in E_n

$$\Delta = (b_5 + a_1 b_4)^3 P_X^2 P_{q_\circ}^2 P_{d^c_\circ} P_{u^c_\circ} z^3 + P_{q_\circ} P_X Q_4 z^4 + O(z^5).$$

Only in the weakly coupled limit it becomes $\Delta \simeq b_5^4 R_5 (b_5 a_1 + z)^2 z^3$.

l and h_d distinguished by monodromy

$E_8 \to SU(3) \times SU(2) \times S[U(1)_Y \times U(5)]$,

$$\mathbf{248} \to \text{adjoints} + q(\mathbf{3}, \mathbf{2}, \mathbf{5})_{1/6} + \cdots + l(\mathbf{1}, \mathbf{2}, \mathbf{10})_{-1/2} + \ldots$$

To distinguish $SU(2)$ doublets l, h_u, h_d, we need more special monodromy on $U(5)$.
Ex. We choose $\mathbb{Z}_4 \subset S_5$ monodromy. [Hayashi, Watari, Tatar] [Marsano, Saulina, Schaefer-Nameki]

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1. Compatible $SU(5)_\perp \to S[U(4) \times U(1)_M]$, $\quad U(1)_M \to \mathbb{Z}_2$ R-parity.
2. Now lepton is distinguished from Higgs
   - $q_\circ(\mathbf{3}, \mathbf{2}, \mathbf{5}) \to q(\mathbf{3}, \mathbf{2}, \mathbf{4})_{\frac{1}{6}} + q'(\mathbf{3}, \mathbf{2}, \mathbf{1})_{\frac{1}{6}}$
   - $l_\circ(\mathbf{1}, \mathbf{2}, \mathbf{10})_{-\frac{1}{2}} \to l(\mathbf{1}, \mathbf{2}, \mathbf{4})_{-\frac{1}{2}, -3} + h_u(\mathbf{1}, \mathbf{2}, \mathbf{4})_{-\frac{1}{2}, 2} + h_d^c(\mathbf{1}, \mathbf{2}, \mathbf{2})_{-\frac{1}{2}, 2}$

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matter	matter curve	section on S	M
X	$t_6 \to 0$	$-c_1$	0
q	$t_i \to 0$	$\eta - 4c_1 - x$	1
q'	$t_5 \to 0$	$-c_1 + x$	-4
d^c	$t_i + t_5 \to 0$	$\eta - 4c_1 + 2x$	-3
D^c	$t_i + t_{i+2} \to 0$	$\eta - 2c_1 - x$	2
D'	$t_i + t_{i+1} \to 0$	$\eta - 4c_1 - x$	2
u^c	$t_i + t_6 \to 0$	$\eta - 4c_1 - x$	1
u'	$t_5 + t_6 \to 0$	$-c_1 + x$	-4
h_u	$t_i + t_{i+1} + t_6 \to 0$	$\eta - 4c_1 - x$	2
h_d^c	$t_i + t_{i+2} + t_6 \to 0$	$\eta - 2c_1 - x$	2
l	$t_i + t_5 + t_6 \to 0$	$\eta - 4c_1 + 2x$	-3
e^c	$t_i - t_6 \to 0$	$\eta - 4c_1 - x$	1
e'	$t_5 - t_6 \to 0$	$-c_1 + x$	-4

Superpotential is renormalizable MSSM superpotential without R-parity violating terms→would be broken cf. [Ambroso, Ovrut]

$$W = W_{MSSM}(\mu = 0) + m_h h_u h_d + m_D D D'$$

2-3-splitting problem should be flavor problem. cf. See talks by Ibanez, Pawelczyk, Kyae

Three generations

Dirac equation in higher dim

$$(i\Gamma^\mu \partial_\mu + \Gamma^m (i\partial_m - A_m + \tfrac{1}{2}\omega_m))\psi = 0$$

- Eigenvalue of $\Gamma^m (i\partial_m - \underbrace{A_m}_{\text{VEV}} + \underbrace{\tfrac{1}{2}\omega_m}_{\text{geometry}}) \equiv i \not\nabla$ looks like 4D mass
- # degenerate massles states is topological and counted by index theorem

$$n_R - n_{\overline{R}} = \text{index} i \not\nabla = \begin{cases} \int_{2D} trF \\ \int_{6D} trF \wedge F \wedge F - \frac{1}{8} trF \wedge trR \wedge R \end{cases}$$

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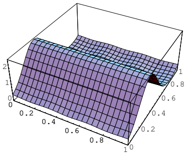
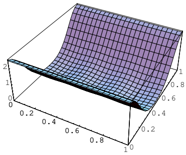
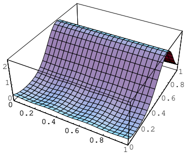
Ex. Torus with 3 units of magnetic flux $\int_T trF = 3$ [Cremades, Marchesano, Ibanez] [Abe, Choi, Kobayashi, Ohki]...

$|\psi_0|^2$ 

$|\psi_1|^2$ 

$|\psi_2|^2$ 

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Since the matter curves Σ_R are induced from spectral cover, at best we can turn on a magnetic flux on the spectral cover $G_{mnpq} = \sum F_{mn} \wedge \omega_{pq}$ also inducing fluxes F_{Σ_R}

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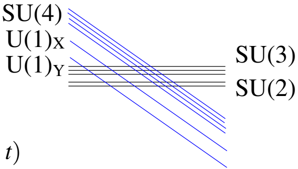
Among 4+1+1 covers (see Fig.), we turn on universal flux on $SU(4)$ cover C_4

$$\gamma_4 = \lambda(4 - p_4^*(5c_1 - t))(C_4 \cap \sigma),\ \gamma_Y = 0,\ \gamma_X = 0,$$

preserving $SO(10)$ unification relation even if we constructed the SM group [a]



$$\begin{aligned} 16: \quad & n_q = n_{d^c} = n_{u^c} = n_l = n_{e^c} = n_{\nu^c} &&= -\lambda(6c_1 - t)\cdot(2c_1 - t) \\ 10: \quad & n_{h_d} = n_{h_u} = n_D = n_{D'} &&= -2\lambda(6c_1 - t)\cdot(2c_1 - t) \end{aligned}$$

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[a] $c_1 \equiv c_1(S),\ -t = c_1(N_{S/B})$

Three generations

Since the matter curves Σ_R are induced from spectral cover, at best we can turn on a magnetic flux on the spectral cover $G_{mnpq} = \sum F_{mn} \wedge \omega_{pq}$ also inducing fluxes F_{Σ_R}

$$n_R - n_{\overline{R}} \quad = \text{index} i \not{\nabla} \quad = \int_{\Sigma_R} tr F_{\Sigma_R}$$

Among 4+1+1 covers (see Fig.), we turn on universal flux on $SU(4)$ cover C_4

$$\gamma_4 = \lambda(4 - p_4^*(5c_1 - t))(C_4 \cap \sigma),\ \gamma_Y = 0,\ \gamma_X = 0,$$

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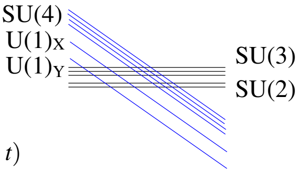

$$16: \quad n_q = n_{d^c} = n_{u^c} = n_l = n_{e^c} = n_{\nu^c} \quad = -\lambda(6c_1 - t)\cdot(2c_1 - t)$$

$$10: \quad n_{h_d} = n_{h_u} = n_D = n_{D'} \quad = -2\lambda(6c_1 - t)\cdot(2c_1 - t)$$

[a] $c_1 \equiv c_1(S)$, $-t = c_1(N_{S/B})$

Choosing the base manifold $S = dP_2$ such that $-\lambda(6c_1 - t)\cdot(2c_1 - t) = 3$

3 generations of quarks and leptons
plus 6 vectorlike Higgs doublets and tiplets

$SU(6)$ Unification [KSC, JE Kim]

$SU(6)$ Unification

$$SU(6) \to \begin{cases} SU(5) & \langle \mathbf{6}_h \rangle = \langle \overline{\mathbf{6}}_h \rangle \text{ [Georgi-Glashow]} \\ SU(3)_c \times SU(3)_w \times U(1)_6 & U(1)_6 \text{ flux [Lee-Weinberg]} \end{cases}$$

The common direction is $SU(3)_c \times SU(2)_w \times U(1)_Y$

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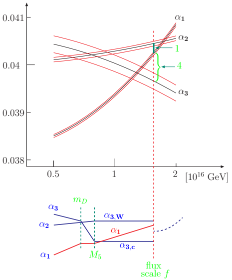
- Simple structure
  $\mathbf{15} + \overline{\mathbf{6}}_M + \overline{\mathbf{6}}_H = \mathbf{27}$ of E_6 naturally unifies quarks, leptons and Higgses

$$\mathbf{15} = \mathbf{10}_M + \mathbf{5}_H \quad \overline{\mathbf{6}}_M \to \overline{\mathbf{5}}_M + \mathbf{1}_H, \quad \overline{\mathbf{6}}_H \to \overline{\mathbf{5}}_H + \mathbf{1}_M$$

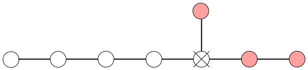
- Color coupling discripancy in unification may be explained running above the GUT breaking scale.
- Large $SU(6) \times SU(3) \times SU(2)$ symmetry forbids proton decay stronger than R
  cf. [Nilles, Ramos-Sanchez, Vaudrevange]
- Doublet-triplet splitting: flux distinguishes triplet
- μ-problem is flavor problem See J.E.Kim's talk



Flipped SU(5) [KSC, Kyae]

See the next talk by Bumseok Kyae.

Conclusion: SM from E_8



Under the maximal breaking incl. SM group
$E_8 \to SU(3) \times SU(2) \times \underbrace{S[U(1)_Y \times U(5)]}$,

$$\begin{aligned} \mathbf{248} \to \text{adjoints} &+ e^c(\mathbf{1},\mathbf{1},\mathbf{5})_1 + l(\mathbf{1},\mathbf{2},\mathbf{10})_{-1/2} \\ &+ q(\mathbf{3},\mathbf{2},\mathbf{5})_{1/6} + X(\mathbf{3},\mathbf{2},\mathbf{1})_{-5/6} \\ &+ d^c(\bar{\mathbf{3}},\mathbf{1},\mathbf{10})_{1/3} + u^c(\bar{\mathbf{3}},\mathbf{1},\mathbf{5})_{-2/3} + c.c. \end{aligned}$$

A desirable spectrum

Different realization via different interactions

- Desirable if only chiral parts are kept. Higgs bundle/instanton
- How to distinguish between l and h_d? $\mathbb{Z}_4$ monodromy
- What happens to X? Spectral flux preserving $SO(10)$ structure
- Why three generations? The base of K3 fibration is dP_2