E_6 grand unified theory with three generations from heterotic string

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参考文献：　arXiv:1012.1690 [hep-ph]　(1104.0765 [hep-th])

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our project

- anomalous *U(1)* GUT

N. Maekawa & T.Y. & …
(2001-)

a scenario of the SUSY-GUT
w/ anomalous *U(1)* gauge symm.

natural setup

(w/ all interactions)

⇒

- doublet-triplet splitting
- gauge coupling unification
- Yukawa hierarchy
- SUSY flavor/CP ($E_6 \times SU(2)_F$)

- anomaly : assumed to be cancelled by GS.

⇒ just an effective theory

We aim to embed it into superstring theory.

our project

- which string?

anomalous *U(1)* GUT

- charged adjoint Higgs
- $E_6 \times SU(2)_F$ model is attractive

⇒ hetero, M, F, …

- easy to realize E_6
- not easy to realize adjoint Higgs

D.C.Lewellen (1990)

As a 1st step, we derive E_6 models.

Ito et.al. (2010)

Plan

- our project
- Introduction
  - why E_6?
- heterotic E_6
- summary

Introduction

- superstring
  - quantum gravity
  - unifies all the forces
  - defined in 10D
  - typical scale >> 100GeV

candidate for ultimate theory

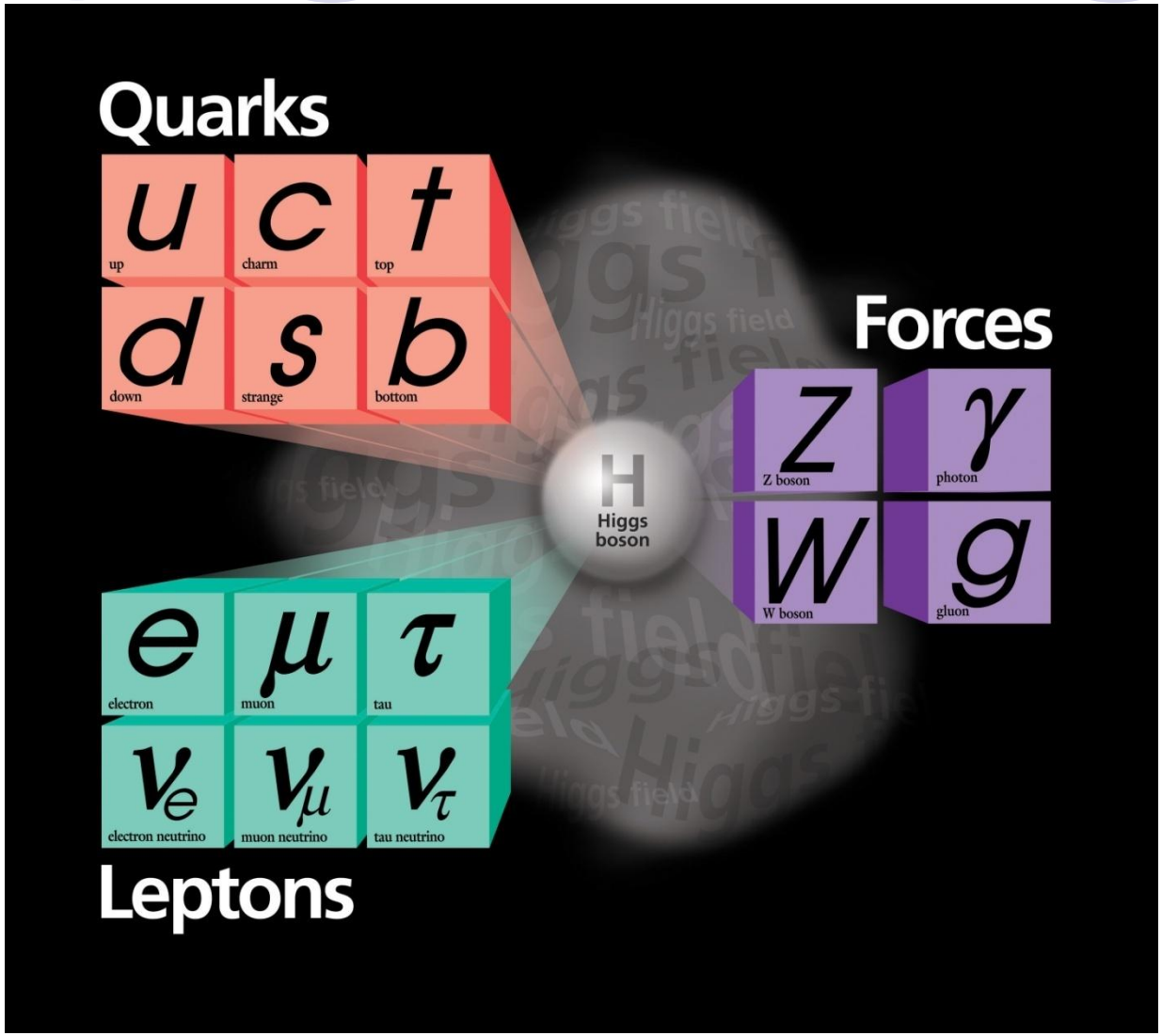
far from the SM

- way to the SM from superstring?
  - heterotic string
  - intersecting D-branes
  - F-theory GUTs

ask hints to ph-studies

⇨ MSSM-like matter content, but not the flavor structures

Standard Model



Standard Model

- renormalizable gauge theory

$$G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

- fermions & Higgs field
  - *s=1/2*: $Q,\ U^c\ \ D^c,\ L,\ E^c\ (\ N^c\ )$ ($\times$3gen.)
  - *s=0* : H

- Higgs mechanism

$$G_{\rm SM} \longrightarrow SU(3)_C \times U(1)_{\rm EM}$$

⇨ fermion masses

$$y_{ij} Q_i U_j^c H$$

$O(20)$ parameters

⇩

Consistent with almost all the experiments.

Standard Model

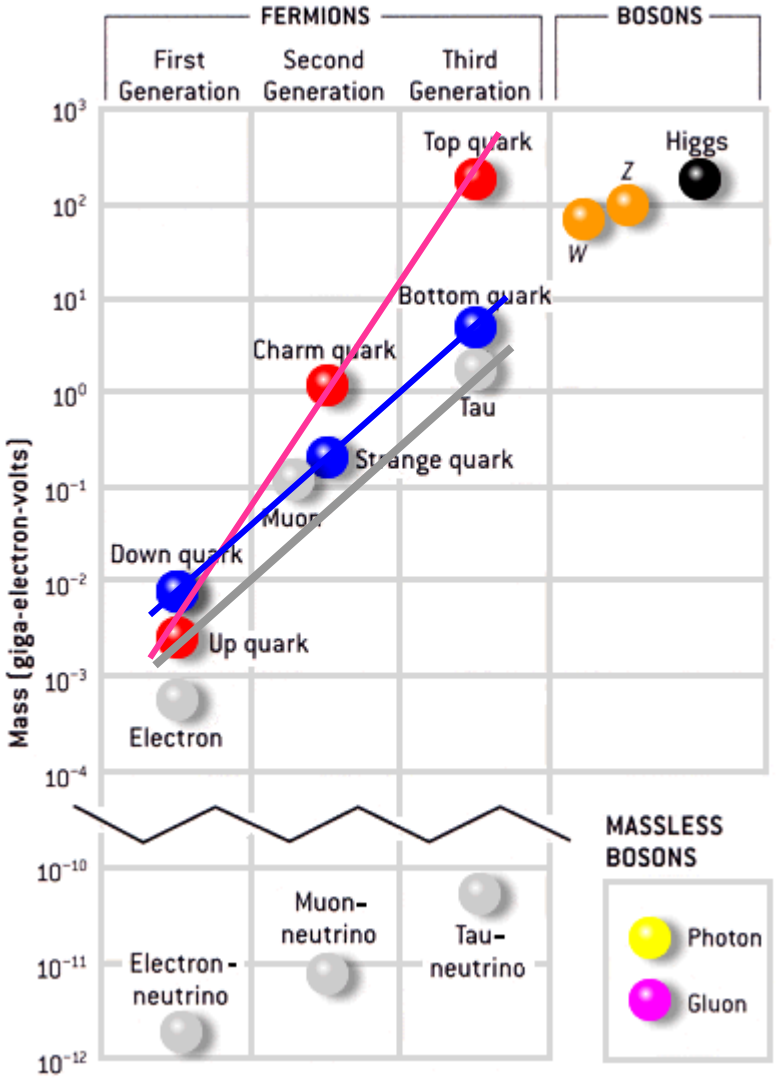
- fermion masses

$$\frac{m_u}{m_c} \sim \frac{m_c}{m_t}$$

$$\ll \frac{m_d}{m_s} \sim \frac{m_s}{m_b} \sim \frac{m_e}{m_\mu} \sim \frac{m_\mu}{m_\tau}$$

$$\ll 1$$

- mixing
  - quark : small
  - lepton : large



Standard Model

- puzzles in SM
  - charge quantization
  - (anomaly cancellations)
  - hierarchal parameters
    - Yukawa couplings
    - Higgs mass
  - dark matter
  - generation #, quantum gravity, etc.

← GUT, string ($SO(10)$, E_6)

← $U(1)_A$, XD

← SUSY, XD

← string ???

SUSY-GUTs

- unify 3 forces : $G \supset SU(3)_C \times SU(2)_L \times U(1)_Y$

  G : non-Abelian ⇨ Charge Quantization

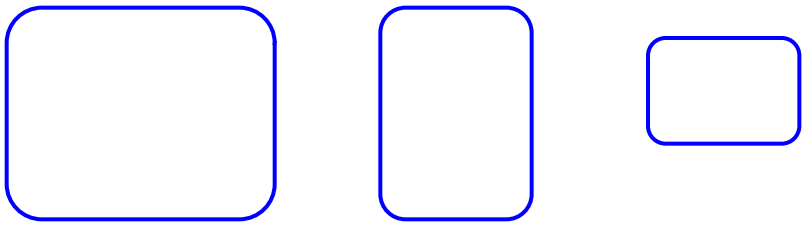
  ⇨ gauge coupling unification

- unify matters

SU(5) $Q \; U^c \; D^c \; L \; E^c \; N^c$ SO(10) E_6

$\mathbf{10} + \bar{\mathbf{5}} + \mathbf{1} = \mathbf{16}$

$+\mathbf{10} + \mathbf{1} = \mathbf{27}$



- Yukawa : $Y_{10}\,\mathbf{10}_i\,\mathbf{10}_j\,\mathbf{5}_H$, $Y_5\,\mathbf{10}_i\,\bar{\mathbf{5}}_j\,\bar{\mathbf{5}}_H$ (*i,j=1,2,3*)

  $\ni Y_u$ $\ni Y_d, Y_e$ milder hierarchy

SUSY-GUTs

- flavor structures : $Y \sim \epsilon_1^{\#\mathbf{10_1}} \epsilon_2^{\#\mathbf{10_2}}$ $\quad \epsilon_1 \ll \epsilon_2 \ll 1$

$$Y_{10} \sim \begin{pmatrix} \epsilon_1^2 & \epsilon_1\epsilon_2 & \epsilon_1 \\ \epsilon_1\epsilon_2 & \epsilon_2^2 & \epsilon_2 \\ \epsilon_1 & \epsilon_2 & 1 \end{pmatrix} \qquad Y_5 \sim \begin{pmatrix} \epsilon_1 & \epsilon_2 & 1 \\ \epsilon_1 & \epsilon_2 & 1 \\ \epsilon_1 & \epsilon_2 & 1 \end{pmatrix}$$

$$\Rightarrow V_{\rm CKM} \sim \begin{pmatrix} 1 & \epsilon_1/\epsilon_2 & \epsilon_1 \\ \epsilon_1/\epsilon_2 & 1 & \epsilon_2 \\ \epsilon_1 & \epsilon_2 & 1 \end{pmatrix} \qquad V_{\rm MNS} \sim \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

small mixing

large mixing

- Yukawa : $Y_{10}\,\mathbf{10}_i\,\mathbf{10}_j\,\mathbf{5}_H$, $\ni Y_u$ $\qquad$ $Y_5\,\mathbf{10}_i\,\bar{\mathbf{5}}_j\,\bar{\mathbf{5}}_H$ $\ni Y_d, Y_e$ $\qquad$ (*i,j=1,2,3*)

milder hierarchy

SUSY-GUTs

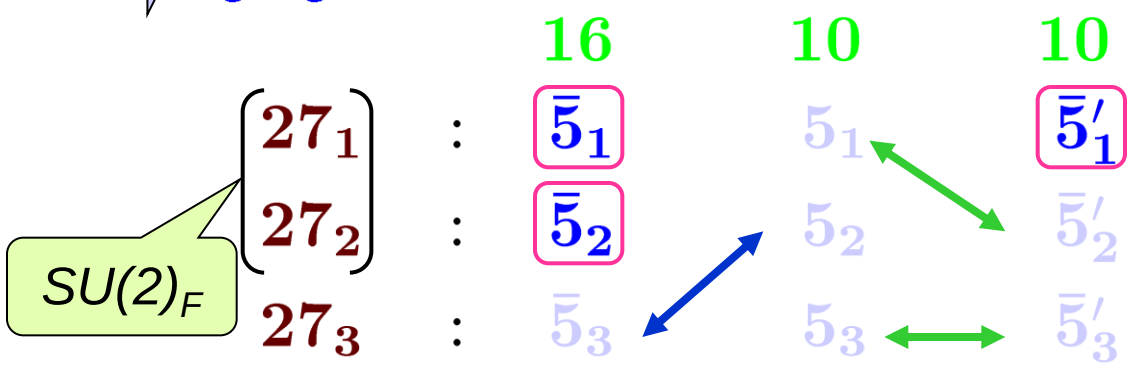
- $\bar{5}$ sector in E_6 model

$$Y \sim \epsilon_1^{\#27_1}\,\epsilon_2^{\#27_2}$$

  - E-twisting M.Bando & T.Kugo (1999)

$$27 \to 16 + 10 + 1 \to (10 + \bar{5} + 1) + (5 + \bar{5}') + (1)$$

⇨ $\bar{5}$ - 5 mass



⇨ massless $\bar{5}$: $(\bar{5}_1, \bar{5}'_1, \bar{5}_2)$

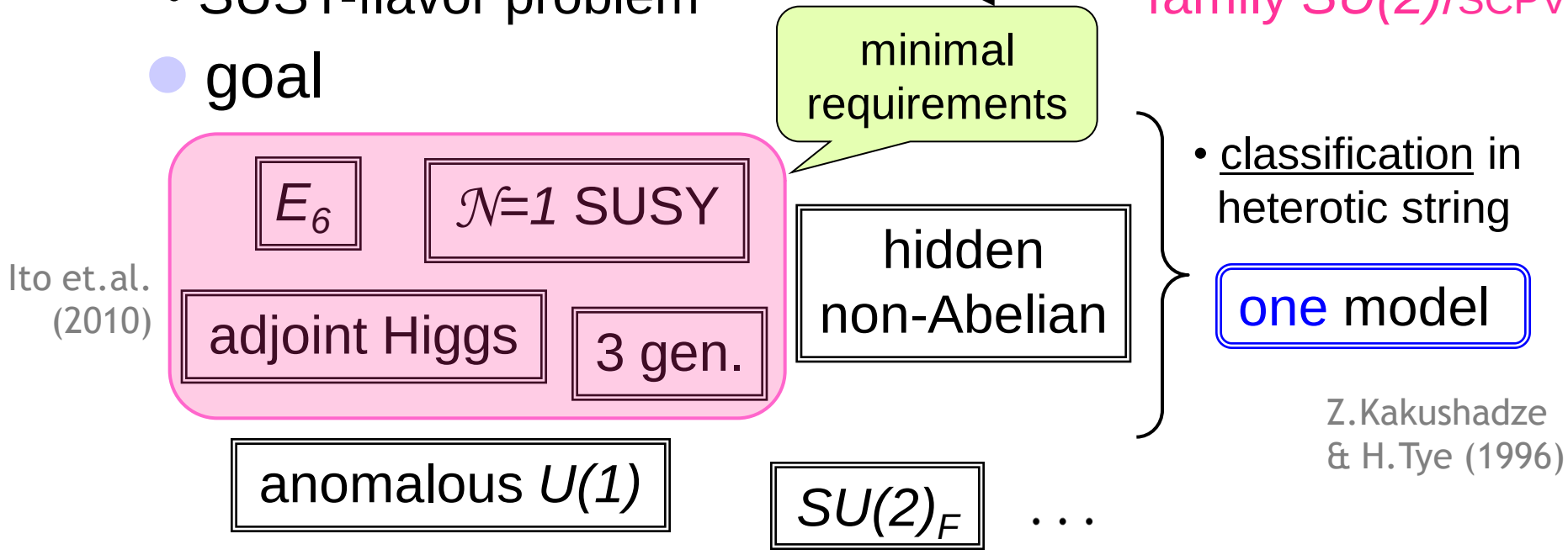
degenerate soft mass

N. Maekawa (2004)

⇨
- milder hierarchy in $\bar{5}$ sector !!
- all $\bar{5}$ come from 27_1 and 27_2.

Introduction

- SUSY E_6 unification
  - good chemistry w/ flavor structures
  - doublet-triplet splitting problem ← anomalous $U(1)$
  - SUSY-flavor problem ← family $SU(2)$/SCPV
- goal



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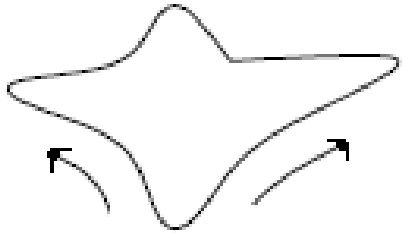
heterotic E_6

- heterotic string



$$|left> \otimes |right>$$

bosonic : 26D

super : 10D

	4D	6D	16D
left			"compactified"
right			

string consistency

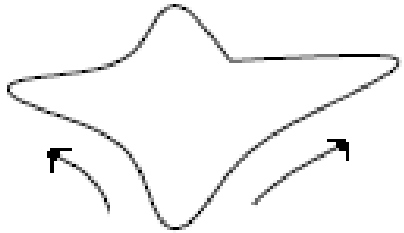
on $E_8{}^2$ or $Spin(32)/\mathbb{Z}_2$ Lie lattice

here?

no geometrical interpretation

heterotic E_6

- heterotic string



$$|left> \otimes |right>$$

bosonic : 26D

super : 10D

	4D	6D	16D
left			"compactified"
right			

string consistency

on a (22,6)-dimensional lattice

which must be even self-dual

K.S.Narain (1986)

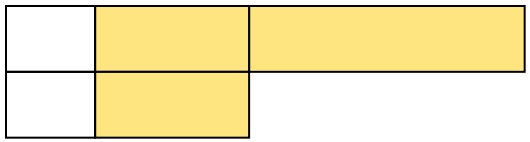
- E_6 Lie lattice in left ⇒ E_6 gauge symmetry
- orbifolding ⇒ $\mathcal{N}=1$ SUSY

heterotic E_6

- our strategy

1.) find a (22,6)-dimensional lattice

- even and self-dual
- $(E_6)^3$ Lie lattice in left



2.) fix the orbifold action

- permutes 3 E_6 factors
- twists right-moving part

diagonal embedding

K.R.Dienes & J.March-Russel (1996)

⇒ adjoint Higgs

⇒ $\mathcal{N}=1$ SUSY

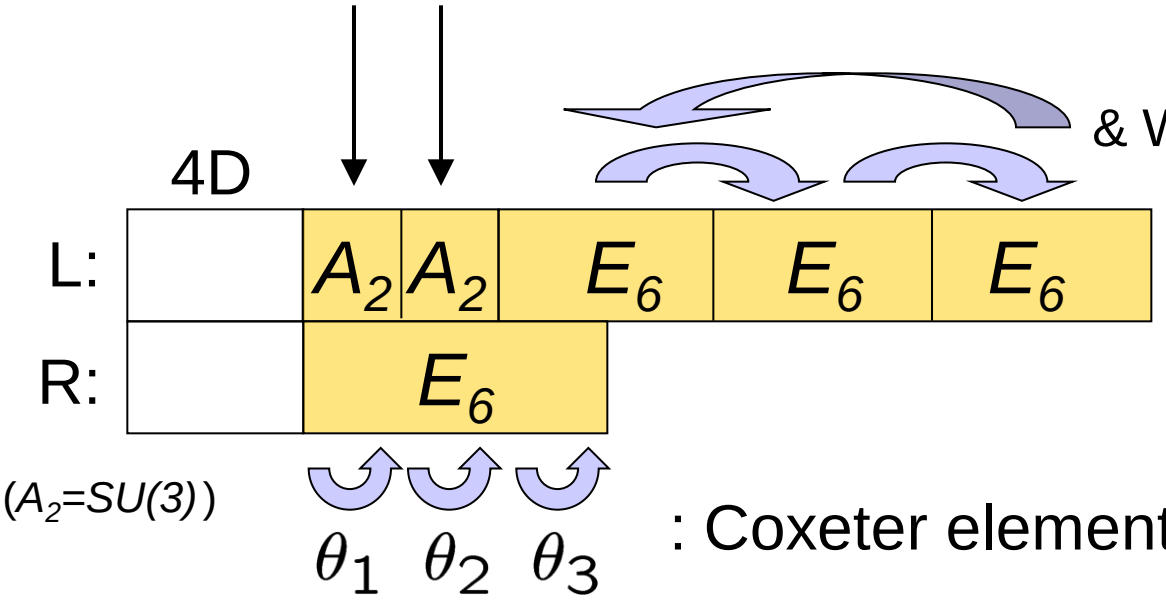
3.) analyze partition function

⇒ find models w/ 3 generations

heterotic E_6

- concrete setup Ito et.al. (2010)

unfixed ⇒ variety of models ⇒
- vector-like $\times 3$
- 3 generations $\times 3$
- 9 generations $\times 2$



: Coxeter element

missed in the classification

: same as the literature

Z.Kakushadze & H.Tye (1996)

$$\theta_i = 2\pi(1, 4, -5)/12$$

$$\theta_i \notin 2\pi\mathbb{Z} \qquad \sum \theta_i \in 2 \times 2\pi\mathbb{Z}$$

: $\mathcal{N}$=1 SUSY

heterotic E_6

- massless spectra

non-Abelian hidden symmetry

same as the known one

Ito et.al. (2010)

	Model 1	Model 2	Model 3
Gauge	$E_6 \times SU(2) \times U(1)^3$	$E_6 \times SU(2) \times U(1)^3$	$E_6 \times U(1)^4$
U	$(1,1,+6,0,0)_{\rm L}$ $(\mathbf{78},1,0,0,0)_{\rm L}$	$(1,1,+6,\pm3,0)_{\rm L}$ $(\mathbf{78},1,0,0,0)_{\rm L}$	$(1,-6,0,0,0)_{\rm L}$ $(1,+3,\pm6,0,0)_{\rm L}$ $(\mathbf{78},0,0,0,0)_{\rm L}$
T_1	$(\mathbf{27},1,+1,0,\pm1)_{\rm L}$	—	$(\mathbf{27},-1,-1,-1,0)_{\rm L}$
T_2	$(\overline{\mathbf{27}},1,-1,\pm1,0)_{\rm L}$	$(\overline{\mathbf{27}},1,+2,0,-2)_{\rm L}$	$(\overline{\mathbf{27}},+1,0,0,\pm1)_{\rm L}$
T_3	$2(1,1,-3,0,\pm3)_{\rm L}$	$(1,1,-3,\pm3,-3)_{\rm L}$	$(1,+3,-3,-3,0)_{\rm L}$ $(1,+3,+3,+3,0)_{\rm L}$
T_4	$(27,1,-2,0,0)_{\rm L}$	$(27,1,-2,\pm1,0)_{\rm L}$	$(27,-1,\pm2,0,0)_{\rm L}$ $(27,-1,+1,+1,0)_{\rm L}$
T_5			$(1,-3,0,0,\pm3)_{\rm L}$
T_6	$(1,2,0,0,\pm3)_{\rm L}$ $(1,1,+3,\pm3,0)_{\rm L}$	$(1,2,0,\pm3,0)_{\rm L}$ $(1,1,-6,0,+6)_{\rm L}$	$(1,0,+6,+2,0)_{\rm L}$ $(1,0,-6,-2,0)_{\rm L}$

- no anomalous *U(1)* gauge symmetry
- no *SU(2)* family symmetry

summary

- We showed E_6 unification is attractive
- We clarified how to realize the minimal requirements in heterotic string.
- We find a $\mathbb{Z}_{12}$ action, missed in the literature
  - ⇨ 3 three-generation models
    - one w/ same spectrum as the known one
    - one w/o non-Abelian hidden gauge
    - one to be added in the classification
- future works
  - *SU(2)* family symmetry
  - anomalous *U(1)* gauge symmetry, charged adjoint

hope for further models