Majorana neutrino mass matrices induced by rigid E-brane instantons

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… based on the collaboration with

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Neutrino oscillation

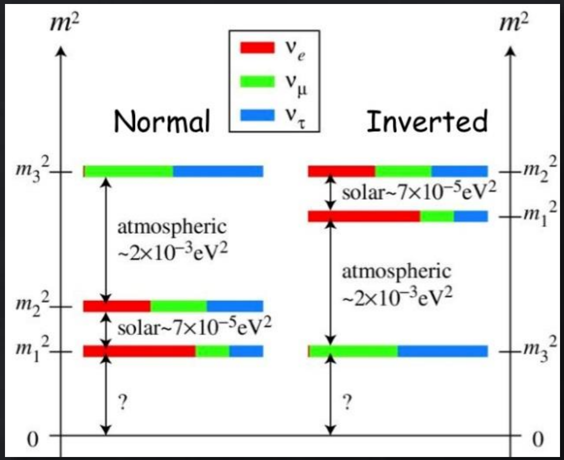
- **Neutrinos have non-vanishing masses,**

… pics from web

$$\Delta m_{21}^2 = 7.62 \times 10^{-5} \quad [\mathrm{eV}^2]$$

$$|\Delta m_{31}^2| = 2.457 \times 10^{-3} \quad [\mathrm{eV}^2]$$

[Gonzalez-Garcia, Maltoni, Schwetz, 16]



- **non-vanishing mixing angles,**

$$\sin^2\theta_{12} = 0.259 - 0.359$$

$$\sin^2\theta_{23} = 0.380 - 0.628$$

$$\sin^2\theta_{13} = 0.0176 - 0.0295$$

[Gonzalez-Garcia, Maltoni, Schwetz, 16]

$$V_{\mathrm{PMNS}} = \begin{pmatrix} 0.82 & 0.55 & 0.16 \\ 0.51 & 0.58 & 0.64 \\ 0.26 & 0.61 & 0.75 \end{pmatrix}$$

Two big issues in neutrinos

Two big issues in neutrinos

- ***What is an origin of large mixing angles ?***

  … discrete flavor symmetries

- ***Why neutrino masses are so tiny ?***

  … seesaw mechanism

!

- **Introduction**
- **Reviews**
  - **Discrete flavor symmetries**
  - **Seesaw mechanism**
- **Our results**
  - **Z_2-symmetric Majorana mass matrices**

… Today's contents

Mixing patterns

- Before 2012, there were well-known mixing patterns in lepton PMNS matrix.
  - Tri-bimaximal (TBM) mixing *[Harrison, Perkins, Scott, 02]*

$$V_{\mathrm{TBM}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

$$\theta_{13} = 0, \quad \theta_{23} = 45^\circ$$
$$\theta_{12} = 35.26^\circ$$

Three elements are maximally mixing.

Two elements are maximally mixing.

  - Bimaximal (BM) mixing *[Vissani, 97]*

$$V_{\mathrm{BM}} = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ -1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & -1/2 & 1/\sqrt{2} \end{pmatrix}$$

$$\theta_{13} = 0, \quad \theta_{23} = 45^\circ$$
$$\theta_{12} = 45^\circ$$

Two elements are maximally mixing.

Discrete flavor symmetries

- **In theoretical model-buildings, discrete symmetries have been used to construct phenomenological models.**
- **In particular, before 2012, discrete symmetries in the SM charged-leptons and neutrinos were used to realize realistic patterns of lepton mixing angles.**
- **Indeed, some discrete (flavor) symmetries can lead to TBM and BM mixing patterns,**

$$S_3, D_4, S_4, A_4, \Delta(27), \ldots$$

e.g., [Ishimori, Kobayashi, Ohki, Shimizu, Okada, Tanimoto, 12]
[King, Merle, Morisi, Shimizu, Tanimoto, 14]

Discrete flavor symmetries (cont'd)

- ***e.g.***, consider residual discrete symmetries,
  - Z_3 in charged-leptons

$$[C, M_l M_l^\dagger] = 0 \qquad C = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$

… element of Z_3 group

  - $Z_2 \times Z_2$ in neutrinos

$$[P, M_\nu] = [P', M_\nu] = 0 \qquad P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \qquad P' = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{pmatrix}$$

… elements of Z_2 groups

Then, these mass matrices lead to TBM mixing,
i.e., $V_{\mathrm{PMNS}} = U_l U_\nu^\dagger = V_{\mathrm{TBM}}$.

- Of course, TBM and BM are gone. Hence, people have studied some extension models.

e.g., [Shimizu, Tanimoto, 15]

(Type I) Seesaw mechanism

- On the other hand, what is an origin of tiny neutrino masses ?

- We assume heavy right-handed Majorana masses.

[Minkowski, 77; Gell-Mann, Ramond, Slansky; Yanagida; Glashow; Mohapatra, Senjanovic, 79]

$$\mathcal{L} \supset \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

Dirac masses

right-handed Majorana mass

$$\rightarrow \quad M_\nu = M_D M_R^{-1} M_D^T$$

… pic from web

Even if $M_D \sim 10^2$ [GeV], $M_R \sim 10^{13}$ [GeV] leads to tiny neutrino masses, $M_\nu \sim \mathcal{O}(1)$ [eV].

Purpose of my talk

- ❑ **Discrete symmetries: still attractive for realizing lepton mixing angles**
- ❑ **Right-handed Majorana masses: very important to obtain light neutrinos**

$$M_\nu = M_D M_R^{-1} M_D^T$$

??

- ❑ **We would like to show …**

what discrete symmetries appear
in Majorana masses,
based on stringy model-buildings

String theory and D-branes

❑ Open and closed strings

… pics from Ibanez and Uranga's textbook

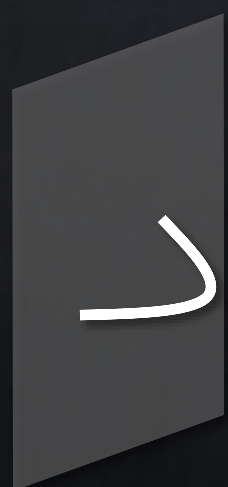
including graviton
… beyond this talk

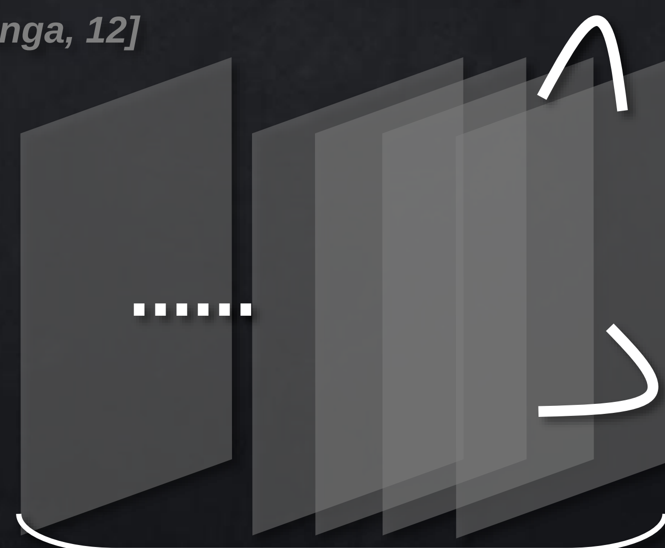
❑ D-branes

… hypersurface on which open strings end

c.f., [Ibanez, Uranga, 12]

NS sector :
$\psi^{\mu}_{-1/2}|0\rangle$
R sector :
$|8_C\rangle$





N sheets

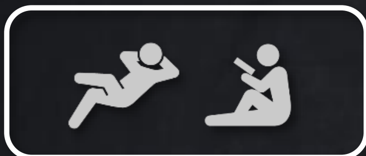
… U(1) vector field
(with U(1) gaugino)

… U(N) vector field
(with U(N) gaugino)

Intersecting D-branes

❑ Generations

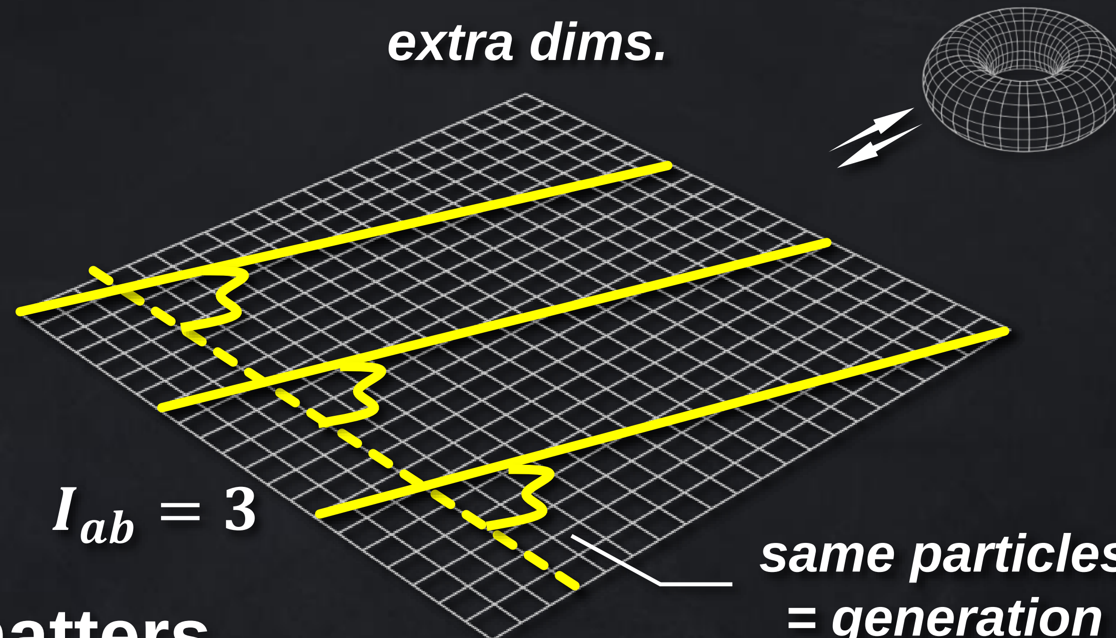
4D spacetime



We are here.

$\otimes$

extra dims.



$I_{ab} = 3$

same particles
= generation

c.f., [Ibanez, Uranga, 12]

❑ Bi-fundamental matters

N_a *D-branes*

$(N_a, \bar{N}_b)$ *repr. bi-fundamental supermultiplet(s)*

c.f., [Ibanez, Uranga, 12]

N_b *D-branes*

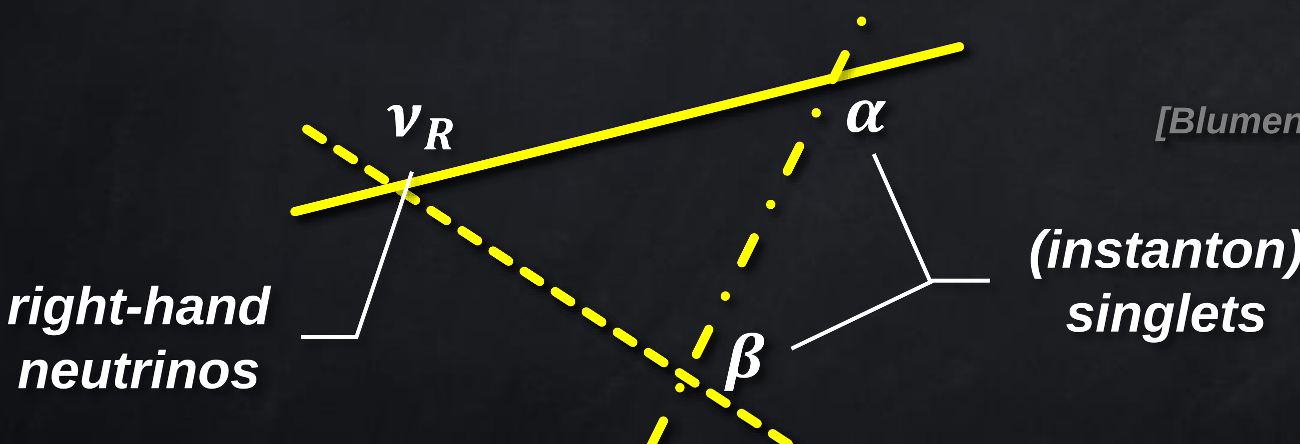
We can obtain desired bi-fundamentals and generations.

E-brane instantons

- **E-branes** *… D-branes wrapping only on extra dims.*
  - **The degeneracy and representation of matters are the same as those of D-branes.**

- **E-branes can induce the Majorana masses.**

[Ibanez, Uranga, 07]
[Blumenhage, Cvetic, Weigand, 07]



$$M_s e^{-V} \int d^2\alpha\, d^2\beta\, e^{-c_a^{ij}\alpha_i \nu_R^a \beta_j} = M_s e^{-V} \sum_{a,b} c_{ab}\, \nu_R^a \nu_R^b$$

string scale

E-brane instantons

- **E-branes** *... D-branes wrapping only on extra dims.*
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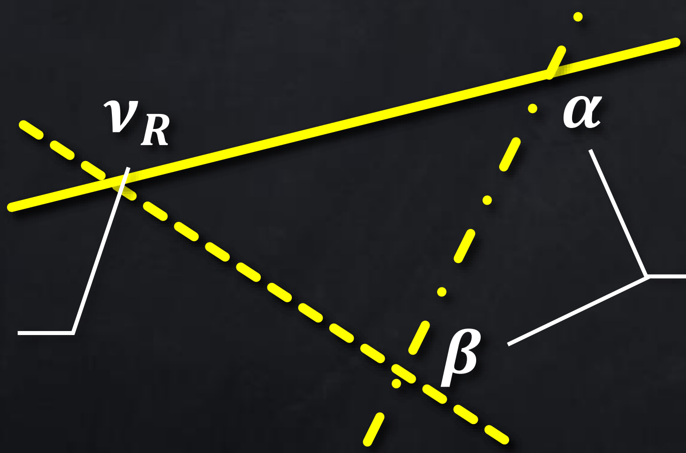


right-hand neutrinos

(instanton) singlets

Majorana mass matrix

$$= M_R$$

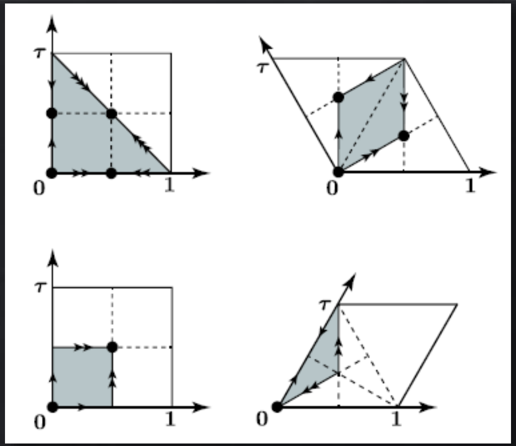
$$M_s e^{-V}\int d^2\alpha\, d^2\beta\, e^{-c_a^{ij}\alpha_i \nu_R^a \beta_j} = M_s e^{-V}\sum_{a,b} c_{ab}\, \nu_R^a \nu_R^b$$

string scale

Rigid cycles

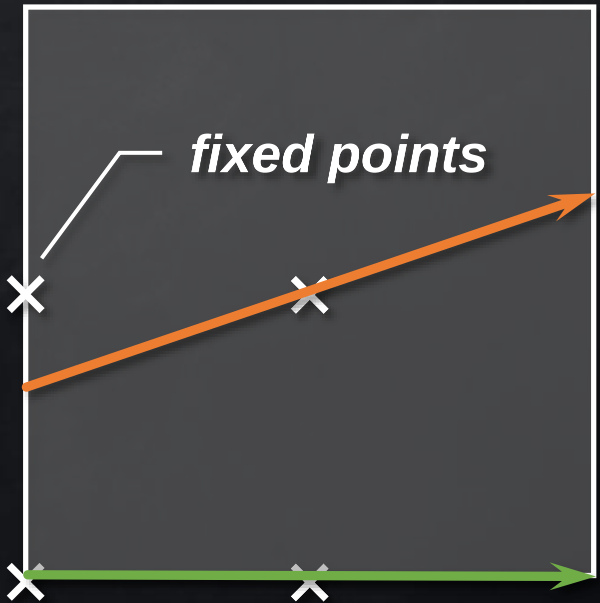
- Z_N orbifolds

$$z \sim z + 1 \sim z + \tau$$
$$z \sim \omega z \quad (\omega \equiv e^{2\pi i/N})$$



… pic from [Abe, Fujimoto, Kobayashi, Miura, Nishiwaki, Sakamoto, 14]

- Rigid cycles
  - new class of model-building
  - eliminating the exotic modes
  - … etc

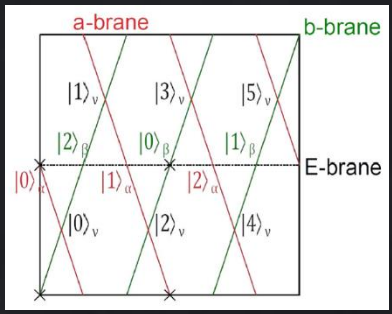


! ***We consider the case of $T^2/Z_2 \times Z_2$ orbifold.***

Properties in Majorana mass matrices

❑ **Example 1:** ***(approx.) bimaximal***

$$M_R \propto \begin{pmatrix} 2y_0y_2 & -y_1^2 & y_0^2+y_2^2 \\ -y_1^2 & -2y_1(y_0+y_2) & -y_1^2 \\ y_0^2+y_2^2 & -y_1^2 & 2y_0y_2 \end{pmatrix} = \begin{pmatrix} A & B & C \\ B & D & B \\ C & B & A \end{pmatrix}$$



… Ex 1

where,

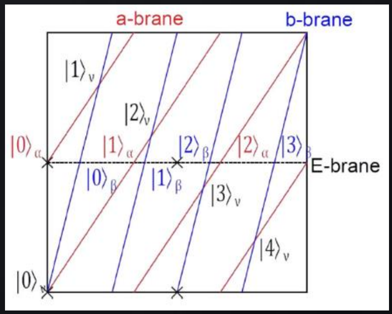
$$y_0 = \vartheta\begin{bmatrix}1/12\\0\end{bmatrix}(0, 6\pi i\mathcal{A}/\alpha'), \qquad y_1 = \vartheta\begin{bmatrix}3/12\\0\end{bmatrix}(0, 6\pi i\mathcal{A}/\alpha'), \qquad y_2 = \vartheta\begin{bmatrix}5/12\\0\end{bmatrix}(0, 6\pi i\mathcal{A}/\alpha')$$

Different configurations of D- and E-branes lead to different coefficients, c_{ab}.

$$(M_R)_{ab}\nu_R^a V_R^b = M_s e^{-V}\sum_{a,\,b} c_{ab}\nu_R^a\nu_R^b$$

❑ **Example 2:** ***Z_2 symmetric***

$$M_R \propto \begin{pmatrix} y_0y_1 & -y_0^2/4 & -y_0^2/4 \\ -y_0^2/4 & y_1^2/2 & y_1^2/2 \\ -y_0^2/4 & y_1^2/2 & y_1^2/2 \end{pmatrix} = \begin{pmatrix} A' & B' & B' \\ B' & C' & C' \\ B' & C' & C' \end{pmatrix}$$



… Ex 2

Numerical analysis in example 1

- We assume $M_S \simeq 10^{16}$ [GeV] and $(M_S/M_C)^2 \simeq 0.6$ in Example 1. Then, neutrino Dirac mass matrices are calculable.

Observables	Example 1	Observed values
$(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$ [eV]	(0.017,0.018,0.052)	< 2.0
$\lvert m_{\nu_2}^2 - m_{\nu_1}^2 \rvert$ [eV^2]	4.8×10^{-5}	7.62×10^{-5}
$\lvert m_{\nu_3}^2 - m_{\nu_2}^2 \rvert$ [eV^2]	2.4×10^{-3}	2.55×10^{-3}
$\sin^2\theta_{12}$	0.341	0.259–0.359
$\sin^2\theta_{23}$	0.758	0.380–0.628
$\sin^2\theta_{13}$	0.0212	0.0176–0.0295

θ_{23} is so large.

The other observables are almost OK.

We need contributions to Majorana masses.

- Majorana mass matrices induced by E-brane instantons are promising as rough sketches.
- However, the Majorana matrices can not realize realistic value of θ_{23}.

We need some contributions to (approx.) bimaximal or Z_2 symmetric cases.

- *for example,*
  - *contribution from non-diagonal mass matrix in charged-leptons*

Summary

- **We have investigated (right-handed) Majorana mass matrices in seesaw models.**
- **Such Majorana mass matrices possess bimaximal or Z_2 symmetric structures, which reflect on a topology of (compact) extra dimensions.**

- **General messages:**
  - **T^2/Z_3 and T^2/Z_6 are interesting, because then both of Dirac and Majorana masses would be Z_2 and/or Z_3 symmetric.**
  - **Extra dimensions can help model-buildings for flavor symmetric models.**