String Phenomenology

Tatsuo Kobayashi

1. Introduction
2. Heterotic models
3. D-brane models
4. Effective theory (gauge/Yukawa couplings)
5. Moduli stabilization and SUSY breaking
6. Summary

1. Introduction
1-1. Introduction to string phenomenology

Superstring theory ： a candidate of unified theory
including gravity

Important issue: (if it is really relevant to particle physics)

Superstring → the 4D Standard Model of particle physics
including values of parameters （@ low energy）

Problem：

There are innumberable 4D string vacua (models)

← Study on nonperturbative aspects to lift up many vacua
and/or to find out a principle leading to a unique vacuum

← Study on particle phenomenological aspects of
already known 4D string vacua

String phenomenology

String phenomenology

Which does class of string models lead to realistic aspects of particle physics ？

We do not need to care about string vacua without leading to e.g.

the top quark mass ＝ １７４ GeV

the electron mass ＝ ０．５ MeV,

no matter how many vacua exist.

Let's study whether we can construct 4D string vacua really relevant to our Nature.

String phenomenology

Superstring ： theory around the Planck scale

SUSY ？

GUT ？

？？？？？ Several scenario ？？？？？？

Standard Model ： we know it up to 100 GeV

Superstring → low energy ？ （top-down）

Low energy → underlying theory ？ （bottom-up）

Both approaches are necessary to connect between underlying theory and our Nature.

1-2. Standard Model

Gauge bosons

SU(3)、 SU(2)、 U(1)

parameters: three gauge couplings

Quarks, Leptons 3 families

hierarchical pattern of masses (mixing)

← Yukawa couplings to the Higgs field

Higgs field

the origin of masses

not discovered yet

our purpose “derivation of the SM”

⇒ realize these massless modes and coupling values

Low energy SUSY

Gauge bosons SU(3)、 SU(2)、 U(1)

3 families of Quarks, Leptons

Higgs scalar

their superpartners may appear

Their masses

← Prediction of a specific 4D string model

(with a certain SUSY breaking scenario)

Gauge couplings

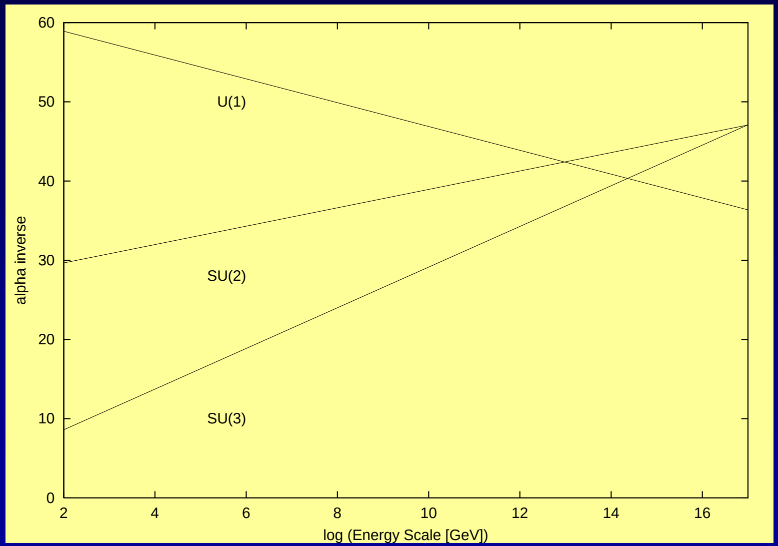
experimental values

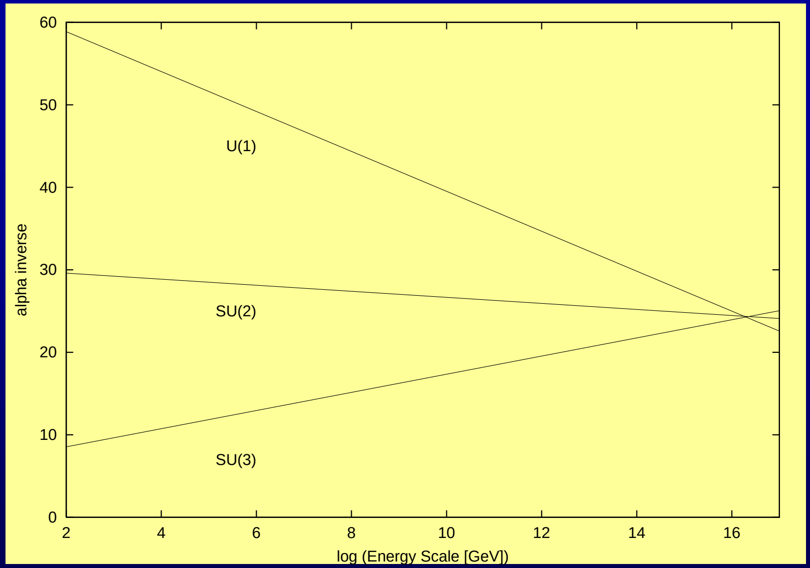
RG flow ⇒

They approach each other and become similar values at high energy

In MSSM, they fit each other in a good accuracy

Gauge coupling unification





Quark masses and mixing angles

$$M_t = 174 \quad GeV, \qquad M_b = 4.3 \quad GeV$$
$$M_c = 1.2 \quad GeV, \qquad M_s = 117 \quad MeV$$
$$M_u = 3 \quad MeV, \qquad M_d = 6.8 \quad MeV$$

$$V_{us} = 0.22, \qquad V_{cb} = 0.04, \qquad V_{ub} = 0.004$$

These masses are obtained by Yukawa couplings to the Higgs field with VEV, v＝175GeV.

strong Yukawa coupling ⇒ large mass

weak ⇒ small mass

top Yukawa coupling =O(1)

other quarks ← suppressed Yukawa couplings

Lepton masses and mixing angles

$$M_e = 0.5 \quad MeV, \qquad M_\mu = 106 \quad MeV$$

$$M_\tau = 1.8 \quad GeV,$$

mass squared differences and mixing angles consistent with neutrino oscillation

$$\Delta M_{21}^2 = 8 \times 10^{-5} \quad eV^2, \qquad \Delta M_{31}^2 = 2 \times 10^{-3} \quad eV^2$$

$$\sin^2 \theta_{12} = 0.3, \qquad \sin^2 \theta_{23} = 0.5, \qquad \sin^2 \theta_{13} = 0.0,$$

large mixing angles

Cosmological aspects

Cosmological constant (Dark energy)

Dark matter

Inflation

…………………………………

1-3. Superstring theory

⇒ predict 6 extra dimensions
in addition to our 4D space-times

Compact space (background)、D-brane configuration、...
← constrained by string theory
(modular invariance, RR-charge cancellation,...)

Once we choose background, all of modes can be investigated in principle (at the perturbative level).

⇒ Massless modes, which appear in low-energy effective field theory, are completely determined.

Oscillations and momenta in compact space correspond to quantum numbers of particles in 4d theory.

It is not allowed to add/reduce some modes by hand.

4D string models

4D Chiral theory ⇒ N=0, 1 SUSY

N=0 theory

Tachyonic modes often appear.

instable vacuum

We often start with N=1 theory,

although this is not necessary.

(N=0 theory with tachyonic modes is fine.)

(low energy SUSY ← hierarchy problem)

Several string models

(before D-brane) 1st string revolution

Heterotic models on Calabi-Yau manifold, Orbifolds,

fermionic construction,

Gepner, ...

(after D-brane) 2nd string revolution

Intersecting D-brane models

Magnetized D-branes, ...

Phenomenological aspects

Massless modes ⇒ section 2, 3

gauge bosons (gauge symmetry),
matter fermions, higgs bosons,
moduli fields, ...

Their action ⇒ section 4

gauge couplings, Yukawa couplings, ...
Kahler potential (kinetic terms)
(discrete/flavor) symmetry, ...

moduli stabilization, SUSY breaking, ⇒ section 5

soft SUSY breaking terms,
cosmology, ...

2. Heterotic models

2-1. Heterotic theory (closed string)

Right-mover: 10D Superstring X, ψ $\quad X \Longleftrightarrow \psi$

Left-mover : 26D bosonic string X

10D L-R common dimension

→ space-time dimension

$$X^{\mu}(\tau,\sigma) = x^{\mu} + \alpha' p^{\mu}\tau + (oscillators)$$

The other 16D L-mover

→ gauge part, which is assumed to be compactified on E8 x E8 torus or SO(32) torus

$$X^{I}(\sigma-\tau) = x^{I} + (\alpha'/2)p^{I}(\sigma-\tau) + (oscillators)$$

$$p^{I} = \underline{(\pm1,\pm1,0,0,0,0,0,0)}(0,0,0,0,0,0,0,0)$$

$$= (\pm1/2,\pm1/2,\ldots\ldots)(0,0,0,0,0,0,0,0)$$

$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$

Massless modes of 10D het. theory

graviton, dilaton,

anti-symmetric tensor $\left| p^t = (\underline{\pm 1, 0, 0, 0}) \right\rangle_R \otimes \overline{\alpha^i_{-1}} \left| 0 \right\rangle_L$

gravitino, dilatino $\left| p^t = (\pm 1/2, \pm 1/2, \ldots) \right\rangle_R \otimes \overline{\alpha^i_{-1}} \left| 0 \right\rangle_L$

Gauge bosons $\left| p^t = (\underline{\pm 1, 0, 0, 0}) \right\rangle_R \otimes \left\{ \alpha^I_{-1} \left| 0 \right\rangle_L, \left| (P^I)^2 = 1 \right\rangle_L \right\}$

gaugino $\left| p^t = (\pm 1/2, \pm 1/2, \ldots) \right\rangle_R \otimes \left\{ \alpha^I_{-1} \left| 0 \right\rangle_L, \left| (P^I)^2 = 1 \right\rangle_L \right\}$

→ 10D N=1 supergravity + (E8 x E8) SYM

or SO(32) SYM

no chiral matter

2-2. Orbifold

Torus compactification 4D N=4 SUSY

We need compactification leading to chiral theory,
e.g. N=1 theory with chiral matter fields.

Such compactification are
Calabi-Yau, orbifold,......
String on the orbifold background can be solved.
⇒ Any stringy perturbative calculations are possible in principle.

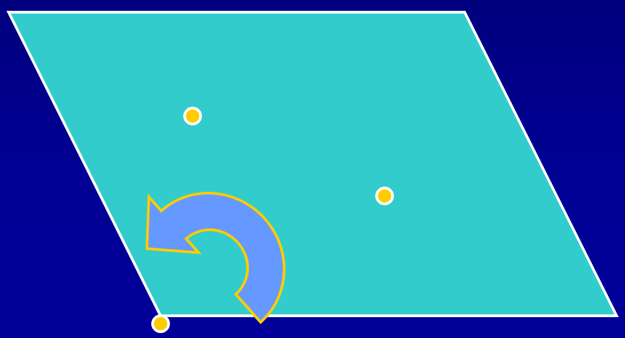
Examples of orbifolds

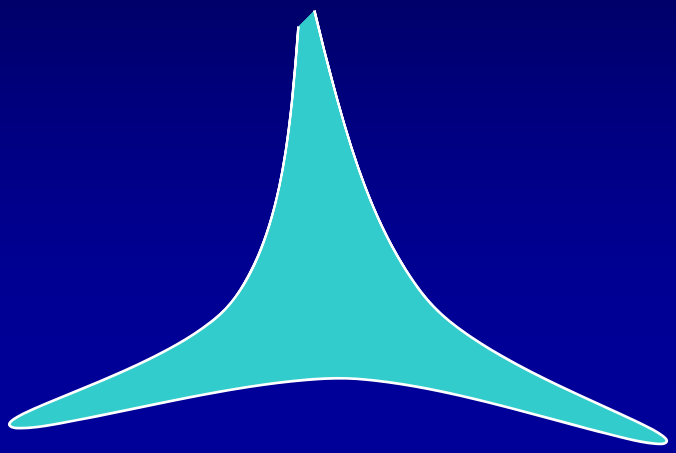
S1/Z2 Orbifold

There are two singular points, which are called fixed points.

Orbifolds

T2/Z3 Orbifold





There are three fixed points on Z3 orbifold

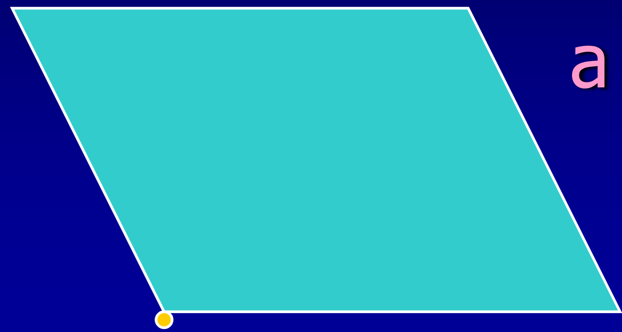
(0,0), (2/3,1/3), (1/3,2/3)   su(3) root lattice

Orbifold = D-dim. Torus /twist

Torus = D-dim flat space/ lattice

2D Z6 orbifold and fixed points

First twisted states T1

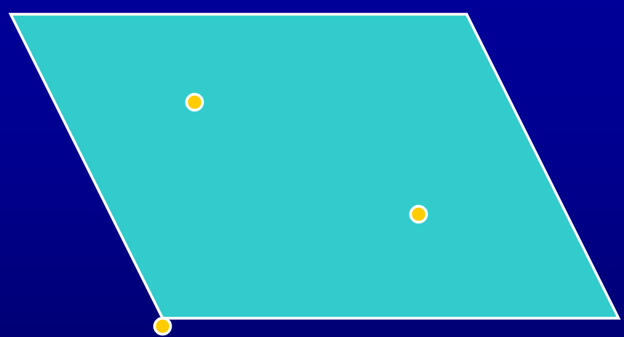


a single fixed point (0,0)

$$(\Theta, 0)$$

$$(1-\Theta)\Lambda = \Lambda$$

Second twisted states T2

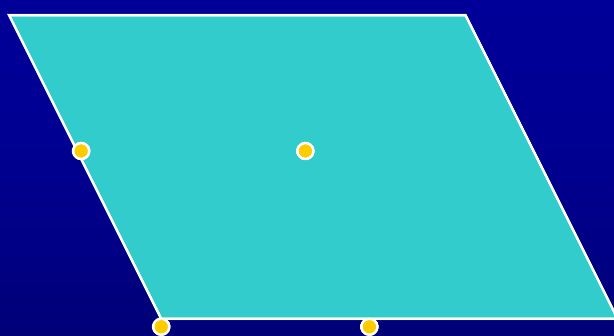


(0,0), (2/3,1/3), (1/3,2/3)

$$(\Theta, ke_1) \qquad k = 0,1,2$$

$$(1-\Theta)\Lambda = \{e_1 - e_2, 3e_1\}$$

third ones T3



(0,0), (1/2,0),(1/2,1/2)(0,1/2)

$$(\Theta, me_1 + ne_2) \qquad m, n = 0,1$$

$$(1-\Theta)\Lambda = \{2e_1, 2e_2\}$$

6D orbifold

Some of 6D orbifolds can be constructed by direct products of 2D orbifolds, e.g.

6D Z_6-II orbifold = a product of Z_6, Z_3 and Z_2

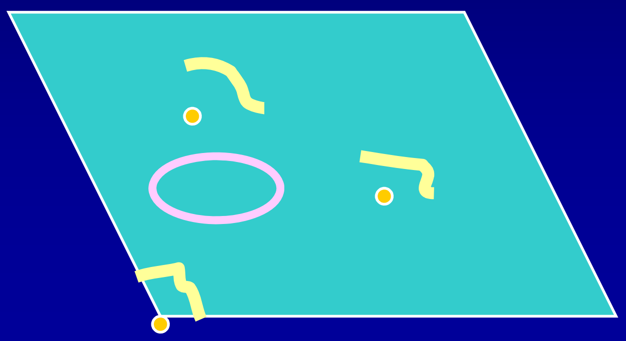
$v=(1, 2, -3)/6$ → D=4 N=1 SUSY

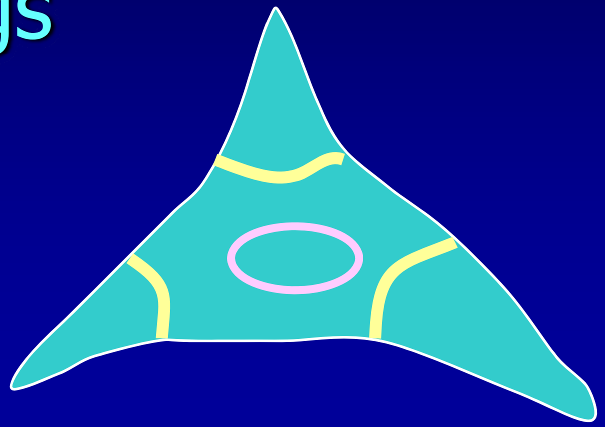
There are other types of orbifolds leading to D=4 N=1 SUSY.

Also, there are orbifolds leading to D=4 N=2 and N=0 SUSY.

Closed strings on orbifold

Untwisted and twisted strings





Twisted strings are associated with fixed points.

"Brane-world" terminology:

untwisted sector   bulk modes

twisted sector   brane (localized) modes

Twisted string

$$X(\sigma=\pi)=\Theta X(\sigma=0)+e$$

→ Center of mass : fixed point

Mode expansions are different from those for periodic boundary condition

oscillator number N

N = integer → integer − 1/M for Z_M

intercept (zero-point energy) also differs

Gauge symmetry breaking

Unbroken E8 is too large

We break the gauge group E8xE8

$\leftarrow$ (gauge) background fields, Wilson line

Modular invariance

Background fields

$\Rightarrow$ resolve degeneracy of massless spectra

on different fixed points.

Explicit Z6-II model: Pati-Salam

T.K. Raby, Zhang '04

4D massless spectrum

$$6V = (22200000)(11000000)$$

$$3W_3 = (1-1000000)(00200000)$$

$$2W_5 = (10000111)(00000000)$$

Gauge group $SU(4)\times SU(2)\times SU(2)\times SO(10)'\times SU(2)'\times U(1)^5$

Chiral fields

$U_1 : (4,2,1),\quad U_2 : (1,2,2)\quad U_1 : (4,1,2)+(\bar{4},1,2)$

$T_1 : 2(4,2,1)+2(\bar{4},1,2)+4(4,1,1)+4(\bar{4},1,1)+8(1,2,1)+8(1,1,2)+2(1,1,2;1,2)$

$T_2 : 2(\bar{4},1,2)+(6,1,1),\quad T_3 : 6(6,1,1)+6(1,2,2),\quad T_4 : (4,1,2)+2(6,1,1)$

Pati-Salam model with 3 generations + extra fields

All of extra matter fields can become massive

Pati-Salam (GUT) model

Gauge group

SU(4)xSU(2)xSU(2)

$\Rightarrow$ SU(3)xSU(2)xU(1)

Matter fields

(4,2,1) $\Rightarrow$ (3,2,1) left-handed quark

(1,2,1) left-handed lepton

(4,1,2) $\Rightarrow$ (3,1,1) up-sector of r-handed quark

(3,1,1) down-sector of r-handed quark

(1,1,1) right-handed charged lepton

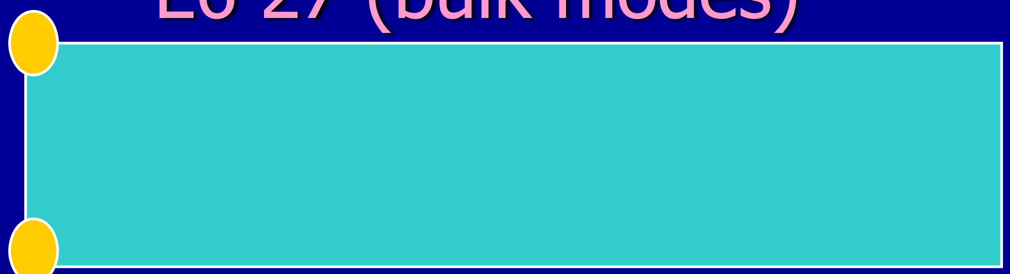
(1,1,1) right-handed neutrino

(1,2,2) $\Rightarrow$ 2x(1,2,1) up, down sector higgs

Heterotic orbifold as brane world

2D Z2 orbifold

E6 27 (bulk modes)



V2 shift　　T2/Z2　　(V2+W2) shfit

SO(10)　　　　SU(6) $*$ SU(2)

unbroken　SU(4) $*$ SU(2) $*$ SU(2)

bulk 27 ⇒ (4,2,1) + (4*,1,2)+...

SO(10) brane 16 ⇒ (4,2,1) + (4*,1,2)

Explicit Z6-II model: MSSM

Buchmuller,et.al. '06, Lebedev, et. al '07

4D massless spectrum

Gauge group $SU(3) \times SU(2) \times U(1)_Y \times G_H$

Chiral fields

3 generations of MSSM + extra fields

All of extra matter fields can become massive along flat directions

There are O(100) models.

Flat directions

realistic massless modes + extra modes
with vector-like rep.

Effective field theory has flat directions.

VEVs of scalar fields along flat directions

⇒ vector-like rep. massive, no extra matter

Such VEVs would correspond to deformation of orbifolds like blow-up of singular points.

That is CY
(as perturbation around the orbifold limit).

Short summary on massless spectra

Once we choose a background(orbifold, gauge shift, wilson lines), a string model is fixed and its full massless spectrum can be analyzed in principle.

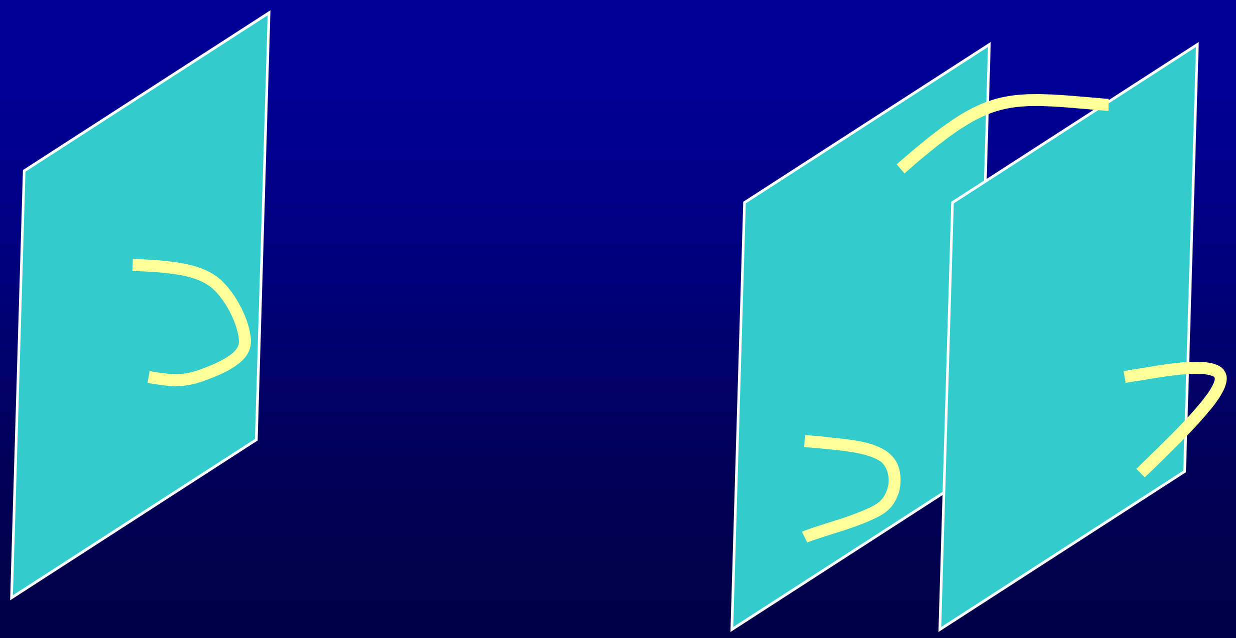
We have 4D string models, whose massless spectra realize the SM gauge group + 3 families（＋extra matter) and its extensions like the Pati-Salam model.

Similar situation for other compactifications

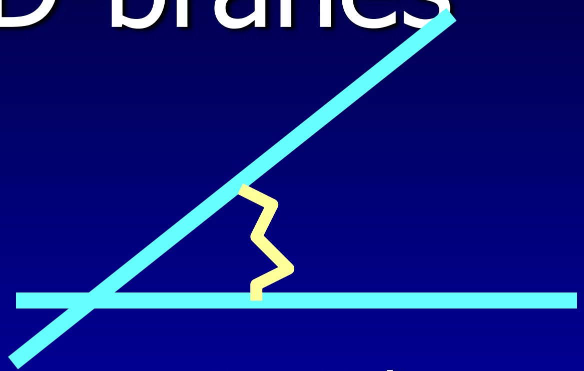
3. Intersecting/magnetized D-brane models

gauge boson: open string, whose two end-points are on the same (set of) D-brane(s)

N parallel D-branes ⇒ U(N) gauge group



3.1 Intersecting D-branes



Where is matter fields ?

New modes appear between intersecting D-branes.
They have charges under both gauge groups, i.e. bi-fundamental matter fields.
boundary condition

$$X^2(\sigma = 0) = 0, \quad \partial_\sigma X^1(\sigma = 0) = 0$$

$$X^1(\sigma = \pi)\tan\theta\pi + X^2(\sigma = \pi) = 0,$$

$$\partial_\sigma X^1(\sigma = \pi) - \partial_\sigma X^2(\sigma = \pi)\tan\theta\pi = 0$$

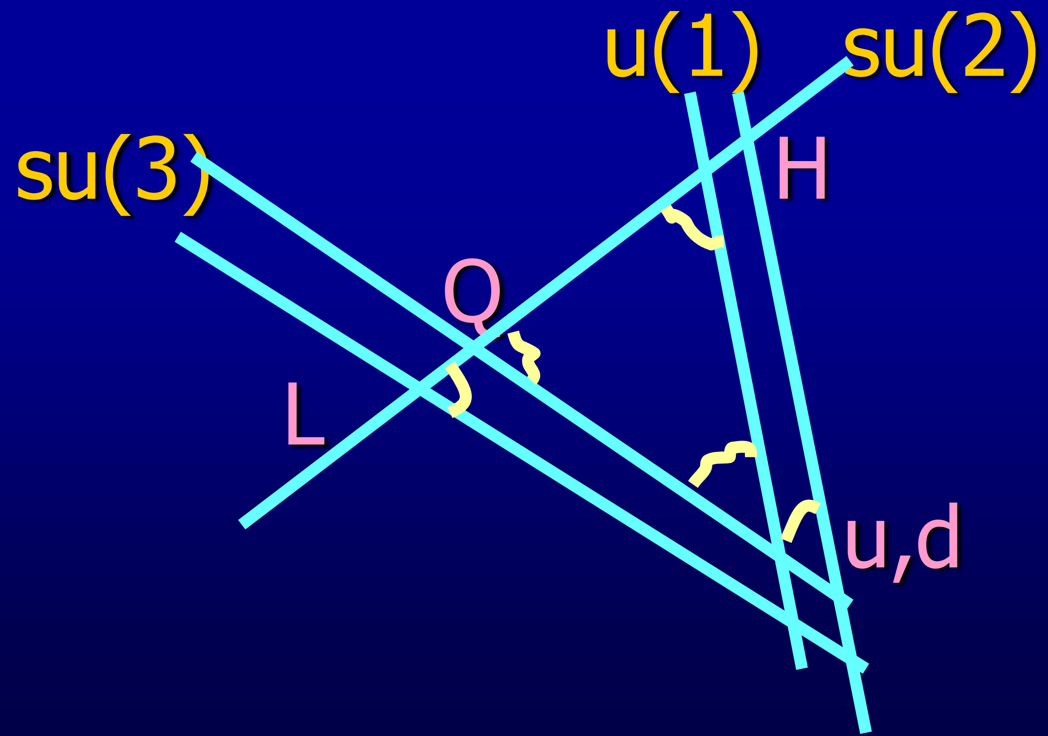
Twisted boundary condition

Toy model (in uncompact space)

gauge bosons : on brane

quarks, leptons, higgs :

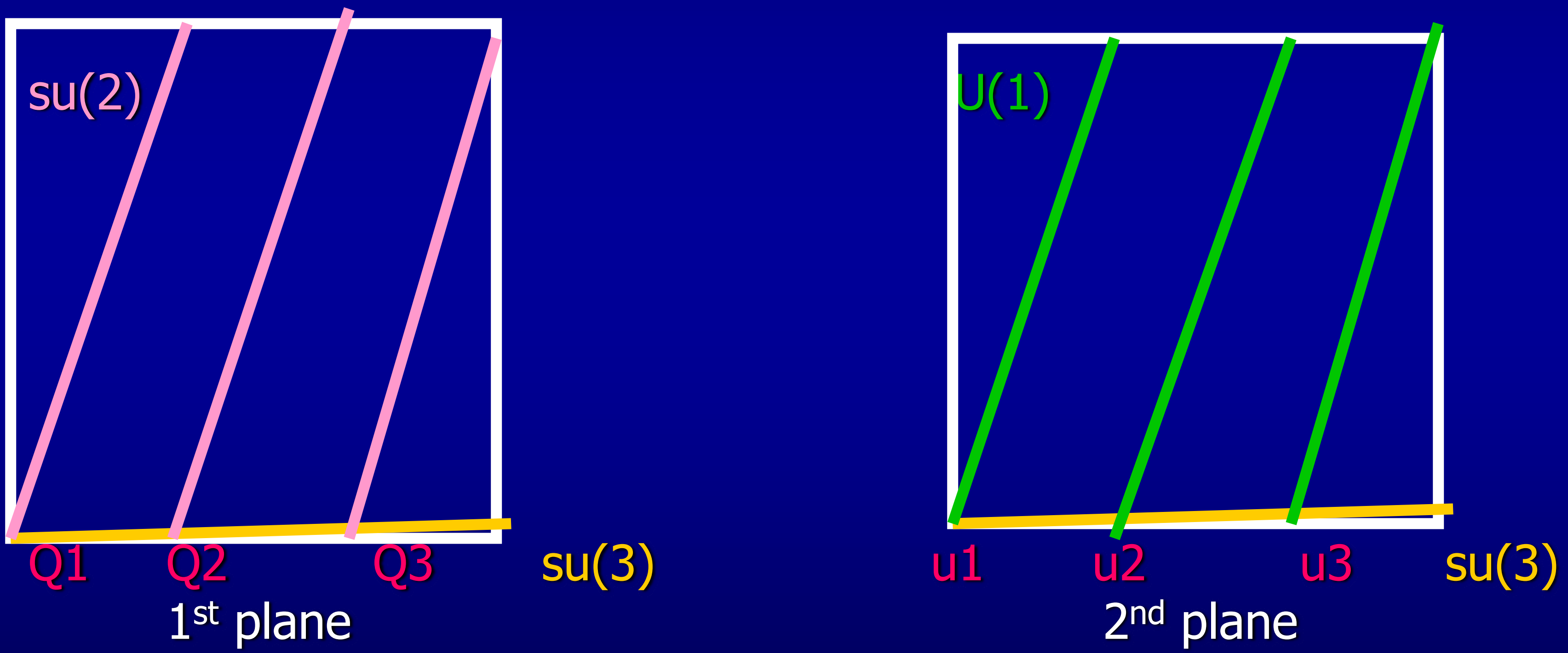
localized at intersecting points



Generation number

compactification

Family number = intersection number



Short summary on massless spectra

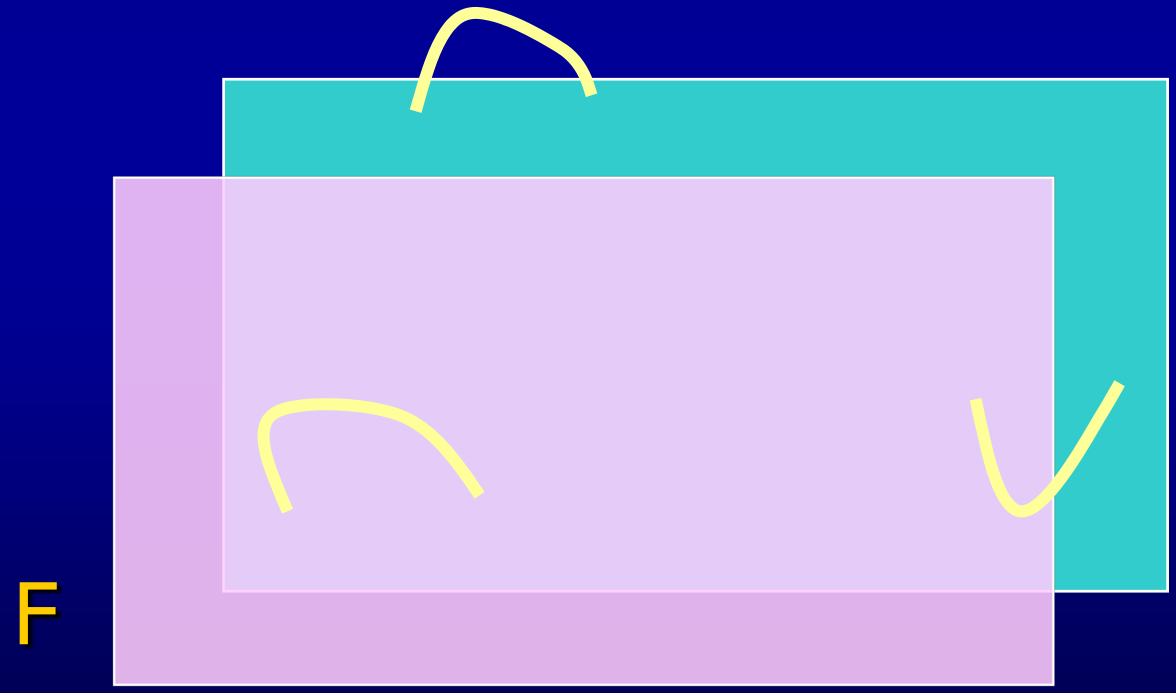
We have 4D string models, whose massless spectra realize
the SM gauge group + 3 families (+extra matter)
and its extensions like the Pati-Salam model.

gauge bosons: (p+1)-dim modes
matter : localized modes on intersecting points (not fixed points)

Similar situation in other models with D-branes, like magnetized D-brane models

3-2. Magnetized D-branes

We consider torus compactification
with magnetic flux background.



Boundary conditions on magnetized D-branes

$$\partial_\sigma X^4 + F_{45}\partial_\tau X^5 = 0,$$
$$F_{45}\partial_\tau X^4 - \partial_\sigma X^5 = 0,$$

similar to the boundary condition of open string between intersecting D-branes

T-dual

$U(N_a) \times U(N_b) \times U(N_c)$ **Models in** $T_1^2 \times T_2^2 \times T_3^2$

$$F_{45,67,89} = 2\pi \begin{pmatrix} M_a \mathbf{1}_{N_a \times N_a} & 0 & 0 \\ 0 & M_b \mathbf{1}_{N_b \times N_b} & 0 \\ 0 & 0 & M_c \mathbf{1}_{N_c \times N_c} \end{pmatrix}_{45,67,89} .$$

Total number of zero-modes of ⇨ $I_{ab} = \prod_{i=1}^{3} |M_a - M_b|_i .$

This class of models include the Pati-Salam model for

$N_a = 4, \ N_b = 2, \ N_c = 2$ $(SU(4) \times SU(2)_L \times SU(2)_R)$

- a-b $\cdots$ ψ_L
- c-a $\cdots$ ψ_R
- b-c $\cdots$ H

Higher Dimensional SYM theory with flux

4D Effective theory <= dimensional reduction

$$\mathcal{L}_{SYM} = -\frac{1}{4g^2} Tr\{F^{MN}F_{MN}\} + \frac{i}{2g^2} Tr\{\bar{\lambda}\Gamma^M D_M \lambda\}$$

$$\begin{aligned} \lambda(x^\mu, y^m) &= \sum_n \chi_n(x^\mu) \times \psi_n(y_m), \\ A_M(x^\mu, y^m) &= \sum_n \varphi_{n,M}(x^\mu) \times \phi_{n,M}(y_m) \end{aligned}$$

$$\begin{aligned} i\Gamma_m D^m \psi_n(y) &= m_n \psi_n, \\ \Delta_6 \phi_{n,M}(y) &= M^2_{n,M} \phi_{n,M} \end{aligned}$$

The wave functions ⟶ eigenstates of corresponding internal Dirac/Laplace operator.

$$\psi = \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}, \quad \Gamma^4 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \Gamma^5 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

Field-theoretical analysis

Zero-modes Dirac equations

$$\begin{pmatrix} \bar{\partial}\psi_+^{aa} & \left[\bar{\partial} + 2\pi(M_a - M_b)y_4\right]\psi_+^{ab} \\ \left[\bar{\partial} + 2\pi(M_b - M_a)y_4\right]\psi_+^{ba} & \bar{\partial}\psi_+^{bb} \end{pmatrix} = 0.$$

$$\begin{pmatrix} \partial\psi_-^{aa} & \left[\partial - 2\pi(M_a - M_b)y_4\right]\psi_-^{ab} \\ \left[\partial - 2\pi(M_b - M_a)y_4\right]\psi_-^{ba} & \partial\psi_-^{bb} \end{pmatrix} = 0.$$

No effect due to magnetic flux for adjoint matter fields, λ^{aa} and λ^{bb}

Total number of zero-modes of λ^{ab} ⇨ $I_{ab} = |M_a - M_b|.$

$M_a - M_b > 0 \Rightarrow$

ψ_+^{ab}, ψ_-^{ba} :Normalizable mode

ψ_-^{ab}, ψ_+^{ba} :Non-Normalizable mode

Dirac equation and chiral fermion

|M| independent zero mode solutions in Dirac equation.

$$\Theta^j(y_4, y_5) = N_j e^{-M\pi y_4^2} \cdot \vartheta \begin{bmatrix} j/M \\ 0 \end{bmatrix} (M(y_4 + iy_5), Mi)$$

$$(j = 0, 1, \cdots, |M| - 1)$$

$$\vartheta \begin{bmatrix} a \\ b \end{bmatrix} (\nu, \tau) \equiv \sum_n e^{\pi i (n+a)^2 \tau} e^{2\pi (a+n)(\nu+b)}$$

(Theta function)

chiral fermion

$M \gtrless 0 \Rightarrow$ $\psi_{+/-}$:Normalizable mode

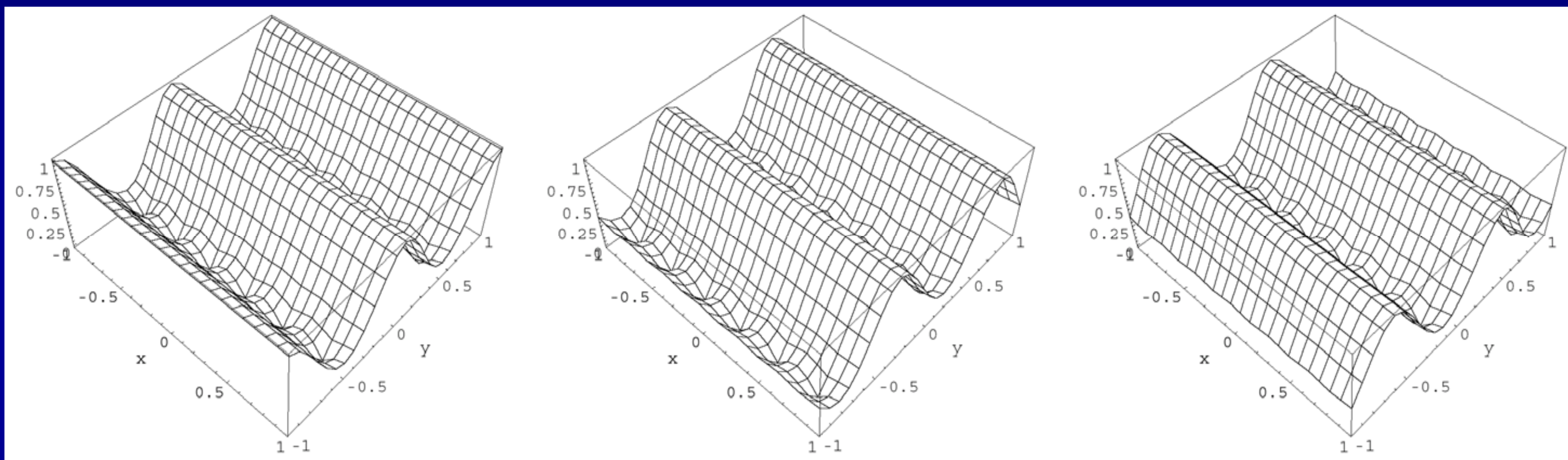
$\psi_{-/+}$:Non-normalizable mode

By introducing magnetic flux, we can obtain chiral theory.

Wave functions

For the case of M=3

$|\Theta^0(y)|$ $|\Theta^1(y)|$ $|\Theta^2(y)|$



Wave function profile on toroidal background

Zero-modes wave functions are quasi-localized far away each other in extra dimensions. Therefore the hierarchically small Yukawa couplings may be obtained.

Short summary on massless spectra

(Extra-dimensional) field-theoretical viewpoint

gauge bosons: (p+1)-dim modes

matter : quasi-localized modes

No. of generation = No. of zero-modes of Dirac eq.

$\Rightarrow$ CY

4. Effective theory

Effective theory of massless modes is described by supergravity- coupled gauge theory.

4-1. Gauge coupling

Extra dimensional theory

⇒ dimensional reduction to 4D theory

$$-\left(1/4g_{4+d}^2\right)\int d^4x d^d y \left(F_{MN}\right)^2 = -\left(V/4g_{4+d}^2\right)\int d^4x \left(F_{\mu\nu}\right)^2$$

$$g_4^2 = g_{4+d}^2 / V$$

Gauge couplings in 4D depend on volume of compact space as well as dilaton.

Gauge kinetic function

Gauge kinetic function in supergravity

$$1/g_4^2 = \mathrm{Re}[f(\mathrm{moduli})]$$

$$f = V/g_{4+d}^2 + \mathrm{imaginary\ \ part}$$

Usually we redefine moduli fields such that gauge kinetic functions are written simply,

e.g. f = S .

heterotic models

Gauge couplings

Gauge sector

10D E8 ⇒ 4D $G_1 * G_2 * \ldots$

(smaller groups)

Gauge couplings at the tree level are unified at the compactification scale for any gauge groups.

$f=S$

Its value is determined by VEV of dilaton/moduli.

D-brane

Dp-brane : (p+1) dimensional extended object

our 4D spacetime

+ (p-3) compact space

For example,

D3-brane : not extend in extra dim. space,

but localize on a point

D6-brane : extend in 3 extra dim. space

D7-brane : extend in 4 extra dim. Space

Gauge sector lives on a set of Dp-branes

Gauge kinetic function

D7/D3 system on T2*T2*T2

Gauge sector on D3

$$-(1/4)\int dx\, e^{-\phi}\left(F_{\mu\nu}\right)^2$$

$$f_{D3} = S = e^{-\phi}$$

Gauge sector on D7(i) extending

on j-th and k-th torus

$$-(1/4)\int dx\, e^{-\phi+2\sigma_j+2\sigma_k}\left(F_{\mu\nu}\right)^2$$

$$f_{D7(i)} = T_i = e^{-\phi+2\sigma_j+2\sigma_k}$$

metric

$$\sum_{i=1,2,3} e^{2\sigma_i}\,|\,dx_i + i dy_i\,|^2$$

Gauge kinetic function

More complicated case

$$f = f(S, T)$$

Example : Intersecting D-branes

Magnetized D-branes

In general, their compact volumes are different from each other.

The gauge coupling unification is not automatic.

4-2. Yukawa couplings

Heterotic orbifold models

Yukawa couplings of untwisted matter (bulk fields)

Untwisted sector is originated from 10D modes.

That is, they respect 4D N=4 (10D N=1) SUSY vector multiplet

Yukawa couplings ← controlled by 4D N=4 SUSY

Certain combinations are allowed: Selection rule

$\Rightarrow$ Y = g = O(1)

That fits to the top Yukawa coupling

Yukawa couplings

Yukawa couplings of twisted matter

twisted matter $\Rightarrow$ localized modes

Extra dimensional field theory

Couplings among local fields are suppressed depending on their distance.

They can explain small Yukawa couplings for light quark/lepton ?

Let's carry out stringy calculation

(stringy selection rule)

Selection rule for allowed couplings

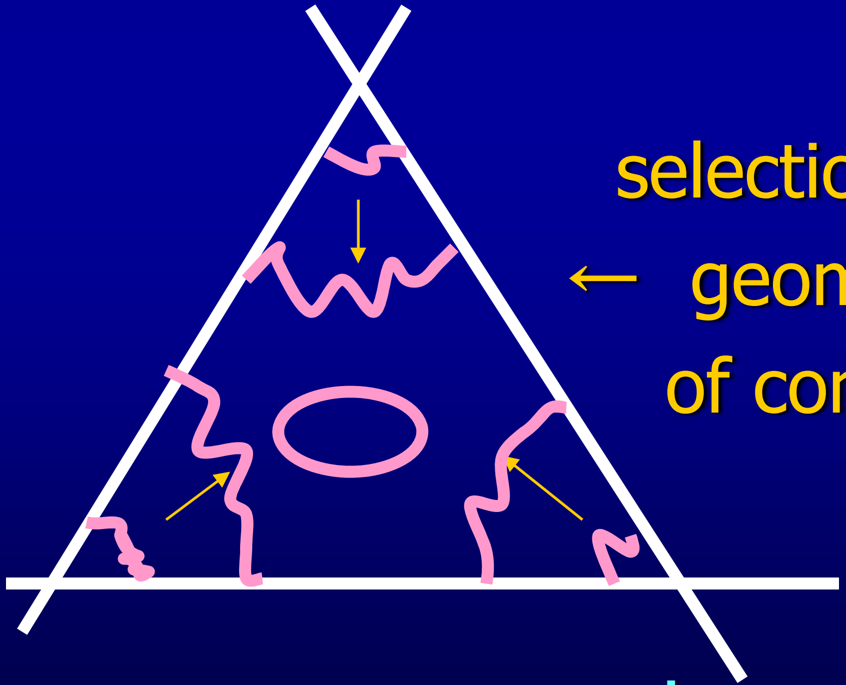
Allowed couplings : gauge invariant

Some selection rules are not understood
by effective field theory.

Stringy selection rule

Coupling selection rule

If three strings can be connected
and it becomes a shrinkable closed string,
their coupling is allowed.

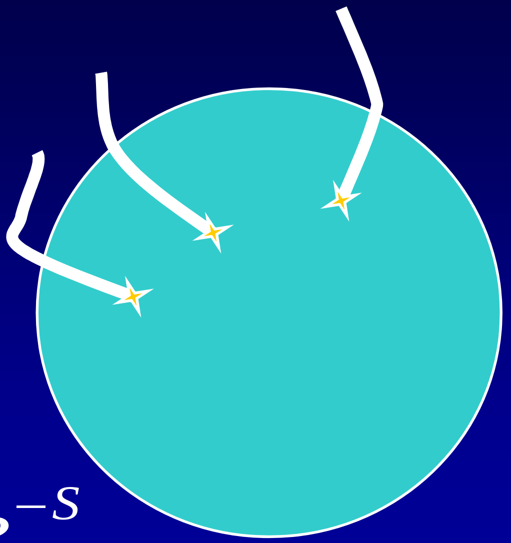


selection rule
← geometrical structure
of compact space

⇒ in general complicated

3-point coupling

Calculate by inserting vertex op.
corresponding to massless modes



$$\langle \sigma_\Theta(z_1)\sigma_\Theta(z_2)\sigma_\Theta(z_3)\rangle = \int dZ e^{-S}$$

$$= \sum_{Z_{cl}} \int dZ_{qu} e^{-S_{cl} - S_{qu}}$$

S_{cl} : *classial action* $\approx$ *Area*

Yukawa couplings are suppressed by the area
that strings sweep to couple.

Those are favorable for light quarks/leptons.

n-point coplings

Choi, T.K. '08

Selection rule ← gauge invariance
H-momentum conservation
space group selection rule

Coupling strength
calculated by inserting Vertex operators

$$\left\langle \sigma_{\Theta}(z_1)\sigma_{\Theta}(z_2)\cdots\sigma_{\Theta}(z_n)\right\rangle = \sum_{Z_{cl}} \int dZ_{qu} e^{-S_{cl}-S_{qu}}$$

S_{cl} : *classial action* ≈ *Area*

Calculations in intersecting D-brane models
are almost the same.

Short summary on effective theory (coupling)

Several couplings are calculable.

← dimensional reduction from

extra dimesion

stringy (non-) perturbative calculation

All couplings are functions depending on moduli (dilaton).

We have to choose proper values of moduli VEVs.

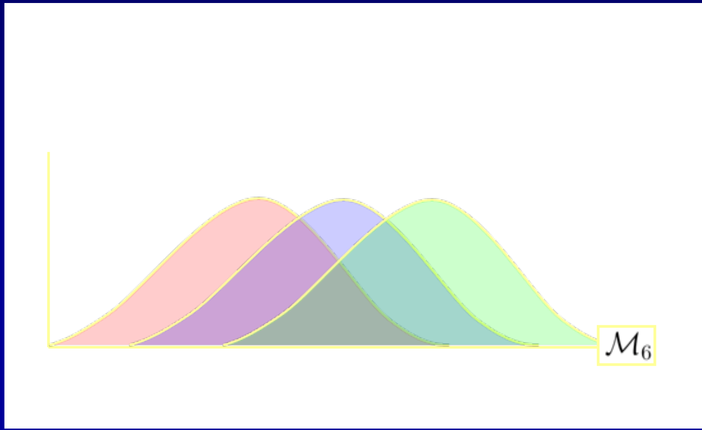
Couplings among zero-modes

Extra dimensional effective field theory

Non-trivial background

→ non-trivial profile

of zero-mode wave function



$$Y_{ijk} = \int dy^{D-4} \psi_L^{i,M_1}(y) \psi_R^{j,M_2}(y) (\psi_H^{k,M_3}(y))^*$$

4D couplings among quasi- localized modes

= overlap integral along extra dimensions

→ suppressed Yukawa couplings

depending on their distance

Flavor structure in intersecting/magnetized D-brane

Simple flavor structure

⇒ not so realistic Yukawa matrices, e.g.

$$\begin{pmatrix} h_3 & \epsilon h_1 & \epsilon h_2 \\ \epsilon h_1 & h_2 & \epsilon h_3 \\ \epsilon h_2 & \epsilon h_3 & h_1 \end{pmatrix} \qquad \begin{pmatrix} a_1 b_1 & a_1 b_2 & a_1 b_3 \\ a_2 b_1 & a_2 b_2 & a_2 b_3 \\ a_3 b_1 & a_3 b_2 & a_3 b_3 \end{pmatrix}$$

Higaki, Kitazawa, T.K., Takahashi, '05

We need richer flavor structures, e.g.
magnetized orbifold models, which can realize semi-realistic Yukawa matrices with a proper value of the modulus.

Abe, T.K., Ohki, '08

Abe, Choi, T.K., Ohki, '08

(Heterotic) explicit models

Explicit models have flat directions and several scalar fields develop their VEVs.

Higher dim. Operators $\left(\phi_1 \ldots \phi_n / M^n\right) HQq$ become effective Yukawa couplings after symmetry breaking.

They would lead to suppressed Yukawa couplings

How to control n-point coupling is important.

So far, such analyses have been done model by model.

Non-abelian discrete flavor symm.

Recently, in field-theoretical model building, several types of discrete flavor symmetries have been proposed with showing interesting results, e.g. S3, D4, A4, S4, Q6, Δ(27), ...

Neutrino oscillation ⇒ large mixing angles

one Ansatz: tri-bimaximal

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

Discrete flavor symmetries

What is the origin of these discrete non-Abelian flavor symmetries ?

e.g.

S3 : symmetry of equilateral triangle

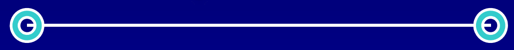
A4 : symmetry of tetrahedora

……

Extra dimensional compact space could be an origin of discrete non-Abelian flavor symmetries.

S1/Z2

There are two fixed points.



$$(\Theta, me), \qquad m = 0,1$$

$$(1-\Theta)\Lambda = 2e$$

Θ: Z2 twist

Space group selection rule

$$\prod_{j=1}^{n} (\Theta, m^{(j)}e) = (\Theta^n, \sum_{j=1}^{n} m^{(j)}e) = (1, (1-\Theta)\Lambda)$$

$$n = even, \qquad \sum_{j=1}^{n} m^{(j)} = even$$

D4 Flavor Symmetry

Stringy symmetries require that Lagrangian has the permutation symmetry between 1 and 2, and each coupling is controlled by two Z2 symmetries.

Flavor symmeties: closed algebra S2 U(Z2xZ2)

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \qquad -1 = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \qquad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

D4 elements

$$\pm 1, \qquad \pm\sigma_1, \qquad \pm i\sigma_2, \qquad \pm\sigma_3$$

modes on two fixed points ⇒ doublet

untwisted (bulk) modes ⇒ singlet

Geometry of compact space

→ origin of finite flavor symmetry

Strings on heterotic orbifold

Actually, we have constructed explicit string models on the Z6 orbifold, which have D4 flavor symmetries and three generations as D4 singlets and doublets.

T.K., Raby and Zhang, ‘04

Other flavor symmetries can appear

T.K., Nilles, Ploger, Raby and Ratz, ’06

Study on discrete anomalies is also important.

Araki, T.K., Kubo, Ramos-Sanchez, Ratz, Vaudrevange, ‘08

Other string models

Non-abelian flavor symmetries

from magnetized/intersecting D-brane models

Abe, Choi, T.K., Ohki, in progress

Flavor in string theory

It is not so difficult to realize the generation number, i.e. the three generation.

We have some explicit examples to lead to semi-realistic patterns of Yukawa matrices for quarks and leptons.

However, realization of realistic Yukawa matrices is still a challenging issue.

(non-abelian flavor symmetries ?)

5. Moduli stabilization, SUSY breaking

5-1. Introduction

Superstring theory has several moduli fields including the dilaton.

Moduli correspond to the size and shape of compact space.

VEVs of moduli fields

→ couplings in low-energy effective theory, e.g. gauge and Yukawa couplings

Thus, it is important to stabilize moduli VEVs at realistic values from the viewpoint of particle physics as well as cosmology

Actually, lots of works have been done so far.

5-2. KKLT scenario

Our scenario is based on 4D N=1 supergravity, which could be derived from type IIB string. (Our supergravity model might be derived from other strings.)

1) Flux compactification

Giddings, Kachru, Polchinski, '01

The dilaton S and complex structure moduli U are assumed to be stabilized by the flux-induced superpotential

$$W_{flux}(S,U)$$

That implies that S and U have heavy masses of O(Mp).
The Kaher moduli T remain not stabilized.

2) Non-perturbative effect

We add T-dependent superpotential induced by e.g. gaugino condensation on D7.

$$W = \left\langle W_{flux}(S,U) \right\rangle + Ae^{-aT}, \qquad A = O(1)$$

$$K = -3\ln(T + \bar{T})$$

Scalar potential

$$V_F = e^K [D_T W (\overline{D_{\bar{T}} W}) K^{T\bar{T}} - 3|W|^2]$$

$$D_T W = K_T W + W_T$$

T is stabilized at $D_T W=0$

→ SUSY Anti de Sitter vacuum $V < 0$

Stabilization of T

$$D_T W = K_T \left(W_{flux} + Ae^{-aT} \right) - aAe^{-aT} = 0$$

$$a = O(10), \qquad aT = \ln(A / W_{flux})$$

$$W_{flux} >> Ae^{-aT}$$

gravitino mass $\qquad m_{3/2} \approx W_{flux}$

Scalar potential

$$V_F = e^K [D_T W (\overline{D_{\bar{T}}} \overline{W}) K^{T\bar{T}} - 3 |W|^2]$$

T is stabilized at $D_T W=0$

→ SUSY Anti de Sitter vacuum $\quad V < 0$

$$V_F = -3m_{3/2}^2$$

Moduli mass $\qquad m_T = (aT) m_{3/2}$

Non-perturbative moduli superpotential

SU(Na) super Yang-Mills theory

gauge kinetic function fa

$$\mathrm{Re}(f_a) = 4\pi / g_a^2$$

gaugino condensation →

$$W_{np} = Ae^{-2\pi f_a / N_a}$$

For example, when $f_a = T$

like the gauge sector on D7-brane,

the gaugino condensation induces

$$W_{np} = Ae^{-2\pi T / N_a}$$

That is the well-known form of non-perturbative terms.

3) Uplifting

We add uplifting potential generated by

e.g. anti-D3 brane at the tip of warp throat

$$V_L = D/(T+\bar{T})^{n_p}, \qquad D = e^{-16\pi^2 mS}$$

The value of D can be suppressed by the warp factor.

We fine-tune such that

$V_F + V_L = 0$ (or slightly positive)

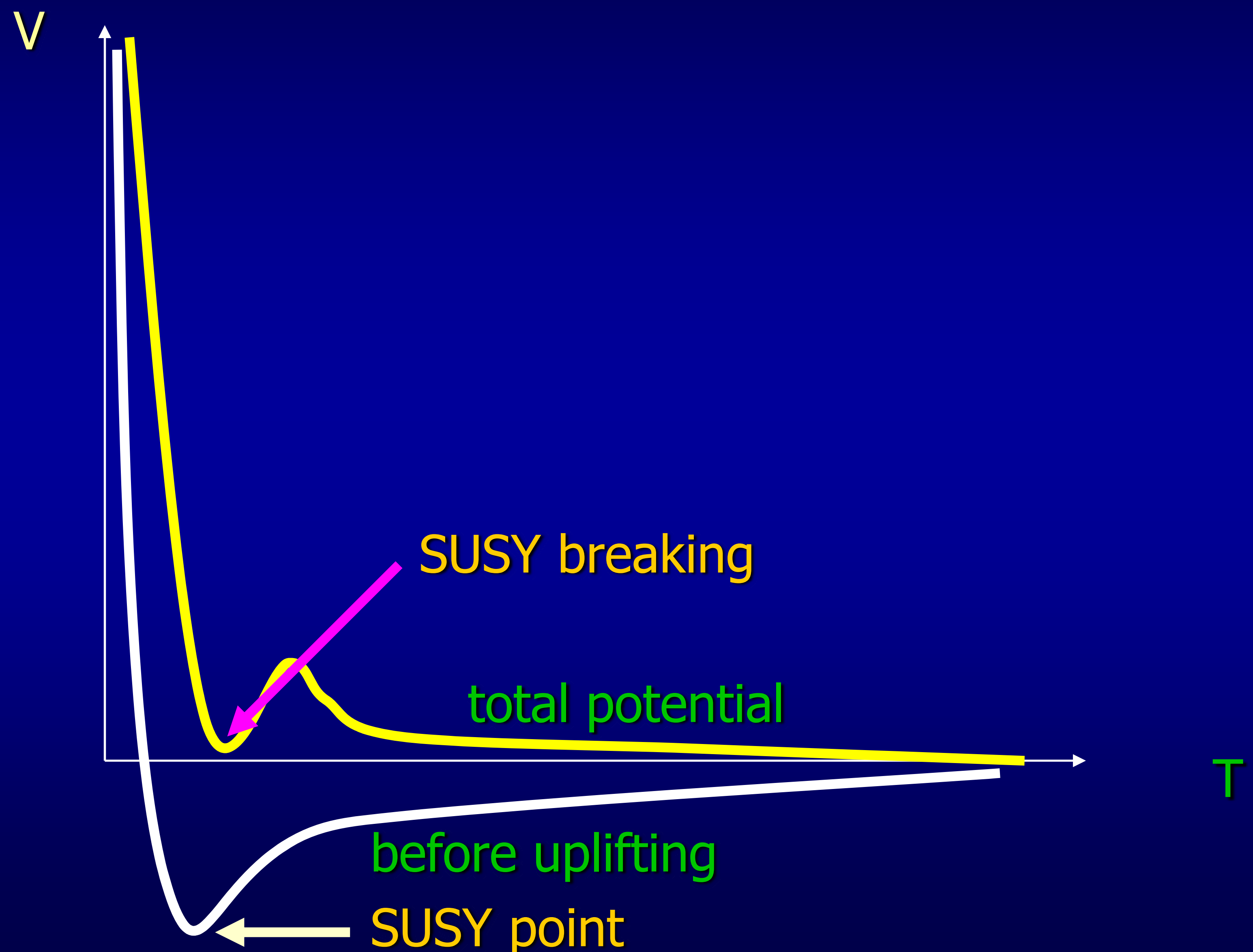
→ SUSY breaking de Sitter/Minkowski vacuum

T is shifted slightly from the point $D_T W = 0$

$$F^T \neq 0, \qquad \frac{F^T}{(T+\bar{T})} \cong \frac{m_{3/2}}{a\,\mathrm{Re}\,T},$$

$$a\,\mathrm{Re}\,T \approx \ln(M_P/m_{3/2}) \approx 4\pi^2 >> 1$$

Uplifting


V
SUSY breaking
total potential
T
before uplifting
SUSY point

5-3. generalization
Moduli mixing in gauge coupling

In several string models, gauge kinetic function f is given by a linear combination of two or more fields.

Weakly coupled hetero. /heterotic M

$$f = S \pm \beta T$$

Similarly,

IIA intersecting D-branes/IIB magnetized D-branes

$$f = \pm mS \pm wT$$

Lust, et. al. '04

Gaugino condensation → exp[-a f]

Moduli mixing superpotential

Positive exponent

Note that S is already stabilized by a heavy mass.

So, we replace S by its VEV.

$$f_a = m_a S + w_a T$$

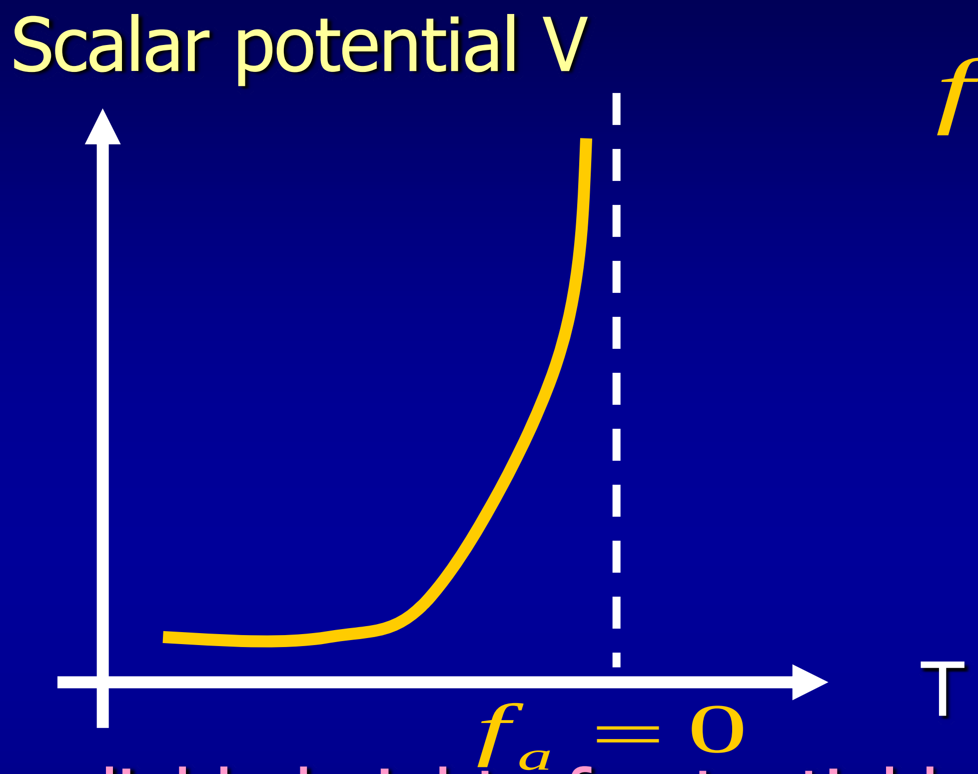
$$\longrightarrow \quad W_{np} = A\exp[-2\pi(m_a S_0 + w_a T)/N_a] = A' e^{-aT}$$

$$f_a = m_a S - w_a T$$

$$\longrightarrow \quad W_{np} = A\exp[-2\pi(m_a S_0 - w_a T)/N_a] = A' e^{aT}$$

non-perturbative superpotential with positive exponent

Positive exponent



$$f_a = m_a S - w_a T$$

strong coupling

$$f_a < O(1)$$

reliable height of potential barrier

$$f_a \approx 1$$

$$\rightarrow \quad W_{np} \approx A \exp[-2\pi / N_a] = O(M_P^3)$$

$$V \approx |A|^2 e^{-4\pi / N_a} = O(M_P^4)$$

Potential forms and implications

Let us study the following superpotential

$$W_{total} = W_0 + \sum A_a e^{-2\pi(m_a S_0 + w_a T)/N_a} + \sum A_b e^{-2\pi(m_b S_0 - w_b T)/N_b}$$

F-term scalar potential

$$V_F = e^K [D_T W (\overline{D_{\bar{T}}} \overline{W}) K^{T\bar{T}} - 3|W|^2]$$

$$D_T W = K_T W + W_T \qquad K = -3\ln(T + \bar{T})$$

Total scalar potential

$$V = V_F + \frac{E}{(T + \bar{T})^n}$$

We tune E such that V=0 at one of minima.

5-3-1. W with a single term

$$W_{total} = Ae^{-2\pi(mS-wT)/N}$$

This is one of the simplest models to stabilize moduli.

For example, n=2

$$4\pi w\,\mathrm{Re}(T) = 5N \qquad \frac{F^T}{T+\bar{T}} = \frac{2}{3}m_{3/2}$$

Similar results for n=3

W is R-symmetric.

global SUSY Nelson, Seiberg, '94

supergravity Abe, T.K., Omura 0708.3148[hep-th]

Im(T) is still flat.

5-3-2 W with two terms

KKLT type

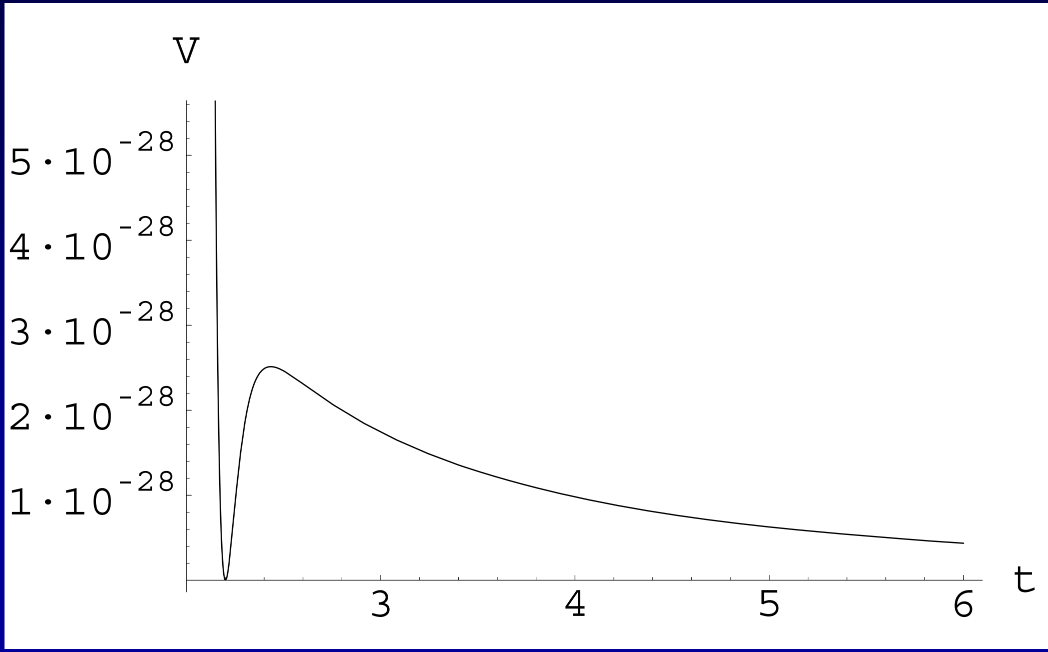
$$W_{total} = W_0 + Ae^{-(mS+nT)},$$
$$W_0 = W_{flux} \qquad or \qquad e^{-kS}$$

Racetrack type

$$W_{total} = A_1 e^{-2\pi(m_1 S + w_1 T)/N_1} + A_2 e^{-2\pi(m_2 S + w_2 T)/N_2}$$

These are well-known.

Cosmology



Height of bump is determined by gravitino mass $\approx m_{3/2}^2 M_P^2$

Overshooting problem Brustein, Steinhardt, '93

Inflation ? (Hubble < gravitino mass)

destabilization due to finite temperature effects

$$\Delta V = (\alpha_0 + \alpha_2 g^2)\hat{T}^4$$

Buchmuller, et. al. '04

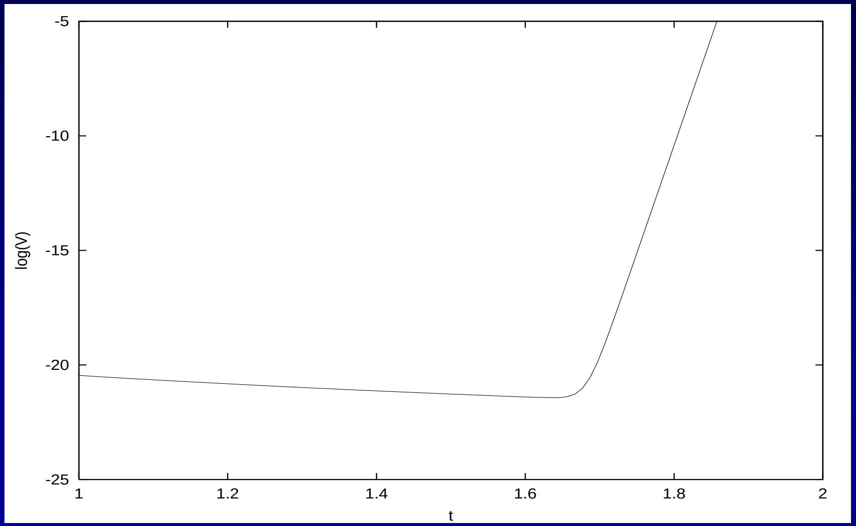
$$\Delta V = [\alpha_0 + \alpha_2 /(mS + wT)]\hat{T}^4$$

New models

Abe, Higaki, T.K., '05

KKLT-like model

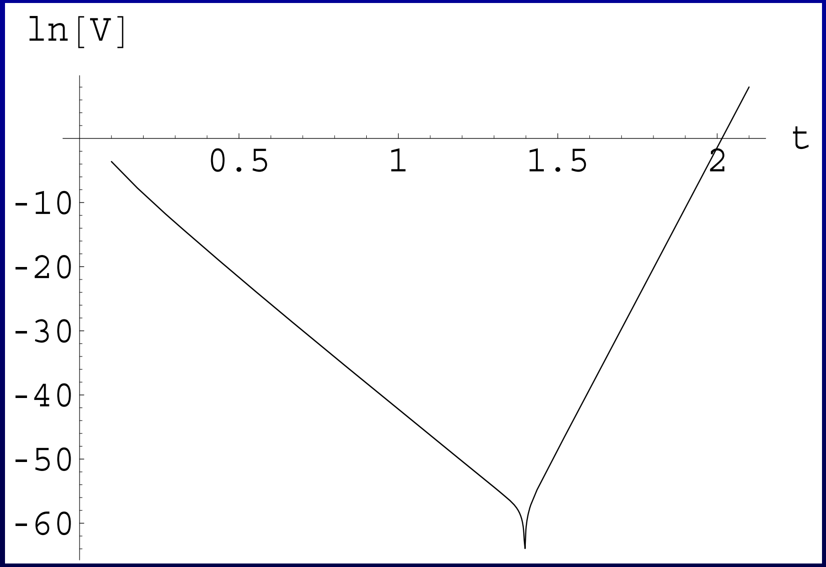
$$W = W_0 + e^{-8\pi^2 (m_b S - w_b T)/N_b}$$



$$\Delta V = [\alpha_0 + \alpha_2 /(mS - wT)]\hat{T}^4$$

Racetrack-like model

$$W = e^{-8\pi^2 (m_a S + w_a T)/N_b} + e^{-8\pi^2 (m_b S - w_b T)/N_b}$$



The above problems may be avoided.

5-3-3 Application: racetrack inflation

$$W = W_0 + \sum_{a=1,2} A_a e^{-2\pi(m_a S_0 + w_a T)/N_a} + A_3 e^{-2\pi(m_3 S_0 - w_3 T)/N_3}$$

When $A_3=0$, this corresponds to the superpotential of racetrack inflation. Blanco-Pillado, et al, '04

$$N_1 / w_1 = 100, \qquad N_2 / w_2 = 90, \qquad W_0 = -1/25000$$

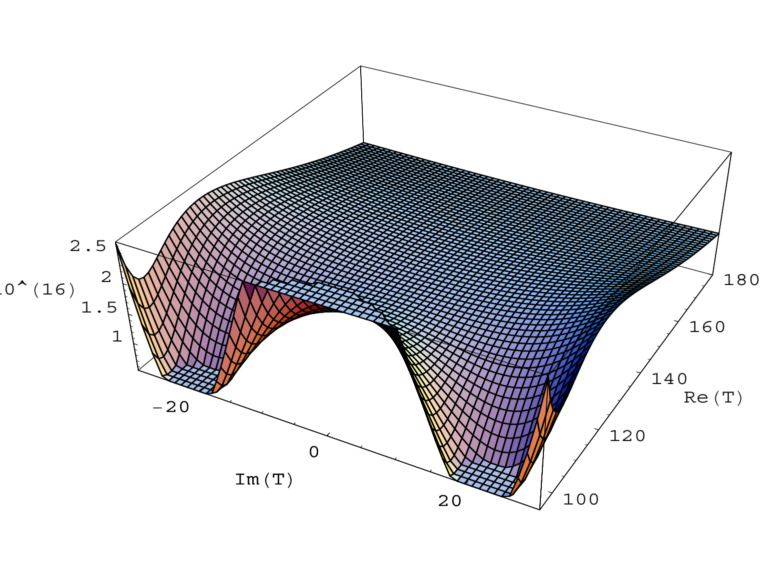
$$A_1 e^{-2\pi m_1 S_0 / N_1} = 1/50, \qquad A_2 e^{-2\pi m_2 S_0 / N_2} = -35/1000$$

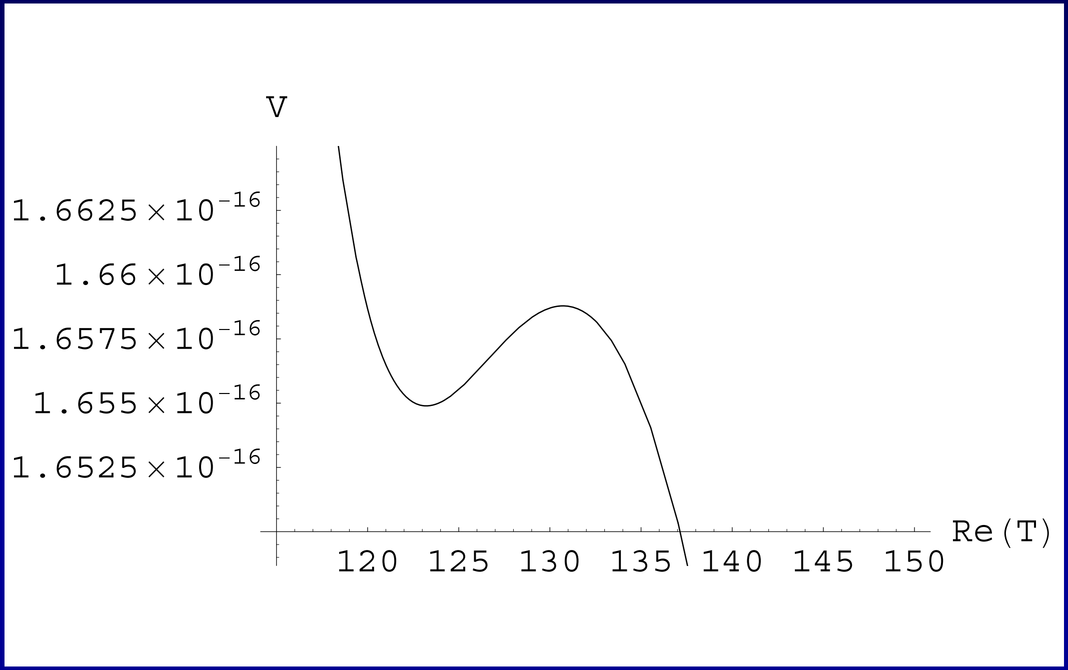
→

slow-roll inflation
around the saddle point

$$\varepsilon = \frac{M_P^2}{2V^2}\left(\frac{dV}{d\phi}\right)^2, \qquad \eta = \frac{M_P^2}{V}\frac{d^2V}{d\phi^2}$$

Racetrack inflation





Slow roll parameters and e-folding

$$\longrightarrow \quad \varepsilon = 0, \qquad \eta = -0.006097$$

$$N = 130$$

Racetrack inflation

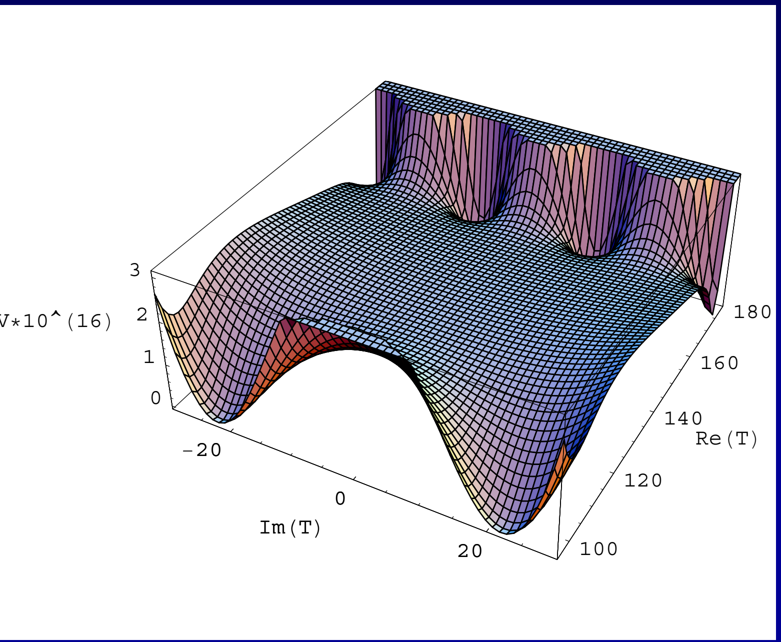
$$W = W_0 + \sum_{a=1,2} A_a e^{-2\pi(m_a S_0 + w_a T)/N_a} + A_3 e^{-2\pi(m_3 S_0 - w_3 T)/N_3}$$

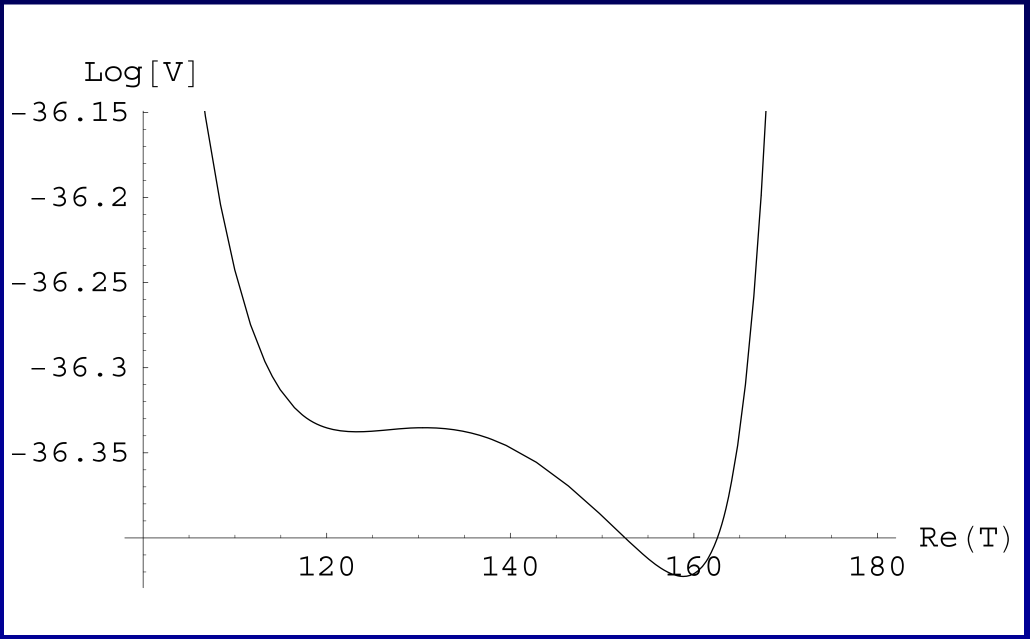
$$A_3 = 1, \qquad m_3 S_0 = 68.8\pi,$$

$$w_3 = 1, \qquad N_3 = 20$$

→ slow-roll inflation
around the saddle point

Racetrack inflation





Slow roll parameters and e-folding

$$\longrightarrow \quad \varepsilon = 0, \qquad \eta = -0.006850$$

$$N = 130$$

Volume modulus inflation

Badziak, Olechowski, '08

There is no runaway direction.

$$W_{total} = A_1 e^{-2\pi(m_1 S - w_1 T)/N_1} + A_2 e^{-2\pi(m_2 S + w_2 T)/N_2}$$

The Hubble constant is independent of the gravitino mass.

5-4. Moduli stabilization and SUSY breaking

Low-energy effective theory = supergravity

Moduli-stabilizing potential may break SUSY.

$$F/M = O(m_{3/2})$$

or ?

$$F/M < O(m_{3/2})$$

That would lead to a specific pattern of SUSY breaking terms, i.e. masses of superpartners.

KKLT scenario

Kachru, Kallosh, Linde, Trivedi, '03

They have proposed a new scenario for moduli stabilization leading to de Sitter (or Minkowski) vacua, where all of moduli are stabilized.

Soft SUSY breaking terms

Choi, Falkowski, Nilles, Olechowski, Pokorski '04, CFNO '05

→ a unique patter of soft SUSY breaking terms

Modulus med. and anomaly med. are comparable.

→ Mirage (unification) scale

Mirage Mediation Choi, Jeong, Okumura, '05

→ little SUSY hierarchy (TeV scale mirage mediation)

Choi, Jeong, T.K., Okumura, '05, '06

More about moduli stabilization

a generic KKLT scenario
with moduli-mixing superpotential
⇒ various mirage scale

Abe, Higaki, T.K., '05
Choi, Jeong, '06
Choi, Jeong, T.K., Okumura, '06

F-term uplifting

Dudas, Papineau, Pokorski, '06
Abe, Higaki, T.K., Omura, '06
Kallosh, Linde, '06
Abe, Higaki, T.K, '07

Summary

We have studied on particle phenomenological aspects on string theory to find out a scenario connecting string theory and the particle physics, in particular the Standard Model.

Several issues:

realistic spectra,

flavor structure、moduli stabilization、SUSY breaking、cosmology、………

Summary

Realistic massless spectra

all types of string theories are not bad

We have known already many string models, which have the same content as the MSSM or its extensions.

Gauge couplings

Yukawa matrices

still a challenging issues

Further studies: Moduli stabilizatin cosmological aspects, …