String Compactification toward GUTs and Standard Model

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With B. Kyae, K-S Choi, I-W Kim, J.-H. Kim, J.-H. Huh

PLB 564, 35 (2003) [hep-th/0301177]: $\sin^2\theta_W$
NPB 770, 47 (2007) [hep-th/0608086]: Z_{12-I} flipped SU(5)
JHEP 03 (2007) 116 [hep-ph/0612107]: Approx. gl. sym.
JHEP 06 (2007) 034 [hep-ph/0702278]: R-parity,etc.
PRD 76, 051701 (2007) [arXiv: 0704.3310]: mini-charged
PLB 647, 275; PLB 651, 407: GMSB(unstable)
PLB 656, 207 [arXiv:0707.3292]: GMSB(stable)
PRD 77, 106008 (2008) [arXiv: 0712.1596]: KK mass
JCAP 05 (2009) 010 [arXiv: 0902.3610 [hep-th]]: quint. ax.
PLB 678, 197 (2009) [arXiv: 0904.1015]: gravitino mass
PRD 80,115012 (2009) [arXiv: 0904.1108]: SU(5)xSU(5)'
NPB 817, 58 (2009) [arXiv: 0811.3511]: Two DM
PRD 80, 075012 (2009) [arXiv: 0908.0152]: Decaying DM
with heavy axino

- Orbifold models from heterotic string

- SUSY GUTs and SSM, Landscape :
  Observable sector, Yukawa coupling texture,
  Vectorlike exotics, Hidden sector and mediation

- R parity

- Approximate global symmetries
  - Approximate PQ symmetry, $U(1)_R$ symmetry

- μ problem

- Multi dark matter

With this basic problem in mind, we look for a TeV scale

- Orbifolding of string theory
- MSSM
- Hidden sector
- Vectorlike pairs are removed above TeV scale
- Approximate or exact R parity
- (Gravitino mass and) hidden sector
- (Possiblity of NMSSM and mini-charged particles)

History:

- Orbifold models from heterotic string in 1987: the string standard-like models in Z_3 orbifold gauge group SU(3)xSU(2)xU(1) three families. But, several phenomenological problems are there.

● SUSY GUTs and SSM

Since 2003, nonprime orbifolds considered toward MSSM

Choi-Kim, Quarks and leptons from orbifolded superstring, LNP 696 [Springer, 2006]

Kobayashi-Raby-Zhang, hep-ph/0409088 on Z(6-II)

Kim-Kyae, hep-th/0608086 on Z(12-I)

What is the gauge group below the string scale?

SUSY GUT?

SUSY SM?

Why is this important?

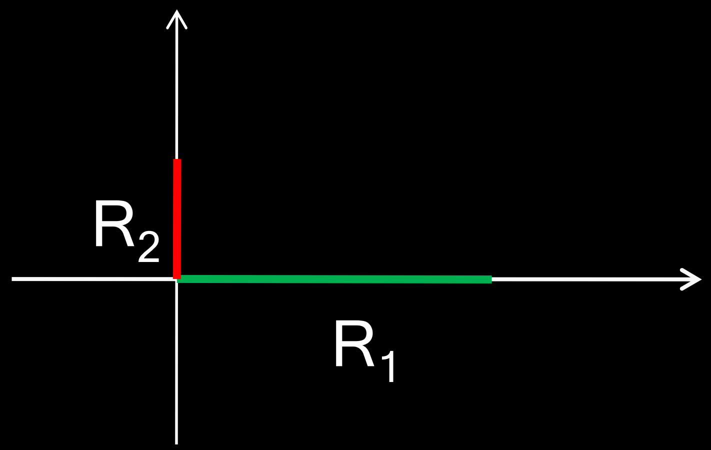
We will see when we attack several problems.

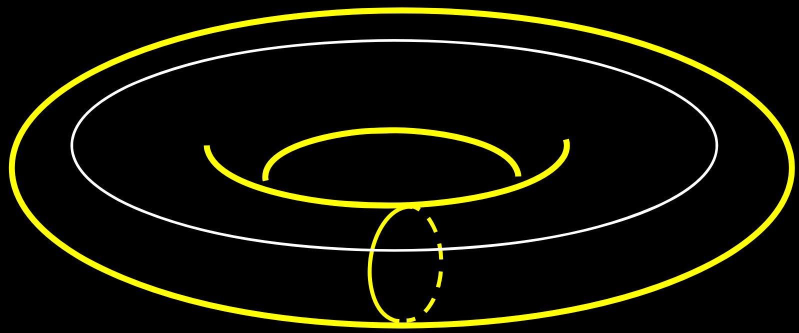
1. Orbifold models from heterotic string

Orbifolds are introduced by Dixon-Harvey-Vafa-Witten in string compactification such that closed strings must satisfy the space moded out by finite group, having fixed points.
Since string is considered, the conditions in string compactification is more involved. This method is used in extra dimensional field theory, e.g. in 5D by Kawamura. This field theoretic orbifold is easier to understand.

Standard-like models were first tried with Z3 orbifold.
[Ibanez-KEK-Nilles-Quevedo, Casas-Munoz]
But Z3 models do not give an effective 5D field theoretic orbifold.

We need non-prime orbifold for this: Z4, Z6, Z8, Z12
These non-prime orbifold has sub-group Z2 or Z2xZ2 which are the only possible field theoretic orbifolds in 5D.
In these cases, R_1 and R_2 are independent and hence can obtain an effective 5D.

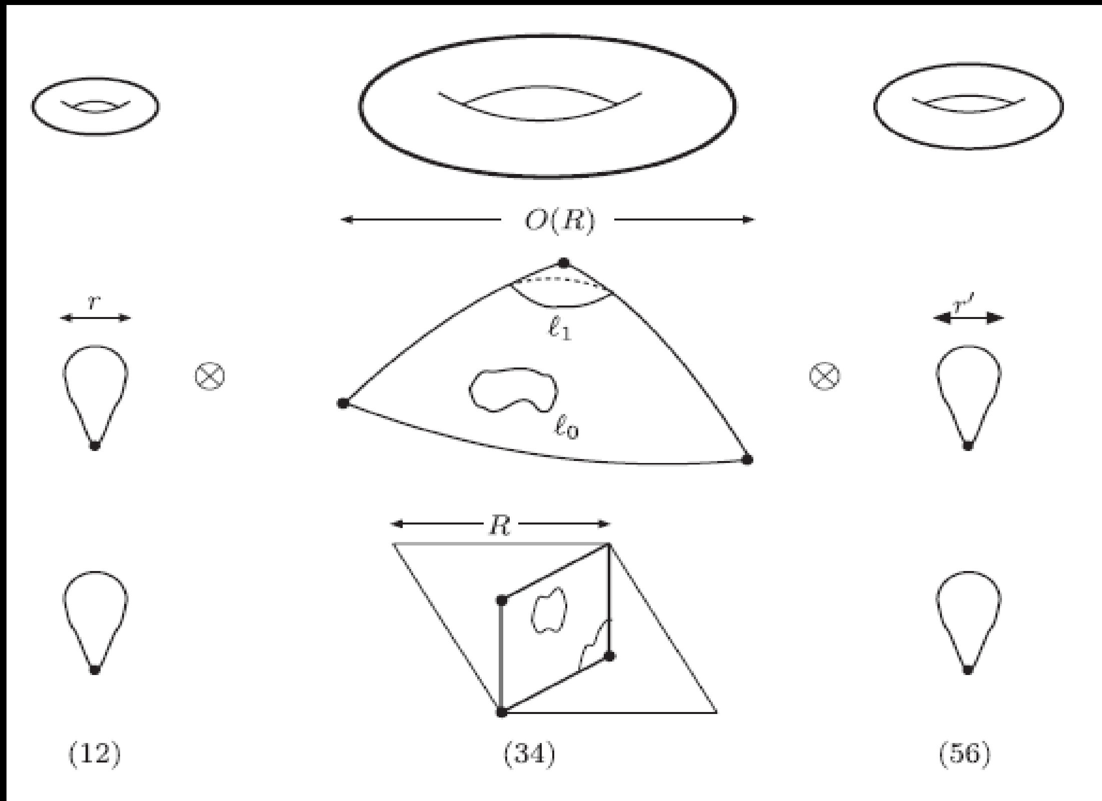




Conditions of the closed string on a 2D sub-torus

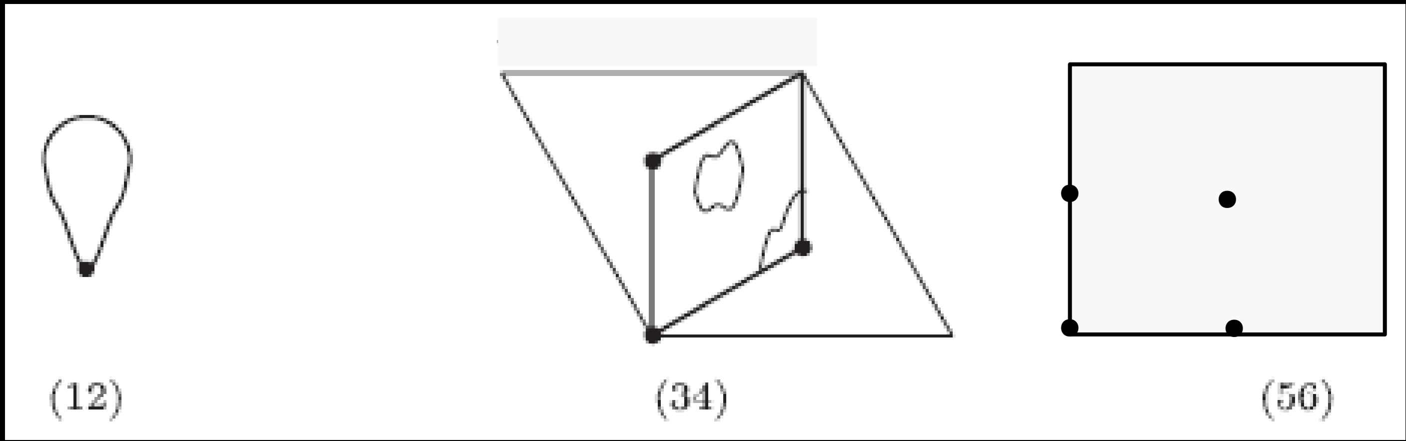
Phenomenologically most-discussed
Non-prime orbifold models are

$Z_{12\text{-I}}$ [K.S. Choi and JEK; JEK and B. Kyae] and
$Z_{6\text{-II}}$ [Kobayashi-Raby-Zhang; Buchmuller et al.; ....]



G$_2$ SU(3) G$_2$

An example of three 2D torii in $Z_{12\text{-}I}$.
Here, one independent length is introduced. In this sense, it is the simplest extension beyond the prime orbifold Z_3.
But an effective 5D is not obtained. Possible in $Z_{12\text{-}II}$.



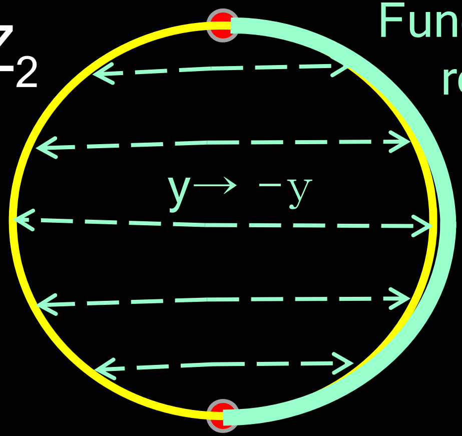
G$_2$ SU(3) SO(4)

An example of three 2D torii in $Z_{6\text{-}II}$
Because of two orthogonal radii in the (56) torus, three independent lengths can be introduced.

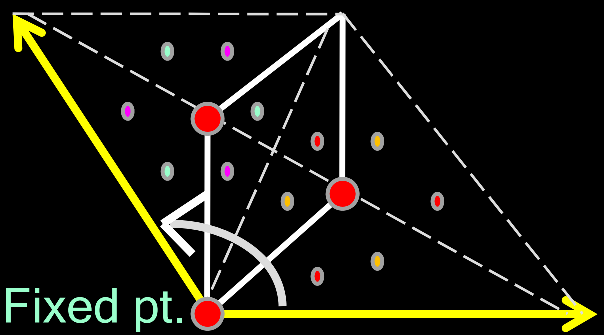
Orbifold

Manifold/discrete symmetry

Ex) S_1/Z_2



Ex) T_2/Z_3



Mapping

$g: S^1/Z_2 \qquad y \rightarrow -y$

$T^2/Z_3 \qquad z \rightarrow e^{2\pi i/3} z$

$$S^1/Z_2 \quad \begin{Bmatrix} V_y(y) = -V_y(-y) \\ V_\mu(y) = +V_\mu(-y) \end{Bmatrix}$$

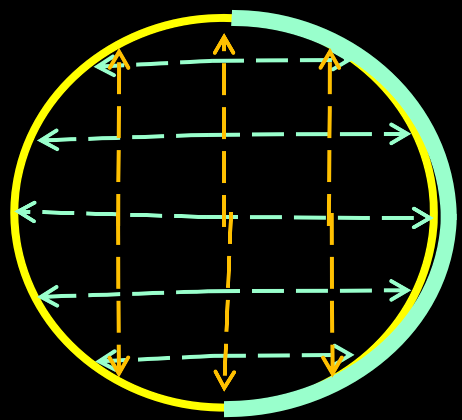
$$T^2/Z_3 \quad \begin{Bmatrix} V_z(z) = e^{2\pi i/3} \cdot V_z(e^{2\pi i/3} z) \\ V_\mu(z) = 1 \cdot V_\mu(e^{2\pi i/3} z) \end{Bmatrix}$$

5D SUSY GUT

$S_1/Z_2 \times Z_2'$

Kawamura(2000) , Hall-Nomura(2001)

g(θ,v)



Gauge multiplet

$$A_\mu^{SM,++}$$

$$\lambda_1^{SM,++} \qquad \lambda_2^{SM,--}$$

$$A_y^{SM,--},\ \phi^{SM,--}$$

N=2 SUSY

$$A_\mu^{SU(5)/SM,+-}$$

$$\lambda_1^{SU(5)/SM,+-} \qquad \lambda_2^{SU(5)/SM,-+}$$

$$A_y^{SM,-+},\ \phi^{SU(5)/SM,-+}$$

N=2 SUSY → N=1 SUSY

SU(5) → SM

$$24_{SU(5)} = \begin{pmatrix} SU(3)^{++}_{U(1)_Y} & (3,2)^{+-}_{-5/6} \\ (\bar{3},2)^{-+}_{5/6} & SU(2)^{++}_{U(1)_Y} \end{pmatrix}$$

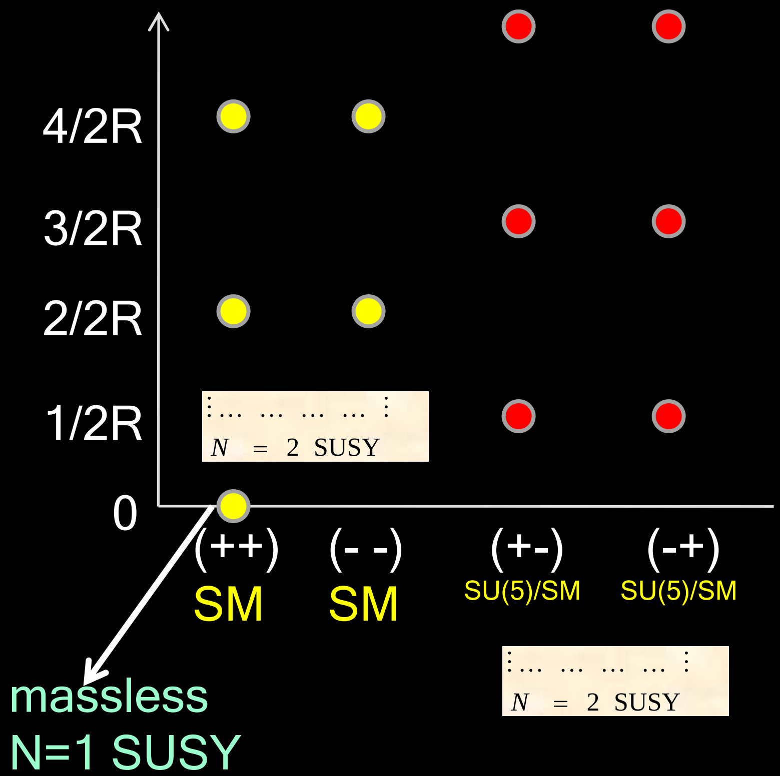
Hyper multiplet

$$5 = \begin{pmatrix} 3^{+-} \\ H_u^{++} \end{pmatrix}, \qquad \bar{5} = \begin{pmatrix} \bar{3}^{+-} \\ H_d^{++} \end{pmatrix}$$

N=2 $\qquad$ N=2

$$5^c = \begin{pmatrix} 3^{c-+} \\ H_u^{c--} \end{pmatrix}, \qquad \bar{5}^c = \begin{pmatrix} \bar{3}^{c-+} \\ H_d^{c--} \end{pmatrix}$$

KK tower: field theory

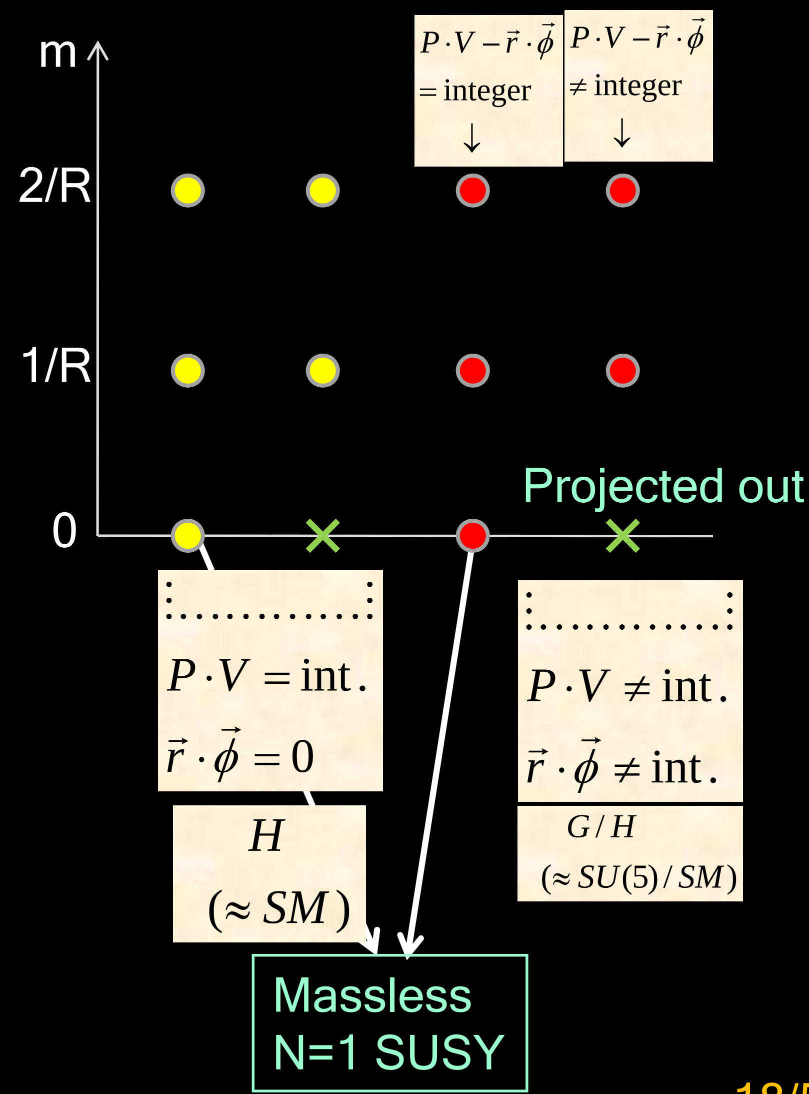


Only (++) modes contain massless states

String

G → H gauge sym. broken

N=2 SUSY → N=1 SUSY



2. SUSY GUTs and SSM, Landscape :

The gauge hierarchy problem needed SUSY as one of its solutions.
SUSY particle searches are the most awaited LHC results: yes or no.

If SUSY is introduced, the most natural framework is from string compactification. In particular, the heterotic string gives a big enough gauge group to play many problems in the SUSY SM and SUSY GUTs. String compactification is therefore fundamentally different from field theoretic tries of SUGRA and extra dimensions. It gives a unique prediction if the compactification path is known. Here, we must succeed in obtaining GOOD

Observable sector,
Yukawa coupling texture,
Hidden sector, and
SUSY breaking mediation mechanism

But DO NOT NEED

Chiral exotics,

Too fast proton decay

Absence of a pair of Higgs doublets

From symmetry principles, they are worked out in

- proton stability → R parity introduction or matter parity
- a light pair of Higgs doublets related to μ solution
- all exotics must be made vectorlike.

For no chiral exotics, the condition is that exotics must be vectorlike. At field theory level, the absence of anomaly is not enough to forbid chiral exotics. So string theory, intrinsically having no anomaly, does not forbid chiral exotics auomatically. String vacua must be chosen in such vector-like exotics directions. If you have not tried this string scheme, note that it will be the future direction.

Chiral exotics must be removed

So, all exotics must be made vectorlike.
This is a nontrivial condition.

Now, we find many exotics-free models.
The weak mixing angle here is usually not 3/8.
Except this, the condition on singlet VEVs is not so strong as requiring models without exotics.

This talk is a top-down approach.
Specific examples if needed will be in Z_{12-I} orbifold models.

One particle directly related SUGRA = gravitino

- TeV SUSY is based on supergravity Lagrangian in the last 24 years. [Cremmer et al]
- TeV SUSY cosmology has been suggested recently.
  [Cremmer et al] This led to SUGRA Higgs inflation.
  [Einhorn and Jones] [Linde et al] [Lee]
- Gravitino phenomenology: reheating temp.<$10^{9\text{-}7}$ GeV [EKN, KKM]
  Attempts exist to detect it at LHC via neutralino decay to gravitino [Buchmuller et al.]

● Supergravity SSB scale → gravitino mass

The landscape study: in $Z_{6\text{-}II}$ satisfying some conditions such as no chiral exotics, R parity, etc.
But if enough phenomenological conditions are imposed, then only one or two survives. Even in these cases they are not 100% satisfactory phenomenologically.

What should we do then?

We cannot impose all phenomenological constraints in a landscape study. One may try to suggest one type of models for a solution of one phenomenological problem. Virtually, this latter method is the one obtained in all compactification models.

Here, I try to illustrate some tries in $Z_{12\text{-}I}$.

Field theory

String

Threshold correction
by KK modes

$$\frac{1}{g_i^2(\mu)} \approx \frac{1}{g_\Lambda^2} + b_i^0 \ln\frac{\Lambda}{\mu} - \left(b_i^{++} + b_i^{--}\right)\ln\frac{\Lambda}{M_R}$$
$$+\left(b_i^{++} + b_i^{--} + b_i^{+-} + b_i^{-+}\right)\left[\ln\frac{\Lambda}{M_c} - 1\right]$$

SM ... SU(5)/SM

N = 2, SU(5)

Still $\frac{1}{g_i^2(\mu)} - \frac{1}{g_j^2(\mu)} \approx \ln\frac{\Lambda}{\mu}$: reliable

Modular invariance

Breaking G symm.

Breaking SUSY

N(V²-φ²)=integer

Gauge symmetry must be broken.
The renormalized couplings are

Not $b_H^{N=2}$

$$\frac{16\pi^2}{g_H^2(\mu)} \approx \frac{16\pi^2}{g_*^2(\mu)} + b_H^0 \ln\frac{M_*^2}{\mu^2} - \frac{1}{4} b_G^{N=2} \ln\frac{M_*^2}{M_R^2}$$
$$+\frac{1}{4} b_G^{N=2}\left[\frac{2\pi}{\sqrt{3}} \ln\frac{M_*^2}{M_c^2} - 2.19\right]$$

The Wilson line shifts up the KK masses.

$$\begin{pmatrix} Wilson & line & breaking & \leftrightarrow & Orbifold & breaking & in \\ in & string & theory & & field & theory & \end{pmatrix}$$

To study N=2 SUSY KK masses: done by the modulus $\rightarrow$ radius R

$\updownarrow$

Non-prime orbifolds

Higher twist sectors include sub-lattice invariant under g.

We need PARTITION FUNCTION to discuss the KK masses, GSO projection, Wilson-line effects, threshold corrections.

One unsatisfactory feature of standard-like models was that $\sin^2\theta_W$ is not necessarily 3/8 at the GUT scale [JEK, PLB B564, 35 (2003): Z3 orbifold for was $\sin^2\theta_W = 3/8$]. This leads to searches for GUTs from string. Mostly, this attempt failed because of the difficulty in obtaining an adjoint represntation. One successful GUT is the flipped SU(5) first noted by AEHN in free fermionic construction.
In orbifold compactification, it was obtained by Kim-Kyae.
But a flipped SU(5) does not give $\sin^2\theta_W$ =3/8 necessarily because of the U(1) factor. However, it is easier to study. And also for global U(1)s.

For a standard-like model to have $\sin^2\theta_W = 3/8$, one must specify the hypercharge Y direction, which cannot be done in the landscape type search. At best, only vectorlike pairs may be removed, but $\sin^2\theta_W$ depends on the hypercharges of all the removed vectorlike pairs also.

This problem however can be fitted in a number of ways, though not as attractive as a solution in a simple-group GUT model.

Unification of couplings needs to consider the Threshold correction

In string compactification, the threshold correction comes from non-prime orbifolds. A general form was discussed before. The non-prime orbifolds have a substructure where a large radius R can be introduced. The simplest case is for Z_3 substructure. Namely, $Z_{6\text{-I}}$ or $Z_{12\text{-I}}$, and $Z_{12\text{-I}}$ has phenomenologically interesting models.

As an example, we use

J.-H. Kim, JEK, B. Kyae, JHEP 0706, 034 (2007): 0702.278

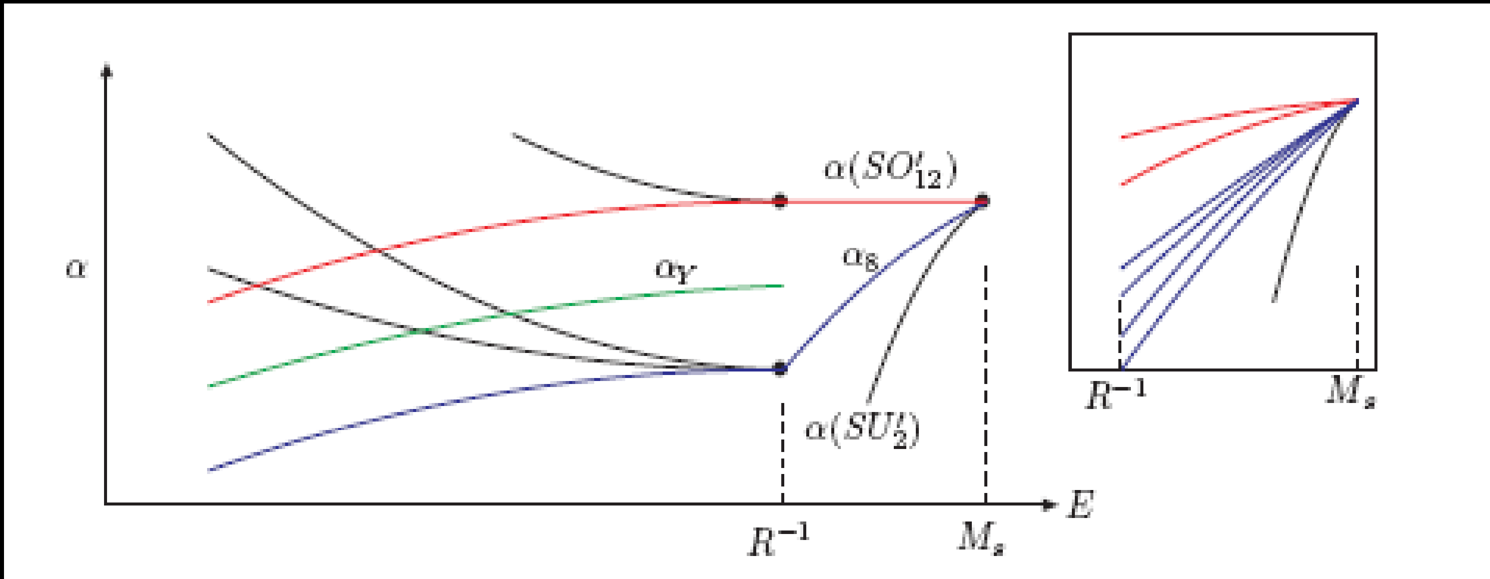
$$\phi = \left(\frac{5}{12}\ \frac{4}{12}\ \frac{1}{12}\right)$$

$$V = \left(\frac{1}{4}\ \frac{1}{4}\ \frac{1}{4}\ \frac{1}{4}\ \frac{1}{4}\ ;\frac{5}{12}\ \frac{5}{12}\ \frac{1}{12}\right)\left(\frac{1}{4}\ \frac{3}{4}\ 0\ ;0^5\right)'$$

$$a_3 = \left(\frac{2}{3}\ \frac{2}{3}\ \frac{2}{3}\ \frac{-2}{3}\ \frac{-2}{3}\ ;\frac{2}{3}\ 0\ \frac{2}{3}\right)\left(0\ \frac{2}{3}\ \frac{2}{3}\ ;0^5\right)'.$$

The 4D gauge group is

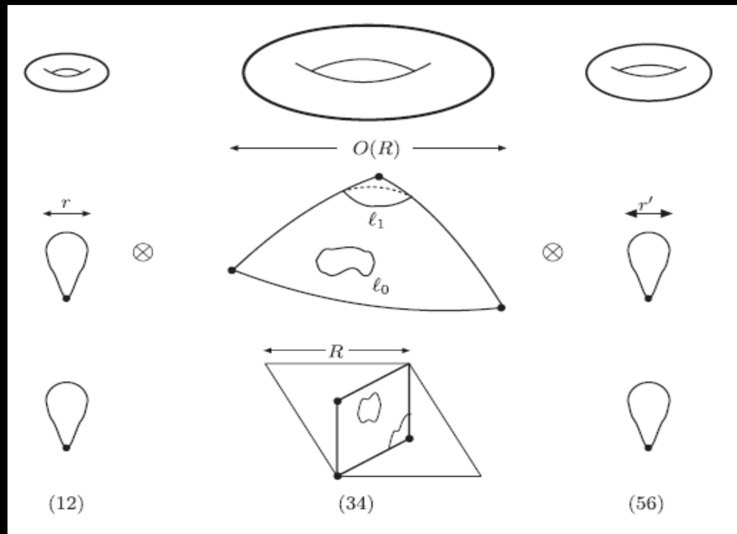
$$SU(3)\times SU(2)\times U(1)_Y\times U(1)^4$$
$$\times SO(10)'\times U(1)'^3$$



We use the partition function approach. Dixon-Kaplunovsky-Louis developed the threshold correction with the shift vector V. We generalized it to include the Wilson lines. The simplest nontrivial example for using this is for the case of $Z_{12\text{-I}}$.

We obtained a form for R dependence

[(34)-torus reliable value for coupling constant at scale μ]. But extra dimensional field theory cannot calculate constant and R^2 term.



$$\frac{4\pi}{\alpha_{H_i}(\mu)} = \frac{4\pi}{\alpha_*} + b_{H_i}^0 \log\frac{M_*^2}{\mu^2} - \frac{b_H}{\mu^2}\left[\log\frac{R^2}{\alpha'} + 1.89\right] + \frac{(b_H + b_{G/H})}{4}\left[\frac{2\pi R^2}{\sqrt{3}\alpha'} - 0.30\right]$$

We can obtain 6D field theory by compactifying 4 internal spaces. This is another check of our partition function approach. Between R and string scale, the contribution to beta function coefficient is given by b_H :
the corresponding group may not be the SM group.

Z_3

$$\Delta_i = \frac{|G'|}{|G|} b_i^{N=2} \int_\Gamma \frac{d^2\tau}{\tau_2} (\hat{Z}_{torus}(\tau,\bar{\tau}) - 1)$$

Z_{12}

Integration in the modular space along the above formula a la Dixon-Kaplunovsky-Louis gives the compactification size dependence.

We use the modular parameter with the metric,

$$\begin{cases} \vec{e}_1 = (\sqrt{2},0) \\ \vec{e}_2 = (-\sqrt{1/2},\sqrt{3/2}) \end{cases}; \qquad g_{ab} = \begin{pmatrix} 2 & -1 \\ -1 & 2 \end{pmatrix}$$

$$\begin{cases} \vec{e}^{*1} = (1/\sqrt{2},\sqrt{1/6}) \\ \vec{e}^{*2} = (0,,\sqrt{2/3}) \end{cases}; \qquad g^{ab} = \frac{1}{3}\begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$$

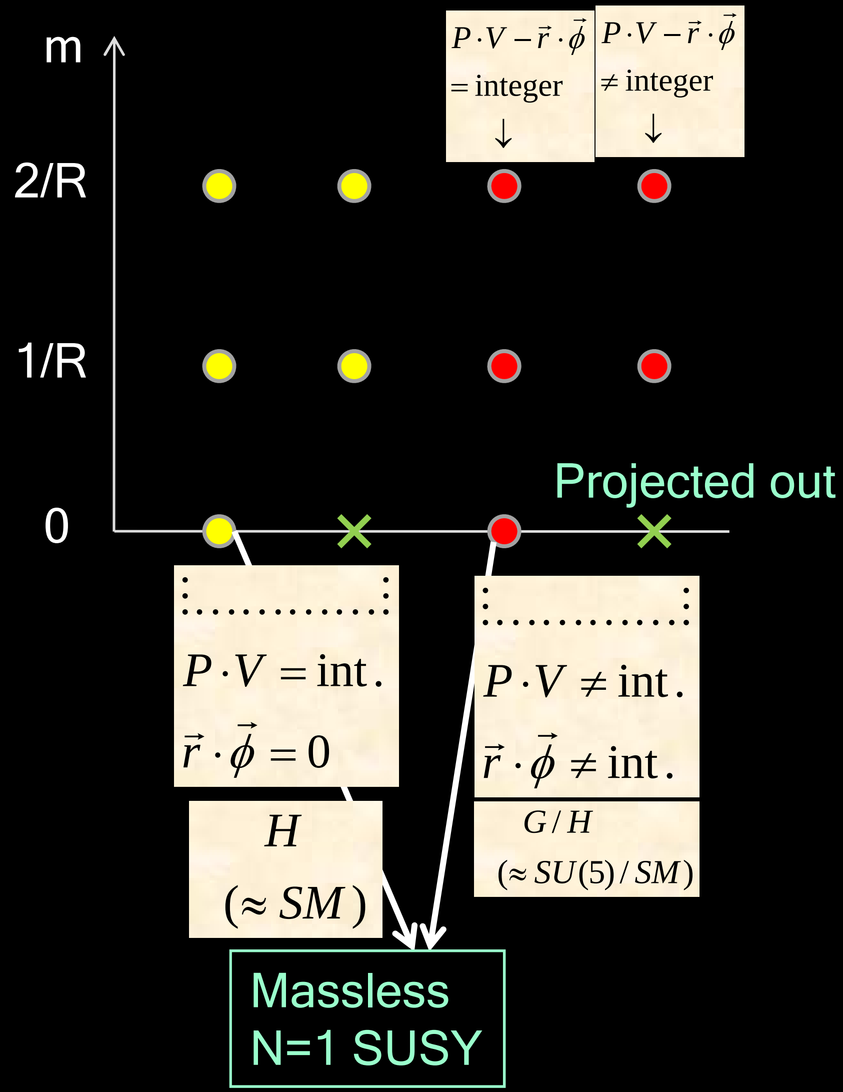
and obtain the R dependence,

$$\frac{4\pi}{\alpha_{H_i}(\mu)} = \frac{4\pi}{\alpha_*} + b^0_{H_i}\log\frac{M_*^2}{\mu^2} - \frac{b_H}{\mu^2}\left[\log\frac{R^2}{\alpha'} + 1.89\right] + \frac{(b_H + b_{G/H})}{4}\left[\frac{2\pi R^2}{\sqrt{3}\alpha'} - 0.30\right]$$

In extra dimensional field theory [Dienes-Dudas-Ghergetta].
R-squared and constant terms are reliable in string calculation, and predicts how gauge couplings behave above the so-called GUT scale.

G $\rightarrow$ H gauge symmetry broken

N=2 SUSY $\rightarrow$ N=1 SUSY



Modular Invariance

Breaking G symm.

Breaking SUSY

N(V^2-φ^2)=integer

Gauge symmetry must be broken

Renormalized gauge coupling

Not $b_H^{N=2}$

$$\frac{16\pi^2}{g_H^2(\mu)} \approx \frac{16\pi^2}{g_*^2(\mu)} + b_H^0 \ln\frac{M_*^2}{\mu^2} - \frac{1}{4} b_G^{N=2}\ln\frac{M_*^2}{M_R^2} + \frac{1}{4} b_G^{N=2}\left[\frac{2\pi}{\sqrt{3}}\ln\frac{M_*^2}{M_c^2} - 2.19\right]$$

$$N=2: \qquad b_{H+G/H} = 24, \quad 0, \quad 48$$

$$SU(8) \quad SO(12)' \quad SU(2)'$$

$$N=2: \qquad b_H = 13, \quad 11, \quad 89/5, \quad -2, \quad 5$$

$$SU(3) \quad SU(4) \quad U(1)_e \quad SO(10)' \quad U(1)_c'$$

$$N=1: \qquad b_{H0} = -3, \quad 1, \quad 33/5$$

$$SU(3) \quad SU(2) \quad U(1)_Y$$

Actually, we need singlet Higgs VEVs to give large masses for exotic particles. This is done by SM singlet VEVs; but these SM singlets can break a larger group in higher dimensions. In our example, so we consider the N=2 b_i in terms of another parameter h_i, [JEK-B. Kyae, PRD77, 106008 (08) [arXiv: 0712.1596[hep-th]]

$$b_i = h_i\left(\log\frac{M_s^2}{M_R^2} + 1.89\right)$$

The hypercharge definition must be made judiciously to avoid chiral exotics or even to remove all exotics.

$$\text{Model E}: \quad Y = \left(\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3}\,\frac{-1}{2}\,\frac{-1}{2}\,;0\,0\,0\right)\left(0\,0\,0;\,0\,0\,0\,0\,0\right)', \qquad \sin^2\theta_W=3/8$$

$$\text{Model S}: \quad \tilde{Y} = \left(\frac{1}{3}\,\frac{1}{3}\,\frac{1}{3}\,\frac{-1}{2}\,\frac{-1}{2}\,;0\,0\,0\right)\left(0\,0\,1;\,0\,0\,0\,0\,0\right)', \qquad \sin^2\theta_W=3/14$$

$$Model\ E: \quad 34.78 \le (7h_3 - 12h_2 + 5h_1) \le 98.02$$

$$\sin^2\theta_W(M_Z) = 0.22306 \pm 0.00033, \qquad \alpha_3 = 0.1216 \pm 0.0017$$

$$Model\ S: \quad \frac{M_R}{M_Z} \approx 1.70\times 10^{15}, \qquad \frac{M_s}{M_R} \approx 3.68$$

3. R parity

R-parity (or some matter parity) in the MSSM is basically put in by hand:

quarks and leptons are odd, Higgses are even

SO(10) GUT advocates that it has a natural R-parity

matter16 odd, Higgs10 even

But it is nothing but the disparity between spinor-vector difference : Spinor(not in the sense of fermion) and Vector representations:
SSV coupling allowed, but SSS coupling not allowed

$u^c d^c d^c$: it is the first step

In heterotic string compactification, we note the E_8 adjoint has

S=(++-+-+++), etc +=1/2, -=-1/2

V=(1 -1 0 0 0 0 0 0), etc

A discrete subgroup of a gauge U(1) is chosen as an R-parity, it is the desired embedding: q, l are S and H are V.

U(1)'s:

Therefore, in heterotic string compactification the strategy is to put matter representations in S type and Higgs reps. in V type of the original E_8.

As a GUT, E_6[Sikivie] is not good in this sense because spinor 16 and vector 10 are put in the same 27.

$$27 = 16+10+1$$

U(1) charge Γ: one case of even Γ VEV, Γ=(2 2 2 0 0 0 0 0) → P

Then, Γ =odd integer for S

Γ =even integer for V. Then P is good.

There are 4 possibilities of U(1)s:

B-L ~ (2 2 2 0 0 0 00), **X** ~ (2 2 2 2 2 0 0 0)

$\mathbf{Q_1}$ ~ (0 0 0 0 0 2 0 0), $\mathbf{Q_2}$ ~ (0 0 0 0 0 0 2 0)

Heterotic strings allow these possibilities. It has been explicitly worked out in a specific Z_{12-I} model.

[JEK-Kyae-JHKim,JHEP 06 (2007) 034 [hep-ph/0702278]: R-parity,etc.]

There are models with approximate R-parities but as shown above an exact R-parity can be achieved also. Since there is no global U(1) except the anomalous U(1), a subgroup of the global U(1) may not be a good symmetry. However, discrete groups are perfectly allowed in string. So, even if we obtain R-parity from a global U(1), some of them can be exact in string models.

4. Approximate global symmetries

If one tries to introduce a very light QCD axion for solving the strong CP problem, one needs to introduce a Peccei-Quinn global symmetry. But the global symmetry corresponding to the model-independent axion of the string models has the decay constant around 10^{16} GeV which does not lead to an acceptable QCD axion.

[K.-S. Choi-JEK-IWKim, JHEP 03 (2007) 116 [hep-ph/0612107];

see also, Choi-Nilles-RamosSanches-Vaudrevange, arXiv:0902.3070]

Another global symmetry much discussed in SUGRA models is the R symmetry. This can also be introduced approximately.

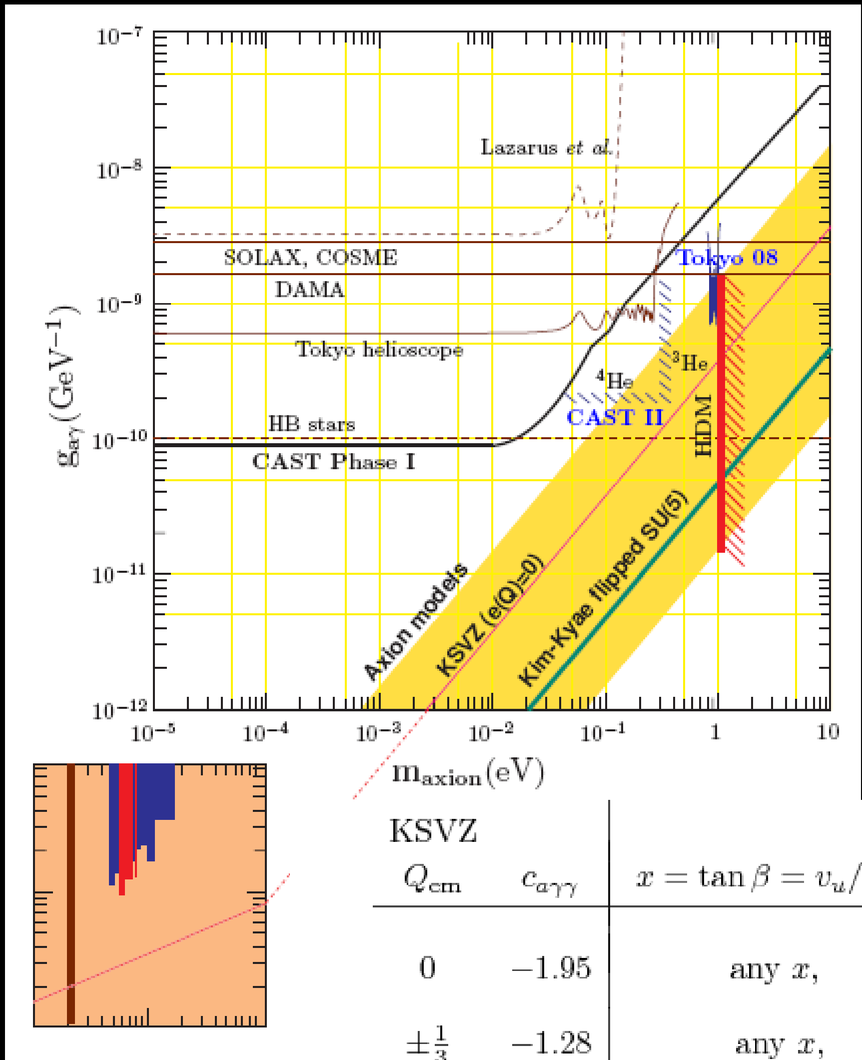
[R. Kappl, H.-P. Nilles, S. Ramos-Sanchez, M. Ratz, K. Schmidt-Hoberg, P.K.S. Vaudrevange, PRL 102 (2009) 121602 [arXiv:0812.2120 [hep-th]]

Of course, the approximate global symmetries must be discussed model by model bases, since the hypothetical models may conflict with other phenomenologies. For interesting U(1)s, we must know all the U(1) charges of the string model: $U(1)_X$ of flipped SU(5): for $\sin^2\theta_W$, approximate $U(1)_{PQ}$.

In our example of the Z_{12-I} model, we searched for all superpotential terms up to order dimension 7 [K.-S. Choi-JEK-IWKim, JHEP 03 (2007) 116, and obtained the approximate PQ symmetry. So, it is a non-trivial task; NOT just a statement that string models might have such and such PQ symmetry.

One cannot introduce just the PQ symmetry in addition to the SM gauge symmetry as in the KSVZ or DFSZ models. String models have a definite spectrum of fermions and we must know all the PQ charges to check whether the model works or not. Because of more than 100 chiral fields in string compactifications, usually it is a tedious task. The only existing example is for a GUT representation of flipped SU(5).

Flipped-SU(5) IS GOOD



KSVZ		DFSZ		
$Q_{\rm em}$	$c_{a\gamma\gamma}$	$x=\tan\beta=v_u/v_d$,	same Higgs for (q^c,e) masses,	$c_{a\gamma\gamma}$
0	-1.95	any x,	(d^c,e)	0.72
$\pm\frac{1}{3}$	-1.28	any x,	(u^c,e)	-1.28
$\pm\frac{2}{3}$	0.72			
± 1	4.05			
(m,m)	-0.28			

5. μ problem

The μ problem can be attacked with the same principle in string compactifications.

The most popular solution is the PQ U(1) global symmetry Such that the mu term H_uH_d is forbidden [K-Nilles]. This PQ symmetry principle is the key in all solutions of the mu problem. The first is forbidding it at string scale from the PQ symmetry. The second is how the required magnitude of TeV scale is obtained. One is again using the PQ symmetry by introducing singlet fields, H_uH_d SS/M with S at the axion scale [K-Nilles]. Another is from the Kaehler Potential [Giudice-Masiero]. Of course, here also the PQ symmetry (or R-sym) is the basic requirement.

If the PQ U(1) global symmetry is the requirement for the μ solution, the approximate global symmetry method must be used in string models. For example, the following W

$$\frac{1}{M^{n-3}} H_u H_d S_1 S_2 \cdots S_{n-2}$$

Such terms satisfy all the selection rules of string compactifications. These rules does not respect any global symmetry but respect only the gauge symmetries. The MI global symmetry is actually an anomalous U(1), so we include MI axion here. In general all global symmetries are broken. Then,

$$S_1 \neq 0, S_1 \neq 0, \cdots, S_{n-2} \neq 0,$$

gives the μ term. If so, n=2 is better.
SUGRA also [Kim, PLB 136 (1984) 378].
Z_3 orbifold has superpotential terms from cubic. So, a μ solution is automatic [Casas-Munoz, PLB 306 (1993) 288].

One of the issues of the μ-problem is why there is only one pair of Higgs doublets. And this must be answered through an explicit model building from string, leading to that discrete symmetry. So, if it comes from a discrete symmetry, it is difficult to persuade without presenting the full model. But if it comes from a gauge symmetry principle, one can accept it easily since string theory allows gauge symmetries.

A $Z_{12\text{-}I}$ Model

This model is very interesting in

- 3 families
- No exotics
- One pair of Higgs doublets
- GMSB at a stable vacuum
- But $\sin^2\Theta_W \neq 3/8$

The shift vector and Wilson line is taken as

V =(1/12)(6 6 6 2 2 2 3 3)(3 3 3 3 3 1 1 1)'

a_3=(1/12)(1 1 2 0 0 0 0 0)(0 0 0 0 0 1 1 -2)'

[JEK, plb 656, 207 (2007) [arXiv:0707.3292]

Gauge group is

$SU(3)_c \times SU(3)_W \times SU(5)' \times SU(3)' \times U(1)s$

Lee-Weinberg electroweak model and no exotics

$$\Gamma = \frac{1}{3}Q_2 + Q_3 + W_8, \quad Lee-Weinberg \quad SU(3)_W$$

$P+[kV+ka]$	No.$\times$(Repts.)$_{Y[Q_1,Q_2,Q_3,Q_4,Q_5]}$	Γ	Label
$(\underline{\frac{-1}{3}\ \frac{-1}{3}\ \frac{-2}{3}}\ \underline{\frac{2}{3}\ \frac{-1}{3}}\ \frac{-1}{3}\ 0\ 0)(0^8)'_{T_{4_-}}$	$3\cdot(\mathbf{3},\mathbf{2})^L_{1/6\ [0,0,0;0,0]}$	1	$q_1,\ q_2,\ q_3$
$(\underline{\frac{1}{6}\ \frac{1}{6}\ \frac{5}{6}}\ \frac{1}{6}\ \frac{1}{6}\ \frac{1}{6}\ \frac{1}{2}\ \frac{1}{2})(0^8)'_{T_{4_-}}$	$2\cdot(\overline{\mathbf{3}},\mathbf{1})^L_{-2/3\ [-3,3,2;0,0]}$	3	$u^c,\ c^c$
$(\underline{\frac{-1}{3}\ \frac{-1}{3}\ \frac{-2}{3}}\ \frac{1}{3}\ \frac{1}{3}\ \frac{1}{3}\ \frac{-1}{4}\ \frac{-1}{4})(\frac{1}{4}^5\ \frac{1}{12}\ \frac{1}{12}\ \frac{1}{12})'_{T_{7_+}}$	$(\overline{\mathbf{3}},\mathbf{1})^L_{-2/3\ [0,6,-1;5,1]}$	1	t^c
$(\underline{\frac{1}{2}\ \frac{1}{2}\ \frac{1}{2}}\ \frac{-1}{6}\ \frac{-1}{6}\ \frac{-1}{6}\ 0\ 0)(0^5\ \frac{-1}{3}\ \frac{-1}{3}\ \frac{-1}{3})'_{T_{2_0}}$	$(\overline{\mathbf{3}},\mathbf{1})^L_{1/3\ [3,-3,0;0,-4]}$	-1	d^c
$(\underline{\frac{1}{6}\ \frac{1}{6}\ \frac{5}{6}}\ \frac{1}{6}\ \frac{1}{6}\ \frac{1}{6}\ \frac{-1}{2}\ \frac{-1}{2})(0^8)'_{T_{4_-}}$	$2\cdot(\overline{\mathbf{3}},\mathbf{1})^L_{1/3\ [-3,3,-2;0,0]}$	1	$s^c,\ b^c$
$(\frac{-1}{3}\ \frac{-1}{3}\ \frac{1}{3}\ \underline{\frac{2}{3}\ \frac{-1}{3}}\ \frac{2}{3}\ 0\ 0)(0^8)'_{T_{4_-}}$	$(\mathbf{1},\mathbf{2})^L_{-1/2\ [-6,6,0;0,0]}$	1	l_1,l_2,l_3
$(0\ 0\ 0\ \underline{\frac{2}{3}\ \frac{-1}{3}}\ \frac{2}{3}\ \frac{-1}{4}\ \frac{-1}{4})(\frac{1}{4}^5\ \frac{1}{12}\ \frac{1}{12}\ \frac{1}{12})'_{T_{1_0}}$	$(\mathbf{1},\mathbf{2})^L_{1/2\ [0,6,-1;5,1]}$	0	H_u
$(\frac{-1}{3}\ \frac{-1}{3}\ \frac{1}{3}\ \underline{\frac{1}{3}\ \frac{-2}{3}}\ \frac{1}{3}\ \frac{-1}{4}\ \frac{-1}{4})(\frac{1}{4}^5\ \frac{1}{12}\ \frac{1}{12}\ \frac{1}{12})'_{T_{7_+}}$	$(\mathbf{1},\mathbf{2})^L_{-1/2\ [-6,0,-1;5,1]}$	-2	H_d

The SM spectrum.

Note that U(1)$_\Gamma$ charges of SM fermions are odd and Higgs doublets are even. By breaking by VEVs of even Γ singlets, we break U(1)$_\Gamma$ to a discrete matter parity P or Dreiner's matter parity Z6 is realized; dim. 5 operator qqql [Sakai-Yanagida, Hall-Weinberg] is not allowed.

After removing vectorlike representations by Γ = even integer singlets, the starred representations remain

$P+n[V\pm a]$	Γ	$\mathrm{No.}\times(\mathrm{Repts.})_{Y[Q_1,Q_2,Q_3,Q_4,Q_5]}$
$(\frac{1}{6}\frac{1}{6}\frac{-1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{4}\frac{1}{4})(\underline{\frac{-3}{4}\frac{1}{4}\frac{1}{4}\frac{1}{4}\frac{1}{4}}\frac{-1}{4}\frac{-1}{4}\frac{-1}{4})'_{T1_-}$	2	$(\mathbf{1};\bar{\mathbf{5}}',\mathbf{1})^L_{0[3,3,1;1,-1]}$
$(\frac{1}{6}\frac{1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6}00)(\underline{\frac{1}{2}\frac{1}{2}\frac{-1}{2}\frac{-1}{2}\frac{-1}{2}}\frac{-1}{6}\frac{-1}{6}\frac{-1}{6})'_{T2_+}$	-1	$\star(\mathbf{1};\mathbf{10}',\mathbf{1})^L_{0[3,-3,0;-2,-2]}$
$(0^6\underline{\frac{1}{4}\frac{-3}{4}})(\underline{\frac{3}{4}\frac{-1}{4}\frac{-1}{4}\frac{-1}{4}\frac{-1}{4}}\frac{1}{4}\frac{1}{4}\frac{1}{4})'_{T3}$	-1	$(\mathbf{2}_n;\mathbf{5}',\mathbf{1})^L_{0[0,0,-1;-1,3]}$
$(0^6\underline{\frac{3}{4}\frac{-1}{4}})(\underline{\frac{-3}{4}\frac{1}{4}\frac{1}{4}\frac{1}{4}\frac{1}{4}}\frac{-1}{4}\frac{-1}{4}\frac{-1}{4})'_{T9}$	1	$(\mathbf{2}_n;\bar{\mathbf{5}}',\mathbf{1})^L_{0[0,0,1;1,-3]}$
$(0^3\frac{-1}{3}\frac{-1}{3}\frac{-1}{3}\frac{1}{4}\frac{1}{4})(\underline{\frac{-3}{4}\frac{1}{4}\frac{1}{4}\frac{1}{4}\frac{1}{4}}\frac{1}{12}\frac{1}{12}\frac{1}{12})'_{T7_0}$	-1	$\star(\mathbf{1};\bar{\mathbf{5}}',\mathbf{1})^L_{0[0,-6,1;1,1]}$
$(\frac{1}{6}\frac{1}{6}\frac{-1}{6}\frac{1}{6}\frac{1}{6}\frac{1}{6}\frac{-1}{4}\frac{-1}{4})(\underline{\frac{3}{4}\frac{-1}{4}\frac{-1}{4}\frac{-1}{4}\frac{-1}{4}}\frac{1}{4}\frac{1}{4}\frac{1}{4})'_{T7_-}$	0	$(\mathbf{1};\mathbf{5}',\mathbf{1})^L_{0[3,3,-1;-1,3]}$
$(0^6\frac{-1}{2}\frac{-1}{2})(\underline{-10000}000)'_{T6}$	-2	$3\cdot(\mathbf{1};\bar{\mathbf{5}}',\mathbf{1})^L_{0[0,0,-2;-4,0]}$
$(0^6\frac{-1}{2}\frac{-1}{2})(\underline{10000}000)'_{T6}$	-2	$2\cdot(\mathbf{1};\mathbf{5}',\mathbf{1})^L_{1[0,0,-2;4,0]}$
$(0^6\frac{1}{2}\frac{1}{2})(\underline{-10000}000)'_{T6}$	2	$2\cdot(\mathbf{1};\bar{\mathbf{5}}',\mathbf{1})^L_{-1[0,0,2;-4,0]}$
$(0^6\frac{1}{2}\frac{1}{2})(\underline{10000}000)'_{T6}$	2	$3\cdot(\mathbf{1};\mathbf{5},\mathbf{1})^L_{0[0,0,2;4,0]}$

The hidden SU(5)' spectrum.

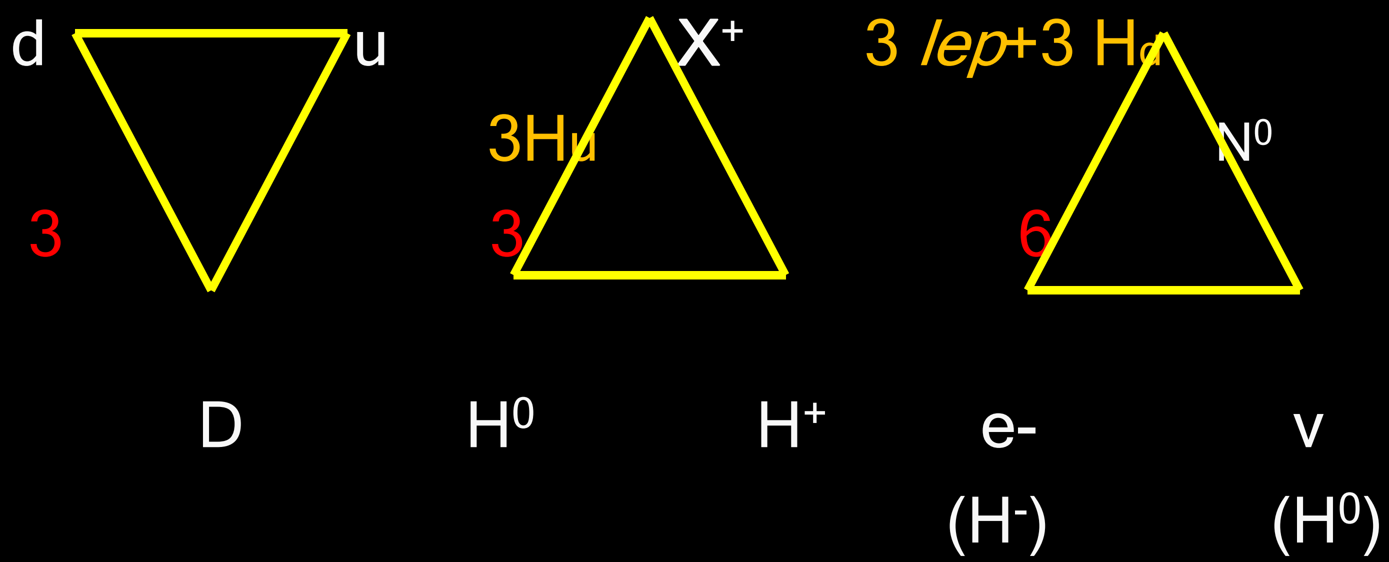
Note that 10'+5*' remain.
It leads to a dynamical SUSY breaking.

Three quark families appear as

$3\ (3_c, 3_W)$

At low energy, we must have nine 3^*_W to cancel $SU(3)_W$ anomaly.

Both H_u and H_d appear from 3*. It is in contrast to the other cases such as in SU(5) or SO(10). Now, the H_u and H_d coupling must come from $3^*_W\ 3^*_W\ 3^*_W$ coupling.



There remain three pairs of $3^*_W(H^+)$ and $3^*_W(H^-)$ plus three families of 3_W(quark) and 3^*_W(lepton)

Thus, there appears the Levi-Civita symbol and two epsilons are appearing, in $SU(3)_W$ space, a, b, c and in flavor space, I, J, ….

Therefore, in the flavor space the H_u-H_d mass matrix is antisymmetric and hence its determinant is zero.

It is interesting to compare an old QCD idea and the present Lee-Weinberg model:

Introduction of color:

56 of old SU(6) in 1960s = completely symm.
But spin-half quarks are fermions →
introduce antisymmetric index= SU(3) color [Han-Nambu]

Introduction of flavor in the Higgs sector:

Lee-Weinberg SU(3)-weak gives
3*-3*-3* SU(3)-weak singlet = antisymmetric gives
antisymmetric bosonic flavor symmetry (SUSY)!
and one pair of Higgs doublets is massless.

But $\sin^2\theta_W$ is not 3/8; we must resort to the string threshold correction.

There is another method. SU(5) xSU(5)': Huh-JEK-Kyae, PRD 80, 115012 (2009) [arXiv: 0904.1108 [hep-ph]]: Merit is a GUT

$$
\begin{array}{cc}
 & \begin{array}{ccc} \bar{5}_{2}^{(0)T4} & \bar{5}_{2}^{(0)T4} & \bar{5}_{2}^{(1)T7} \end{array} \\
\begin{array}{c} 5^{a\,(1)T4}_{-2} \\ 5^{b\,(1)T4}_{-2} \\ 5^{c\,(2)T7}_{-2} \end{array} &
\begin{pmatrix}
S_1(-1)_{T4} & S_1(-1)_{T4} & 0 \\
S_1(-1)_{T4} & S_1(-1)_{T4} & 0 \\
S_{19}(-2)_{T1} & S_{19}(-2)_{T1} & 0
\end{pmatrix}
\end{array}
$$

SU(5) xSU(5)’: Huh-JEK-Kyae, PRD 80, 115012 (2009) [arXiv: 0904.1108 [hep-ph]]: Merit is a GUT

$$V=\left(0\quad 0\quad 0\quad 0\quad 0\quad -\frac{1}{6}\quad -\frac{1}{6}\quad -\frac{1}{6}\right)\left(0\quad 0\quad 0\quad 0\quad 0\quad \frac{1}{4}\quad \frac{1}{4}\quad -\frac{2}{4}\right)$$

$$W=\left(\frac{2}{3}\quad \frac{2}{3}\quad \frac{2}{3}\quad \frac{2}{3}\quad \frac{2}{3}\quad 0\quad -\frac{2}{3}\quad \frac{2}{3}\right)\left(\frac{2}{3}\quad \frac{2}{3}\quad \frac{2}{3}\quad \frac{2}{3}\quad 0\quad -\frac{2}{3}\quad 0\quad 0\right)$$

It is a flipped SU(5) GUT model with
(1) three families, (2) $\sin^2\theta_W = 3/8$, (3) no chiral exotics,
(4) one pair of 10_H and 10^*_H for the SU(5)xU(1) breaking, and

(5) 10’ + 5’* for dynamical SUSY breaking.

[G. Veneziano, PLB128, 199 (1983); I. Affleck, M. Dine, N. Seiberg, NPB256, 557 (1985); E. Poppitz, S. P. Trivedi, PLB 365, 125 (1996)]

6. Multi dark matter

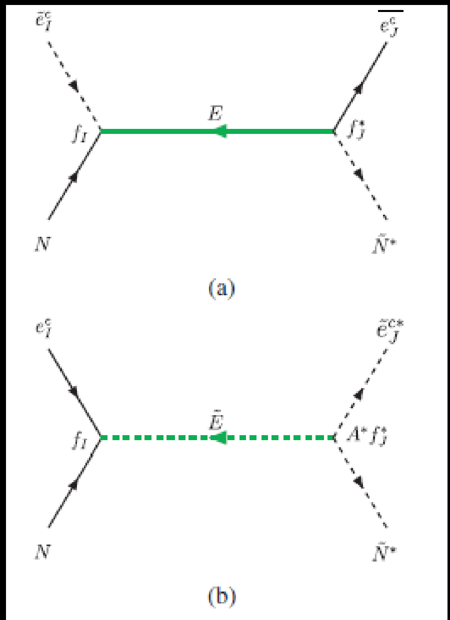
There are two issues on multi DM from string compact.

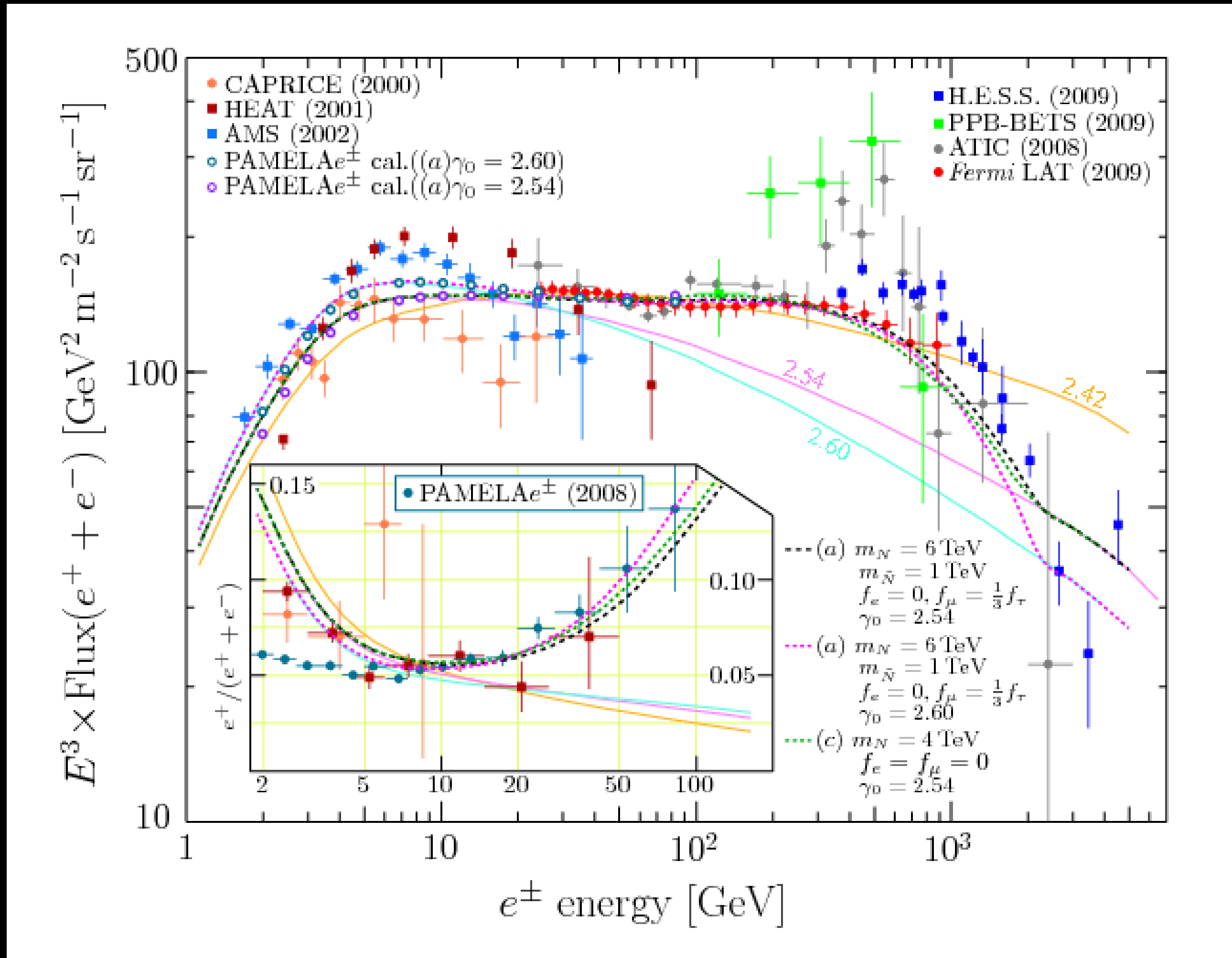
(1) Heavy DM (10 GeV, 100 GeV, 3 TeV ?) MSSM particles plus a 2-3 TeV decaying DM with dim 6 operators suppressed by 10^{14} GeV. An explicit SUSY model constructed, with its number density determined by the decay of a heavy axino.
[Huh-JEK, PRD80, 075012 (2009) [arXiv: 0908.0152[hep-ph]]; Kyae, JCAP 0907, 028 (09), 0902.0071; Bae-Kyae, JHEP 0905 ,102 (09); Arvanitaki-Dimopoulos et al., PRD80, 055011 (09), 0904.2789]

(2) Mini-charged DM (eV, or milli, micro eV order?), photon-U(1)' kinetic mixing present from string compactification?

[JEK, PRD76, 051701 (2007) [arXiv: 0704.3310]]

A milli-charged model is commented from a Z_{12-I} model of JHKim-K-Kyae on the SM. It depends on how the vacuum direction is chosen.





Huh-K, PRD 80 (2009) 075012 [arXiv:0908.0152]

Conclusion

I reviewed SUGRA phenomenological issues from Z_{12-I} string compactifications:

- Orbifold models, ● SUSY GUTs and SSM

And short comments on

- R parity
- Approximate global symmetries
  Approximate PQ symmetry, $U(1)_{1R}$ symmetry
- μ problem
- Multi dark matter