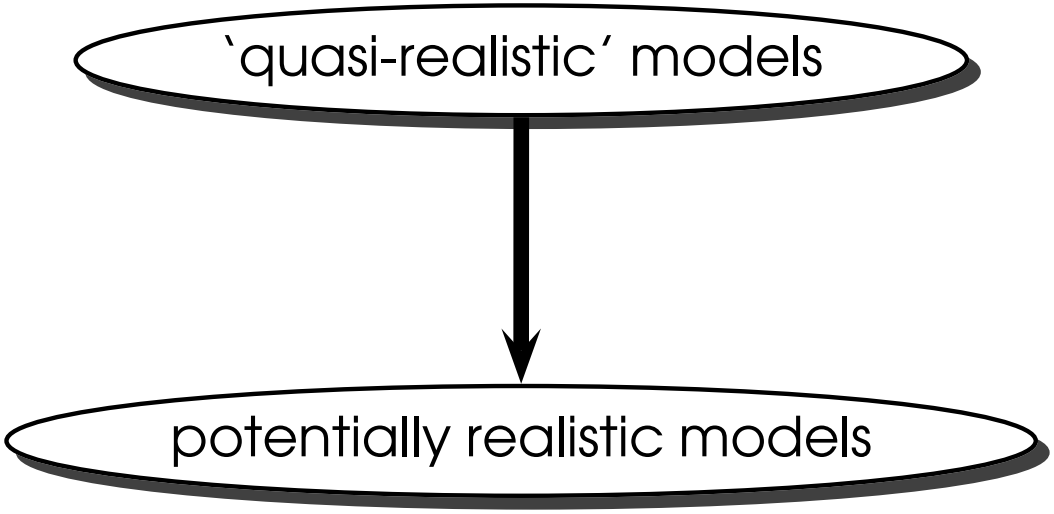
The role of discrete symmetries in string models of particle physics

Michael Ratz

Based on collaborations with:
M. Blaszczyk, F. Brümmer, S. Groot Nibbelink, R. Kappl, B. Petersen, H.P. Nilles, S. Ramos-Sánchez, F. Ruehle, K. Schmidt-Hoberg, M. Trapletti & P. Vaudrevange
. . . building on earlier work with:
W. Buchmüller, K. Hamaguchi, T. Kobayashi, O. Lebedev, F. Plöger & S. Raby

Heterotic model building: status

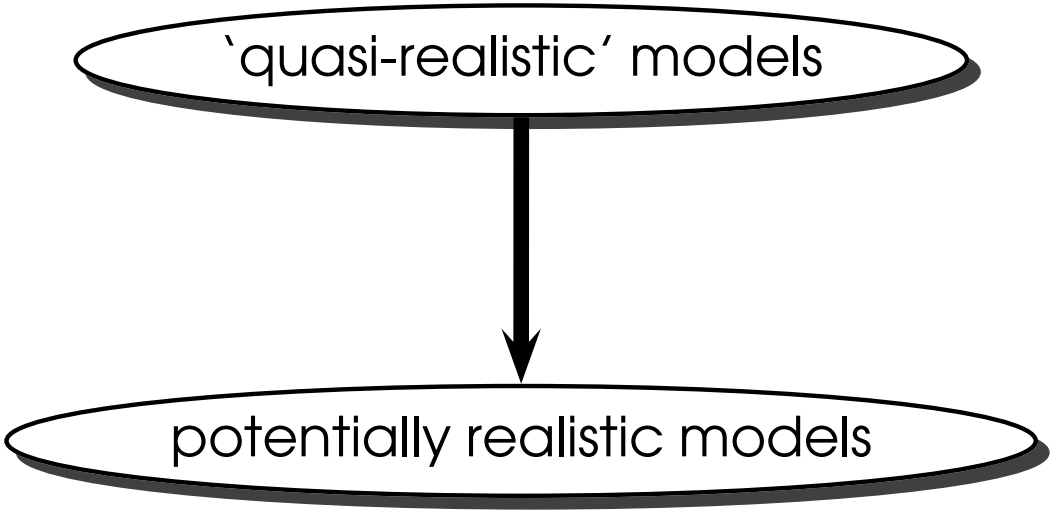
- In the 200x years there has been progress in (heterotic) string model building:



Buchmüller et al.
Bouchard, Donagi
Braun, He, Ovrut, Pantev
Lebedev et al.
Kim, Kyae
Anderson, Gray, He, Lukas

Heterotic model building: status

- In the 200x years there has been progress in (heterotic) string model building:

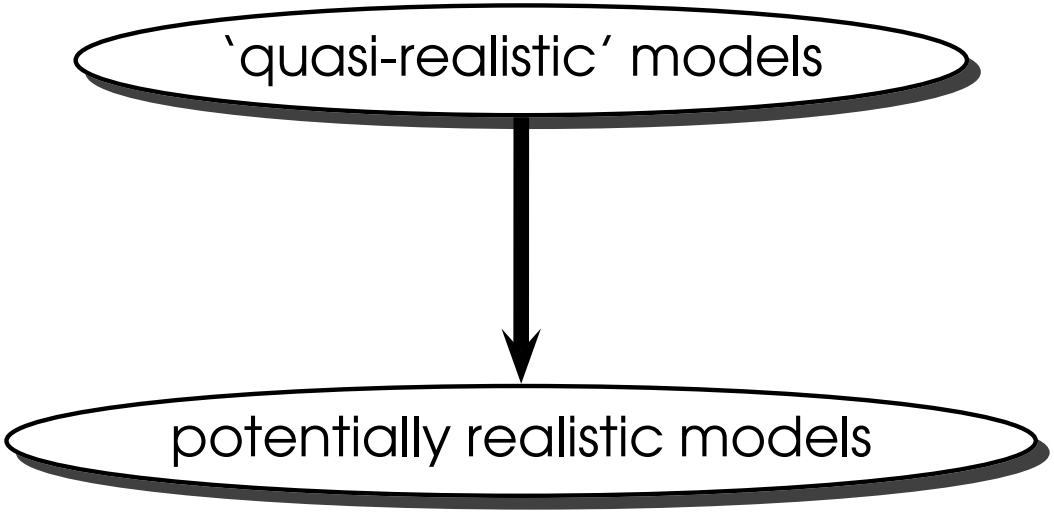


translation: interesting features but immediately ruled out

translation: not yet explored well enough to tell whether ruled out or not

Heterotic model building: status

- In the 200x years there has been progress in (heterotic) string model building:



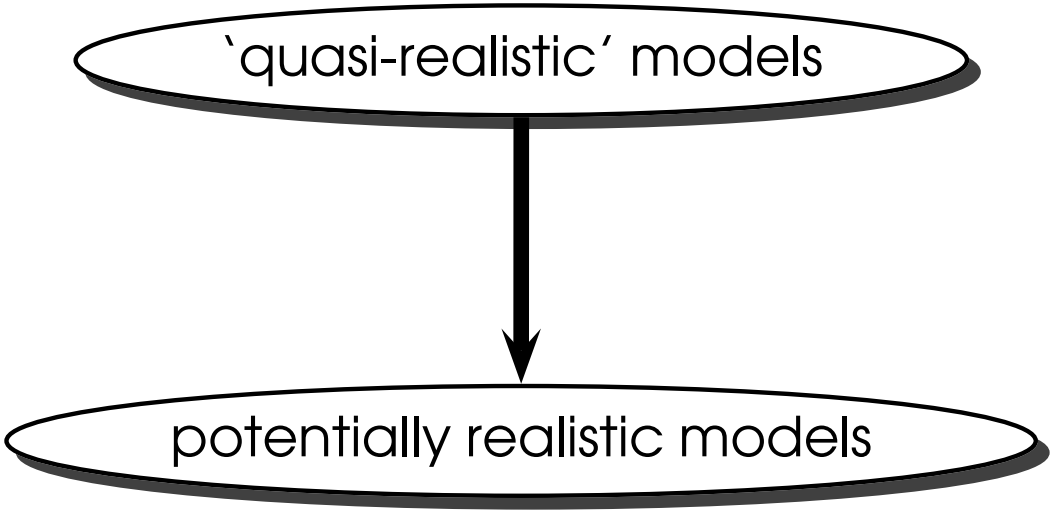
translation: interesting features but immediately ruled out

translation: not yet explored well enough to tell whether ruled out or not

- Obvious next step: explore these constructions

Heterotic model building: status

- In the 200x years there has been progress in (heterotic) string model building:



translation: interesting features but immediately ruled out

translation: not yet explored well enough to tell whether ruled out or not

- Obvious next step: explore these constructions
- Ultimate hope:

Predictions for LHC

Why do string model building at all?

- **Wish list**:
  1. find a model that is consistent with observation

Why do string model building at all?

☞ **Wish list**:

1. find a model that is consistent with observation
2. try to obtain a better understanding of observation (quantum numbers of matter, couplings, etc.)

Why do string model building at all?

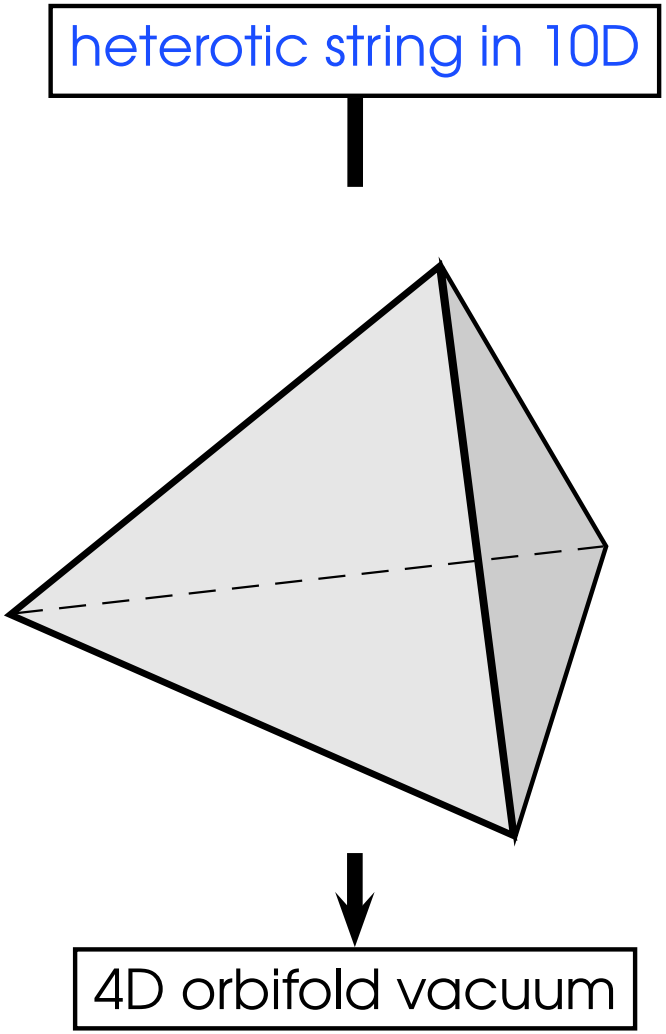
☞ **Wish list**:

1. find a model that is consistent with observation
2. try to obtain a better understanding of observation (quantum numbers of matter, couplings, etc.)
3. try to find answers to open questions within this model
   - scale of soft ~~SUSY~~ terms
   - MSSM μ problem
   - strong CP problem
   - ...

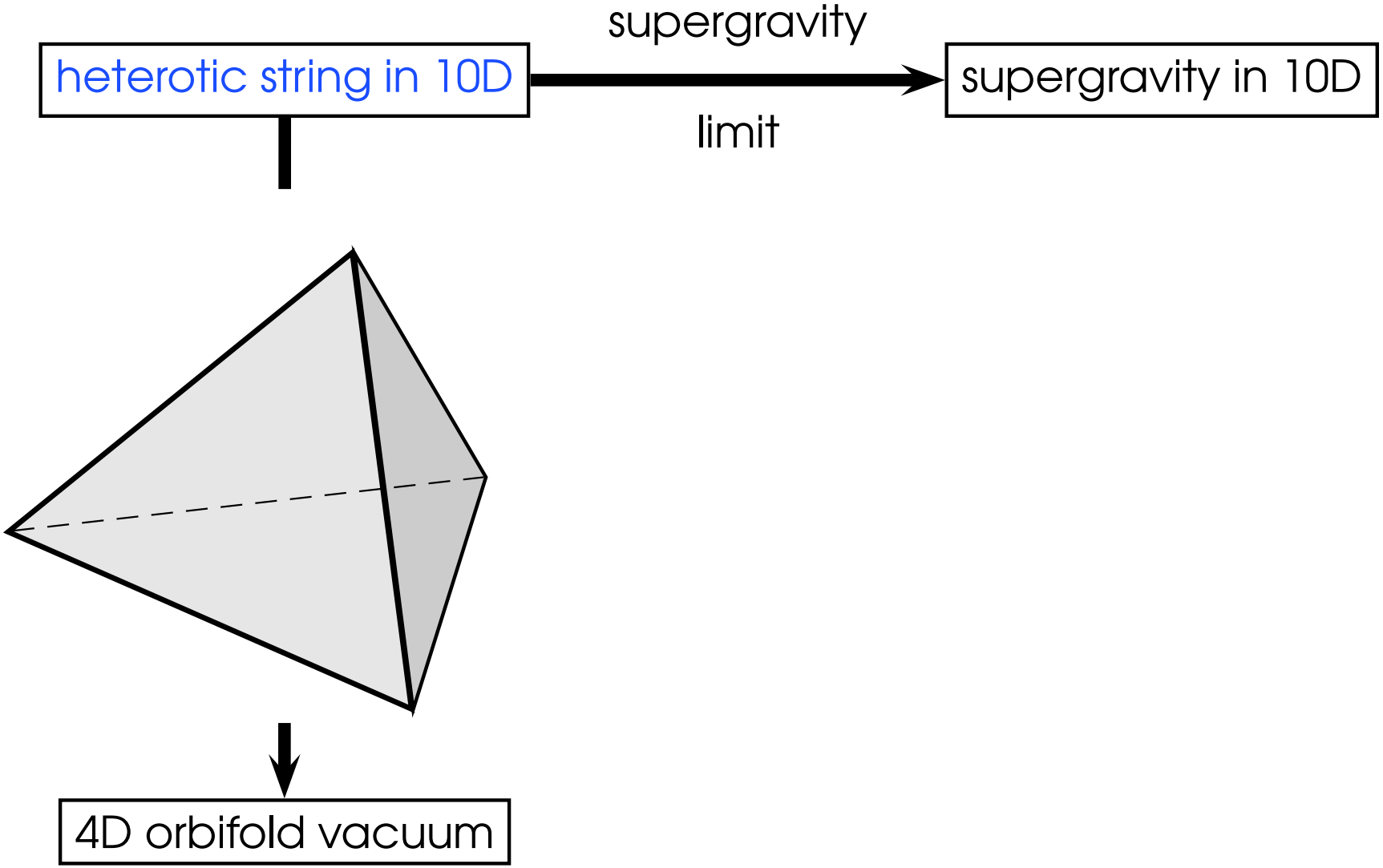
Why do string model building at all?

- **Wish list**:
  1. find a model that is consistent with observation
  2. try to obtain a better understanding of observation (quantum numbers of matter, couplings, etc.)
  3. try to find answers to open questions within this model
     - scale of soft ~~SUSY~~ terms
     - MSSM μ problem
     - strong CP problem
     - ...
- **This talk**: strategy to answer the open questions : symmetries

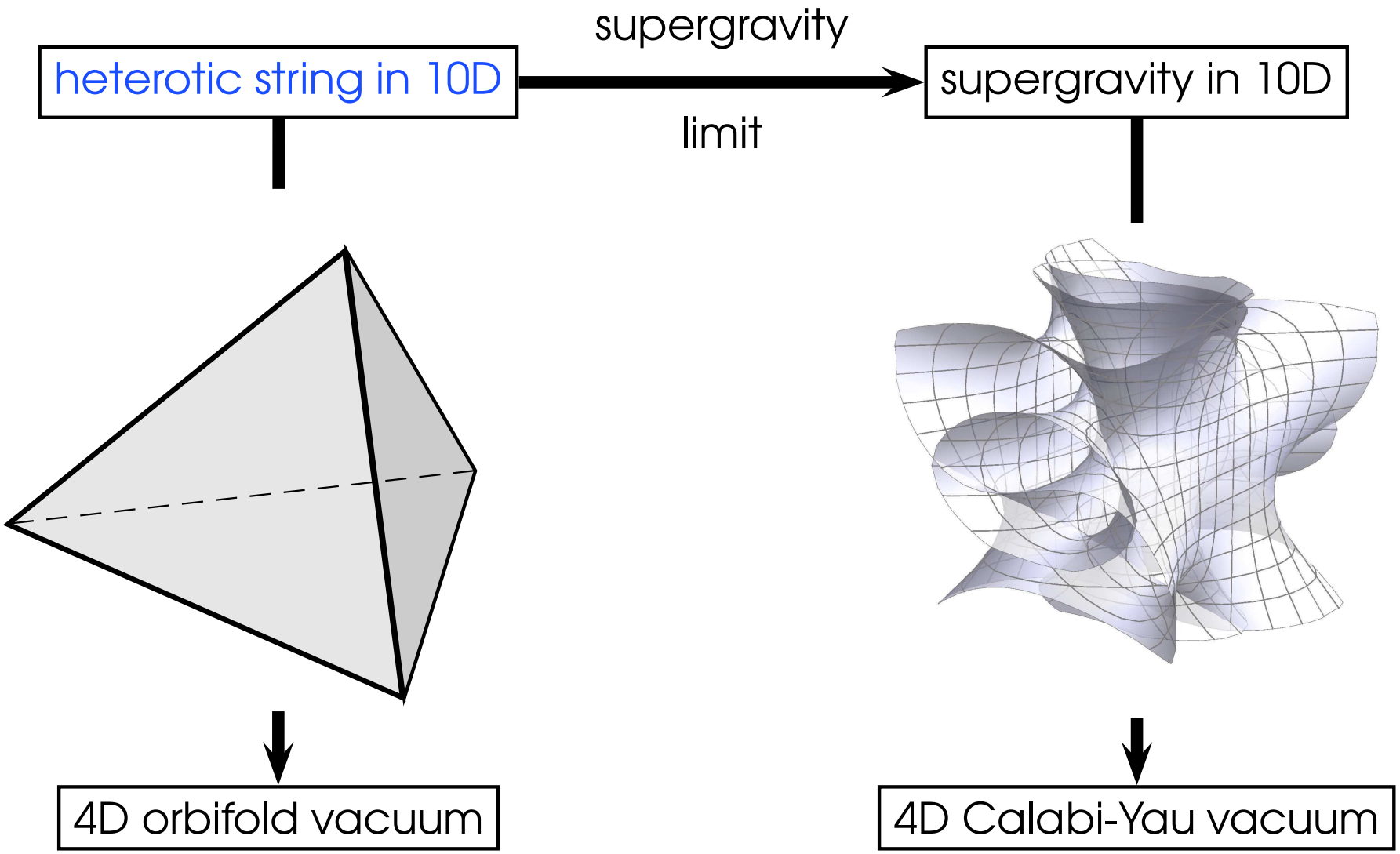
Orbifolds vs. Calabi-Yau compactifications



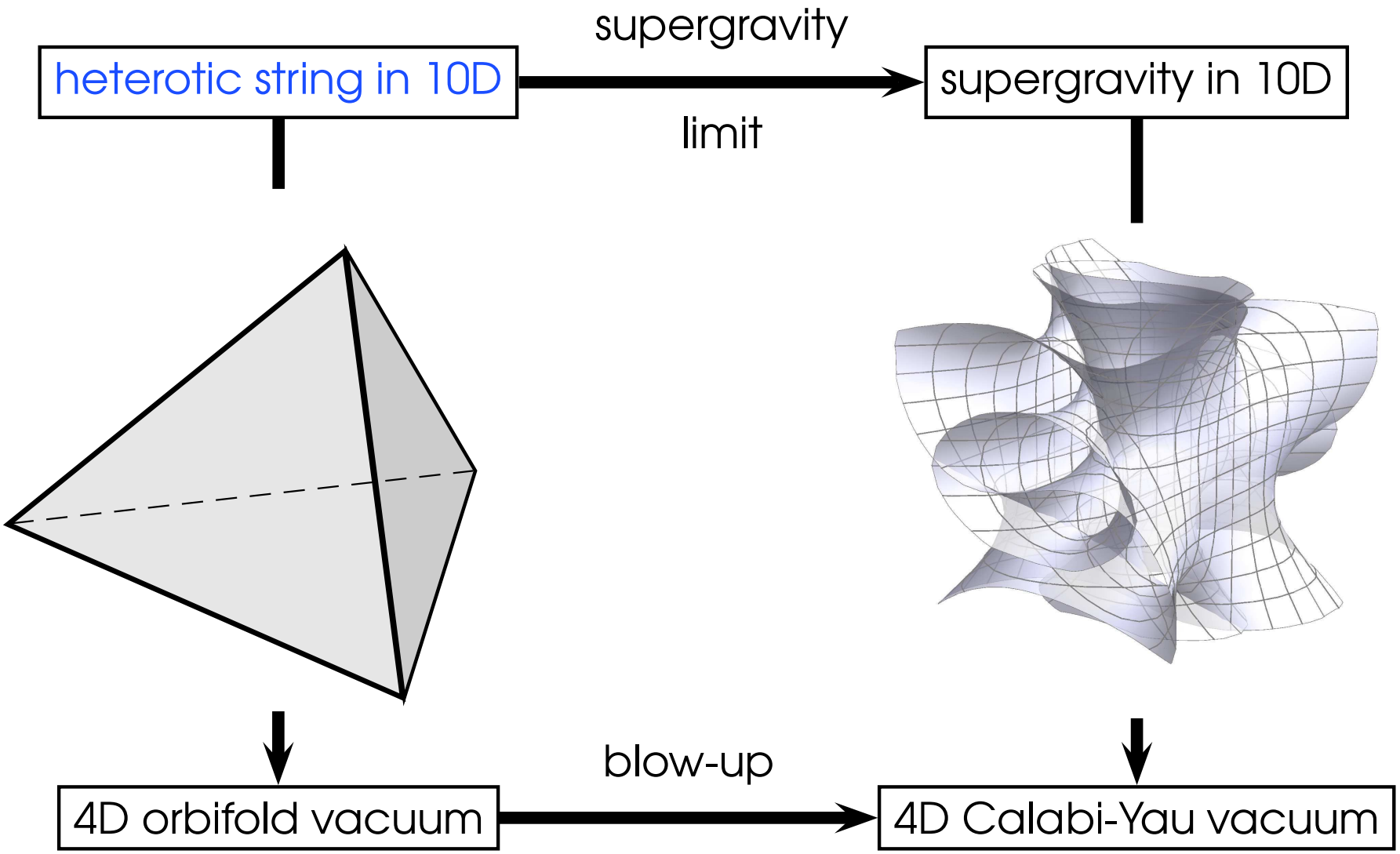
Orbifolds vs. Calabi-Yau compactifications



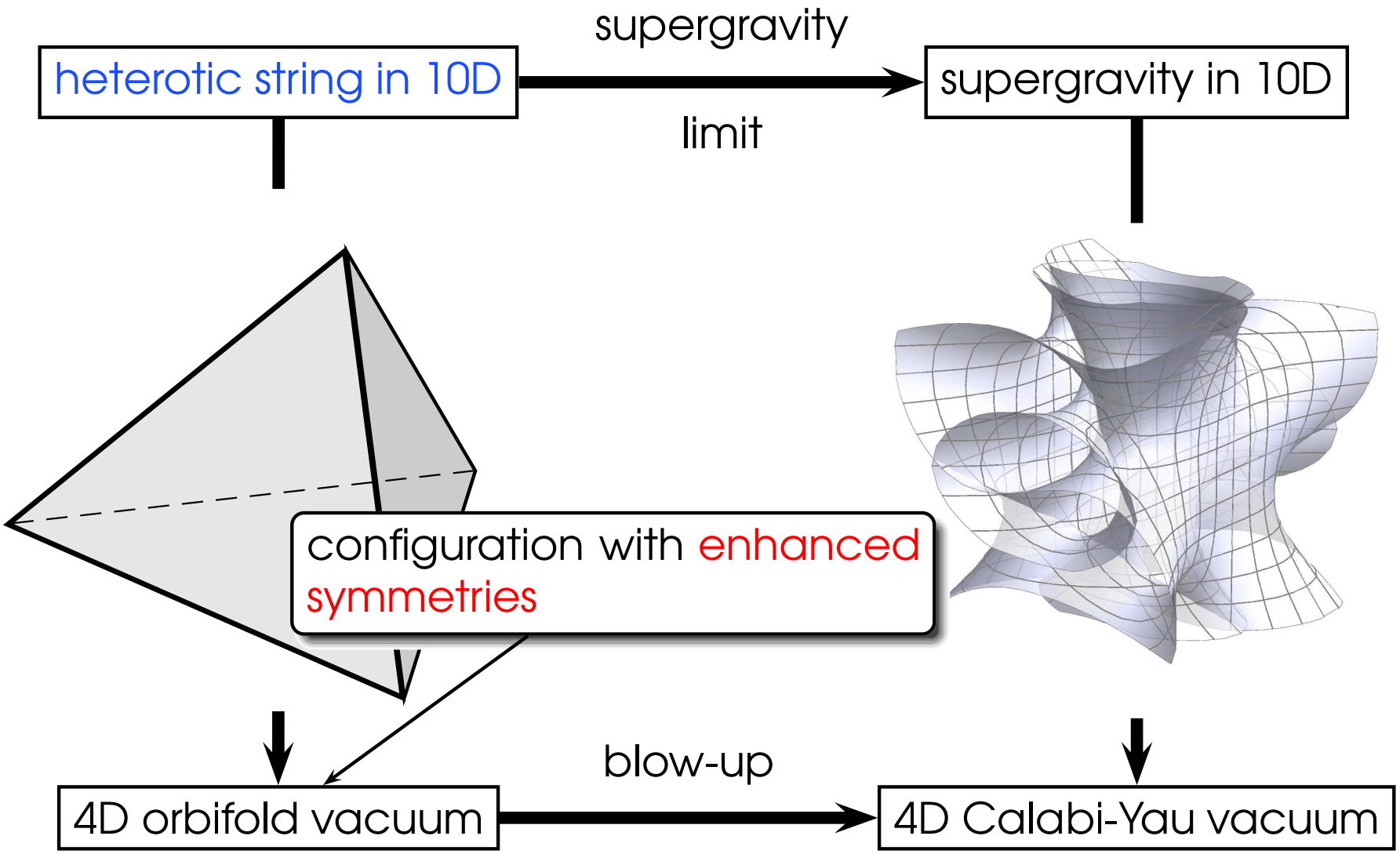
Orbifolds vs. Calabi-Yau compactifications



Orbifolds vs. Calabi-Yau compactifications



Orbifolds vs. Calabi-Yau compactifications



Towards fully realistic models

☞ Strategy in this talk: use exact and approximate symmetries

Towards fully realistic models

- Strategy in this talk: use exact and approximate symmetries
- Focus on the following questions:

Towards fully realistic models

- ☞ Strategy in this talk: use exact and approximate symmetries
- ☞ Focus on the following questions:

1. hierarchically small scale of $\langle \mathscr{W} \rangle$ & $m_{3/2}$

Towards fully realistic models

- ☞ Strategy in this talk: use exact and approximate symmetries
- ☞ Focus on the following questions:

1. hierarchically small scale of $\langle \mathscr{W} \rangle$ & $m_{3/2}$
2. MSSM μ term

Towards fully realistic models

- ☞ Strategy in this talk: use exact and approximate symmetries
- ☞ Focus on the following questions:

1. hierarchically small scale of $\langle \mathscr{W} \rangle$ & $m_{3/2}$
2. MSSM μ term
3. matter parity (a.k.a. R-parity)

Towards fully realistic models

- ☞ Strategy in this talk: use exact and approximate symmetries
- ☞ Focus on the following questions:

1. hierarchically small scale of $\langle \mathscr{W} \rangle$ & $m_{3/2}$
2. MSSM μ term
3. matter parity (a.k.a. R-parity)
4. SUSY flavor structure

Towards fully realistic models

- ☞ Strategy in this talk: use exact and approximate symmetries
- ☞ Focus on the following questions:

1. hierarchically small scale of $\langle \mathscr{W} \rangle$ & $m_{3/2}$
2. MSSM μ term
3. matter parity (a.k.a. R-parity)
4. SUSY flavor structure
5. proton stability

Outline

1. Introduction & Motivation ✓
2. The role of (discrete) R-symmetries in understanding:
   - a small gravitino mass
   - a suppressed μ term
3. The role of remnant symmetries in understanding
   - SUSY flavor structure
   - proton stability
4. Summary

Small superpotential VEVs

from

approximate R symmetries

Hierarchically small $\langle \mathscr{W} \rangle$

Two ingredients:

1. in the presence of an exact $\mathrm{U}(1)_R$ symmetry

$$\boxed{\frac{\partial \mathscr{W}}{\partial \phi_i} = 0} \curvearrowright \boxed{\langle \mathscr{W} \rangle = 0}$$

Hierarchically small $\langle \mathscr{W} \rangle$

Two ingredients:

1. in the presence of an exact $\mathrm{U}(1)_R$ symmetry

$$\frac{\partial \mathscr{W}}{\partial \phi_i} = 0 \quad \curvearrowright \quad \langle \mathscr{W} \rangle = 0$$

fields

superpotential

Hierarchically small $\langle \mathscr{W} \rangle$

Two ingredients:

1. in the presence of an exact $\mathrm{U}(1)_R$ symmetry

$$\boxed{\frac{\partial \mathscr{W}}{\partial \phi_i} = 0} \curvearrowright \boxed{\langle \mathscr{W} \rangle = 0}$$

2. for an approximate R symmetries

$$\boxed{\langle \mathscr{W} \rangle \sim \langle \phi \rangle^N}$$

typical field VEV

order of explicit $\mathrm{U}(1)_R$ breaking terms

$\langle \mathscr{W} \rangle = 0$ because of $\mathrm{U}(1)_R$ (I)

aim: show that

$$\boxed{\frac{\partial \mathscr{W}}{\partial \phi_i} = 0} \curvearrowright \boxed{\langle \mathscr{W} \rangle = 0}$$

$\langle \mathscr{W} \rangle = 0$ because of $\mathrm{U}(1)_R$ (I)

aim: show that

$$\boxed{\frac{\partial \mathscr{W}}{\partial \phi_i} = 0} \curvearrowright \boxed{\langle \mathscr{W} \rangle = 0}$$

Consider a superpotential

$$\mathscr{W} = \sum c_{n_1 \cdots n_M} \phi_1^{n_1} \cdots \phi_M^{n_M}$$

with an exact R-symmetry

$$\mathscr{W} \to \mathrm{e}^{2\mathrm{i}\,\alpha}\, \mathscr{W} \,, \quad \phi_j \to \phi_j' = \mathrm{e}^{\mathrm{i}\, r_j\, \alpha}\, \phi_j$$

where each monomial in $\mathscr{W}$ has total R-charge 2

$\langle \mathscr{W} \rangle = 0$ because of $\mathrm{U}(1)_R$ (II)

Consider a field configuration $\langle \phi_i \rangle$ with

$$F_i = \frac{\partial \mathscr{W}}{\partial \phi_i} = 0 \quad \text{at } \phi_j = \langle \phi_j \rangle$$

Under an infinitesimal $\mathrm{U}(1)_R$ transformation, the superpotential transforms nontrivially

$$\mathscr{W}(\phi_j) \to \mathscr{W}(\phi'_j) = \mathscr{W}(\phi_j) + \sum_i \frac{\partial \mathscr{W}}{\partial \phi_i} \Delta \phi_i$$

$\langle \mathscr{W} \rangle = 0$ because of $\mathrm{U}(1)_R$ (II)

Consider a field configuration $\langle \phi_i \rangle$ with

$$F_i = \frac{\partial \mathscr{W}}{\partial \phi_i} = 0 \quad \text{at } \phi_j = \langle \phi_j \rangle$$

Under an infinitesimal $\mathrm{U}(1)_R$ transformation, the superpotential transforms nontrivially

$$\mathscr{W}(\phi_j) \to \mathscr{W}(\phi_j') = \mathscr{W}(\phi_j) + \sum_i \cancel{\frac{\partial \mathscr{W}}{\partial \phi_i}} \Delta \phi_i$$

$\langle \mathscr{W} \rangle = 0$ because of $\mathrm{U}(1)_R$ (II)

Consider a field configuration $\langle \phi_i \rangle$ with

$$F_i = \frac{\partial \mathscr{W}}{\partial \phi_i} = 0 \quad \text{at } \phi_j = \langle \phi_j \rangle$$

Under an infinitesimal $\mathrm{U}(1)_R$ transformation, the superpotential transforms nontrivially

$$\mathscr{W}(\phi_j) \to \mathscr{W}(\phi_j') = \mathscr{W}(\phi_j) + \sum_i \cancel{\frac{\partial \mathscr{W}}{\partial \phi_i}} \Delta\phi_i \stackrel{!}{=} \mathrm{e}^{2\mathrm{i}\,\alpha}\, \mathscr{W}$$

This is only possible if $\langle \mathscr{W} \rangle = 0$!

bottom-line:

$$\boxed{\frac{\partial \mathscr{W}}{\partial \phi_i} = 0} \curvearrowright \boxed{\langle \mathscr{W} \rangle = 0}$$

Comments

1. Statement $\langle \mathscr{W} \rangle = 0$ holds regardless of whether $\mathrm{U}(1)_R$ is unbroken (where it is trivial) or broken

Comments

1. Statement $\langle \mathscr{W} \rangle = 0$ holds regardless of whether $\mathrm{U}(1)_R$ is unbroken (where it is trivial) or broken

2. Relation to Nelson-Seiberg theorem Nelson & Seiberg (1994)

$$\left\{ \begin{array}{c} \text{setting without} \\ \text{supersymmetric} \\ \text{ground state} \end{array} \right\} \xrightarrow{\text{requires}} \mathrm{U}(1)_R \text{ symmetry}$$

Comments

1. Statement $\langle \mathscr{W} \rangle = 0$ holds regardless of whether $\mathrm{U}(1)_R$ is unbroken (where it is trivial) or broken

2. Relation to Nelson-Seiberg theorem

Nelson & Seiberg (1994)

$$\left\{ \begin{array}{c} \text{setting without} \\ \text{supersymmetric} \\ \text{ground state} \end{array} \right\} \underset{\text{does not imply}}{\overset{\text{requires}}{\rightleftarrows}} \mathrm{U}(1)_R \text{ symmetry}$$

Comments

1. Statement $\langle \mathscr{W} \rangle = 0$ holds regardless of whether $\mathrm{U}(1)_R$ is unbroken (where it is trivial) or broken

2. Relation to Nelson-Seiberg theorem — Nelson & Seiberg (1994)

$$\left\{ \begin{array}{c} \text{setting without} \\ \text{supersymmetric} \\ \text{ground state} \end{array} \right\} \underset{\text{does not imply}}{\overset{\text{requires}}{\rightleftarrows}} \mathrm{U}(1)_R \text{ symmetry}$$

3. in local SUSY : $\dfrac{\partial \mathscr{W}}{\partial \phi_i} = 0$ and $\langle \mathscr{W} \rangle = 0$ imply $D_i \mathscr{W} = 0$

(That is, a $\mathrm{U}(1)_R$ symmetry implies Minkowski solutions.)

Approximate R symmetries

- Consider now the case of an **approximate R symmetry**, i.e. explicit R symmetry breaking terms appear at order N in the fields ϕ_i

Approximate R symmetries

- Consider now the case of an **approximate R symmetry**, i.e. explicit R symmetry breaking terms appear at order N in the fields ϕ_i
- This allows us to avoid certain problems:
  - for a continuous $\mathrm{U}(1)_R$ symmetry we would have
    - a supersymmetric ground state with $\langle \mathscr{W} \rangle = 0$ and $\mathrm{U}(1)_R$ spontaneously broken
    - a problematic R-Goldstone boson

Approximate R symmetries

- Consider now the case of an **approximate R symmetry**, i.e. explicit R symmetry breaking terms appear at order N in the fields ϕ_i

- This allows us to avoid certain problems:
  - for a continuous $\mathrm{U}(1)_R$ symmetry we would have
    - a supersymmetric ground state with $\langle \mathscr{W} \rangle = 0$ and $\mathrm{U}(1)_R$ spontaneously broken
    - a problematic R-Goldstone boson
  - however, for an **approximate** $\mathrm{U}(1)_R$-symmetry one has
    - Goldstone-Boson massive and harmless
    - a non-trivial VEV of $\mathscr{W}$ at order N in ϕ VEVs

$$\langle \mathscr{W} \rangle \sim \langle \phi \rangle^N$$

Approximate R symmetries

- Consider now the case of an **approximate R symmetry**, i.e. explicit R symmetry breaking terms appear at order N in the fields ϕ_i

- This allows us to avoid certain problems:
  - for a continuous $\mathrm{U}(1)_R$ symmetry we would have
    - a supersymmetric ground state with $\langle \mathscr{W} \rangle = 0$ and $\mathrm{U}(1)_R$ spontaneously broken
    - a problematic R-Goldstone boson
  - however, for an **approximate** $\mathrm{U}(1)_R$-symmetry one has
    - Goldstone-Boson massive and harmless
    - a non-trivial VEV of $\mathscr{W}$ at order N in ϕ VEVs

$$\langle \mathscr{W} \rangle \sim \langle \phi \rangle^N$$

- Such **approximate** $\mathrm{U}(1)_R$ symmetries can be a consequence of discrete $\mathbb{Z}_N^R$ symmetries

Approximate R symmetries

- Consider now the case of an **approximate R symmetry**, i.e. explicit R symmetry breaking terms appear at order N in the fields ϕ_i
- This allows us to avoid certain problems:
  - for a continuous $\mathrm{U}(1)_R$ symmetry we would have
    - a supersymmetric ground state with $\langle \mathscr{W} \rangle = 0$ and $\mathrm{U}(1)_R$ spontaneously broken
    - a problematic R-Goldstone boson
  - however, for an **approximate** $\mathrm{U}(1)_R$-symmetry one has
    - Goldstone-Boson massive and harmless
    - a non-trivial VEV of $\mathscr{W}$ at order N in ϕ VEVs

$$\langle \mathscr{W} \rangle \sim \langle \phi \rangle^N$$

- Such **approximate** $\mathrm{U}(1)_R$ symmetries can be a consequence of discrete $\mathbb{Z}_N^R$ symmetries
- Various field-theoretic examples

F. Brümmer, R. Kappl, M.R., K. Schmidt-Hoberg (2010)

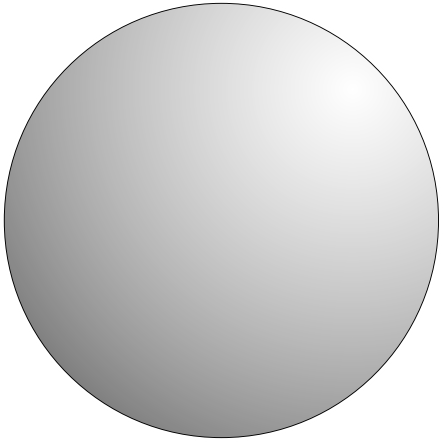
Explicit

string theory

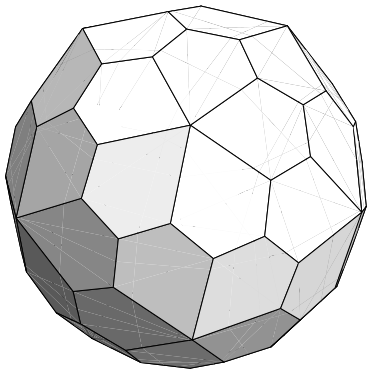
realization

Origin of high-power discrete R-symmetries

- Discrete R symmetries arise as remnants of Lorentz symmetries of compact space

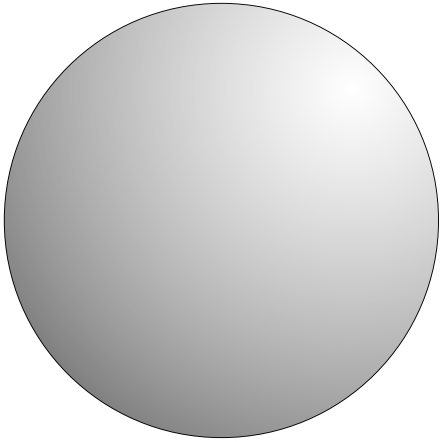


$\longrightarrow$

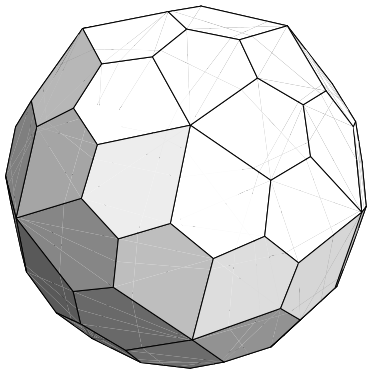


Origin of high-power discrete R-symmetries

- Discrete R symmetries arise as remnants of Lorentz symmetries of compact space



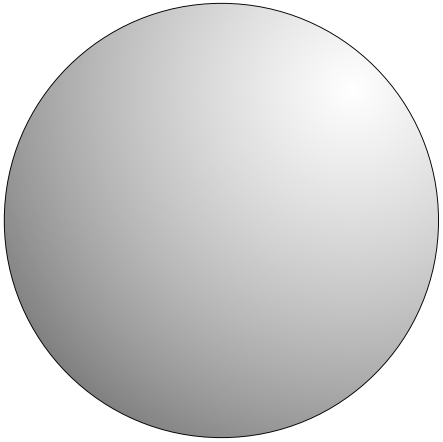
$\longrightarrow$



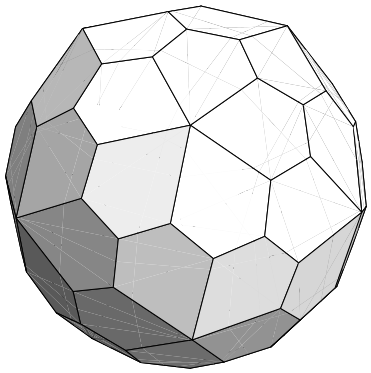
- Orbifolds break $\mathrm{SO}(6) \simeq \mathrm{SU}(4)$ Lorentz symmetry of compact space to discrete subgroups

Origin of high-power discrete R-symmetries

- Discrete R symmetries arise as remnants of Lorentz symmetries of compact space



$\longrightarrow$



- Orbifolds break $\mathrm{SO}(6) \simeq \mathrm{SU}(4)$ Lorentz symmetry of compact space to discrete subgroups
- For example, in $\mathbb{Z}_6$-II orbifolds one has

$$G_R \;=\; [\mathbb{Z}_6 \times \mathbb{Z}_3 \times \mathbb{Z}_2]_R$$

see e.g. Araki, Kobayashi, Kubo, Ramos-Sánchez, M.R., Vaudrevange (2008)

Realization in heterotic mini-landscape

- ☞ Heterotic orbifolds appear 'tailor-made' for applying these ideas

Realization in heterotic mini-landscape

- Heterotic orbifolds appear 'tailor-made' for applying these ideas
- To be specific, focus on the heterotic mini-landscape
  $=$ potentially realistic string models with attractive features:
  - matter parity from $\mathbb{Z}_2$ subgroup of
    $\mathrm{U}(1)_{B-L} \not\subset \mathrm{E}_8$

Realization in heterotic mini-landscape

- Heterotic orbifolds appear 'tailor-made' for applying these ideas
- To be specific, focus on the heterotic mini-landscape
  = potentially realistic string models with attractive features:
  - matter parity
  - MSSM spectrum with one Higgs pair

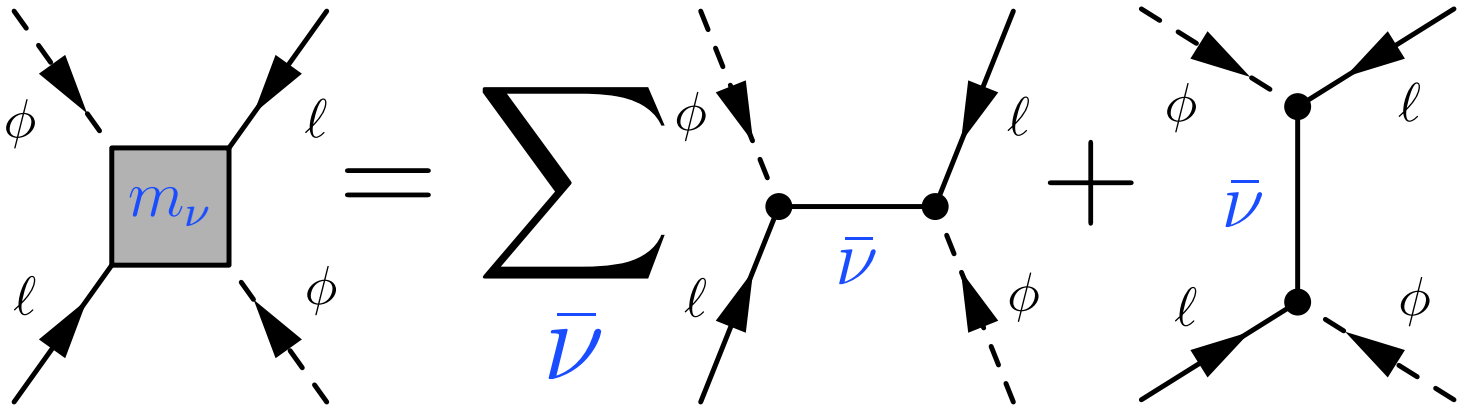
Realization in heterotic mini-landscape

- Heterotic orbifolds appear 'tailor-made' for applying these ideas
- To be specific, focus on the heterotic mini-landscape
  = potentially realistic string models with attractive features:
  - matter parity
  - MSSM spectrum with one Higgs pair
  - gauge coupling unification

Realization in heterotic mini-landscape

- Heterotic orbifolds appear 'tailor-made' for applying these ideas

- To be specific, focus on the heterotic mini-landscape
  = potentially realistic string models with attractive features:
  - matter parity
  - MSSM spectrum with one Higgs pair
  - gauge coupling unification
  - see-saw



Realization in heterotic mini-landscape

- Heterotic orbifolds appear 'tailor-made' for applying these ideas
- To be specific, focus on the heterotic mini-landscape
  = potentially realistic string models with attractive features:
  - matter parity
  - MSSM spectrum with one Higgs pair
  - gauge coupling unification
  - see-saw
  - $y_t \simeq g$ and all other Yukawas suppressed á la Frogatt-Nielsen

Realization in heterotic mini-landscape

- Heterotic orbifolds appear 'tailor-made' for applying these ideas
- To be specific, focus on the heterotic mini-landscape = potentially realistic string models with attractive features:
  - matter parity
  - MSSM spectrum with one Higgs pair
  - gauge coupling unification
  - see-saw
  - $y_t \simeq g$ and all other Yukawas suppressed á la Frogatt-Nielsen
  - potential solution to μ, SUSY flavor and proton decay problems

Realization in heterotic mini-landscape

- Heterotic orbifolds appear 'tailor-made' for applying these ideas
- To be specific, focus on the heterotic mini-landscape = potentially realistic string models with attractive features:
  - matter parity
  - MSSM spectrum with one Higgs pair
  - gauge coupling unification
  - see-saw
  - $y_t \simeq g$ and all other Yukawas suppressed á la Frogatt-Nielsen
  - potential solution to μ, SUSY flavor and proton decay problems
  - many standard model singlets s_i (potential "blow-up modes")

Realization in heterotic mini-landscape

- Heterotic orbifolds appear 'tailor-made' for applying these ideas

- To be specific, focus on the heterotic mini-landscape
  = potentially realistic string models with attractive features:
  - matter parity
  - MSSM spectrum with one Higgs pair
  - gauge coupling unification

  } ...searched for

  - see-saw
  - $y_t \simeq g$ and all other Yukawas suppressed á la Frogatt-Nielsen
  - potential solution to μ, SUSY flavor and proton decay problems

  } ...got 'for free'

  - many standard model singlets s_i (potential "blow-up modes")

  $\rightarrow$ effective couplings etc.

Some details

- We studied one example (heterotic benchmark model IA) with 23 SM singlets s_i getting a VEV

Some details

- We studied one example (heterotic benchmark model IA) with 23 SM singlets s_i getting a VEV
- R symmetry breaking terms appear at order 9

Some details

- We studied one example (heterotic benchmark model IA) with 23 SM singlets s_i getting a VEV
- R symmetry breaking terms appear at order 9
- We solve $D_a = 0$ as well as global $F_i = 0$ at order 9

Some details

- We studied one example (heterotic benchmark model IA) with 23 SM singlets s_i getting a VEV
- R symmetry breaking terms appear at order 9
- We solve $D_a = 0$ as well as global $F_i = 0$ at order 9
- We specifically search for solutions $|s_i| < 1$, and find/argue that they exist

Note: in order to prove the existence a full understanding of coupling coefficients is required

Some details

- We studied one example (heterotic benchmark model IA) with 23 SM singlets s_i getting a VEV
- R symmetry breaking terms appear at order 9
- We solve $D_a = 0$ as well as global $F_i = 0$ at order 9
- We specifically search for solutions $|s_i| < 1$, and find/argue that they exist
- All fields acquire positive m^2
  (no flat directions; not destroyed by supergravity corrections)

Some details

- We studied one example (heterotic benchmark model IA) with 23 SM singlets s_i getting a VEV
- R symmetry breaking terms appear at order 9
- We solve $D_a = 0$ as well as global $F_i = 0$ at order 9
- We specifically search for solutions $|s_i| < 1$, and find/argue that they exist
- All fields acquire positive m^2
  (no flat directions; not destroyed by supergravity corrections)
- Superpotential VEV $\langle \mathscr{W} \rangle \sim \langle s_i \rangle^9 \ll 1$ (as expected)

Some details

- We studied one example (heterotic benchmark model IA) with 23 SM singlets s_i getting a VEV
- R symmetry breaking terms appear at order 9
- We solve $D_a = 0$ as well as global $F_i = 0$ at order 9
- We specifically search for solutions $|s_i| < 1$, and find/argue that they exist
- All fields acquire positive m^2
  (no flat directions; not destroyed by supergravity corrections)
- Superpotential VEV $\langle \mathscr{W} \rangle \sim \langle s_i \rangle^9 \ll 1$ (as expected)

bottom-line:

straightforward embedding in heterotic orbifolds

General picture

R. Kappl, H.P. Nilles, S. Ramos-Sánchez, M.R., K. Schmidt-Hoberg, P. Vaudrevange (2008)

F. Brümmer, R. Kappl, M.R., K. Schmidt-Hoberg (2010)

☞ The more fields are switched on, the lower N we obtain examples:

- benchmark model 1A with 23 fields $\curvearrowright N = 9$
- model with 7 fields $\curvearrowright N = 26$

General picture

R. Kappl, H.P. Nilles, S. Ramos-Sánchez, M.R., K. Schmidt-Hoberg, P. Vaudrevange (2008)

F. Brümmer, R. Kappl, M.R., K. Schmidt-Hoberg (2010)

- The more fields are switched on, the lower N we obtain examples:
  - benchmark model 1A with 23 fields $\curvearrowright N = 9$
  - model with 7 fields $\curvearrowright N = 26$
- Suppressed s_i in accord with scale set by Fayet-Iliopoulos term

General picture

R. Kappl, H.P. Nilles, S. Ramos-Sánchez, M.R., K. Schmidt-Hoberg, P. Vaudrevange (2008)
F. Brümmer, R. Kappl, M.R., K. Schmidt-Hoberg (2010)

- The more fields are switched on, the lower N we obtain examples:
  - benchmark model 1A with 23 fields $\curvearrowright N = 9$
  - model with 7 fields $\curvearrowright N = 26$
- Suppressed s_i in accord with scale set by Fayet-Iliopoulos term
- One approximate Goldstone mode η

$m_\eta \sim \langle \mathscr{W} \rangle / \langle s \rangle^2$ ...somewhat heavier than the gravitino

General picture

R. Kappl, H.P. Nilles, S. Ramos-Sánchez, M.R., K. Schmidt-Hoberg, P. Vaudrevange (2008)
F. Brümmer, R. Kappl, M.R., K. Schmidt-Hoberg (2010)

- The more fields are switched on, the lower N we obtain examples:
  - benchmark model 1A with 23 fields $\curvearrowright N = 9$
  - model with 7 fields $\curvearrowright N = 26$
- Suppressed s_i in accord with scale set by Fayet-Iliopoulos term
- One approximate Goldstone mode η

  $m_\eta \sim \langle \mathscr{W} \rangle / \langle s \rangle^2$ ...somewhat heavier than the gravitino
- In most examples: all other s_i fields acquire masses $\gg m_\eta$ i.e. isolated points in s_i space with $F_i = D_a = 0$

General picture

R. Kappl, H.P. Nilles, S. Ramos-Sánchez, M.R., K. Schmidt-Hoberg, P. Vaudrevange (2008)
F. Brümmer, R. Kappl, M.R., K. Schmidt-Hoberg (2010)

- The more fields are switched on, the lower N we obtain examples:
  - benchmark model 1A with 23 fields $\curvearrowright N = 9$
  - model with 7 fields $\curvearrowright N = 26$
- Suppressed s_i in accord with scale set by Fayet-Iliopoulos term
- One approximate Goldstone mode η

  $m_\eta \sim \langle \mathscr{W} \rangle / \langle s \rangle^2$ ...somewhat heavier than the gravitino
- In most examples: all other s_i fields acquire masses $\gg m_\eta$ i.e. isolated points in s_i space with $F_i = D_a = 0$
- Minima survive supergravity corrections

Applications

- MSSM μ term
- Moduli stabilization

μ from strings

Cvetič, Louis, Ovrut (1988)

- Kähler potential for orbifold $\mathbb{Z}_2$ plane

$$K = -\ln\left[\left(T+\overline{T}\right)\left(Z+\overline{Z}\right) - \left(H_u+\overline{H_d}\right)\left(H_d+\overline{H_u}\right)\right]$$

Kähler modulus

complex structure

structure enforced by higher-dimensional gauge invariance

μ from strings

- Kähler potential for orbifold $\mathbb{Z}_2$ plane

Cvetič, Louis, Ovrut (1988)

$$K = -\ln\left[\left(T+\overline{T}\right)\left(Z+\overline{Z}\right)-\left(H_u+\overline{H_d}\right)\left(H_d+\overline{H_u}\right)\right]$$

- Giudice-Masiero type contribution

Antoniadis, Gava, Narain, Taylor (1994)

$$\mu = F_T + \ldots$$

μ from strings

- Kähler potential for orbifold $\mathbb{Z}_2$ plane

Cvetič, Louis, Ovrut (1988)

$$K = -\ln\left[\left(T+\overline{T}\right)\left(Z+\overline{Z}\right) - \left(H_u+\overline{H_d}\right)\left(H_d+\overline{H_u}\right)\right]$$

- Giudice-Masiero type contribution

Antoniadis, Gava, Narain, Taylor (1994)

$$\mu = F_T + \ldots$$

- Holomorphic contribution

Brümmer, Kappl, M.R., Schmidt-Hoberg (2010)

$$K \simeq -\ln\left[\left(T+\overline{T}\right)\left(Z+\overline{Z}\right)\right] + \frac{\left[|H_u|^2 + |H_d|^2 + (H_u H_d + \text{c.c.})\right]}{\left(T+\overline{T}\right)\left(Z+\overline{Z}\right)}$$

$$= -\ln\left[\left(T+\overline{T}\right)\left(Z+\overline{Z}\right)\right] + \left[|\widehat{H}_u|^2 + |\widehat{H}_d|^2 + (\widehat{H}_u \widehat{H}_d + \text{c.c.})\right]$$

canonically normalized fields

μ from strings

- Kähler potential for orbifold $\mathbb{Z}_2$ plane

Cvetič, Louis, Ovrut (1988)

$$K = -\ln\left[\left(T+\overline{T}\right)\left(Z+\overline{Z}\right)-\left(H_u+\overline{H_d}\right)\left(H_d+\overline{H_u}\right)\right]$$

- Giudice-Masiero type contribution

Antoniadis, Gava, Narain, Taylor (1994)

$$\mu = F_T + \ldots$$

- Holomorphic contribution

Brümmer, Kappl, M.R., Schmidt-Hoberg (2010)

$$K \simeq -\ln\left[\left(T+\overline{T}\right)\left(Z+\overline{Z}\right)\right]+\left[|\widehat{H}_u|^2+|\widehat{H}_d|^2+(\widehat{H}_u\,\widehat{H}_d+\text{c.c.})\right]$$

➥ induces F_T-independent μ term

$$\mu \sim \langle \mathscr{W} \rangle \simeq m_{3/2}$$

Application: moduli stabilization

- Another important application: fix the dilaton

Application: moduli stabilization

- Another important application: fix the dilaton
- Effective superpotential

similar to KKLT

$$\mathscr{W}_{\rm eff} = \langle \mathscr{W} \rangle + A\, {\rm e}^{-a\, S} + \frac{1}{2} m_\eta\, \eta^2$$

approximate R axion

perturbative superpotential $\sim 10^{-\mathcal{O}(10)}$

"gaugino condensate"

Application: moduli stabilization

- Another important application: fix the dilaton
- Effective superpotential

$$\mathscr{W}_{\rm eff} = \langle \mathscr{W} \rangle + A\, {\rm e}^{-a\, S} + \frac{1}{2} m_\eta\, \eta^2$$

- Dilaton adjusts to $\langle \mathscr{W} \rangle$

$$m_{3/2} \simeq \langle \mathscr{W}_{\rm eff} \rangle \sim \langle \mathscr{W} \rangle$$

Application: moduli stabilization

- Another important application: fix the dilaton
- Effective superpotential

$$\mathscr{W}_{\rm eff} = \langle \mathscr{W} \rangle + A\, {\rm e}^{-a\, S} + \frac{1}{2} m_\eta\, \eta^2$$

- Dilaton adjusts to $\langle \mathscr{W} \rangle$

$$m_{3/2} \simeq \langle \mathscr{W}_{\rm eff} \rangle \sim \langle \mathscr{W} \rangle$$

bottom-line:

- dilaton fixed
- true origin of hierarchically small $m_{3/2} (\sim m_{\rm W})$: approximate R symmetry

Toy example

Dundee, Raby, Westphal (2010)

- Orbifold-inspired Kähler and superpotential

$$K = -\ln\left(S+\overline{S}\right) - 3\ln\left(T+\overline{T}\right) + \overline{\phi_1}\phi_1 + \overline{\phi_2}\phi_2 + \overline{\chi}\chi$$

dilaton

Kähler modulus

MSSM singlet fields

Toy example

Dundee, Raby, Westphal (2010)

- Orbifold-inspired Kähler and superpotential

$$
\begin{aligned}
K &= -\ln\left(S+\overline{S}\right) - 3\,\ln\left(T+\overline{T}\right) + \overline{\phi_1}\phi_1 + \overline{\phi_2}\phi_2 + \overline{\chi}\chi \\
\mathscr{W} &= \mathrm{e}^{-b\,T}\left[w_0 + \chi\,\left(\phi_1^{10}\right)\right] + A\,\phi_2^{p}\,\mathrm{e}^{-a\,S - b_2\,T}
\end{aligned}
$$

explained by approximate R symmetry

needs to acquire VEV in order to cancel FI term

Toy example

Dundee, Raby, Westphal (2010)

- Orbifold-inspired Kähler and superpotential

$$
\begin{aligned}
K &= -\ln\left(S+\overline{S}\right) - 3\,\ln\left(T+\overline{T}\right) + \overline{\phi_1}\phi_1 + \overline{\phi_2}\phi_2 + \overline{\chi}\chi \\
\mathscr{W} &= \mathrm{e}^{-b\,T}\left[w_0 + \chi\,\left(\phi_1^{10}\right)\right] + A\,\phi_2^p\,\mathrm{e}^{-a\,S - b_2\,T}
\end{aligned}
$$

- Features:
  - KKLT-type stabilization of S
  - race-track stabilization of T, F_T dominates
  - all fields fixed
  - vacuum energy: $V_0/(3m_{3/2}^2) \simeq -3\,\%$

Toy example

Dundee, Raby, Westphal (2010)

- Orbifold-inspired Kähler and superpotential

$$
\begin{aligned}
K &= -\ln\left(S+\overline{S}\right) - 3\,\ln\left(T+\overline{T}\right) + \overline{\phi_1}\phi_1 + \overline{\phi_2}\phi_2 + \overline{\chi}\chi \\
\mathscr{W} &= \mathrm{e}^{-b\,T}\left[w_0 + \chi\,\left(\phi_1^{10}\right)\right] + A\,\phi_2^p\,\mathrm{e}^{-a\,S - b_2\,T}
\end{aligned}
$$

- Features:
  - KKLT-type stabilization of S
  - race-track stabilization of T, F_T dominates
  - all fields fixed
  - vacuum energy: $V_0/(3m_{3/2}^2) \simeq -3\,\%$

bottom-line:

application to explicit string models may be feasible

Comment on naive idea

F. Brümmer, R. Kappl, M.R., K. Schmid-Hoberg (2010)

☞ Alternative stabilization of the T- and Z-moduli

$$\mathscr{W} = \sum_i c_i(T_j, Z_k)\, \mathscr{M}_i(\phi_\ell)$$

couplings depend on geometry e.g. $c \sim \mathrm{e}^{-a\,T}$

monomials in MSSM singlet fields ϕ_ℓ

Comment on naive idea

F. Brümmer, R. Kappl, M.R., K. Schmid-Hoberg (2010)

- Alternative stabilization of the T- and Z-moduli

$$\mathscr{W} = \sum_i c_i(T_j, Z_k)\, \mathscr{M}_i(\phi_\ell)$$

- As many F-equations as fields $\curvearrowright$ expect 'point-like' solutions with masses of the fundamental scale (i.e. very heavy T- and Z-moduli)

Comment on naive idea

F. Brümmer, R. Kappl, M.R., K. Schmid-Hoberg (2010)

- Alternative stabilization of the T- and Z-moduli

$$\mathscr{W} = \sum_i c_i(T_j, Z_k)\, \mathscr{M}_i(\phi_\ell)$$

- As many F-equations as fields $\curvearrowright$ expect 'point-like' solutions with masses of the fundamental scale (i.e. very heavy T- and Z-moduli)

- Whether or not these solutions are at 'reasonable' points in field space (i.e. $\langle \phi_\ell \rangle < 1$, T_j, Z_k moderately large) will depend on the precise form of the c_i and the chosen ϕ_ℓ configuration

R. Kappl et al. work in progress

Comment on naive idea

F. Brümmer, R. Kappl, M.R., K. Schmid-Hoberg (2010)

- Alternative stabilization of the T- and Z-moduli

$$\mathscr{W} = \sum_i c_i(T_j, Z_k)\, \mathscr{M}_i(\phi_\ell)$$

- As many F-equations as fields $\curvearrowright$ expect 'point-like' solutions with masses of the fundamental scale (i.e. very heavy T- and Z-moduli)

- Whether or not these solutions are at 'reasonable' points in field space (i.e. $\langle \phi_\ell \rangle < 1$, T_j, Z_k moderately large) will depend on the precise form of the c_i and the chosen ϕ_ℓ configuration

R. Kappl et al. work in progress

- As before: in the presence of approximate $\mathrm{U}(1)_R$ 'reasonable' solutions will have suppressed $\langle \mathscr{W} \rangle$

Matter Parity,

SUSY Flavor Structure

and

Proton Stability

Matter parity from $\mathbf{U}(1)_{B-L}$

Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange, Wingerter (2006)

- In the heterotic mini-landscape search we obtained a $\mathbb{Z}_2^{\mathcal{M}}$ matter parity like in $\mathrm{SO}(10)$ GUTs, i.e. as a subgroup of a gauged $\mathrm{U}(1)_{B-L}$ symmetry

$$\mathrm{U}(1)_{B-L} \xrightarrow{\chi \to \langle \chi \rangle} \mathbb{Z}_2^{\mathcal{M}}$$

carries even $B-L$ charge

Matter parity from $\mathbf{U}(1)_{B-L}$

Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange, Wingerter (2006)

- In the heterotic mini-landscape search we obtained a $\mathbb{Z}_2^{\mathcal{M}}$ matter parity like in $\mathrm{SO}(10)$ GUTs, i.e. as a subgroup of a gauged $\mathrm{U}(1)_{B-L}$ symmetry

$$\mathrm{U}(1)_{B-L} \xrightarrow{\chi \to \langle \chi \rangle} \mathbb{Z}_2^{\mathcal{M}}$$

- Obvious generalization:

$$q_{B-L}(\chi) = \frac{\text{even}}{\text{odd}}$$

Matter parity from $\mathbf{U}(1)_{B-L}$

Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange, Wingerter (2006)

- In the heterotic mini-landscape search we obtained a $\mathbb{Z}_2^{\mathcal{M}}$ matter parity like in $\mathrm{SO}(10)$ GUTs, i.e. as a subgroup of a gauged $\mathrm{U}(1)_{B-L}$ symmetry

$$\mathrm{U}(1)_{B-L} \xrightarrow{\chi \to \langle \chi \rangle} \mathbb{Z}_2^{\mathcal{M}}$$

- Obvious generalization:

$$q_{B-L}(\chi) = \frac{\text{even}}{\text{odd}}$$

- In orbifolds: many discrete and continuous symmetries $\curvearrowright$ non-trivial embedding of $\mathbb{Z}_2^{\mathcal{M}}$

Matter parity from $\mathbf{U}(1)_{B-L}$

Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange, Wingerter (2006)

- In the heterotic mini-landscape search we obtained a $\mathbb{Z}_2^{\mathcal{M}}$ matter parity like in $\mathrm{SO}(10)$ GUTs, i.e. as a subgroup of a gauged $\mathrm{U}(1)_{B-L}$ symmetry

$$\mathrm{U}(1)_{B-L} \xrightarrow{\chi \to \langle \chi \rangle} \mathbb{Z}_2^{\mathcal{M}}$$

- Obvious generalization:

$$q_{B-L}(\chi) = \frac{\text{even}}{\text{odd}}$$

- In orbifolds: many discrete and continuous symmetries $\curvearrowright$ non-trivial embedding of $\mathbb{Z}_2^{\mathcal{M}}$

- Related discussion

W. Buchmüller, J. Schmidt (2009)

Skip

How to extract residual discrete symmetries

- Generalization to many $\mathrm{U}(1)$ factors, non-Abelian symmetries and several $\mathbb{Z}_N$'s

How to extract residual discrete symmetries

- Generalization to many $\mathrm{U}(1)$ factors, non-Abelian symmetries and several $\mathbb{Z}_N$'s
- Assume certain charged fields $\phi^{(i)}$ attain VEVs

How to extract residual discrete symmetries

- Generalization to many $\mathrm{U}(1)$ factors, non-Abelian symmetries and several $\mathbb{Z}_N$'s
- Assume certain charged fields $\phi^{(i)}$ attain VEVs
- What is the residual discrete symmetry?

A simple example

- 3 VEV fields $\phi^{(i)}$, 2 matter fields $\psi^{(j)}$, 2 $\mathrm{U}(1)$ factors

A simple example

- 3 VEV fields $\phi^{(i)}$, 2 matter fields $\psi^{(j)}$, 2 $\mathrm{U}(1)$ factors

	$\mathrm{U}(1)$	$\mathrm{U}(1)'$
$\phi^{(1)}$	8	-2
$\phi^{(2)}$	4	2
$\phi^{(3)}$	2	4

	$\mathrm{U}(1)$	$\mathrm{U}(1)'$
$\psi^{(1)}$	1	3
$\psi^{(2)}$	1	5

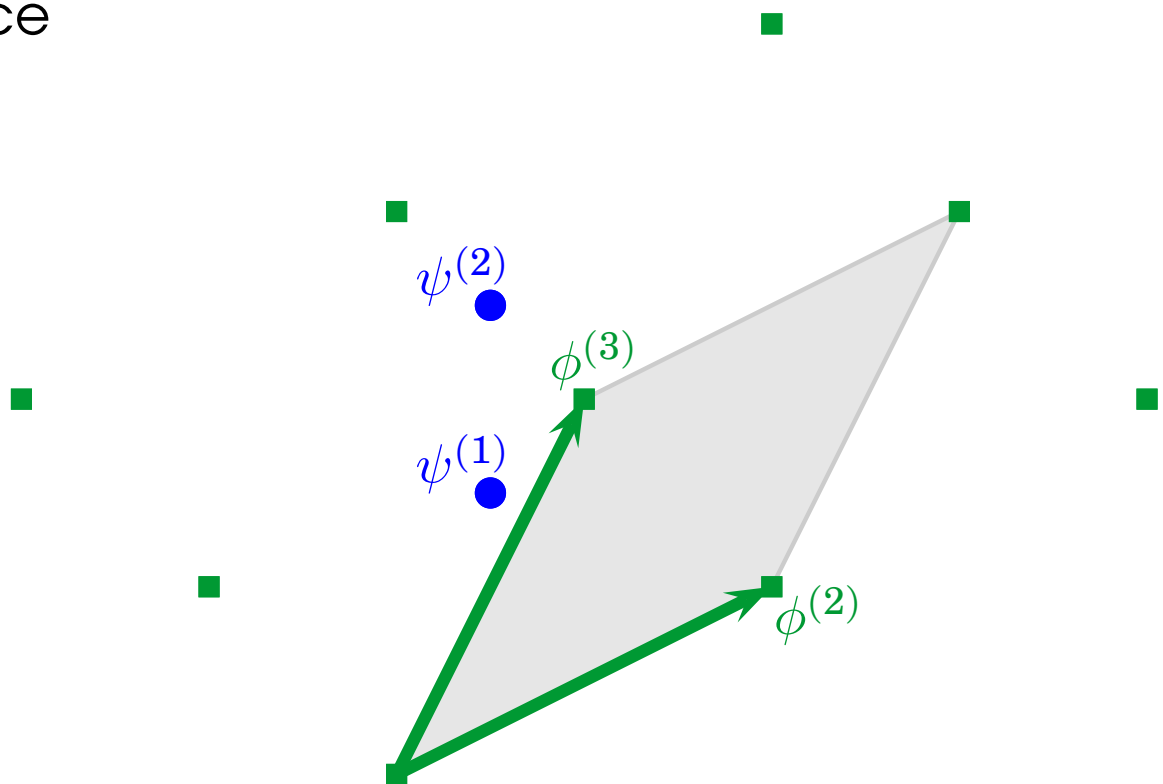
A simple example

- 3 VEV fields $\phi^{(i)}$, 2 matter fields $\psi^{(j)}$, 2 $\mathrm{U}(1)$ factors

	$\mathrm{U}(1)$	$\mathrm{U}(1)'$
$\phi^{(1)}$	8	-2
$\phi^{(2)}$	4	2
$\phi^{(3)}$	2	4

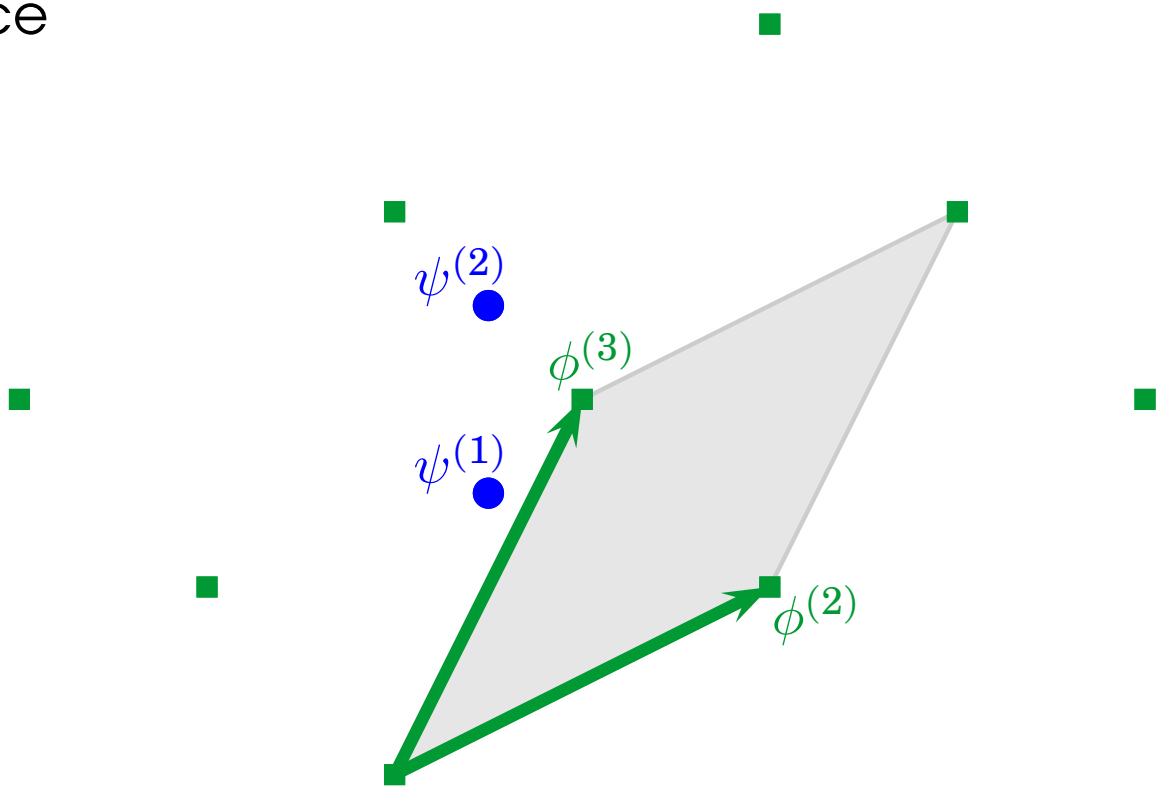
	$\mathrm{U}(1)$	$\mathrm{U}(1)'$
$\psi^{(1)}$	1	3
$\psi^{(2)}$	1	5

- Charge lattice



A simple example (cont'd)

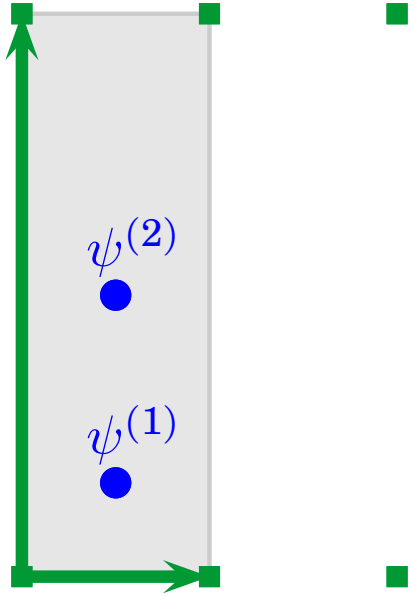
☞ Charge lattice



$$\left\{ \begin{array}{c} \text{Coupling} \\ (\psi^{(1)})^{n_1} (\psi^{(2)})^{n_2} \\ \text{allowed} \end{array} \right\} \Longleftrightarrow \left\{ \begin{array}{c} n_1\, q(\psi^{(1)}) + n_2\, q(\psi^{(2)}) \\ \text{lies on} \\ \text{lattice node} \end{array} \right\}$$

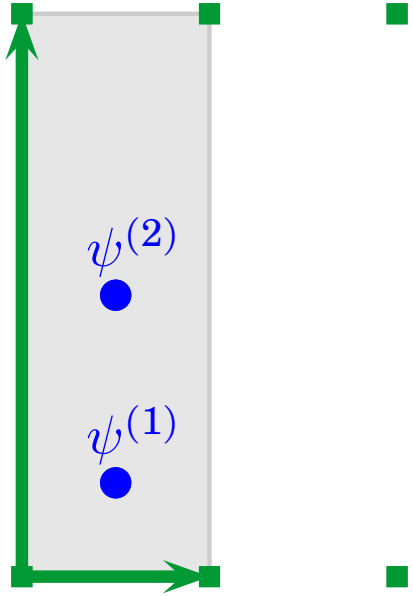
A simple example (cont'd)

- Charge lattice after diagonalization by unimodular transformation



A simple example (cont'd)

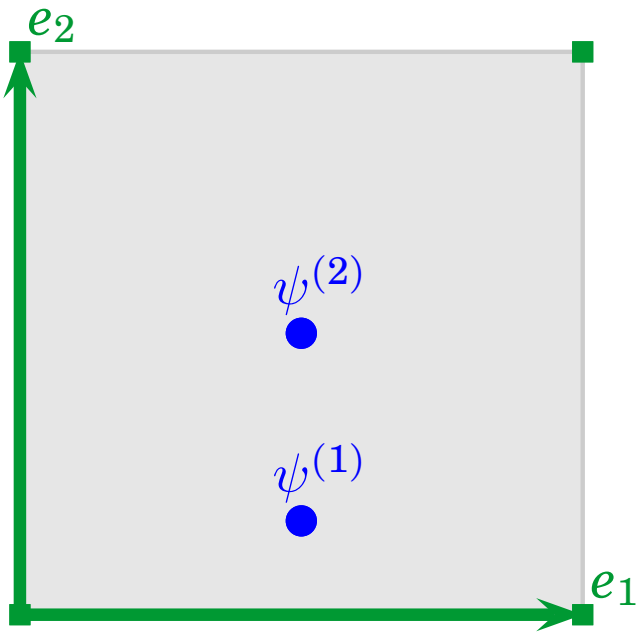
- Charge lattice after diagonalization by unimodular transformation



- Premature result: $\mathbb{Z}_2 \times \mathbb{Z}_6$ symmetry with discrete charges $q(\psi^{(1)}) = (1,1)$ and $q(\psi^{(2)}) = (1,3)$

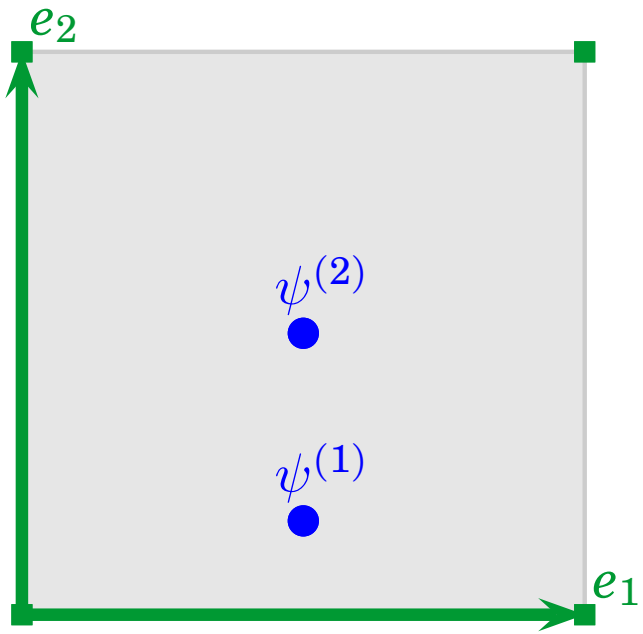
A simple example (cont'd)

☞ 'Blown up' diagonal charge lattice



A simple example (cont'd)

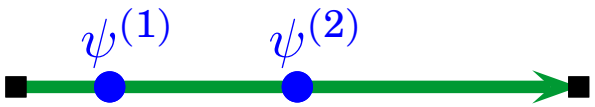
- 'Blown up' diagonal charge lattice



- 'Blown up' symmetry: $\mathbb{Z}_6 \times \mathbb{Z}_6$ with discrete charges $q(\psi^{(1)}) = (3,1)$ and $q(\psi^{(2)}) = (3,3)$

A simple example (cont'd)

- Canonical form 'blown up' diagonal charge lattice and charges



- Final result: $\mathbb{Z}_6$ symmetry with discrete charges $q(\psi^{(1)}) = 1$ and $q(\psi^{(2)}) = 3$

General algorithm

B. Petersen, M.R., R. Schieren (2009)

1. Build and diagonalize charge lattice

General algorithm

B. Petersen, M.R., R. Schieren (2009)

1. Build and diagonalize charge lattice
2. Extend charge lattice to $\mathbb{Z}_N^n$

General algorithm

B. Petersen, M.R., R. Schieren (2009)

1. Build and diagonalize charge lattice
2. Extend charge lattice to $\mathbb{Z}_N^n$
3. Bring the result to 'normal form' and omit trivial $\mathbb{Z}_1$ factors

General algorithm

B. Petersen, M.R., R. Schieren (2009)

1. Build and diagonalize charge lattice
2. Extend charge lattice to $\mathbb{Z}_N^n$
3. Bring the result to 'normal form' and omit trivial $\mathbb{Z}_1$ factors

☞ Extension to mixed case $(\mathrm{U}(1)^N \times \mathbb{Z}_{n_1} \times \mathbb{Z}_{n_1} \cdots)$ and non-Abelian groups straightforward

General algorithm

B. Petersen, M.R., R. Schieren (2009)

1. Build and diagonalize charge lattice
2. Extend charge lattice to $\mathbb{Z}_N^n$
3. Bring the result to 'normal form' and omit trivial $\mathbb{Z}_1$ factors

☞ Extension to mixed case $(\mathrm{U}(1)^N \times \mathbb{Z}_{n_1} \times \mathbb{Z}_{n_1} \cdots)$ and non-Abelian groups straightforward

☞ Automatization (by R. Schieren)

http://einrichtungen.physik.tu-muenchen.de/T30e/codes/DiscreteBreaking/

General algorithm

B. Petersen, M.R., R. Schieren (2009)

1. Build and diagonalize charge lattice
2. Extend charge lattice to $\mathbb{Z}_N^n$
3. Bring the result to 'normal form' and omit trivial $\mathbb{Z}_1$ factors

☞ Extension to mixed case $(\mathrm{U}(1)^N \times \mathbb{Z}_{n_1} \times \mathbb{Z}_{n_1} \cdots)$ and non-Abelian groups straightforward

☞ Automatization (by R. Schieren)

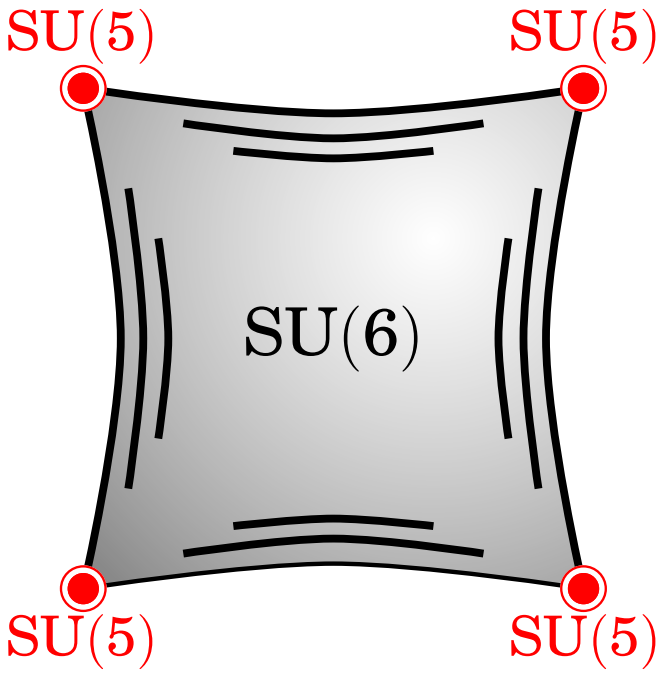
http://einrichtungen.physik.tu-muenchen.de/T30e/codes/DiscreteBreaking/

☞ Main applications:
- matter parity
- forbid μ term to all orders

cf. W. Buchmüller, J. Schmidt (2009)

$\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold example

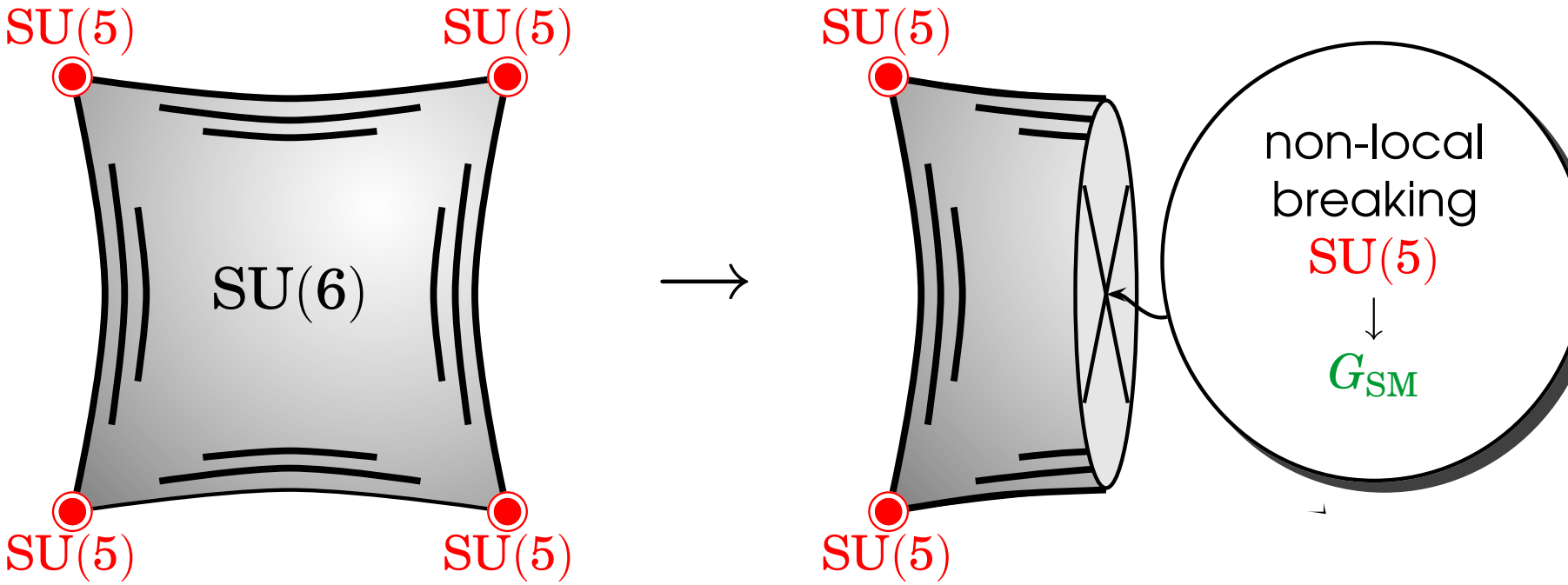
M. Blaszczyk, S. Groot Nibbelink, M.R., F. Ruehle, M. Trapletti, P. Vaudrevange (2009)



1. step: 6 generation $\mathbb{Z}_2 \times \mathbb{Z}_2$ model with $\mathrm{SU}(5)$ symmetry

$\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold example

M. Blaszczyk, S. Groot Nibbelink, M.R., F. Ruehle, M. Trapletti, P. Vaudrevange (2009)



1. step: 6 generation $\mathbb{Z}_2 \times \mathbb{Z}_2$ model with $\mathrm{SU}(5)$ symmetry
2. step: mod out a freely acting $\mathbb{Z}_2$ symmetry which:
   - breaks $\mathrm{SU}(5) \to \mathrm{SU}(3)_C \times \mathrm{SU}(2)_{\rm L} \times \mathrm{U}(1)_Y$
   - reduces the number of generations to 3

analogous mechanism in CY MSSMs Bouchard & Donagi (2005)
Braun, He, Ovrut, Pantev (2005)

Main features

1. GUT symmetry breaking non-local
   $\curvearrowright$ no 'logarithmic running above the GUT scale'

Hebecker, Trapletti (2004)

Main features

1. GUT symmetry breaking non-local
2. No localized flux in hypercharge direction
   $\curvearrowright$ complete blow-up without breaking SM gauge symmetry in principle possible

Main features

1. GUT symmetry breaking non-local
2. No localized flux in hypercharge direction
3. 4D gauge group:
   $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L} \times [\mathrm{SU}(3) \times \mathrm{SU}(2)^2 \times \mathrm{U}(1)^7]$

Main features

1. GUT symmetry breaking non-local
2. No localized flux in hypercharge direction
3. 4D gauge group:
   $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L} \times [\mathrm{SU}(3) \times \mathrm{SU}(2)^2 \times \mathrm{U}(1)^7]$
4. massless spectrum

#	representation	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{6},\frac{1}{3})}$	q
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},-\frac{1}{3})}$	$\overline{d}$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(1,1)}$	$\overline{e}$
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},0)}$	h
5	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},\frac{2}{3})}$	$\overline{\delta}$
5	$(\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1})_{(0,\xi)}$	x
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})_{(0,0)}$	y

#	representation	label
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{2}{3},-\frac{1}{3})}$	$\overline{u}$
3	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},-1)}$	ℓ
33	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(0,\sigma)}$	s
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{2},0)}$	$\overline{h}$
5	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{3},-\frac{2}{3})}$	δ
5	$(\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1})_{(0,-\xi)}$	$\overline{x}$
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2},\mathbf{1})_{(0,0)}$	z

Main features

1. GUT symmetry breaking non-local
2. No localized flux in hypercharge direction
3. 4D gauge group:
   $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L} \times [\mathrm{SU}(3) \times \mathrm{SU}(2)^2 \times \mathrm{U}(1)^7]$
4. massless spectrum

   spectrum $= 3 \times$ generation $+$ vector-like

Spectrum and matter parity

#	representation	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{6},\frac{1}{3})}$	q
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},-\frac{1}{3})}$	$\overline{d}$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(1,1)}$	$\overline{e}$
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},0)}$	h
5	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},\frac{2}{3})}$	$\overline{\delta}$
5	$(\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1})_{(0,\xi)}$	x
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})_{(0,0)}$	y

#	representation	label
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{2}{3},-\frac{1}{3})}$	$\overline{u}$
3	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},-1)}$	ℓ
33	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(0,\mathcal{O})}$	s
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{2},0)}$	$\overline{h}$
5	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{3},-\frac{2}{3})}$	δ
5	$(\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1})_{(0,-\xi)}$	$\overline{x}$
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2},\mathbf{1})_{(0,0)}$	z

$\mathrm{U}(1)_{B-L}$: discriminate between matter and Higgs/exotics

Spectrum and matter parity

#	representation	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{6},\frac{1}{3})}$	q
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},-\frac{1}{3})}$	$\overline{d}$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(1,1)}$	$\overline{e}$
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},0)}$	h
5	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},\frac{2}{3})}$	$\overline{\delta}$
5	$(\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1})_{(0,\xi)}$	x
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})_{(0,0)}$	y

#	representation	label
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{2}{3},-\frac{1}{3})}$	$\overline{u}$
3	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},-1)}$	ℓ
33	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(0,\sigma)}$	s
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{2},0)}$	$\overline{h}$
5	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{3},-\frac{2}{3})}$	δ
5	$(\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1})_{(0,-\xi)}$	$\overline{x}$
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2},\mathbf{1})_{(0,0)}$	z

☞ $\sigma \in \{0, \pm 1, \pm 2, \pm 3\}$ $\curvearrowright$ can break $\mathrm{U}(1)_{B-L} \to \mathbb{Z}_2^{\mathcal{M}}$

Spectrum and matter parity

#	representation	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{6},\frac{1}{3})}$	q
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},-\frac{1}{3})}$	$\overline{d}$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(1,1)}$	$\overline{e}$
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},0)}$	h
5	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},\frac{2}{3})}$	$\overline{\delta}$
5	$(\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1})_{(0,\xi)}$	x
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})_{(0,0)}$	y

#	representation	label
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{2}{3},-\frac{1}{3})}$	$\overline{u}$
3	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},-1)}$	ℓ
33	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(0,\sigma)}$	s
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{2},0)}$	$\overline{h}$
5	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{3},-\frac{2}{3})}$	δ
5	$(\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1})_{(0,-\xi)}$	$\overline{x}$
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2},\mathbf{1})_{(0,0)}$	z

- can break $\mathrm{U}(1)_{B-L} \to \mathbb{Z}_2^{\mathcal{M}}$
- Many other good features:
  - exotics decouple at the linear level in SM singlets
  - non-trivial Yukawa couplings
  - gauge-top unification
  - SU(5) relation $y_\tau \simeq y_b$ (but also for light generations)

P. Hosteins, R. Kappl, M.R., K. Schmidt-Hoberg (2009)

Spectrum and matter parity

#	representation	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{6},\frac{1}{3})}$	q
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},-\frac{1}{3})}$	$\overline{d}$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(1,1)}$	$\overline{e}$
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},0)}$	h
5	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},\frac{2}{3})}$	$\overline{\delta}$
5	$(\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1})_{(0,\xi)}$	x
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})_{(0,0)}$	y

#	representation	label
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{2}{3},-\frac{1}{3})}$	$\overline{u}$
3	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},-1)}$	ℓ
33	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(0,\sigma)}$	s
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{2},0)}$	$\overline{h}$
5	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{3},-\frac{2}{3})}$	δ
5	$(\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1})_{(0,-\xi)}$	$\overline{x}$
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2},\mathbf{1})_{(0,0)}$	z

- ☞ can break $\mathrm{U}(1)_{B-L} \to \mathbb{Z}_2^{\mathcal{M}}$
- ☞ Many other good features
- ☹ However: generically the Higgs pair as heavy as the exotics

Spectrum and matter parity

#	representation	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{6},\frac{1}{3})}$	q
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},-\frac{1}{3})}$	$\overline{d}$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(1,1)}$	$\overline{e}$
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},0)}$	h
5	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{3},\frac{2}{3})}$	$\overline{\delta}$
5	$(\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1})_{(0,\xi)}$	x
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})_{(0,0)}$	y

#	representation	label
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{2}{3},-\frac{1}{3})}$	$\overline{u}$
3	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{2},-1)}$	ℓ
33	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(0,\sigma)}$	s
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{(\frac{1}{2},0)}$	$\overline{h}$
5	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{(-\frac{1}{3},-\frac{2}{3})}$	δ
5	$(\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1})_{(0,-\xi)}$	$\overline{x}$
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2},\mathbf{1})_{(0,0)}$	z

- ☞ can break $\mathrm{U}(1)_{B-L} \to \mathbb{Z}_2^{\mathcal{M}}$
- ☞ Many other good features
- ☹ However: generically the Higgs pair as heavy as the exotics
- ☹ Dimension five proton decay operators as problematic as in 4D GUTs

Solving the μ and proton decay problems

- There are *many* inequivalent VEV configurations with matter parity

Solving the μ and proton decay problems

- There are *many* inequivalent VEV configurations with matter parity
- The μ problem and proton decay problems can be solved simultaneously by a simple $\mathbb{Z}_2^R$ symmetry

Solving the μ and proton decay problems

- There are *many* inequivalent VEV configurations with matter parity
- The μ problem and proton decay problems can be solved simultaneously by a simple $\mathbb{Z}_2^R$ symmetry
- $\mathbb{Z}_2^R$ properties

1. $\mathscr{W} \xrightarrow{\mathbb{Z}_2^R} -\mathscr{W}$

Solving the μ and proton decay problems

- There are *many* inequivalent VEV configurations with matter parity
- The μ problem and proton decay problems can be solved simultaneously by a simple $\mathbb{Z}_2^R$ symmetry
- $\mathbb{Z}_2^R$ properties

1. $\mathscr{W} \xrightarrow{\mathbb{Z}_2^R} -\mathscr{W}$
2. superfields transform with $+$ or $-$

Solving the μ and proton decay problems

- There are *many* inequivalent VEV configurations with matter parity
- The μ problem and proton decay problems can be solved simultaneously by a simple $\mathbb{Z}_2^R$ symmetry
- $\mathbb{Z}_2^R$ properties

1. $\mathscr{W} \xrightarrow{\mathbb{Z}_2^R} -\mathscr{W}$
2. superfields transform with $+$ or $-$
3. for fermions and θ-coordinates it is a $\mathbb{Z}_4$ symmetry

General aspects of $\mathbb{Z}_2^R$

- Structure of the superpotential : $\mathscr{W} = \psi f(\phi) + \mathcal{O}(\psi^3)$

$\mathbb{Z}_2^R$ odd

$\mathbb{Z}_2^R$ even

General aspects of $\mathbb{Z}_2^R$

- Structure of the superpotential : $\mathscr{W} \;=\; \psi f(\phi) + \mathcal{O}(\psi^3)$
- $\mathbb{Z}_2^R$ preserving configurations $\langle \psi \rangle = 0 \curvearrowright F$-term equations

$$\begin{aligned} F_\psi &= f(\phi) \stackrel{!}{=} 0 \\ F_\phi &= \psi f'(\phi) \;=\; 0 \quad \text{at } \psi = 0 \end{aligned}$$

General aspects of $\mathbb{Z}_2^R$

- Structure of the superpotential : $\mathscr{W} \;=\; \psi f(\phi) + \mathcal{O}(\psi^3)$
- $\mathbb{Z}_2^R$ preserving configurations $\langle \psi \rangle = 0 \curvearrowright \boldsymbol{F}$-term equations

$$\begin{aligned} \boldsymbol{F}_\psi &= f(\phi) \stackrel{!}{=} 0 \quad \text{fixes } \phi \text{ possibly at } \langle \phi \rangle \neq 0 \\ \boldsymbol{F}_\phi &= \psi f'(\phi) \;=\; 0 \quad \text{at } \psi = 0 \quad \text{automatic} \end{aligned}$$

General aspects of $\mathbb{Z}_2^R$

- Structure of the superpotential : $\mathscr{W} \;=\; \psi f(\phi) + \mathcal{O}(\psi^3)$
- $\mathbb{Z}_2^R$ preserving configurations $\langle \psi \rangle = 0 \curvearrowright F$-term equations

$$F_\psi \;=\; f(\phi) \stackrel{!}{=} 0 \quad \text{fixes } \phi \text{ possibly at } \langle \phi \rangle \neq 0$$
$$F_\phi \;=\; \psi f'(\phi) \;=\; 0 \quad \text{at } \psi = 0 \quad \text{automatic}$$

- Mass term

$$\frac{\partial^2 \mathscr{W}}{\partial \phi \, \partial \psi} \;=\; f'(\phi) \;\neq\; 0 \quad \text{in general at } \psi = 0$$

General aspects of $\mathbb{Z}_2^R$

- Structure of the superpotential : $\mathscr{W} = \psi f(\phi) + \mathcal{O}(\psi^3)$
- $\mathbb{Z}_2^R$ preserving configurations $\langle \psi \rangle = 0 \curvearrowright F$-term equations

$$F_\psi = f(\phi) \stackrel{!}{=} 0 \quad \text{fixes } \phi \text{ possibly at } \langle \phi \rangle \neq 0$$
$$F_\phi = \psi f'(\phi) = 0 \quad \text{at } \psi = 0 \quad \text{automatic}$$

- Mass term

$$\frac{\partial^2 \mathscr{W}}{\partial \phi \, \partial \psi} = f'(\phi) \neq 0 \quad \text{in general at } \psi = 0$$

➥ fields fixed ($\langle \phi \rangle \neq 0$ & $\langle \psi \rangle = 0$) with $\mathscr{W} = 0$

General aspects of $\mathbb{Z}_2^R$

- Structure of the superpotential : $\mathscr{W} \;=\; \psi f(\phi) + \mathcal{O}(\psi^3)$
- $\mathbb{Z}_2^R$ preserving configurations $\langle \psi \rangle = 0 \curvearrowright \boldsymbol{F}$-term equations

$$\begin{aligned} \boldsymbol{F}_\psi &= f(\phi) \stackrel{!}{=} 0 \quad \text{fixes } \phi \text{ possibly at } \langle \phi \rangle \neq 0 \\ \boldsymbol{F}_\phi &= \psi f'(\phi) \;=\; 0 \quad \text{at } \psi = 0 \quad \text{automatic} \end{aligned}$$

- Mass term

$$\frac{\partial^2 \mathscr{W}}{\partial \phi \, \partial \psi} \;=\; f'(\phi) \;\neq\; 0 \quad \text{in general at } \psi = 0$$

➥ fields fixed ($\langle \phi \rangle \neq 0$ & $\langle \psi \rangle = 0$) with $\mathscr{W} = 0$

➥ Generalization: $\boldsymbol{N}$ $\psi^{(i)}$ and $\boldsymbol{M}$ $\phi^{(j)}$
$\curvearrowright$ expect non-trivial solution, i.e. $\langle \phi^{(j)} \rangle \neq 0$, for $\boldsymbol{N} \leq \boldsymbol{M}$

$\mathbb{Z}_2^{\mathcal{M}} \times \mathbb{Z}_2^{R}$ vacuum configuration

R. Kappl, B. Petersen, M.R., R. Schieren, P. Vaudrevange, in preparation

#	representation	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{\frac{1}{6}}$	q
$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{\frac{1}{3}}$	$\overline{d}$
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{-\frac{1}{2}}$	ℓ
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{1}$	$\overline{e}$
3	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{-\frac{1}{2}}$	h
4	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{\frac{1}{3}}$	$\overline{\delta}$
5	$(\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1})_{0}$	x
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})_{0}$	y

#	representation	label
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{-\frac{2}{3}}$	$\overline{u}$
1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{-\frac{1}{3}}$	d
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{\frac{1}{2}}$	ℓ
33	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{0}$	s
3	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{\frac{1}{2}}$	$\overline{h}$
4	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{-\frac{1}{3}}$	δ
5	$(\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1})_{0}$	$\overline{x}$
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2},\mathbf{1})_{0}$	z

$\mathbb{Z}_2^{\mathcal{M}} \times \mathbb{Z}_2^{R}$ vacuum configuration

R. Kappl, B. Petersen, M.R., R. Schieren, P. Vaudrevange, in preparation

#	representation	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{\frac{1}{6}}$	q
$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{\frac{1}{3}}$	$\overline{d}$
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{-\frac{1}{2}}$	ℓ
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{1}$	$\overline{e}$
3	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{-\frac{1}{2}}$	h
4	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{\frac{1}{3}}$	$\overline{\delta}$
5	$(\mathbf{1},\mathbf{1};\mathbf{3},\mathbf{1},\mathbf{1})_{0}$	x
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})_{0}$	y

#	representation	label
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{-\frac{2}{3}}$	$\overline{u}$
1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{-\frac{1}{3}}$	d
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{\frac{1}{2}}$	ℓ
33	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{0}$	s
3	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1},\mathbf{1})_{\frac{1}{2}}$	$\overline{h}$
4	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{1})_{-\frac{1}{3}}$	δ
5	$(\mathbf{1},\mathbf{1};\overline{\mathbf{3}},\mathbf{1},\mathbf{1})_{0}$	$\overline{x}$
6	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2},\mathbf{1})_{0}$	z

☞ Exact $\mathbb{Z}_2^{\mathcal{M}}$ symmetry allows to distinguish between

- $\ell - \bar{\ell}$ and $h - \bar{h}$
- $d - \bar{d}$ and $\delta - \bar{\delta}$

$\mathbb{Z}_2^{\mathcal{M}} \times \mathbb{Z}_2^{R}$ quantum numbers & implications

quarks and leptons

q_1	1	1	$\bar{u}_1$	1	1
q_2	1	1	$\bar{u}_2$	1	1
q_3	1	0	$\bar{u}_3$	1	0
$\bar{d}_1$	1	1	ℓ_1	1	1
$\bar{d}_2$	1	1	ℓ_2	1	1
$\bar{d}_3$	1	0	ℓ_3	1	0
$\bar{d}_4$	1	0	ℓ_4	1	0
d_1	1	1	$\bar{\ell}_1$	1	1
$\bar{e}_1$	1	1			
$\bar{e}_2$	1	1			
$\bar{e}_3$	1	0			

Higgs and exotics

$\bar{h}_1$	0	1	h_1	0	1
$\bar{h}_2$	0	0	h_2	0	1
$\bar{h}_3$	0	0	h_3	0	1
$\bar{\delta}_1$	0	1	δ_1	0	1
$\bar{\delta}_2$	0	0	δ_2	0	0
$\bar{\delta}_3$	0	1	δ_3	0	0
$\bar{\delta}_4$	0	1	δ_4	0	0

$\mathbb{Z}_2^{\mathcal{M}} \times \mathbb{Z}_2^{R}$ quantum numbers & implications

quarks and leptons						Higgs and exotics					
q_1	1	1	$\bar{u}_1$	1	1	$\bar{h}_1$	0	1	h_1	0	1
q_2	1	1	$\bar{u}_2$	1	1	$\bar{h}_2$	0	0	h_2	0	1
q_3	1	0	$\bar{u}_3$	1	0	$\bar{h}_3$	0	0	h_3	0	1
$\bar{d}_1$	1	1	ℓ_1	1	1	$\bar{\delta}_1$	0	1	δ_1	0	1
$\bar{d}_2$	1	1	ℓ_2	1	1	$\bar{\delta}_2$	0	0	δ_2	0	0
$\bar{d}_3$	1	0	ℓ_3	1	0	$\bar{\delta}_3$	0	1	δ_3	0	0
$\bar{d}_4$	1	0	ℓ_4	1	0					0	0
d_1	1	1	$\bar{\ell}_1$	1	1						
$\bar{e}_1$	1	1									
$\bar{e}_2$	1	1									
$\bar{e}_3$	1	0									

fields with VEV

$$\mathcal{M}_d = \mathcal{M}_\ell = \begin{pmatrix} 0 & 0 & \tilde{\phi}^9 & \tilde{\phi}^9 \end{pmatrix}$$

- mass might be suppressed
- complete $\mathrm{SU}(5)$ multiplets $\mathbf{5} + \overline{\mathbf{5}}$ with equal masses due to $\mathrm{SU}(5)$ relation
  $\curvearrowright$ doesn't spoil unification

$\mathbb{Z}_2^{\mathcal{M}} \times \mathbb{Z}_2^{R}$ quantum numbers & implications

quarks and leptons						Higgs and exotics					
q_1	1	1	$\bar{u}_1$	1	1	$\bar{h}_1$	0	1	h_1	0	1
q_2	1	1	$\bar{u}_2$	1	1	$\bar{h}_2$	0	0	h_2	0	1
q_3	1	0	$\bar{u}_3$	1	0	$\bar{h}_3$	0	0	h_3	0	1
$\bar{d}_1$	1	1	ℓ_1	1	1	$\bar{\delta}_1$	0	1	δ_1	0	1
$\bar{d}_2$	1	1	ℓ_2	1	1	$\bar{\delta}_2$	0	0	δ_2	0	0
$\bar{d}_3$	1	0	ℓ_3	1	0	$\bar{\delta}_3$	0	1	δ_3	0	0
$\bar{d}_4$	1	0	ℓ_4	1	0	$\bar{\delta}_4$	0	1	δ_4	0	0
d_1	1	1	$\bar{\ell}_1$	1	1						
$\bar{e}_1$	1	1									
$\bar{e}_2$	1	1									
$\bar{e}_3$	1	0									

$$\mathcal{M}_\delta = \begin{pmatrix} 0 & \widetilde{\phi} & 0 & 0 \\ \widetilde{\phi} & 0 & \widetilde{\phi} & \widetilde{\phi} \\ \widetilde{\phi} & 0 & \widetilde{\phi} & \widetilde{\phi}^3 \\ \widetilde{\phi} & 0 & \widetilde{\phi}^3 & \widetilde{\phi} \end{pmatrix}$$

- δ exotics decouple at the linear level in VEV fields

$\mathbb{Z}_2^{\mathcal{M}} \times \mathbb{Z}_2^{R}$ quantum numbers & implications

quarks and leptons						Higgs and exotics					
q_1	1	1	$\bar{u}_1$	1	1	$\bar{h}_1$	0	1	h_1	0	1
q_2	1	1	$\bar{u}_2$	1	1	$\bar{h}_2$	0	0	h_2	0	1
q_3	1	0	$\bar{u}_3$	1	0	$\bar{h}_3$	0	0	h_3	0	1
$\bar{d}_1$	1	1	ℓ_1	1	1	$\bar{\delta}_1$	0	1	δ_1	0	1
$\bar{d}_2$	1	1	ℓ_2	1	1	$\bar{\delta}_2$	0	0	δ_2	0	0
$\bar{d}_3$	1	0									
$\bar{d}_4$	1	0									
d_1	1	1									
$\bar{e}_1$	1	1									
$\bar{e}_2$	1	1									
$\bar{e}_3$	1	0									

$$\mathcal{M}_h = \begin{pmatrix} 0 & 0 & 0 \\ \widetilde{\phi}^{11} & \widetilde{\phi} & \widetilde{\phi}^{3} \\ \widetilde{\phi}^{11} & \widetilde{\phi}^{3} & \widetilde{\phi} \end{pmatrix}$$

- extra Higgs decouple at the linear level in VEV fields
- one pair of massless Higgs

$$\begin{aligned} h_u &= \bar{h}_1 \\ h_d &= a_1 h_1 + a_2 h_2 + a_3 h_3 \end{aligned}$$

$\mathbb{Z}_2^{\mathcal{M}} \times \mathbb{Z}_2^{R}$ quantum numbers & implications

quarks and leptons						Higgs and exotics					
q_1	1	1	$\bar{u}_1$	1	1	$\bar{h}_1$	0	1	h_1	0	1
q_2	1	1	$\bar{u}_2$	1	1	$\bar{h}_2$	0	0	h_2	0	1
q_3	1	0	$\bar{u}_3$	1	0	$\bar{h}_3$	0	0	h_3	0	1
$\bar{d}_1$	1	1	ℓ_1	1	1	$\bar{\delta}_1$	0	1	δ_1	0	1
$\bar{d}_2$	1	1	ℓ_2	1	1	$\bar{\delta}_2$	0	0	δ_2	0	0
$\bar{d}_3$	1	0	ℓ_3								
$\bar{d}_4$	1	0	ℓ_4								
d_1	1	1	$\bar{\ell}_1$								
$\bar{e}_1$	1	1									
$\bar{e}_2$	1	1									
$\bar{e}_3$	1	0									

$$Y_u = \begin{pmatrix} \widetilde{\phi}^6\,\bar{h}_1 & \widetilde{\phi}^6\,\bar{h}_1 & 0 \\ \widetilde{\phi}^6\,\bar{h}_1 & \widetilde{\phi}^6\,\bar{h}_1 & 0 \\ 0 & 0 & \bar{h}_1 \end{pmatrix}$$

- gauge-top unification : $y_t \simeq g$ at high energies
- Yukawa hierarchies & non-trivial 1-2 mixing
- but no mixing with $3^{\rm rd}$ family

$\mathbb{Z}_2^{\mathcal{M}} \times \mathbb{Z}_2^{R}$ quantum numbers & implications

quarks and leptons							Higgs and exotics					
q_1	1	1		$\bar{u}_1$	1	1	$\bar{h}_1$	0	1	h_1	0	1
q_2	1	1		$\bar{u}_2$	1	1	$\bar{h}_2$	0	0	h_2	0	1
q_3	1	0		$\bar{u}_3$	1	0	$\bar{h}_3$	0	0	h_3	0	1
$\bar{d}_1$	1	1		ℓ_1	1	1	$\bar{\delta}_1$	0	1	δ_1	0	1
$\bar{d}_2$	1	1		ℓ_2	1	1	$\bar{\delta}_2$	0	0	δ_2	0	0
$\bar{d}_3$	1	0		ℓ_3	1	0	$\bar{\delta}_3$	0	1	δ_3	0	0
$\bar{d}_4$	1	0		ℓ_4	1	0	$\bar{\delta}_4$	0	1	δ_4	0	0
$\bar{d}_1$	1	1		$\bar{\ell}_1$	1	1						

$$Y_d = \begin{pmatrix} h_1\,\widetilde{\phi}^{10} + h_2 + h_3\,\widetilde{\phi}^{4} & h_1\widetilde{\phi}^{10} + h_3 + h_2\,\widetilde{\phi}^{4} & 0 \\ h_1\,\widetilde{\phi}^{10} + h_3\,\widetilde{\phi}^{6} + h_2\,\widetilde{\phi}^{4} & h_1\,\widetilde{\phi}^{10} + h_2\,\widetilde{\phi}^{6} + h_3\,\widetilde{\phi}^{4} & 0 \\ 0 & 0 & h_1\,\widetilde{\phi}^{10} + h_2 + h_3\,\widetilde{\phi}^{4} \\ 0 & 0 & h_1\,\widetilde{\phi}^{10} + h_3 + h_2\,\widetilde{\phi}^{2} \end{pmatrix}$$

- Yukawa hierarchies & non-trivial 1-2 mixing
- but no mixing with 3rd family

$\mathbb{Z}_2^{\mathcal{M}} \times \mathbb{Z}_2^{R}$ quantum numbers & implications

quarks and leptons						Higgs and exotics					
q_1	1	1	$\bar{u}_1$	1	1	$\bar{h}_1$	0	1	h_1	0	1
q_2	1	1	$\bar{u}_2$	1	1	$\bar{h}_2$	0	0	h_2	0	1
q_3	1	0	$\bar{u}_3$	1	0	$\bar{h}_3$	0	0	h_3	0	1
$\bar{d}_1$	1	1	ℓ_1	1	1	$\bar{\delta}_1$	0	1	δ_1	0	1
$\bar{d}_2$	1	1	ℓ_2	1	1	$\bar{\delta}_2$	0	0	δ_2	0	0
$\bar{d}_3$	1	0	ℓ_3	1	0	$\bar{\delta}_3$	0	1	δ_3	0	0
$\bar{d}_4$	1	0	ℓ_4	1	0	$\bar{\delta}_4$	0	1	δ_4	0	0
d_1	1	1	$\bar{\ell}_1$	1	1						
$\bar{e}_1$	1	1									
$\bar{e}_2$	1	1									
$\bar{e}_3$	1	0									

$$Y_e^T = Y_d$$

- SU(5) relations : good for $3^{\rm rd}$ family but bad for $1^{\rm st}$ & $2^{\rm nd}$ families
- eigenvalues might be too small

$\mathbb{Z}_2^{\mathcal{M}} \times \mathbb{Z}_2^{R}$ quantum numbers & implications

quarks and leptons						Higgs and exotics					
q_1	1	1	$\bar{u}_1$	1	1	$\bar{h}_1$	0	1	h_1	0	1
q_2	1	1	$\bar{u}_2$	1	1	$\bar{h}_2$	0	0	h_2	0	1
q_3	1	0	$\bar{u}_3$	1	0	$\bar{h}_3$	0	0	h_3	0	1
$\bar{d}_1$	1	1	ℓ_1	1	1	$\bar{\delta}_1$	0	1	δ_1	0	1
$\bar{d}_2$	1	1	ℓ_2	1	1	$\bar{\delta}_2$	0	0	δ_2	0	0
$\bar{d}_3$	1	0	ℓ_3	1	0	$\bar{\delta}_3$	0	1	δ_3	0	0
$\bar{d}_4$	1	0	ℓ_4	1	0	$\bar{\delta}_4$	0	1	δ_4	0	0
d_1	1	1	$\bar{\ell}_1$	1	1						
$\bar{e}_1$	1	1									
$\bar{e}_2$	1	1									
$\bar{e}_3$	1	0									

$q_i\, q_j\, q_k\, \ell_m$

- proton decay operators involve always 3rd generation field
  $\curvearrowright$ proton stable at this level

$\mathbb{Z}_2^R$ anomaly

- $\mathbb{Z}_2^R$ turns out to be 'anomalous' (partly descends from the so-called 'anomalous $\mathrm{U}(1)$')

$\mathbb{Z}_2^R$ anomaly

- $\mathbb{Z}_2^R$ turns out to be 'anomalous' (partly descends from the so-called 'anomalous $\mathrm{U}(1)$')

- Extra terms at the non-perturbative level:
  - μ term; dominated by $\langle \mathscr{W} \rangle$, which appears at non-perturbative level as well

    $$\mu \sim \langle \mathscr{W} \rangle \sim \widetilde{\phi}^{11}\, \mathrm{e}^{-a\,S}$$
  - proton decay operators

    $$[q\,q\,q\,\ell]_{\text{light generations}} \sim \widetilde{\phi}^{15}\, \mathrm{e}^{-a\,S}$$
  - mixing between first two and third generations

    $$(Y_u)_{13} \sim \widetilde{\phi}^{4}\, \mathrm{e}^{-a\,S}$$

$\mathbb{Z}_2^R$ anomaly

- ☞ $\mathbb{Z}_2^R$ turns out to be 'anomalous' (partly descends from the so-called 'anomalous $\mathrm{U}(1)$')

- ➥ Extra terms at the non-perturbative level:
  - μ term; dominated by $\langle \mathscr{W} \rangle$, which appears at non-perturbative level as well
    $$\mu \sim \langle \mathscr{W} \rangle \sim \widetilde{\phi}^{11}\, \mathrm{e}^{-a\,S}$$
  - proton decay operators
    $$[q\,q\,q\,\ell]_{\text{light generations}} \sim \widetilde{\phi}^{15}\, \mathrm{e}^{-a\,S}$$
  - mixing between first two and third generations
    $$(Y_u)_{13} \sim \widetilde{\phi}^{4}\, \mathrm{e}^{-a\,S}$$

- ➥ 'Anomalous' $\mathbb{Z}_2^R$ explains suppressed μ term and relates the suppression of proton decay operators to mixing between first two and third generations

$\mathbb{Z}_2^R$ anomaly

- ☞ $\mathbb{Z}_2^R$ turns out to be 'anomalous' (partly descends from the so-called 'anomalous $\mathrm{U}(1)$')

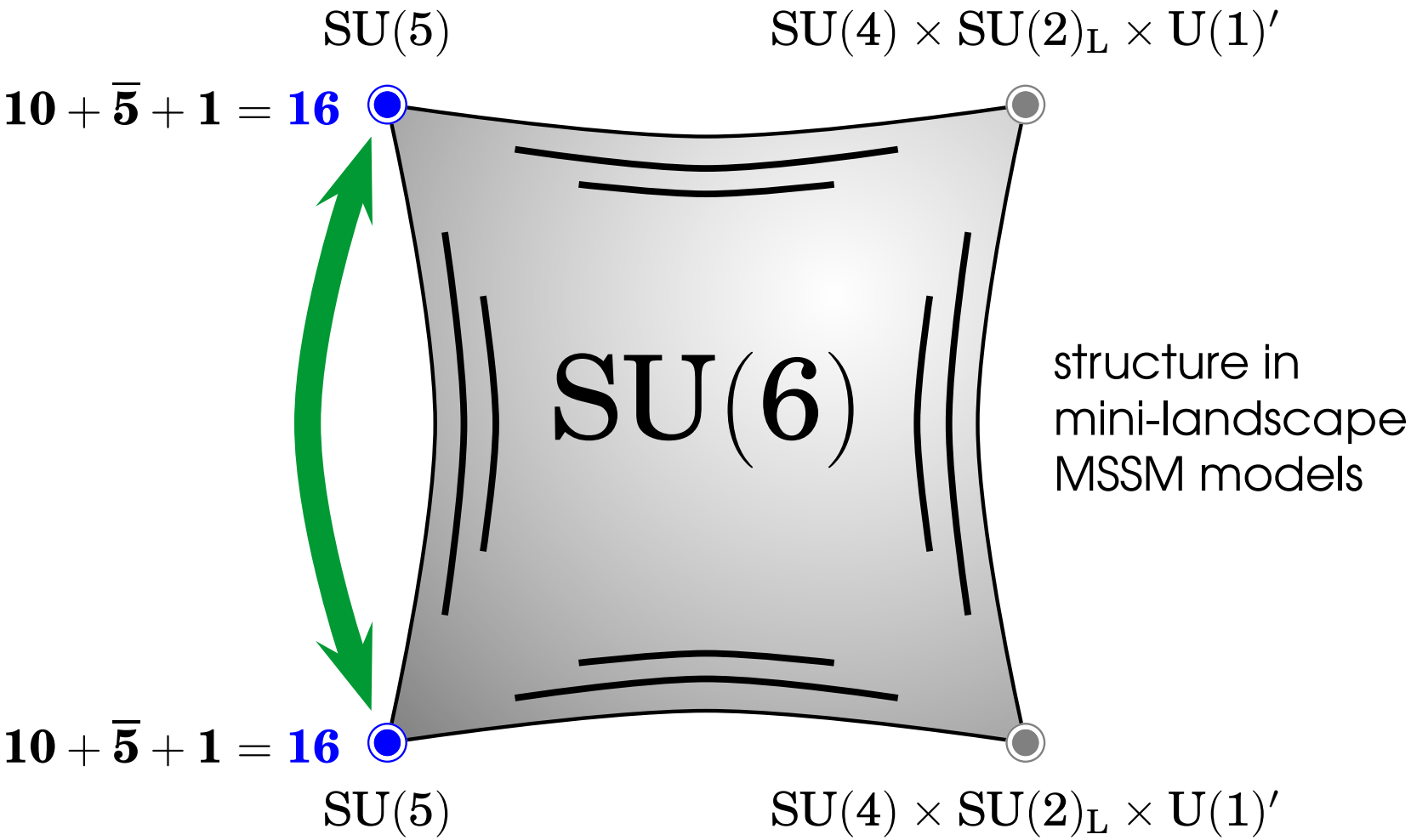
- ➥ Extra terms at the non-perturbative level:
  - μ term; dominated by $\langle \mathscr{W} \rangle$, which appears at non-perturbative level as well
    $$\mu \sim \langle \mathscr{W} \rangle \sim \widetilde{\phi}^{11}\, \mathrm{e}^{-a\,S}$$
  - proton decay operators
    $$[q\,q\,q\,\ell]_{\text{light generations}} \sim \widetilde{\phi}^{15}\, \mathrm{e}^{-a\,S}$$
  - mixing between first two and third generations
    $$(Y_u)_{13} \sim \widetilde{\phi}^{4}\, \mathrm{e}^{-a\,S}$$

- ➥ 'Anomalous' $\mathbb{Z}_2^R$ explains suppressed μ term and relates the suppression of proton decay operators to mixing between first two and third generations

- ☞ Many similar configurations. . .

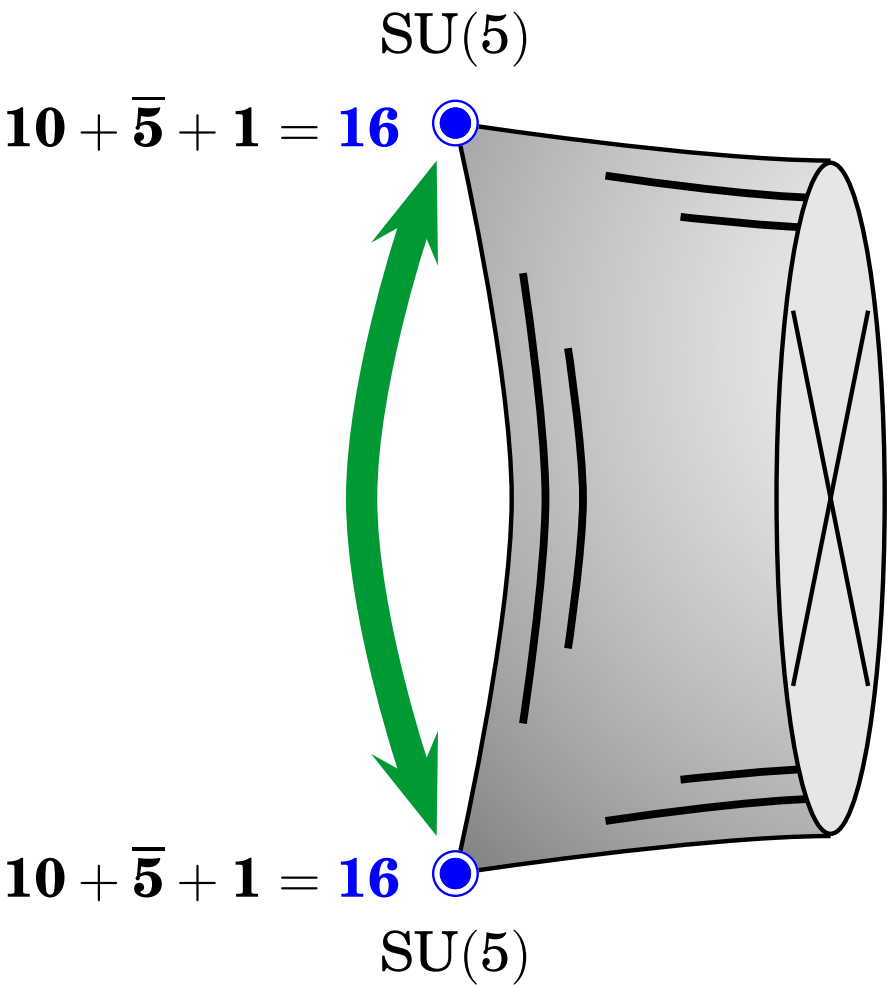
Comments on the structure of soft masses

☞ Two families reside on two equivalent orbifold fixed points



Comments on the structure of soft masses

☞ Two families reside on two equivalent orbifold fixed points



same structure in $\mathbb{Z}_2 \times \mathbb{Z}_2$ MSSM models with non-local GUT breaking

Comments on the structure of soft masses

- ☞ Two families reside on two equivalent orbifold fixed points
- ➥ This leads to a discrete D_4 flavor symmetry under which the first two generations transform as a doublet

Dixon, Harvey, Martinec, Shenker (1987)

⋮

Kobayashi, Raby, Zhang (2004)

Kobayashi, Nilles, Plöger, Raby, M.R. (2006)

- ☞ Note: anomalies of non-Abelian discrete symmetries cancel in string-derived models

Araki, Kobayashi, Kubo, Ramos-Sánchez, M.R., Vaudrevange (2008)

Comments on the structure of soft masses

- Two families reside on two equivalent orbifold fixed points
- This leads to a discrete D_4 flavor symmetry under which the first two generations transform as a doublet
- At this level, the structure of the soft mass terms is

$$\widetilde{m}^2 = \begin{pmatrix} a & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & b \end{pmatrix}$$

Comments on the structure of soft masses

- Two families reside on two equivalent orbifold fixed points
- This leads to a discrete D_4 flavor symmetry under which the first two generations transform as a doublet
- At this level, the structure of the soft mass terms is

$$\widetilde{m}^2 = \begin{pmatrix} a & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & b \end{pmatrix}$$

- The singlet VEVs $\langle s_i \rangle$ that generate the Yukawa coupling also break D_4

Comments on the structure of soft masses

- Two families reside on two equivalent orbifold fixed points
- This leads to a discrete D_4 flavor symmetry under which the first two generations transform as a doublet
- At this level, the structure of the soft mass terms is

$$\widetilde{m}^2 = \begin{pmatrix} a & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & b \end{pmatrix}$$

- The singlet VEVs $\langle s_i \rangle$ that generate the Yukawa coupling also break D_4
- MFV-like structure of soft masses

$$\widetilde{m}^2 \sim \alpha \, \mathbb{1} + \beta \, Y^\dagger \, Y$$

MFV = Minimal Flavor Violation

Buras, Gambino, Gorbahn, Jäger, Silvestrini (2000)
D'Ambrosio, Giudice, Isidori, Strumia (2002)

Example: soft masses of squark doublets

Paradisi, M.R., Schieren, Simonetto (2008)
Colangelo, Nikolidakis, Smith (2008)

☞ Ansatz (@ $M_{\rm GUT}$):

$$\widetilde{m}_Q^2 \;=\; \alpha_1\,\mathbb{1} + \beta_1\,Y_u^\dagger Y_u + \beta_2\,Y_d^\dagger Y_d + (\beta_3\,Y_d^\dagger Y_d\,Y_u^\dagger Y_u + \text{h.c.})$$

Example: soft masses of squark doublets

Paradisi, M.R., Schieren, Simonetto (2008)
Colangelo, Nikolidakis, Smith (2008)

- Ansatz (@ $M_{\rm GUT}$):

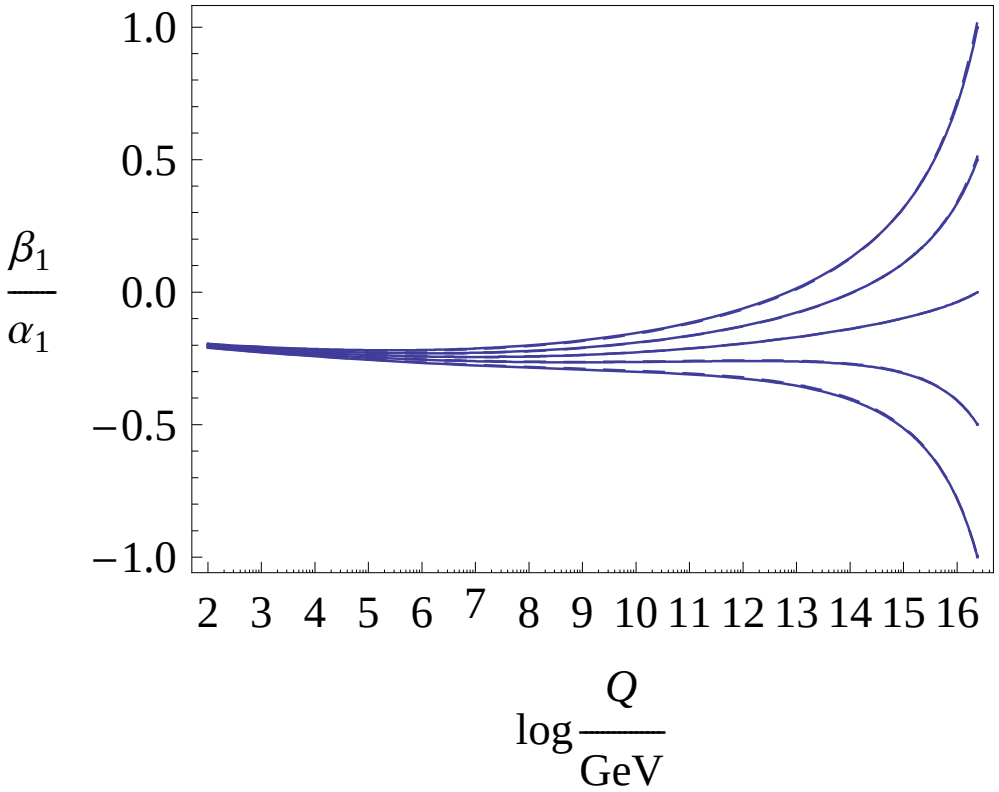
$$\widetilde{m}_Q^2 \;=\; \alpha_1\,\mathbb{1} + \beta_1\,Y_u^\dagger Y_u + \beta_2\,Y_d^\dagger Y_d + (\beta_3\,Y_d^\dagger Y_d\,Y_u^\dagger Y_u + \text{h.c.})$$

- The form of $\widetilde{m}_Q^2$ is RG invariant, only the coefficients α_i & β_i run

Example: Running of β_1

"SPS + MFV"

$$\beta_i = \beta_0 \text{ @ } M_{\mathrm{GUT}}$$
$$\alpha_i = m_0^2 \text{ @ } M_{\mathrm{GUT}}$$

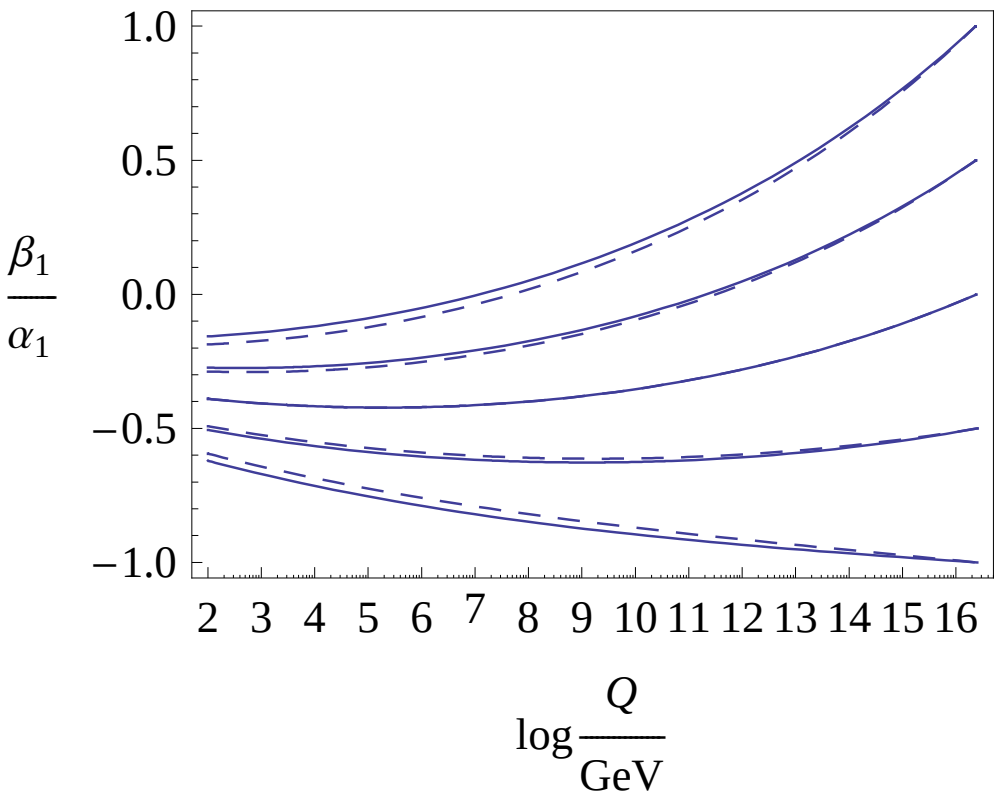


SPS Point	m_0	$m_{1/2}$	A	$\tan\beta$
1a	100 GeV	250 GeV	-100 GeV	10

Example: Running of β_1

"SPS + MFV"

$\beta_i = \beta_0$ @ M_{GUT}
$\alpha_i = m_0^2$ @ M_{GUT}

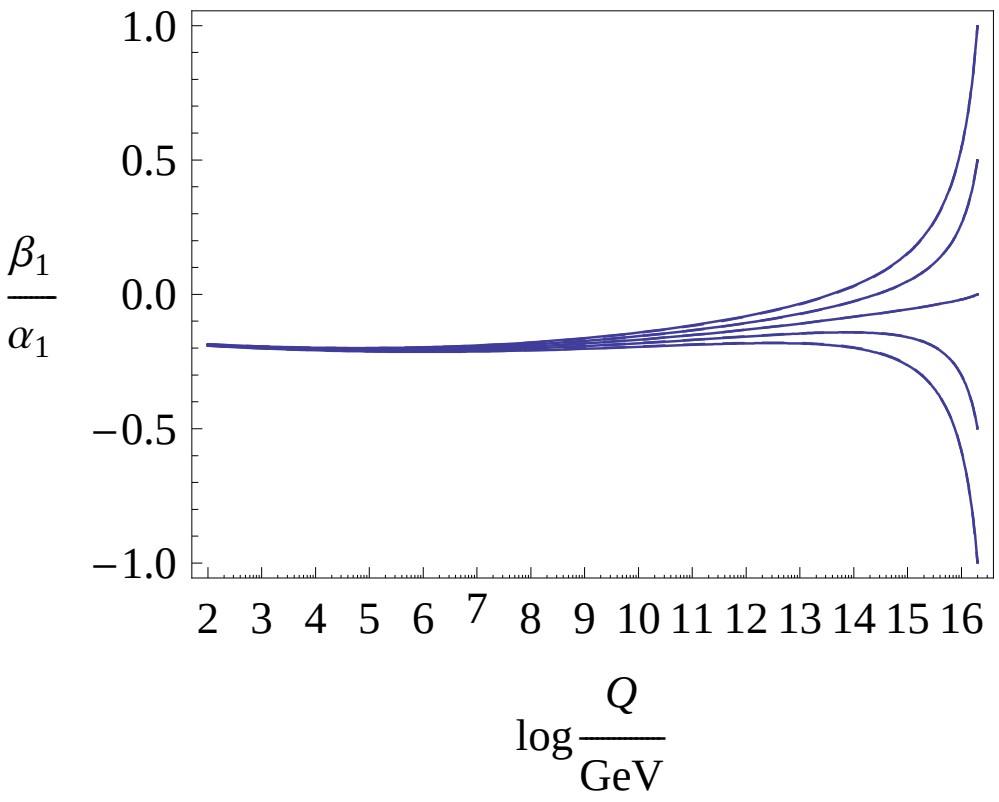


SPS Point	m_0	$m_{1/2}$	A	$\tan\beta$
2	1450 GeV	300 GeV	0	10

Example: Running of β_1

"SPS + MFV"

$$\beta_i = \beta_0 \text{ @ } M_{\mathrm{GUT}}$$
$$\alpha_i = m_0^2 \text{ @ } M_{\mathrm{GUT}}$$



SPS Point	m_0	$m_{1/2}$	A	$\tan\beta$
3	90 GeV	400 GeV	0	10

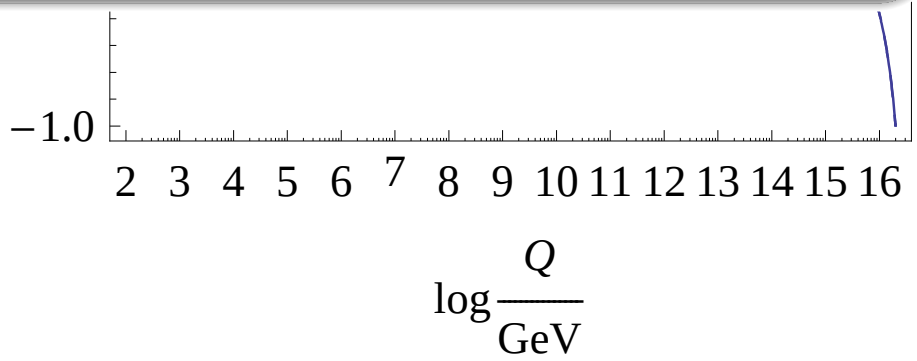
Example: Running of β_1

"SPS

$\beta_i =$
$\alpha_i =$

Bottom-line:

- SUSY flavor problem(s) may be avoided/ameliorated because of stringy D_4 flavor symmetry
- Deviation of $\widetilde{m}^2$ from unit matrices at $M_{\rm GUT}$ might not even be measurable at low energies



SPS Point	m_0	$m_{1/2}$	A	$\tan\beta$
3	90 GeV	400 GeV	0	10

Summary

&

outlook

Summary

1. Approximate R symmetries can explain a suppressed expectation value of the perturbative superpotential

$$\langle \mathscr{W} \rangle \sim \langle \phi \rangle^{N} \quad \text{with } \langle \phi \rangle < 1$$

order of $\cancel{U(1)_R}$

typical VEV

Summary

1. Approximate R symmetries can explain a suppressed expectation value of the perturbative superpotential
2. Suppressed superpotential VEV can play an important role in moduli fixing

Summary

1. Approximate R symmetries can explain a suppressed expectation value of the perturbative superpotential
2. Suppressed superpotential VEV can play an important role in moduli fixing
3. Suppressed superpotential VEV can provide a solution to the μ problem

Summary

1. Approximate R symmetries can explain a suppressed expectation value of the perturbative superpotential
2. Suppressed superpotential VEV can play an important role in moduli fixing
3. Suppressed superpotential VEV can provide a solution to the μ problem
4. Many explicit MSSM models with exact matter parity

Summary

1. Approximate R symmetries can explain a suppressed expectation value of the perturbative superpotential
2. Suppressed superpotential VEV can play an important role in moduli fixing
3. Suppressed superpotential VEV can provide a solution to the μ problem
4. Many explicit MSSM models with exact matter parity
5. A simple 'anomalous'/approximate $\mathbb{Z}_2^R$ symmetry can
   - provide a solution to the μ problem
   - suppress proton decay operators
6. D_4 symmetry can ameliorate/solve SUSY flavor problems

Summary

1. Approximate R symmetries can explain a suppressed expectation value of the perturbative superpotential
2. Suppressed superpotential VEV can play an important role in moduli fixing
3. Suppressed superpotential VEV can provide a solution to the μ problem
4. Many explicit MSSM models with exact matter parity
5. A simple 'anomalous'/approximate $\mathbb{Z}_2^R$ symmetry can
   - provide a solution to the μ problem
   - suppress proton decay operators
6. D_4 symmetry can ameliorate/solve SUSY flavor problems

bottom-line:

discrete symmetries appear crucial for realistic pheno

Outlook

- Many things still need to be done
  - (verify) moduli stabilization
  - SUSY breaking
  - ...

Outlook

- Many things still need to be done
- Perhaps most important question:

coupling strengths

Outlook

- Many things still need to be done
- Perhaps most important question:

coupling strengths

... might allow us really test the $\mathcal{O}(100)$ MSSM candidates

Outlook

- Many things still need to be done
- Perhaps most important question:

coupling strengths

... might allow us really test the $\mathcal{O}(100)$ MSSM candidates and, in the best case, make detailled

Outlook

- Many things still need to be done
- Perhaps most important question:

coupling strengths

... might allow us really test the $\mathcal{O}(100)$ MSSM candidates and, in the best case, make detailled

predictions for LHC


Thank you very much for your attention!