# CP-Violation from Strings

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# Role of CP and its violation

CP (violation) is relevant for several phenomena:

- CP violation in standard model (CKM phase)
- the strong CP-problem ($\Theta_{\rm QCD}$)
- matter-antimatter asymmetry of the universe

While P and C are maximally violated in weak interactions, CP seems only to be "slightly" broken

- Origin of CP symmetry? How is it broken?
- Is it related to flavour symmetries?

CP: make it and break it. Is there a top-down explanation?

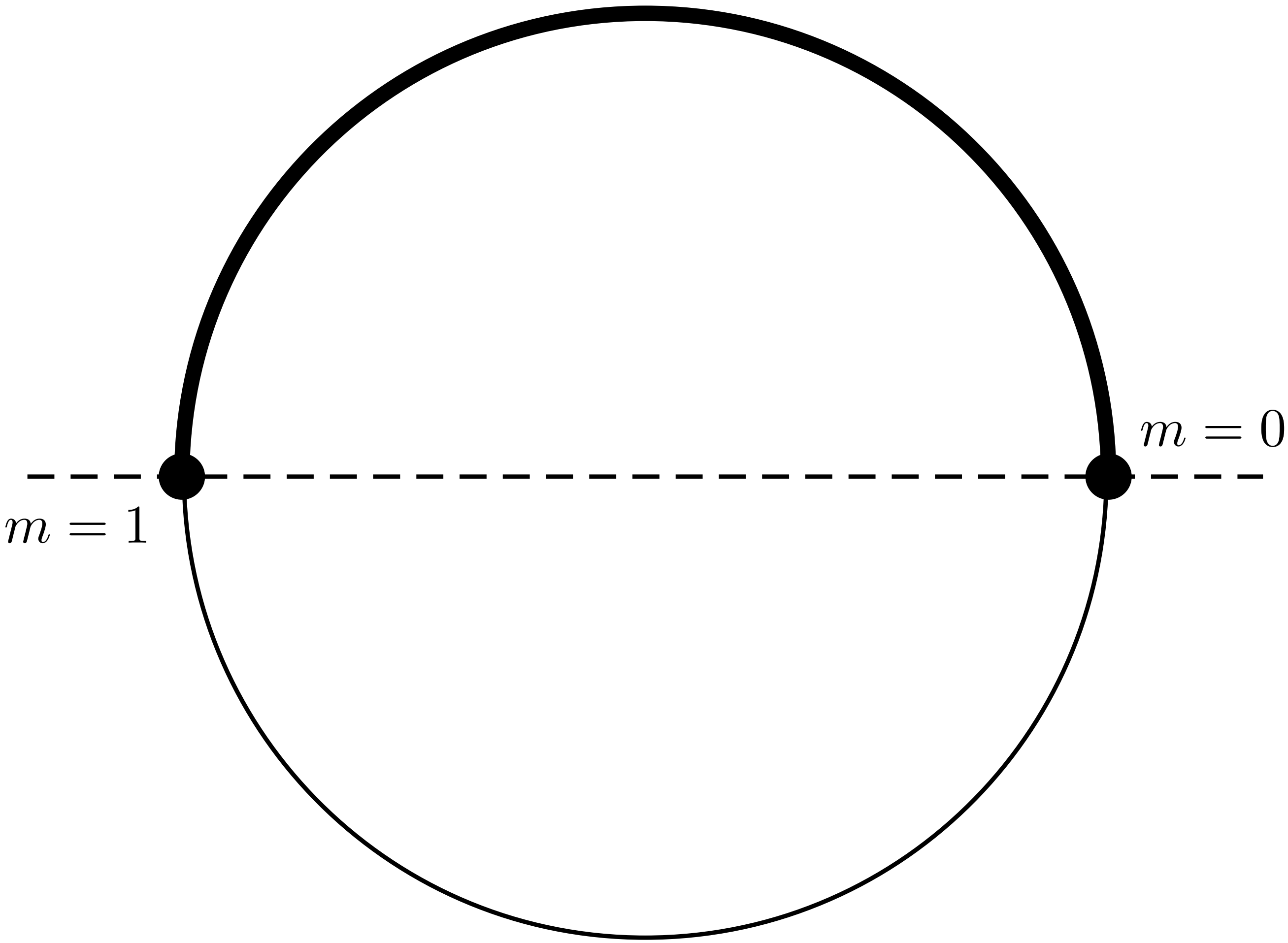
# Outline

CP as a discrete symmetry from string theory. A low energy symmetry broken in the presence of heavy string modes.

- discrete symmetries in string theory
- flavour groups and CP as outer automorphism
- the concept of "explicit geometric CP-violation"
- model examples from the heterotic Mini-Landscape
- CP symmetry in low-energy effective theory
- the role of massive winding modes
- Lepto-genesis from decay of heavy particles
- intrinsic sources for $\Theta$ angle and Jarlskog determinant

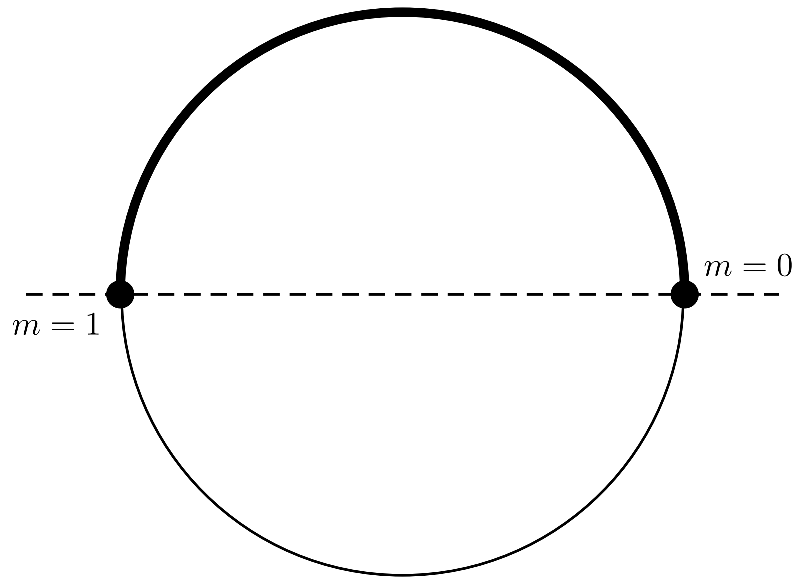
(Nilles, Ratz, Trautner, Vaudrevange, to appear)

# Interval $S_1/Z_2$



# Discrete symmetry $D_4$

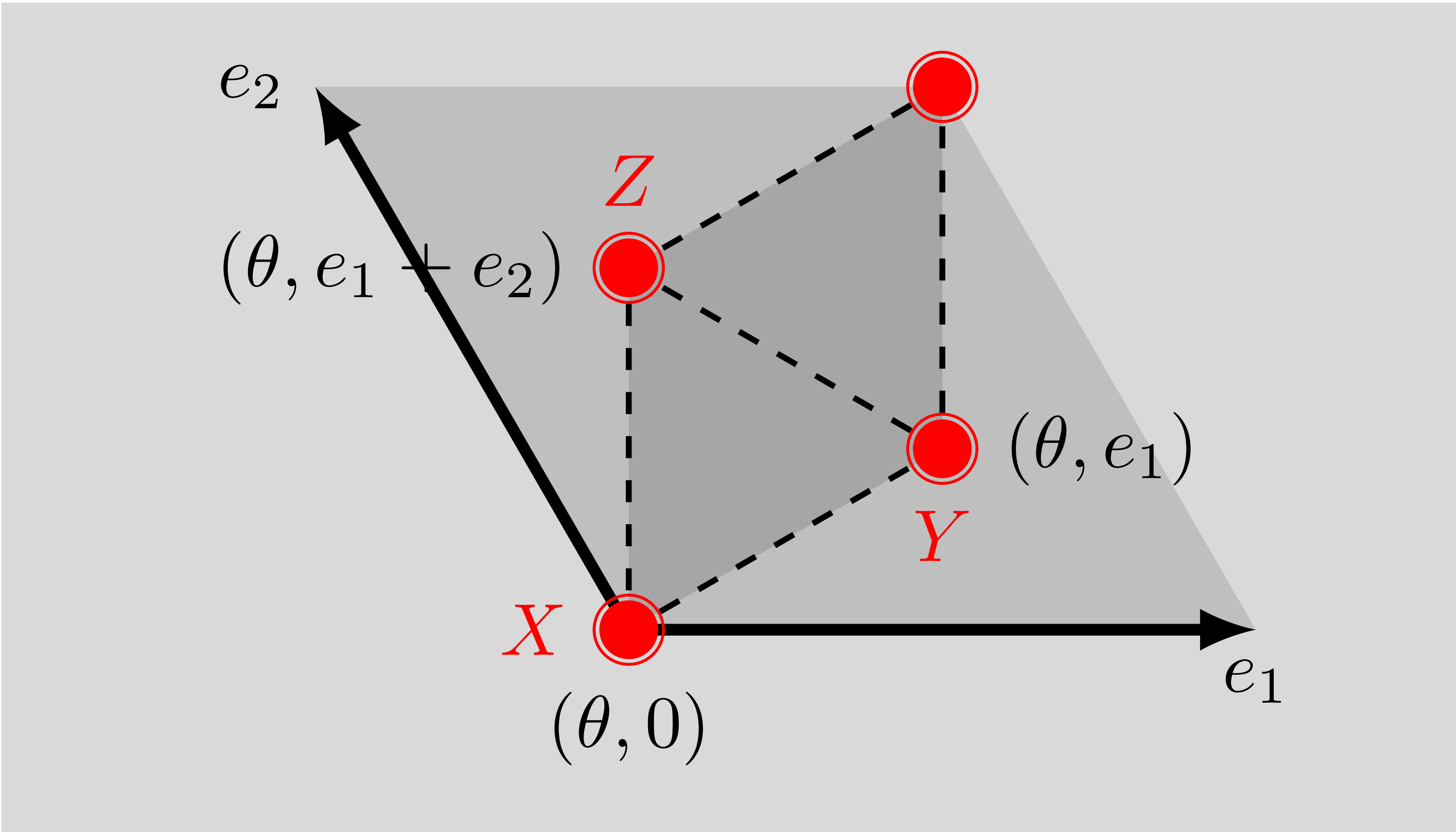
- bulk and brane fields
- $S_2$ symmetry from interchange of fixed points
- $Z_2 \times Z_2$ symmetry from brane field selection rules




- $D_4$ as multiplicative closure of $S_2$ and $Z_2 \times Z_2$
- $D_4$ – a nonabelian subgroup of $SU(2)_{\text{flavor}}$
- flavor symmetry for the two lightest families

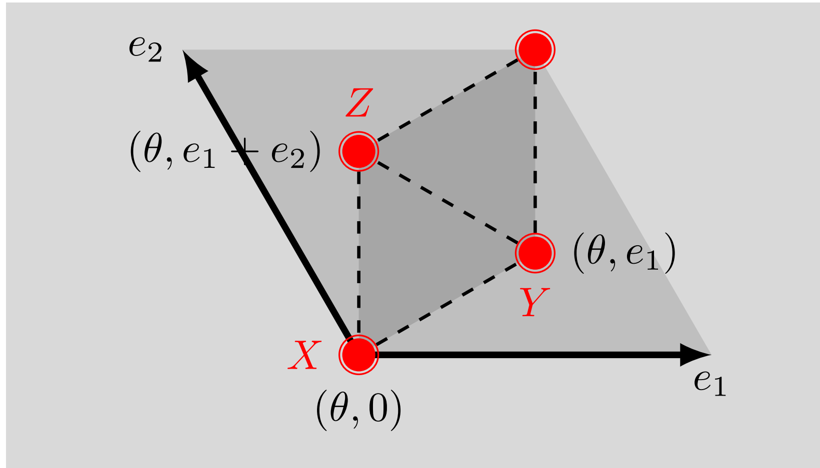
(Kobayashi, Nilles, Ploeger, Raby, Ratz, 2006)

# Orbifold $T_2/Z_3$



# Discrete symmetry $\Delta(54)$

- untwisted and twisted fields
- $S_3$ symmetry from interchange of fixed points
- $Z_3 \times Z_3$ symmetry from orbifold selection rules




- $\Delta(54)$ as multiplicative closure of $S_3$ and $Z_3 \times Z_3$
- $\Delta(54)$ – a nonabelian subgroup of $SU(3)_{\text{flavor}}$
- flavor symmetry for three families of quarks and leptons

(Kobayashi, Nilles, Ploeger, Raby, Ratz, 2006)

# $\Delta(54)$ group theory

$\Delta(54)$ is a nonabelian group and has representations:

- one trivial singlet $1_0$ and one nontrivial singlet $1_-$
- two triplets $3_1$, $3_2$ and corresponding anti-triplets $\bar{3}_1$, $\bar{3}_2$
- four doublets $2_k$ $(k = 1, 2, 3, 4)$

Some relevant tensor products are:

- $3_1 \otimes \bar{3}_1 = 1_0 \oplus 2_1 \oplus 2_2 \oplus 2_3 \oplus 2_4$
- $2_k \otimes 2_k = 1_0 \oplus 1_- \oplus 2_k$

$\Delta(54)$ is a good candidate for a flavour symmetry.

But where is CP?

# CP as outer automorphism

Outer automorphisms map group to itself but are not group elements themselves

- $\Delta(54)$ has outer automorphism group $S_4$
- CP could be $Z_2$ subgroup of this $S_4$
- Physical CP transforms $(rep)$ to $(rep)^*$

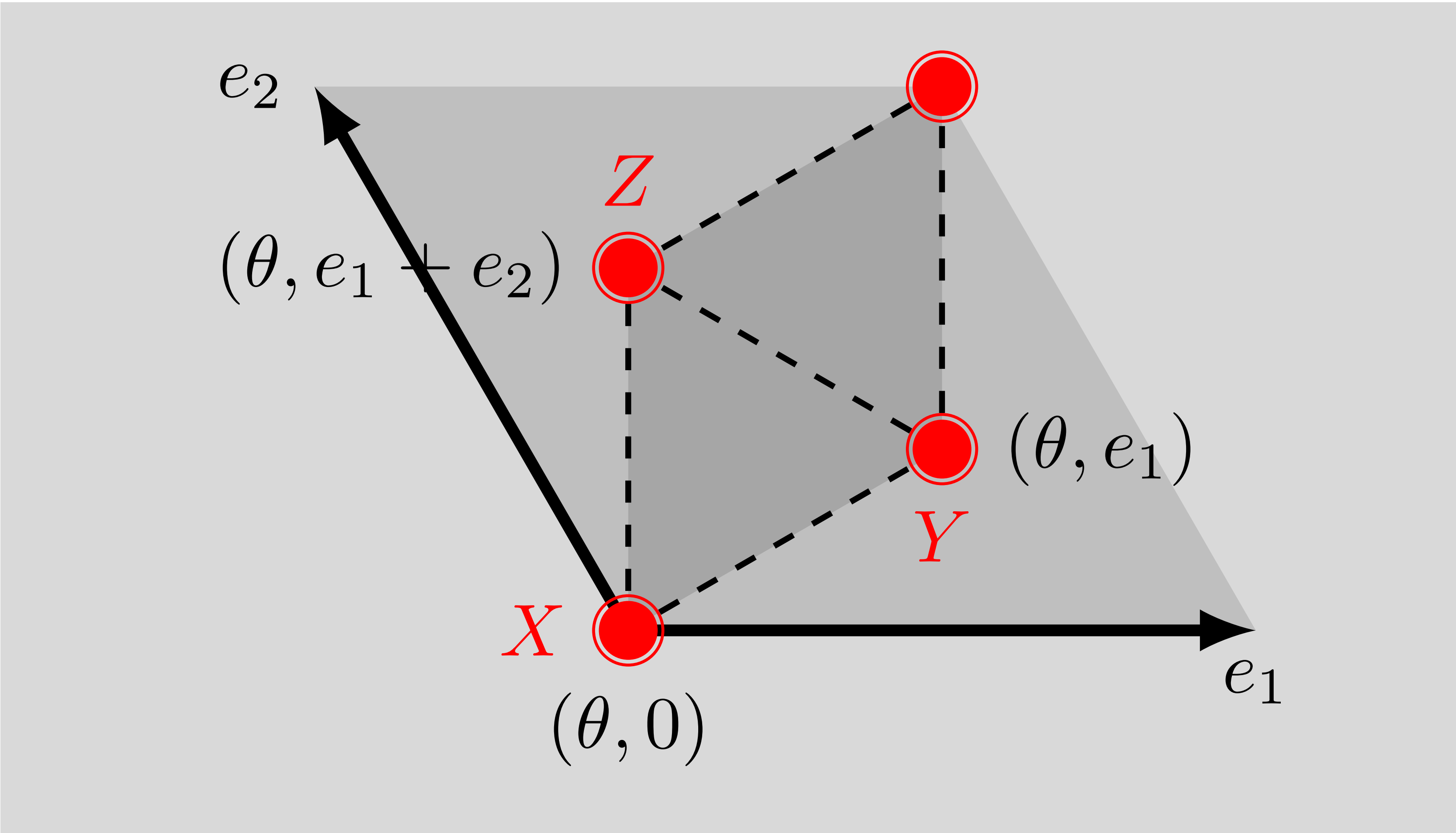
This gives an intimate relation of flavour and CP symmetry

- possible obstructions for a successful definition of CP
- controlled by "twisted Frobenius-Schur indicator"
- could lead to "explicit geometric CP violation"

(Holthausen, Lindner, Schmidt, 2012;

Chen, Fallbacher, Mahanthappa, Ratz, Trautner, 2014)

# Orbifold $T_2/Z_3$



# $T_2/Z_3$ orbifold examples

We label a string state by its constructing element $g = (\theta^k, n_\alpha e_\alpha)$ of the orbifold space group with

- $SU(3)$ lattice vectors $e_1$ and $e_2$
- twist $\theta$ (of 120 degrees) with $\theta^3 = 1$

This leads to different classes of closed string states

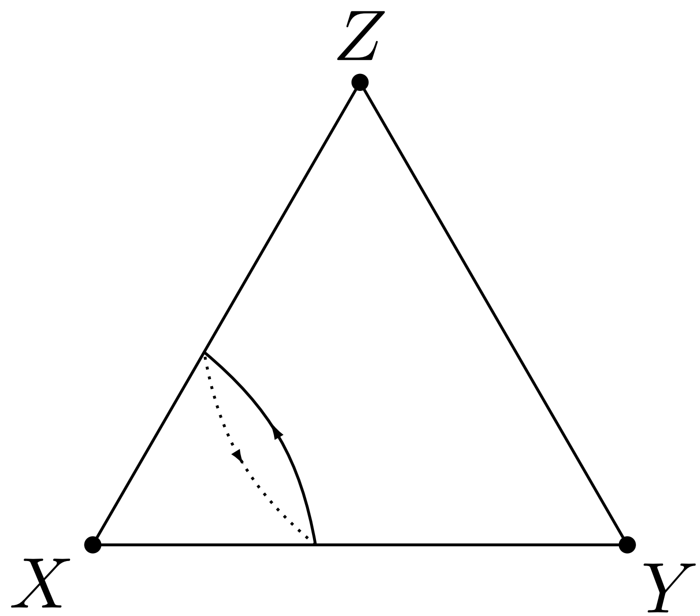
- untwisted states closed on the 2d plane
- winding states $(1, e_i)$ closed on the torus
- twisted states $(\theta, e_i)$ closed on the orbifold

How do they transform under $\Delta(54)$ and CP?

# Twisted States

While untwisted states transform as singlets, the twisted states transform nontrivially

- twisted fields $(\theta, 0)$, $(\theta, e_1)$ and $(\theta, e_1 + e_2)$ transform as triplets under $\Delta(54)$
- states in the $\theta^2$ sector are anti-triplets
- they wind around fixed points $X$, $Y$ and $Z$



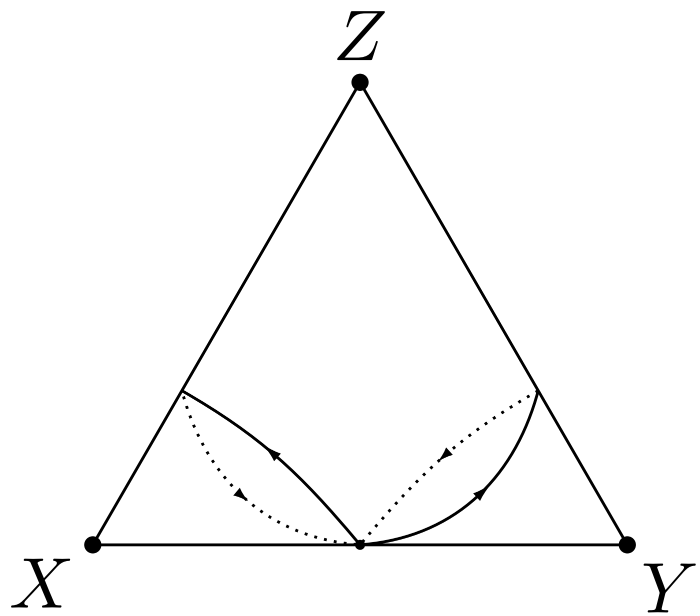

CP maps triplets (anti-triplets) to their complex conjugates

# Winding States

Winding states are represented by the geometric elements:

$$V_1 = (1, e_1),\ V_2 = (1, e_2) \text{ and } V_3 = (1, -e_1 - e_2)$$

- the $V_i$ wind around two fixed points with opposite orientation
- winding states $\overline{V}_i$ $i = 1, 2, 3$ have negative winding number




- the geometric winding states $V_i$ and $\overline{V}_i$ do not transform covariantly under $\Delta(54)$

# Doublets of $\Delta(54)$

We have to consider linear combinations $[n,\gamma]$

- $$[1,\gamma] = V_1 + \exp(-2\pi i\gamma)V_2 + \exp(-4\pi i\gamma)V_3$$

to obtain covariant states. This leads to doublets of $\Delta(54)$:

- $2_1 = (W_1, \overline{W}_1)$ with $W_1 = [-1, 0]$
- $2_3 = (W_2, \overline{W}_2)$ with $W_2 = \exp(4\pi i/3)[-1, -1/3]$
- $2_4 = (\overline{W}_3, W_3)$ with $W_3 = \exp(2\pi i/3)[-1, 1/3]$

States with positive and negative winding number form the two components of the individual doublets.

Generically, the windings modes are massive. Otherwise we would have symmetry enhancement (Narain lattice).

# Examples from MiniLandscape

There are many examples in the heterotic MiniLandscape

(Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006-2008)

- with $T_2/Z_3$ subsectors
- and potential $\Delta(54)$ symmetry

An inspection of the spectrum reveals that the massless modes transform as

- singlets (untwisted sector)
- triplets (anti-triplets) in $\theta$- ($\theta^2$-) twisted sectors
- there are no doublets in the massless spectrum!!!

For an example see: (Carballo-Perez, Peinado, Ramos-Sanchez, 2016)

# CP-symmetry and its violation

We consider CP as a subgroup of $S_4$ of the outer automorphism of $\Delta(54)$

- CP transforms $(rep)$ to $(rep)^*$
- this is possible for singlets and triplets
- possible simultaneously for up to two doublets
- impossible in the presence of three or more doublets

The low-energy effective theory allows CP symmetry

- which is broken in the presence of winding modes
- physical CP-violation arises if there are at least three doublets (here $2_1$, $2_3$ and $2_4$) (Trautner, 2017)

# CP-violation in physics

The relevance for physics includes

- CP-violation in the standard model (Jarlskog angle)
- the $\Theta$-parameter of QCD
- CP violation for baryo/lepto-genesis

We have special form of of CP symmetry and CP-violation

- "Explicit geometric CP-violation"
- CP as outer automorphism of flavour symmetry
- CP symmetry for the low energy effective theory broken in the presence of (at least three) $\Delta(54)$ doublets
- Example for "CP made and broken"

# Signals of CP-violation

The specific signals of CP-violation are strongly model dependent. We consider as a (toy) example the explicit model of (Carballo-Perez, Peinado, Ramos-Sanchez, 2016)

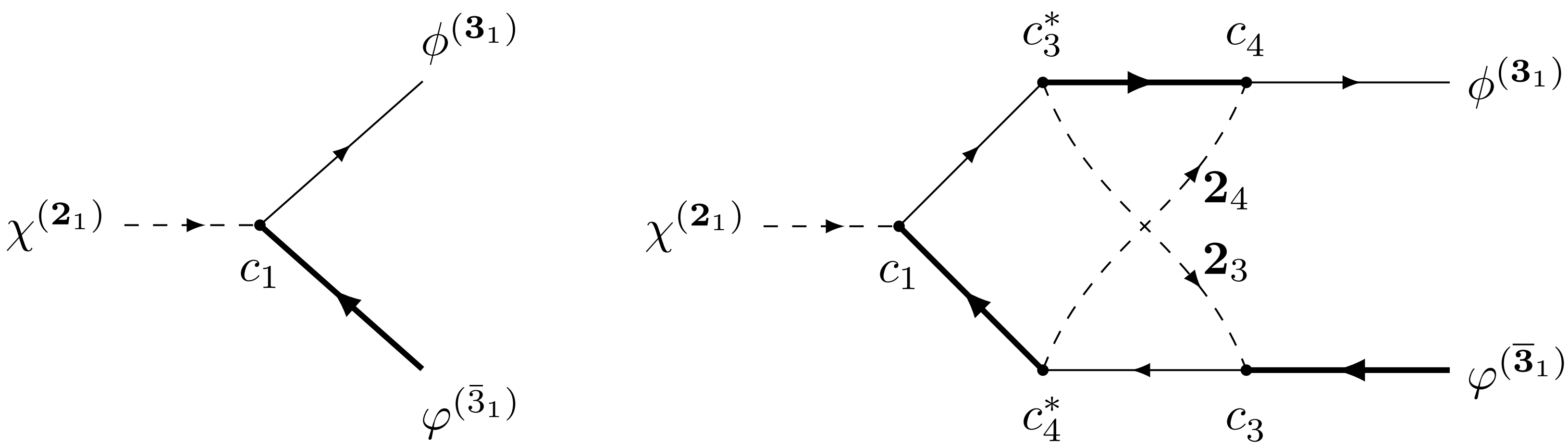
- it contains singlets, triplets and anti-triplets of $\Delta(54)$
- quarks and leptons as triplets
- Higgs as singlet
- right handed neutrinos as anti-triplets
- SM singlets as triplets and anti-triplets

The relevant couplings to the winding modes $2_i$ are

- $3 \otimes \bar{3} \to 2_i$ and $3 \otimes 3 \otimes 3 \to 2_i \quad (i = 1, 3, 4)$

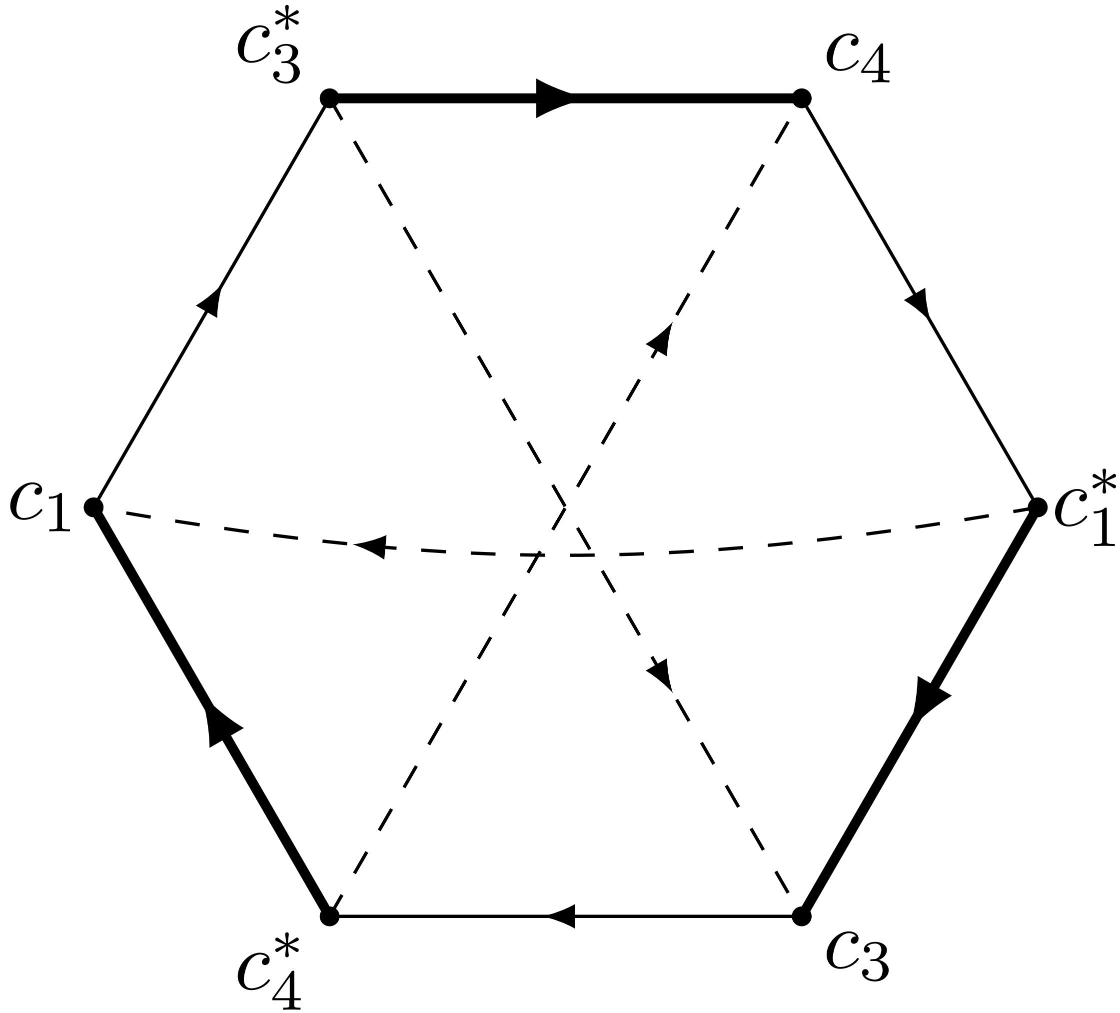
# CP violation through decays

CP-violation from the decay of heavy doublets.
All three doublets have to appear in the process.
CP-violation from the interference of two decay diagrams.




- $2_3$ and $2_4$ in (non-planar) two-loop diagram
- Decay to right-handed neutrinos and SM singlets as source for lepto-genesis

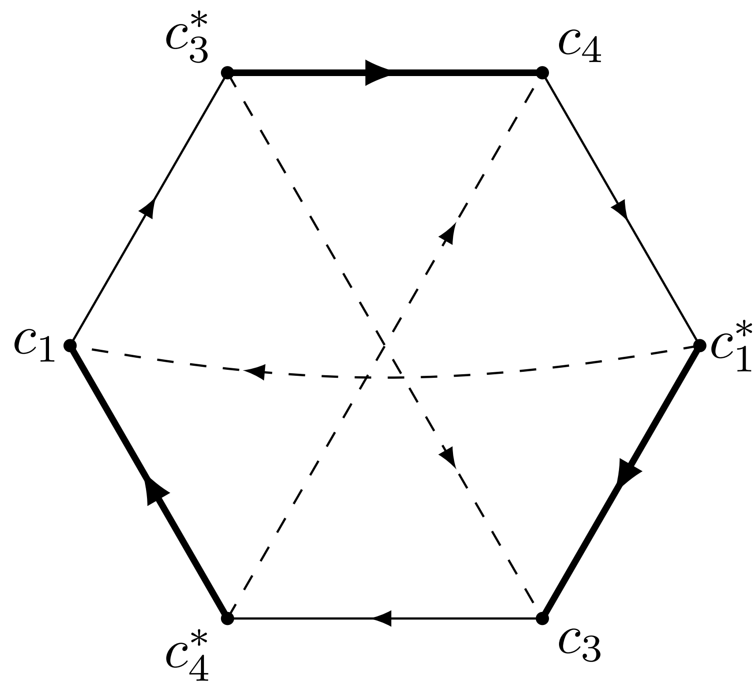
# CP-odd basis invariant



# CP-violation in physics

The "CP-odd basis invariant" controls all possible CP-violation in physics

- CP-violating decay of heavy doublets
- CP violation in the standard model (Jarlskog determinant)
- QCD $\Theta$-angle




- We need explicit model building to study these effects (coupling of doublets to CKM matrix and $\Theta_{\mathrm{QCD}}$)

# Conclusions

Discussion of CP requires

- the origin of the symmetry ("Make It")
- and its violation ("Break It")

String theory could provide such a mechanism through

- "Explicit geometric CP-violation"
- Unification of flavour symmetry and CP
- CP symmetry for the low energy effective theory
- broken in the presence of heavy winding modes

It provides explicit sources for CP-violating decay of heavy modes, and potentially the CKM phase and $\Theta_{\mathrm{QCD}}$

# The missing doublet $2_2$