

# CP-Violation from Strings

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# Do we need CP as a Symmetry?

CP (and its violation) is relevant for several phenomena:

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

The strong CP-problem requires CP to be a symmetry

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

CP: you have to make it and to break it.

Is there a top-down explanation (UV completion)?

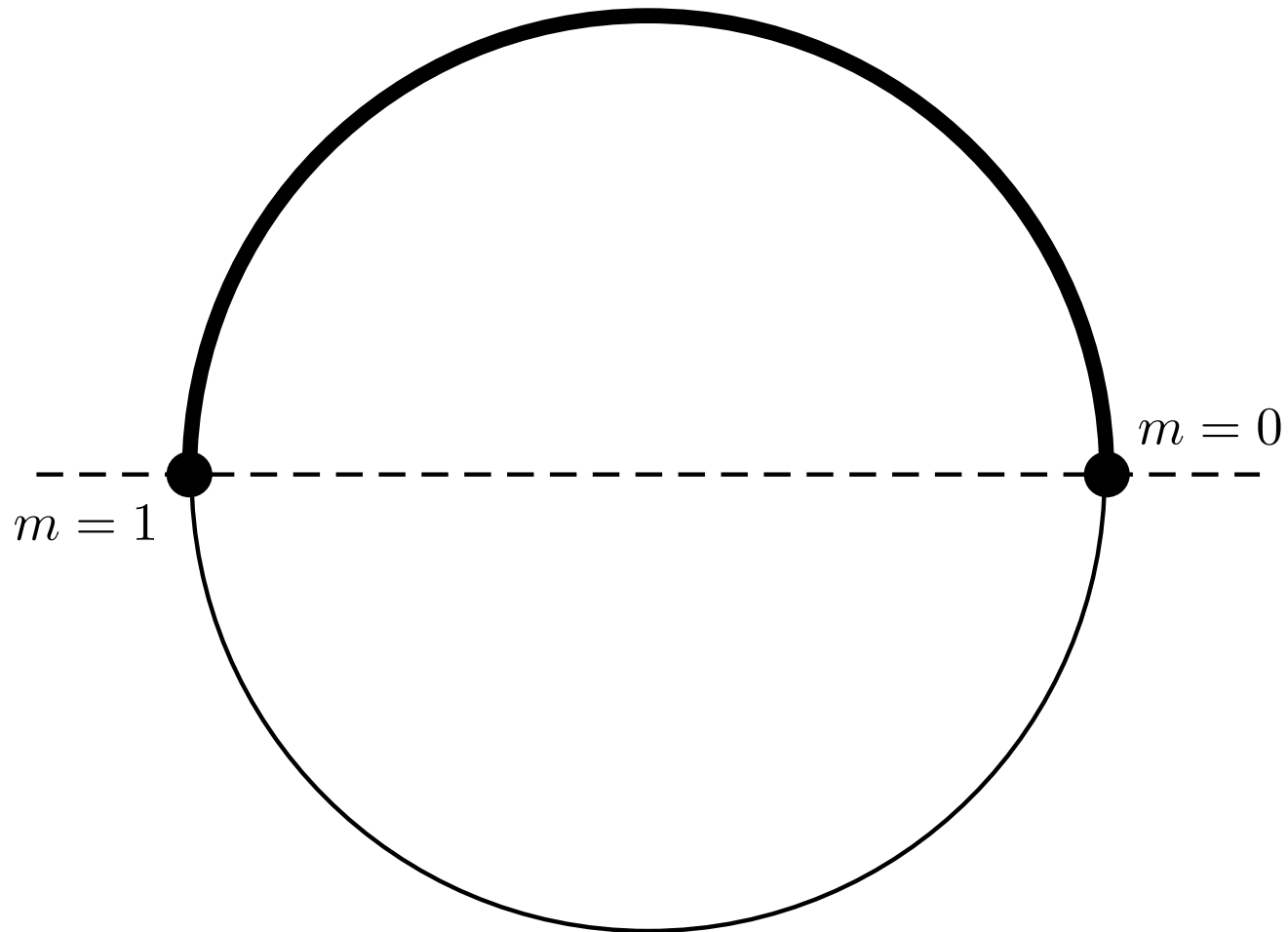
# Outline

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 the low-energy effective field theory
- the role of massive winding modes
- Lepto-genesis from decay of heavy particles
- intrinsic sources for  $\Theta$  angle and Jarlskog determinant

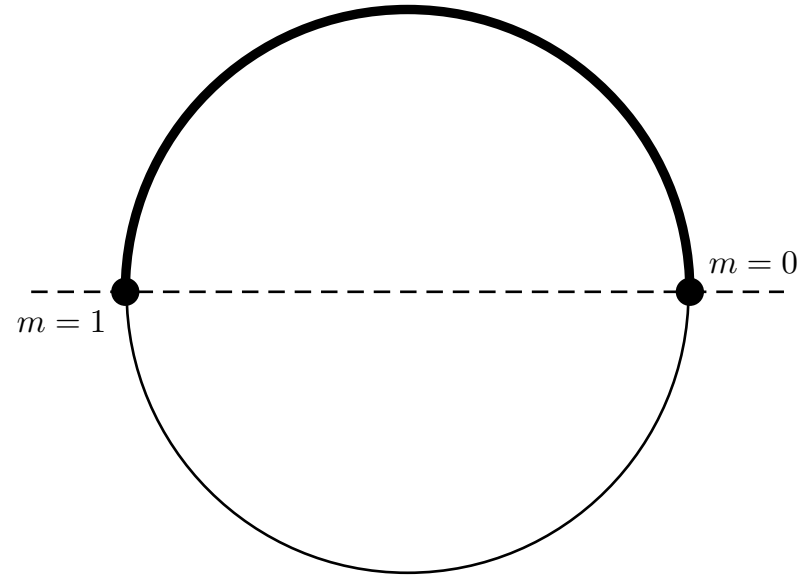
(Nilles, Ratz, Trautner, Vaudrevange, 2018)

# Interval $S_1/Z_2$



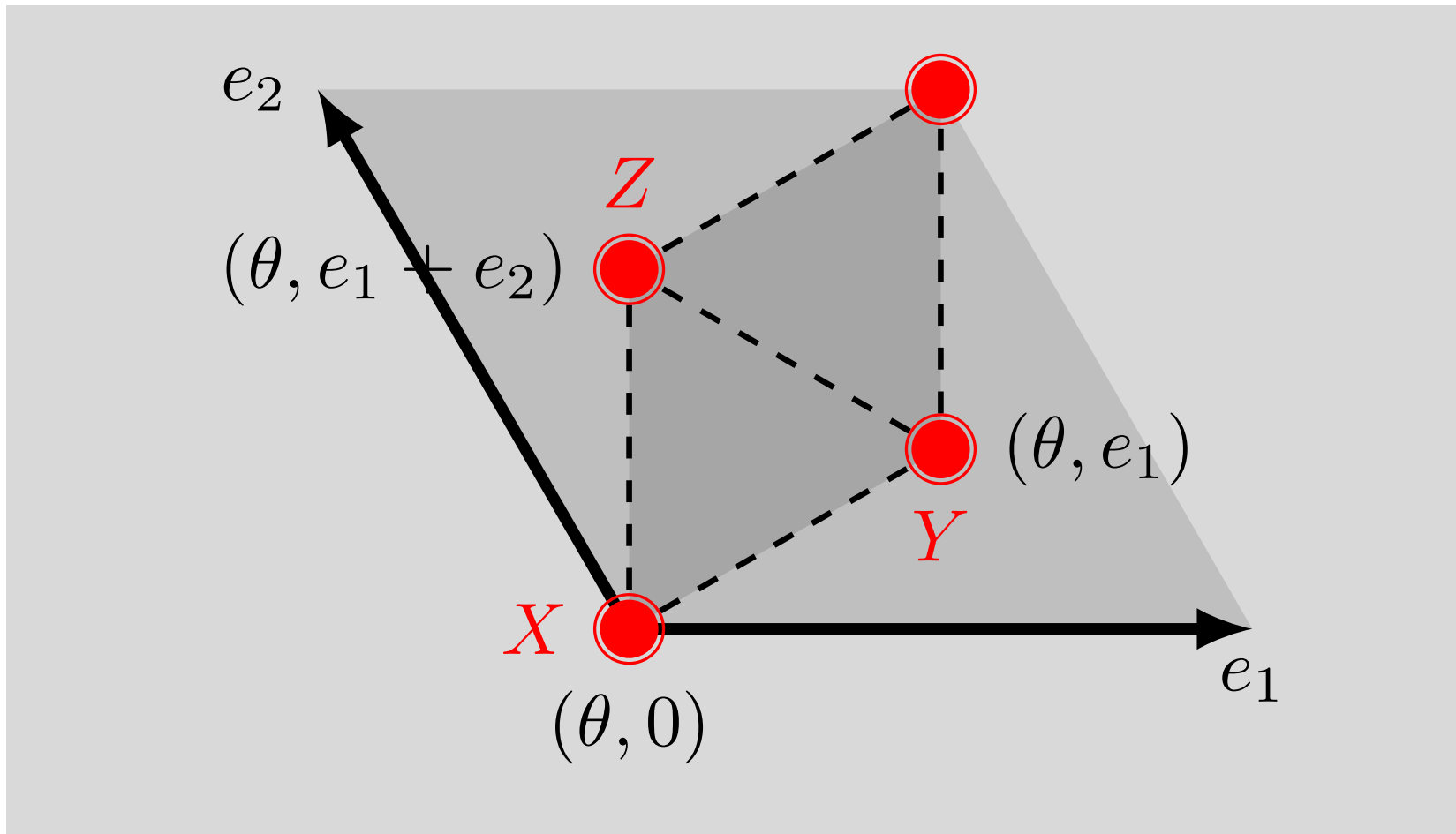
# Discrete symmetry $D_4$

- 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 non-abelian subgroup of  $SU(2)_{\text{flavor}}$
- flavor symmetry for the two lightest families



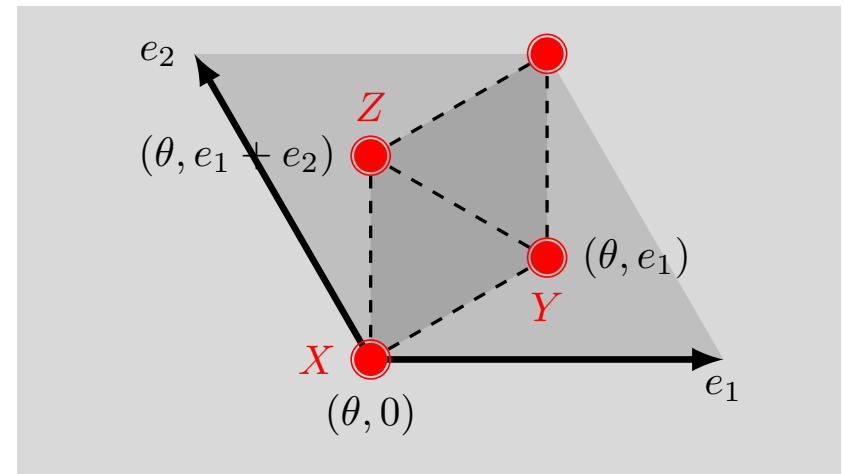
(Kobayashi, Nilles, Ploeger, Raby, Ratz, 2006)

# 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 non-abelian 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 non-abelian 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 the 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  $(rep)^*$

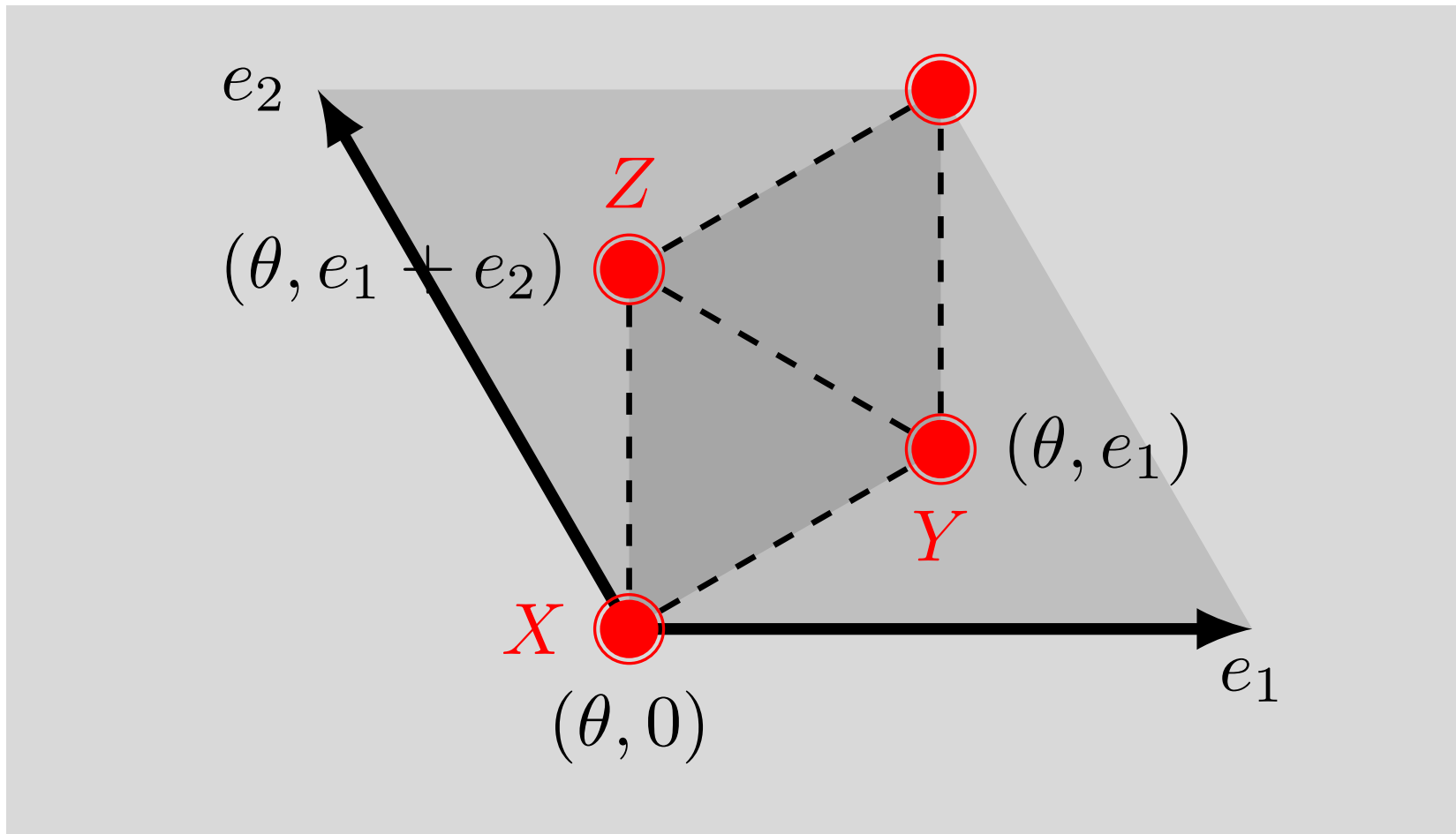
This gives an intimate relation of flavour and CP symmetry

- possible obstructions for a successful definition of CP
- controlled by "representation content" of the symmetry
- 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

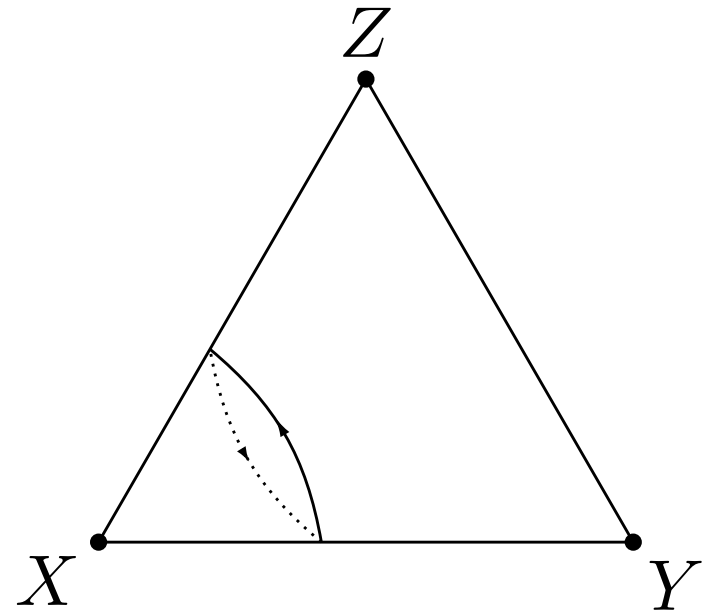
- **untwisted states** closed on the 2d plane
- **winding states**  $(1, e_i)$  closed on the torus
- **twisted states**  $(\theta, e_i)$  closed on the orbifold

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  $Z$



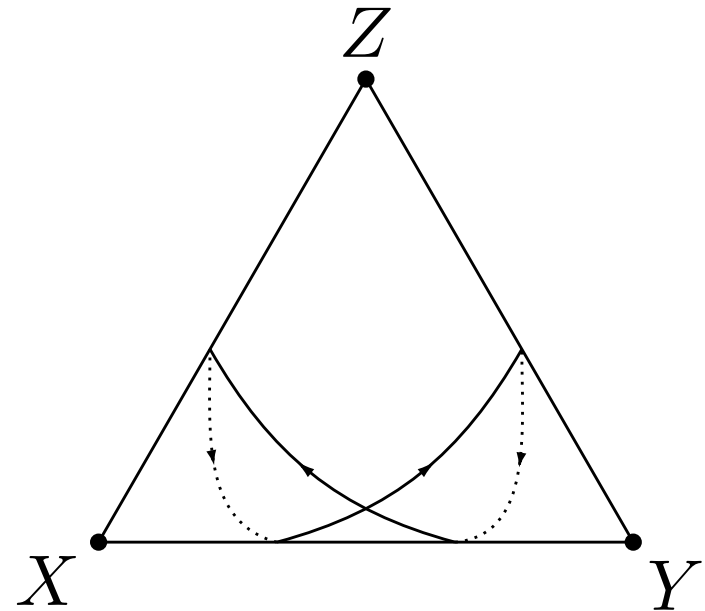
CP maps triplets (anti-triplets) to their complex conjugates

# 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  $\bar{V}_i$   
 $i = 1, 2, 3$  have negative winding number



- the geometric winding states  $V_i$  and  $\bar{V}_i$  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 winding 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 automorphisms 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 can arise 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 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 of  $\Delta(54)$

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

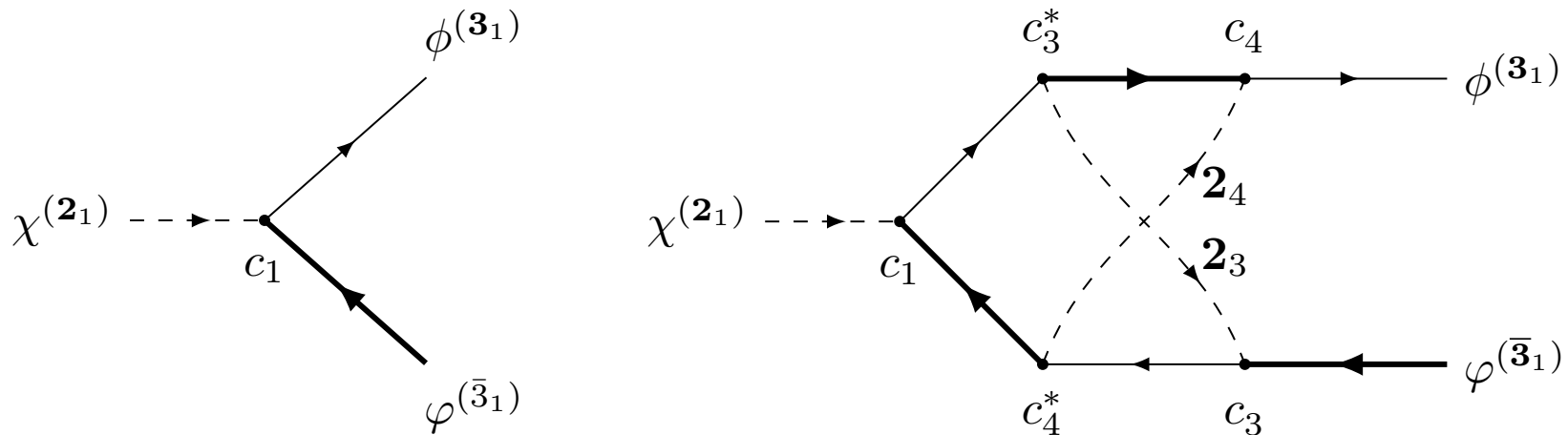
- $3 \otimes \bar{3} \rightarrow 2_i$  and  $3 \otimes 3 \otimes 3 \rightarrow 2_i$  ( $i = 1, 3, 4$ )

# CP violation through decays

CP-violation from the decay of heavy doublets.

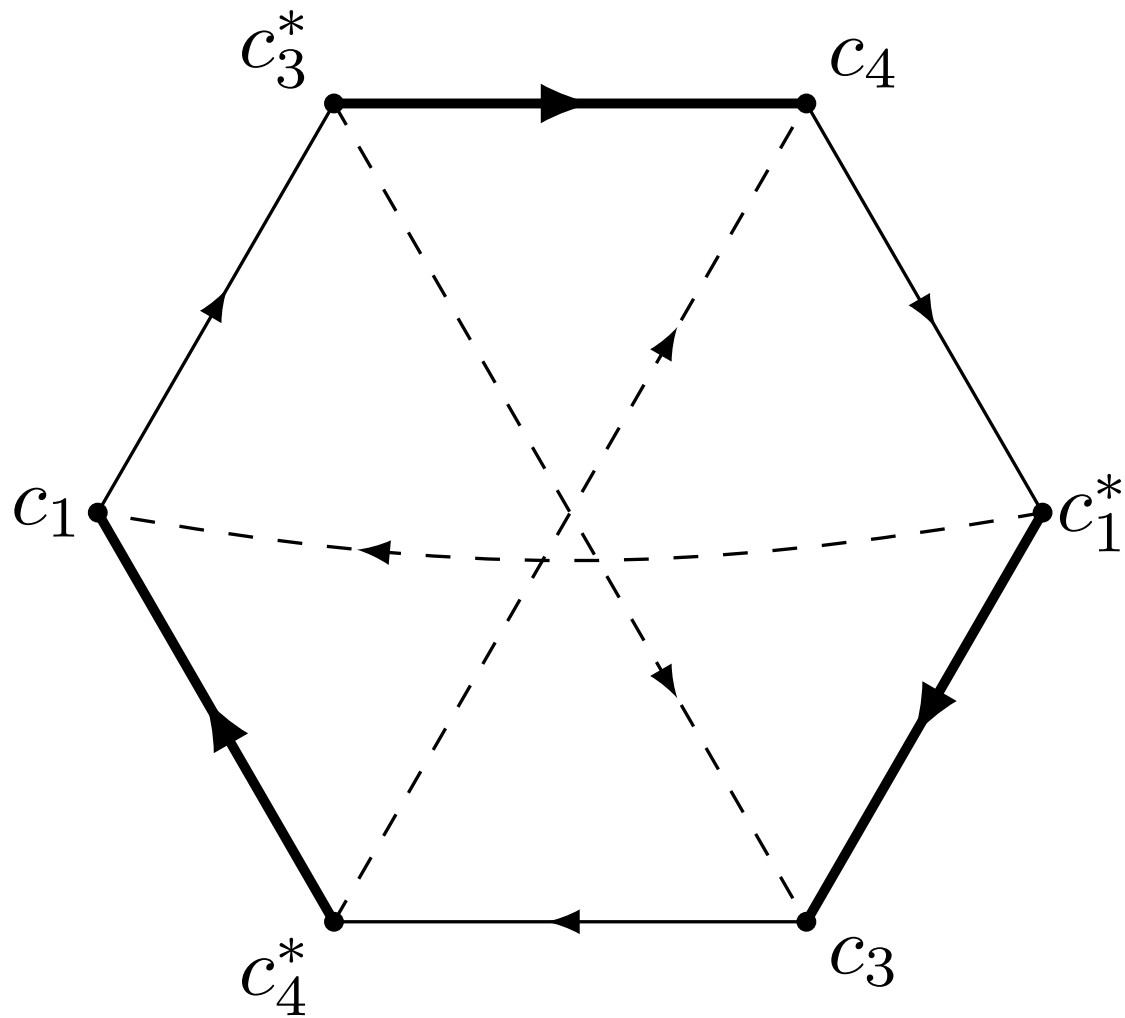
All three doublets have to appear in the process.

CP-violation from the interference of two decay diagrams.

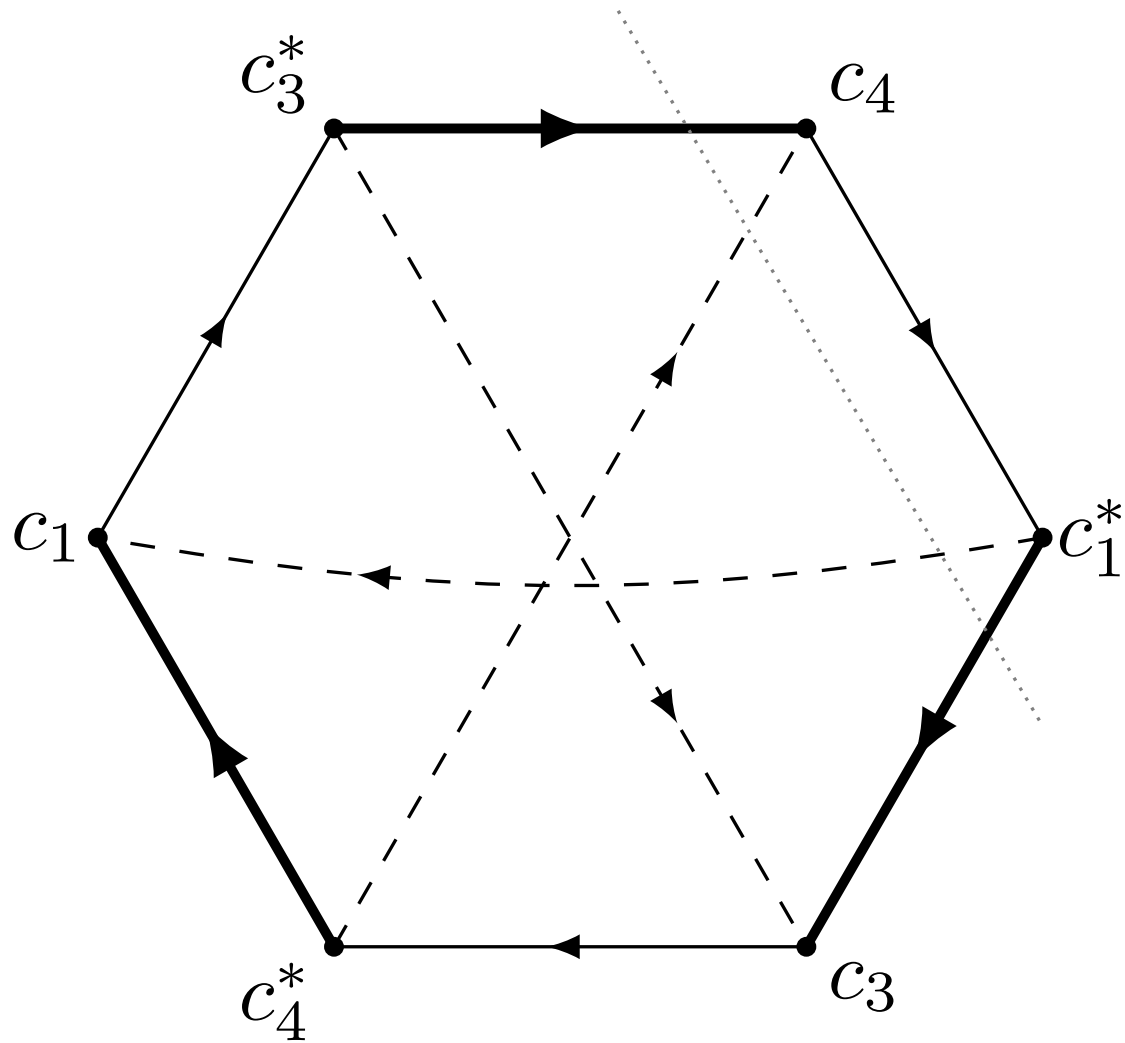


- $2_3$  and  $2_4$  in (non-planar) two-loop diagram
- Decay to right-handed neutrinos and SM singlets as source for lepto-genesis

# CP-odd basis invariant

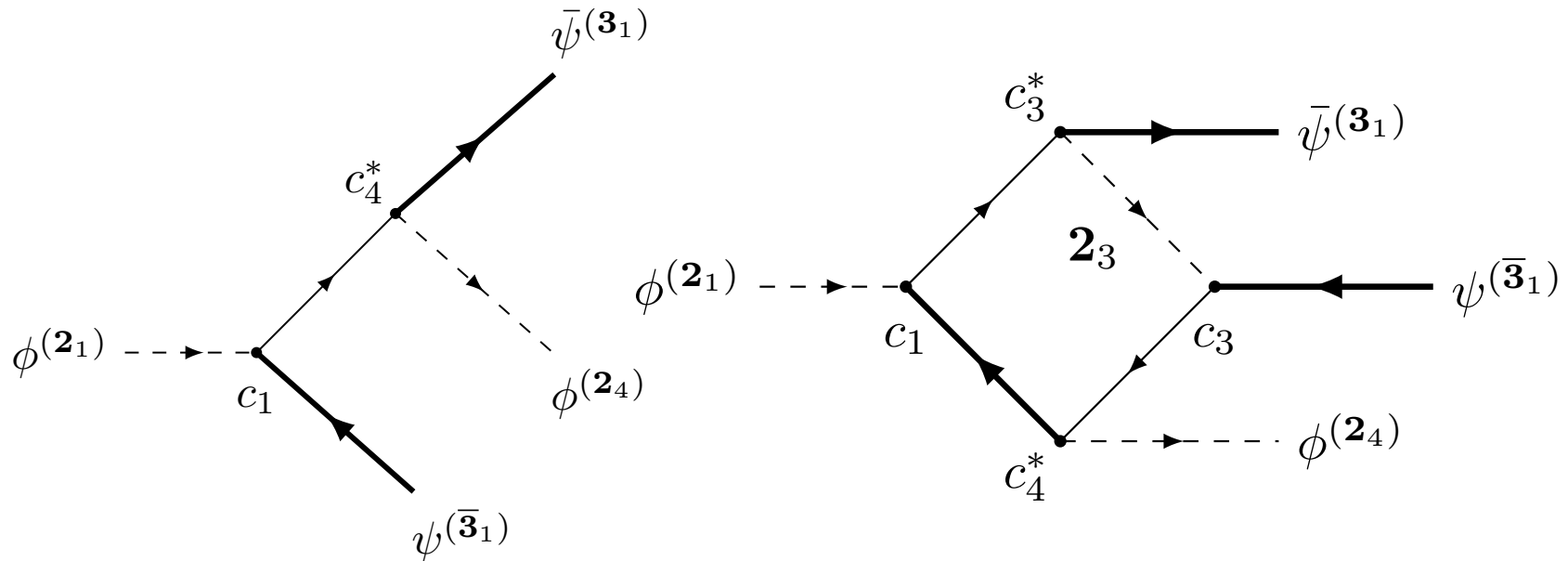


# CP-odd basis invariant



# CP violation through decays

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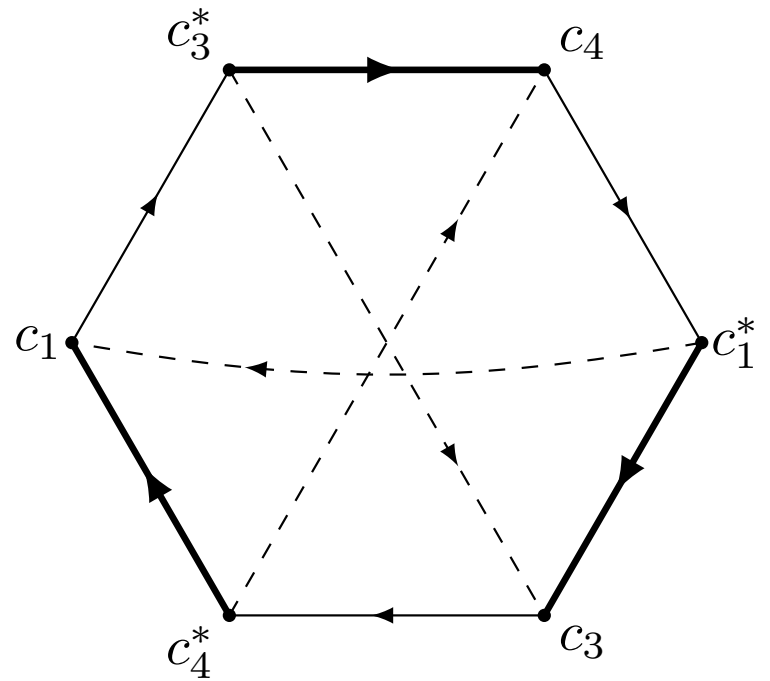


●  $2_3$  in the one-loop diagram

# CP-violation in physics

The "CP-odd basis invariants" control 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  $\Theta_{\text{QCD}}$ )



# 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 string modes

It provides calculable effects for CP-violating decay of heavy particles and a solution to the strong CP-problem



# Origin of CP-symmetry

CP should be a discrete gauge symmetry:

- spontaneous rather than explicit breakdown

Enhancement of flavor symmetry because of T-duality

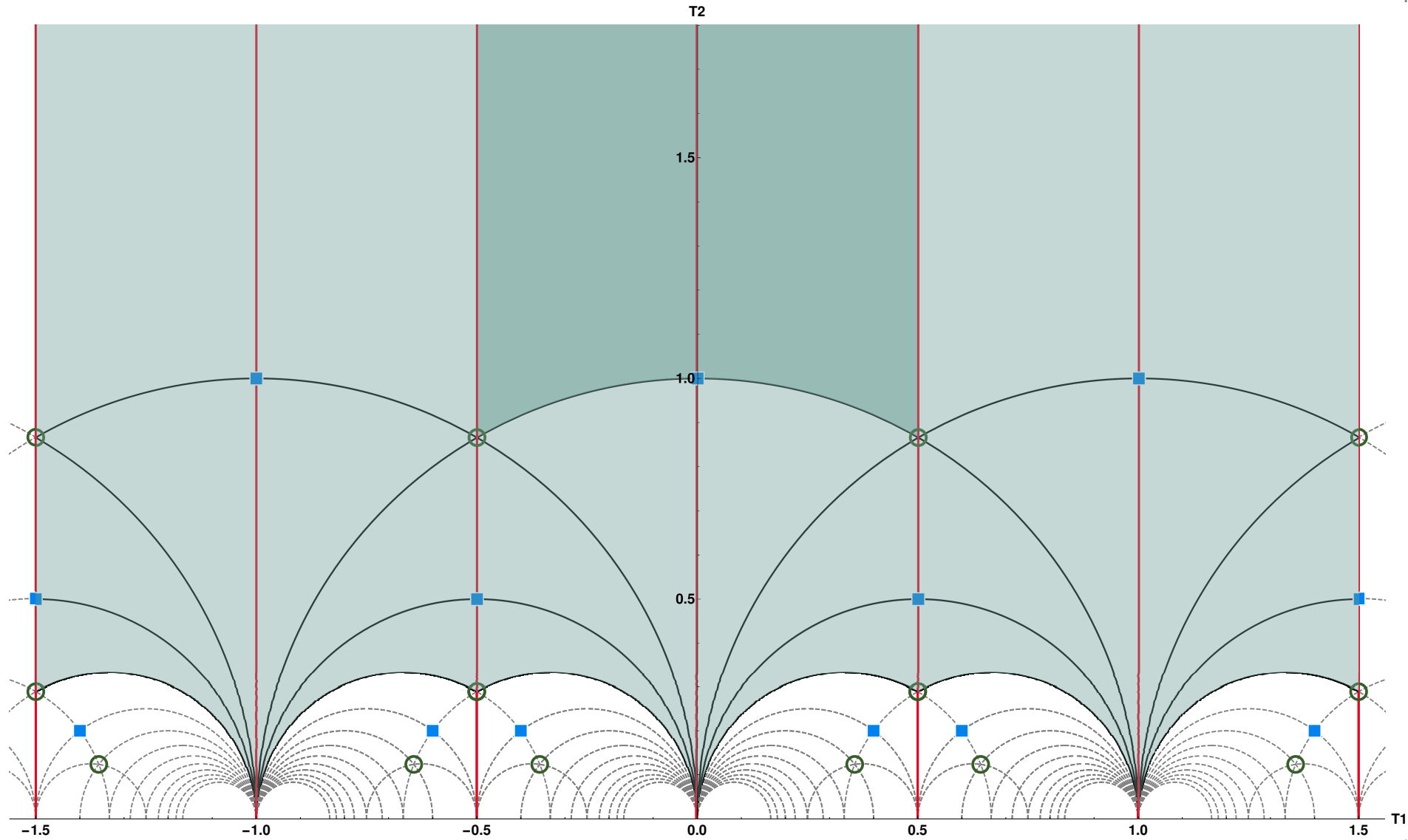
(Lauer, Mas, Nilles, 1989; Ferrara, Lüst, Shapere, Theisen, 1989)

- derivation of flavor symmetries as outer automorphisms of the "Narain lattice" (Baur, Nilles, Vaudrevange, Trautner, 2019)
- outer automorphism of flavour group becomes inner automorphism of (duality) enhanced symmetry group
- spontaneous breakdown of CP

Unification of flavour symmetry, string dualities and CP

(talk by Alexander Baur)

# Moduli space of $\Gamma(3)$



# Moduli space of flavour groups

