String islands and discrete theta angles

Hector Parra De Freitas
Harvard U.

Based on
[Fraiman, HPF '22], [Montero, HPF '22]
and [Baykara, HPF, Tarazi – to appear]

Parallel talk @ String Pheno 2024, Padova

The string landscape is a very complicated object, but it is *anything but arbitrary*.

The string landscape is a very complicated object, but it is *anything but arbitrary*.

String compactifications always turn out to obey various (Swampland) principles.

[Most in this conference have contributed to this idea!]

The string landscape is a very complicated object, but it is *anything but arbitrary*.

String compactifications always turn out to obey various (Swampland) principles.

[Most in this conference have contributed to this idea!]

Supersymmetric vacua in dimensions 7,8,9 have been studied in greath depth in the past few years, from the bottom-up and from top-down.

[Bedroya, Cvetic, Dierigl, Font, Fraiman, Graña, Hamada, Kim, Lin, Montero, Nuñez, HPF, Tarazi, Vafa, Zhang]

Building on a lot of past work,

specially [de Boer et al '01]

I believe this region of the landscape is completely charted.

In [Fraiman, HPF '22] we proposed an organizing principle for string vacua in 6D with $N = (1,1)$,

recovering known 17 theories and predicting 30 more.

In [Fraiman, HPF '22] we proposed an organizing principle for string vacua in 6D with $N = (1,1)$,

recovering known 17 theories and predicting 30 more.

Here I will report on the construction of five of these new theories,
which have only one modulus: the dilaton
[Baykara, HPF, Tarazi]

Outline

1. Brief history and motivation behind the main idea of this work: unified frameworks for string vacua

2. The case of six dimensions with 16 supercharges

3. Presentation of the five new theories and some of their properties

A strategy for understanding the landscape:

Look for structures connecting different vacua in a given regime.

E.g. theories with Minkowski spacetime with some number of dimensions and supercharges

A strategy for understanding the landscape:

Look for structures connecting different vacua in a given regime.

E.g. theories with Minkowski spacetime with some number of dimensions and supercharges

32 SUSY: Only gravity multiplet, trivial

A strategy for understanding the landscape:

Look for structures connecting different vacua in a given regime.

E.g. theories with Minkowski spacetime with some number of dimensions and supercharges

32 SUSY: Only gravity multiplet, trivial

16 SUSY: Gravity multiplet and vector multiplets

Landscape: disconnected components labeled by gauge group rank

[de Boer et al '01] constructed most of these in 7D using orbifolds, orientifolds, etc

A strategy for understanding the landscape:

Look for structures connecting different vacua in a given regime.

E.g. theories with Minkowski spacetime with some number of dimensions and supercharges

32 SUSY: Only gravity multiplet, trivial

16 SUSY: Gravity multiplet and vector multiplets

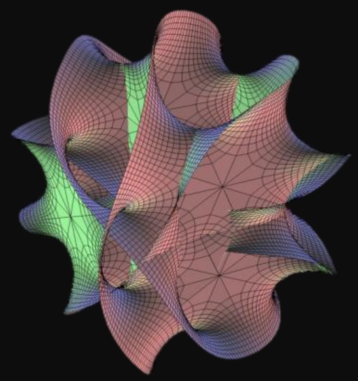
Landscape: disconnected components labeled by gauge group rank

[de Boer et al ‘01] constructed most of these in 7D using orbifolds, orientifolds, etc

More importantly, they proposed an uniform way of describing them using M-theory.

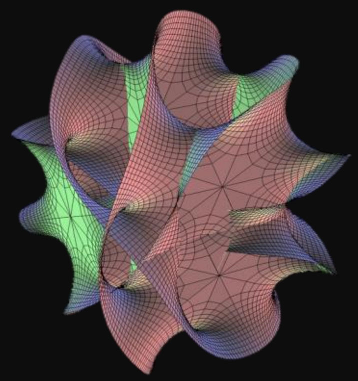
M/K3: 7D with 16 SUSY
Choice of K3 defines the metric
To get new vacua, need to turn on 3-form

[de Boer et al '01] inferred a set of rules for turning on the 3-form on ADE singularities, freezing their deformations and transforming the gauge groups localized on them.



For example, $E_8 \;\rightarrow\; F_4$

[de Boer et al '01] inferred a set of rules for turning on the 3-form on ADE singularities, freezing their deformations and transforming the gauge groups localized on them.

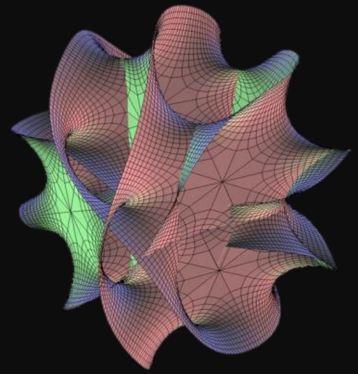


For example, $E_8 \rightarrow F_4$

This frozen singularity procedure recovered all known string theories, but one.

Heterotic description	Orientifold description	M theory on K3 with frozen singularities of type	F theory compactified on
"standard component"	$(-^8)$	smooth $K3$	$K3 \times S^1$
$\mathbb{Z}_2$ triple CHL string no vector structure	$(-^6, +^2)$	$D_4 \oplus D_4$	$(K3 \times S^1)/\mathbb{Z}_2$
$\mathbb{Z}_3$ triple		$E_6 \oplus E_6$	$(K3 \times S^1)/\mathbb{Z}_3$
$\mathbb{Z}_4$ triple		$E_7 \oplus E_7$	$(K3 \times S^1)/\mathbb{Z}_4$
$\mathbb{Z}_5$ triple		$E_8 \oplus E_8$	$(K3 \times S^1)/\mathbb{Z}_5$
$\mathbb{Z}_6$ triple		$E_8 \oplus E_8$	$(K3 \times S^1)/\mathbb{Z}_6$
	$(-^4, +^4)_1$	$(D_4)^4$	$(T^4 \times S^1)/\mathbb{Z}_2$
	$(-^4, +^4)_2$		
		$(E_6)^3$	$(T^4 \times S^1)/\mathbb{Z}_3$
		$D_4 \oplus E_7 \oplus E_7$	$(T^4 \times S^1)/\mathbb{Z}_4$
		$D_4 \oplus E_6 \oplus E_8$	$(T^4 \times S^1)/\mathbb{Z}_6$

[de Boer et al '01] inferred a set of rules for turning on the 3-form on ADE singularities, freezing their deformations and transforming the gauge groups localized on them.



For example, $E_8 \to F_4$

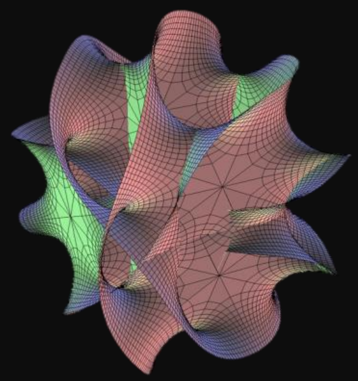
This frozen singularity procedure recovered all known string theories, but one.

To recover every theory, a refinement Involving the gauge group topology was needed.

There were in fact 3 unnoticed ways of freezing singularities, predicting 2 new string theories [HPF '22] in 7D.

Heterotic description	Orientifold description	M theory on K3 with frozen singularities of type	F theory compactified on
"standard component"	$(-^8)$	smooth $K3$	$K3 \times S^1$
$\mathbb{Z}_2$ triple CHL string no vector structure	$(-^6, +^2)$	$D_4 \oplus D_4$	$(K3 \times S^1)/\mathbb{Z}_2$
$\mathbb{Z}_3$ triple		$E_6 \oplus E_6$	$(K3 \times S^1)/\mathbb{Z}_3$
$\mathbb{Z}_4$ triple		$E_7 \oplus E_7$	$(K3 \times S^1)/\mathbb{Z}_4$
$\mathbb{Z}_5$ triple		$E_8 \oplus E_8$	$(K3 \times S^1)/\mathbb{Z}_5$
$\mathbb{Z}_6$ triple		$E_8 \oplus E_8$	$(K3 \times S^1)/\mathbb{Z}_6$
	$(-^4, +^4)_1$	$(D_4)^4$	$(T^4 \times S^1)/\mathbb{Z}_2$
	$(-^4, +^4)_2$		
		$(E_6)^3$	$(T^4 \times S^1)/\mathbb{Z}_3$
		$D_4 \oplus E_7 \oplus E_7$	$(T^4 \times S^1)/\mathbb{Z}_4$
		$D_4 \oplus E_6 \oplus E_8$	$(T^4 \times S^1)/\mathbb{Z}_6$

[de Boer et al '01] inferred a set of rules for turning on the 3-form on ADE singularities, freezing their deformations and transforming the gauge groups localized on them.



For example, $E_8 \rightarrow F_4$

This frozen singularity procedure recovered all known string theories, but one.

To recover every theory, a refinement Involving the gauge group topology was needed.

There were in fact 3 unnoticed ways of freezing singularities, predicting 2 new string theories [HPF '22] in 7D.

These 3 alternatives can be understood In terms of discrete theta angles. [Montero, HPF '22]

Heterotic description	Orientifold description	M theory on K3 with frozen singularities of type	F theory compactified on
"standard component"	$(-^8)$	smooth $K3$	$K3 \times S^1$
$\mathbb{Z}_2$ triple CHL string no vector structure	$(-^6, +^2)$	$D_4 \oplus D_4$	$(K3 \times S^1)/\mathbb{Z}_2$
$\mathbb{Z}_3$ triple		$E_6 \oplus E_6$	$(K3 \times S^1)/\mathbb{Z}_3$
$\mathbb{Z}_4$ triple		$E_7 \oplus E_7$	$(K3 \times S^1)/\mathbb{Z}_4$
$\mathbb{Z}_5$ triple		$E_8 \oplus E_8$	$(K3 \times S^1)/\mathbb{Z}_5$
$\mathbb{Z}_6$ triple		$E_8 \oplus E_8$	$(K3 \times S^1)/\mathbb{Z}_6$
	$(-^4, +^4)_1$	$(D_4)^4$	$(T^4 \times S^1)/\mathbb{Z}_2$
	$(-^4, +^4)_2$		
		$(E_6)^3$	$(T^4 \times S^1)/\mathbb{Z}_3$
		$D_4 \oplus E_7 \oplus E_7$	$(T^4 \times S^1)/\mathbb{Z}_4$
		$D_4 \oplus E_6 \oplus E_8$	$(T^4 \times S^1)/\mathbb{Z}_6$

We were successful in predicting and constructing new string vacua systematically!

No more theories should exist in this regime. Would require something other than K3, but this goes against Swampland considerations! [Bedroya, Hamada, Montero, Vafa '22]

Can we push these ideas further?

We were successful in predicting and constructing new string vacua systematically!

No more theories should exist in this regime. Would require something other than K3, but this goes against Swampland considerations! [Bedroya, Hamada, Montero, Vafa ‘22]

Can we push these ideas further?

Yes!

In [Fraiman, HPF ‘22] we extended the rank reduction map from 7D to 6D with 16 supercharges.

Here something remarkable happens! The rank reduction map has a clear logic allowing generalization.

In [Fraiman, HPF '22] we extended the rank reduction map from 7D to 6D with 16 supercharges.

Here something remarkable happens! The rank reduction map has a clear logic allowing generalization.

Given any non-simply-connected gauge group G, its fundamental group elements determine possible transformations of G. [Schweigert '97]

Example (CHL string):

$$\frac{Spin(32)}{\mathbb{Z}_2} \rightarrow Spin(17)$$

Order	$\tilde{G}_i$	$\tilde{G}'_i$	ℓ_i
q	$SU(q)$	$\emptyset$	1
q	$SU(qn)$	$SU(n)$	$n \geq 2$
2	$Spin(2n)$	$Sp(n-2)$	v
2	$Spin(4n)$	$Spin(2n+1)$	s
2	E_7	F_4	1
3	E_6	G_2	1
4	$Spin(4n+2)$	$Sp(n-1)$	1
2	$Spin(2n+1)$	$Spin(2n-1)$	1
2	$Sp(2n)$	$Spin(2n+1)$	1
2	$Sp(2n+1)$	$Sp(n)$	1

In [Fraiman, HPF '22] we extended the rank reduction map from 7D to 6D with 16 supercharges.

Here something remarkable happens! The rank reduction map has a clear logic allowing generalization.

Given any non-simply-connected gauge group G, its fundamental group elements determine possible transformations of G. [Schweigert '97]

Example (CHL string):

$$\frac{Spin(32)}{\mathbb{Z}_2} \rightarrow Spin(17)$$

Order	$\tilde{G}_i$	$\tilde{G}'_i$	ℓ_i
q	$SU(q)$	$\emptyset$	1
q	$SU(qn)$	$SU(n)$	$n \geq 2$
2	$Spin(2n)$	$Sp(n-2)$	v
2	$Spin(4n)$	$Spin(2n+1)$	s
2	E_7	F_4	1
3	E_6	G_2	1
4	$Spin(4n+2)$	$Sp(n-1)$	1
2	$Spin(2n+1)$	$Spin(2n-1)$	1
2	$Sp(2n)$	$Spin(2n+1)$	1
2	$Sp(2n+1)$	$Sp(n)$	1

If we apply this map in every possible way starting from the standard component, we recover all of the known 17 theories, and predict that there are 30 more.

But should we trust this map in general?

Task: construct predicted theories

STANDARD COMPONENT

Heterotic on T^4 or Type IIA on K3

STANDARD COMPONENT

Heterotic on T^4 or Type IIA on K3

Rank reduction map

CYCLIC COMPONENTS (23)

(Z_n - orbifolds)

STANDARD COMPONENT

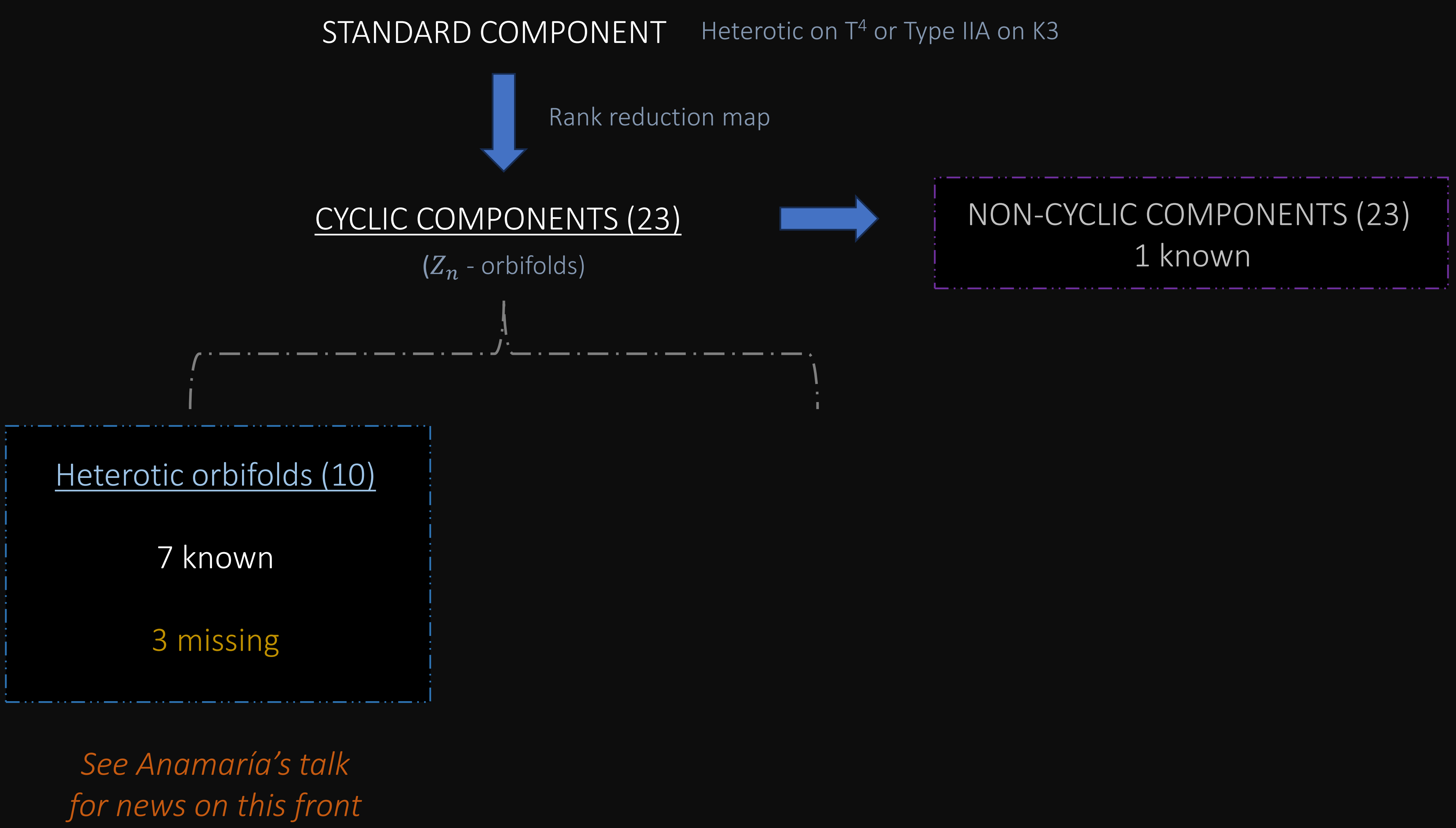
Heterotic on T^4 or Type IIA on K3

Rank reduction map

CYCLIC COMPONENTS (23)

(Z_n - orbifolds)

NON-CYCLIC COMPONENTS (23)
1 known


STANDARD COMPONENT
Heterotic on T4 or Type IIA on K3
Rank reduction map
CYCLIC COMPONENTS (23)
(Z_n - orbifolds)
NON-CYCLIC COMPONENTS (23)
1 known
Heterotic orbifolds (10)
7 known
3 missing
See Anamaría's talk
for news on this front

STANDARD COMPONENT

Heterotic on T^4 or Type IIA on K3

Rank reduction map

<u>CYCLIC COMPONENTS (23)</u>

(Z_n - orbifolds)

NON-CYCLIC COMPONENTS (23)

1 known

<u>Heterotic orbifolds (10)</u>

7 known

3 missing

<u>Type II orbifolds (13)</u>

8 known

5 missing

See Anamaría's talk for news on this front

These we constructed

The five missing type II cyclic orbifolds are *string islands.*

Theories like this were studied by [Dabholkar, Harvey ‘98] One was found in 6D N = (1,1)

The five missing type II cyclic orbifolds are *string islands.*

Theories like this were studied by [Dabholkar, Harvey '98] One was found in 6D N = (1,1)

We predict 4 string islands, 2 admitting discrete theta angle:

The five missing type II cyclic orbifolds are *string islands.*

Theories like this were studied by [Dabholkar, Harvey ‘98] One was found in 6D N = (1,1)

We predict 4 string islands, 2 admitting discrete theta angle:

The discrete theta angles are non-trivial values of RR axions compatible with the orbifolds. They alter the brane spectrum and spoil BPS completeness [Montero, HPF ‘22].

The Dabholkar-Harvey Z_5 island admits an order 5 theta angle.
The Z_8 island admits an order 2 theta angle.

Together with Houri Tarazi and Kaan Baykara we were able to construct the five missing theories using asymmetric orbifolds of Type IIA on T^4, generalizing the constructions of [Dabholkar, Harvey '98] and [Montero, HPF '22].

Together with Houri Tarazi and Kaan Baykara we were able to construct the five missing theories using asymmetric orbifolds of Type IIA on T^4, generalizing the constructions of [Dabholkar, Harvey '98] and [Montero, HPF '22].

Their compactified versions were recently found in 5D as of quasycristallographic orbifolds [Baykara, Tarazi, Vafa '24], and were known in 4D as particular CHL models [Persson, Volpato '16].

Together with Houri Tarazi and Kaan Baykara we were able to construct the five missing theories using asymmetric orbifolds of Type IIA on T^4, generalizing the constructions of [Dabholkar, Harvey '98] and [Montero, HPF '22].

Their compactified versions were recently found in 5D as of quasycristallographic orbifolds [Baykara, Tarazi, Vafa '24], and were known in 4D as particular CHL models [Persson, Volpato '16].

Important points:

- These models have no vector multiplets, a novelty available in 6D.
  Can be used to study the effect of discrete theta angles in a simple moduli space.
  Complete description of the moduli spaces is feasible.

- Our trust in the rank reduction map increases. If non-cyclic are obtained, this implies:

  1) Odd rank reduction (imposible in 7D [Montero, Vafa '20])
  2) Existence of gauge group SO(3) (imposible in 7D)

- Physical mechanism for the map is missing.

Conclusions:

At least with 16 supercharges there exist unifying frameworks for the allowed vacua in quantum gravity.

They give us a grasp on the structure of the string landscape, and also predict new theories with novel properties.

Could this be part of a more general principle in Quantum Gravity…?

Conclusions:

At least with 16 supercharges there exist unifying frameworks for the allowed vacua in quantum gravity.

They give us a grasp on the structure of the string landscape, and also predict new theories with novel properties.

Could this be part of a more general principle in Quantum Gravity…?

Thanks for your attention!