STRING UNIVERSALITY & CLASSIFICATION OF STRING VACUA

Review talk @ Landscapia

Miguel Montero

IFT Madrid

Dec 1st 2023

Picture the following:

Picture the following:

December 1st, 2023.

Picture the following:

December 1st, 2023. A grey, gloomy, rainy morning.

Picture the following:

December 1st, 2023. A grey, gloomy, rainy morning.

You wake up,

Picture the following:

December 1st, 2023. A grey, gloomy, rainy morning.

You wake up, tired.

Picture the following:

December 1st, 2023. A grey, gloomy, rainy morning.

You wake up, tired. Very tired.

Picture the following:

December 1st, 2023. A grey, gloomy, rainy morning.

You wake up, tired. Very tired.

You were partying hard last night in the Landscapia conference dinner. Too much fun, dancing, drinks.

Picture the following:

December 1st, 2023. A grey, gloomy, rainy morning.

You wake up, tired. Very tired.

You were partying hard last night in the Landscapia conference dinner. Too much fun, dancing, drinks.

You are in no shape to do anything.

Picture the following:

December 1st, 2023. A grey, gloomy, rainy morning.

You wake up, tired. Very tired.

You were partying hard last night in the Landscapia conference dinner. Too much fun, dancing, drinks.

You are in no shape to do anything.

And the prospect of a RER commute to IPhT does not make things more appealing, precisely.

Picture the following:

December 1st, 2023. A grey, gloomy, rainy morning.

You wake up, tired. Very tired.

You were partying hard last night in the Landscapia conference dinner. Too much fun, dancing, drinks.

You are in no shape to do anything.

And the prospect of a RER commute to IPhT does not make things more appealing, precisely.

First talk is a review talk, isn't it?

Picture the following:

December 1st, 2023. A grey, gloomy, rainy morning.

You wake up, tired. Very tired.

You were partying hard last night in the Landscapia conference dinner. Too much fun, dancing, drinks.

You are in no shape to do anything.

And the prospect of a RER commute to IPhT does not make things more appealing, precisely.

First talk is a review talk, isn't it?

Why not skip it, go straight to the research talks?

You close your eyes again, a satisfied smile on your face.

You close your eyes again, a satisfied smile on your face.

"Yes, that's right" you think. "I'll rest some more, go later"

You close your eyes again, a satisfied smile on your face.

"Yes, that's right" you think. "I'll rest some more, go later"

But, as you doze off, and Morpheus is about to take you in his arms again…

You close your eyes again, a satisfied smile on your face.

"Yes, that's right" you think. "I'll rest some more, go later"

But, as you doze off, and Morpheus is about to take you in his arms again…

…a question floats up to your conscious mind.

You close your eyes again, a satisfied smile on your face.

"Yes, that's right" you think. "I'll rest some more, go later"

But, as you doze off, and Morpheus is about to take you in his arms again…

…a question floats up to your conscious mind.

"Do we know for sure we have discovered all quantum gravities with 32 supercharges in 10 dimensions?"

You close your eyes again, a satisfied smile on your face.

"Yes, that's right" you think. "I'll rest some more, go later"

But, as you doze off, and Morpheus is about to take you in his arms again…

…a question floats up to your conscious mind.

"Do we know for sure we have discovered all quantum gravities with 32 supercharges in 10 dimensions?"

The question won't let you sleep. If we do not know the answer to *that*, how can we be sure of anything else?

You remember that the review talk is on “string universality”.

You remember that the review talk is on “string universality”.

Maybe the speaker will cover this, or if not, you can ask.

You remember that the review talk is on “string universality”.

Maybe the speaker will cover this, or if not, you can ask.

Maybe someone knows.

You remember that the review talk is on “string universality”.

Maybe the speaker will cover this, or if not, you can ask.

Maybe someone knows.

With a deep sigh, you get up and get on your way.

Indeed, in this talk, we will discuss this question, and many more similar ones, centered on the idea of

String Universality [Adams De Wolfe Taylor '10]

(a.k.a. String Lamppost Principle)

Indeed, in this talk, we will discuss this question, and many more similar ones, centered on the idea of

String Universality [Adams De Wolfe Taylor '10]

(a.k.a. String Lamppost Principle)

The idea that every consistent EFT with gravity arises as a low-energy limit of some string theory construction

Indeed, in this talk, we will discuss this question, and many more similar ones, centered on the idea of

String Universality [Adams De Wolfe Taylor '10]

(a.k.a. String Lamppost Principle)

The idea that every consistent EFT with gravity arises as a low-energy limit of some string theory construction

In a sense, it is the "endgame" of the Swampland Program: ST is the only game in town.

Indeed, in this talk, we will discuss this question, and many more similar ones, centered on the idea of

String Universality [Adams De Wolfe Taylor '10]

(a.k.a. String Lamppost Principle)

The idea that every consistent EFT with gravity arises as a low-energy limit of some string theory construction

In a sense, it is the "endgame" of the Swampland Program: ST is the only game in town.

We have not realized this story **completely**, but much progress has taken place.

Indeed, in this talk, we will discuss this question, and many more similar ones, centered on the idea of

String Universality [Adams De Wolfe Taylor '10]

(a.k.a. String Lamppost Principle)

The idea that every consistent EFT with gravity arises as a low-energy limit of some string theory construction

In a sense, it is the "endgame" of the Swampland Program: ST is the only game in town.

We have not realized this story **completely**, but much progress has taken place.

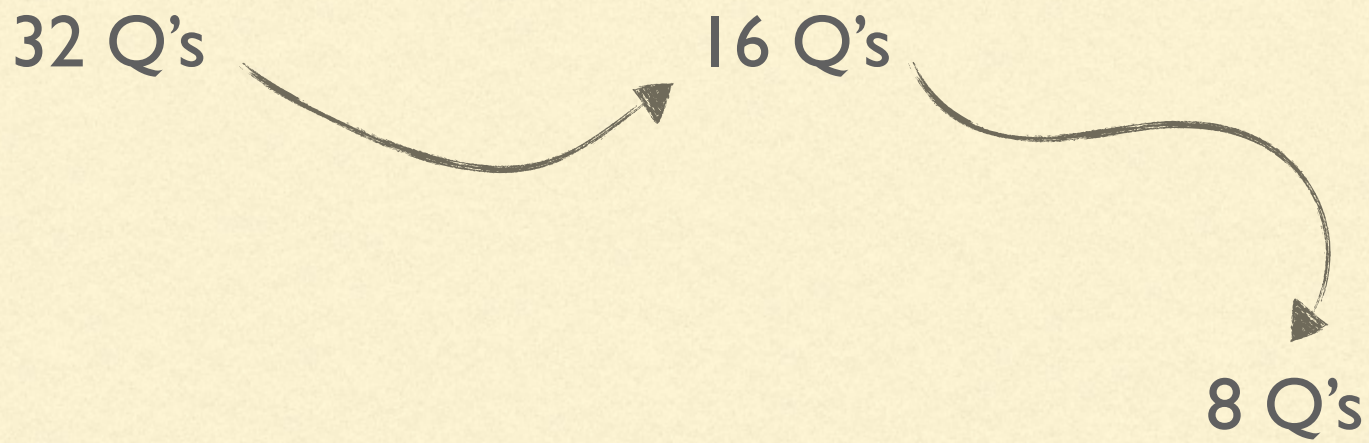
We will cover this briefly, by # of supercharges

Plan of the talk

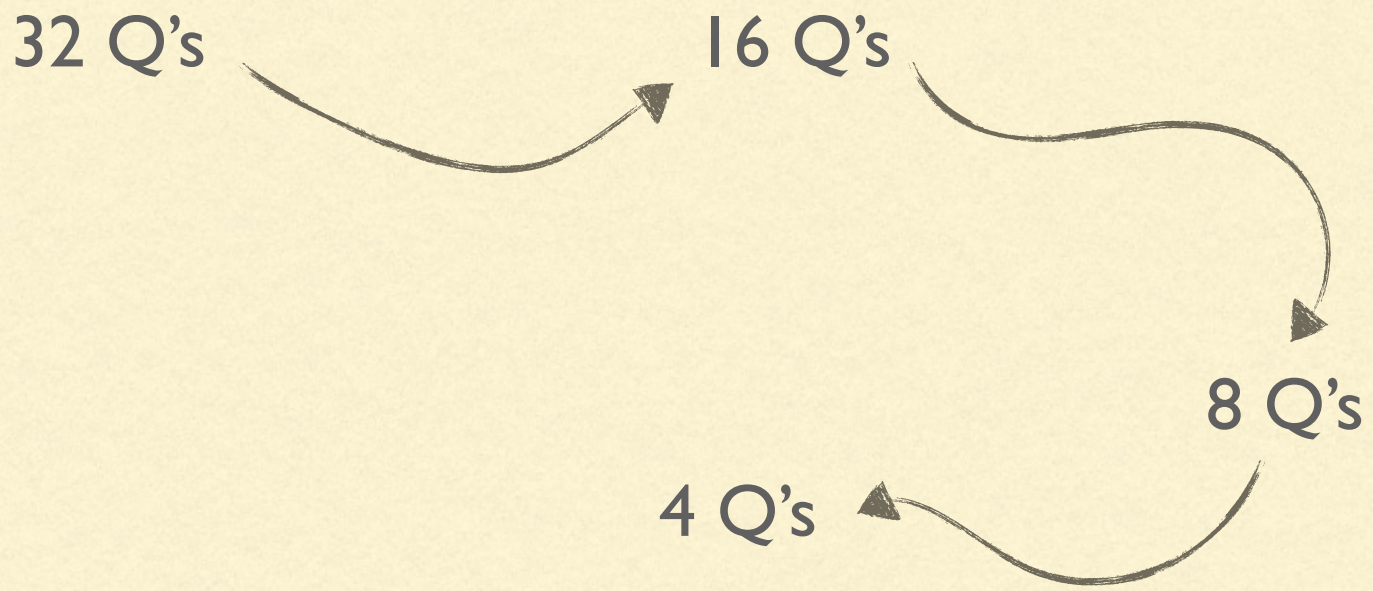
32 Q's

Plan of the talk

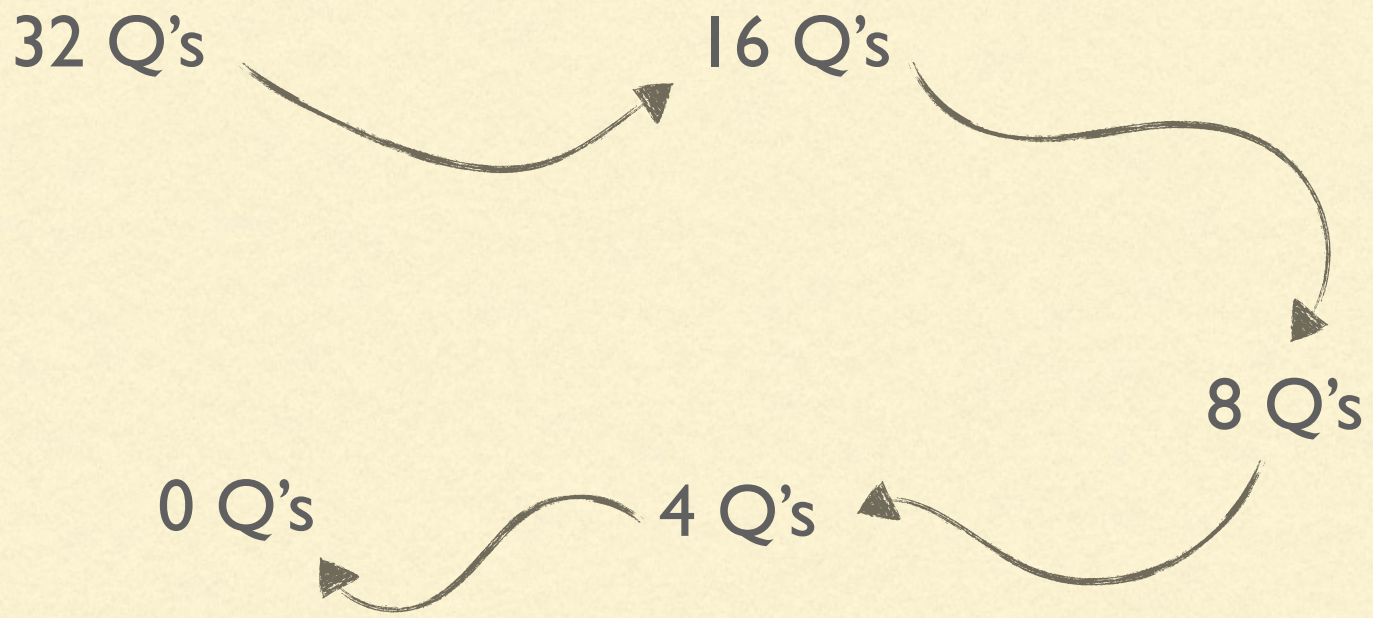
Plan of the talk



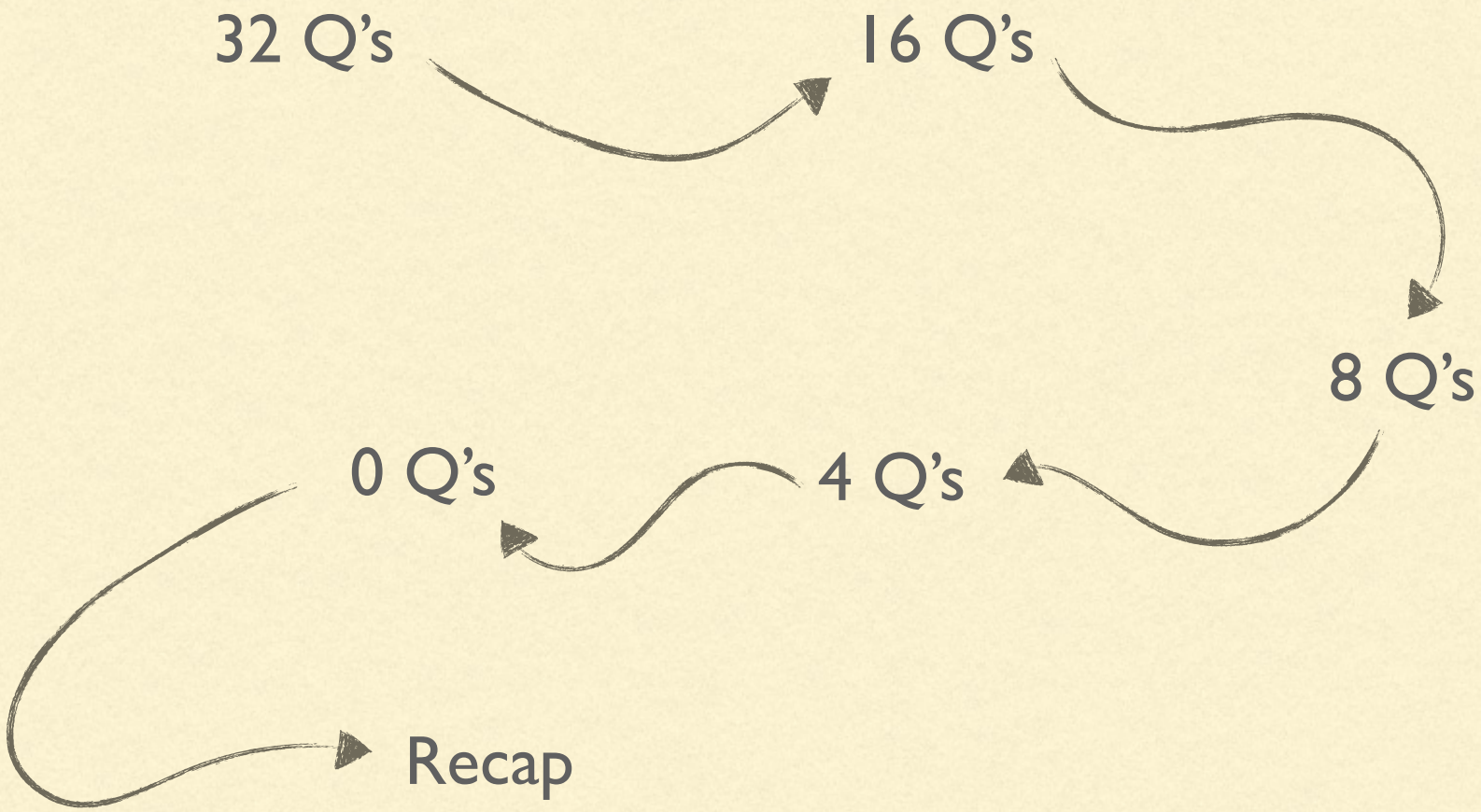
Plan of the talk



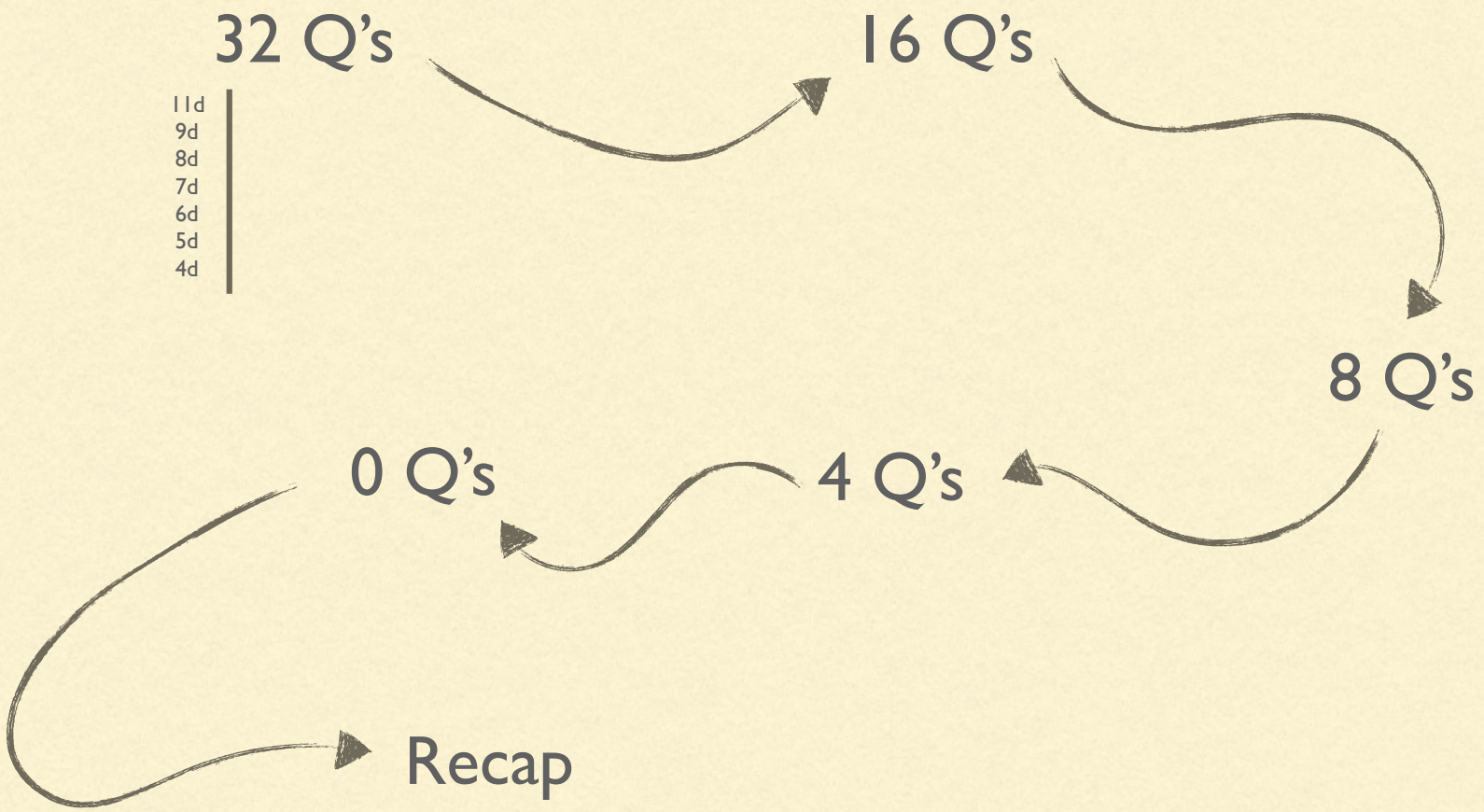
Plan of the talk



Plan of the talk



Plan of the talk



Please interrupt me!!

(at any point with questions, comments, whatever!)

32 supercharges

With this much SUSY, **there is a single multiplet** containing massless fields: Gravity multiplet

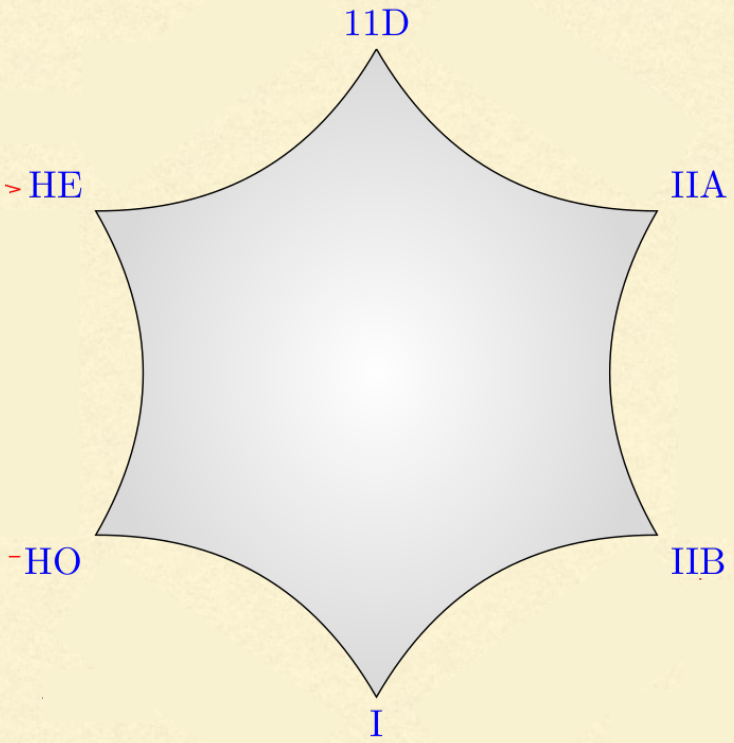
Low energy SUGRA fixed by consistency

32 supercharges

With this much SUSY, **there is a single multiplet** containing massless fields: Gravity multiplet

Low energy SUGRA fixed by consistency

E.g. in 10d/11d: Usual "star"

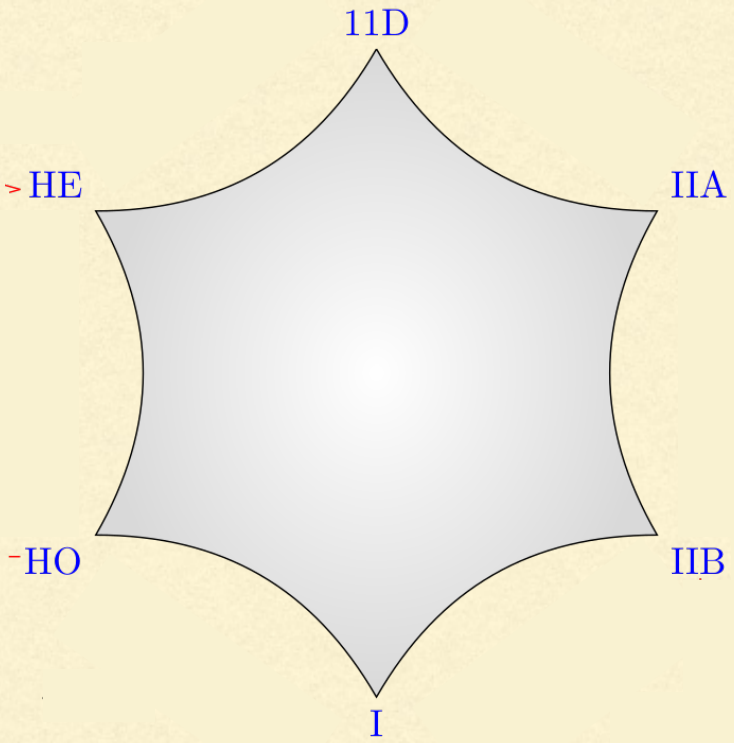


32 supercharges

With this much SUSY, **there is a single multiplet** containing massless fields: Gravity multiplet

Low energy SUGRA fixed by consistency

E.g. in 10d/11d: Usual "star"



d<10: Toroidal compactification of these

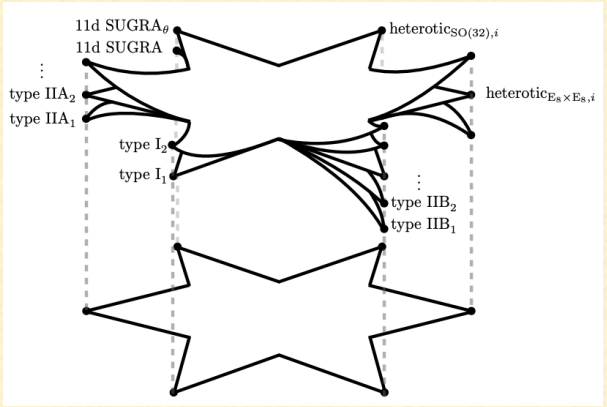
32 supercharges

but the spectrum of **massive states** is not determined!

32 supercharges

but the spectrum of **massive states** is not determined!

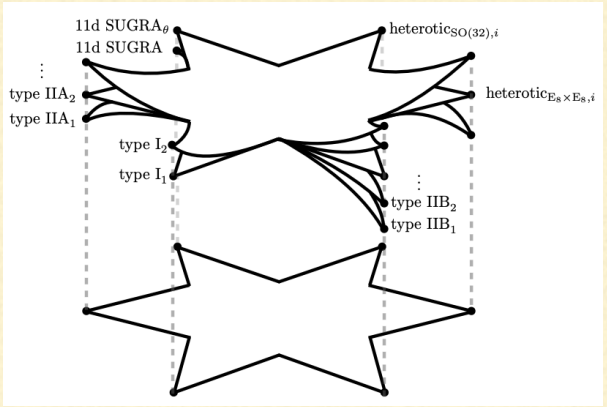
There could be e.g. **two different theories** which are type IIB at low energies.



32 supercharges

but the spectrum of **massive states** is not determined!

There could be e.g. **two different theories** which are type IIB at low energies.



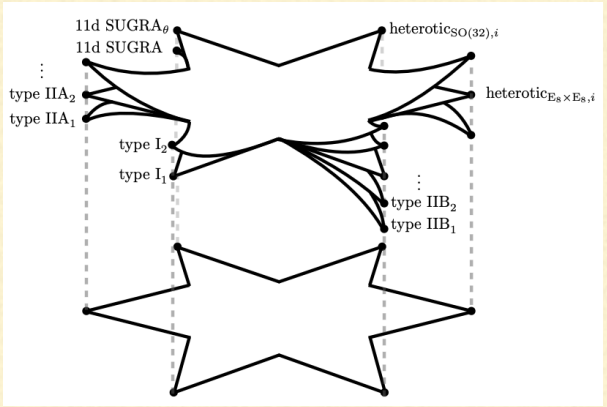
One way this happens: **Discrete theta angles**

[Sethi '13, Freed-Hopkins '19, Cecotti, Vafa '20, Debray, Dierigl, MM, Heckman '21]

32 supercharges

but the spectrum of **massive states** is not determined!

There could be e.g. **two different theories** which are type IIB at low energies.



One way this happens: **Discrete theta angles**

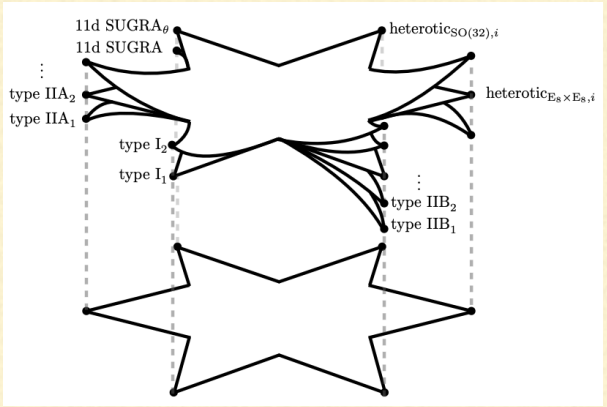
[Sethi '13, Freed-Hopkins '19, Cecotti, Vafa '20, Debray, Dierigl, MM, Heckman '21]

$$\theta \int F \wedge F$$

32 supercharges

but the spectrum of **massive states** is not determined!

There could be e.g. **two different theories** which are type IIB at low energies.



One way this happens: **Discrete theta angles**

[Sethi '13, Freed-Hopkins '19, Cecotti, Vafa '20, Debray, Dierigl, MM, Heckman '21]

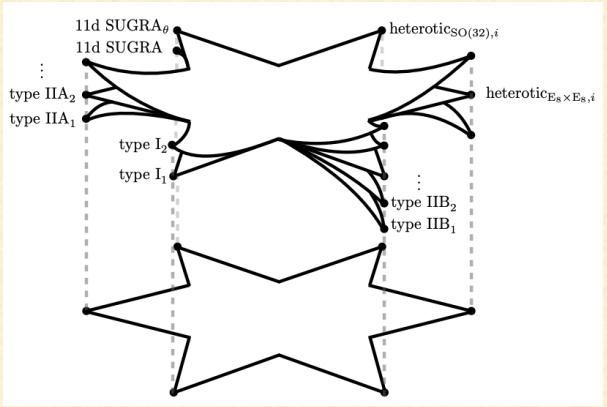
$$\theta \int F \wedge F$$

$$\theta_{\text{Discr}} \int \text{Top.}$$

32 supercharges

but the spectrum of **massive states** is not determined!

There could be e.g. **two different theories** which are type IIB at low energies.



One way this happens: **Discrete theta angles**

[Sethi '13, Freed-Hopkins '19, Cecotti, Vafa '20, Debray, Dierigl, MM, Heckman '21]

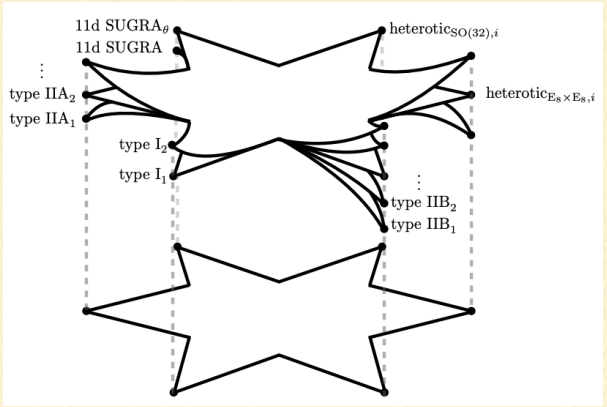
$$\theta \int F \wedge F \qquad\qquad \Omega_d^{SUGRA}$$

$$\theta_{\text{Discr}} \int \text{Top.}$$

32 supercharges

but the spectrum of **massive states** is not determined!

There could be e.g. **two different theories** which are type IIB at low energies.



One way this happens: **Discrete theta angles**

[Sethi '13, Freed-Hopkins '19, Cecotti, Vafa '20, Debray, Dierigl, MM, Heckman '21]

$$\theta \int F \wedge F \qquad \Omega_d^{SUGRA} \qquad \Omega_{10}^{\mathrm{IIB}} = \mathbb{Z}_2^4$$

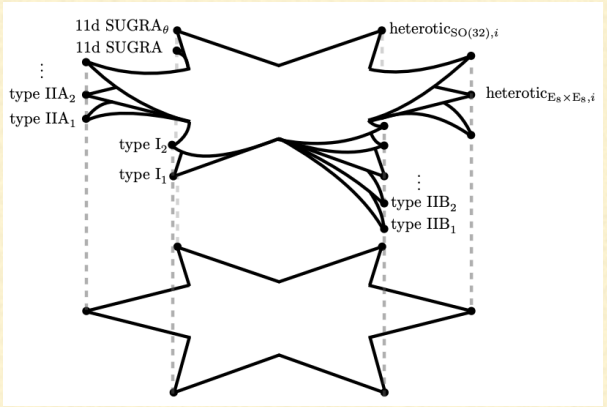
[Debray, Dierigl, MM, Heckman '23]

$$\theta_{\mathrm{Discr}} \int \mathrm{Top.}$$

32 supercharges

but the spectrum of **massive states** is not determined!

There could be e.g. **two different theories** which are type IIB at low energies.



One way this happens: **Discrete theta angles**

[Sethi '13, Freed-Hopkins '19, Cecotti, Vafa '20, Debray, Dierigl, MM, Heckman '21]

$$\theta \int F \wedge F \qquad \Omega_d^{SUGRA} \qquad \Omega_{10}^{\mathrm{IIB}} = \mathbb{Z}_2^4$$

[Debray, Dierigl, MM, Heckman '23]

$$\theta_{\mathrm{Discr}} \int \mathrm{Top.}$$

This can happen with **any** number of Q's

32 supercharges

Another way: Extra dim/ KK spectrum

(for instance, AdS5 without the S5)

32 supercharges

Another way: Extra dim/ KK spectrum
(for instance, AdS5 without the S5)

"Extreme scale separation"

32 supercharges

Another way: Extra dim/ KK spectrum

(for instance, AdS5 without the S5)

Swampland!

[MM, Vafa, Rocek '22]

"Extreme scale separation"

32 supercharges

Another way: Extra dim/ KK spectrum
(for instance, AdS5 without the S5)

Swampland!

[MM, Vafa, Rocek '22]

"Extreme scale separation"

Right now, we do not have a way to control the massive spectrum **rigorously** and generally

32 supercharges

Another way: Extra dim/ KK spectrum
(for instance, AdS5 without the S5)

Swampland!

[MM, Vafa, Rocek '22]

"Extreme scale separation"

Right now, we do not have a way to control the massive spectrum **rigorously** and generally

[See Jose's talk]

Some cases better: E.g. Distance Conjecture in AdS/CFT

[Rastelli-Perlmutter-Vafa-Valenzuela '20, Baume-Calderon Infante '20, '23]

"As you send gYM->0, an infinite tower of states appear"

32 superchargers

32 supercharges

One more mysterious corner: The (4,0) and (3,1) 6d superalgebras

32 supercharges

One more mysterious corner: The (4,0) and (3,1) 6d superalgebras

Not the gravity multiplet!

$$g_{ab} \rightarrow A_{abcd} \sim R_{abcd}$$

32 supercharges

One more mysterious corner: The (4,0) and (3,1) 6d superalgebras

Not the gravity multiplet!

$$g_{ab} \rightarrow A_{abcd} \sim R_{abcd}$$

But when on a circle, becomes 5d maximal SUGRA.

[Hull '01]

32 supercharges

One more mysterious corner: The (4,0) and (3,1) 6d superalgebras

Not the gravity multiplet!

$$g_{ab} \rightarrow A_{abcd} \sim R_{abcd}$$

But when on a circle, becomes 5d maximal SUGRA.

[Hull '01]

(Landscape or Swampland?) [MM, Tartaglia, Work in progress]

The take-home message with 32 supercharges is that we are **not so good** at showing uniqueness of ST including massive states.

The take-home message with 32 supercharges is that we are **not so good** at showing uniqueness of ST including massive states.

That's OK. It is a hard question.

The take-home message with 32 supercharges is that we are **not so good** at showing uniqueness of ST including massive states.

That's OK. It is a hard question.

Instead, for the remainder of this talk, we will focus on **the low-energy EFT;**

The take-home message with 32 supercharges is that we are **not so good** at showing uniqueness of ST including massive states.

That's OK. It is a hard question.

Instead, for the remainder of this talk, we will focus on **the low-energy EFT;**

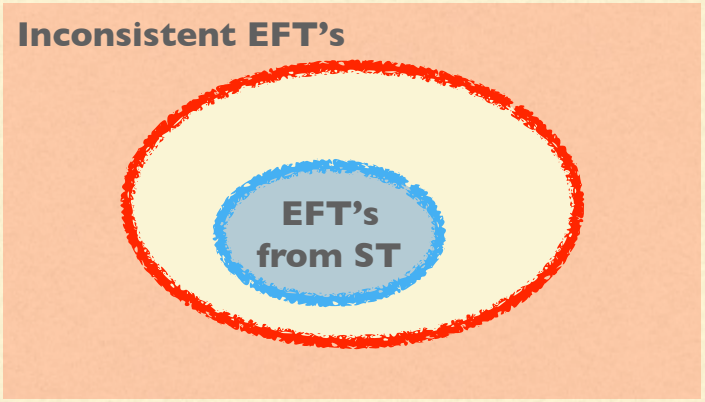
String universality = "All EFT's consistent with consistency principles are somewhere in the string Landscape"

The take-home message with 32 supercharges is that we are **not so good** at showing uniqueness of ST including massive states.

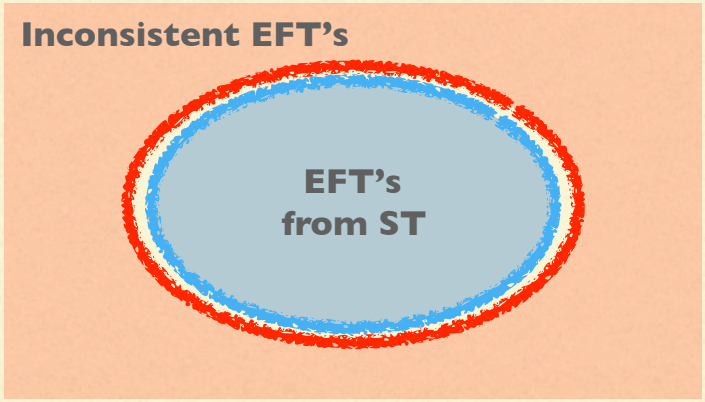
That's OK. It is a hard question.

Instead, for the remainder of this talk, we will focus on **the low-energy EFT;**

String universality = "All EFT's consistent with consistency principles are somewhere in the string Landscape"



String universality not achieved; room from improvement



String universality achieved; no room for EFT's not part of String Theory

Which consistency principles?

Anomalies

EFT unitarity

Causality

Which consistency principles?

Anomalies

EFT unitarity

Causality

Swampland constraints

No global symmetries

Completeness Principle

Weak Gravity

Which consistency principles?

Anomalies

EFT unitarity

Causality

Swampland constraints

No global symmetries

Completeness Principle

Weak Gravity

Let us see a concrete example of this!

16 supercharges

- Minimal SUSY in d>6 = 16 supercharges

16 supercharges

- Minimal SUSY in d>6 = 16 supercharges

- Life is simple: There are just **two multiplets**

16 supercharges

- Minimal SUSY in d>6 = 16 supercharges

- Life is simple: There are just **two multiplets**

  - Gravity: $g, A_i, B \;\; \phi$

16 supercharges

- Minimal SUSY in d>6 = 16 supercharges

- Life is simple: There are just **two multiplets**

  - Gravity: $g, A_i, B \;\; \phi$

  - Gauge: A, ϕ_i

16 supercharges

- Minimal SUSY in d>6 = 16 supercharges

- Life is simple: There are just **two multiplets**

  - Gravity: $g, A_i, B \;\; \phi$

  - Gauge: A, ϕ_i

Lagrangian fully fixed by SUSY

16 supercharges

- Minimal SUSY in d>6 = 16 supercharges

- Life is simple: There are just **two multiplets**
  - Gravity: $g, A_i, B \;\; \phi$
  - Gauge: A, ϕ_i

Lagrangian fully fixed by SUSY

10d: Green-Schwarz fixes group to

$$E_8 \times E_8, \quad SO(32), \quad U(1)^{496}, \quad E_8 \times U(1)^{248}$$

16 supercharges

- Minimal SUSY in d>6 = 16 supercharges

- Life is simple: There are just **two multiplets**
  - Gravity: $g, A_i, B \;\; \phi$
  - Gauge: A, ϕ_i

Lagrangian fully fixed by SUSY

10d: Green-Schwarz fixes group to [Shiu-Kim-Vafa '19] [Adams-de Wolfe-Taylor'10]

$$E_8 \times E_8, \quad SO(32), \quad \sout{U(1)^{496}}, \quad \sout{E_8 \times U(1)^{248}}$$

16 supercharges

- Minimal SUSY in d>6 = 16 supercharges

- Life is simple: There are just **two multiplets**
  - Gravity: $g, A_i, B \;\; \phi$
  - Gauge: A, ϕ_i

Lagrangian fully fixed by SUSY

10d: Green-Schwarz fixes group to [Shiu-Kim-Vafa '19] [Adams-de Wolfe-Taylor'10]

$$E_8 \times E_8, \quad SO(32), \quad U(1)^{496}, \quad E_8 \times U(1)^{248}$$

String universality achieved!

16 supercharges

What about d<10?

16 supercharges

What about d<10?

- There is a **Narain** moduli space parametrized by the scalars in vector and gravity multiplets

16 supercharges

What about d<10?

- There is a **Narain** moduli space parametrized by the scalars in vector and gravity multiplets
- On a **generic point** in moduli space, the group is $U(1)^{r+d}$

16 supercharges

What about d<10?

- There is a **Narain** moduli space parametrized by the scalars in vector and gravity multiplets

- On a **generic point** in moduli space, the group is $U(1)^{r+d}$
- At some points in moduli space, **symmetry enhancement** can occur.

16 supercharges

What about d<10?

- There is a **Narain** moduli space parametrized by the scalars in vector and gravity multiplets

- On a **generic point** in moduli space, the group is $U(1)^{r+d}$
- At some points in moduli space, **symmetry enhancement** can occur.

- So a sugra is **fully specified** by the **rank** of the gauge group…

16 supercharges

What about d<10?

- There is a **Narain** moduli space parametrized by the scalars in vector and gravity multiplets

- On a **generic point** in moduli space, the group is $U(1)^{r+d}$
- At some points in moduli space, **symmetry enhancement** can occur.

- So a sugra is **fully specified** by the **rank** of the gauge group…

…and a choice of **Lie algebra** (at special points in moduli space)

Let us first discuss **rank.**

Let us first discuss **rank.**

- Upper bound r<26-d from Swampland [Kim Tarazi Vafa '19]

Let us first discuss **rank.**

- Upper bound r<26-d from Swampland [Kim Tarazi Vafa '19]
- r= 1 mod 8 in 9d, r= 2 mod 8 in 8d

[MM Vafa '20]

Let us first discuss **rank.**

- Upper bound r<26-d from Swampland [Kim Tarazi Vafa '19]
- r= 1 mod 8 in 9d, r= 2 mod 8 in 8d [MM Vafa '20]
- r even in 7d, even & odd in 6d

Let us first discuss **rank.**

- Upper bound r<26-d from Swampland [Kim Tarazi Vafa '19]
- r= 1 mod 8 in 9d, r= 2 mod 8 in 8d [MM Vafa '20]
- r even in 7d, even & odd in 6d
- Some values of r are repeated (discrete theta angles)

Let us first discuss **rank.**

- Upper bound r<26-d from Swampland [Kim Tarazi Vafa '19]
- r= 1 mod 8 in 9d, r= 2 mod 8 in 8d [MM Vafa '20]
- r even in 7d, even & odd in 6d
- Some values of r are repeated (discrete theta angles)
- Bottom-up classification from "rank reduction map" [Fraiman, Parra de Freitas '21, '22]

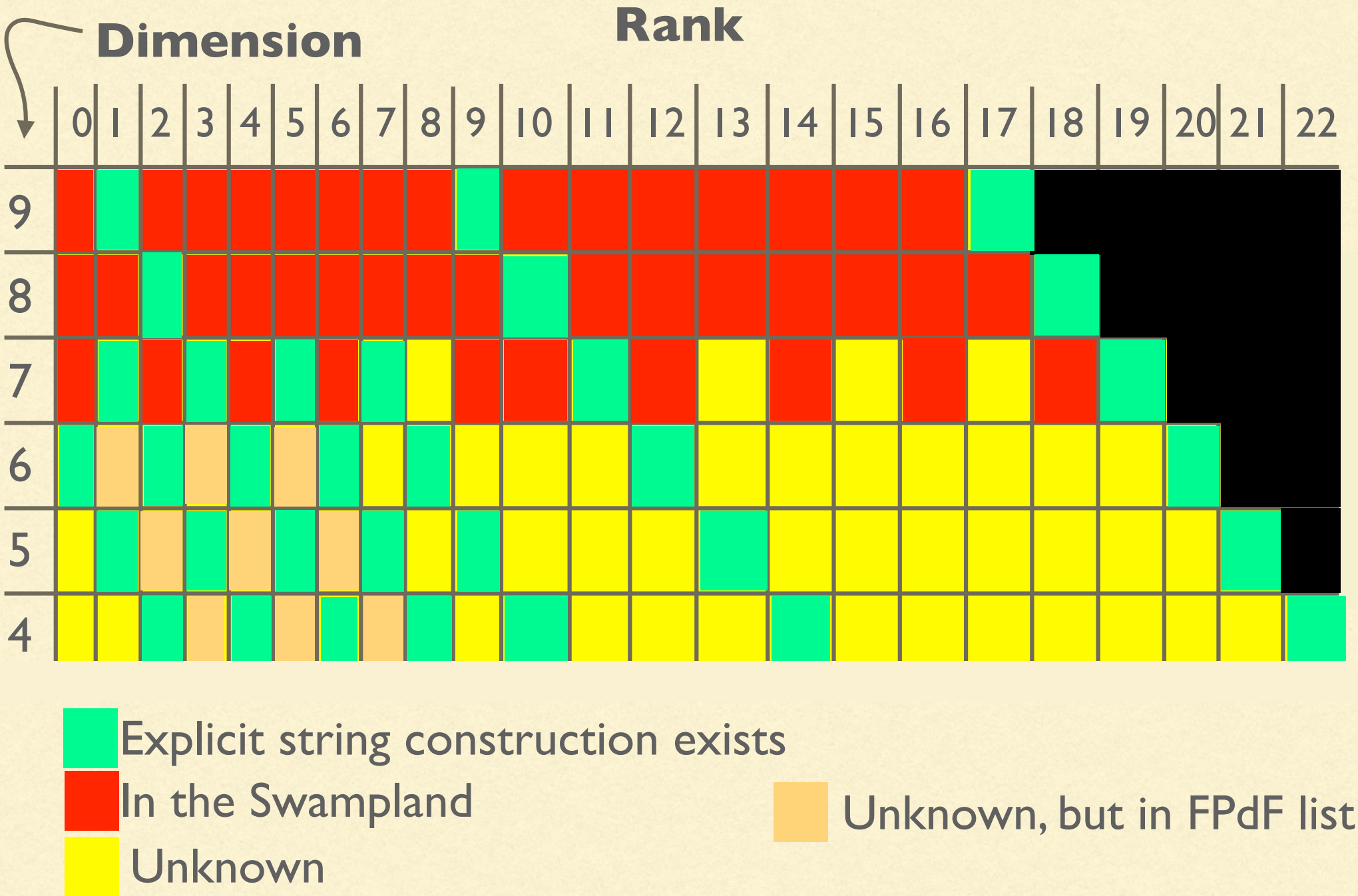
47 components in 6 dimensions, 30 of them new!

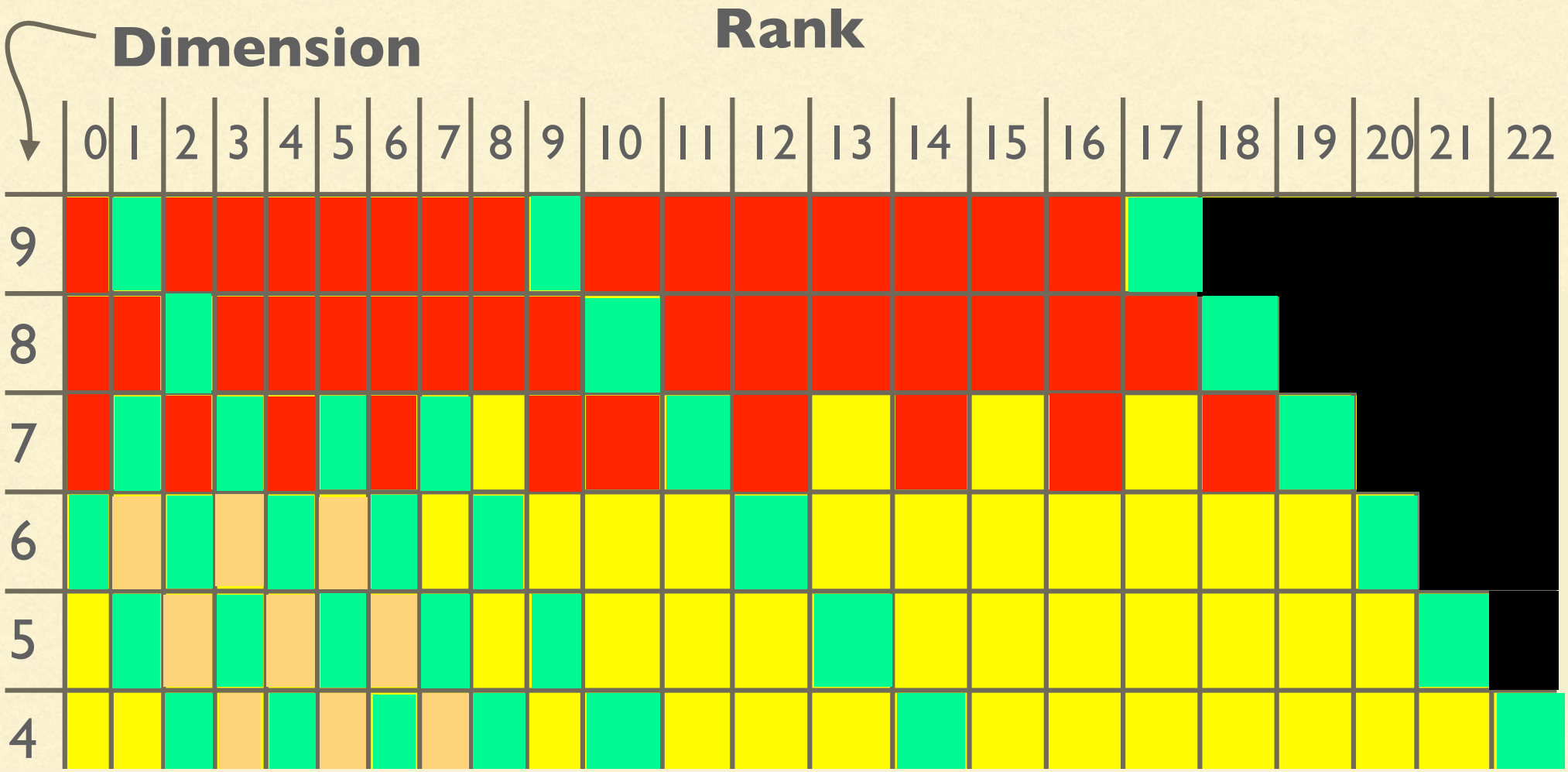
Let us first discuss **rank.**

- Upper bound r<26-d from Swampland [Kim Tarazi Vafa '19]
- r= 1 mod 8 in 9d, r= 2 mod 8 in 8d [MM Vafa '20]
- r even in 7d, even & odd in 6d
- Some values of r are repeated (discrete theta angles)
- Bottom-up classification from "rank reduction map" [Fraiman, Parra de Freitas '21, '22]

47 components in 6 dimensions, 30 of them new!

We don't know whether they have a stringy embedding


Dimension
Rank
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
9
8
7
6
5
4
Explicit string construction exists
In the Swampland
Unknown
Unknown, but in FPdF list



Explicit string construction exists

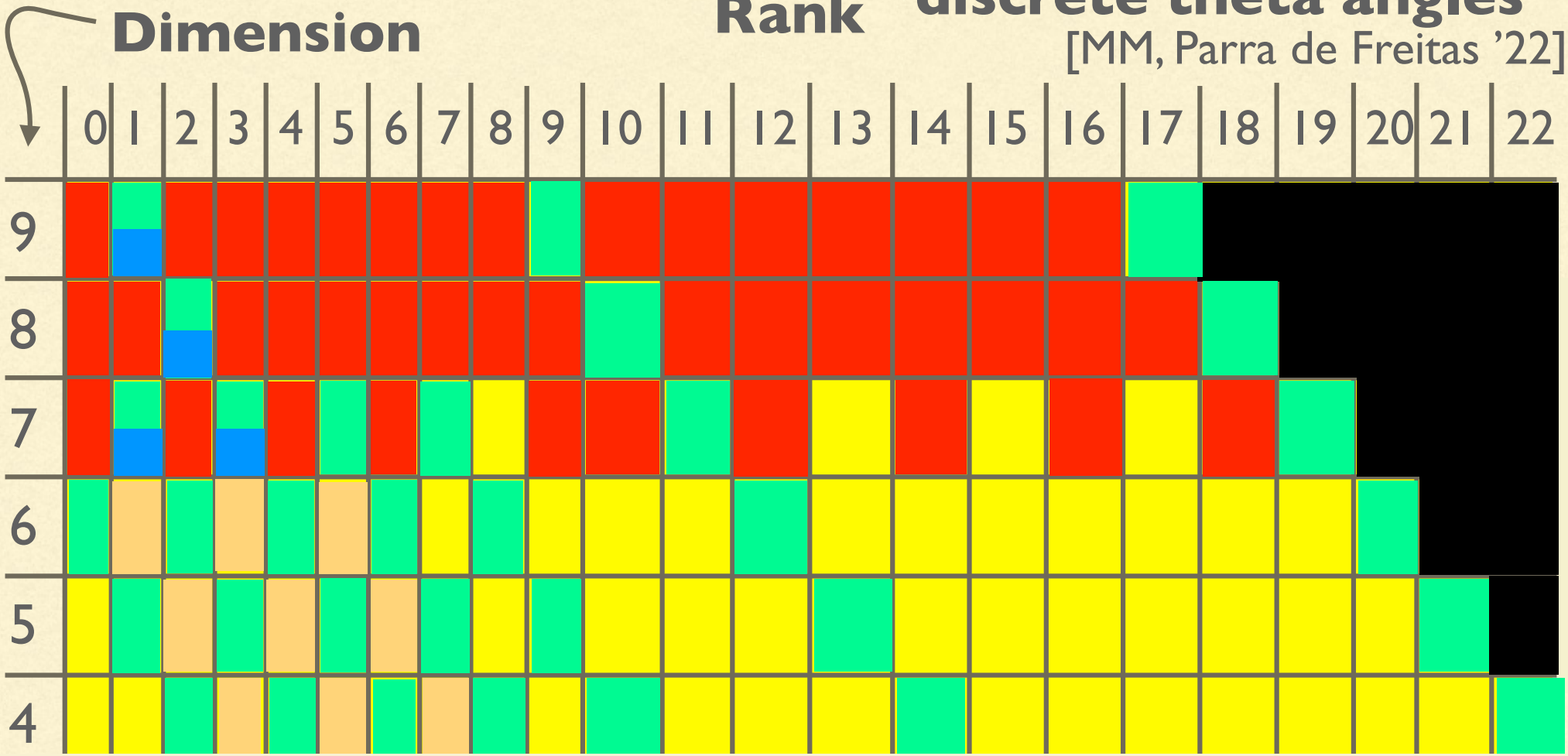
In the Swampland

Unknown

Unknown, but in FPdF list

What about 4d N=4 pure sugra?

Some numbers repeated due to **discrete theta angles**
[MM, Parra de Freitas '22]



Explicit string construction exists

In the Swampland

Unknown

Unknown, but in FPdF list

What about 4d N=4 pure sugra?

What about non-abelian groups?

What about non-abelian groups?

- Brane Probes classify 9d, 8d (partial results 7d)

  [Hamada, Vafa '21, Bedroya-MM-Hamada-Vafa '21]

What about non-abelian groups?

- Brane Probes classify 9d, 8d (partial results 7d)

  [Hamada, Vafa '21, Bedroya-MM-Hamada-Vafa '21]

- Constraints in global form of gauge group

  [Cvetic-Dierigl-Ling-Zhang '20, Montero-Vafa '20, Fraiman-Parra de Freitas '22]

What about non-abelian groups?

- Brane Probes classify 9d, 8d (partial results 7d)

  [Hamada, Vafa '21, Bedroya-MM-Hamada-Vafa '21]

- Constraints in global form of gauge group

  [Cvetic-Dierigl-Ling-Zhang '20, Montero-Vafa '20, Fraiman-Parra de Freitas '22]

  Independent string calculation:

  [Font-Fraiman-Graña-Nuñez-Parra de Freitas '20, '21]

What about non-abelian groups?

- Brane Probes classify 9d, 8d (partial results 7d)

[Hamada, Vafa '21, Bedroya-MM-Hamada-Vafa '21]

- Constraints in global form of gauge group

[Cvetic-Dierigl-Ling-Zhang '20, Montero-Vafa '20, Fraiman-Parra de Freitas '22]

Independent string calculation:

[Font-Fraiman-Graña-Nuñez-Parra de Freitas '20, '21]

Scattered results, no systematics in d<7

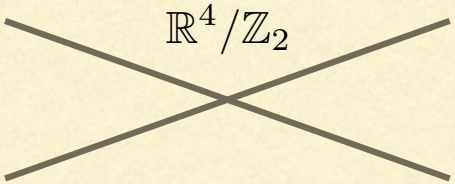
Fraiman-Parra approach: **systematic classification of frozen singularities** and how to glue them

What is a “frozen" singularity?

What is a “frozen" singularity?

M-theory perspective: Orbifold singu with discrete flux.

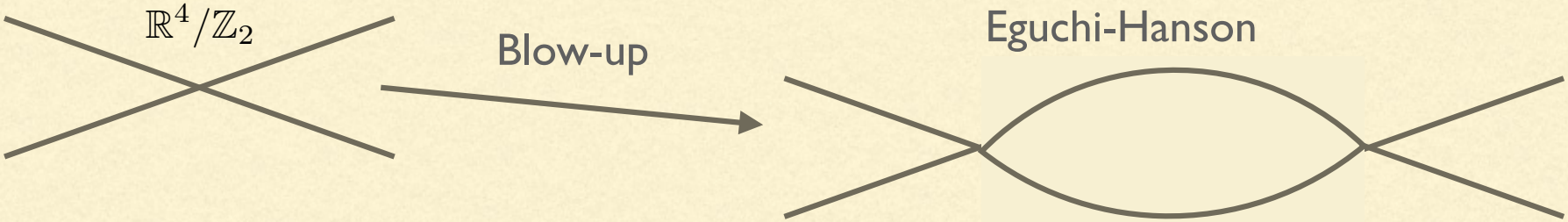
[Tachikawa ’15]



What is a “frozen" singularity?

M-theory perspective: Orbifold singu with discrete flux.

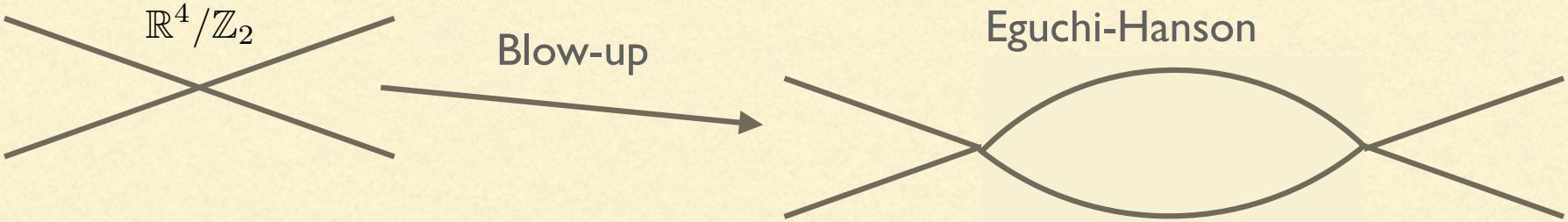
[Tachikawa ’15]



What is a “frozen" singularity?

M-theory perspective: Orbifold singu with discrete flux.

[Tachikawa ’15]

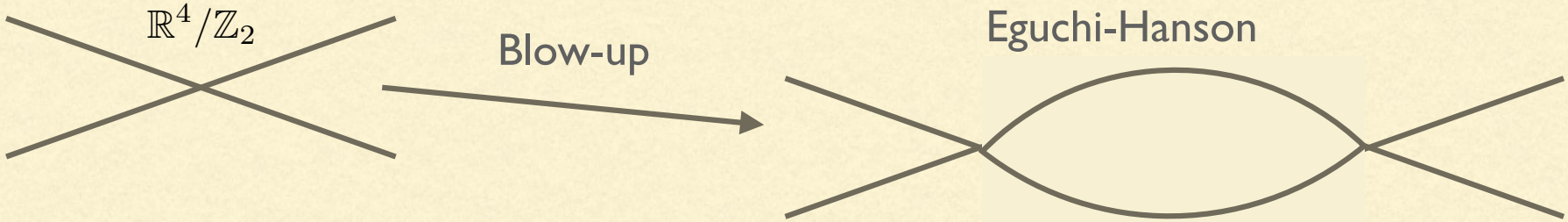


$$\int_{S^3/\mathbb{Z}_2} C_3 \neq 0$$

What is a “frozen" singularity?

M-theory perspective: Orbifold singu with discrete flux.

[Tachikawa ’15]



$$\int_{S^3/\mathbb{Z}_2} C_3 \neq 0$$

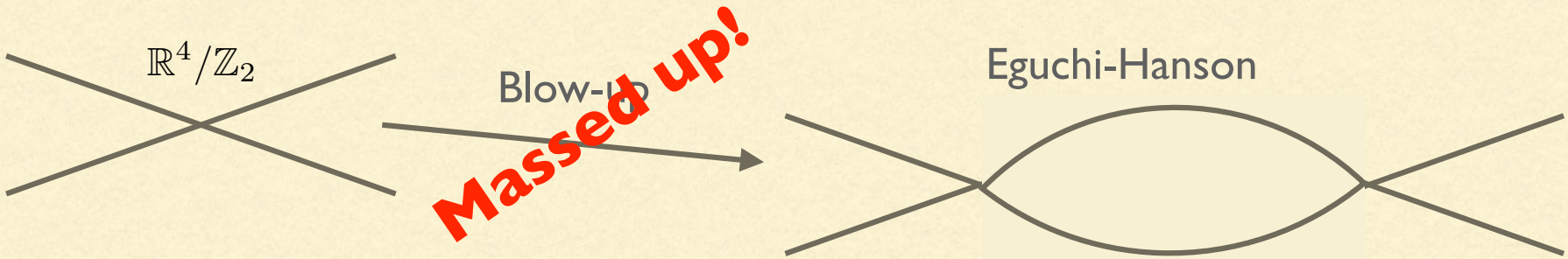
$$\int_{S^3/\mathbb{Z}_2} C_3 = \int_{\text{Eguchi-Hanson}} G_4 \neq 0$$

$$\int |G_4|^2 = \text{Potential for blow-up mode}$$

What is a “frozen" singularity?

M-theory perspective: Orbifold singu with discrete flux.

[Tachikawa ’15]



$$\int_{S^3/\mathbb{Z}_2} C_3 \neq 0$$

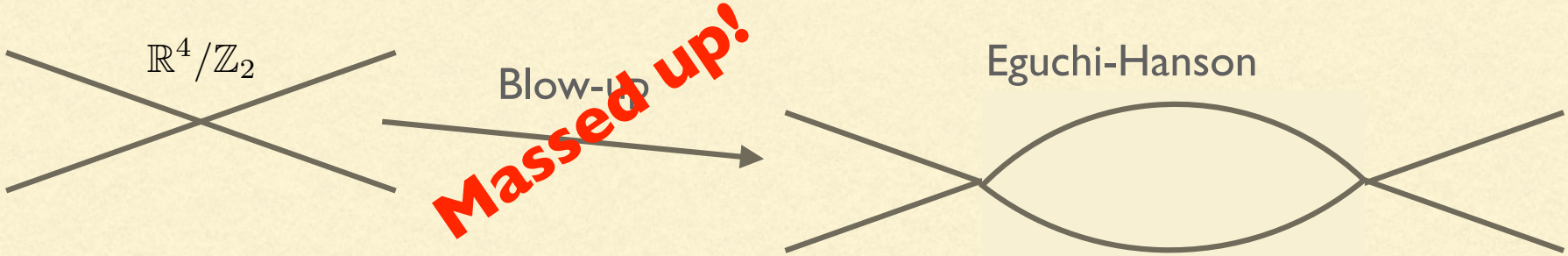
$$\int_{S^3/\mathbb{Z}_2} C_3 = \int_{\text{Eguchi-Hanson}} G_4 \neq 0$$

$$\int |G_4|^2 = \text{Potential for blow-up mode}$$

What is a “frozen" singularity?

M-theory perspective: Orbifold singu with discrete flux.

[Tachikawa ’15]



$$\int_{S^3/\mathbb{Z}_2} C_3 \neq 0$$

$$\int_{S^3/\mathbb{Z}_2} C_3 = \int_{\text{Eguchi-Hanson}} G_4 \neq 0$$

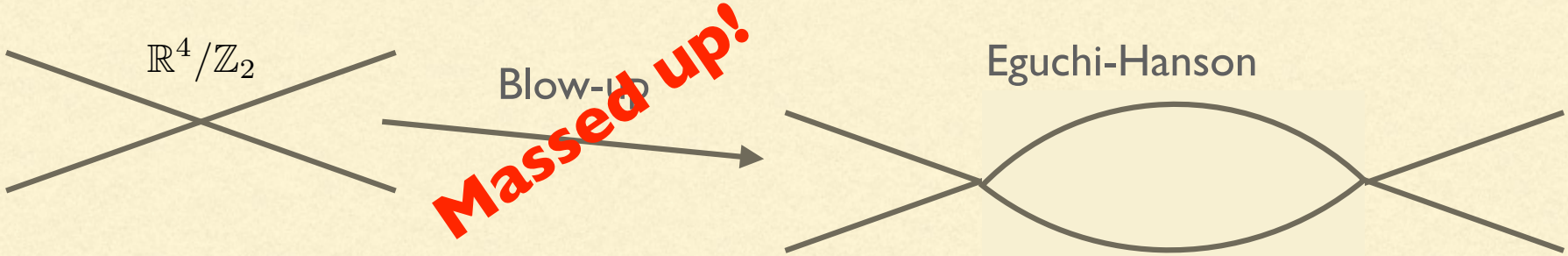
$$\int |G_4|^2 = \text{Potential for blow-up mode}$$

So e.g. M theory on frozen K3 = M theory on K3 with frozen singus

What is a “frozen" singularity?

M-theory perspective: Orbifold singu with discrete flux.

[Tachikawa ’15]



$$\int_{S^3/\mathbb{Z}_2} C_3 \neq 0$$

$$\int_{S^3/\mathbb{Z}_2} C_3 = \int_{\text{Eguchi-Hanson}} G_4 \neq 0$$

$$\int |G_4|^2 = \text{Potential for blow-up mode}$$

So e.g. M theory on frozen K3 = M theory on K3 with frozen singus

More to explore? $\int_{S^7/\Gamma} C_7$

Another promising idea:

Cobordism Conjecture

[McNamara-Vafa '19]

Another promising idea:

Cobordism Conjecture

[McNamara-Vafa '19]

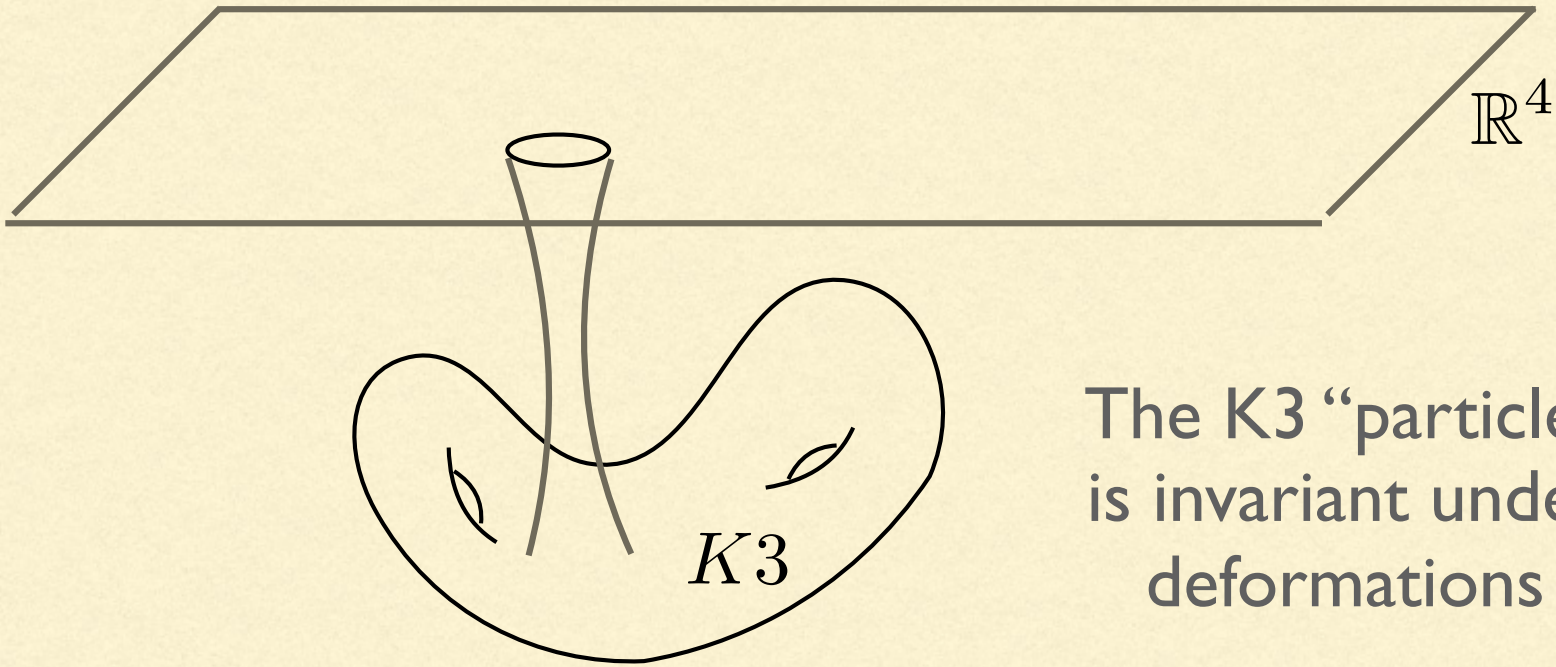
Basic idea: Nontrivial topology can lead to **global charges**

Another promising idea:

Cobordism Conjecture

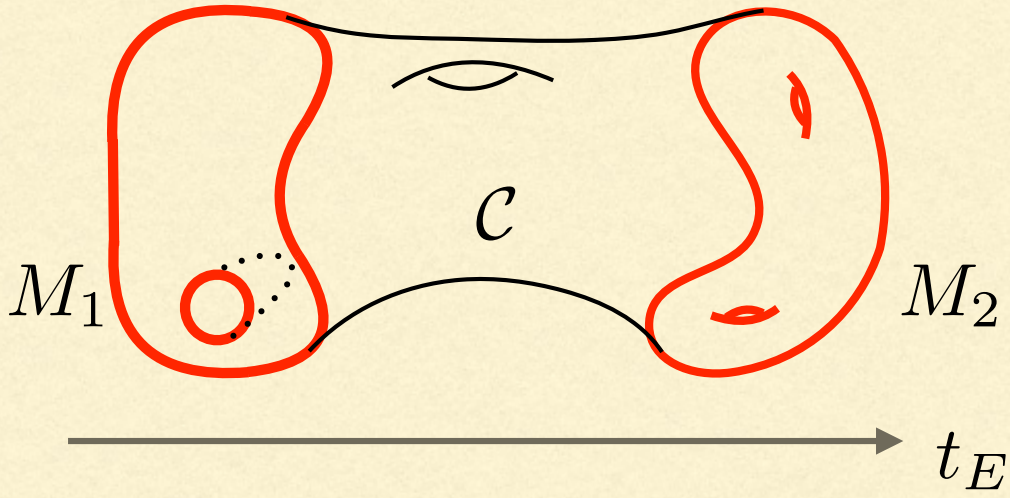
[McNamara-Vafa '19]

Basic idea: Nontrivial topology can lead to **global charges**

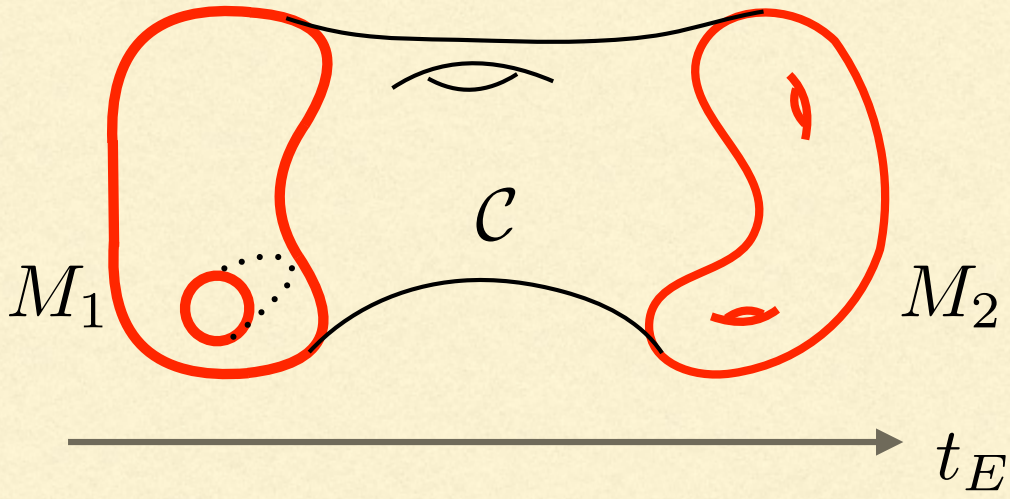


The K3 "particle" is invariant under deformations

But in QG, topology is **dynamical...** One kind of global charge is **preserved** under smooth topology fluctuations: the **cobordism class**



But in QG, topology is **dynamical...** One kind of global charge is **preserved** under smooth topology fluctuations: the **cobordism class**



C is a **cobordism** between M1 and M2

The set of cobordism classes forms a group, the **cobordism group**

e.g. $\Omega_4^{\mathrm{Spin}} = \mathbb{Z}$ generated by [K3]

The **cobordism groups** capture (generalized) topological global symmetries that cannot be killed via **smooth** topological transitions

The **cobordism groups** capture (generalized) topological global symmetries that cannot be killed via **smooth** topological transitions

(the transitions you can describe with the low-energy EFT)

The **cobordism groups** capture (generalized) topological global symmetries that cannot be killed via **smooth** topological transitions

(the transitions you can describe with the low-energy EFT)

But there are no global symmetries in QG…

The **cobordism groups** capture (generalized) topological global symmetries that cannot be killed via **smooth** topological transitions

(the transitions you can describe with the low-energy EFT)

But there are no global symmetries in QG…

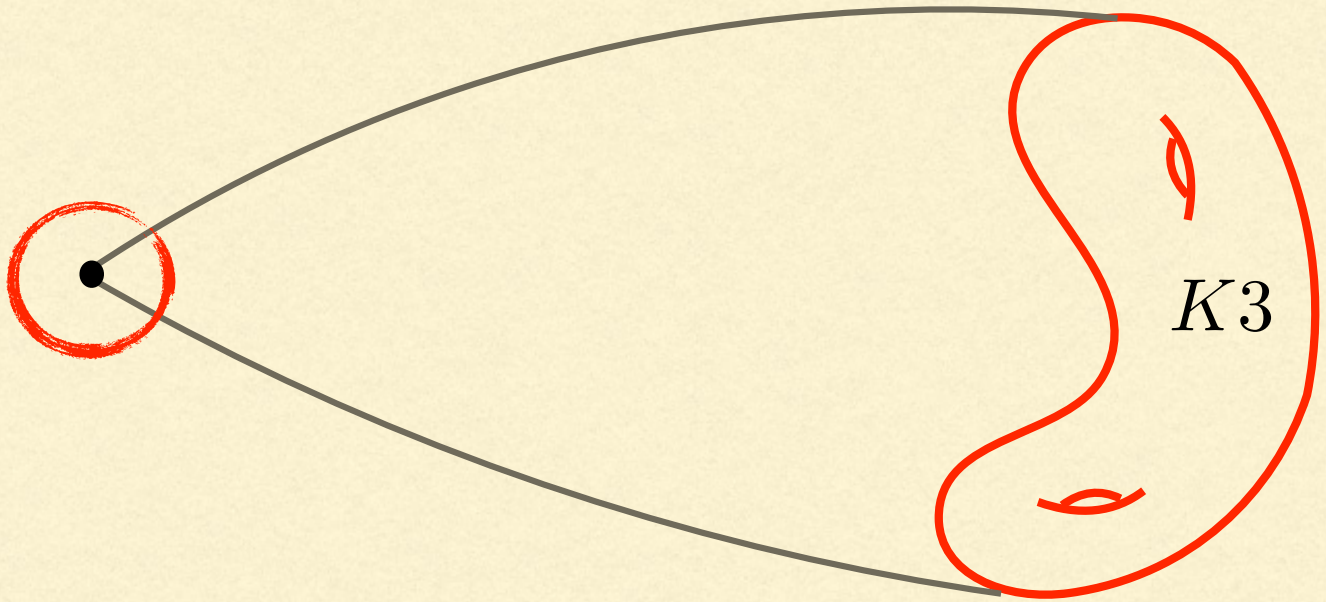
…so it must be possible to kill these global charges somehow!

The **cobordism groups** capture (generalized) topological global symmetries that cannot be killed via **smooth** topological transitions

(the transitions you can describe with the low-energy EFT)

But there are no global symmetries in QG…

…so it must be possible to kill these global charges somehow!



$\Omega_{\mathrm{QG}} = 0$

Killing the global symmetry forces the introduction of **defects**

Great deal of recent work on cobordism conjecture

[Angius, Basile, Bedroya, Berglund, Blumenhagen, Buratti, Calderón Infante, Cribiori, Cvetič, De Biasio, Debray, Delgado, Dierigl, Gonzalo, Hamada, Hebecker, Heckman, Herráez, Hertog, Huertas, Hübner, Hübsch, Ibanez, Kaidi, Karch, Kneissl, Lanza, Lin, Lüst, Makridou, Marchesano, Martucci, McNamara, Milutin Minic, Montella, Montero, Mourad, Ohmori, Parra De Freitas, Parra-Martinez, Raucci, Reece, Rudelius, Sagnotti, Sati, Schreiber, Sterckx, Tachikawa, Tatitscheff, Torres, Trivedi, Uranga, Vafa, Valenzuela, Van Riet, Wan, Wang, Yonekura, You, Zhang]

Great deal of recent work on cobordism conjecture

[Angius, Basile, Bedroya, Berglund, Blumenhagen, Buratti, Calderón Infante, Cribiori, Cvetič, De Biasio, Debray, Delgado, Dierigl, Gonzalo, Hamada, Hebecker, Heckman, Herráez, Hertog, Huertas, Hübner, Hübsch, Ibanez, Kaidi, Karch, Kneissl, Lanza, Lin, Lüst, Makridou, Marchesano, Martucci, McNamara, Milutin Minic, Montella, Montero, Mourad, Ohmori, Parra De Freitas, Parra-Martinez, Raucci, Reece, Rudelius, Sagnotti, Sati, Schreiber, Sterckx, Tachikawa, Tatitscheff, Torres, Trivedi, Uranga, Vafa, Valenzuela, Van Riet, Wan, Wang, Yonekura, You, Zhang]

Gives restrictions on the rank of theories, establishing rank universality in 8d and 9d

[MM-Vafa'20]

Great deal of recent work on cobordism conjecture

[Angius, Basile, Bedroya, Berglund, Blumenhagen, Buratti, Calderón Infante, Cribiori, Cvetič, De Biasio, Debray, Delgado, Dierigl, Gonzalo, Hamada, Hebecker, Heckman, Herráez, Hertog, Huertas, Hübner, Hübsch, Ibanez, Kaidi, Karch, Kneissl, Lanza, Lin, Lüst, Makridou, Marchesano, Martucci, McNamara, Milutin Minic, Montella, Montero, Mourad, Ohmori, Parra De Freitas, Parra-Martinez, Raucci, Reece, Rudelius, Sagnotti, Sati, Schreiber, Sterckx, Tachikawa, Tatitscheff, Torres, Trivedi, Uranga, Vafa, Valenzuela, Van Riet, Wan, Wang, Yonekura, You, Zhang]

Gives restrictions on the rank of theories, establishing rank universality in 8d and 9d

[MM-Vafa'20]

Can be used to produce similar constraints in 6d

[MM, unpublished]

Great deal of recent work on cobordism conjecture

[Angius, Basile, Bedroya, Berglund, Blumenhagen, Buratti, Calderón Infante, Cribiori, Cvetič, De Biasio, Debray, Delgado, Dierigl, Gonzalo, Hamada, Hebecker, Heckman, Herráez, Hertog, Huertas, Hübner, Hübsch, Ibanez, Kaidi, Karch, Kneissl, Lanza, Lin, Lüst, Makridou, Marchesano, Martucci, McNamara, Milutin Minic, Montella, Montero, Mourad, Ohmori, Parra De Freitas, Parra-Martinez, Raucci, Reece, Rudelius, Sagnotti, Sati, Schreiber, Sterckx, Tachikawa, Tatitscheff, Torres, Trivedi, Uranga, Vafa, Valenzuela, Van Riet, Wan, Wang, Yonekura, You, Zhang]

Gives restrictions on the rank of theories, establishing rank universality in 8d and 9d

[MM-Vafa'20]

Can be used to produce similar constraints in 6d

[MM, unpublished]

Can be used to predict new branes = new compactifications!

[Debray, Dierigl, Heckman, MM, Torres, Tachikawa, Kaidi, Ohmori '22, '23]

There has been a recent surge of work on theories with 16 Q's, not directly related to the question of universality.

There has been a recent surge of work on theories with 16 Q's, not directly related to the question of universality.

- Systematic study of their infinite distance limits & check of emergent string conjecture

  [Lee-Lerche-Weigand '21, Cvetic-Dierigl-Lin-Zhang '22, Etheredge-Heidenreich-McNamara-Rudelius-Ruiz-Valenzuela '23]

There has been a recent surge of work on theories with 16 Q's, not directly related to the question of universality.

- Systematic study of their infinite distance limits & check of emergent string conjecture

  [Lee-Lerche-Weigand '21, Cvetic-Dierigl-Lin-Zhang '22, Etheredge-Heidenreich-McNamara-Rudelius-Ruiz-Valenzuela '23]

- Consistency of counterterms in 8d [Lao-Minasian '23]

There has been a recent surge of work on theories with 16 Q's, not directly related to the question of universality.

- Systematic study of their infinite distance limits & check of emergent string conjecture

  [Lee-Lerche-Weigand '21, Cvetic-Dierigl-Lin-Zhang '22, Etheredge-Heidenreich-McNamara-Rudelius-Ruiz-Valenzuela '23]

- Consistency of counterterms in 8d [Lao-Minasian '23]

- Bootstrap studies [Bachu-Hillman '22]

There has been a recent surge of work on theories with 16 Q's, not directly related to the question of universality.

- Systematic study of their infinite distance limits & check of emergent string conjecture

  [Lee-Lerche-Weigand '21, Cvetic-Dierigl-Lin-Zhang '22, Etheredge-Heidenreich-McNamara-Rudelius-Ruiz-Valenzuela '23]

- Consistency of counterterms in 8d [Lao-Minasian '23]

- Bootstrap studies [Bachu-Hillman '22]

Promising arena to check both Landscape & Swampland ideas

8 supercharges

Highest dim possible: 6d (1,0)

8 supercharges

Highest dim possible: 6d (1,0)

- Can have vector, tensor, hypermultiplets

8 supercharges

Highest dim possible: 6d (1,0)

$$273 = n_T + n_H - n_V$$

- Can have vector, tensor, hypermultiplets

Many constraints from anomalies & brane probes… [See Markus' talk]

[Kim-Shiu-Vafa '19, Lee-Weigand '19, Martucci Risso Weigand '22, Dierigl-Oehlmann-Schimannek '22]

8 supercharges

Highest dim possible: 6d (1,0)

$$273 = n_T + n_H - n_V$$

- Can have vector, tensor, hypermultiplets

Many constraints from anomalies & brane probes… [See Markus' talk]

[Kim-Shiu-Vafa '19, Lee-Weigand '19, Martucci Risso Weigand '22, Dierigl-Oehlmann-Schimannek '22]

… but many infinite families remain (thank you, Greg & Yuta)

[Raghuram Taylor '18, Li-Taylor '22,Hamada-Loges '23]

8 supercharges

Highest dim possible: 6d (1,0)

$$273 = n_T + n_H - n_V$$

- Can have vector, tensor, hypermultiplets

Many constraints from anomalies & brane probes… [See Markus' talk]

[Kim-Shiu-Vafa '19, Lee-Weigand '19, Martucci Risso Weigand '22, Dierigl-Oehlmann-Schimannek '22]

… but many infinite families remain (thank you, Greg & Yuta)

[Raghuram Taylor '18, Li-Taylor '22,Hamada-Loges '23]

Seems unlikely to fully classify without new ideas

…like [Dierigl-Oehlmann-Schimannek '22, Basile, Leone '23]?

8 supercharges

Highest dim possible: 6d (1,0)

$$273 = n_T + n_H - n_V$$

- Can have vector, tensor, hypermultiplets

Many constraints from anomalies & brane probes… [See Markus' talk]

[Kim-Shiu-Vafa '19, Lee-Weigand '19, Martucci Risso Weigand '22, Dierigl-Oehlmann-Schimannek '22]

… but many infinite families remain (thank you, Greg & Yuta)

[Raghuram Taylor '18, Li-Taylor '22,Hamada-Loges '23]

Seems unlikely to fully classify without new ideas

…like [Dierigl-Oehlmann-Schimannek '22, Basile, Leone '23]?

- Theories with infinitely many massles modes are in Swampland

[Tarazi Vafa '21]

8 supercharges

With so many possibilities, it makes sense to switch gears and ask about **constructive** methods

8 supercharges

With so many possibilities, it makes sense to switch gears and ask about **constructive** methods

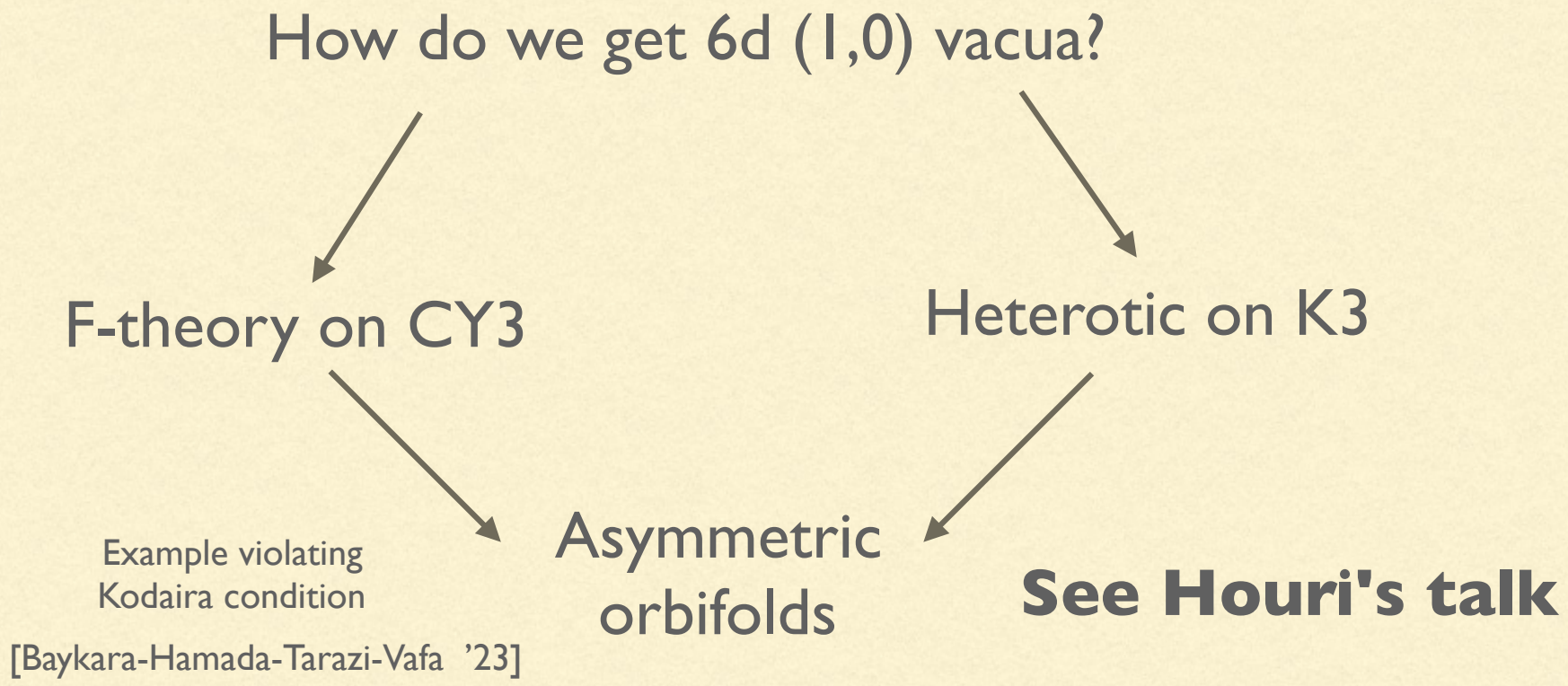
How do we get 6d (1,0) vacua?

F-theory on CY3

Heterotic on K3

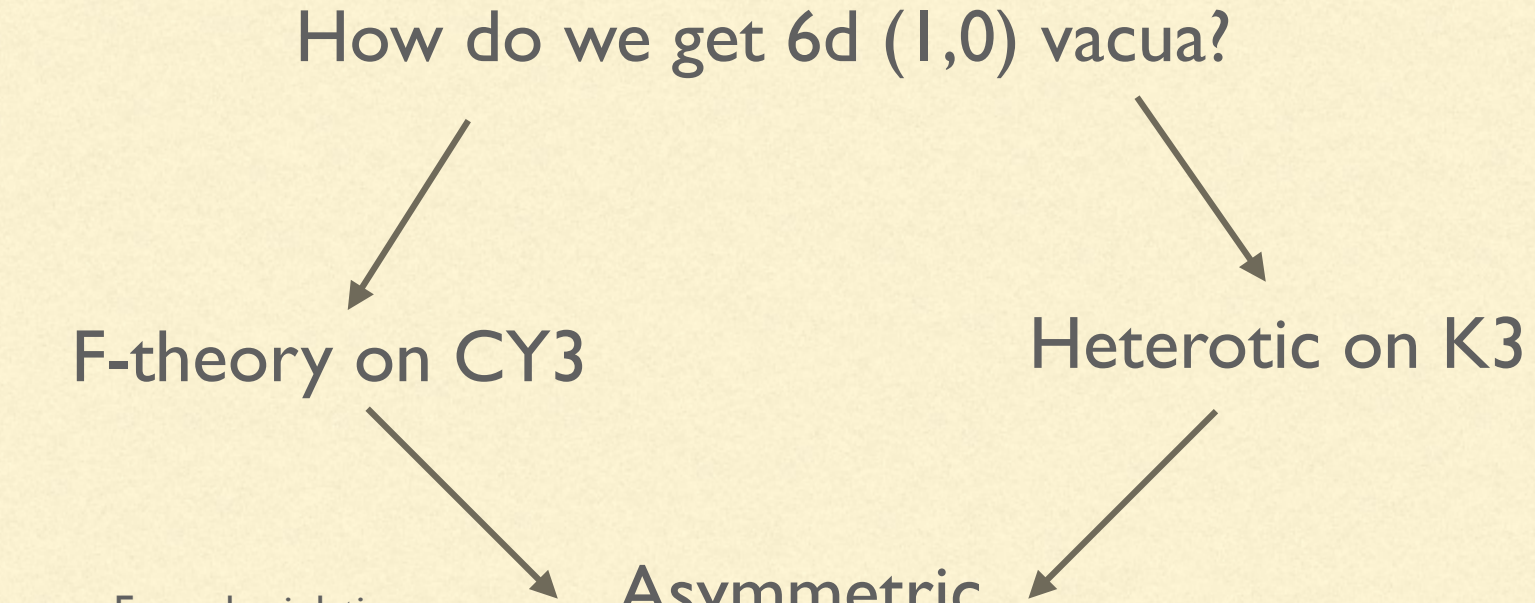
8 supercharges

With so many possibilities, it makes sense to switch gears and ask about **constructive** methods



8 supercharges

With so many possibilities, it makes sense to switch gears and ask about **constructive** methods



Example violating Kodaira condition

[Baykara-Hamada-Tarazi-Vafa '23]

See Houri's talk

How to orbifold away from the worldsheet?

[Giaccari Volpato '22]

8 supercharges

One way: Constructions of **Riemann-Flat manifolds**

8 supercharges

One way: Constructions of **Riemann-Flat manifolds**

(see also Peng Cheng's talk)

T^n → Torus

$\frac{T^n}{\Gamma}$ → Isometry group of torus

Allowed Gamma's classified up to dim. 5. Some give you SUSY!

8 supercharges

One way: Constructions of **Riemann-Flat manifolds**

(see also Peng Cheng's talk)

$$\frac{T^n}{\Gamma}$$

T^n → Torus

Γ → Isometry group of torus

Allowed Gamma's classified up to dim. 5. Some give you SUSY!

$\frac{T^6}{\mathbb{Z}_2^3}$ Calabi-Yau [Braun-Cvetic-Donagi-Poretschkin '17]

8 supercharges

One way: Constructions of **Riemann-Flat manifolds**

(see also Peng Cheng's talk)

T^n → Torus

$\frac{T^n}{\Gamma}$ → Isometry group of torus

Allowed Gamma's classified up to dim. 5. Some give you SUSY!

$\frac{T^6}{\mathbb{Z}_2^3}$ Calabi-Yau [Braun-Cvetic-Donagi-Poretschkin '17]

Useful for lower SUSY, too, in a controlled way!

Can include duality twists [Gkountoumis, Hull, Stemerdink, Vandoren '22]

8 supercharges

One way: Constructions of **Riemann-Flat manifolds**

(see also Peng Cheng's talk)

$$\frac{T^n}{\Gamma}$$

$T^n \longrightarrow$ Torus

$\Gamma \longrightarrow$ Isometry group of torus

Allowed Gamma's classified up to dim. 5. Some give you SUSY!

$\frac{T^6}{\mathbb{Z}_2^3}$ Calabi-Yau [Braun-Cvetic-Donagi-Poretschkin '17]

Useful for lower SUSY, too, in a controlled way!

Can include duality twists [Gkountoumis, Hull, Stemerdink, Vandoren '22]

More generally: T-folds, double field theor/gen. geometry, nilmanifolds… [e.g. Andriot-Tsimpis '18]

8 supercharges

5d N=1 and 4d N=2 (pretty similar)

- General relationship of UV cutoff (species scale) and towers of states

[Van de Heisteeg-Vafa-Wiesner ’22,’23, + Wu '23, Cribiori-Lust-Montella ’23, Castellano-Ruiz-Valenzuela ’23]

8 supercharges

5d N=1 and 4d N=2 (pretty similar)

- General relationship of UV cutoff (species scale) and towers of states

[Van de Heisteeg-Vafa-Wiesner ’22,’23, + Wu '23, Cribiori-Lust-Montella ’23, Castellano-Ruiz-Valenzuela ’23]

- Relationship between moduli space curvature & decoupling

[Marchesano, Melotti, Paoloni ’23]

8 supercharges

5d N=1 and 4d N=2 (pretty similar)

- General relationship of UV cutoff (species scale) and towers of states

[Van de Heisteeg-Vafa-Wiesner ’22,’23, + Wu '23, Cribiori-Lust-Montella ’23, Castellano-Ruiz-Valenzuela ’23]

- Relationship between moduli space curvature & decoupling

[Marchesano, Melotti, Paoloni ’23]

- Construction of numerical metrics (see Jim's talk)

[Halverson-Ruehle '23 + many others]

8 supercharges

5d N=1 and 4d N=2 (pretty similar)

- General relationship of UV cutoff (species scale) and towers of states

[Van de Heisteeg-Vafa-Wiesner '22,'23, + Wu '23, Cribiori-Lust-Montella '23, Castellano-Ruiz-Valenzuela '23]

- Relationship between moduli space curvature & decoupling

[Marchesano, Melotti, Paoloni '23]

- Construction of numerical metrics (see Jim's talk)

[Halverson-Ruehle '23 + many others]

- Even the basic Q: is # of CY3's finite? is not answered

8 supercharges

5d N=1 and 4d N=2 (pretty similar)

- General relationship of UV cutoff (species scale) and towers of states

[Van de Heisteeg-Vafa-Wiesner '22,'23, + Wu '23, Cribiori-Lust-Montella '23, Castellano-Ruiz-Valenzuela '23]

- Relationship between moduli space curvature & decoupling

[Marchesano, Melotti, Paoloni '23]

- Construction of numerical metrics (see Jim's talk)

[Halverson-Ruehle '23 + many others]

- Even the basic Q: is # of CY3's finite? is not answered

- Is 5d N=1 pure sugra (only gravity multiplet) in the Swampland?

4 supercharges

(A lot of discussion on Wednesday & Thursday, so I will be brief)

4 supercharges

(A lot of discussion on Wednesday & Thursday, so I will be brief)

- 4d and below
- Generically spontaneously broken
- Work on structure of flux potential

  [Grimm-Li-Valenzuela '19, Calderon Infante-Ruiz-Valenzuela '22]

  Tameness

  [Grimm, Lanza, Douglas, Schlechter, Monee, van Vliet, '21, '22, '23]

4 supercharges

(A lot of discussion on Wednesday & Thursday, so I will be brief)

- 4d and below
- Generically spontaneously broken
- Work on structure of flux potential

  [Grimm-Li-Valenzuela '19, Calderon Infante-Ruiz-Valenzuela '22]

  Tameness

  [Grimm, Lanza, Douglas, Schlechter, Monee, van Vliet, '21, '22, '23]
- Numerical flux vacua [Krippendorf-Schachner '23]
- Tadpole conjecture [See Iosif's talk]
- Interior of moduli space [See Max's talk]
- Scale separation [Wednesday discussion]

4 supercharges

- Progress on KKLT construction [See Jakob's talk]
  - Some issues (e.g. small gsM), no obvious roadblock
  - How does antibrane affect F-term stabilization?
  - How to e.g. add SM?
  - What about LVS?
- dS no go theorems (generalizing Maldacena-Nuñez)

For isntance, the ones in

[Andriot '18]

[Grimm-Li-Valenzuela '19]

[Andriot, Horer, Marconnet '22]

0 supercharges

Most interesting case. Most **natural** place to find dS

0 supercharges

Most interesting case. Most **natural** place to find dS

…and all sorts of weird stuff!

0 supercharges

Most interesting case. Most **natural** place to find dS

…and all sorts of weird stuff!

- For instance, **scale separation** $AdS_4 \times T^7$

(although no hologr. dual)

[De Luca-De Ponti-Mondino-Tomassiello '23]

0 supercharges

Most interesting case. Most **natural** place to find dS

…and all sorts of weird stuff!

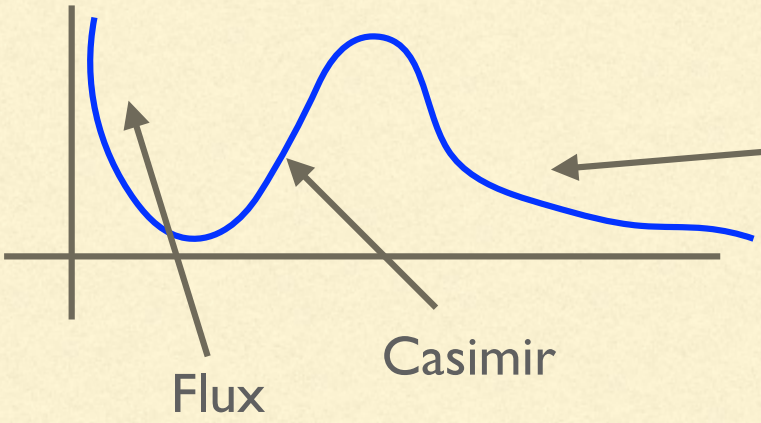
- For instance, **scale separation**

  (although no hologr. dual)

$$AdS_4 \times T^7$$

[De Luca-De Ponti-Mondino-Tomassiello '23]

- And remarkably simple **dS constructions** [See Bruno's talk]



$$AdS_4 \times \mathcal{H}_7$$

[De Luca-Torroba-Silverstein '21]

Curvature

We need **explicit** example (with numbers)

But shows the power of just "leaving CY"

0 supercharges

Most interesting case. Most **natural** place to find dS

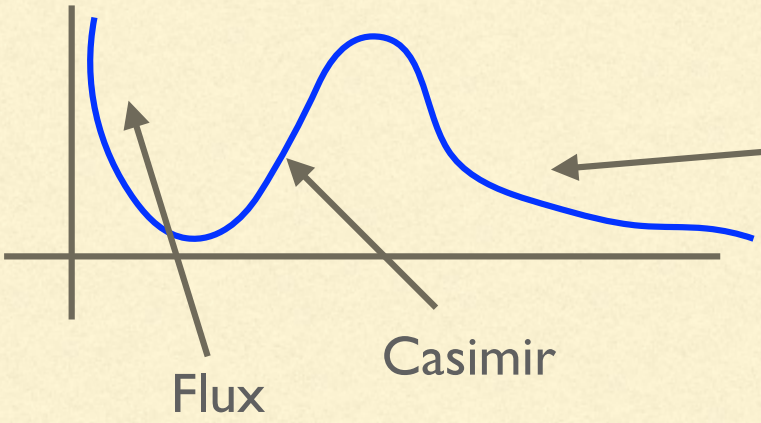
…and all sorts of weird stuff!

- For instance, **scale separation** $AdS_4 \times T^7$

  (although no hologr. dual)

  [De Luca-De Ponti-Mondino-Tomassiello '23]

- And remarkably simple **dS constructions** [See Bruno's talk]



$AdS_4 \times \mathcal{H}_7$ [De Luca-Torroba-Silverstein '21]

Curvature

We need **explicit** example (with numbers)

But shows the power of just "leaving CY"

Doesn't have to be hyperbolic!

0 supercharges

Also arena for **non-susy strings**

(Check out Youngst@rs workshop "Strings breaking SUSY" just last week!)

0 supercharges

Also arena for **non-susy strings**

(Check out Youngst@rs workshop "Strings breaking SUSY" just last week!)

- Progress in closed-string tachyon condensation a la Hellerman

[Kaidi '20, Kaidi-Ohmori-Tachikawa '23]

0 supercharges

Also arena for **non-susy strings**

(Check out Youngst@rs workshop "Strings breaking SUSY" just last week!)

- Progress in closed-string tachyon condensation a la Hellerman

  [Kaidi '20, Kaidi-Ohmori-Tachikawa '23]

- Recent classification of non-susy heterotic strings

  [**Philip Boyle Smith, Ying-Hsuan Lin, Yuji Tachikawa, Yunqin Zheng** '23]

0 supercharges

Also arena for **non-susy strings**

(Check out Youngst@rs workshop "Strings breaking SUSY" just last week!)

- Progress in closed-string tachyon condensation a la Hellerman

  [Kaidi '20, Kaidi-Ohmori-Tachikawa '23]

- Recent classification of non-susy heterotic strings

  [**Philip Boyle Smith, Ying-Hsuan Lin, Yuji Tachikawa, Yunqin Zheng** '23]

- Open string models: New stuff yet to be found

  [Courdachet, Dudas, Partouche '21]

0 supercharges

Also arena for **non-susy strings**

(Check out Youngst@rs workshop "Strings breaking SUSY" just last week!)

- Progress in closed-string tachyon condensation a la Hellerman
  [Kaidi '20, Kaidi-Ohmori-Tachikawa '23]
- Recent classification of non-susy heterotic strings
  [**Philip Boyle Smith, Ying-Hsuan Lin, Yuji Tachikawa, Yunqin Zheng** '23]
- Open string models: New stuff yet to be found
  [Courdachet, Dudas, Partouche '21]
- Systematic exploration of moduli space of SO(16)^2
  [Fraiman-Graña-Parra de Freitas-Sethi '23]

0 supercharges

Also arena for **non-susy strings**

(Check out Youngst@rs workshop "Strings breaking SUSY" just last week!)

- Progress in closed-string tachyon condensation a la Hellerman
  [Kaidi '20, Kaidi-Ohmori-Tachikawa '23]
- Recent classification of non-susy heterotic strings
  [**Philip Boyle Smith, Ying-Hsuan Lin, Yuji Tachikawa, Yunqin Zheng** '23]
- Open string models: New stuff yet to be found
  [Courdachet, Dudas, Partouche '21]
- Systematic exploration of moduli space of SO(16)^2
  [Fraiman-Graña-Parra de Freitas-Sethi '23]
- 10d nonsusy tachyon-free = anomaly free

0 supercharges

Also arena for **non-susy strings**

(Check out Youngst@rs workshop "Strings breaking SUSY" just last week!)

- Progress in closed-string tachyon condensation a la Hellerman
  [Kaidi '20, Kaidi-Ohmori-Tachikawa '23]
- Recent classification of non-susy heterotic strings
  [**Philip Boyle Smith, Ying-Hsuan Lin, Yuji Tachikawa, Yunqin Zheng** '23]
- Open string models: New stuff yet to be found
  [Courdachet, Dudas, Partouche '21]
- Systematic exploration of moduli space of SO(16)^2
  [Fraiman-Graña-Parra de Freitas-Sethi '23]
- 10d nonsusy tachyon-free = anomaly free
- Constructions of AdS3 + higher-dim AdS vacua
  [Basile, Mourad Sagnotti '20, Baykara-Robbins-Sethi '22, Fraiman, Graña, Parra de Freitas, Sethi '23]

0 supercharges

Also arena for **non-susy strings**

(Check out Youngst@rs workshop "Strings breaking SUSY" just last week!)

- Progress in closed-string tachyon condensation a la Hellerman
  [Kaidi '20, Kaidi-Ohmori-Tachikawa '23]
- Recent classification of non-susy heterotic strings
  [**Philip Boyle Smith, Ying-Hsuan Lin, Yuji Tachikawa, Yunqin Zheng** '23]
- Open string models: New stuff yet to be found
  [Courdachet, Dudas, Partouche '21]
- Systematic exploration of moduli space of SO(16)^2
  [Fraiman-Graña-Parra de Freitas-Sethi '23]
- 10d nonsusy tachyon-free = anomaly free
- Constructions of AdS3 + higher-dim AdS vacua Stability?
  [Basile, Mourad Sagnotti '20, Baykara-Robbins-Sethi '22, Fraiman, Graña, Parra de Freitas, Sethi '23]

0 supercharges

[See Severin's talk for the SAME SLIDE]

Very interestingly, nonsusy, tachyon-free strings have a **positive potential**

$$V > 0$$

0 supercharges

[See Severin's talk for the SAME SLIDE]

Very interestingly, nonsusy, tachyon-free strings have a **positive potential**

$$V > 0$$

which violates assumptions of Maldacena-Nuñez no go theorem for dS [Maldacena-Nuñez '01]

0 supercharges

[See Severin's talk for the SAME SLIDE]

Very interestingly, nonsusy, tachyon-free strings have a **positive potential**

$$V > 0$$

which violates assumptions of Maldacena-Nuñez no go theorem for dS [Maldacena-Nuñez '01]

However, there are extensions of this theorem applying to non-susy strings

[Basile-Lanza '20, Bernardo-Brahma-Faruk '22,Leedom-Righi-Westphal '22, Hebecker-Schreyer-Venken '23]

To sum up:

To sum up:

To sum up:

"But hasn't string theory been proven wrong already?"

"You guys have been at it for over 40 years! When will you give up and acknowledge defeat?"

To sum up:

"But hasn't string theory been proven wrong already?"

"You guys have been at it for over 40 years! When will you give up and acknowledge defeat?"

You now know what to say:

The string Landscape is vast.

40 years is enough only to scratch the surface.

We need more people — not less! to help us explore it.

Come on and join us!

Merci beaucoup!

(Hope taking the early RER today was worth it!)