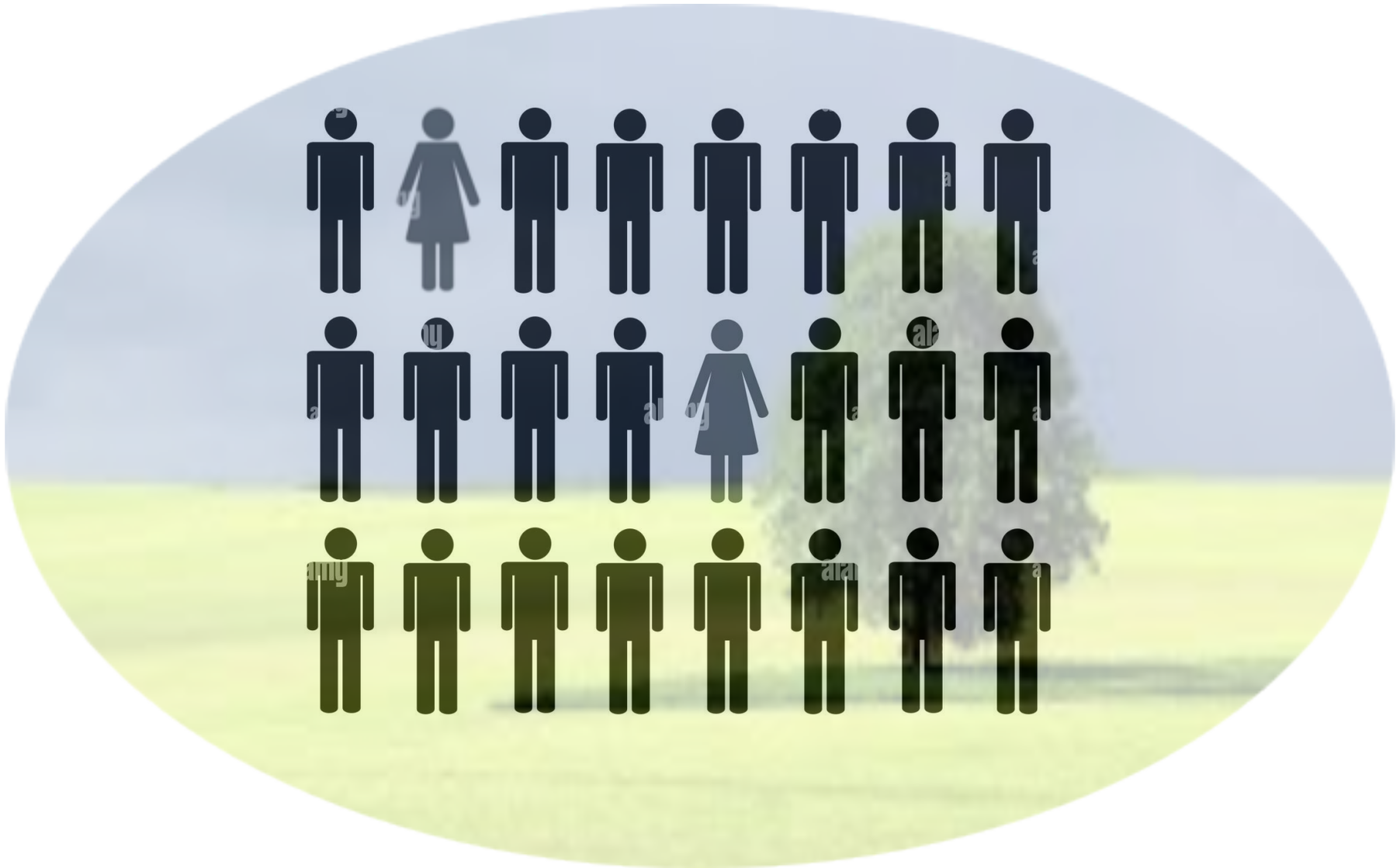
Diversity in the string theory landscape

Mariana Graña

Institut de Physique Théorique, CEA / Saclay
Université de Paris-Saclay

Beate Naroska Celebration, April 23 2024

The string theory landscape



Looking for a more diverse landscape:

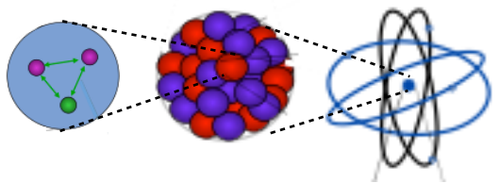
Special thank to Beate Naroska initiative!

Why string theory ?

Why string theory ?

strong force

electroweak force



10^{-15} m

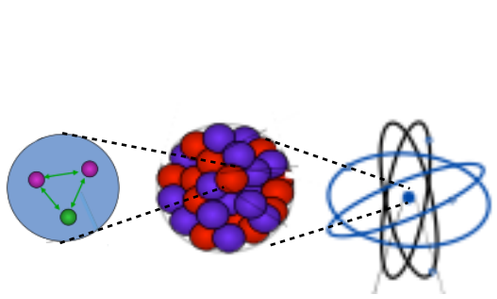
10^{-10} m

Why string theory ?

gravitational force

strong force

electroweak force



10^{-15} m

10^{-10} m

1 m

10^{6} m

10^{12} m

10^{18} m

Why string theory ?

Quantum mechanics (QED, QCD)

strong force

electroweak force

gravitational force

10^{-15} m

10^{-10} m

1 m

10^{6} m

10^{12} m

10^{18} m

Why string theory ?

Quantum mechanics (QED, QCD)

General relativity

strong force

electroweak force

gravitational force

10^{-15} m

10^{-10} m

1 m

10^{6} m

10^{12} m

10^{18} m

Why string theory ?

Quantum mechanics ***General relativity***

strong force

electroweak force

gravitational force

10^{-15} m 10^{-10} m 1 m 10^{6} m 10^{12} m 10^{18} m

Why string theory ?

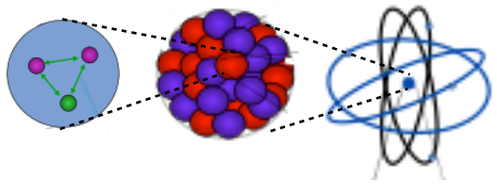
Quantum mechanics

General relativity

strong force

electroweak force

gravitational force



10^{-15} m

10^{-10} m

1 m

10^{6} m

10^{12} m

10^{18} m

Why string theory ?

Quantum mechanics + **General relativity**

Non-renormalizable:
∞ number of counter-terms

strong force

electroweak force

gravitational force

10^{-15} m

10^{-10} m

1 m

10^{6} m

10^{12} m

10^{18} m

Why string theory ?

Quantum mechanics (QED, QCD)

General relativity

strong force

electroweak force

gravitational force

10^{-15} m

10^{-10} m

1 m

10^{6} m

10^{12} m

10^{18} m

Why string theory ?

Quantum mechanics (QED, QCD)

General relativity

strong force

electroweak force

gravitational force

10^{-15} m

10^{-10} m

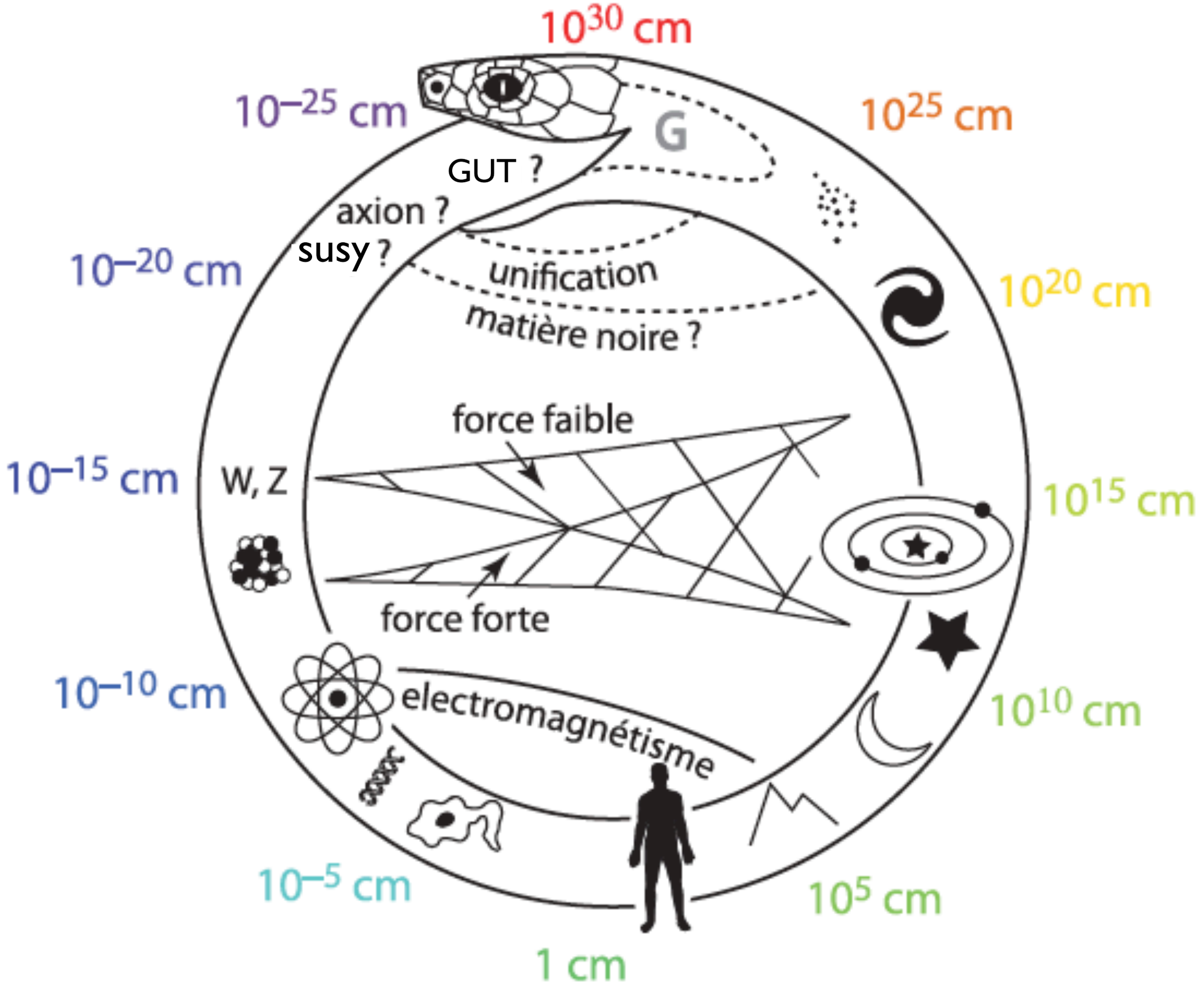
1 m

10^{6} m

10^{12} m

10^{18} m

We could be happy with two theories, except…


10^{30} cm
10^{-25} cm
10^{25} cm
G
GUT ?
axion ?
susy ?
10^{-20} cm
10^{20} cm
unification
matière noire ?
force faible
10^{-15} cm
W, Z
10^{15} cm
force forte
10^{-10} cm
électromagnétisme
10^{10} cm
10^{-5} cm
10^{5} cm
1 cm

Since a naive theory of quantum gravity does not work…

Since a naive theory of quantum gravity does not work…

We have to think radically differently

Since a naive theory of quantum gravity does not work…

We have to think radically differently

Since a naive theory of quantum gravity does not work…

We have to think radically differently

Quantisation should be done in a different way

(e.g. non-pertubatively)

Since a naive theory of quantum gravity does not work…

We have to think radically differently

Quantisation should be done in a different way

(e.g. non-pertubatively)

The basic degrees of freedom are different

Since a naive theory of quantum gravity does not work…

We have to think radically differently

Quantisation should be done in a different way

(e.g. non-pertubatively)

The basic degrees of freedom are different

String theory

Since a naive theory of quantum gravity does not work…

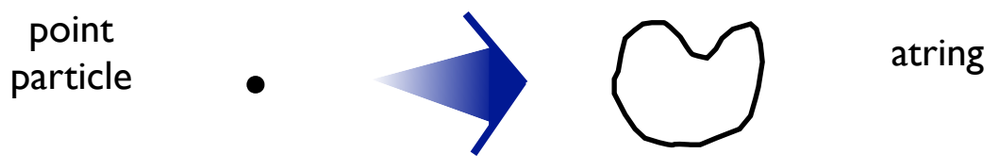
We have to think radically differently

Quantisation should be done in a different way

(e.g. non-pertubatively)

The basic degrees of freedom are different

String theory



Since a naive theory of quantum gravity does not work…

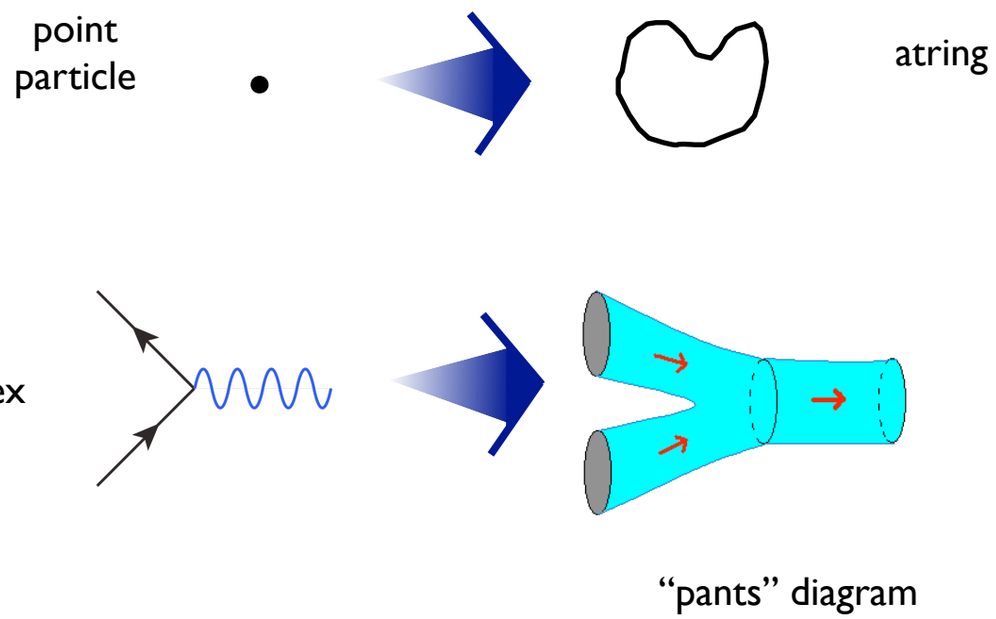
We have to think radically differently

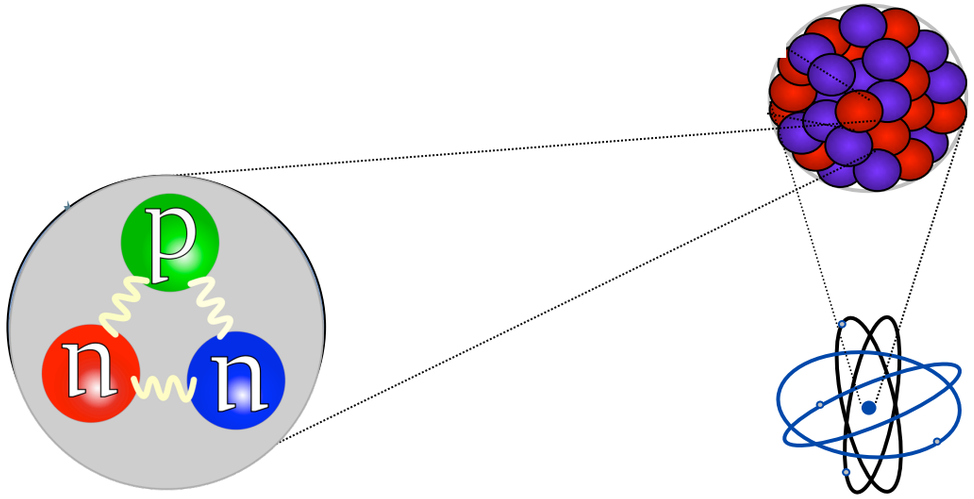
Quantisation should be done in a different way

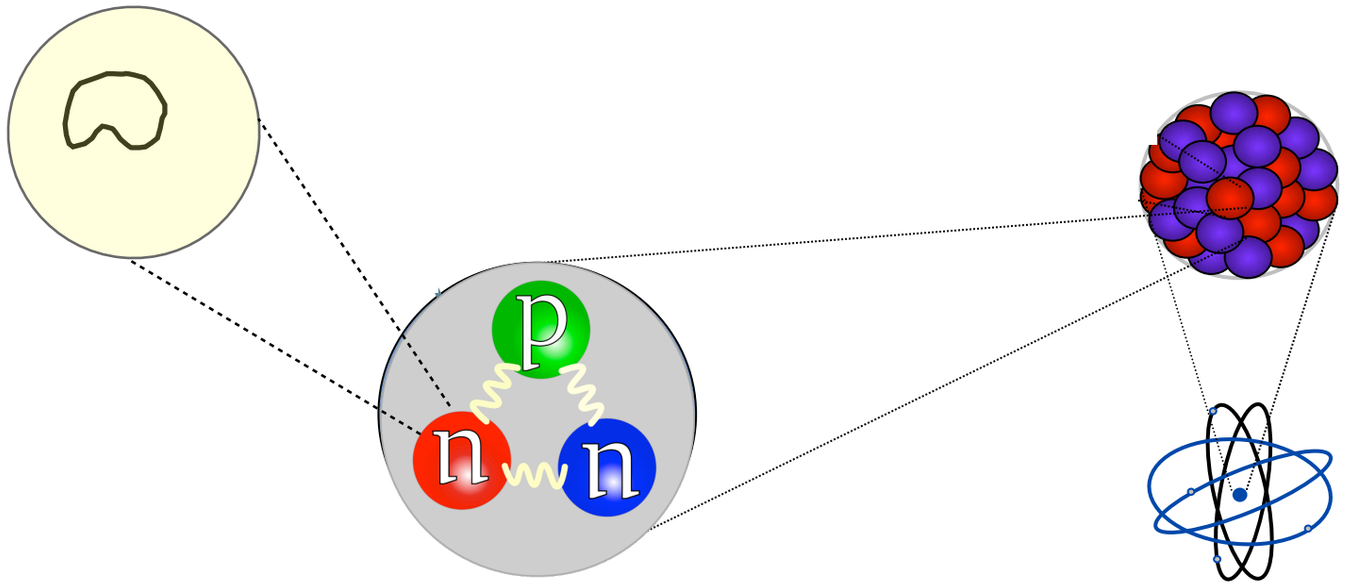
(e.g. non-pertubatively)

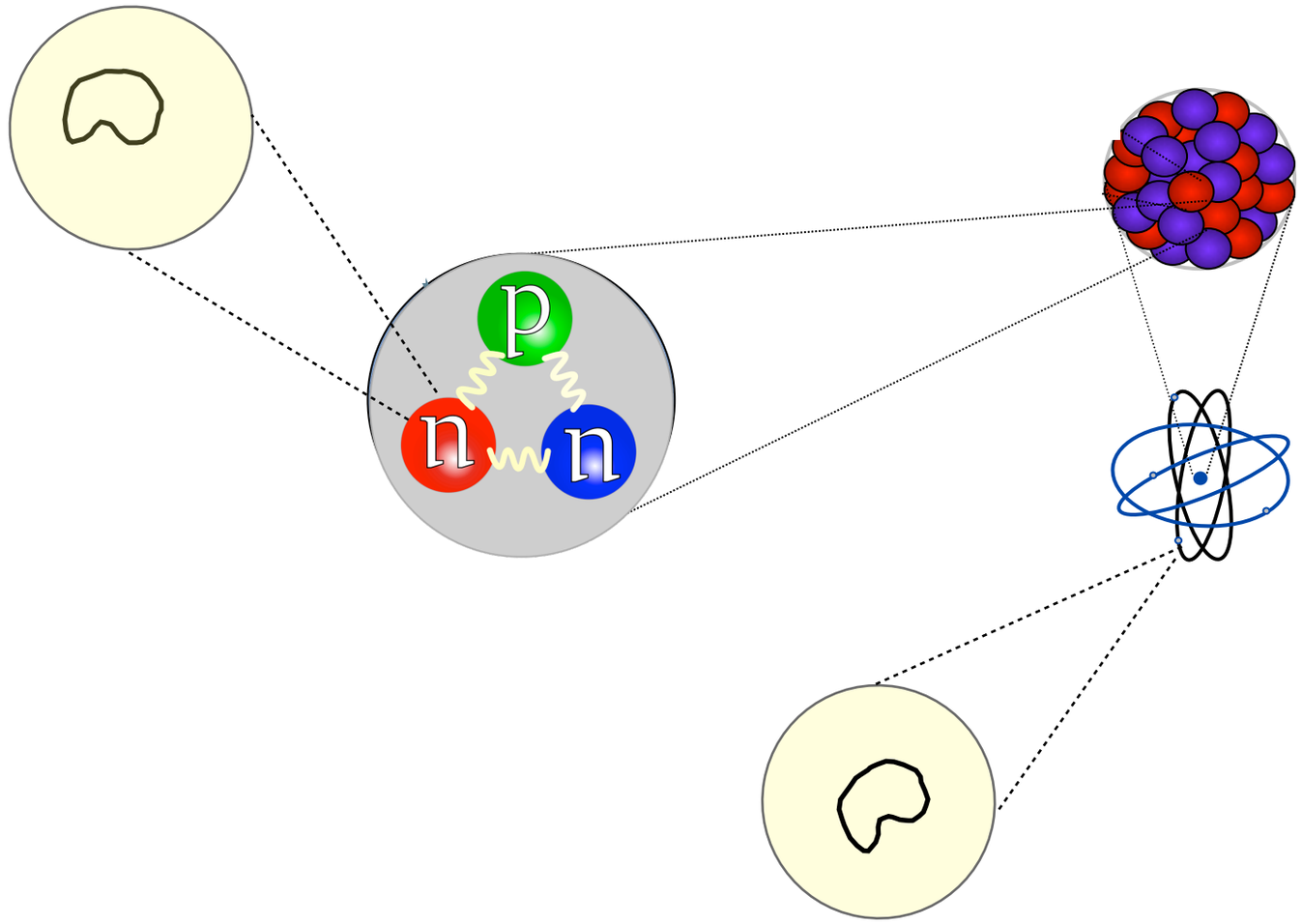
The basic degrees of freedom are different

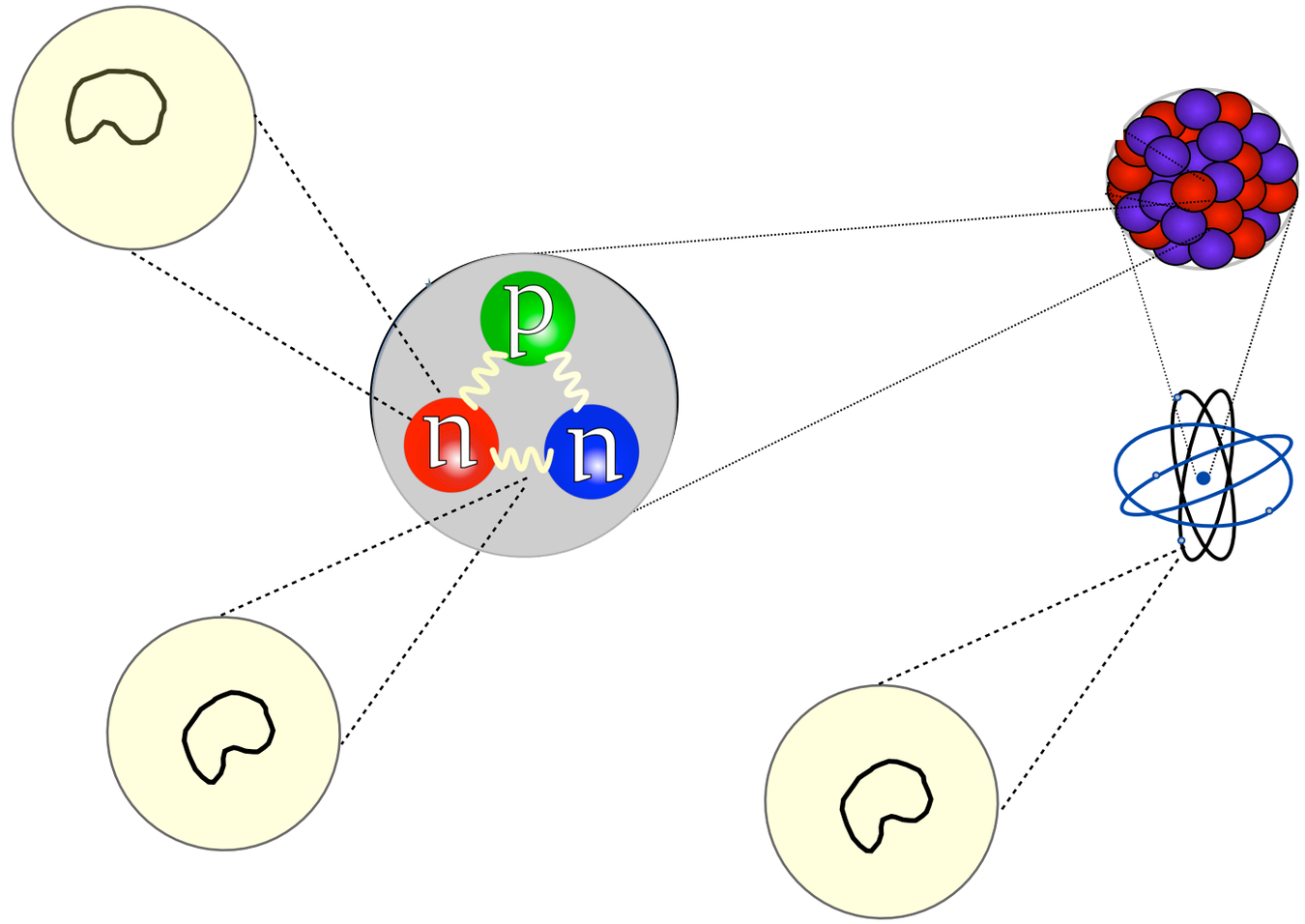
String theory

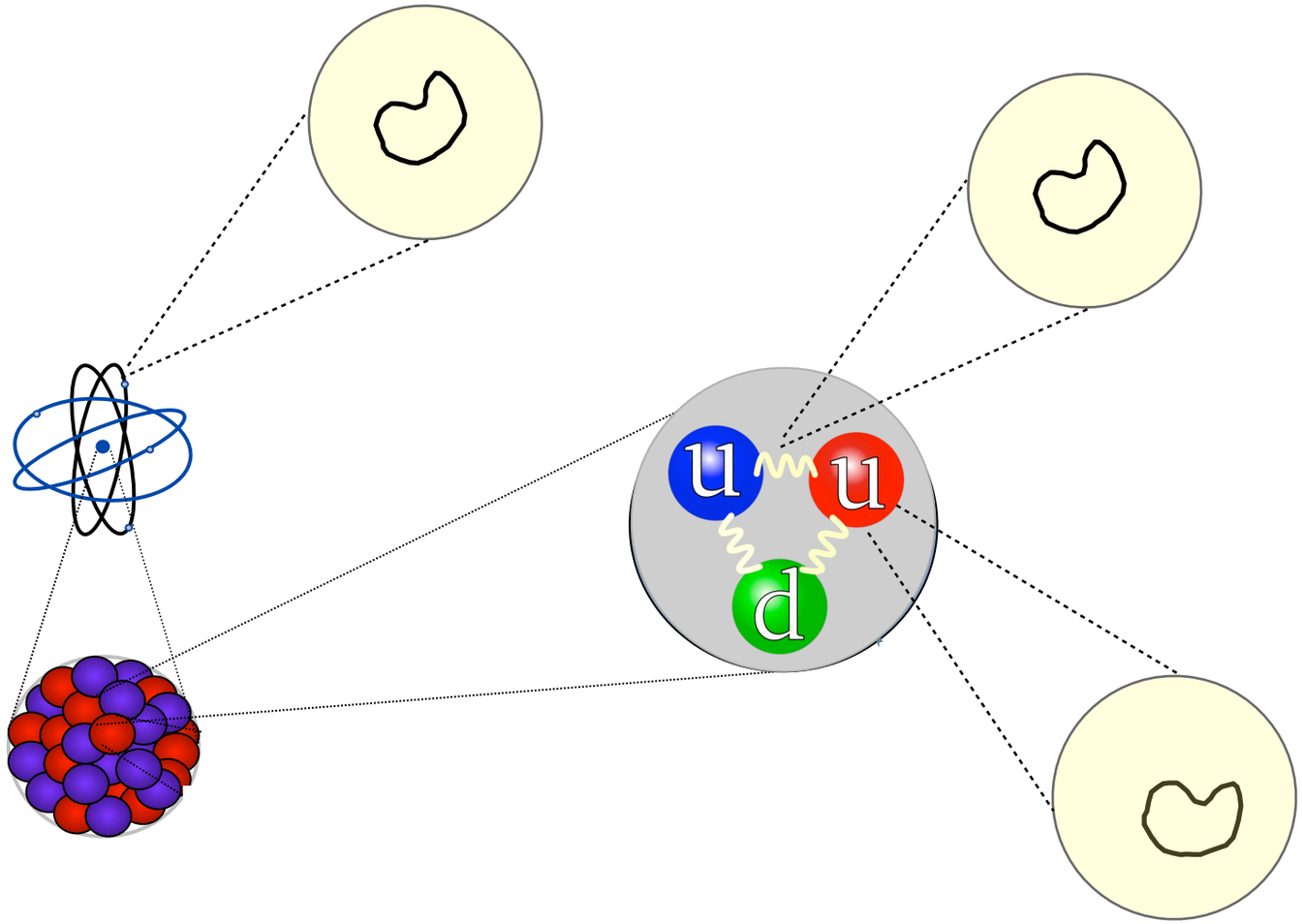


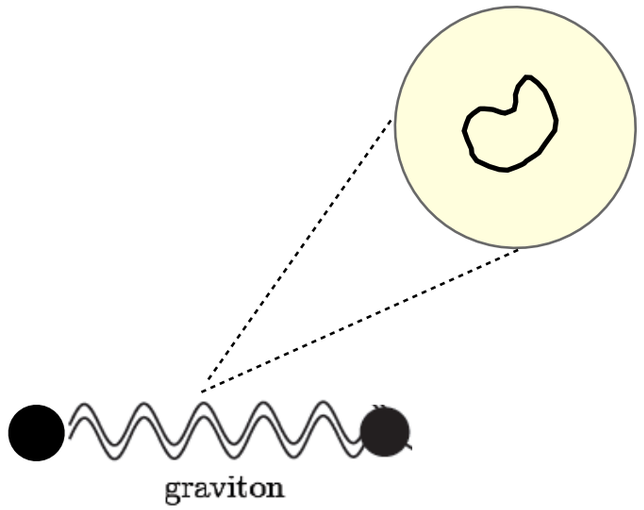

p
n
n

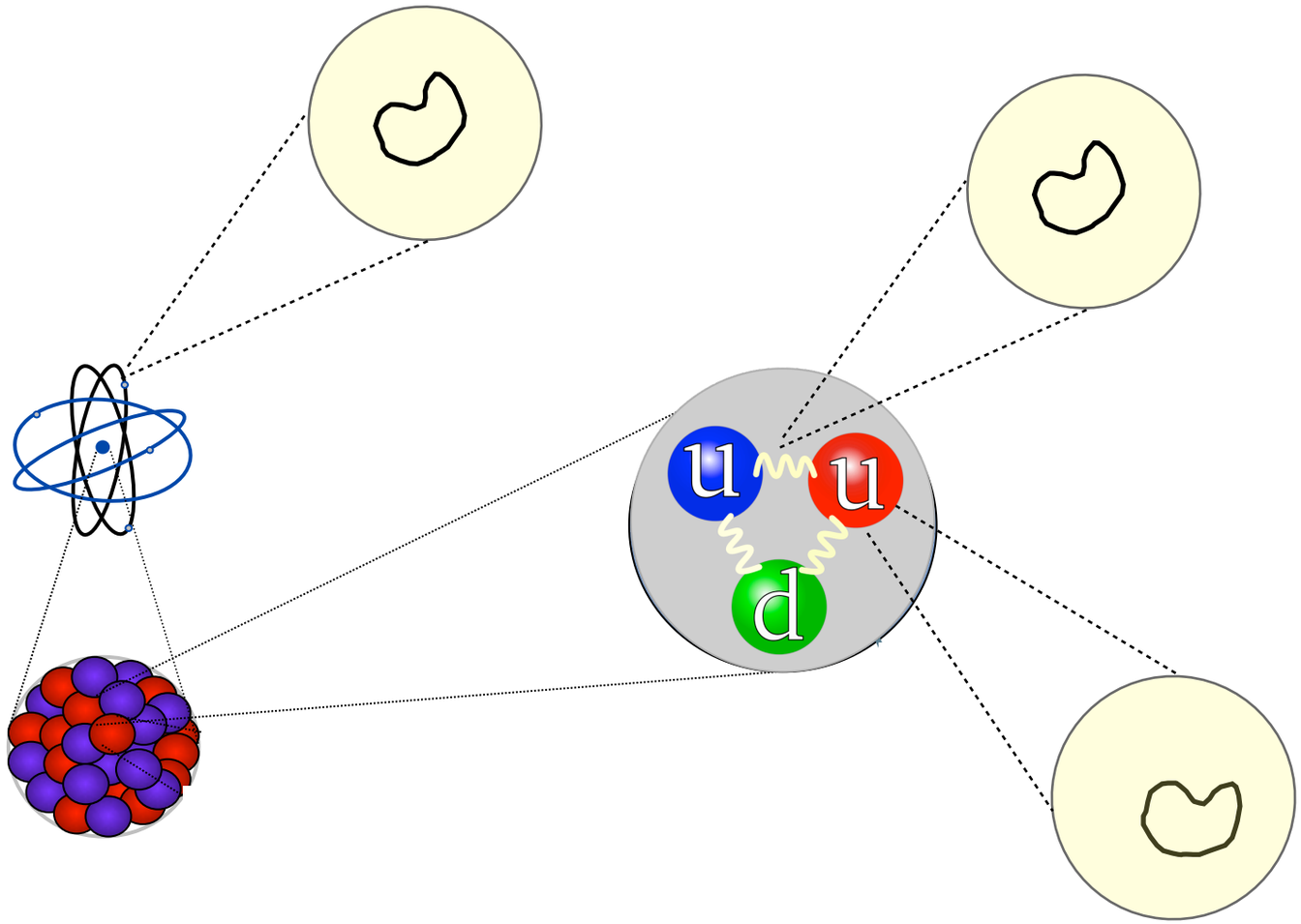

p
n
n

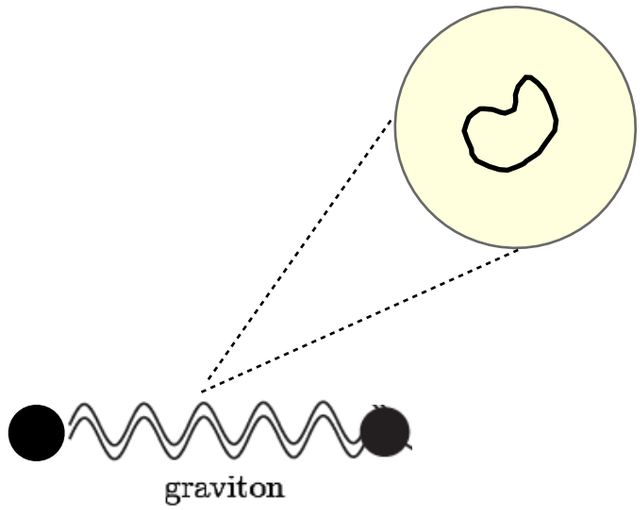

p
n
n


p
n
n

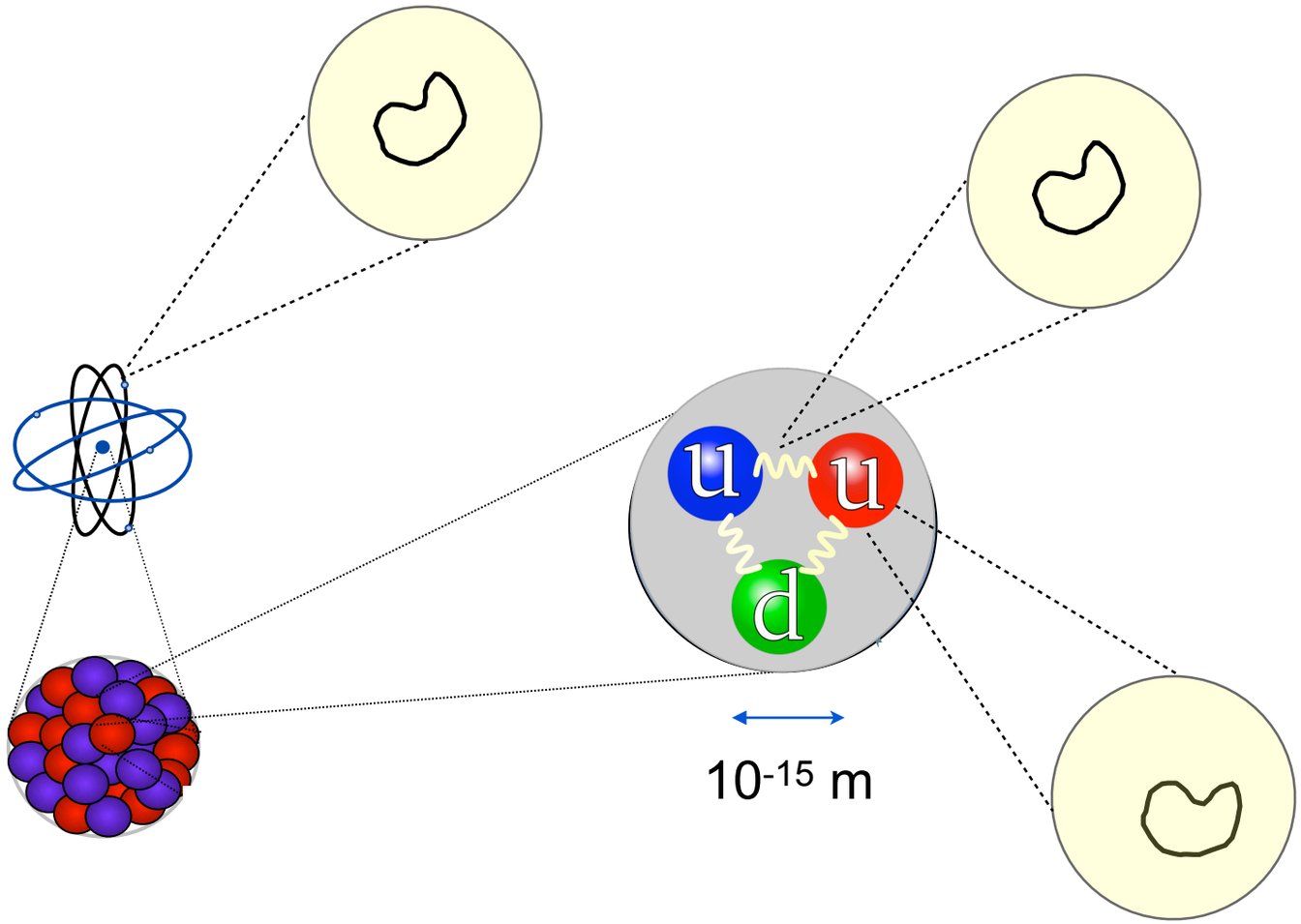

u
u
d

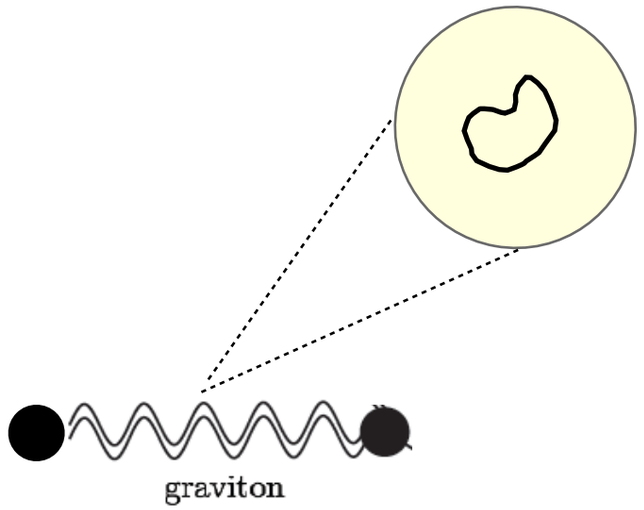

graviton



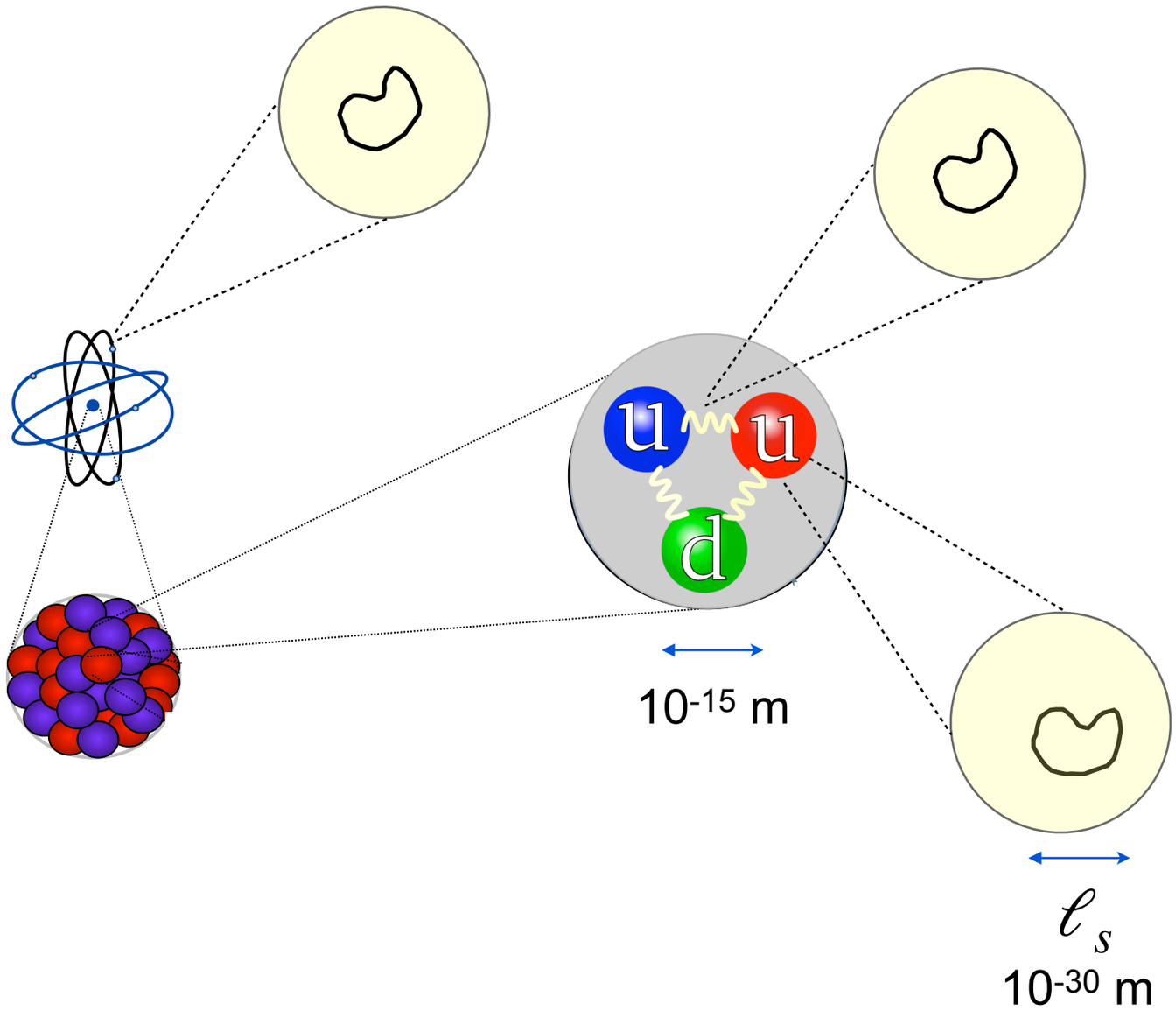


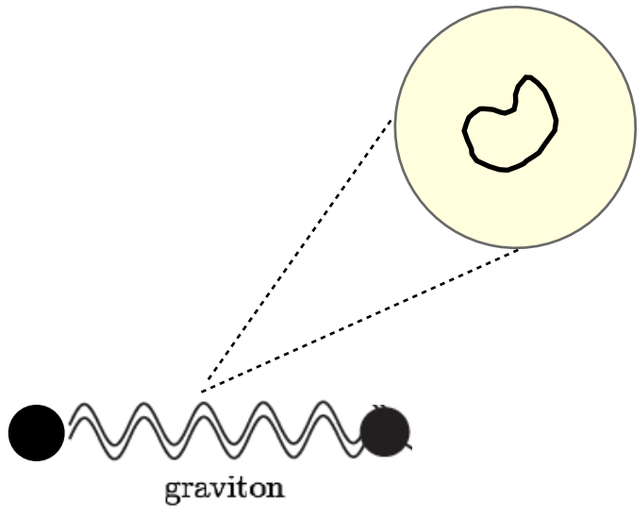
They are all strings!



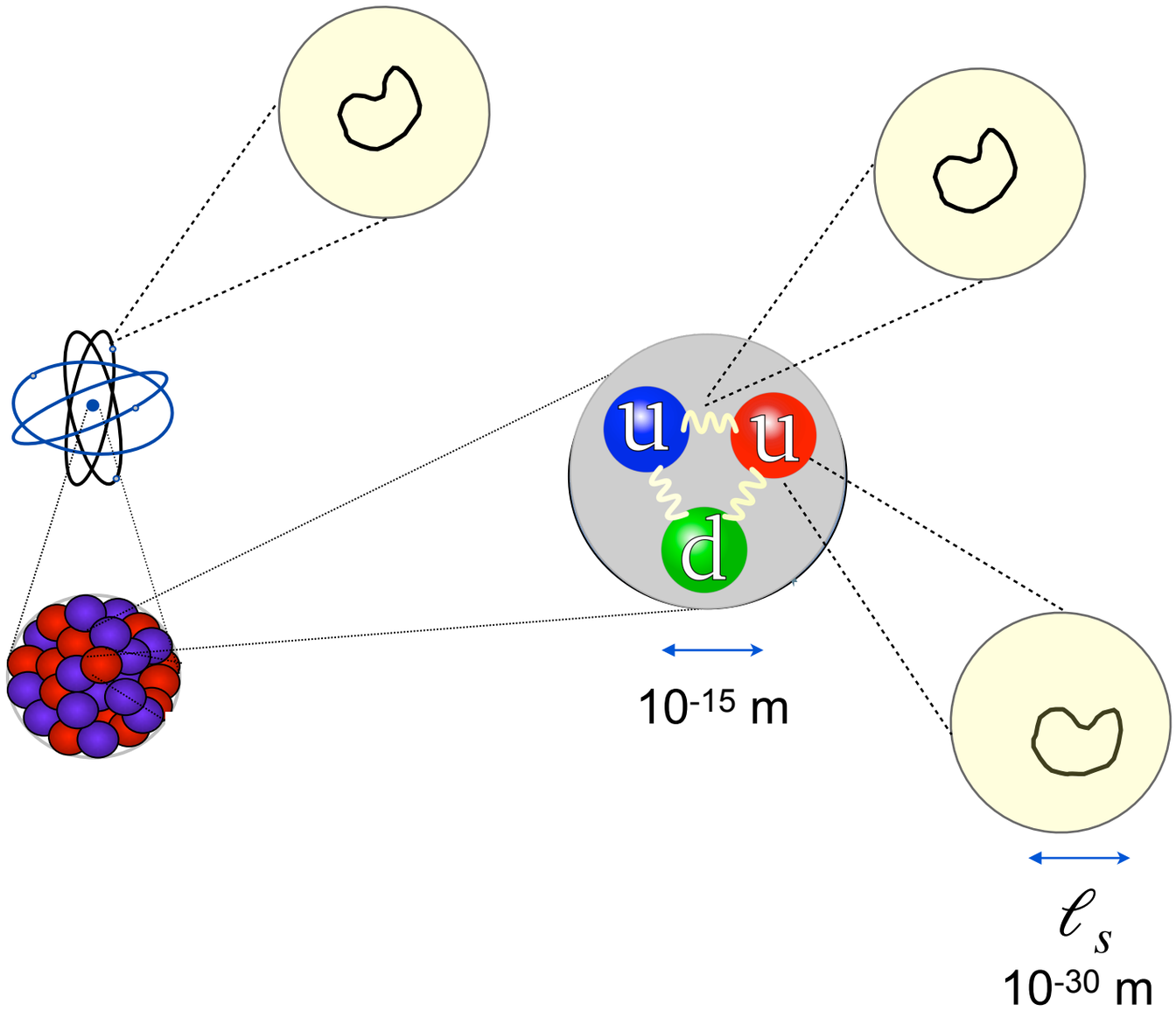


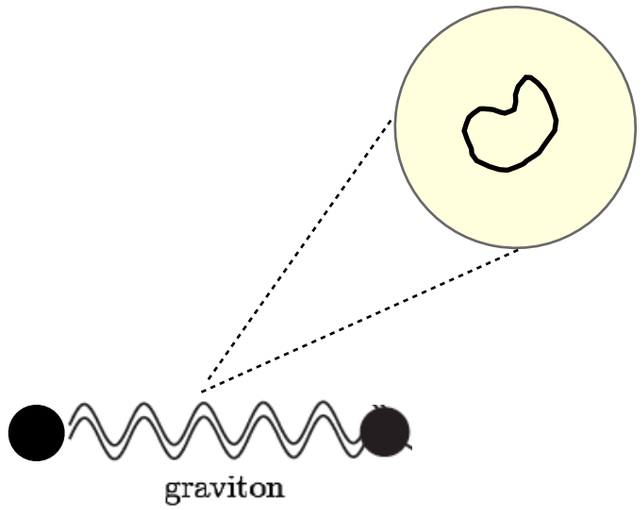
They are all strings!





They are all strings!





They are all strings!

They are so small that we cannot observe them directly

String theory

- A remarkable theory of quantum gravity, calculable

String theory

- A remarkable theory of quantum gravity, calculable
- Its spectrum contains the graviton, gauge fields, fermions and scalars

String theory

- A remarkable theory of quantum gravity, calculable
- Its spectrum contains the graviton, gauge fields, fermions and scalars
- First superstring revolution ('85): quantum consistency

String theory

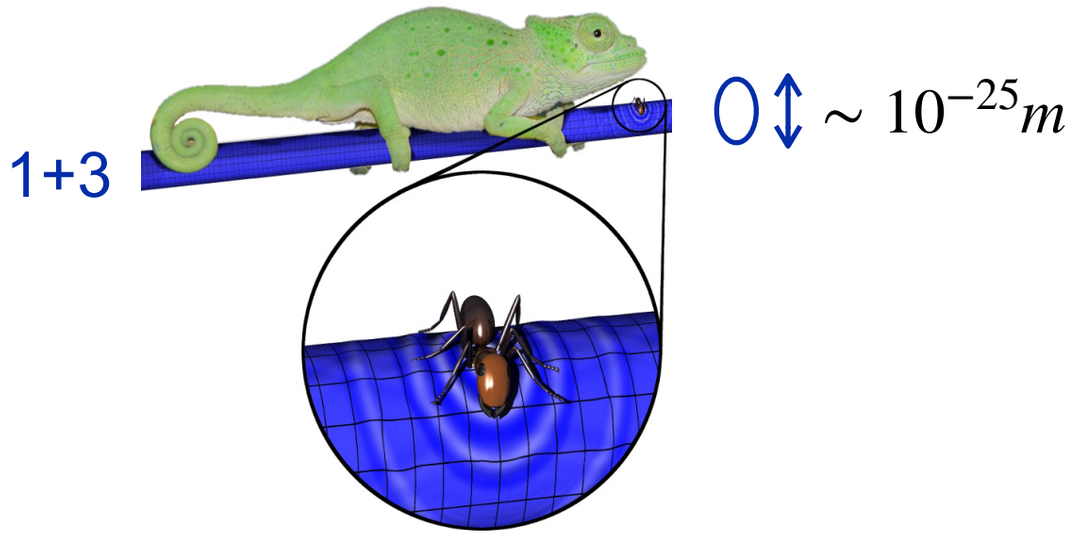
- A remarkable theory of quantum gravity, calculable
- Its spectrum contains the graviton, gauge fields, fermions and scalars
- First superstring revolution ('85): quantum consistency if…

String theory

- A remarkable theory of quantum gravity, calculable
- Its spectrum contains the graviton, gauge fields, fermions and scalars
- First superstring revolution ('85): quantum consistency if… there are 10 space-time dimensions!

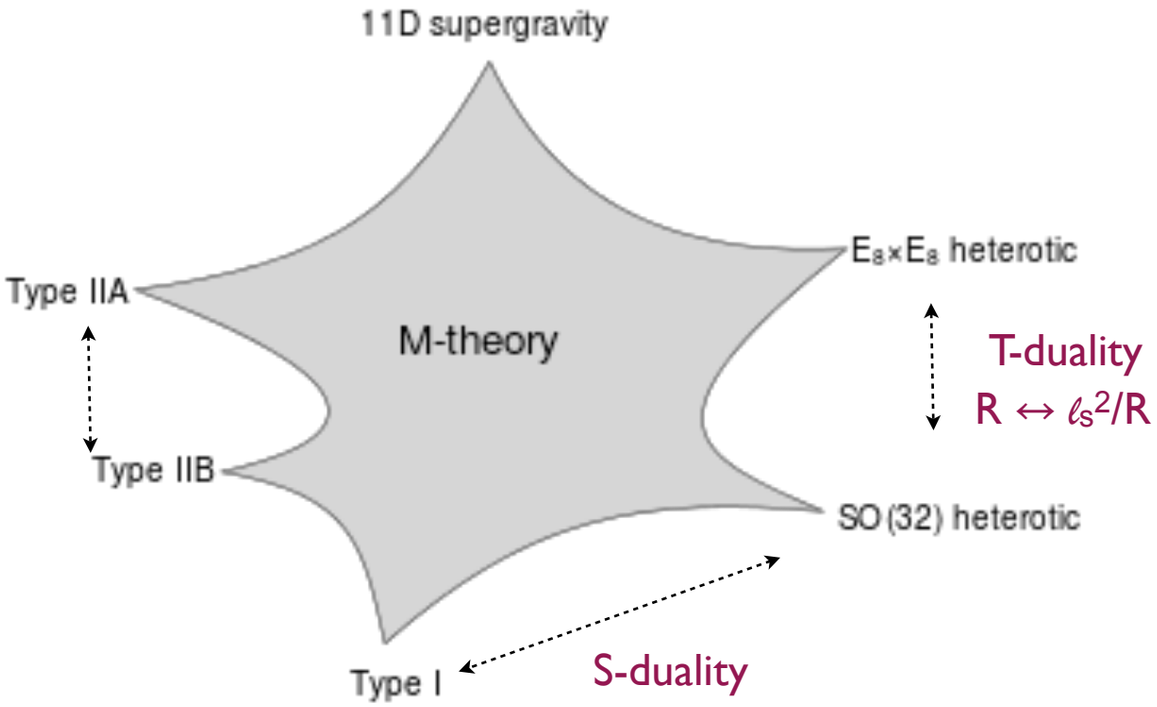
String theory

- A remarkable theory of quantum gravity, calculable
- Its spectrum contains the graviton, gauge fields, fermions and scalars
- First superstring revolution ('85): quantum consistency if… there are 10 space-time dimensions!



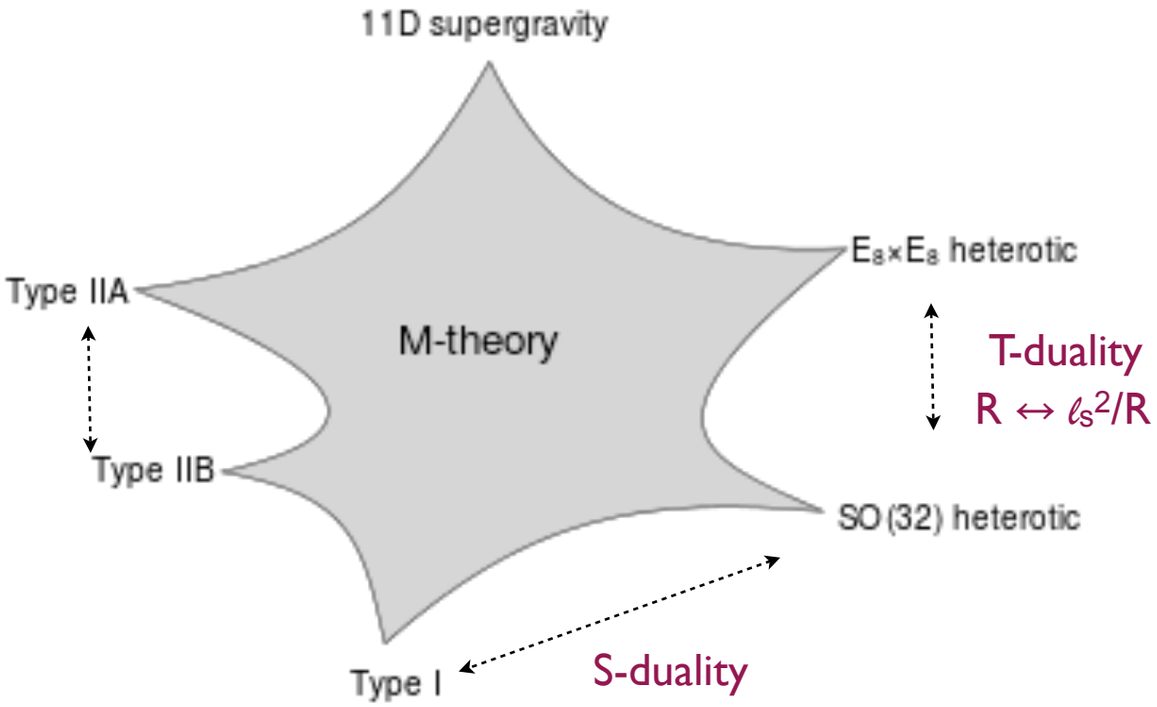
String theory

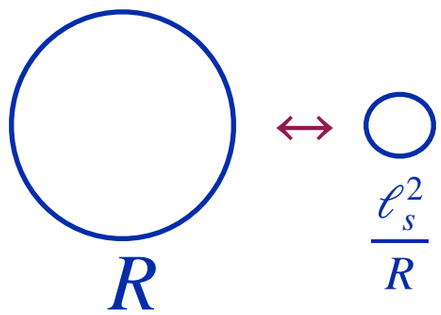
- Second superstring revolution (‘95): unique theory!



String theory

- Second superstring revolution (‘95): unique theory!



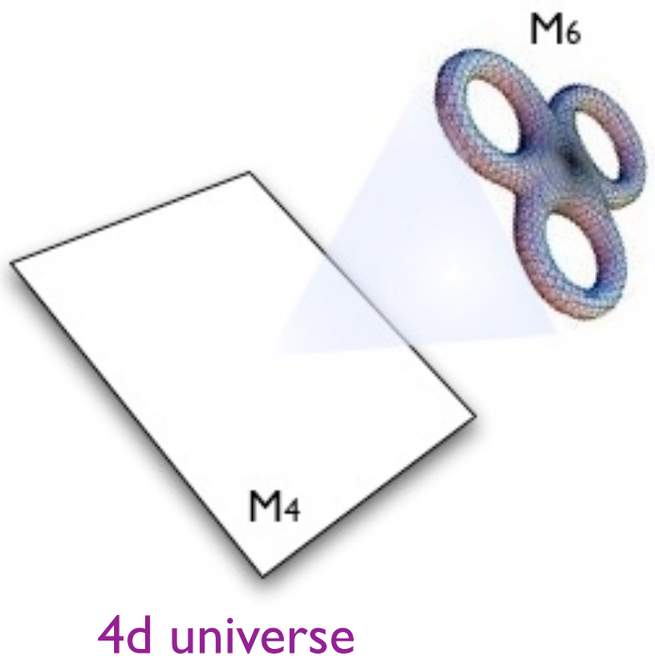


But

Consistent and **Unique** theory in10 d

6d compact space

$M_{10}=M_4 \times M_6$



4d universe

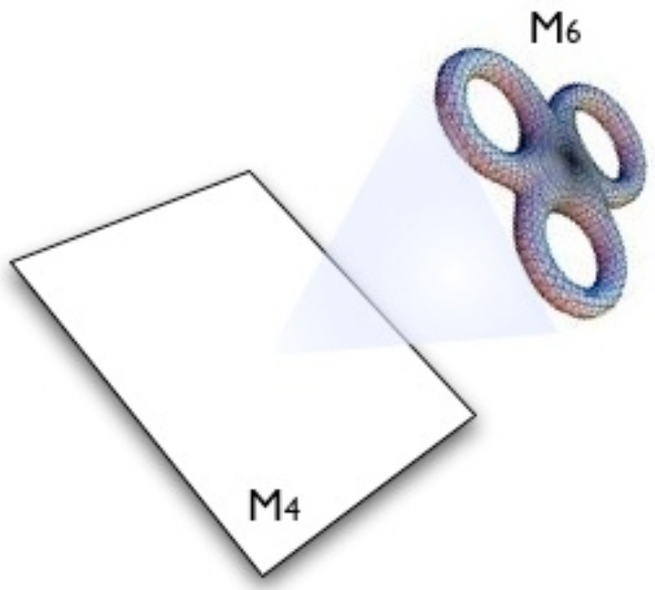
Geometry of M_6 determines physics in 4d

But

Consistent and **Unique** theory in10 d

6d compact space

$M_{10}=M_4 \times M_6$



4d universe

Geometry of M_6 determines physics in 4d

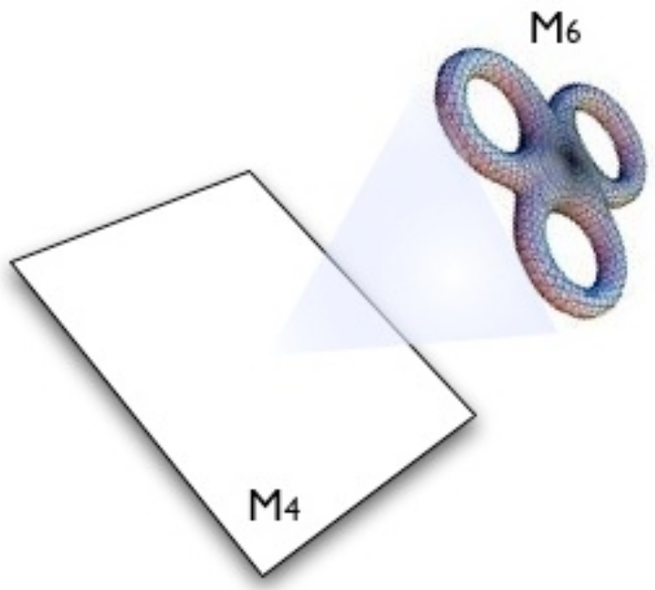
Multiple possibilities

But

Consistent and **Unique** theory in10 d

6d compact space

$M_{10}=M_4 \times M_6$



4d universe

Geometry of M_6 determines physics in 4d

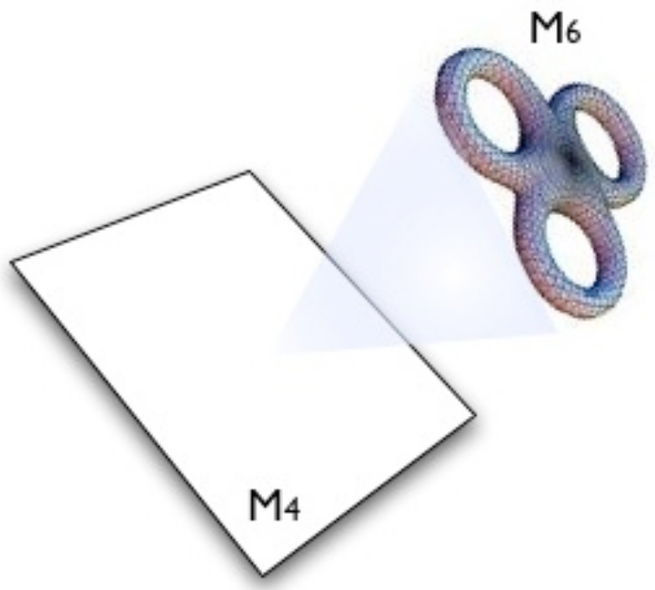
Multiple possibilities :10^{500}

But

Consistent and **Unique** theory in10 d

6d compact space

$M_{10}=M_4 \times M_6$



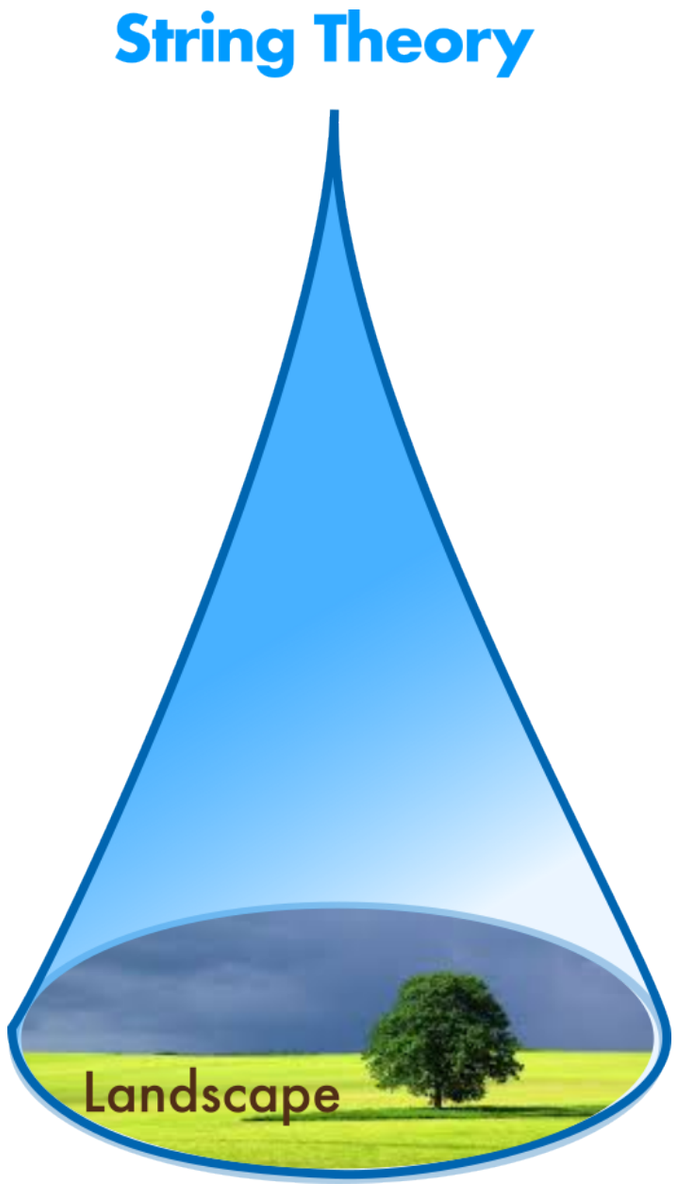
Geometry of M_6 determines physics in 4d

4d universe

Multiple possibilities :10^{500}

Landscape of possible 4d "universes"

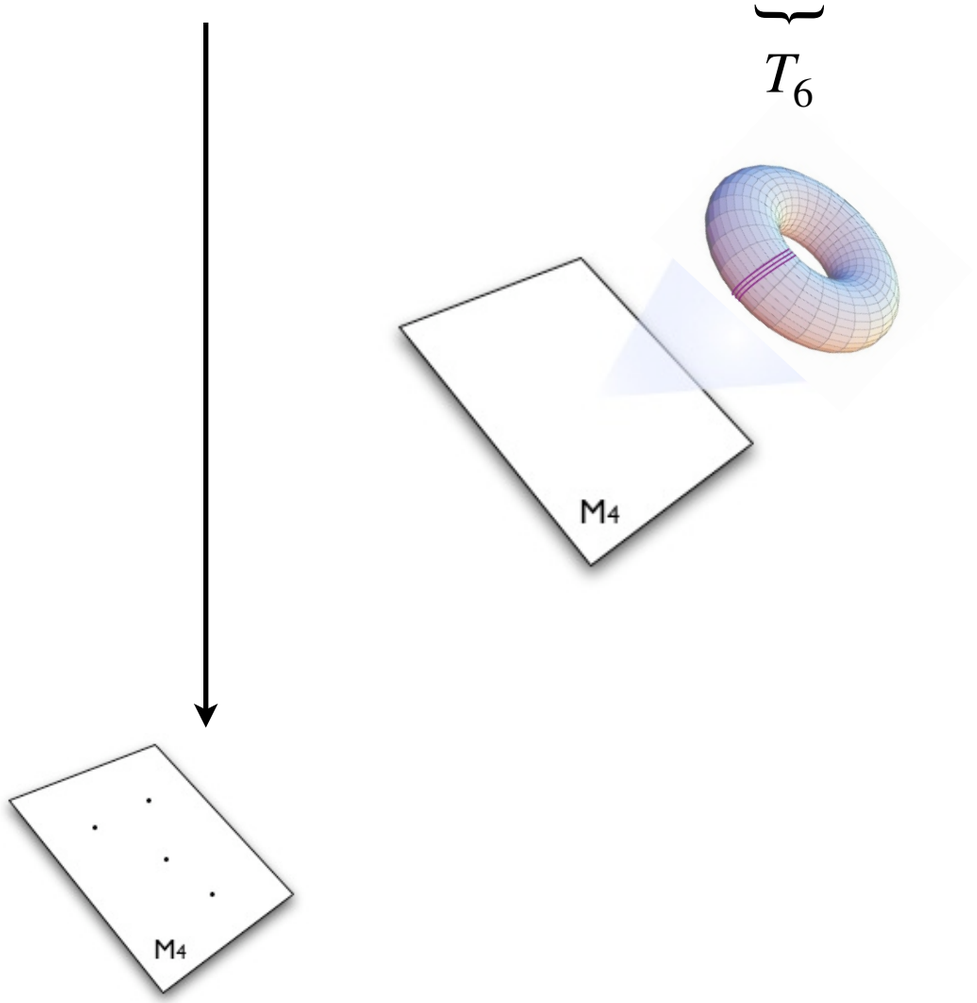
The string theory landscape



Simplest exemple

10 d

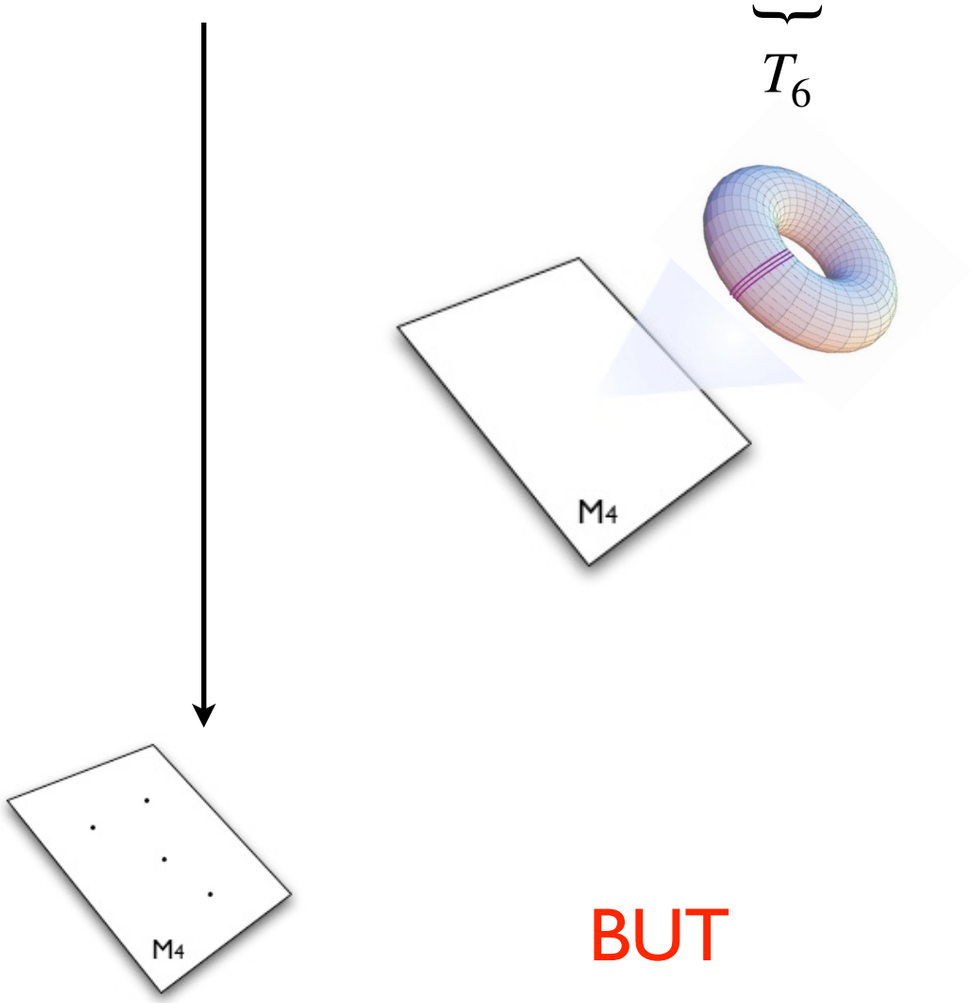
$$M_{10} = M_4 \times \underbrace{M_6}_{T_6}$$



Simplest exemple

10 d

$$M_{10} = M_4 \times \underbrace{M_6}_{T_6}$$



BUT

→ supersymmetric spectrum

→ no cosmological constant

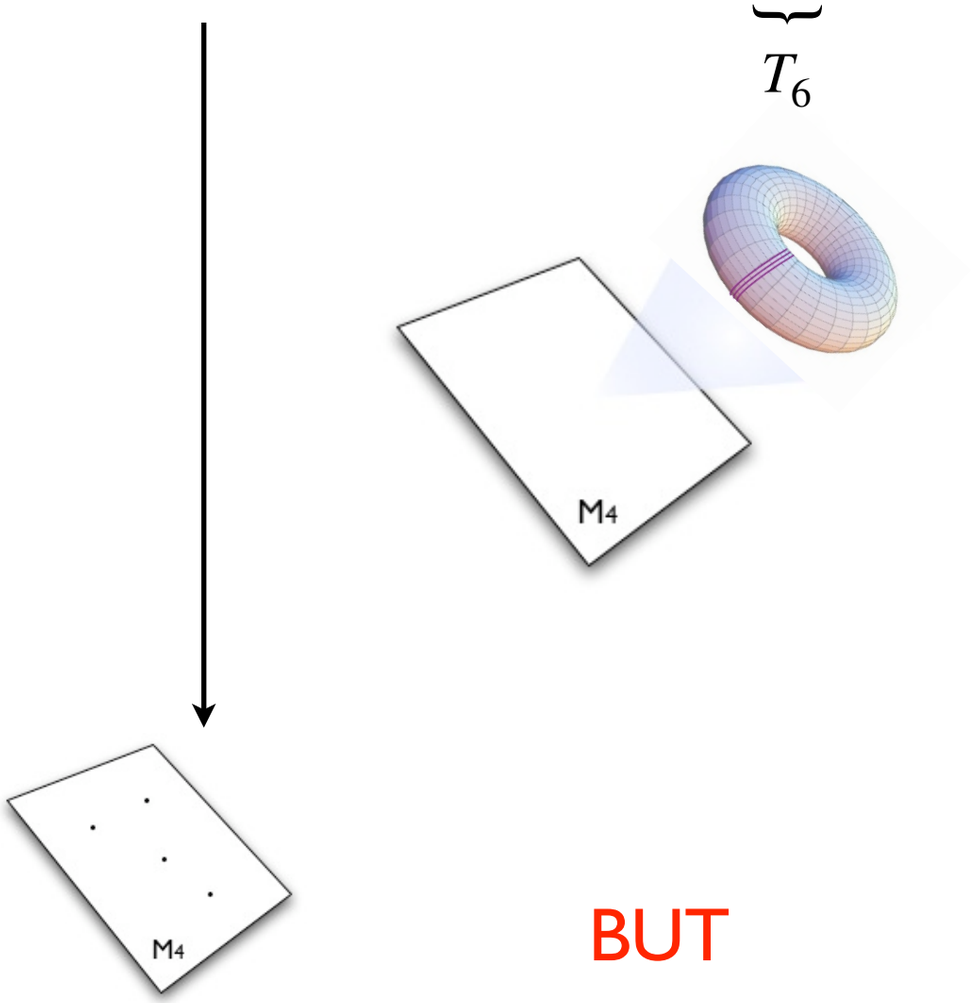
→ Massless scalar particles

(radii of circles, can be changed at no cost)

Simplest exemple

10 d

$$M_{10} = M_4 \times \underbrace{M_6}_{T_6}$$



BUT

→ supersymmetric spectrum

→ no cosmological constant

→ Massless scalar particles

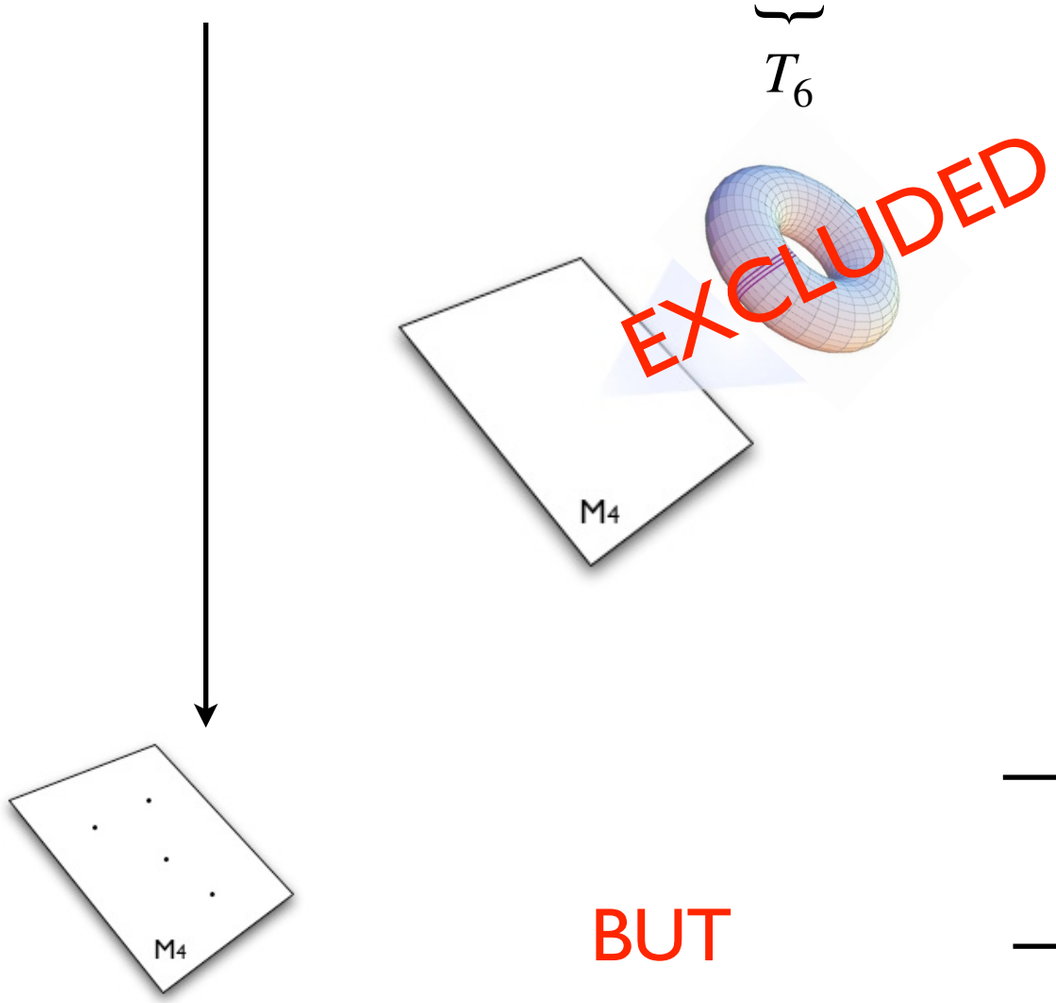
(radii of circles, can be changed at no cost)

Would lead to unobserved long-range fifth force(s)

Simplest exemple

10 d

$$M_{10} = M_4 \times \underbrace{M_6}_{T_6}$$



BUT

→ supersymmetric spectrum

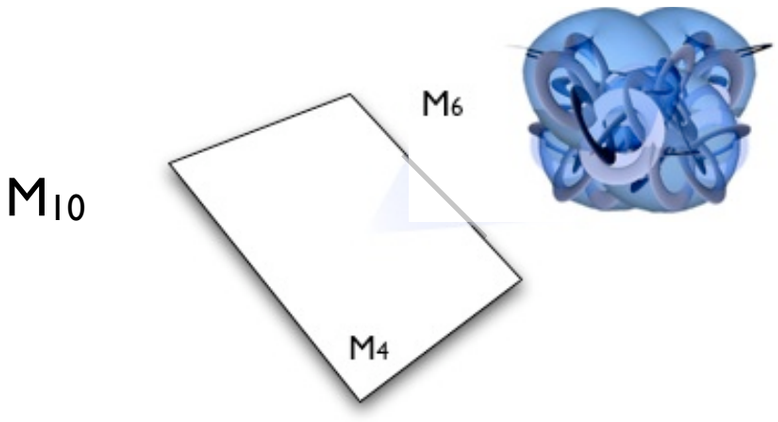
→ no cosmological constant

→ Massless scalar particles

(radii of circles, can be changed at no cost)

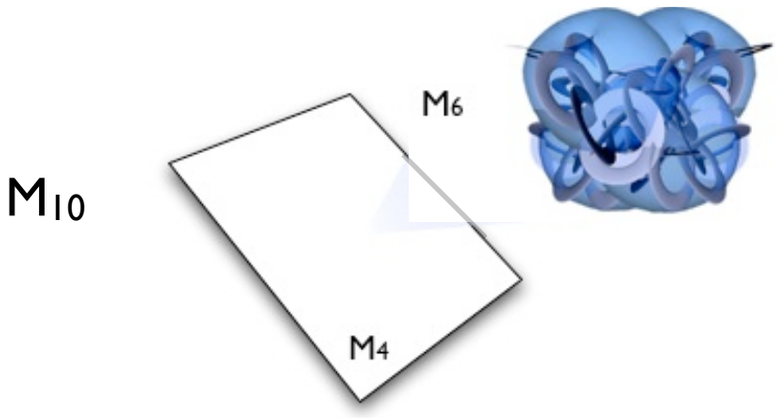
Would lead to unobserved long-range fifth force(s)

Next to simplest example:



$$M_{10} = M_4 \times M_6$$

Next to simplest example:



$$M_{10} = M_4 \times M_6$$

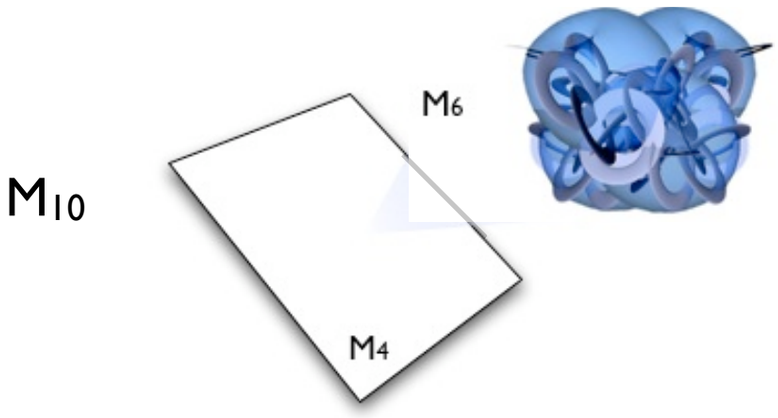
Eq. of motion:

$$E \ll M_s \lesssim M_P$$

M_6 : R_{mn}=0 Ricci-flat

Calabi-Yau manifolds

Next to simplest example:



$$M_{10} = M_4 \times M_6$$

Eq. of motion:

$$E \ll M_s \lesssim M_P$$

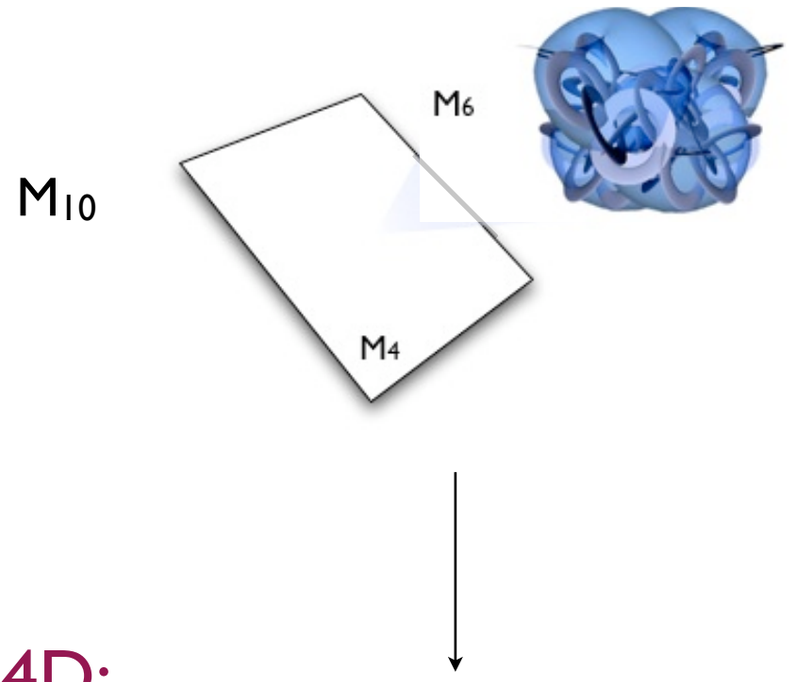
M_6 : R_{mn}=0 Ricci-flat

Calabi-Yau manifolds

4D:

Still supersymmetric (less than for tori, $\mathcal{N} = 1$)

Next to simplest example:



$$M_{10} = M_4 \times M_6$$

Eq. of motion:

$$E \ll M_s \lesssim M_P$$

M_6 : R_{mn}=0 Ricci-flat

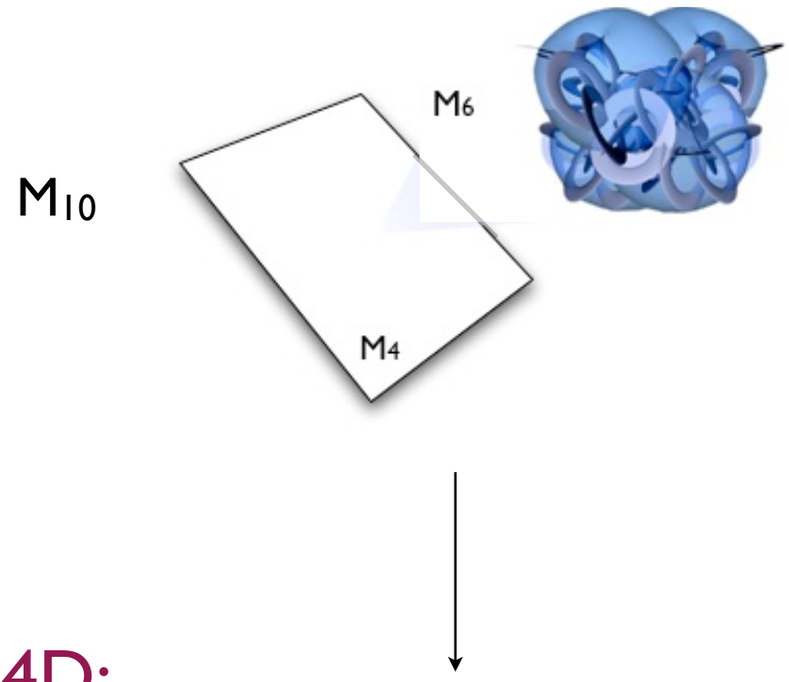
Calabi-Yau manifolds

4D:

Still supersymmetric (less than for tori, $\mathcal{N} = 1$)

Massless particles (e.g. the volume)

Next to simplest example:



$$M_{10} = M_4 \times M_6$$

Eq. of motion:

$$E \ll M_s \lesssim M_P$$

M_6 : R_{mn}=0 Ricci-flat

Calabi-Yau manifolds

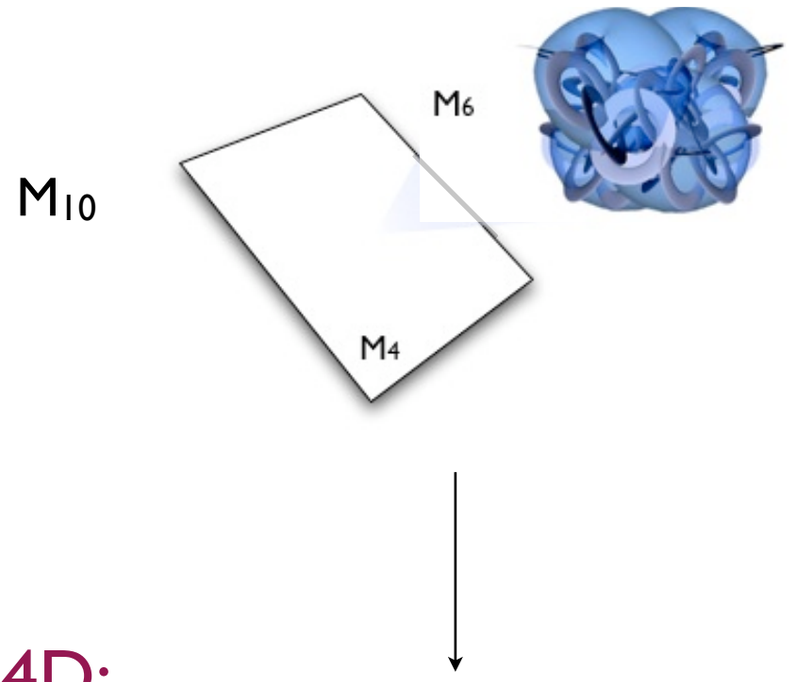
4D:

Still supersymmetric (less than for tori, $\mathcal{N} = 1$)

Massless particles (e.g. the volume)

4D space-time= Minkowski (no cosmological constant)

Next to simplest example:



$$M_{10} = M_4 \times M_6$$

Richer than tori, can overcome problems

Eq. of motion:

$$E \ll M_s \lesssim M_P$$

M_6 : R_{mn}=0 Ricci-flat

Calabi-Yau manifolds

4D:

Still supersymmetric (less than for tori, $\mathcal{N} = 1$)

Massless particles (e.g. the volume)

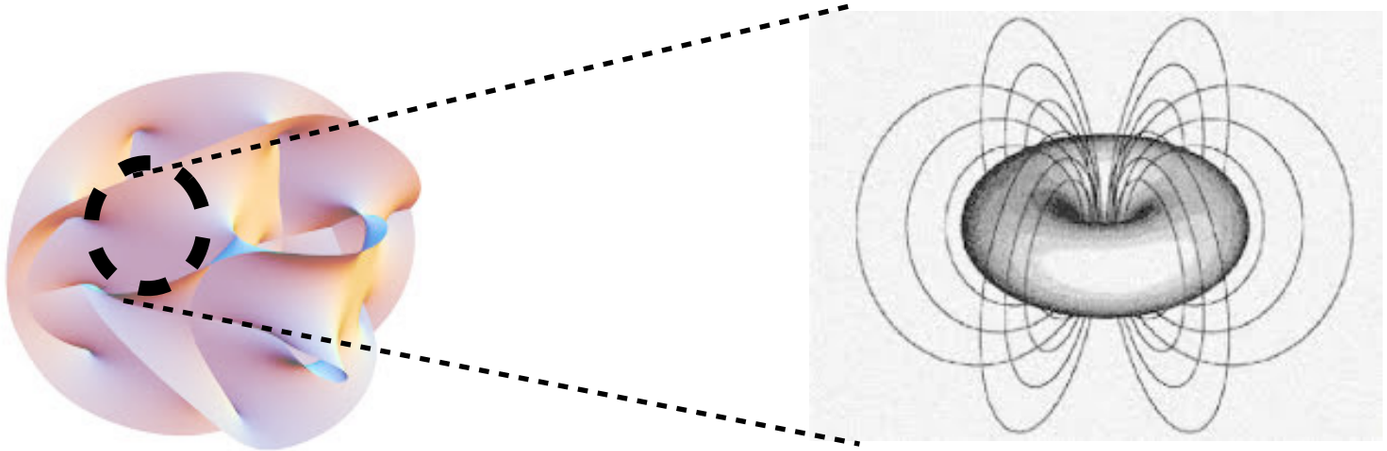
4D space-time= Minkowski (no cosmological constant)

How to avoid massless scalar particles?

Add fluxes

How to avoid massless scalar particles?

Add fluxes



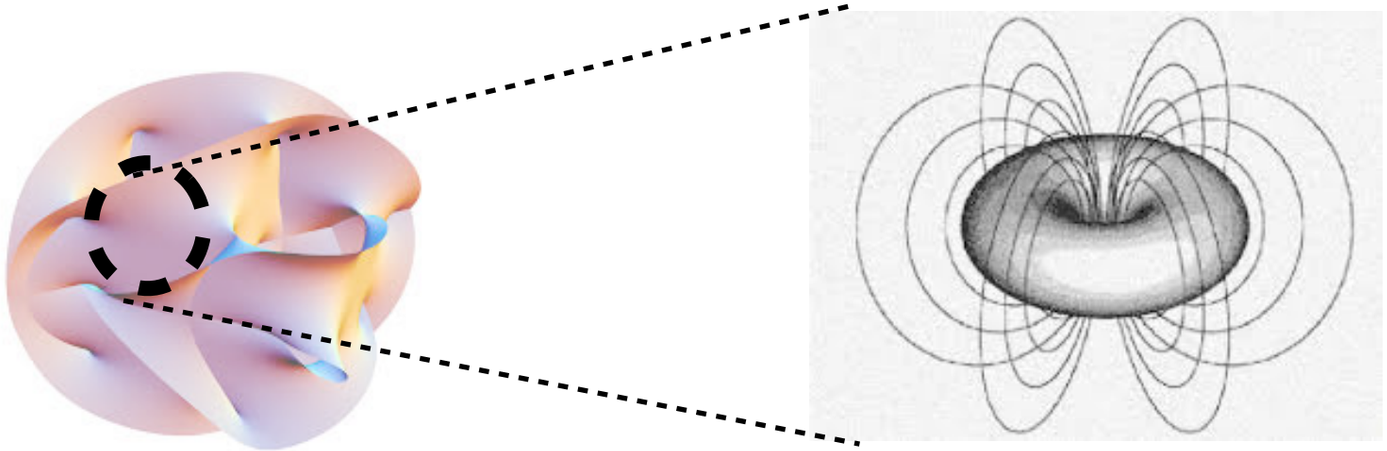
flux

fixed radius where gravitational attraction = electromagnetic repulsion

M. Graña, "Flux compactifications in string theory: a comprehensive review"
Phys. Repts, 2006

How to avoid massless scalar particles?

Add fluxes



flux

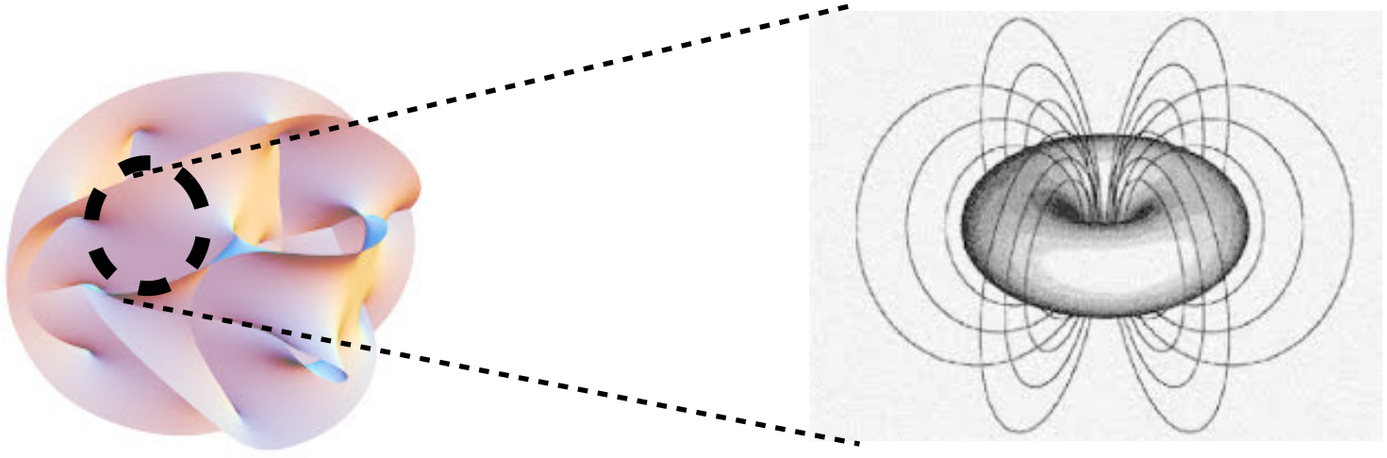
fixed radius where gravitational attraction = electromagnetic repulsion

M. Graña, "Flux compactifications in string theory: a comprehensive review"
Phys. Repts, 2006

Fluxes can also break supersymmetry!

How to avoid massless scalar particles?

Add fluxes



flux

fixed radius where gravitational attraction = electromagnetic repulsion

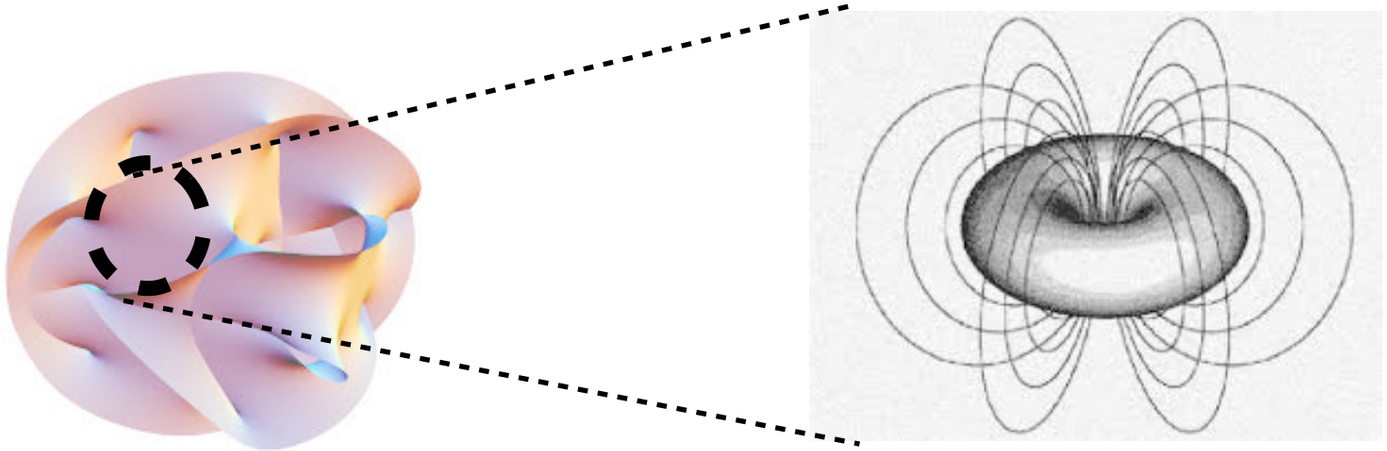
M. Graña, "Flux compactifications in string theory: a comprehensive review"
Phys. Repts, 2006

Fluxes can also break supersymmetry!

Large number (finite?) of 6d CY and (for each of them) 10^{500} possible flux configurations below the upper bound given by "tadpole cancelation"

How to avoid massless scalar particles?

Add fluxes



flux

fixed radius where gravitational attraction = electromagnetic repulsion

M. Graña, "Flux compactifications in string theory: a comprehensive review"
Phys. Repts, 2006

Fluxes can also break supersymmetry!

Large number (finite?) of 6d CY and (for each of them) 10^{500} possible flux configurations below the upper bound given by "tadpole cancelation"

Landscape of possibles 4d universes

But: as is, this is still far from our universe, which has

But: as is, this is still far from our universe, which has

- Standard Model of particles

- Positive cosmological constant (4d de Sitter space)

But: as is, this is still far from our universe, which has

- Standard Model of particles

  1980's: We'll find THE Calabi-Yau that gives Standard Model spectrum

- Positive cosmological constant (4d de Sitter space)

But: as is, this is still far from our universe, which has

- Standard Model of particles

  1980's: We'll find THE Calabi-Yau that gives Standard Model spectrum

  2020: 10^{700} constructions with a Standard Model spectrum! (minimal supersymmetric)

- Positive cosmological constant (4d de Sitter space)

But: as is, this is still far from our universe, which has

- Standard Model of particles

  1980's: We'll find THE Calabi-Yau that gives Standard Model spectrum

  2020: 10^{700} constructions with a Standard Model spectrum! (minimal supersymmetric)

  Found using machine learning.
  Next step ~2025?: compute masses (by Yukawa couplings to Higgs): need metric of CY, itself found using machine learning)

- Positive cosmological constant (4d de Sitter space)

But: as is, this is still far from our universe, which has

- Standard Model of particles

  1980's: We'll find THE Calabi-Yau that gives Standard Model spectrum

  2020: 10^{700} constructions with a Standard Model spectrum! (minimal supersymmetric)

  Found using machine learning.
  Next step ~2025?: compute masses (by Yukawa couplings to Higgs): need metric of CY, itself found using machine learning)

- Positive cosmological constant (4d de Sitter space)

  Much more difficult!!!

  2003: generic construction for the 10^{500} possibilities

But: as is, this is still far from our universe, which has

- Standard Model of particles

  1980's: We'll find THE Calabi-Yau that gives Standard Model spectrum

  2020: 10^{700} constructions with a Standard Model spectrum! (minimal supersymmetric)

  Found using machine learning.
  Next step ~2025?: compute masses (by Yukawa couplings to Higgs): need metric of CY, itself found using machine learning)

- Positive cosmological constant (4d de Sitter space)

  Much more difficult!!!

  2003: generic construction for the 10^{500} possibilities

  Many issues found (e.g. instabilities, but not clear their end-point)

But: as is, this is still far from our universe, which has

- Standard Model of particles

  1980's: We'll find THE Calabi-Yau that gives Standard Model spectrum

  2020: 10^{700} constructions with a Standard Model spectrum! (minimal supersymmetric)

  Found using machine learning.
  Next step ~2025?: compute masses (by Yukawa couplings to Higgs): need metric of CY, itself found using machine learning)

- Positive cosmological constant (4d de Sitter space)

  Much more difficult!!!

  2003: generic construction for the 10^{500} possibilities

  Many issues found (e.g. instabilities, but not clear their end-point)

  Since 2003: Other solutions found, but far less solid

But: as is, this is still far from our universe, which has

- Standard Model of particles

  1980's: We'll find THE Calabi-Yau that gives Standard Model spectrum

  2020: 10^{700} constructions with a Standard Model spectrum! (minimal supersymmetric)

  Found using machine learning.
  Next step ~2025?: compute masses (by Yukawa couplings to Higgs): need metric of CY, itself found using machine learning)

- Positive cosmological constant (4d de Sitter space)

  Much more difficult!!!

  2003: generic construction for the 10^{500} possibilities

  Many issues found (e.g. instabilities, but not clear their end-point)

  Since 2003: Other solutions found, but far less solid

Both together..?

But: as is, this is still far from our universe, which has

- Standard Model of particles

  1980's: We'll find THE Calabi-Yau that gives Standard Model spectrum

  2020: 10^{700} constructions with a Standard Model spectrum! (minimal supersymmetric)

  Found using machine learning.
  Next step ~2025?: compute masses (by Yukawa couplings to Higgs): need metric of CY, itself found using machine learning)

- Positive cosmological constant (4d de Sitter space)

  Much more difficult!!!

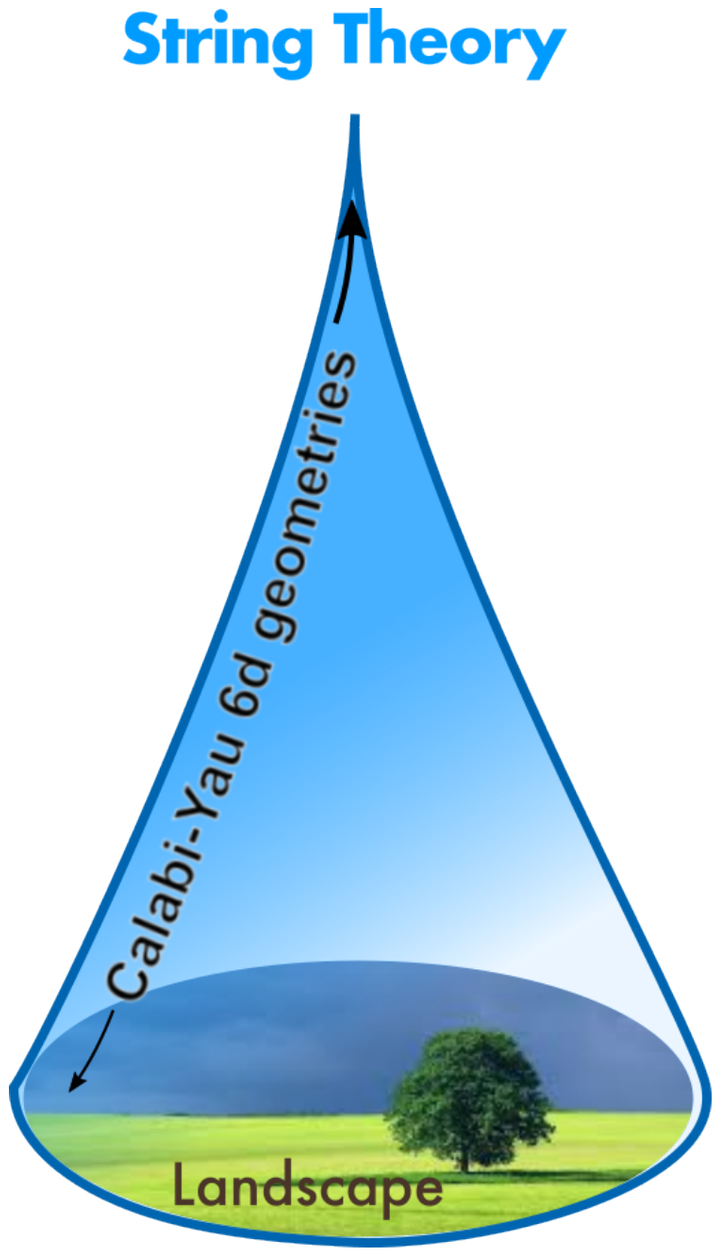
  2003: generic construction for the 10^{500} possibilities

  Many issues found (e.g. instabilities, but not clear their end-point)

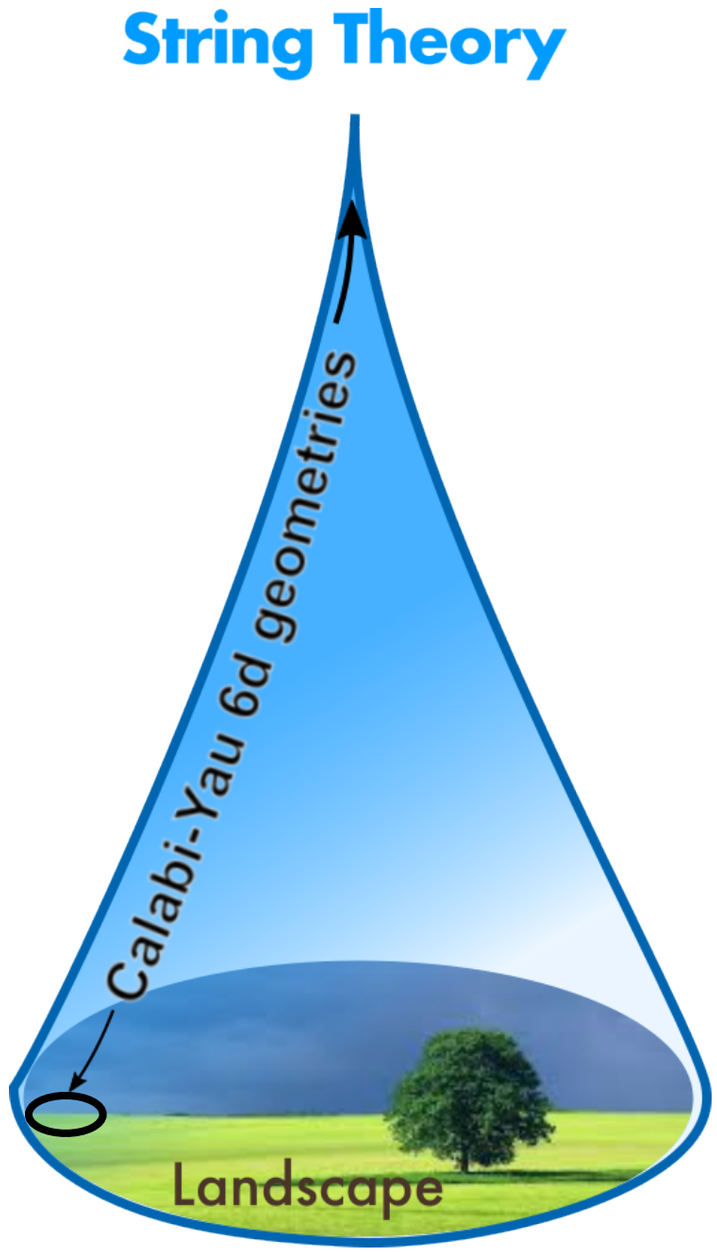
  Since 2003: Other solutions found, but far less solid

Both together..?

Is this all the landscape?



Not diverse enough to fit all



Not diverse enough to fit all

Summary

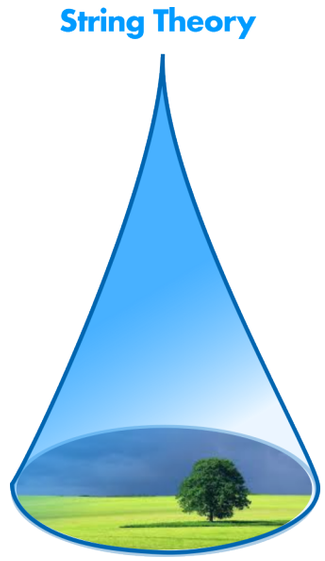
Summary

String theory is a remarkable and unique theory of quantum gravity

Summary

String theory is a remarkable and unique theory of quantum gravity

- Unique in 10d, but leads to many 4d universes (landscape)

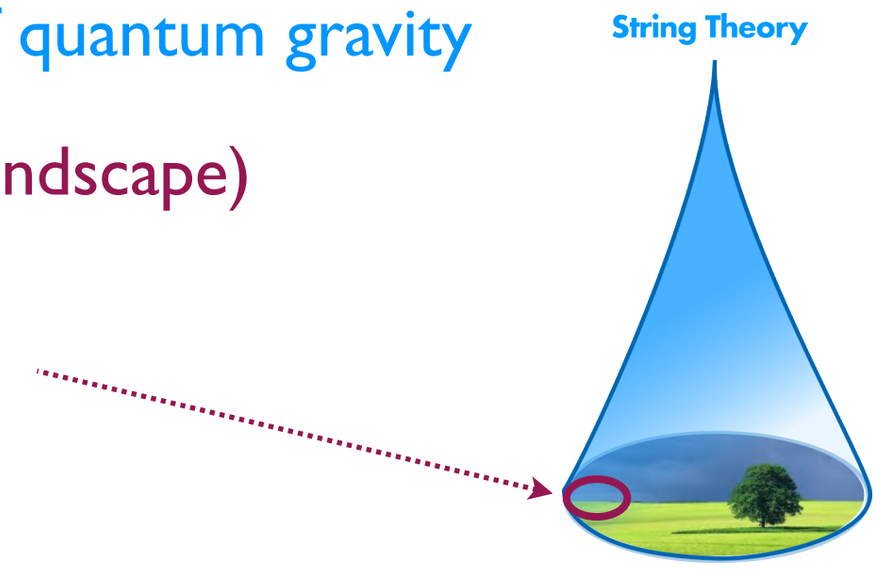


Summary

String theory is a remarkable and unique theory of quantum gravity

- Unique in 10d, but leads to many 4d universes (landscape)

- Mostly explored: landscape CY compactifications



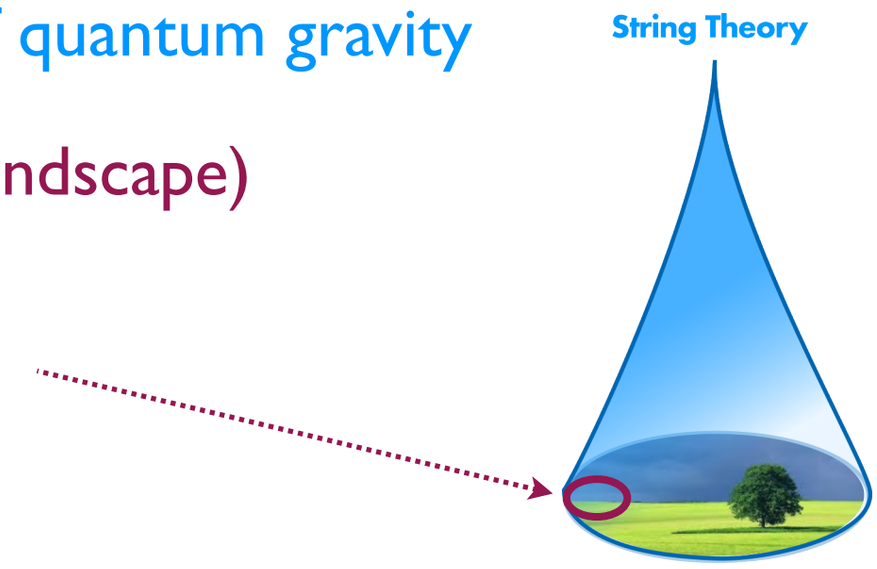
Summary

String theory is a remarkable and unique theory of quantum gravity

- Unique in 10d, but leads to many 4d universes (landscape)

- Mostly explored: landscape CY compactifications

  - Spectrum of standard model, masses to be computed



Summary

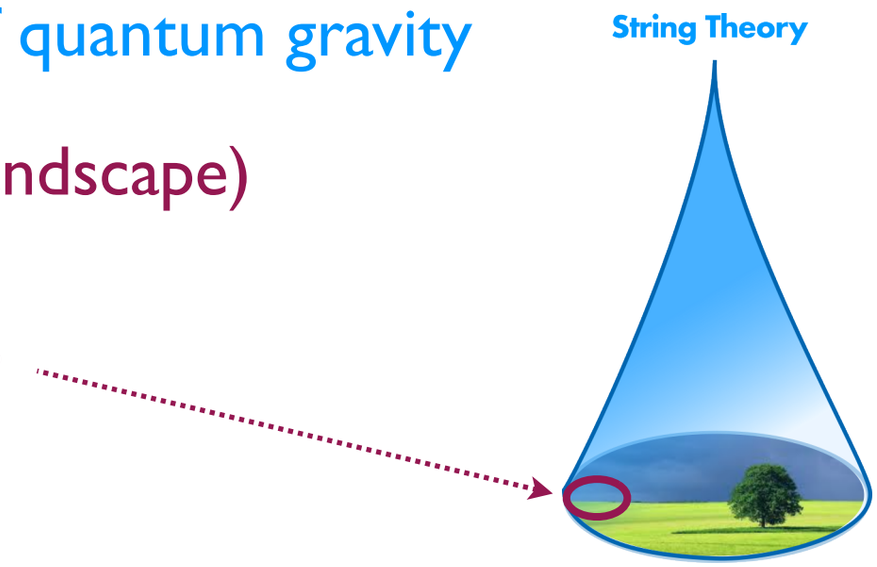
String theory is a remarkable and unique theory of quantum gravity

- Unique in 10d, but leads to many 4d universes (landscape)

- Mostly explored: landscape CY compactifications

  - Spectrum of standard model, masses to be computed

  - Cosmological constant?



Summary

String theory is a remarkable and unique theory of quantum gravity

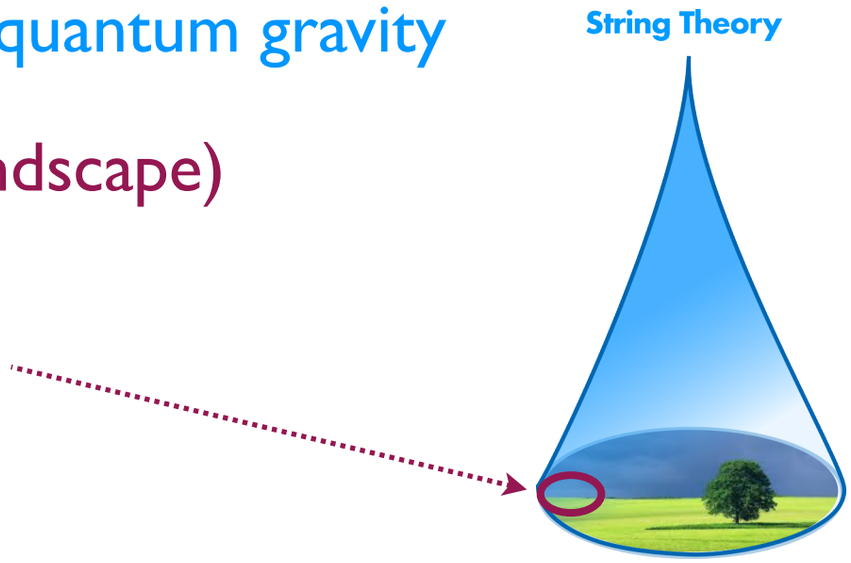
- Unique in 10d, but leads to many 4d universes (landscape)

- Mostly explored: landscape CY compactifications

  - Spectrum of standard model, masses to be computed

  - Cosmological constant?

  - Both together?



Summary

String theory is a remarkable and unique theory of quantum gravity

- Unique in 10d, but leads to many 4d universes (landscape)

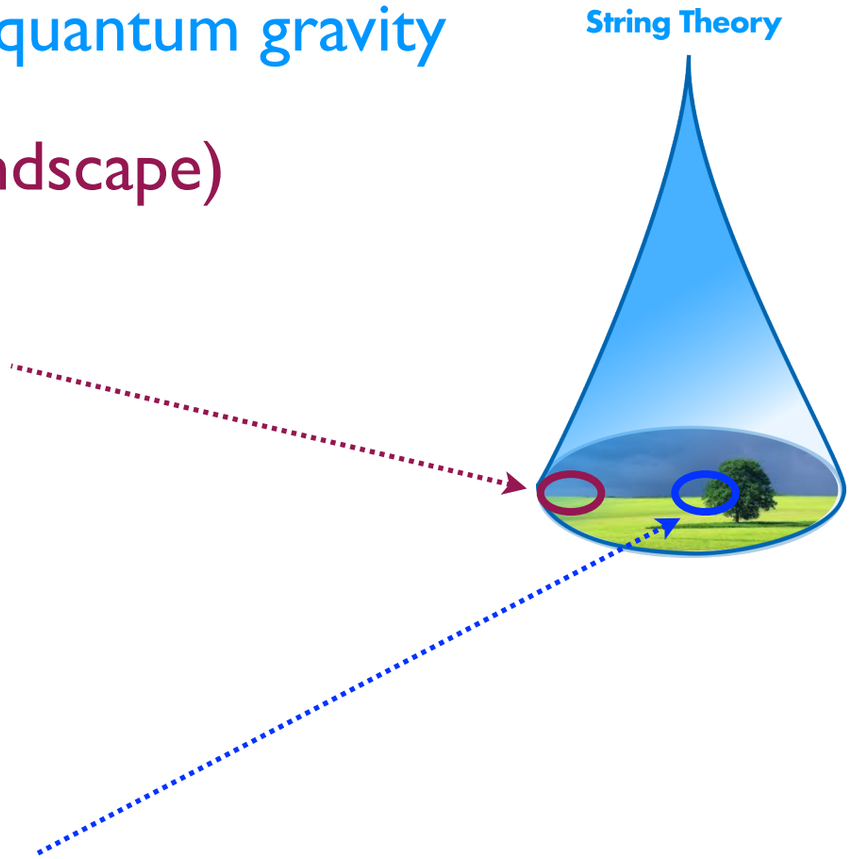
- Mostly explored: landscape CY compactifications

  - Spectrum of standard model, masses to be computed

  - Cosmological constant?

  - Both together?

  All seems to indicate that our universe is here



Summary

String theory is a remarkable and unique theory of quantum gravity

- Unique in 10d, but leads to many 4d universes (landscape)

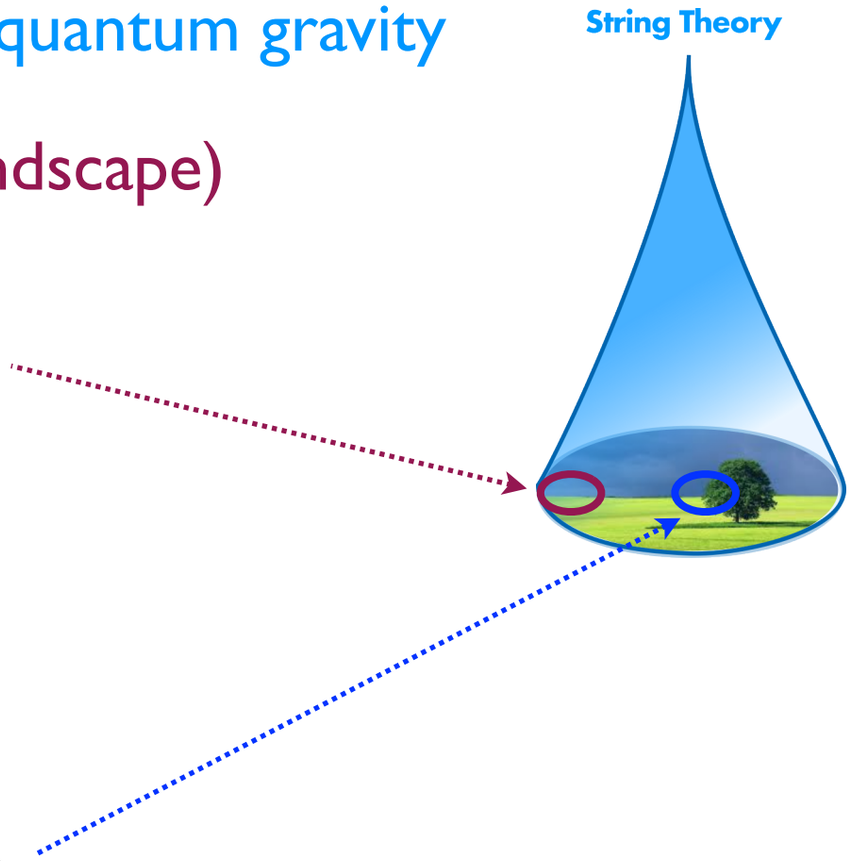
- Mostly explored: landscape CY compactifications

  - Spectrum of standard model, masses to be computed

  - Cosmological constant?

  - Both together?

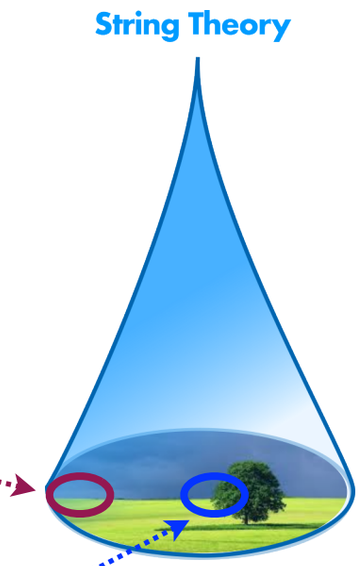
  All seems to indicate that our universe is here



- The string landscape is mostly unexplored

Summary

String theory is a remarkable and unique theory of quantum gravity



- Unique in 10d, but leads to many 4d universes (landscape)

- Mostly explored: landscape CY compactifications

  - Spectrum of standard model, masses to be computed

  - Cosmological constant?

  - Both together?

  All seems to indicate that our universe is here

- The string landscape is mostly unexplored

  - Go beyond Calabi-Yau manifolds

with Jan Louis, 2005-2014, Cortes

Summary

String theory is a remarkable and unique theory of quantum gravity

- Unique in 10d, but leads to many 4d universes (landscape)

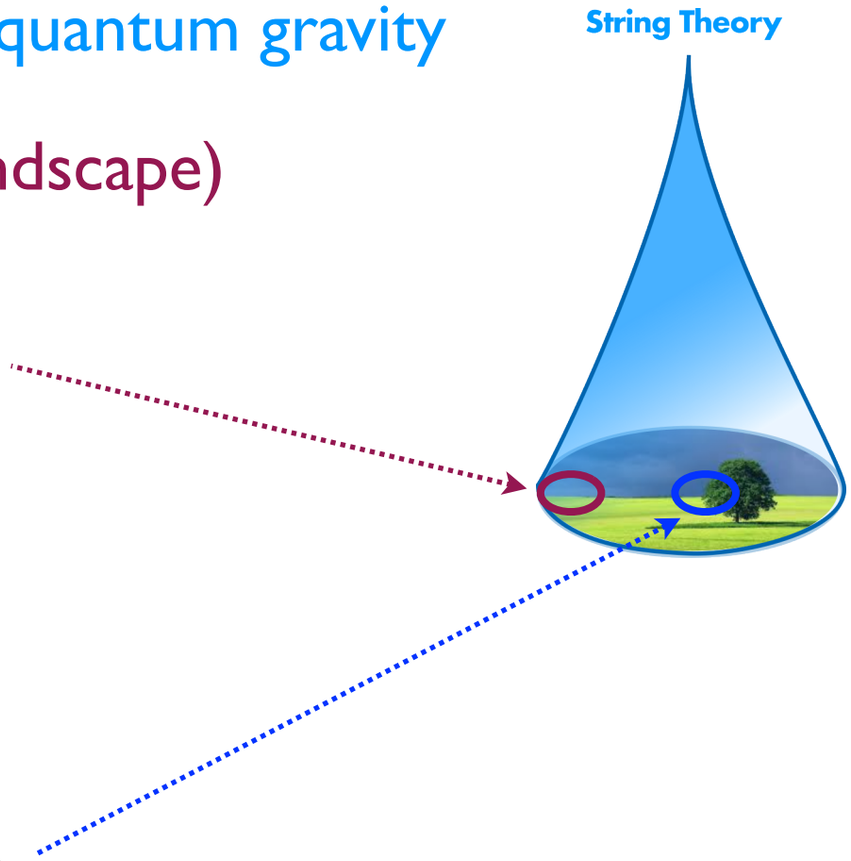
- Mostly explored: landscape CY compactifications

  - Spectrum of standard model, masses to be computed

  - Cosmological constant?

  - Both together?

  All seems to indicate that our universe is here



- The string landscape is mostly unexplored

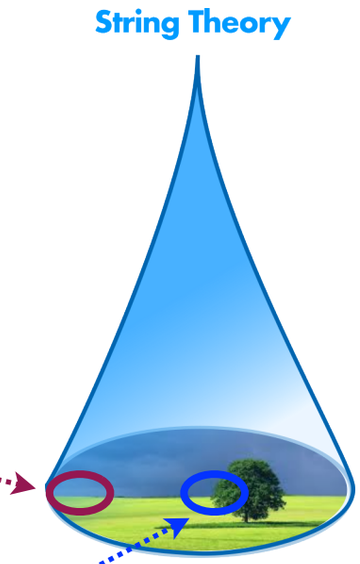
  - Go beyond Calabi-Yau manifolds

    with Jan Louis, 2005-2014, Cortes

  - Go beyond geometry!

Summary

String theory is a remarkable and unique theory of quantum gravity



- Unique in 10d, but leads to many 4d universes (landscape)

- Mostly explored: landscape CY compactifications

  - Spectrum of standard model, masses to be computed

  - Cosmological constant?

  - Both together?

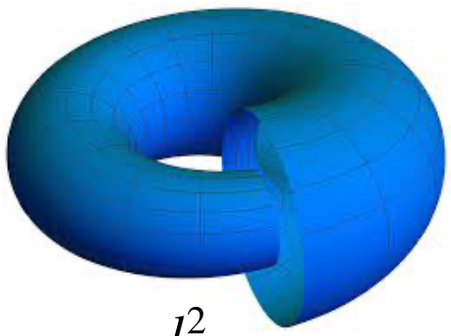
  All seems to indicate that our universe is here

- The string landscape is mostly unexplored

  - Go beyond Calabi-Yau manifolds

    with Jan Louis, 2005-2014, Cortes

  - Go beyond geometry!

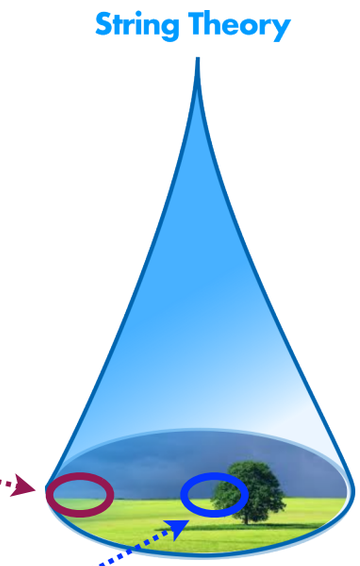


T-folds

$$R = \frac{l_s^2}{R} \qquad R$$

Summary

String theory is a remarkable and unique theory of quantum gravity



- Unique in 10d, but leads to many 4d universes (landscape)

- Mostly explored: landscape CY compactifications

  - Spectrum of standard model, masses to be computed

  - Cosmological constant?

  - Both together?

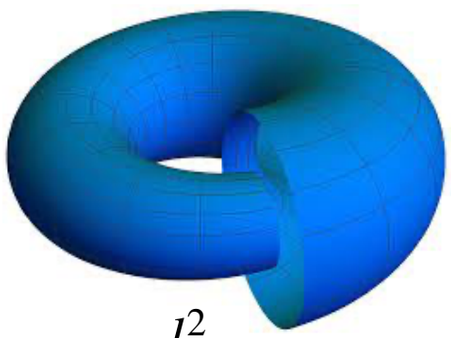
  All seems to indicate that our universe is here

- The string landscape is mostly unexplored

  - Go beyond Calabi-Yau manifolds

    with Jan Louis, 2005-2014, Cortes

  - Go beyond geometry!



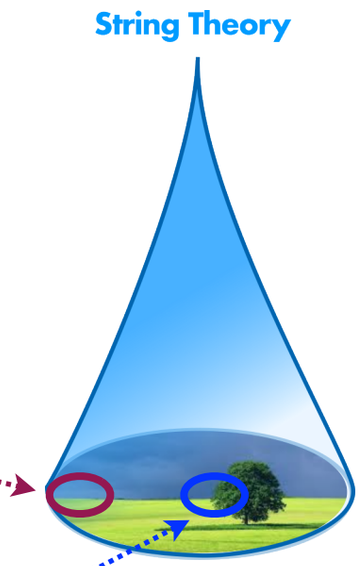
T-folds

$$R = \frac{l_s^2}{R} \qquad R$$

Beautiful, diverse and still largely unexplored landscape

Summary

String theory is a remarkable and unique theory of quantum gravity



- Unique in 10d, but leads to many 4d universes (landscape)

- Mostly explored: landscape CY compactifications

  - Spectrum of standard model, masses to be computed

  - Cosmological constant?

  - Both together?

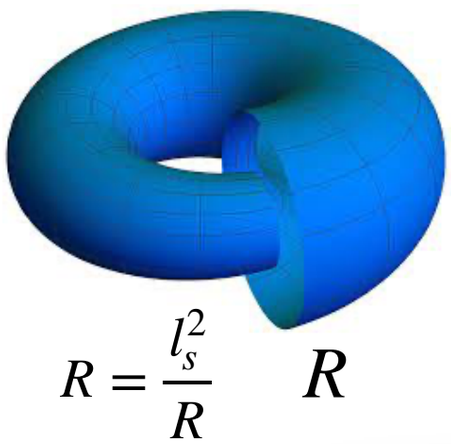
  All seems to indicate that our universe is here

- The string landscape is mostly unexplored

  - Go beyond Calabi-Yau manifolds

  with Jan Louis, 2005-2014, Cortes

  - Go beyond geometry!



T-folds

Beautiful, diverse and still largely unexplored landscape

Special thank to Beate Naroska initiative for diversity!