What is String Theory?

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Outline

Overview talk. Only basic concepts, no details.

- Why String Theory?
- What is String Theory?
  - New degrees of freedom
  - 10 dimensions
  - New symmetries
  - What else do we have?
- Can we detect it?
- What can we do with it?
- Summary

Why String Theory?

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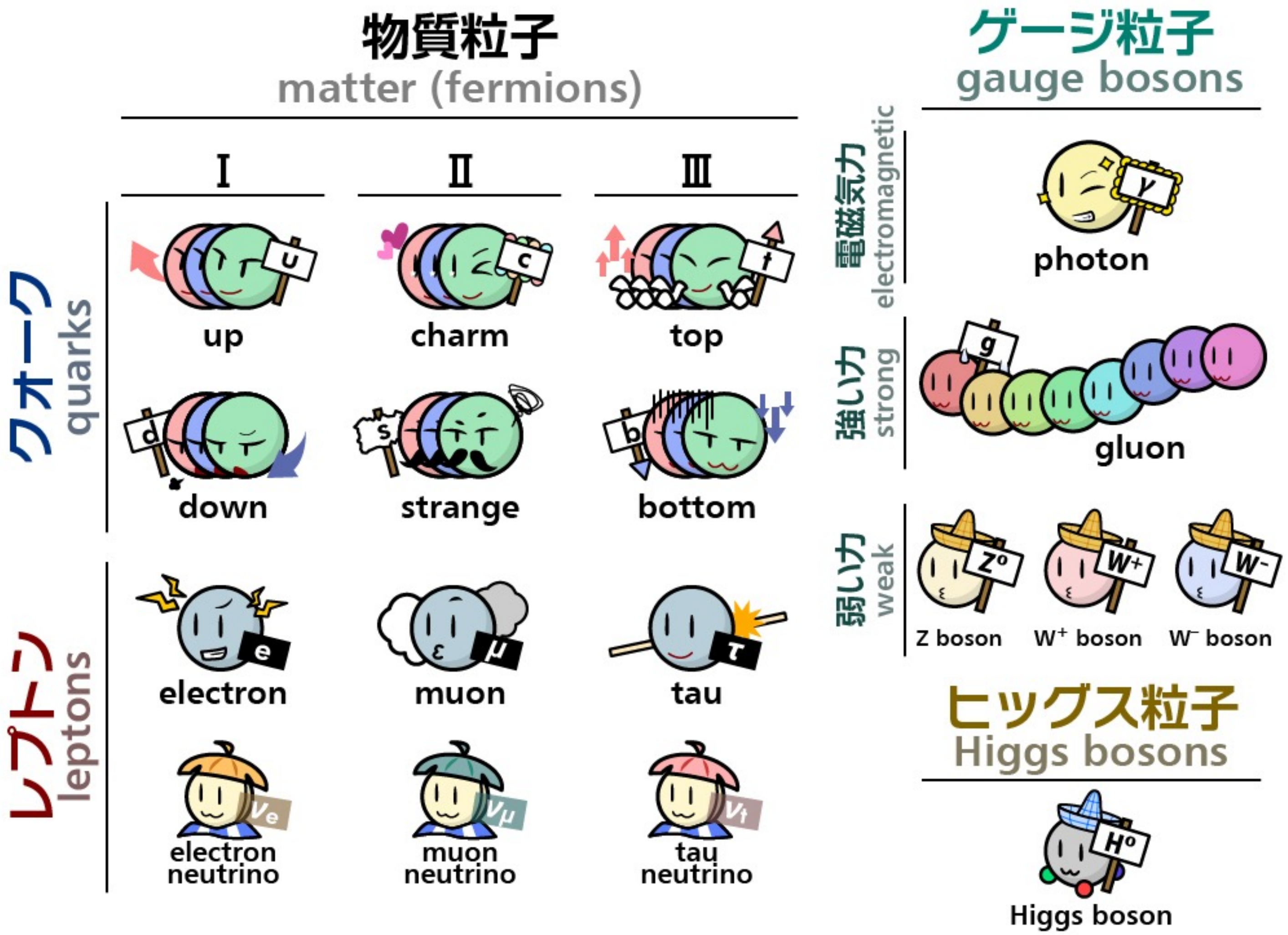
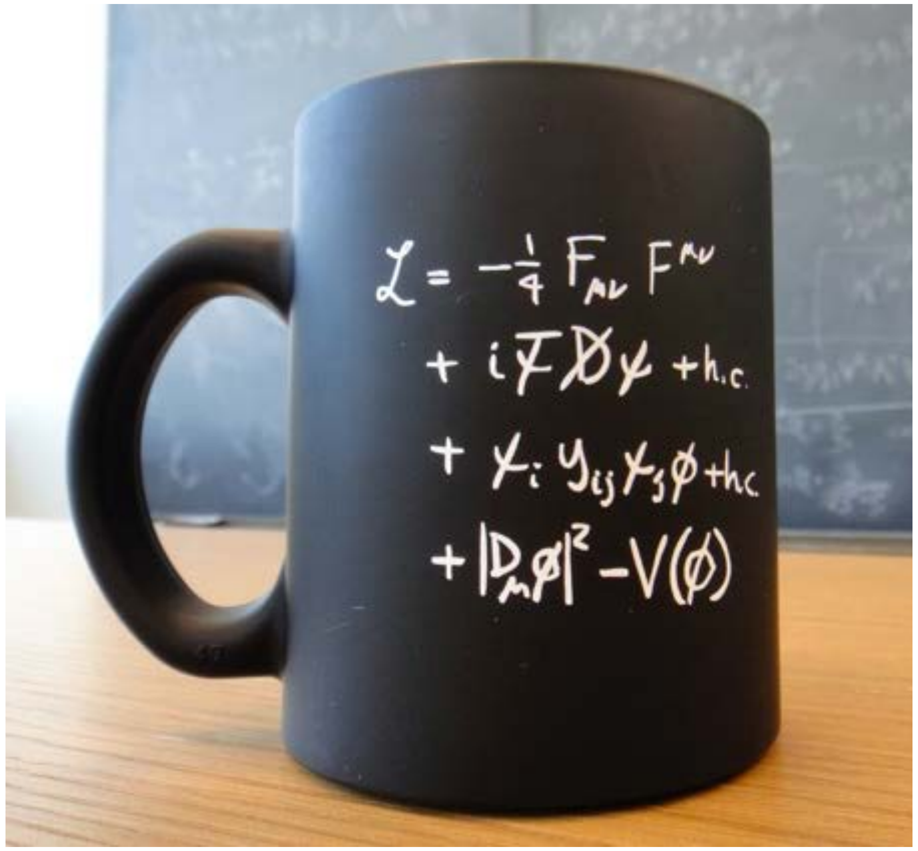
Why String Theory?

We have the Standard Model of Particle Physics.



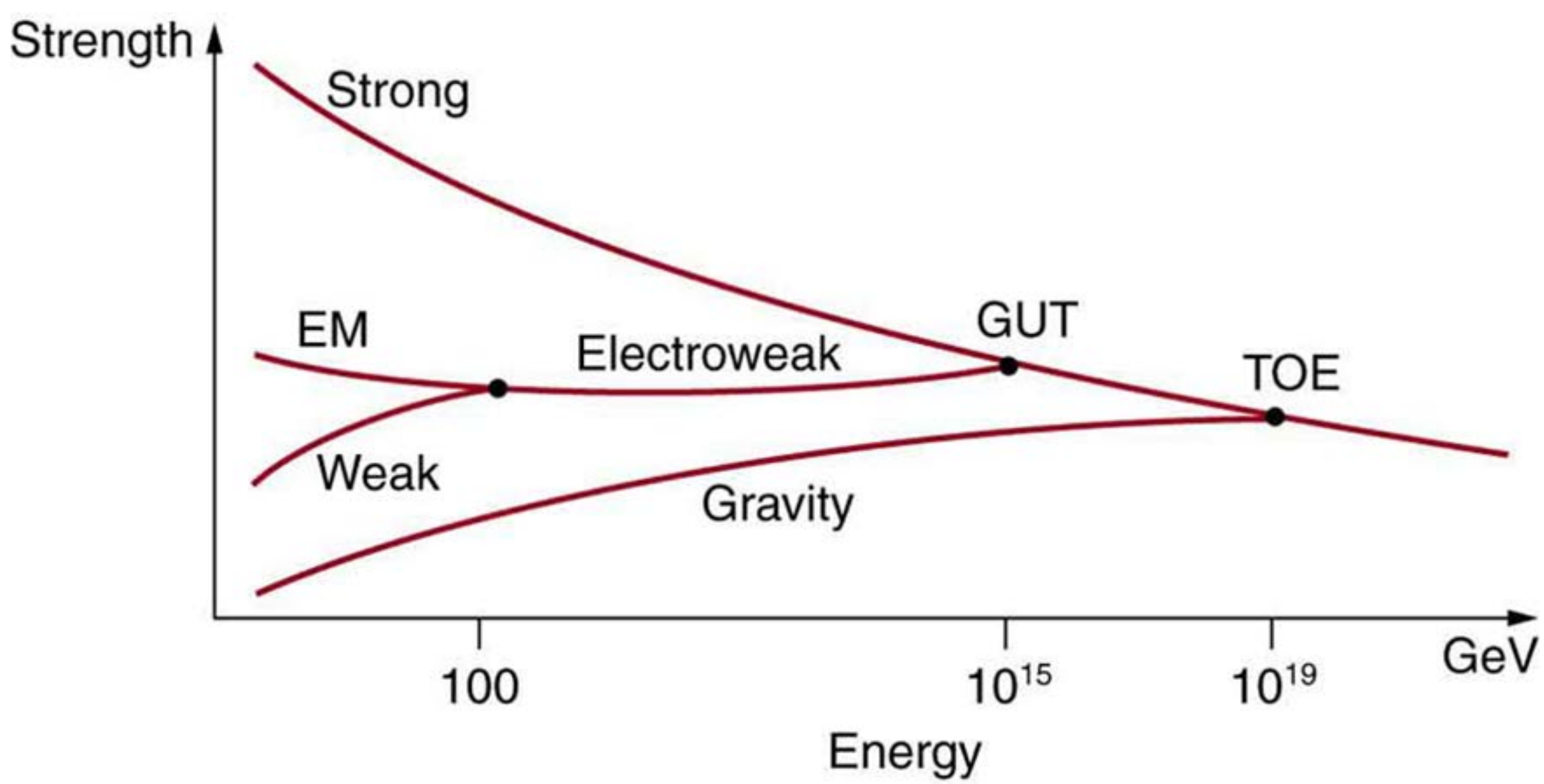


Why String Theory?

The Standard Model works pretty well!

Why would we be looking for a different theory?

One motivation: unification of strong and electroweak forces with gravity.



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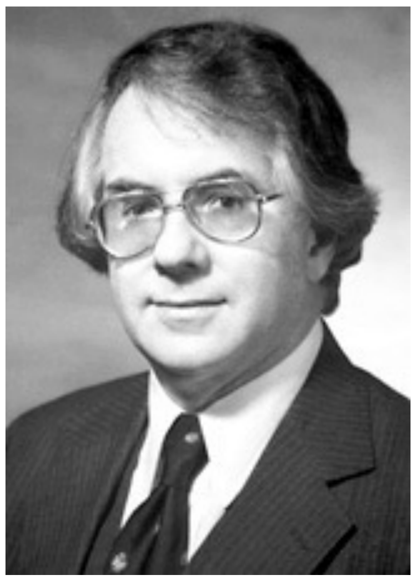
Why String Theory?

Glashow



Salam

Weinberg

Nobel prize 1979

Electrodynamics and the weak interaction were unified into the electroweak force.

The strong and electroweak forces are described in the common framework of gauge theories (qft).

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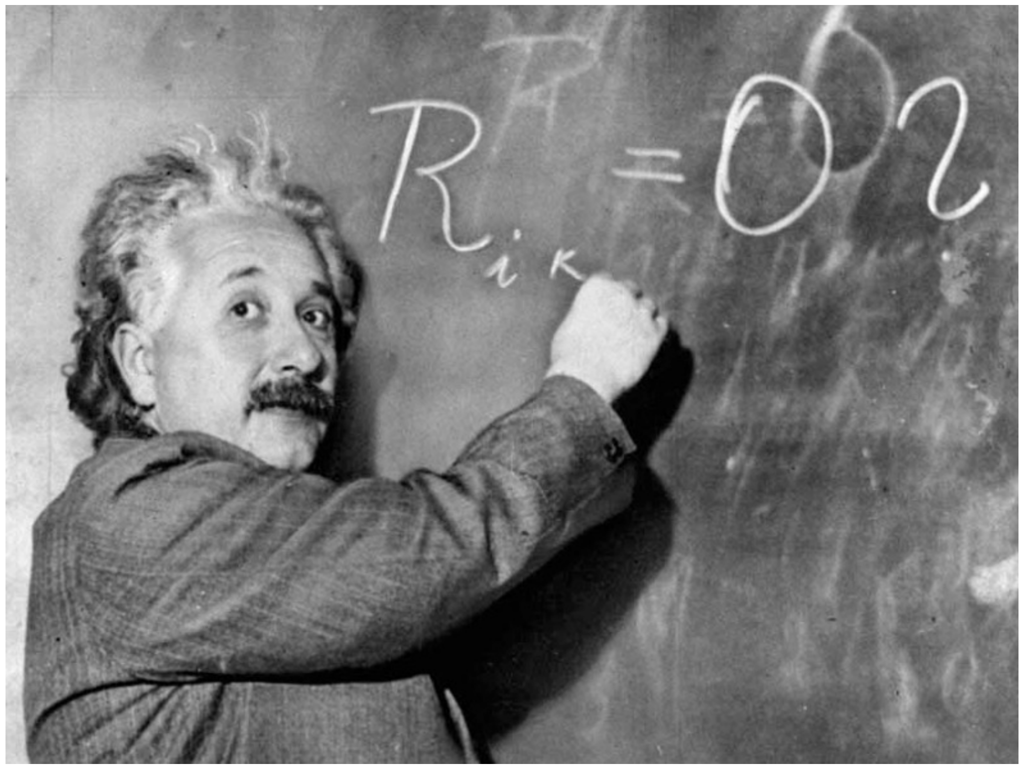
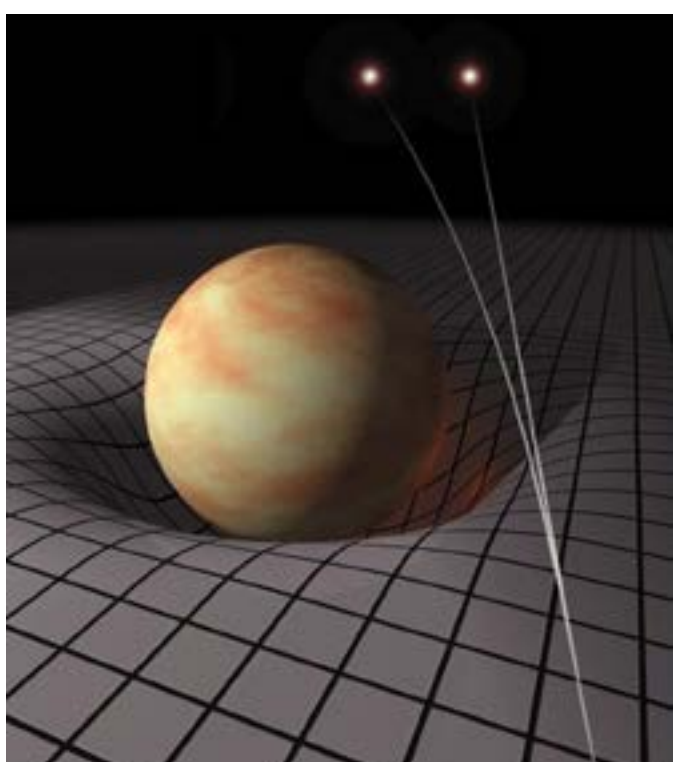
Why String Theory?



Einstein

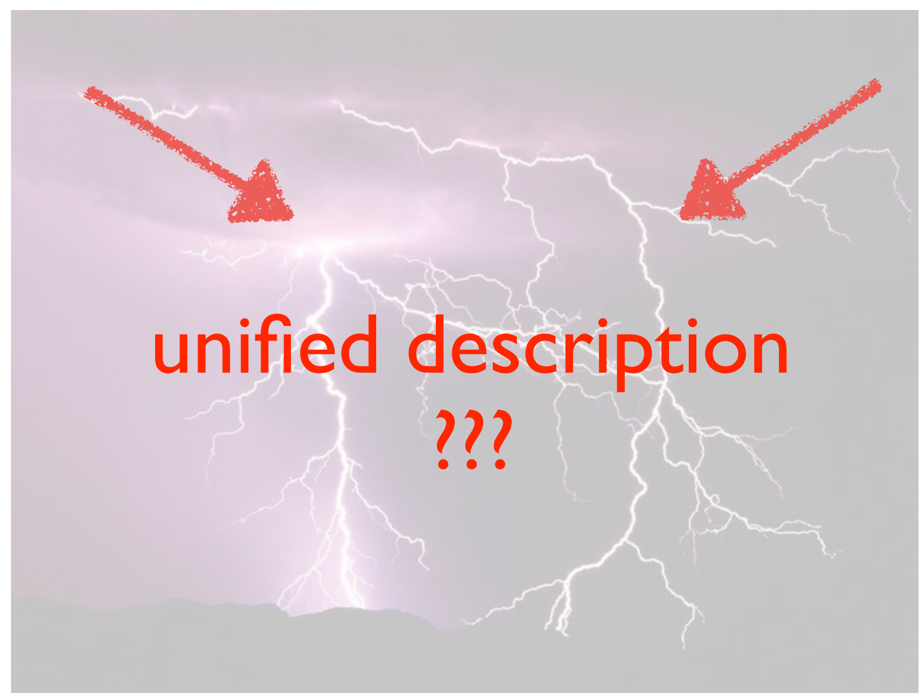
Gravity is different from the other forces.
Not a quantum field theory.
Classical theory. Geometric interpretation of gravity (curvature of space).



Why String Theory?

"Theory of Everything"

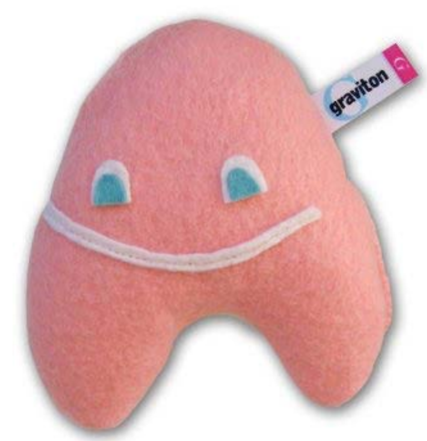
Standard model of
particle physics



general Relativity

quantum gravity?

carrier particle:
graviton (spin 2)



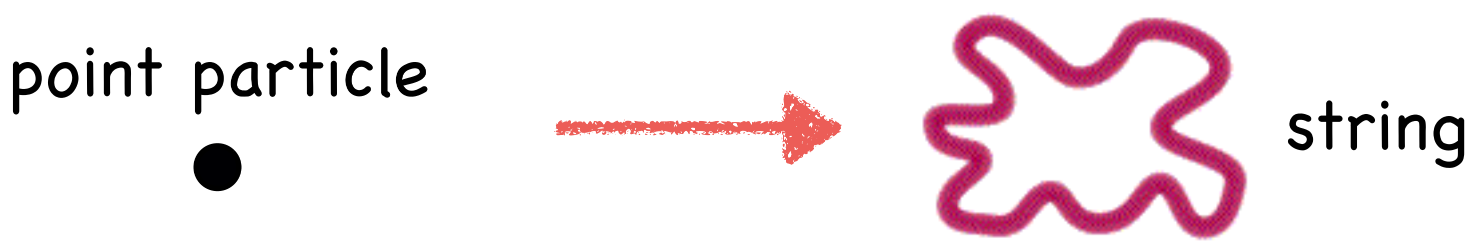
Problem: quantum gravity is
not renormalizable.

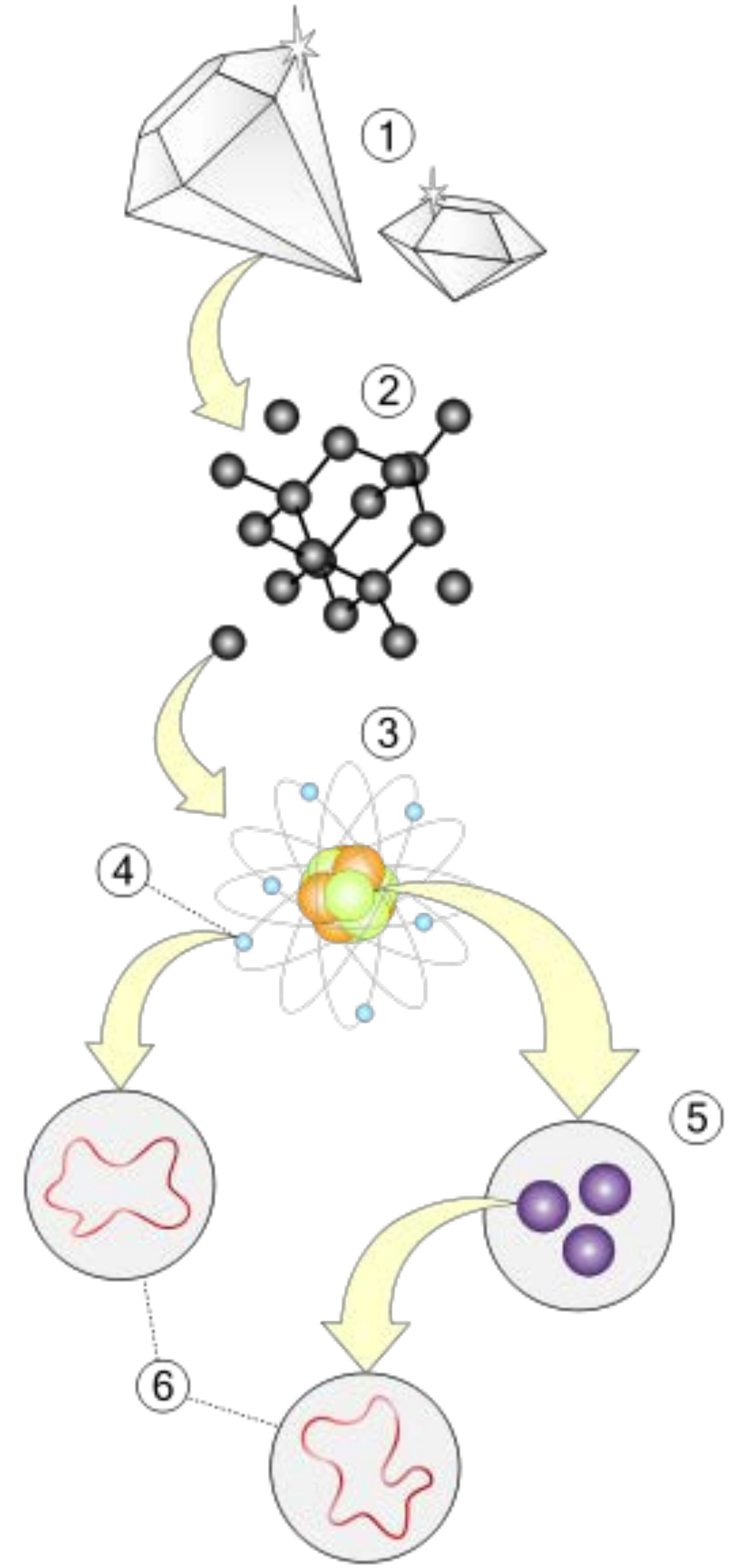
possible solution: String Theory

What is String Theory?

What is String Theory?

Basic idea is simple: elementary particles are 1-dimensional strings instead of point particles.





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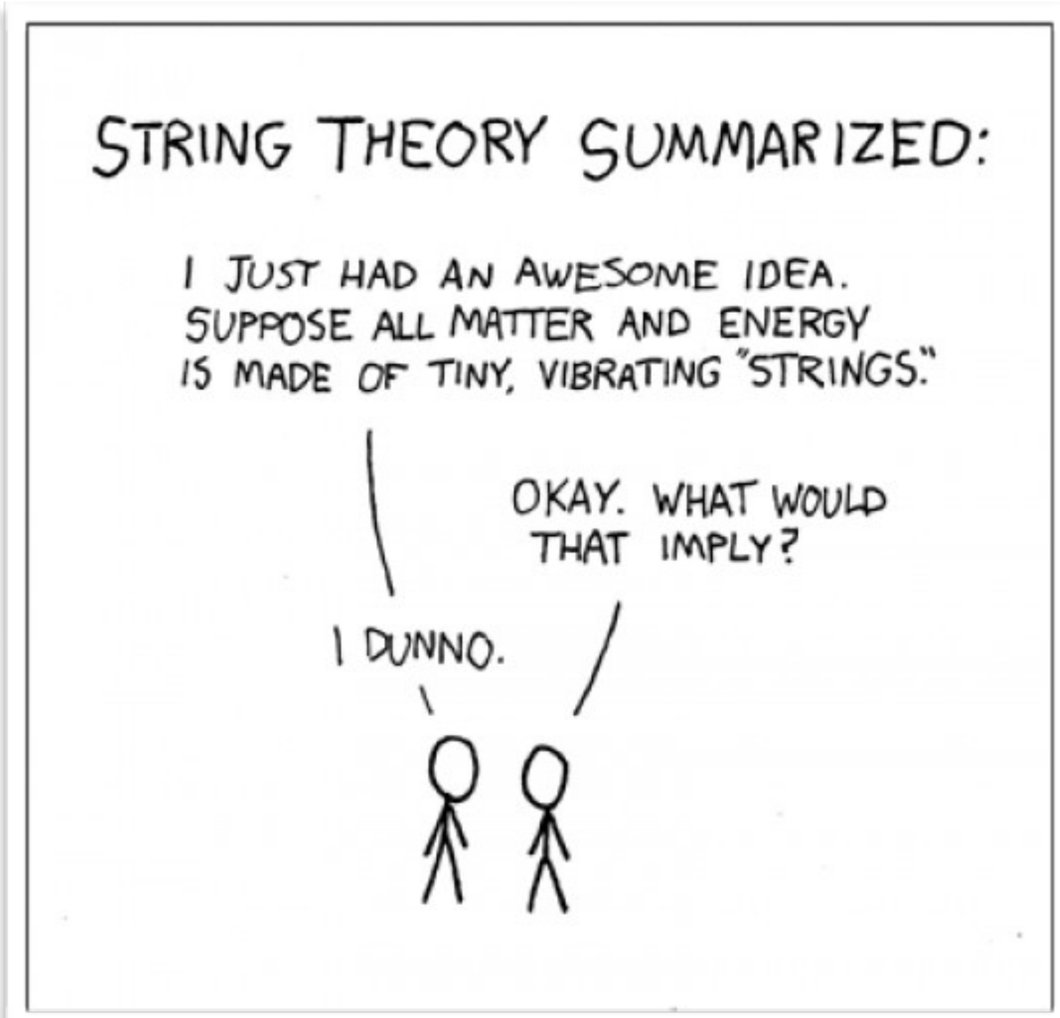
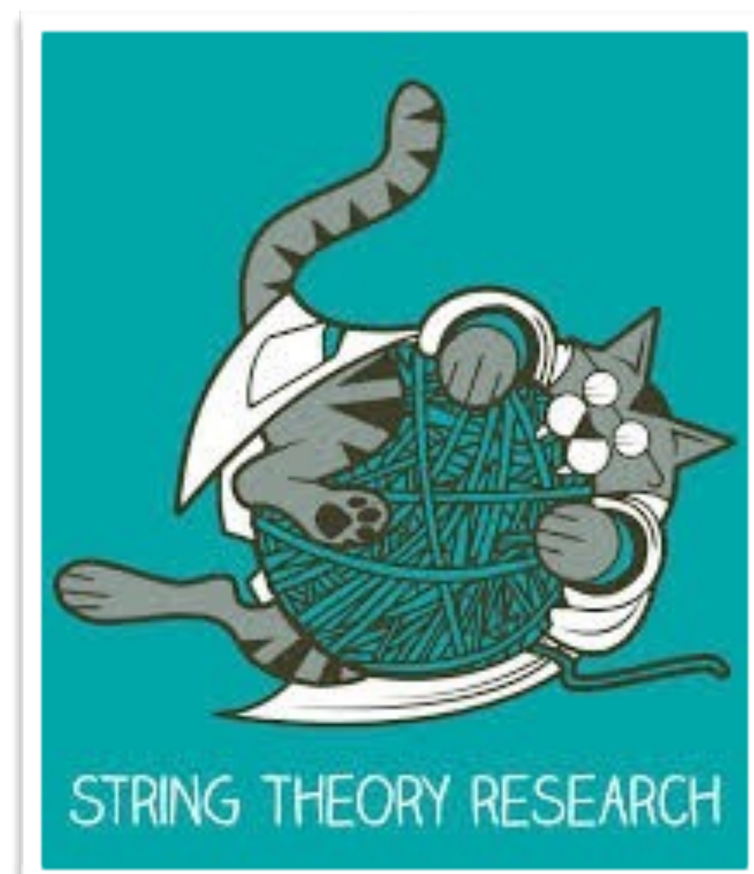
What is String Theory?

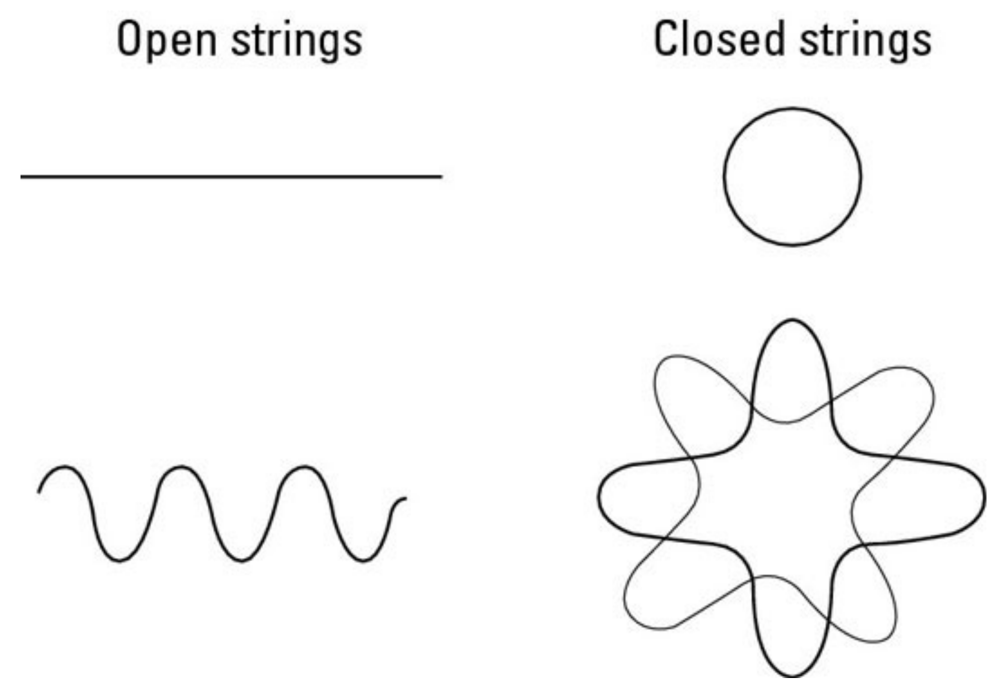


So what are the consequences of this idea?

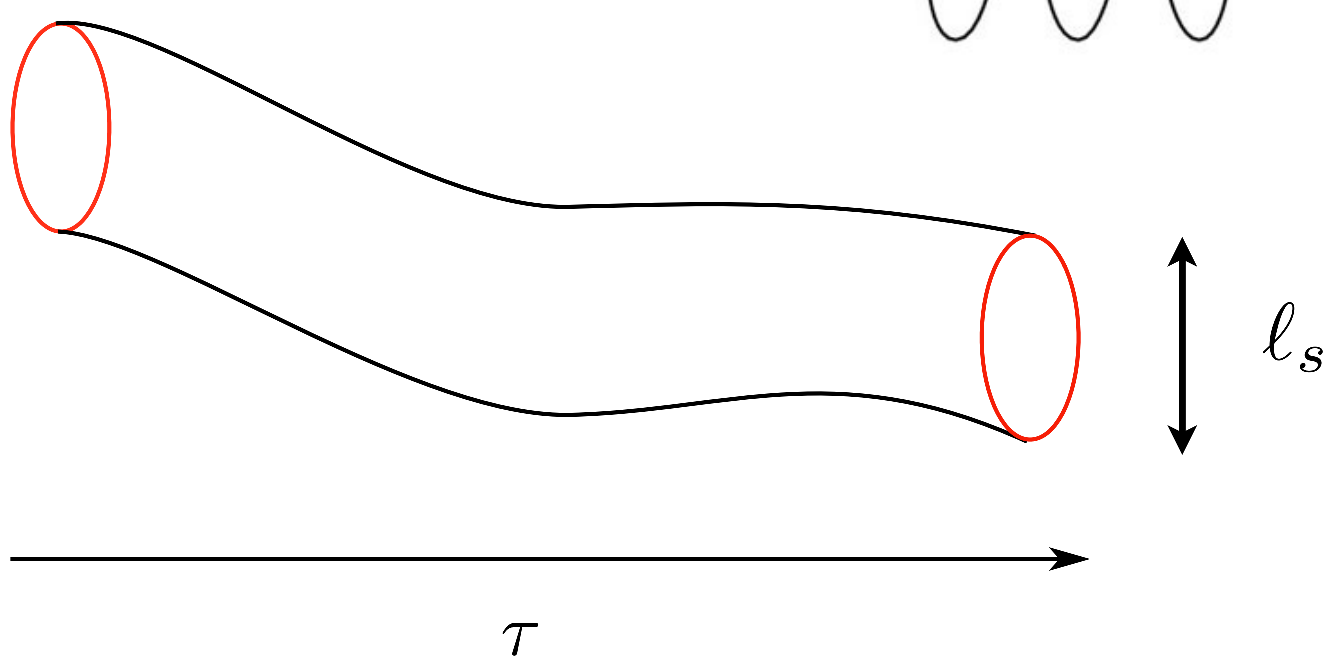


What is String Theory?

There are open and closed strings.



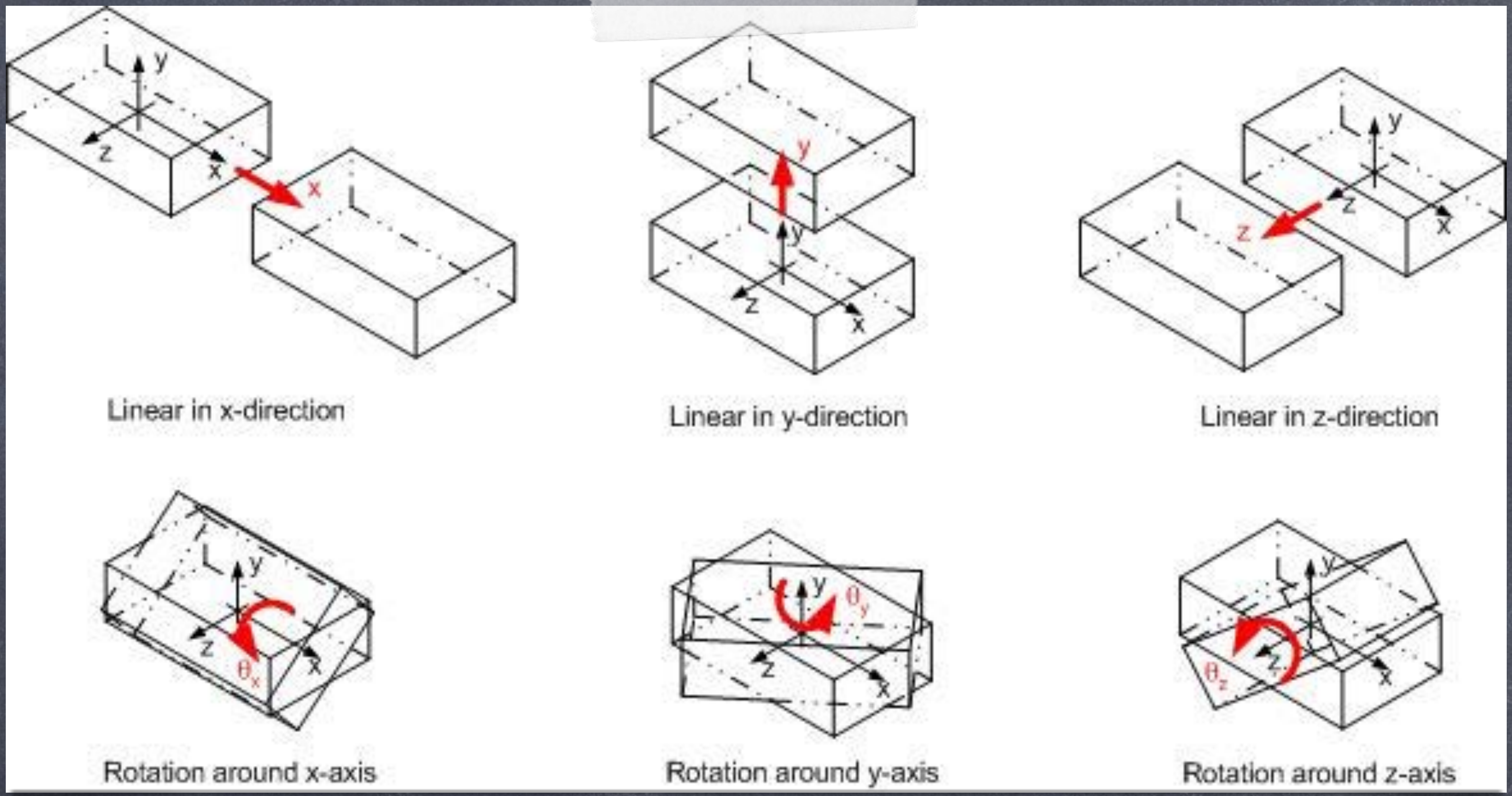
New fundamental parameter:
string length



String length corresponds roughly to the Planck length,

$$l_s \sim 10^{-35}\,\mathrm{cm}$$

For $l_s \to 0$, we recover point particle theory.



New Degrees of Freedom

New degrees of freedom

There are new degrees of freedom compared to the point particle!

It has vibration modes.

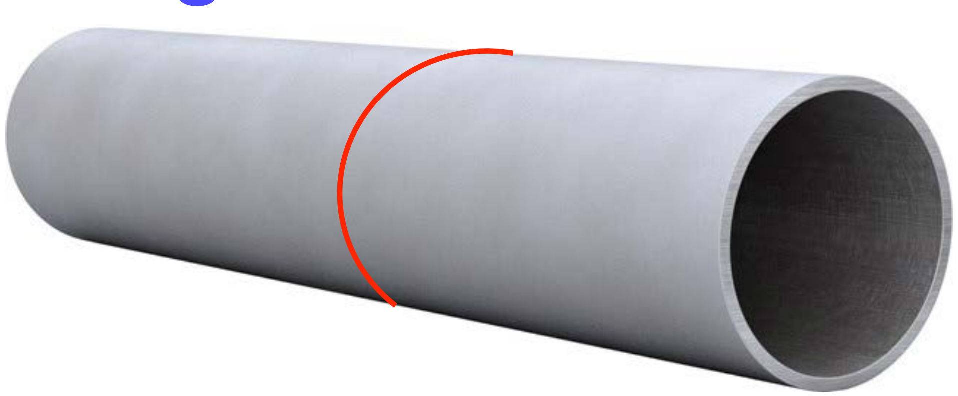
Different vibrations correspond to different particles.

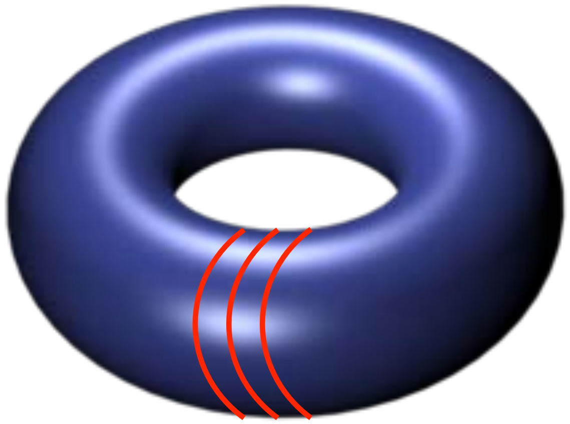
A spin-2 particle (graviton!) is automatically part of the spectrum.

String theory is a candidate for a consistent theory of quantum gravity.

There is yet another thing that can happen with a string.

It has winding modes.

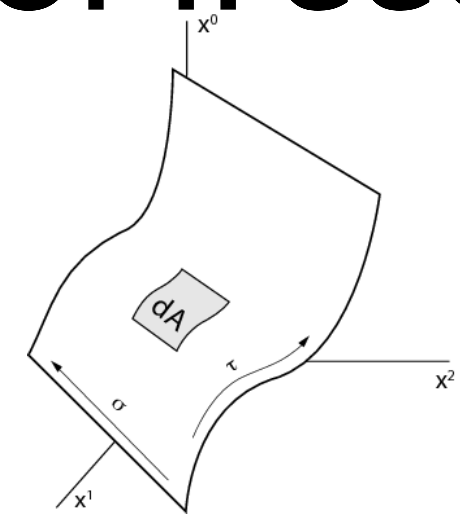




New degrees of freedom

How do we describe the interactions of strings?

A propagating string sweeps out a 2d surface: worldsheet



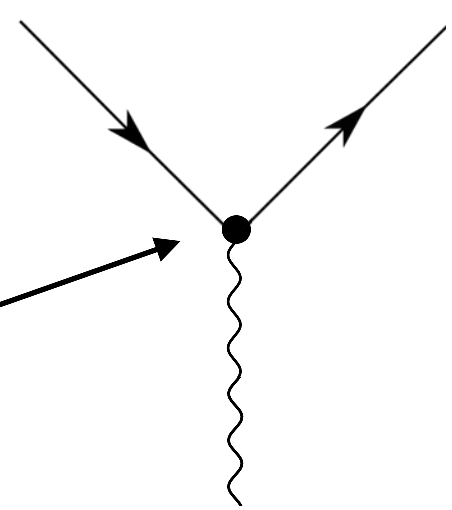
The physics on the world-sheet is encoded by a 2d conformal field theory.

$$S_{NG} = -\frac{1}{l_s^2}\int_{WS} \mathrm{d}\tau \mathrm{d}\sigma \sqrt{-\det h_{ab}}$$

world-sheet metric

The action is proportional to the area of the world-sheet.

The interaction diagrams are now surfaces instead of line drawings!



problems with UV singularities at interaction point

smooth surface, no singularities

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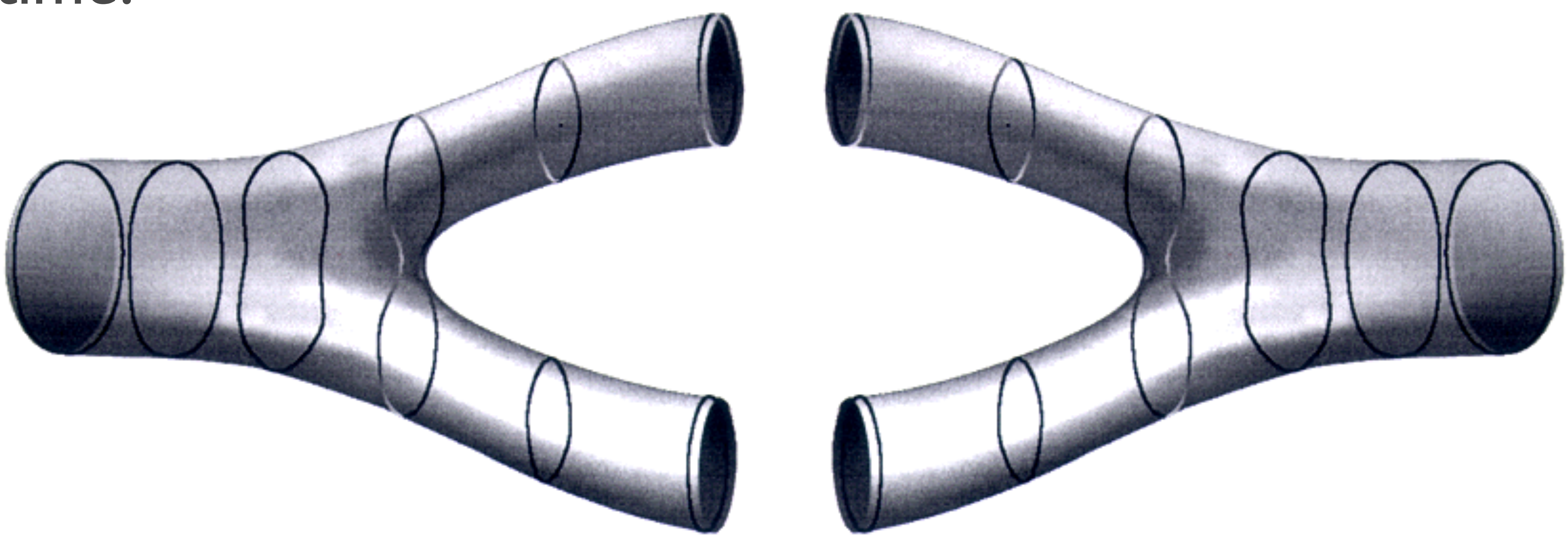
New degrees of freedom

The surfaces show the movement of the strings through time.

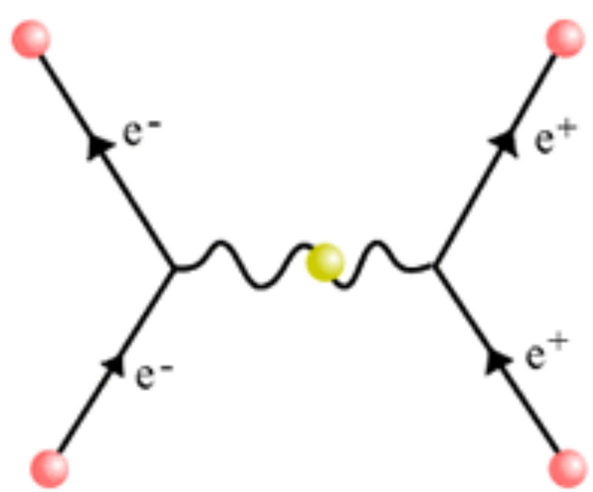


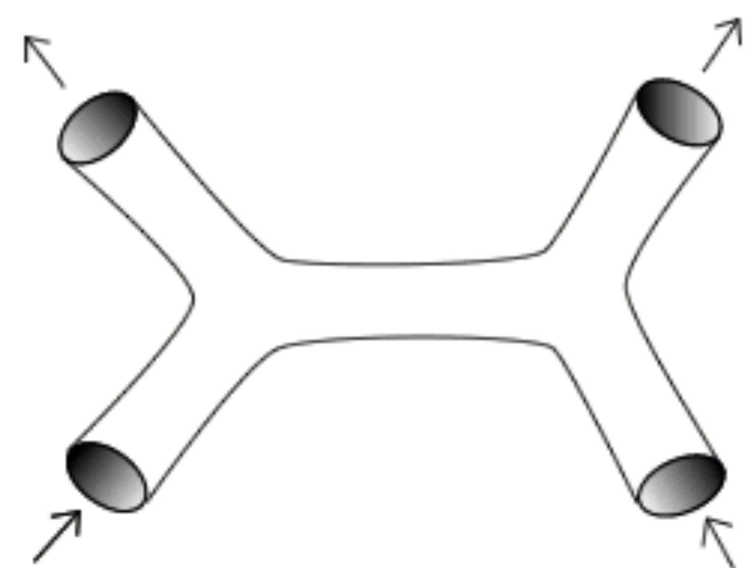
Strings interact by splitting and joining.

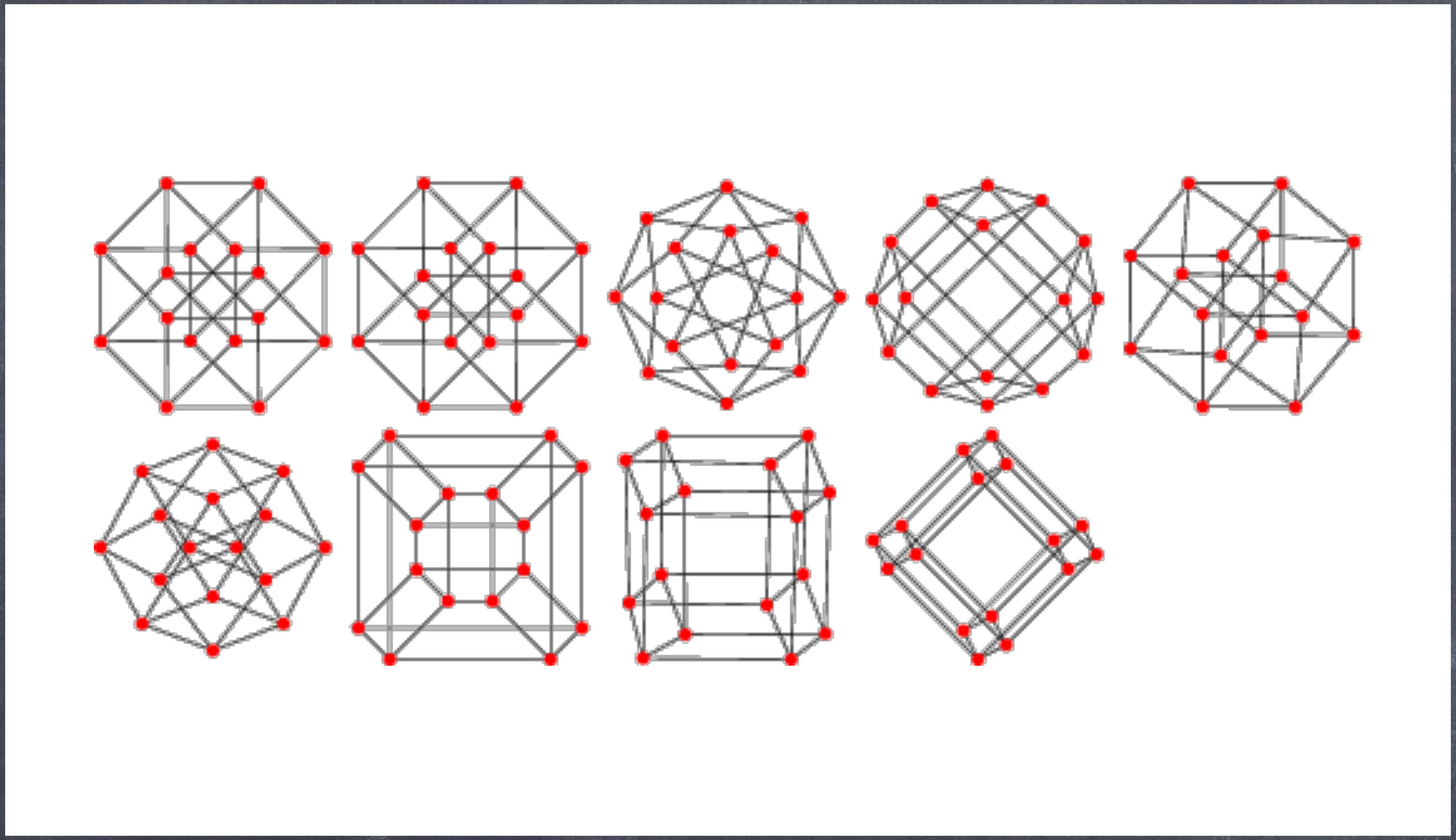
Each vertex contributes a factor of the string coupling.

New degrees of freedom

Example: electron-electron scattering:







10 Dimensions

10 dimensions

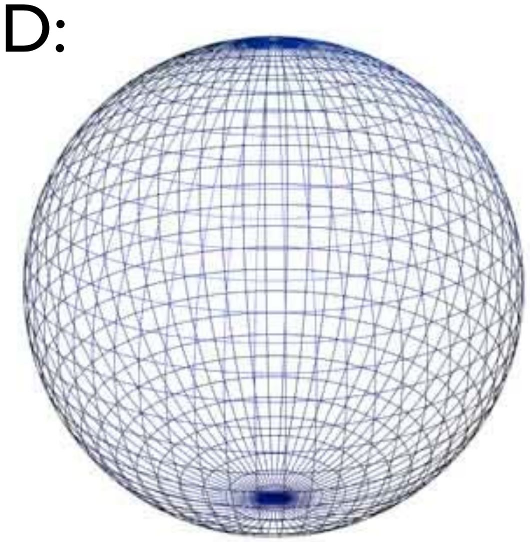
Fun fact: the conformal field theory on the world-sheet is only consistent (anomaly free) in 26 (bosonic string) or 10 dimensions (superstring).

Our world however appears to be 3+1 dimensional.

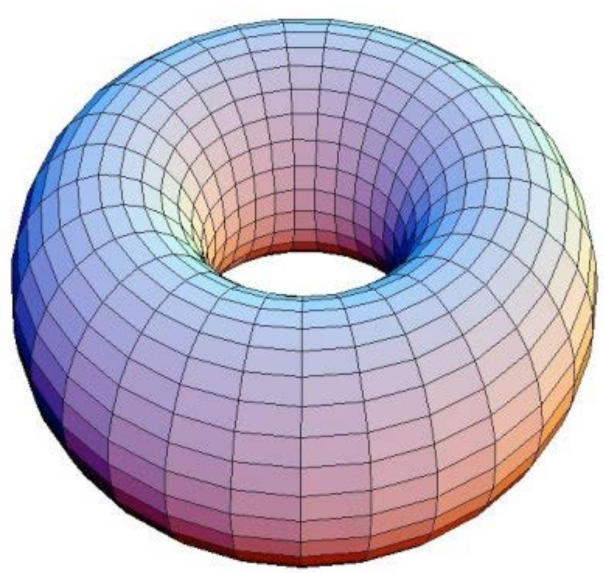
What about those extra six dimensions??

They might be compactified to an undetectably small size.

2D:

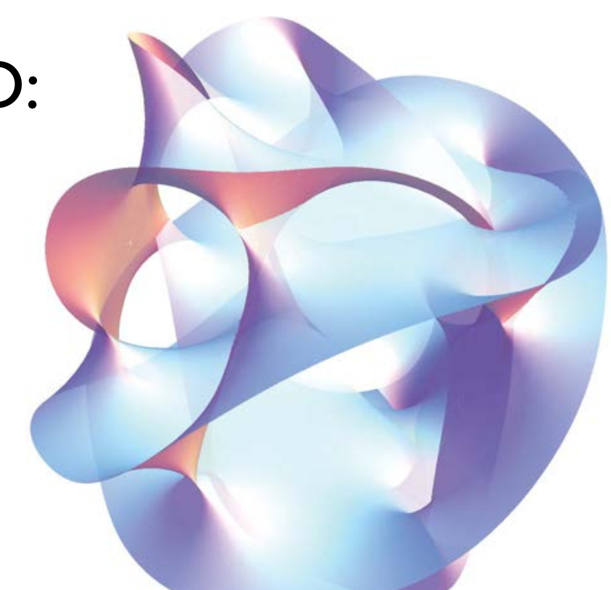


sphere



torus

6D:



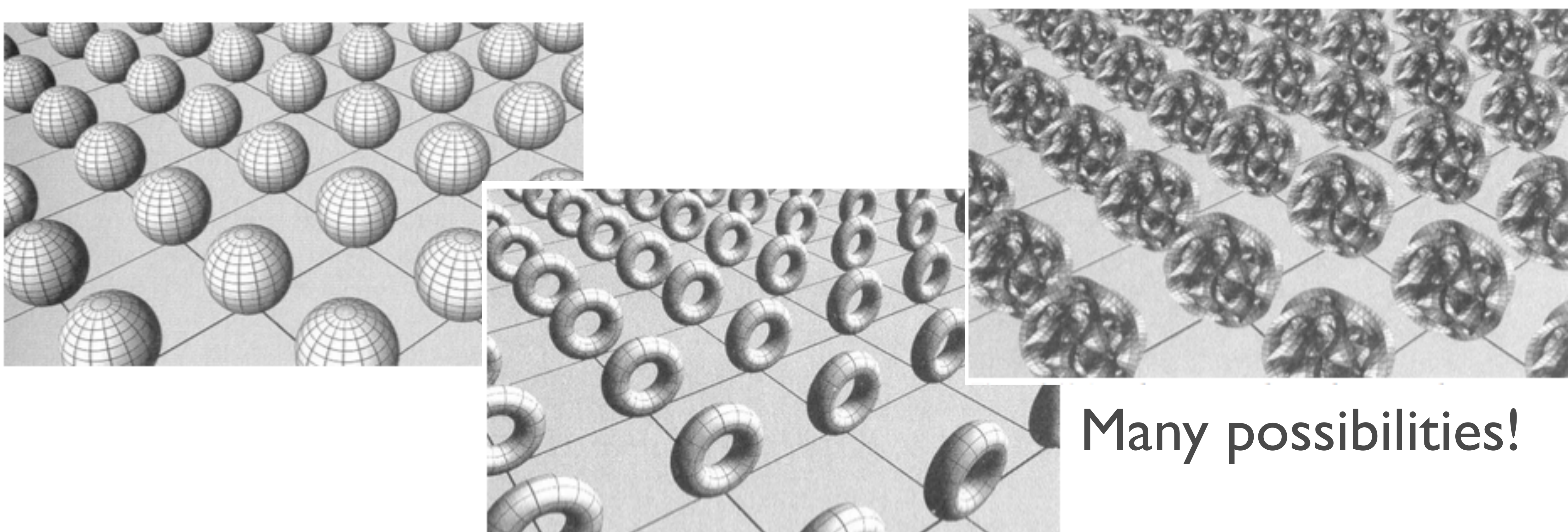
section of a Calabi-Yau manifold

10 dimensions

Not any given 6D manifold will produce a valid string theory solution. Must fulfill certain conditions (Calabi-Yau: compact Kähler manifold with a vanishing first Chern class, that is also Ricci flat)

How can we imagine 4+6 D spacetime?

Each point in 4D space-time also contains a tiny compactified 6D space.



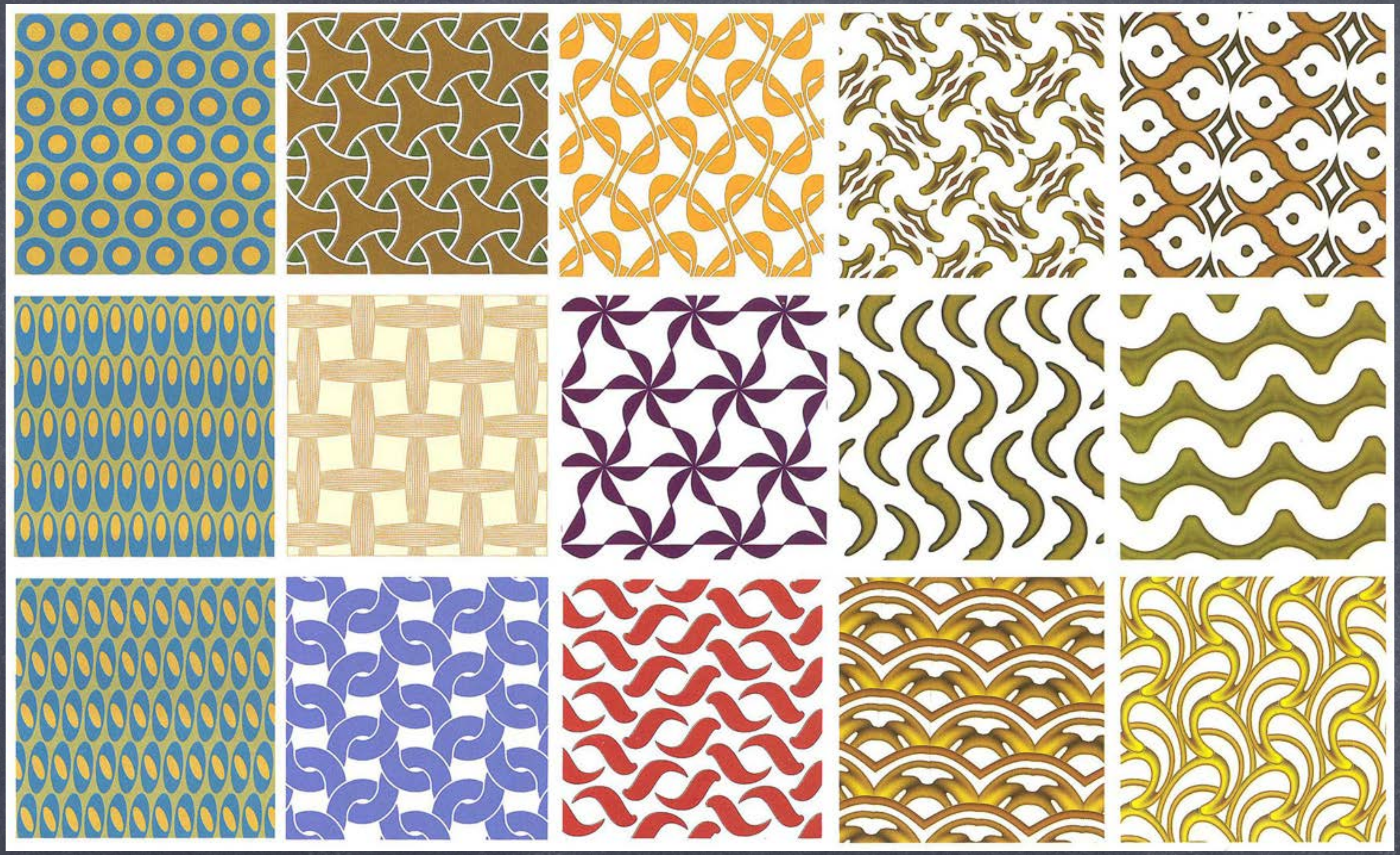
Many possibilities!

10 dimensions

The geometric properties of the compactification manifold determine the natural constants of the resulting theory.

Each solution of string theory describes a different universe with different physical constants.

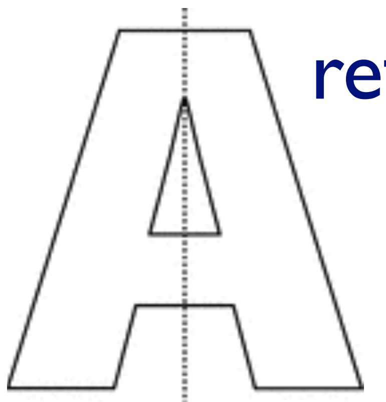
There are $> 10^{500}$ such solutions. It is likely that one of them resembles the universe we live in.



New Symmetries

New symmetries

We are familiar with various symmetries from daily life



reflection symmetry

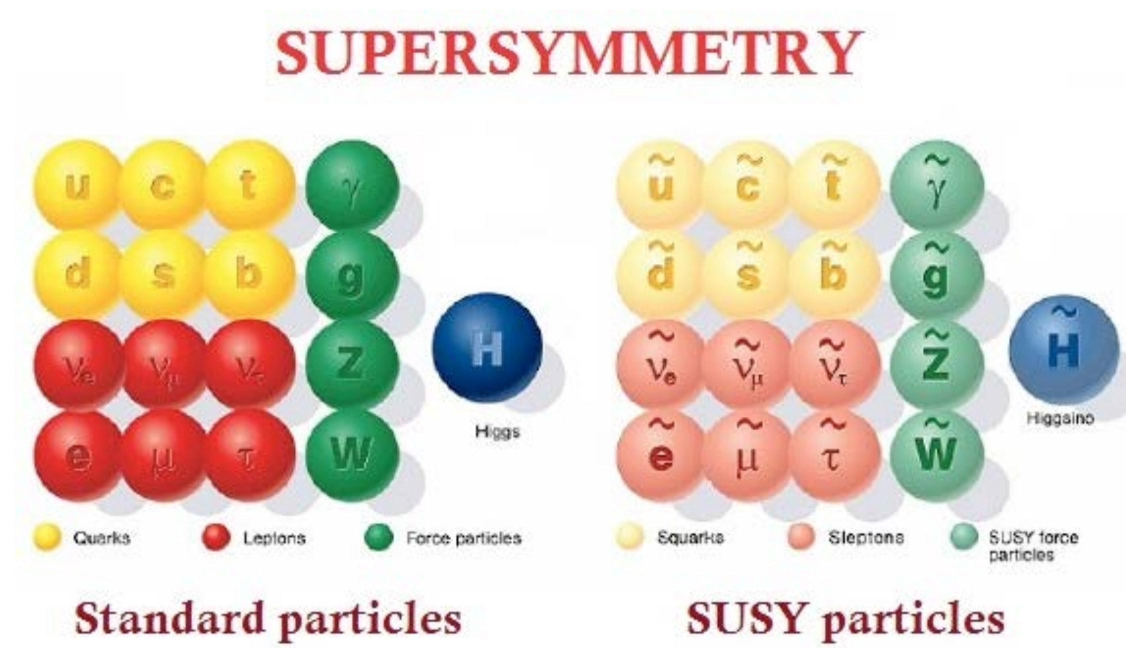
rotation symmetry

and particle physics (gauge groups U(1), SU(2), SU(3)).

String theory also has supersymmetry, which relates fermions and bosons.

Each particle has a superpartner.

Not experimentally observed.



New symmetries

In string theory, we have even more symmetries.

There is T-duality.

Say we have a compactified dimension of radius R.

T-duality states, that the physics of a string theory on this manifold is equivalent to the physics of a manifold with inverse radius 1/R, if we also interchange momentum and winding modes.

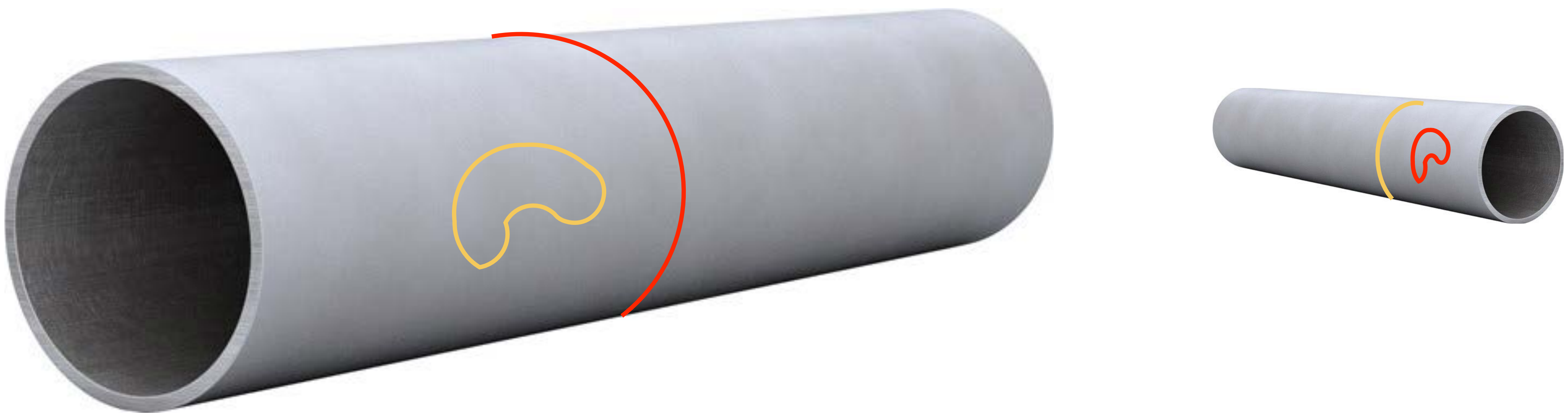
Momentum modes: $E_n = n/R$

Winding modes: $E_m = mR$

T-duality:

$$R \to 1/R$$
$$(n, m) \to (m, n)$$

New symmetries



equivalent configurations under T-duality

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New symmetries

Duality: exact equivalence between two seemingly different systems.

solvable

two descriptions

$$H = H_0 + gH_1,$$
$$= H_0' + g'H_1'$$

Observables given by perturbation series in g (g small!).

Strong/weak duality:

$$g' = 1/g.$$

When g becomes large, the perturbation series in g' becomes an accurate description.

Important tool to study non-perturbative regimes in QFT!

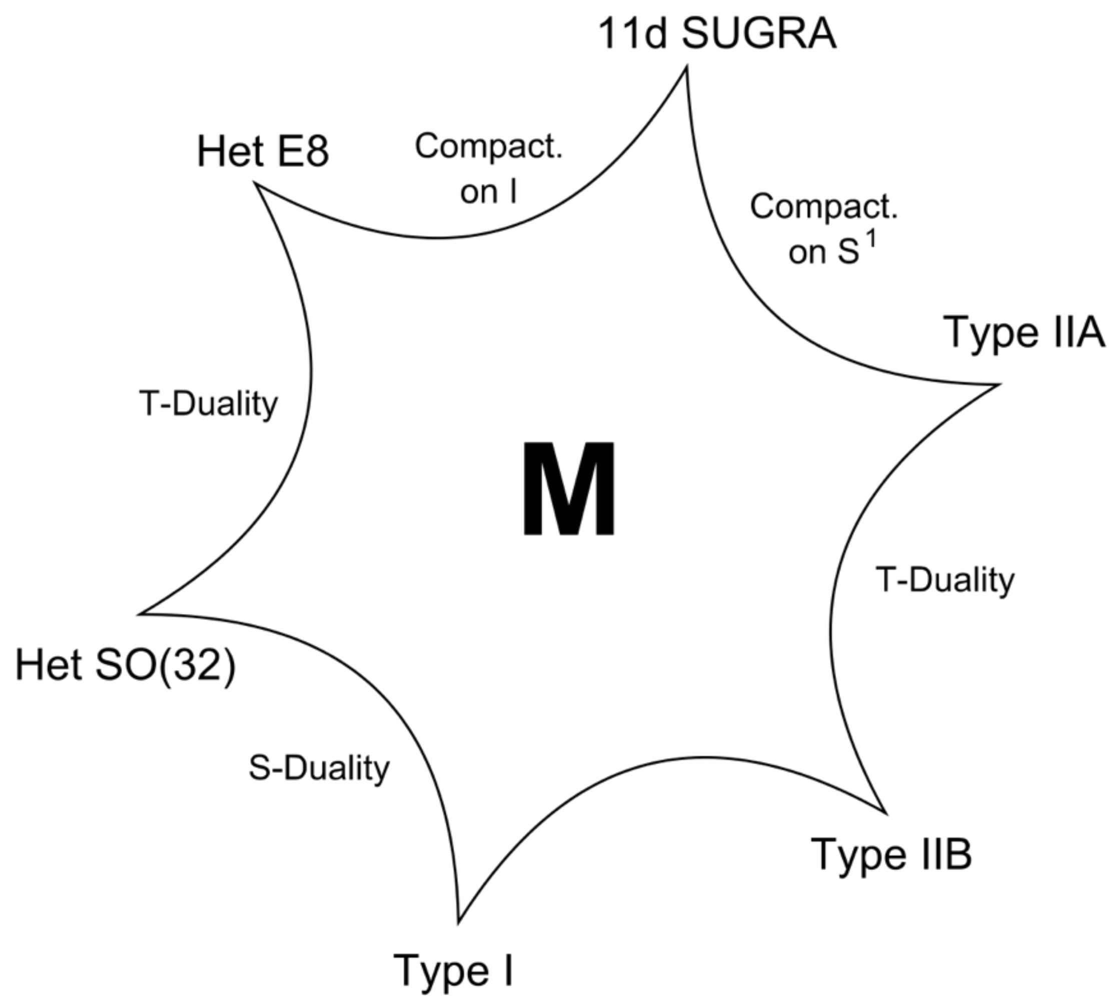
Simplest example: electric/magnetic duality in source-free Maxwell theory.

$$e \to e' = \frac{2\pi}{e}.$$

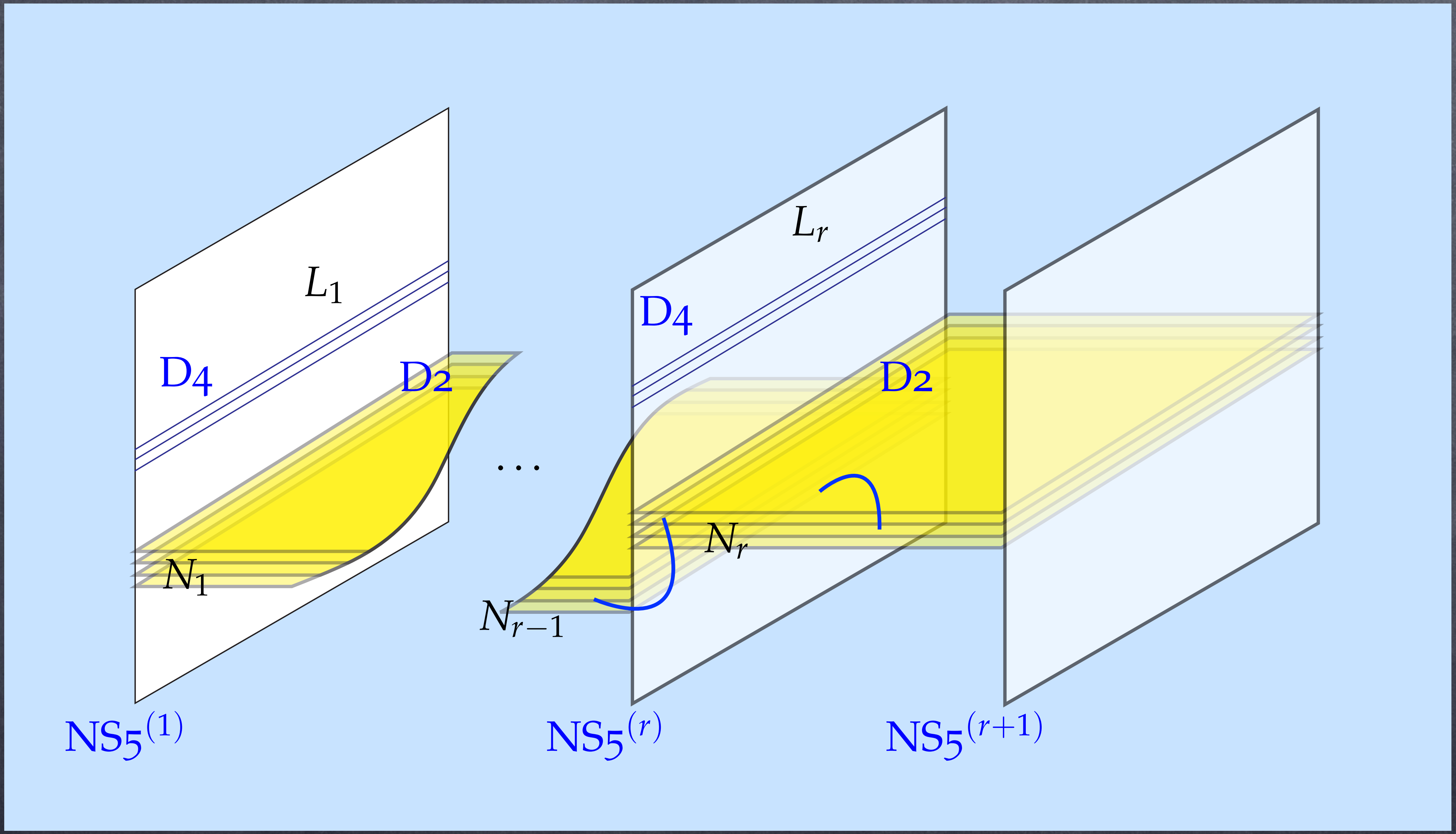
New symmetries

Even more dualities in string theory: S-duality

Different string theories are related via $g' = 1/g$.



Dualities: the five string theories are not all distinct theories but different limits of a single theory called M-theory.

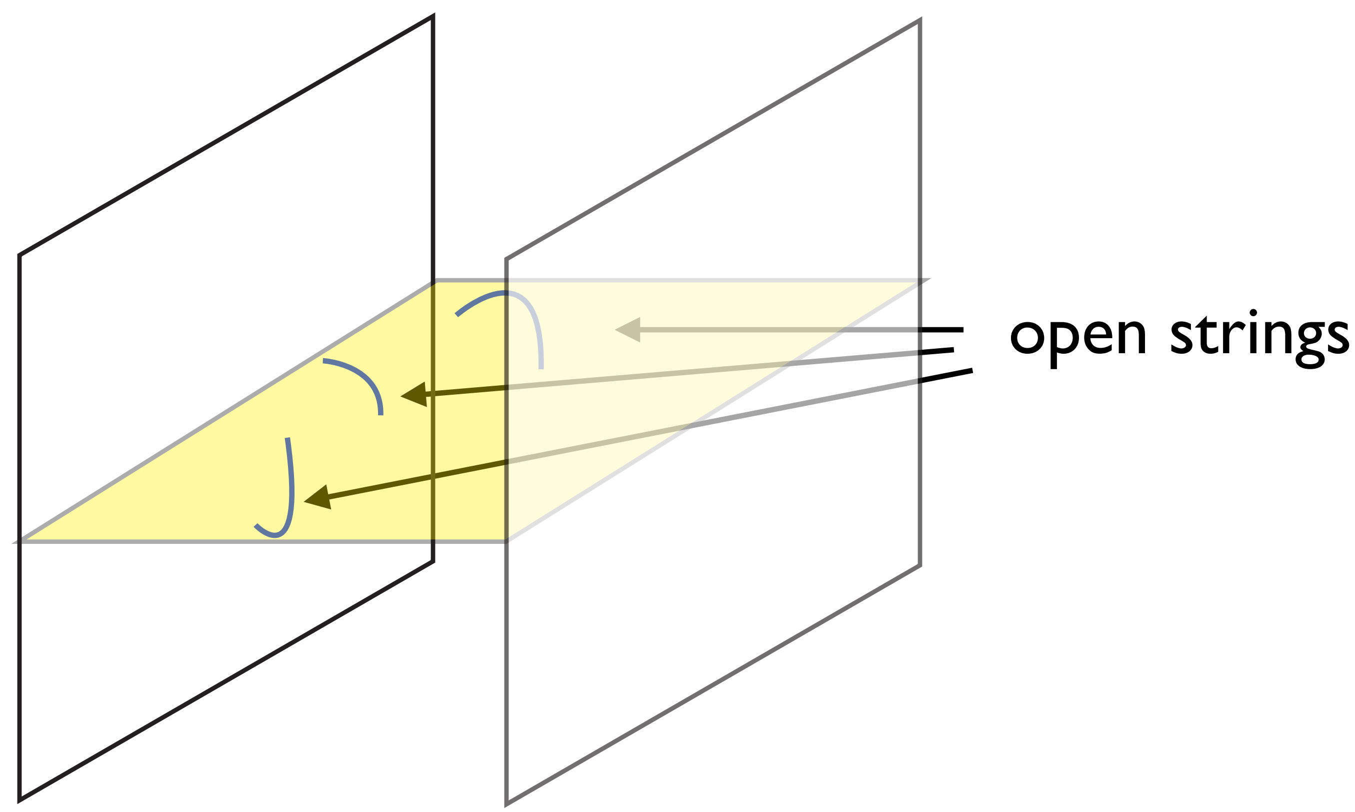


What else do we have?

What else do we have?

Fundamental strings are not the only solutions of string theory.

There are also higher-dimensional dynamical objects in string theory: branes.



String theory is really a theory of strings and branes!

What else do we have?

Types of branes:

- D-branes
- NS5-branes
- O-planes

Dirichlet p - brane (Dp): p+1 dimensional object on which open strings can end. Depending on the type of string theory (IIA or IIB), p can be even or odd, between 0 and 9.

D-branes are dynamical objects and source p+1 form fields.

A Dp-brane breaks half of the supersymmetry of the string theory background (type II: 32 supercharges).

What else do we have?

One Dp-brane has gauge symmetry U(1), the gauge theory is p+1-dimensional. For a stack of N coincident Dp-branes, the gauge symmetry gets enhanced to U(N).

Neveu-Schwarz 5-brane (NS5): extended in 6D.
NS5 branes are solitonic and very heavy compared to D-branes. D-branes can end on them.

Also NS5-branes break half of the supersymmetry of the string theory bulk.

Orientifold plane (Op-plane): p+1-dim. planes that act as a kind of parity inversion. Give rise to SO/Sp gauge theories.

What else do we have?

Branes are actually heavy objects, that cause a backreaction of space-time.

Placing D3-branes into flat space results in a curved geometry: anti-de Sitter space (negative curvature)

There is a gauge/gravity duality, also called the AdS/CFT correspondence.

It relates string theory on (10D) AdS5 x S5 space to a conformal field theory on the boundary of AdS5, which is 4D Minkowski space!

Holographic principle (same information on boundary as in higher-dim. bulk)

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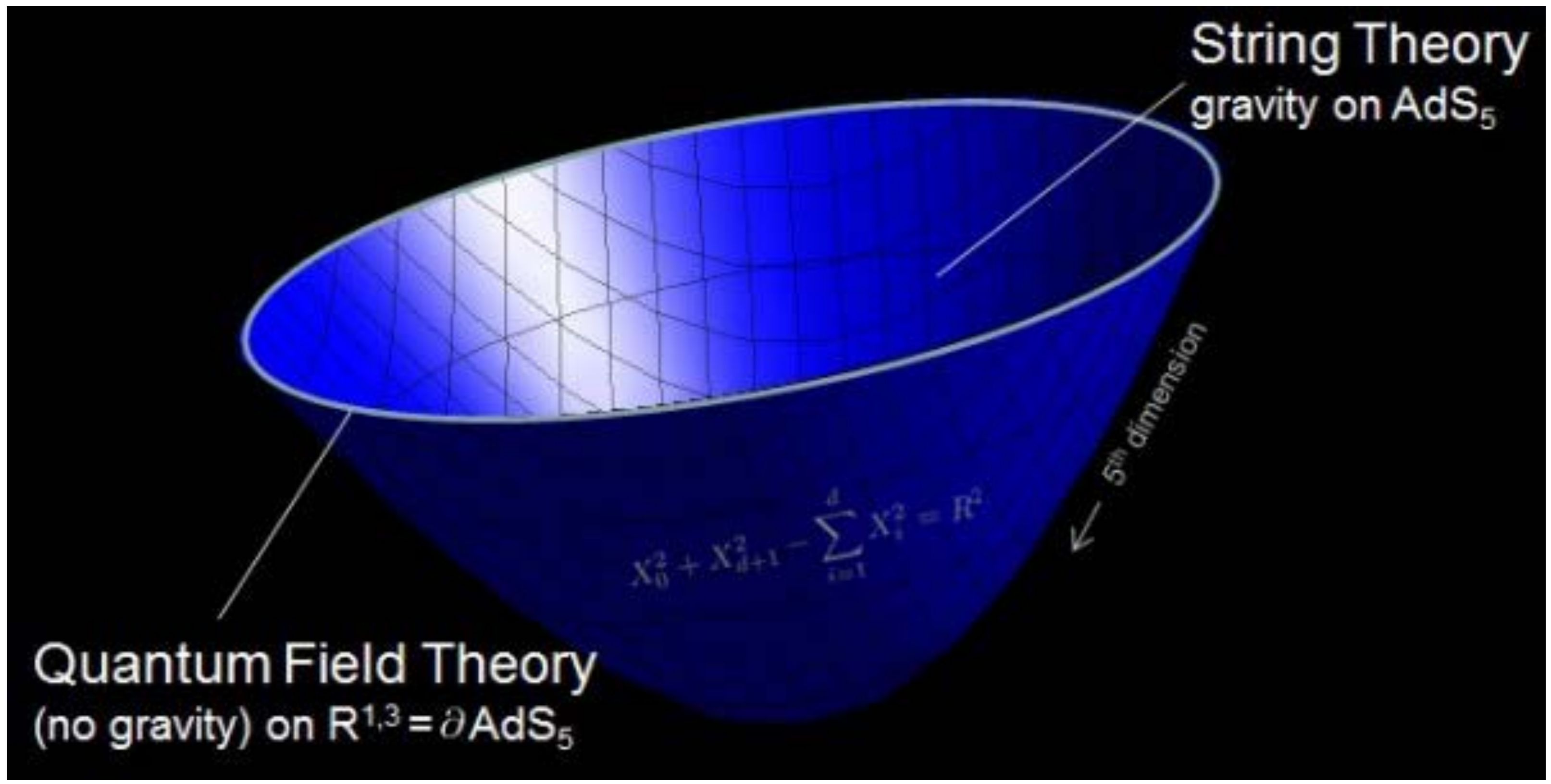
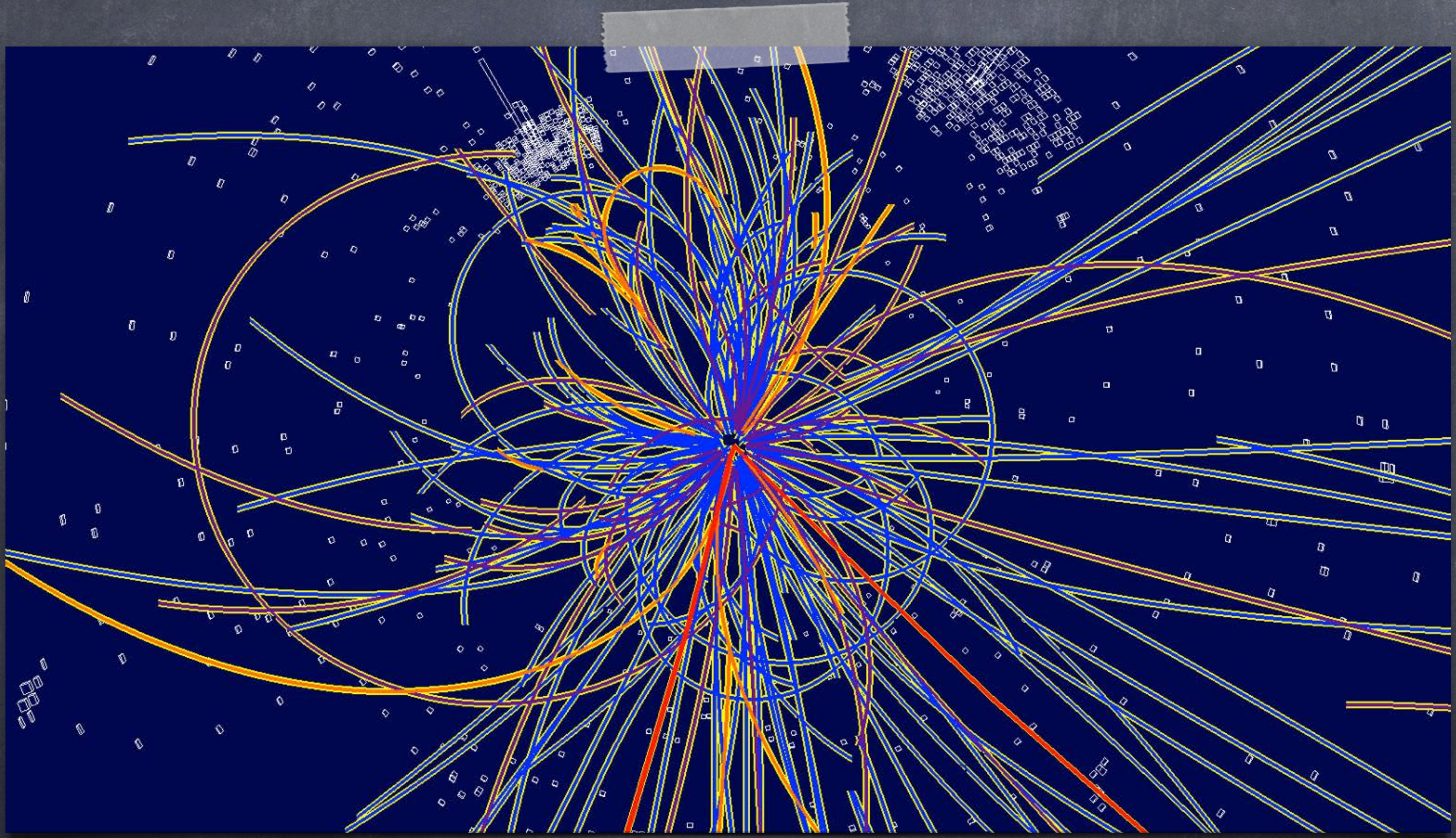
What else do we have?



Strong-weak duality: when the fields of the CFT are strongly interacting, the ones in the gravitational theory are weakly interacting.

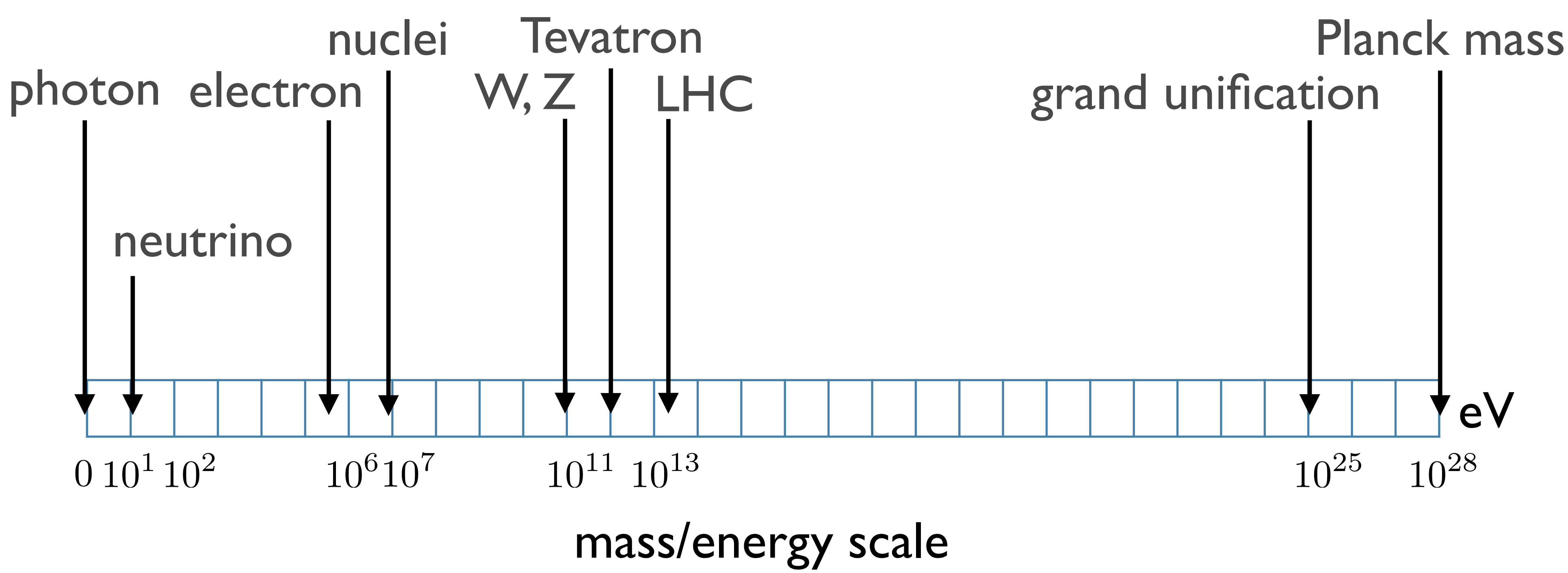


Can we detect it?

Can we detect it?

Q: Can we detect strings directly?

A: Seeing the energy scales involved, this is practically speaking completely out of reach (LHC: 13 TeV (10^12 eV). Strings are visible at 10^28 eV).



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Can we detect it?

Q: Would finding superpartners of the known particles prove string theory?

A: Um… no. It would only prove the existence of (broken) susy. But since supersymmetry is a central concept in string theory, it would be a good sign that we're on to something.

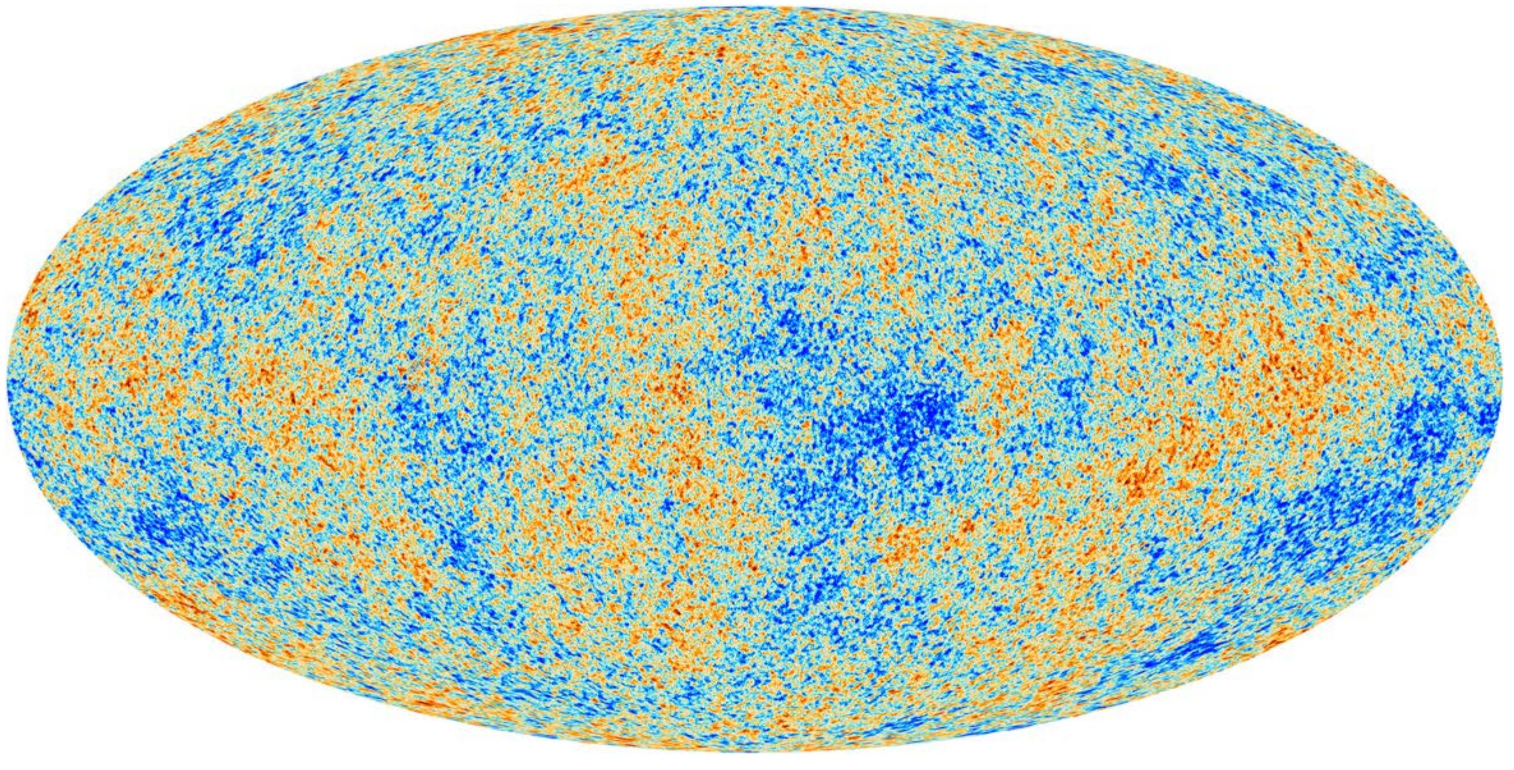
Q: Can we detect the compactified extra dimensions?

A: The extra dimensions may be as large as a 10th of a millimeter. Gravitational experiments (which so far have a sensitivity of about 1mm) could detect them. Smaller extra dimensions could be detected by particle experiments.

Can we detect it?

Q: Is an experimental verification of string theory completely hopeless?

A: No! There are several possibilities.
There are string gas cosmology models, that make predictions (characteristic blue tilt in the spectrum of gravitational waves) which should be testable with the new CMB data within about 5 years!



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Can we detect it?

Another way of testing string theory predictions is via the gauge/gravity duality: use the duality to describe the quantum critical states of high-temperature superconductors.

The detection of a cosmic string left over from the early universe could confirm string theory. Such a cosmic string could stretch across the universe and could be detected by gravitational lensing or via gravitational waves.

As a theory, string theory is still in its infancy, it is far from being completely understood. As research goes on, it will hopefully produce more sharp predictions, which can be tested experimentally.

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Can we detect it?

Q: If we can't (so far) test string theory experimentally, why have you been wasting our time?

A: String theory is a conceptual framework which extends quantum field theory. It is a very good tool to better understand gauge theories which we use to describe the fundamental interactions.

Gauge theories are the fundamental paradigm of particle physics. Despite this, we don't know as much about them as we would like. We need to learn more about gauge theories at strong coupling, non-perturbative effects, confinement, etc.

What can we do with it?

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What can we do with it?

We can use string theory as a tool to better understand our fundamental interactions.

Use it to realize "toy model" supersymmetric gauge theories.

Susy is not experimentally observed, makes the theory less realistic.

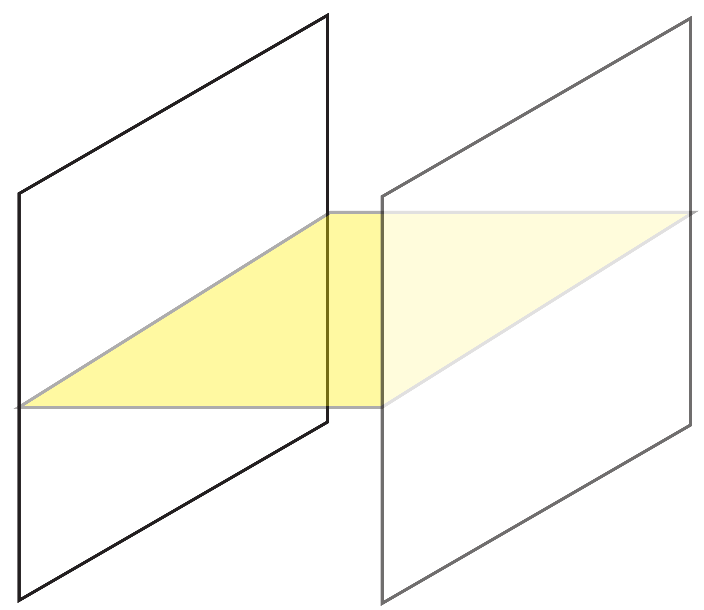
Supersymmetric theories become well-behaved: protected against quantum corrections, exactly solvable.

Get a better understanding of general underlying principles, learn lessons applicable to general case.

What can we do with it?

String theory as a unifying paradigm.

Realize gauge theories by placing branes into the 10-dimensional bulk:



The fluctuations on the world-volume of the branes are encoded by a gauge theory.

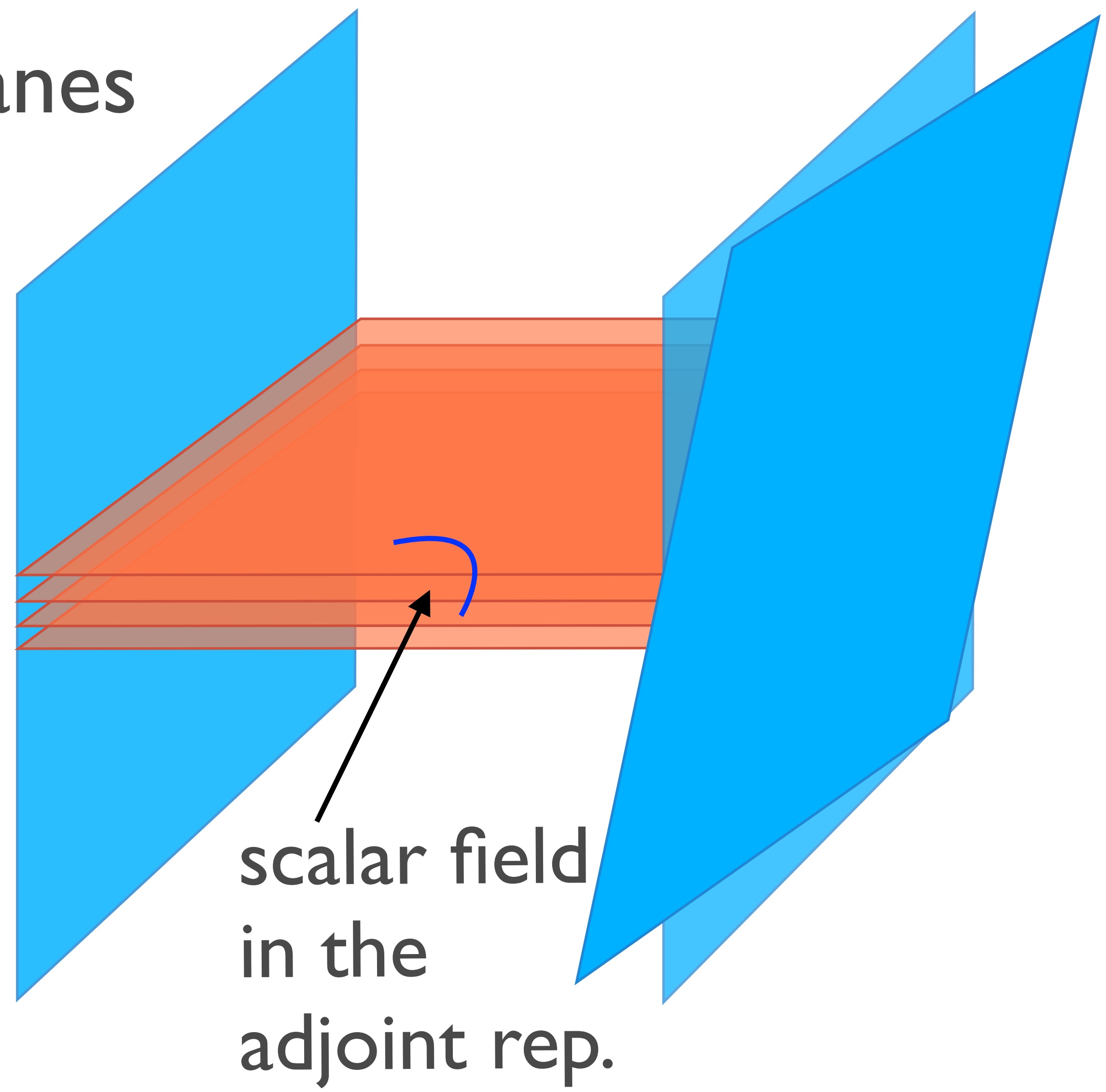
String theory is a superstructure that contains the gauge theories we are interested in.

Example: SQCD in 4D

We want to construct a 4D gauge theory with
- gauge group SU(Nc)
- flavor group SU(Nf)
- N=1 supersymmetry (4 supercharges)

Take Nc D3-branes

Take Nc D4-branes between parallel NS5-branes



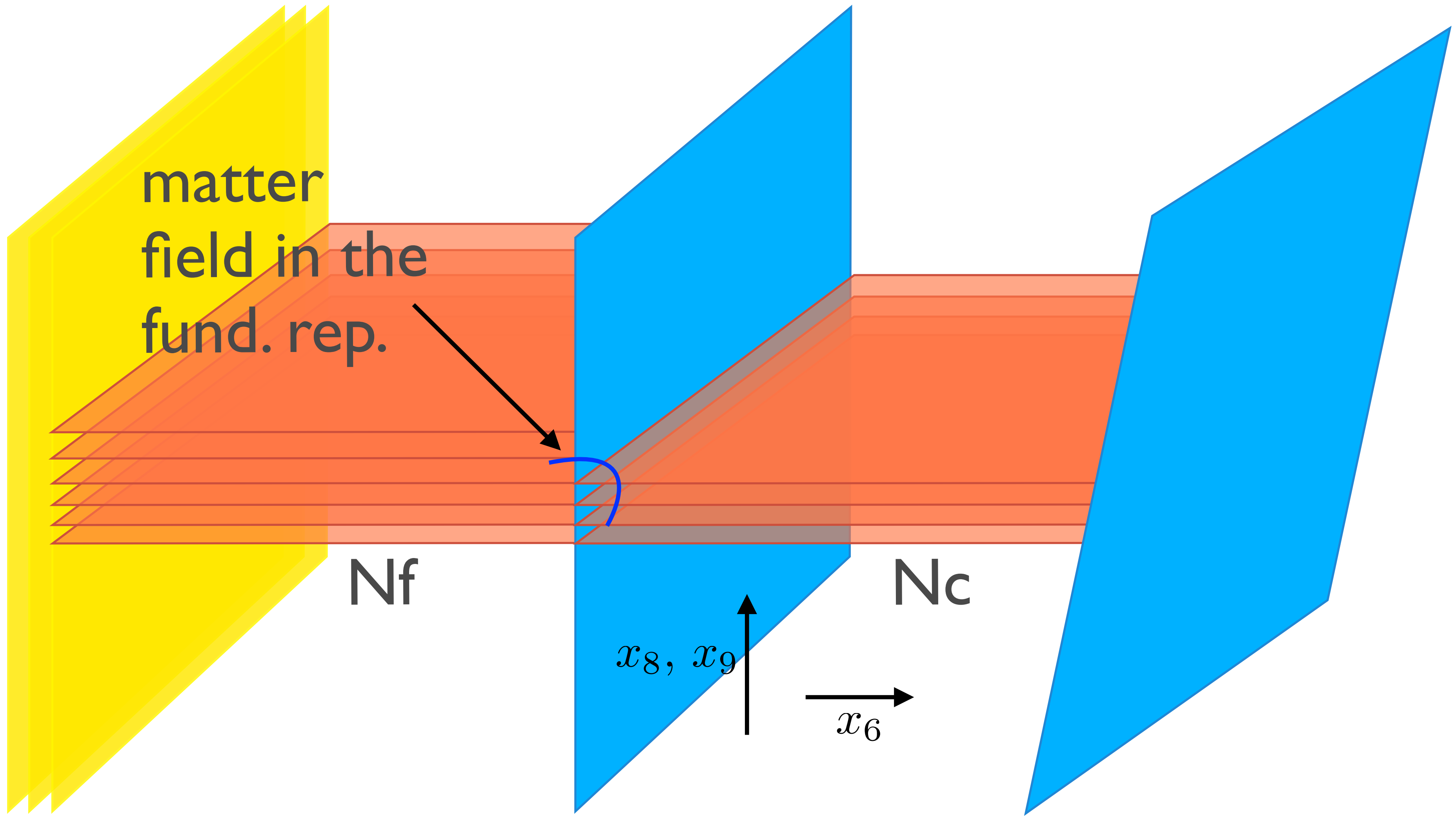
16 supercharges: too much susy

8 supercharges: still too much susy

Take two different NS5-branes: 4 supercharges!

Example: SQCD in 4D

Adding flavor: Nf D6-branes (heavy w.r.t. D4s)



	0	1	2	3	4	5	6	7	8	9
NS	×	×	×	×	×	×				
NS′	×	×	×	×					×	×
D4	×	×	×	×			×			
D6	×	×	×	×				×	×	×

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What can we do with it?

Possible to study susy gauge theories directly with field theoretic methods.

Different approach: embed them into 10D string theory.

This may seem a little roundabout, but it has its advantages.

Some things are actually simpler in string theory, we can get a more intuitive understanding, and a unified approach that works for many different gauge theories.

Things I study via branes:

- Dualities between susy gauge theories
- Deformations in susy gauge theories
- Spectrum of line operators in susy gauge theories

Deformations

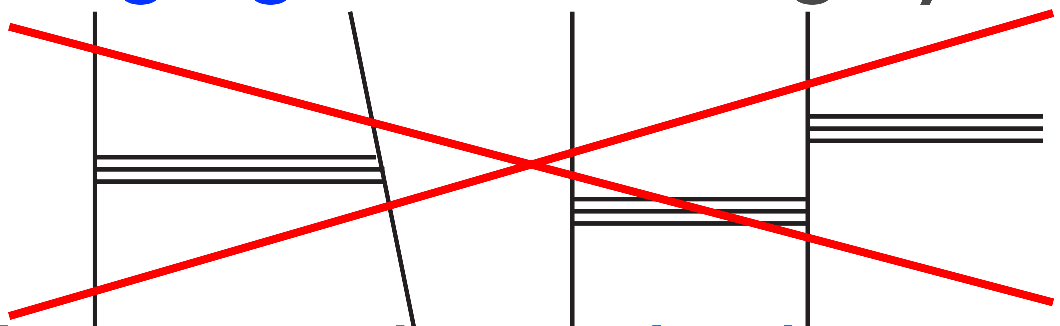
Deformed gauge theory: parameter is turned on which deforms the theory away from a well-understood system while largely retaining its original properties (e.g. mass term).

$$\mathscr{L} = \frac{1}{4g_{\mathrm{YM}}^2}\Bigg[\underbrace{F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\sum_{k=1}^{3}\partial^\mu\phi_k\,\partial_\mu\bar{\phi}_k}_{\text{standard kinetic term}} + \underbrace{\frac{1}{2}\,|\epsilon|^2\,\phi_1\bar{\phi}_1 + \frac{1}{2}\,|\epsilon|^2\,\phi_2\bar{\phi}_2}_{\text{deformation: mass terms}}\Bigg]$$

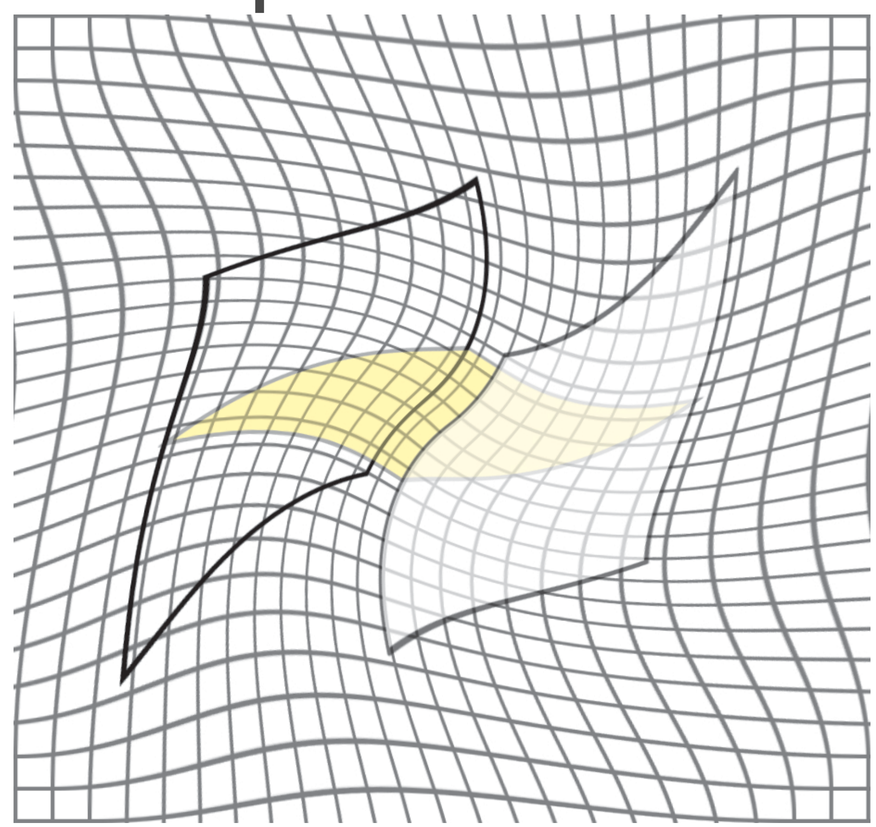
Look at deformations that break some of the supersymmetry in a controlled way.

Deformations in String Theory

Realize deformed gauge theories. E.g. by varying the brane geometry.

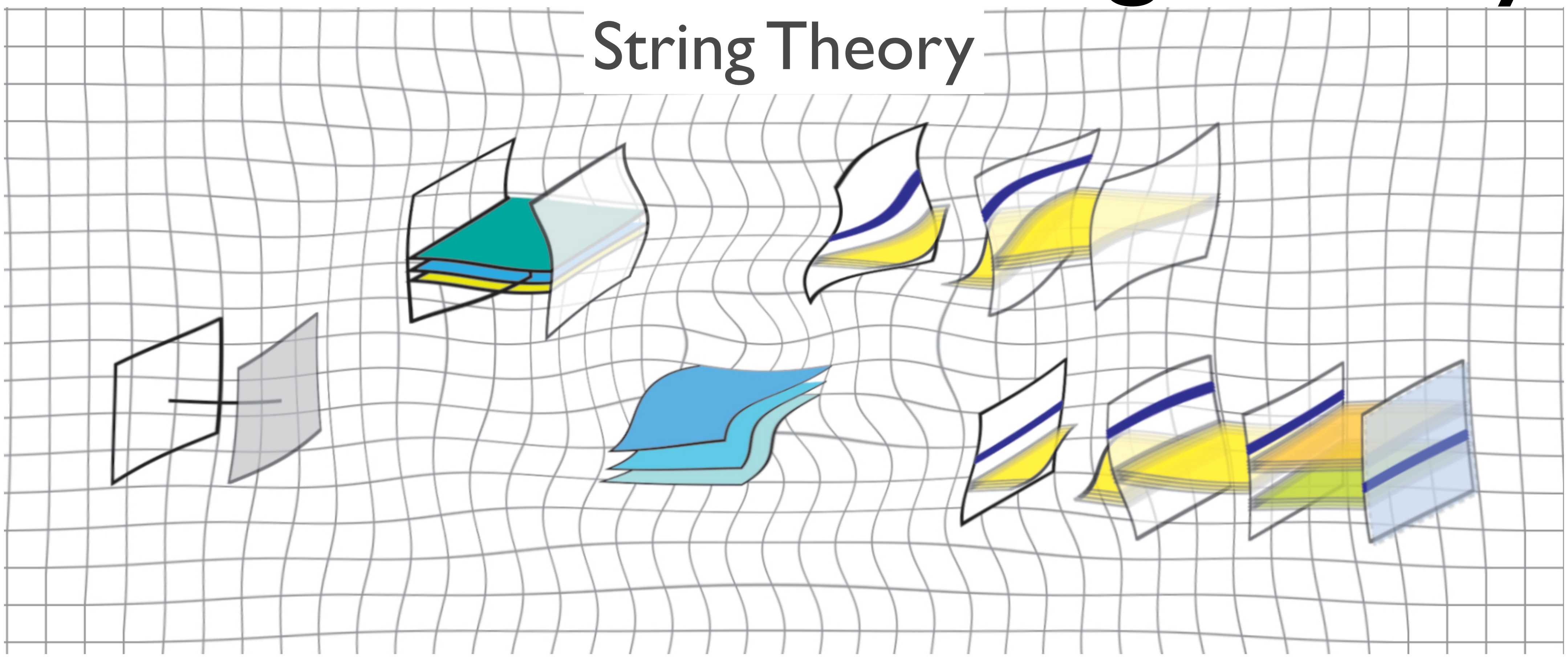


Here: deform the string theory background ("fluxtrap") into which the branes are placed.



⇒ different brane set-ups give rise to different gauge theories with seemingly unrelated deformations!

Deformations in String Theory



Gauge Theory

2D	3D	4D	5D	6D	…

twisted masses Omega-deformation

real masses

Wilson lines mass terms for scalar fields

The same string theory background gives rise to many different deformations!

Summary

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Summary

- In string theory, elementary particles are assumed to be one-dimensional strings.
- Compared to point-particles, string have new degrees of freedom (vibration and winding modes).
- String theory lives in 10 space-time dimensions. For a realistic description of our universe, six of them must be compactified.
- String theory has new kinds of symmetries.
- String theory is also a theory of branes
- Direct detection of strings is out of reach, but indirect test might be possible.
- Whether or not it is the theory of everything, string theory is a useful mathematical framework for the formal study of gauge theories and is here to stay.

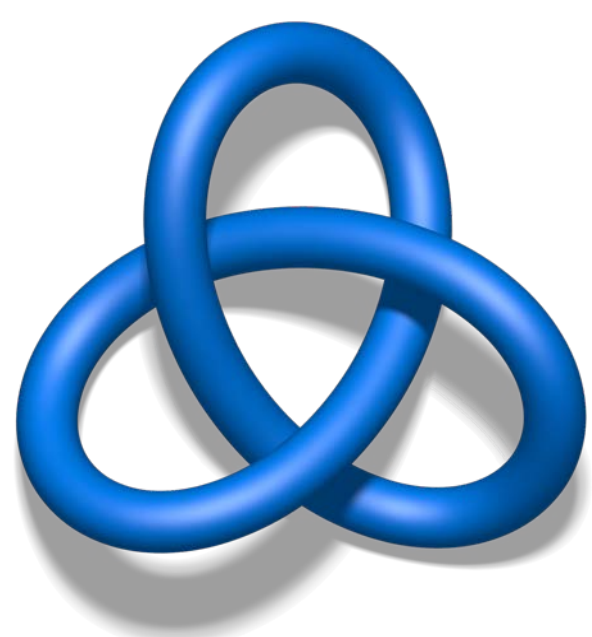
Summary

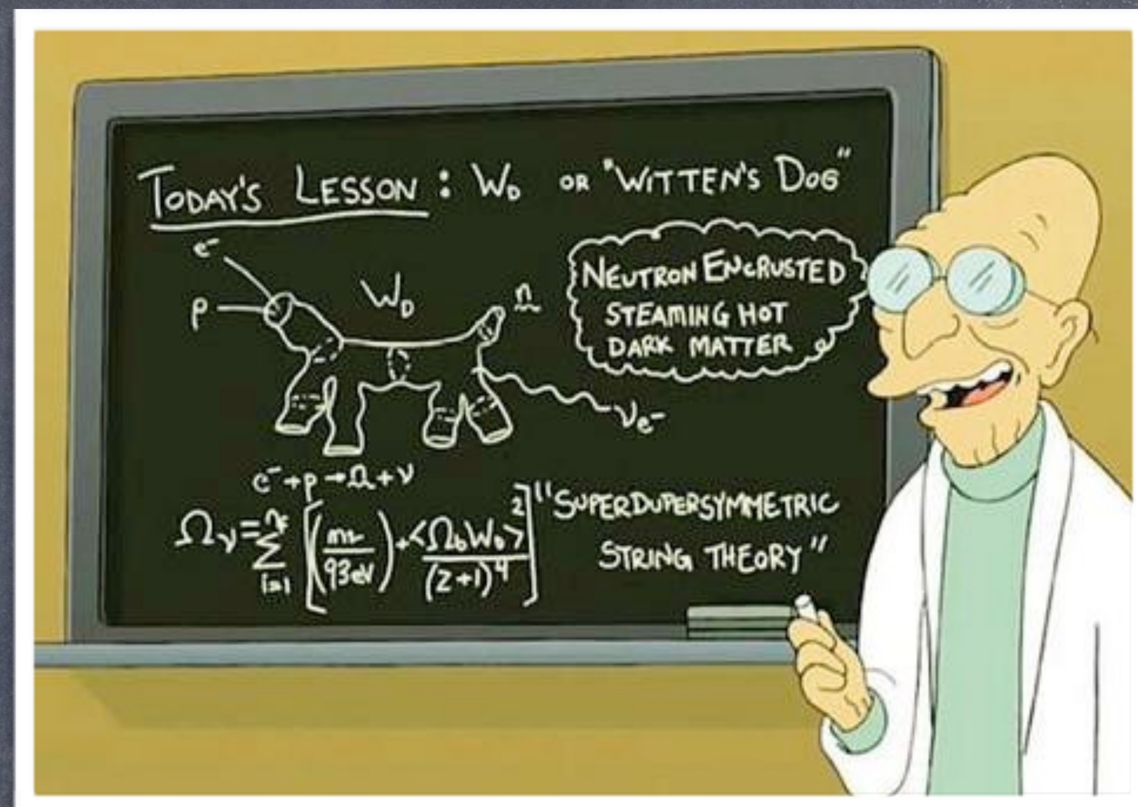
Q: Is string theory the theory of everything?

A: Maybe.

Q: Can string theory research gives us useful insights that lead to a better understanding of the fundamental interactions?

A: Absolutely!





Thank you for your attention!