What is F-theory?

Federico Bonetti

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MAX-PLANCK-GESELLSCHAFT

F-theory is a geometric formulation of strongly-coupled Type IIB string theory

Aim of the talk:

→ **What does it mean?**

→ **Why is it interesting?**

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Introducing strings

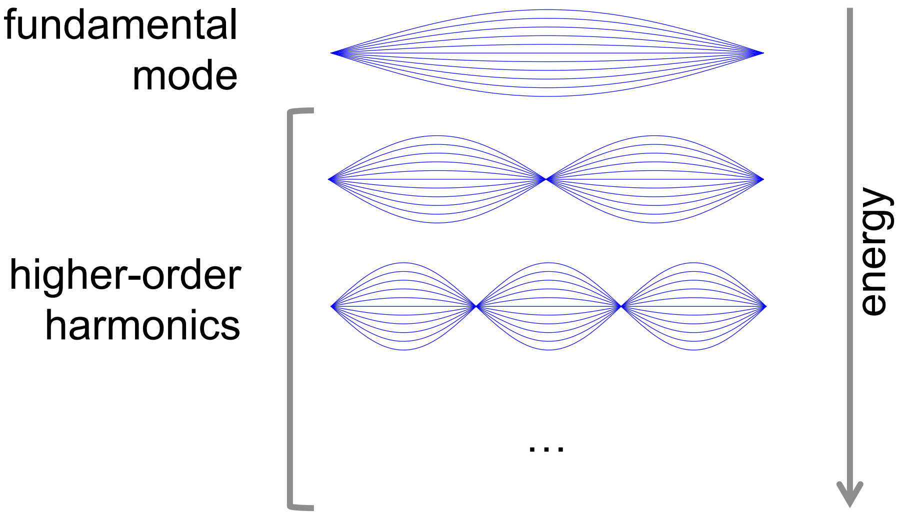
Simple basic idea: replace particles with one-dimensional extended objects

Far reaching consequences: string theory is the best candidate for a "theory of everything"

- quantum gravity
- unification of all known interactions at high energies
- core features of SM physics…
  - gauge bosons, chiral fermions, family replication
- … and coherent framework for BSM physics
  - supersymmetry & grand unification
  - extra dimensions
  - hidden sectors, axions

Vibrational modes

An extended object has both translational and vibrational modes
Tower of normal-modes of oscillation (cf. stationary waves)



After quantization:

a single string describes
different particles
of increasing mass and spin

If string theory is a theory of quantum gravity

typical mass scale ~ Planck mass ~ 10^{19} GeV

All known particles are come from massless excitations in first approximation

Smearing spacetime

Principles of QM:

→ sum over all possible intermediate virtual states

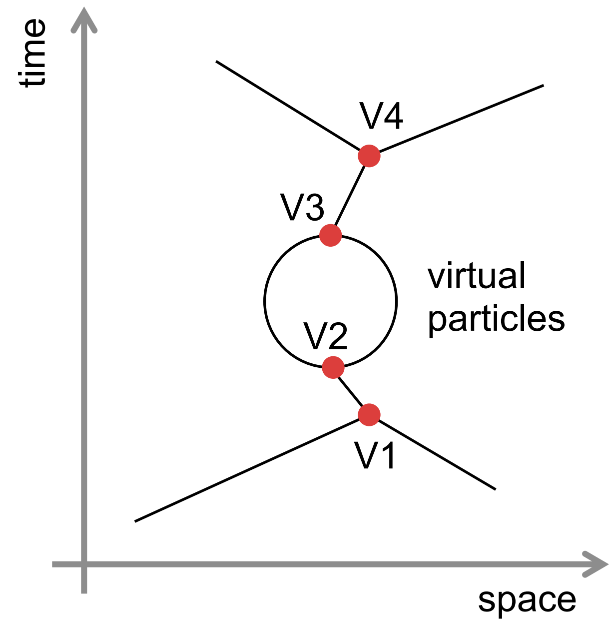
Interactions happen at a specific point in time and space

→ tension with the uncertainty principle

e.g. V2 and V3 can come arbitrarily close

→ unphysical divergence in computations

Particle interactions



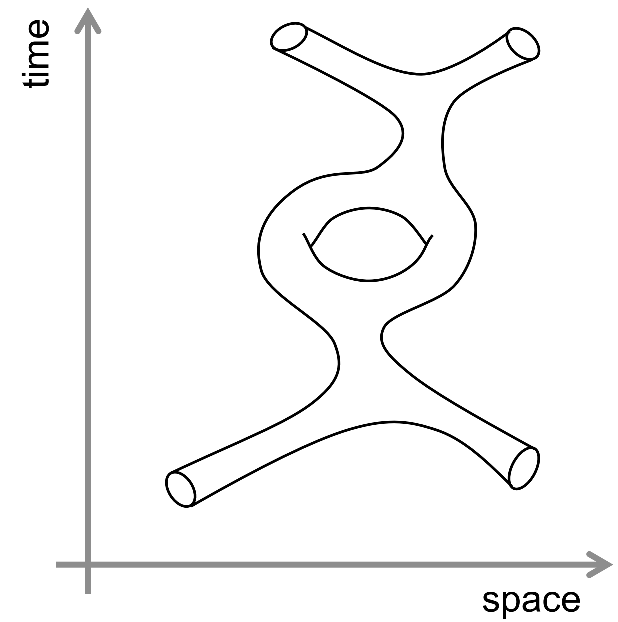
In many theories (including the SM) these divergences can be reabsorbed systematically and we can get unambiguous predictions: renormalization

This is impossible for gravity

Smearing spacetime

The worldline of a particle is replaced by the worldsheet of a string

String interactions



Interactions are smeared out

- the typical length scale of strings provides a natural cutoff
- no arbitrarily short distances
- finite outcome of the computation

Extra bonus:
a single string diagram can describe many Feynman diagrams

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Consistent string theories

The mathematical structure of the theory of a propagating relativistic string is extremely rich

Two mild requirements

1. mathematical consistency
2. physical stability of the vacuum

give very strong constraints on the dynamics of strings

Only 5 consistent theories:
Type I, Type IIA, Type IIB, SO(32) Heterotic, E_8 x E_8 Heterotic

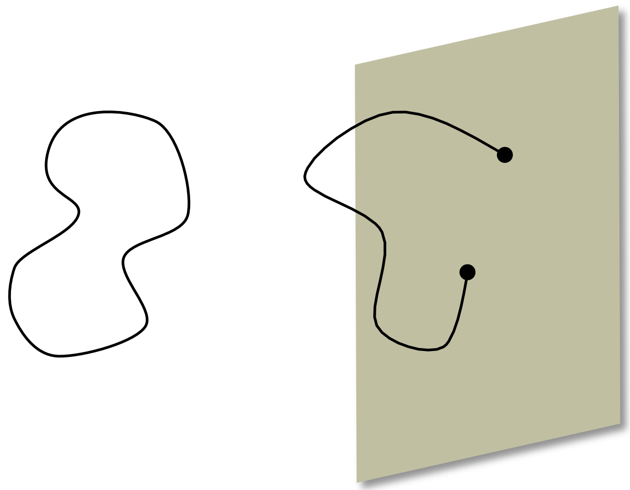
(cf. the infinite number of renormalizable QFTs and the even larger class of EFTs…)

Universal features:

- a massless spin 2 excitation: the graviton
- ten dimensions of spacetime
- supersymmetry
- no free parameter

The basic objects of Type IIB

Closed strings
propagating
in the (9+1)d bulk



Open strings
attached to
Dirichlet *p*-branes

(*p*+1)-dim. subspace
with *p* odd

Massless vibrational modes:

- gravity
- dilaton (a scalar)
- axion
- higher-rank tensor fields
  (a generalization of gauge bosons)
- their fermionic susy partners

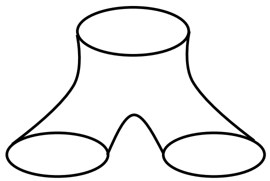
living in (9+1)d

- gauge bosons
- their scalar and fermionic susy partners

living in (*p*+1)d

The string coupling constant

All string interactions can be analyzed in terms of the “panty decomposition”

e.g.: closed strings  ~ g_s

String theories have no tunable parameter

→ what measures the strength of string interactions?

The VEV of the dilaton field:

$$g_s = e^{\langle \phi \rangle}$$

The string coupling constant is determined dynamically and is a property of the vacuum (cf. Higgs VEV)

Explicit string computations are possible when g_s is constant throughout spacetime and everywhere small, but string theory admits also much more interesting vacua

F-theory is a geometric formulation of <u>strongly-coupled</u> Type IIB string theory

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Beyond weak coupling

In many interesting situations interactions are a small perturbation…

$$\mathcal{A}(g) = \mathcal{A}_0 + g\,\mathcal{A}_1 + g^2\mathcal{A}_2 + \ldots \qquad g \ll 1$$

… but in many others $g \sim 1$ (or even $g \gg 1$) and perturbation theory breaks down

Physics at strong coupling can look completely different

e.g.: confinement in QCD, quark/gluons VS mesons/baryons

Non-perturbative effects in string theory introduce new physics. E.g.

- Dirichlet *p*-branes can become light and 'mix' with strings
- New gauge symmetries are possible that are forbidden at weak coupling
- Additional extra dimensions can be generated dynamically!

$\longrightarrow$ from 10d Type IIA to 11d M-theory

S-duality

How is it possible to perform any computation if $g_s \gg 1$?

Type IIB has a powerful symmetry called S-duality that relates physics at strong coupling with physics at weak coupling

Define the "axio-dilaton"

$$\tau = C_0 + ie^{-\phi}$$

dilaton

axion

S-duality acts on the axio-dilaton as

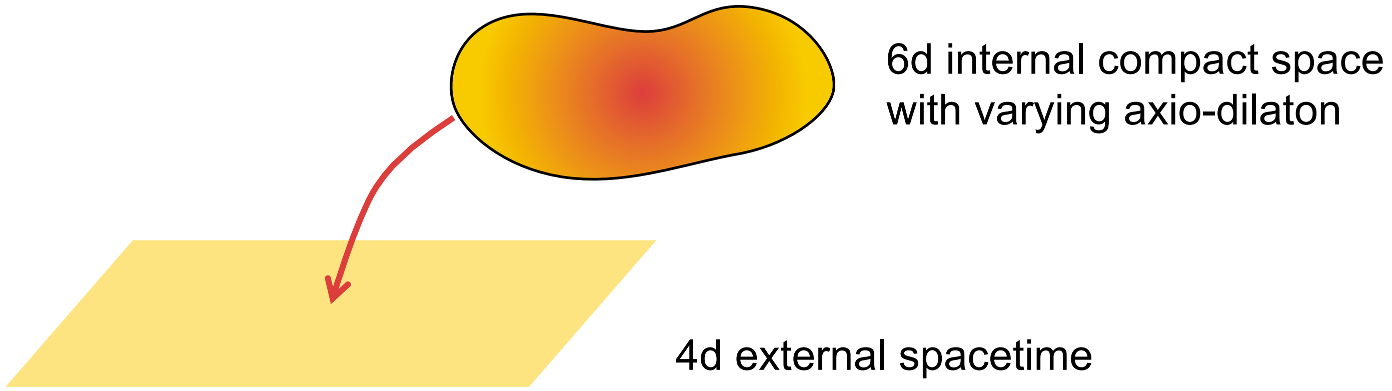
$$\tau \to \frac{a + b\tau}{c + d\tau} \qquad \begin{array}{l} a, b, c, d \ \ \text{integers} \\ ad - bc = 1 \end{array}$$

A special case is $\tau \to -1/\tau$. In the vacuum (if C_0 = 0) this means

$$g_s \to \frac{1}{g_s}$$

Varying axio-dilaton backgrounds

With S-duality we can study vacua where g_s is everywhere constant and large, but we can go even further



The compact space comes with a characteristic length L

At energies $E \ll L^{-1}$ the 6 compact directions are undetectable

NB: a non-constant profile in the internal space is required by some configurations of Dirichlet branes

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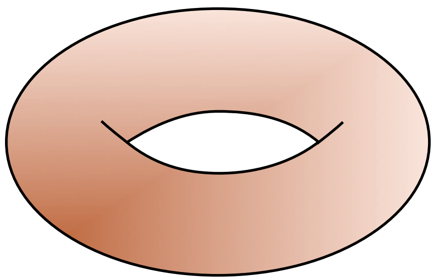
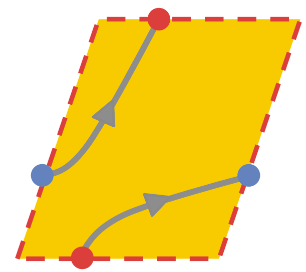
The geometry of tori

Familiar picture: embedding in 3d space
Can be misleading: tori are flat, not curved



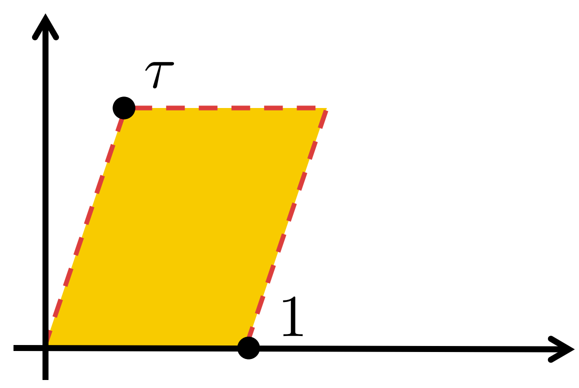
Parallelogram with periodic boundary conditions



We are interested in the shape
but not in the overall size

- rescale the base to unit length

The shape is encoded in a complex number in the upper half plane



Tori and S-duality

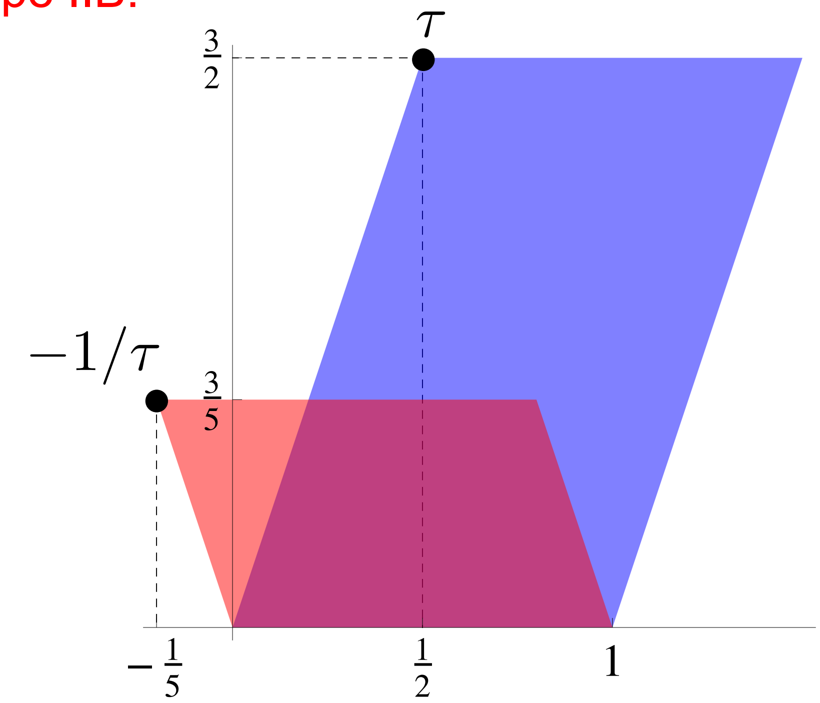
Different values of τ can describe the same shape of the torus

The choice of the side that is rescaled to 1 is arbitrary
We can swap the sides of the parallelogram acting on τ

$$\tau \to -\frac{1}{\tau}$$

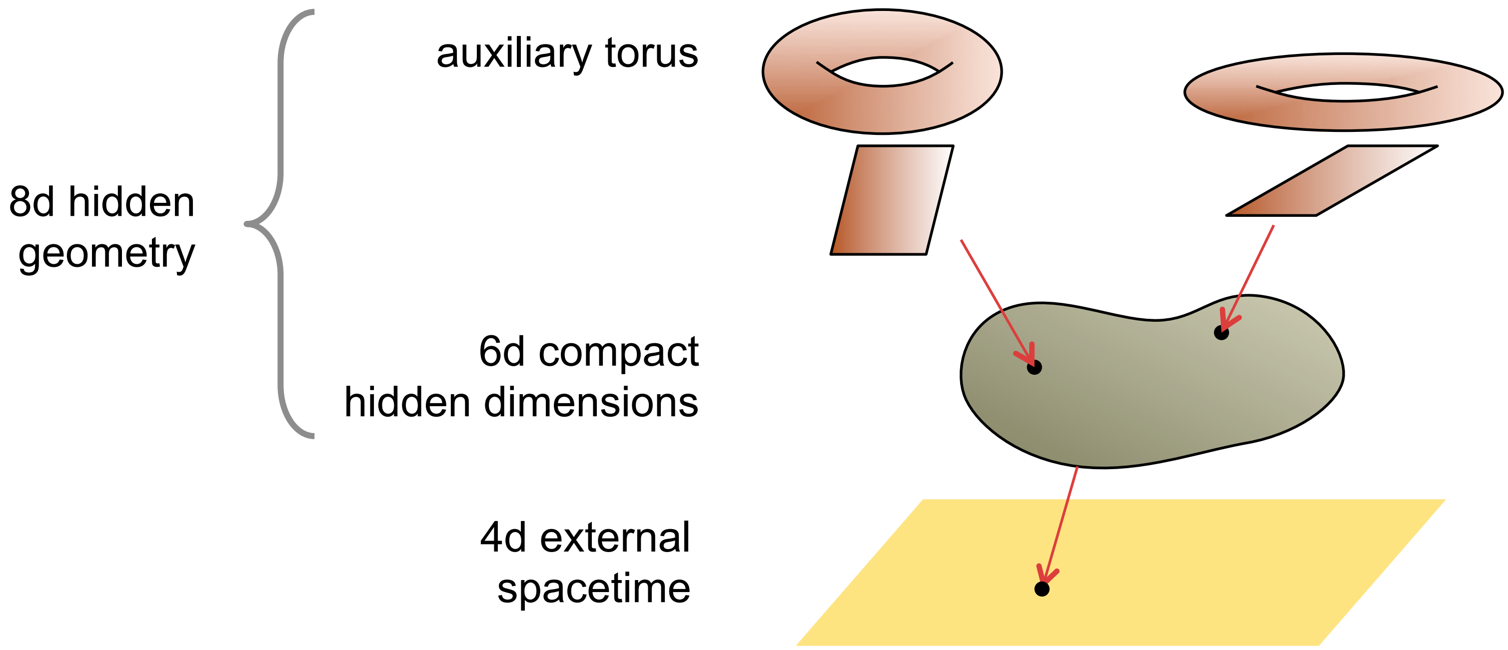
Same symmetry as the axio-dilaton of Type IIB!

This consideration is generalized:
all symmetries of the axio-dilaton
can be interpreted as symmetries
of a torus



Auxiliary torus to describe how the axio-dilaton varies over the internal space

F-theory compactifications



- 8d hidden geometry: torus fibration over 6d base space
- Geometry encodes
  - varying axio-dilaton profile over the base
  - data of 4d low-energy physics (gauge group, matter, couplings…)

Degenerate tori

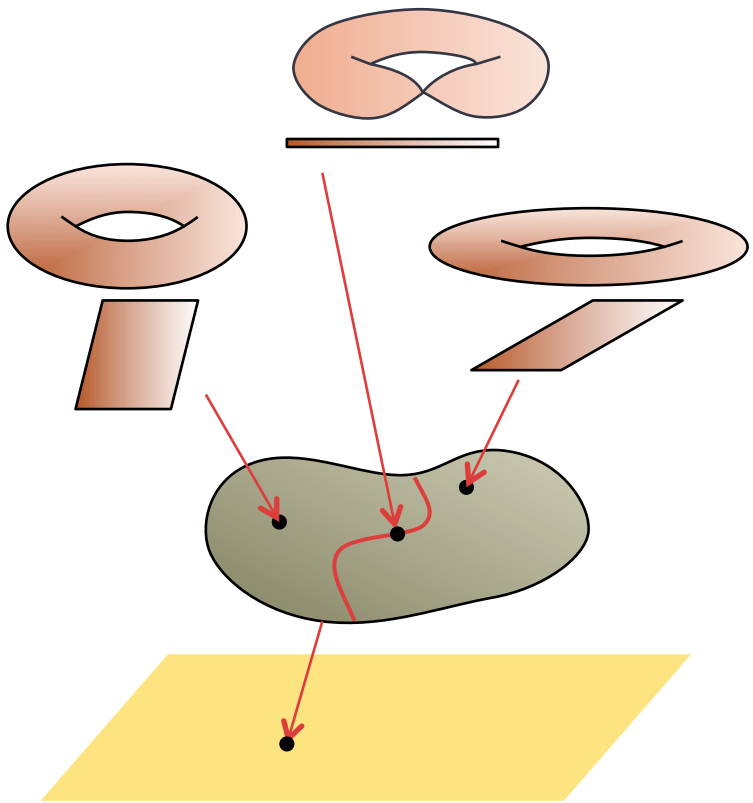
The torus is allowed to pinch over some points on the base

↓

spacetime-filling 7-branes

↓

non-Abelian gauge theory in 4d



Strong-coupling effects allow for gauge groups that cannot be found in weakly coupled Type IIB

If the geometry becomes even more singular:

- charged chiral matter
- Yukawa couplings

New F-theory constructions

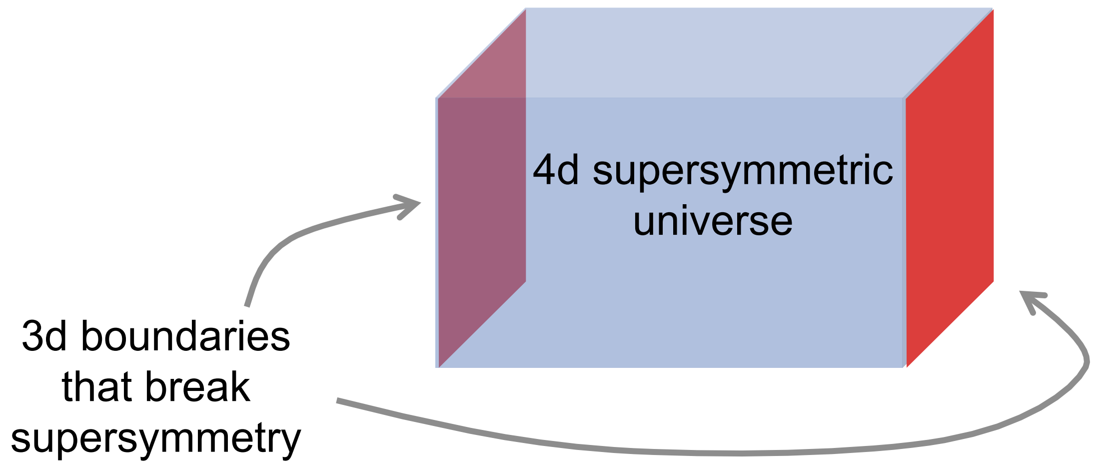
F-theory is well understood if the 8d hidden geometry is a Calabi-Yau manifold

- ➢ supersymmetry in 4d external world

Can we make sense of F-theory on more general geometries?
Can this give a non-supersymmetric 4d theory in a controlled way?

We have recently explored these possibilities: F-theory on Spin(7) manifolds

At low energies:
bulk + boundary



F-theory compactifications might be richer than expected…

Thank you!