String Theory : Failure or Victory?

Mehdi Ameri

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FERDOWSI
Department of Physics
دانشگاه فردوسی مشهد

What we will learn in this lecture ...

- **Historical Overview**
- **Problems with Quantizing Gravity**
- **Introduction to String Theory**
- **Supersymmetry**
- **Types of String Theory**
- **Compactification and the Real World**
- **Conclusion: failures and victories**

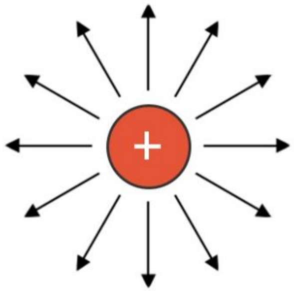
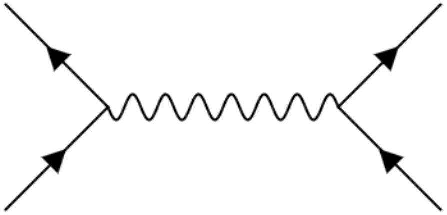
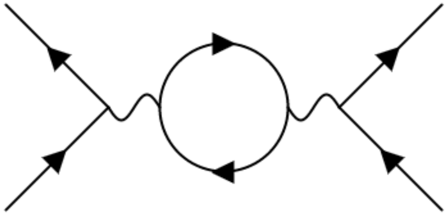
Historical Overview

Historical Overview

Early Beginnings (1900-1960)

- Development of Quantum Mechanics

- The birth of Quantum Field Theory and S-matrix theory

- Field quantisation introduces quanta (particles):
- Electromagnetism: Photon
- Strong nuclear force: Gluons
- Weak nuclear force: W^+, W^- and Z bosons
- Gravity: Graviton (?!)

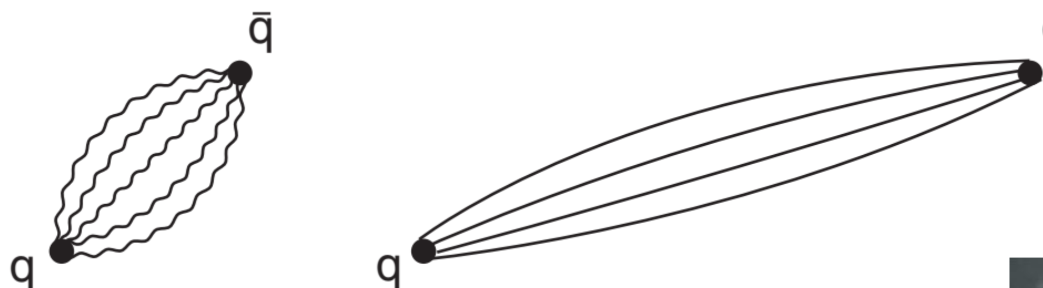
- Matter fields (fermions): Electrons, Quarks, Neutrinos, …

Historical Overview

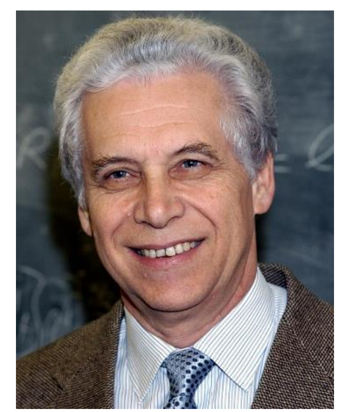
Emergence of String Theory (1960s-1970s)

- Fundamental unit of matter as extended objects rather than point-like entities

- Birth of **hadronic string theory** (before QCD): Explanation for strong nuclear force



- Veneziano model (1968)



Historical Overview

First Superstring Revolution (1980s)

- Superstring theory: String theory + Supersymmetry
- Unification of all fundamental forces, including gravity.

Second Superstring Revolution (1990s)

- M-theory
- Holography
- Compactification
- Brane Cosmology

Modern Developments (2000-present)

- Relation to low-dimensional gravity theories
- Relation to deeper mathematical structures (Number theory, Category, etc)
- *Waiting for a new revolution!!!!!*

Problems within Original Quantum Gravity

Can we quantize gravitational field like other fields?!

- **Classical Gravity**
  - Newtonian Gravity (non-relativistic)
  - General Relativity (relativistic, geometry of spacetime)

- **Semi-Classical Gravity**
  - Studying quantum mechanics in curved space-time (fixed background)
  - Gravitational back-reactions are assumed to be negligible
  - Hawking discovered black hole radiation in this limit

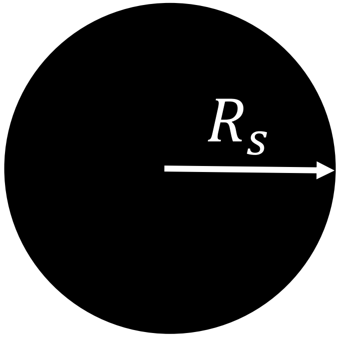
- **Quantum Gravity**
  - We know that nature is quantum mechanical (gravity as graviton)
  - Gravity must also be quantum for **consistency** with the **other fundamental forces**
  - Its effects mostly play a role in the **early universe** and **black hole thermodynamics**

$$G_N \sim \hbar \sim c \sim 1$$

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} \sim 1.61 \times 10^{-35}$$

$$\lambda > R_s$$

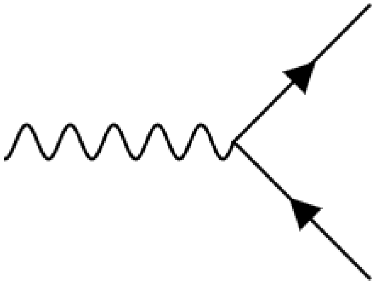
λ: de Broglie wavelength



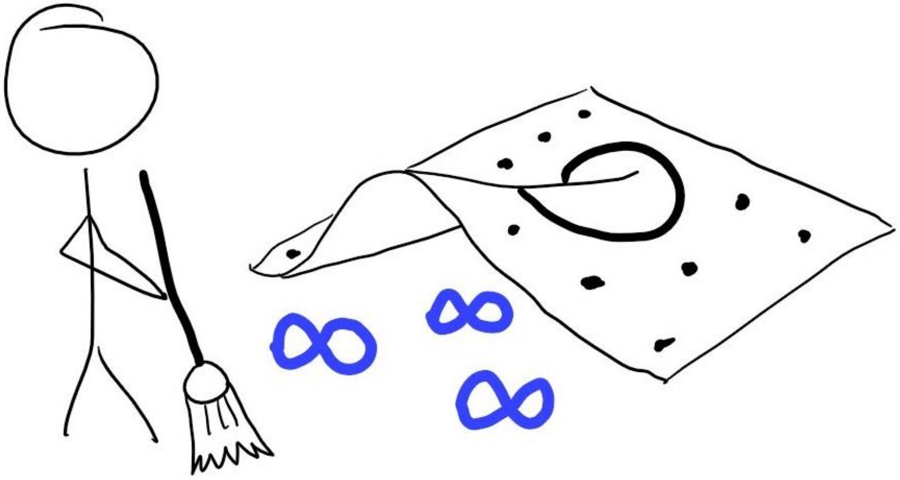
- **Problems with quantizing gravity (by QFT techniques)**
  - Without a cut-off on energy, the entropy of black hole will be infinite!
  - The wave function possesses a **non-unitary** collapse in the gravitational field!
  - It’s ***Non-Renormalizable*****!**

- **Renormalization**

- Addresses the infinite quantities that arise in the calculations of particle interactions

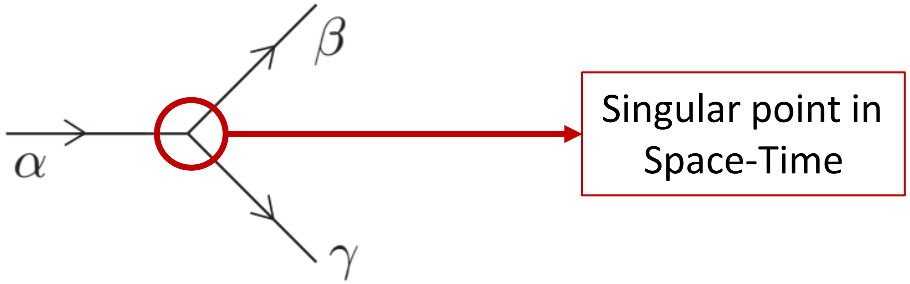


- Modifying the original parameters of the theory (like masses and coupling constants) to absorb infinities and yield finite, physically meaningful results

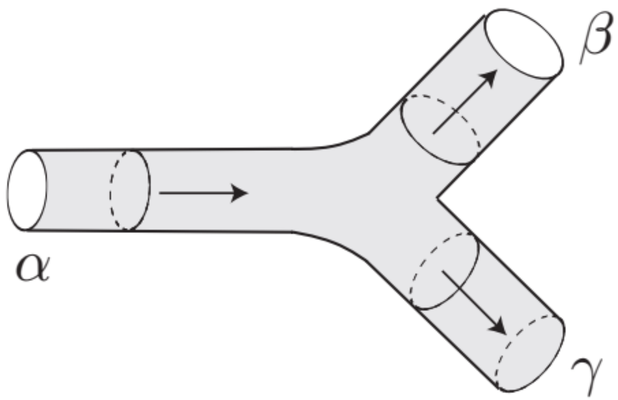


- **Renormalization**

- We **can't** absorb infinities in quantum gravity (quantized by QFT techniques):



- String theory offers a ***solution*** to the problem of quantum gravity by considering the fundamental objects as **strings:**



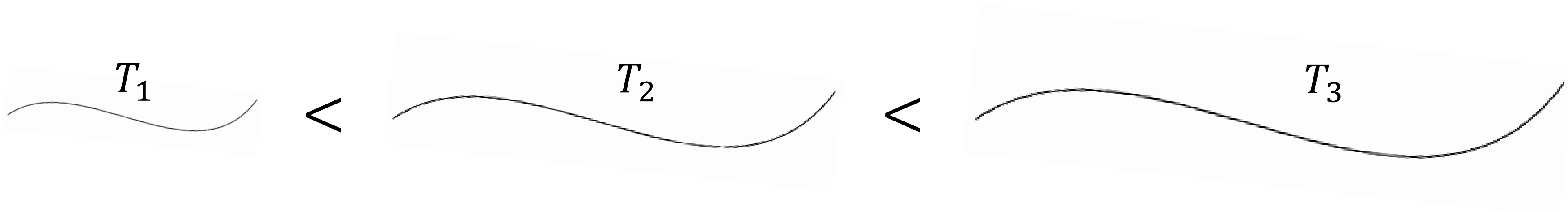
- **Other Candidates**
  - Loop Quantum Gravity (LQG)
  - Causal Dynamical Triangulations (CDT)
  - Asymptotic Safety
  - Entanglement Gravity
  - SU(∞)-Quantum Gravity

Introduction to String Theory

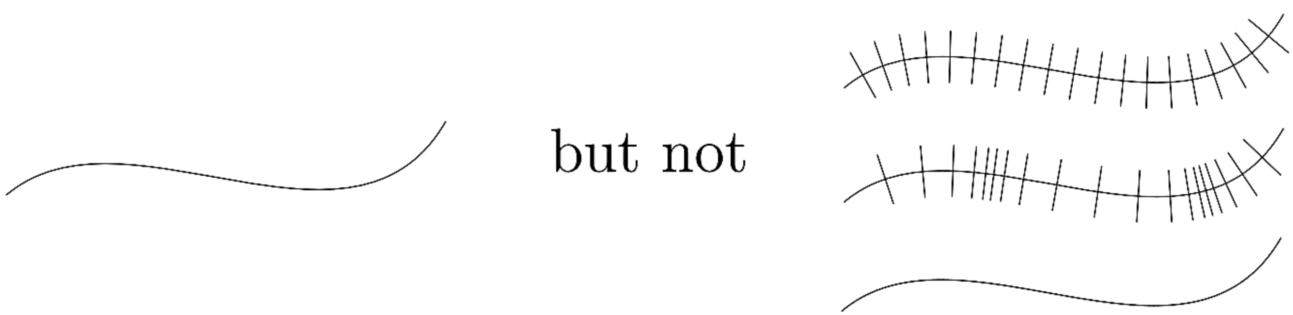
Introduction

- String theory describes the **mechanics** of **one-dimensional** (relativistic) extended objects in an ambient space:

- Particles have mass M. Strings have tension T:

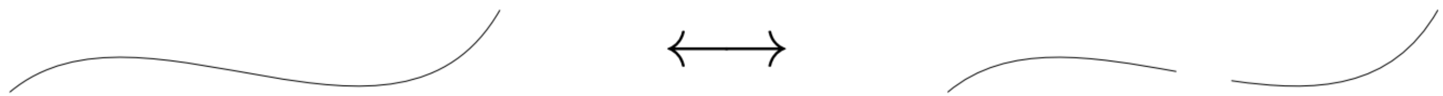


- Strings have no inner structure (it's fundamental):



Introduction

- Several pieces of string can **interact**:



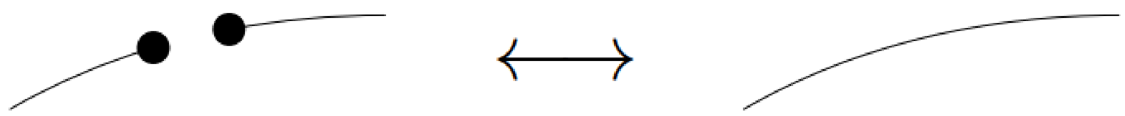
- Strings can be **classical** or **quantum**:

- Strings can be **open** or **closed**:

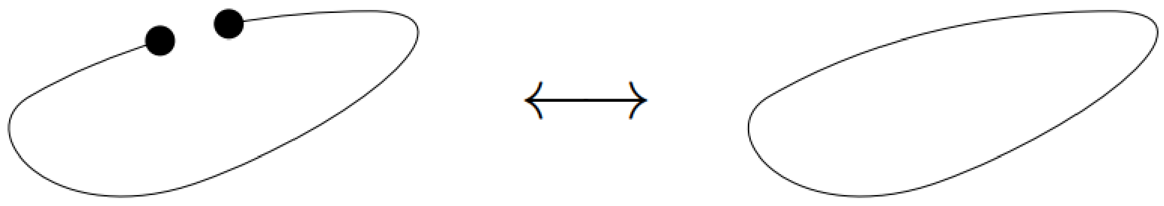
- The string length (l_s) is scaled with the **Planck length** $\boldsymbol{l_p}$

Introduction

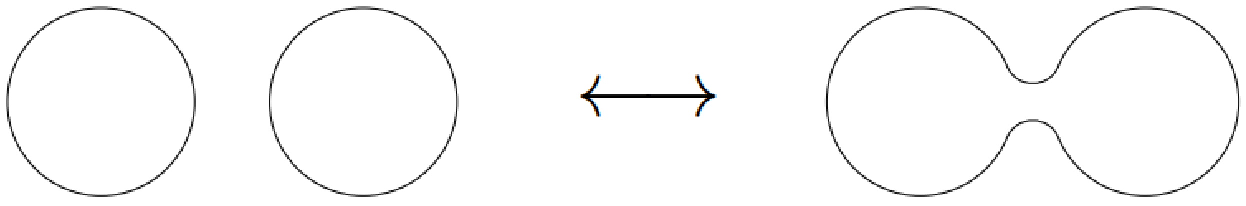
- Interactions of open strings certainly involves that two ends of string can ***join***:



- When the two ends belong to a single open string, this string closes:

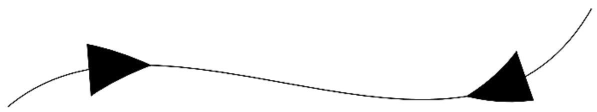


- Closed strings can live on their own with interactions splitting or joining stings:

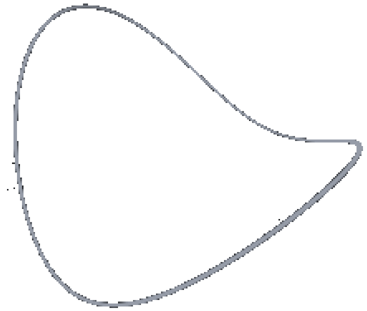


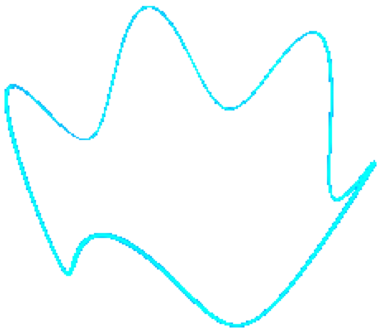
Introduction

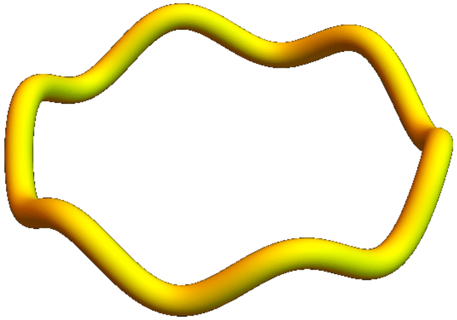
- Strings can carry charge with specific direction:



- Strings can have different vibrating modes:

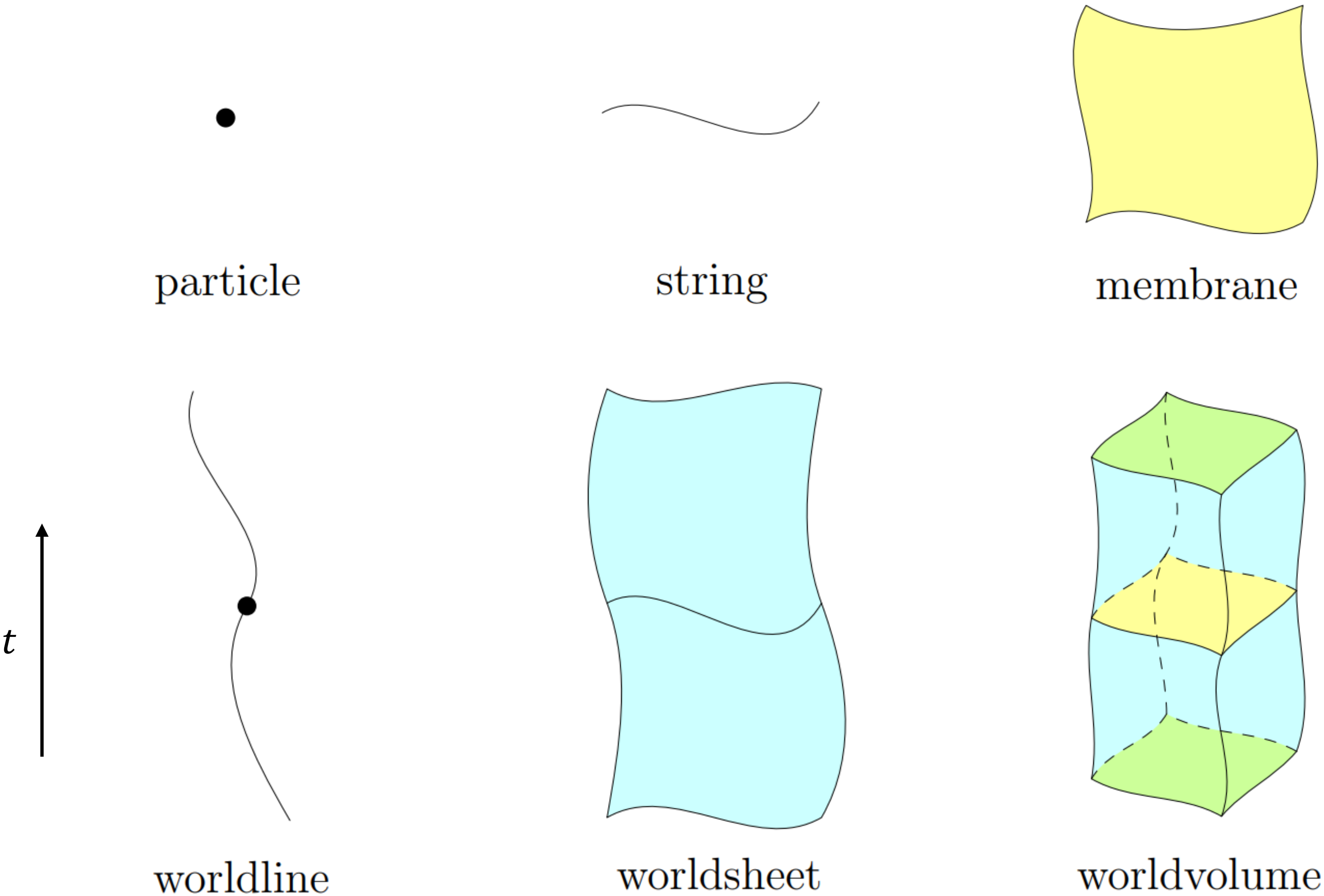






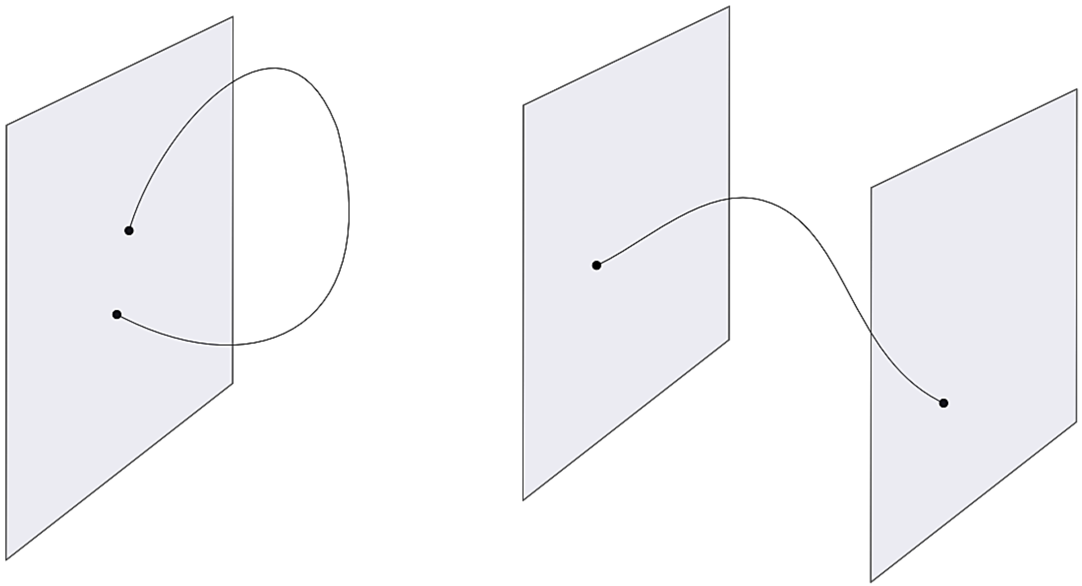
Introduction

- There can be other (higher dimensional) extended objects:



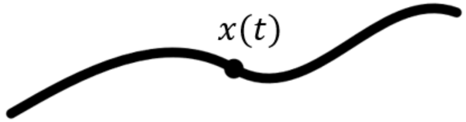
Introduction

- **Open** strings ends are confined to so-called "**D-branes**":

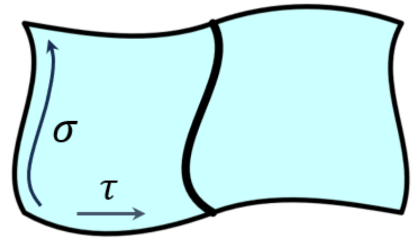


- D-branes has a well-known dynamics and shows the excitation of open strings
- One can show (Bosonic) string endpoint moves with the speed of light

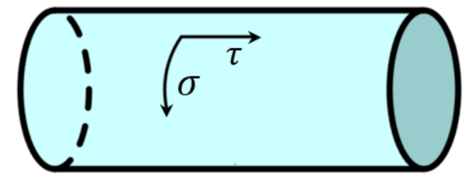
Introduction



World-line



World-Sheet (Open String)

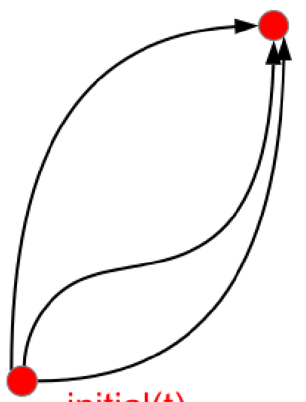


World-Sheet (Closed String)

Riemann Surface

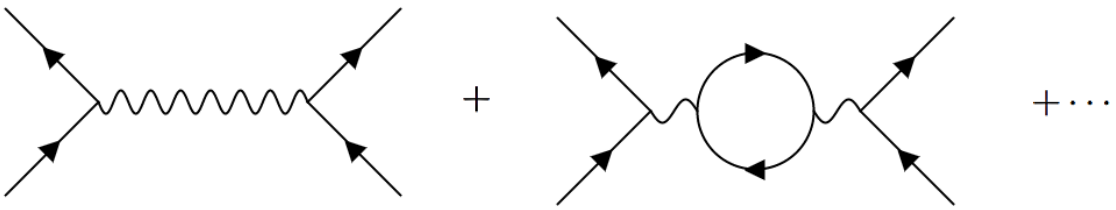
- A particle follows the maximum lifetime trajectory in the space-time (**shortest path**)

- Similarly, string should follow the **minimum area**

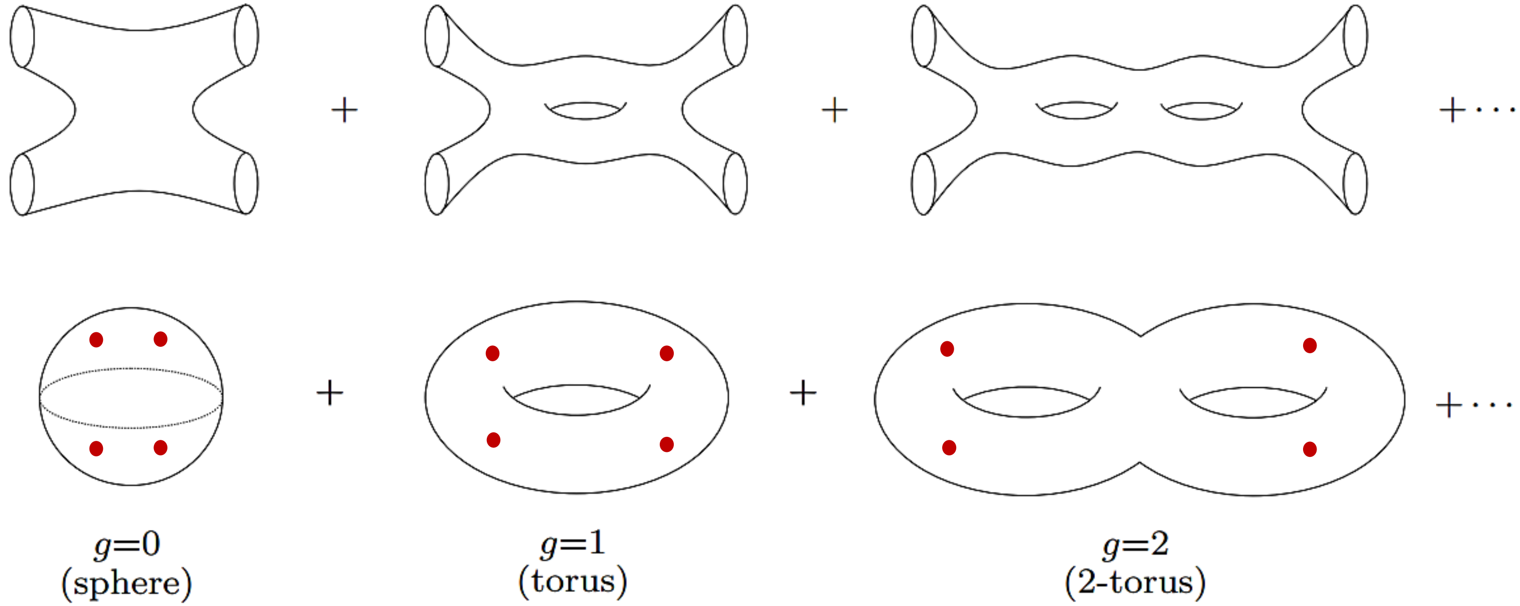


- **Amplitude and stuff!**

- In Quantum Field Theory, we sum over *Feynman diagrams*:



- In String Theory, we sum over *Riemann surfaces*:



Bosonic String Theory

- At first, string theory only included bosons
- Easier
- Only include closed strings
- Include tachyon in its spectrum (string with negative mass)
- The laws of quantum mechanics impose that the dimension **must** be:

$$D = 26$$

- To include ***fermions*** and ***remove tachyon*** the theory must be ***supersymmetric***

↓

Superstring

- **Superstring Theory**

- Supersymmetry posits that for every known particle, there exists a **partner** particle

- It's a symmetry under which the action (spectrum) would be preserved:

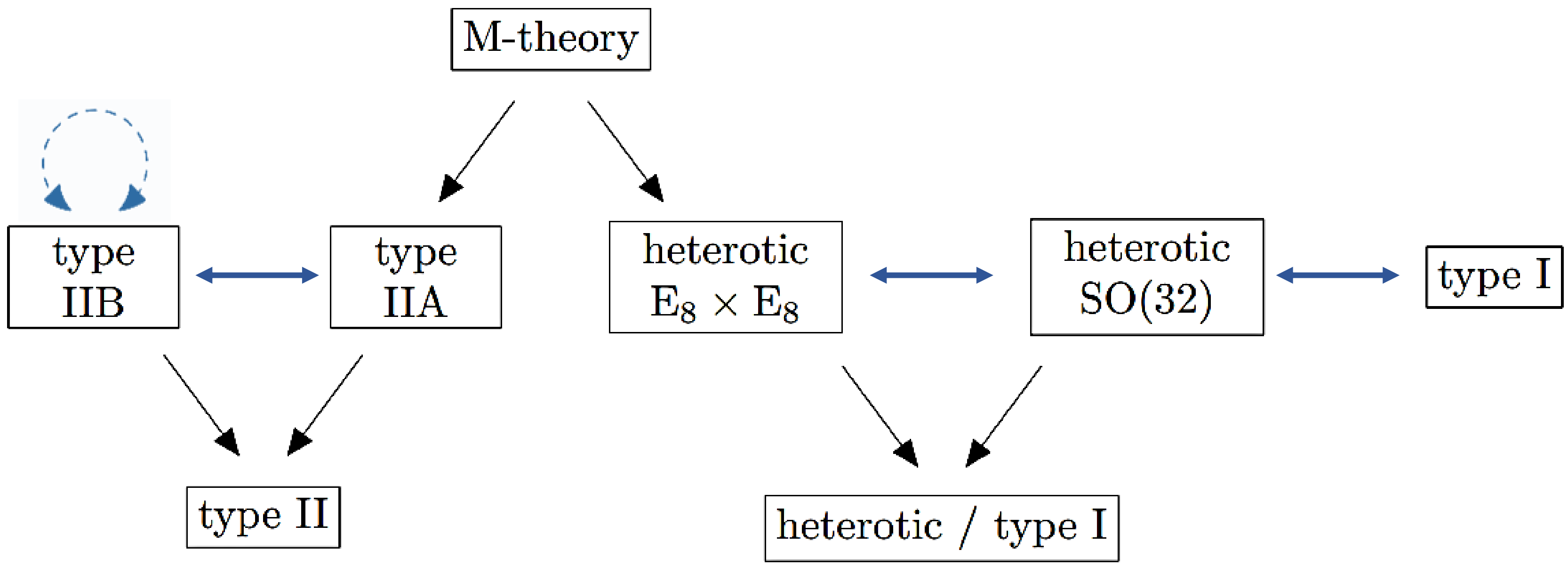
$$\text{Bosons } (\phi) \longleftrightarrow \text{Fermions } (\psi)$$

- The laws of quantum mechanics impose that the dimension **must** be:

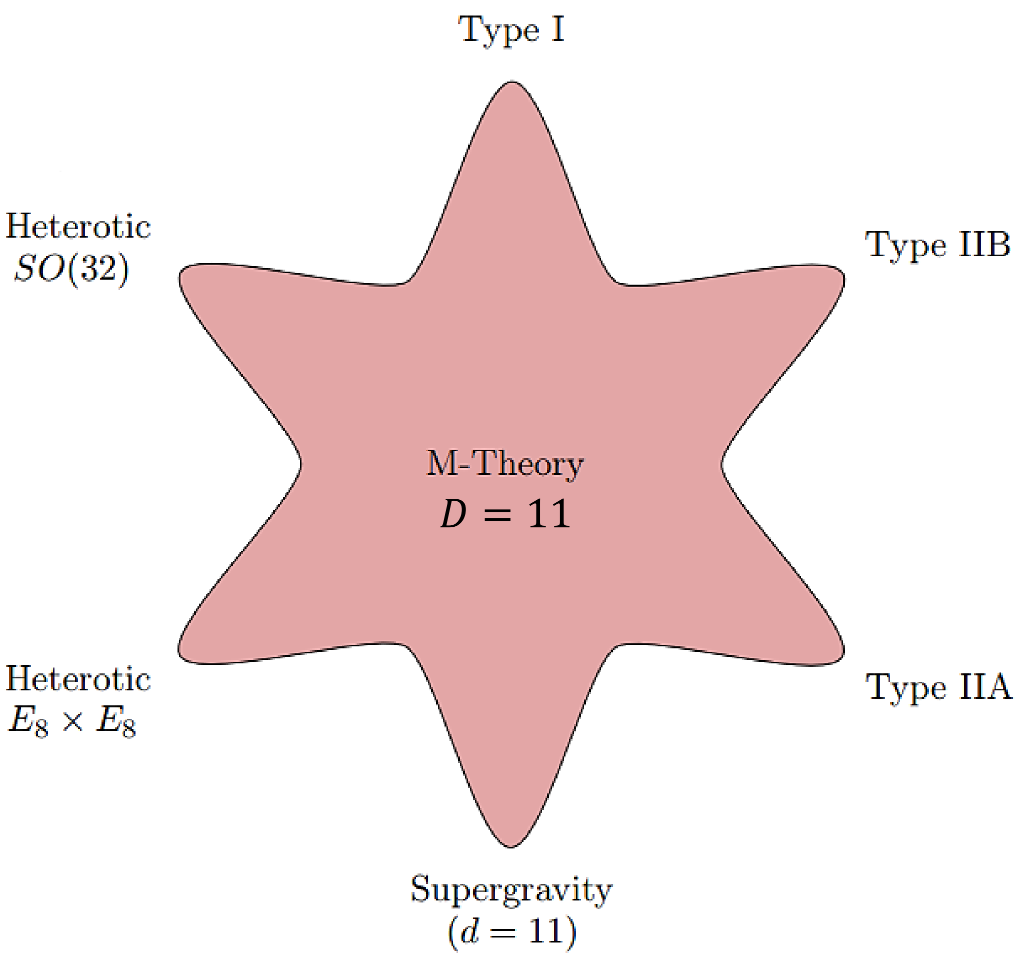
$$\boxed{D = 10}$$

- Without supersymmetry, string theory would produce **<u>inconsistencies</u>** and anomalies at the quantum level

- There are 5 types of Superstring theories



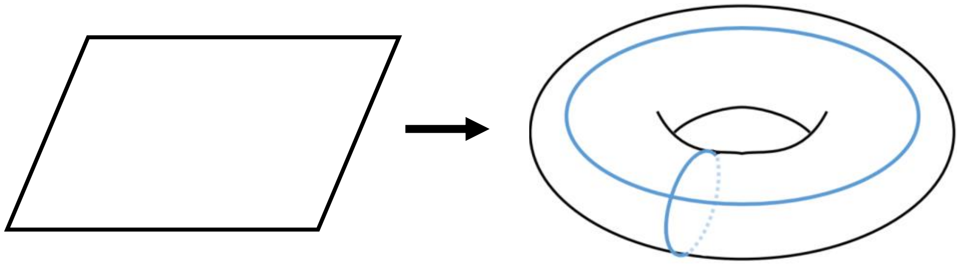
M-theory



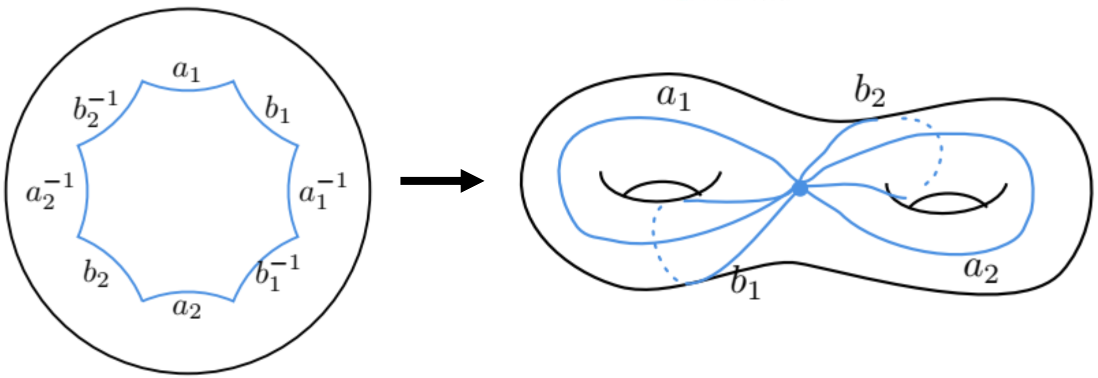
Edward Witten

The Real World

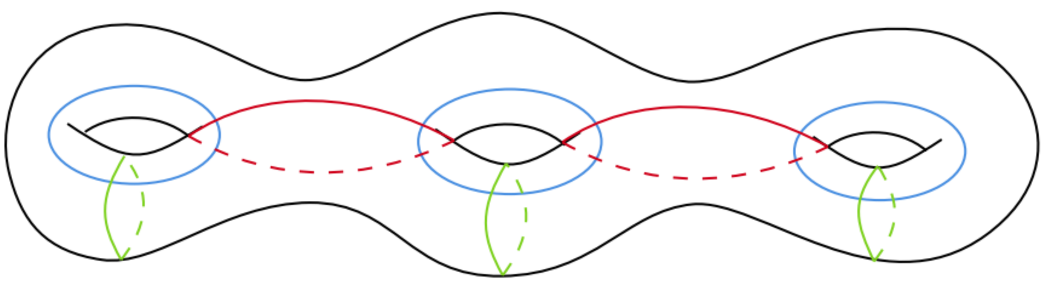
Compactification



 # cycles = 2



 # cycles = 5



 # cycles = 8

Surface with ***g*** holes:

 # cycles = 3g-1

- **The Real World:** Supersymmetry Breaking

  - The value of Supersymmetry is given by a number N
  - This number is different in each Superstring
  - For example Type II has $N = 2$ supersymmetry
  - Our world **does not** have supersymmetry in low energy

It should break or reduced

  - Compactification on **cycles** reduces this symmetry
  - Compactification on “**Calabi-Yau**” manifold can reduce & even remove it
  - It’s 6 dimensional. After compactification: $\mathrm{D} = 10 - 6 = \mathbf{4}$

The Real World: Number of Black Hole Microstates

The laws of quantum mechanics imply that black holes emit thermal radiation:

$$S = \frac{(\text{Area})}{Constant} \quad \text{(Hawking, 1974)}$$

They used string theory to count the microstates of certain black holes (late 90s):

$$S = \log\ (\#\ microstates)$$

What exactly are the

microstates

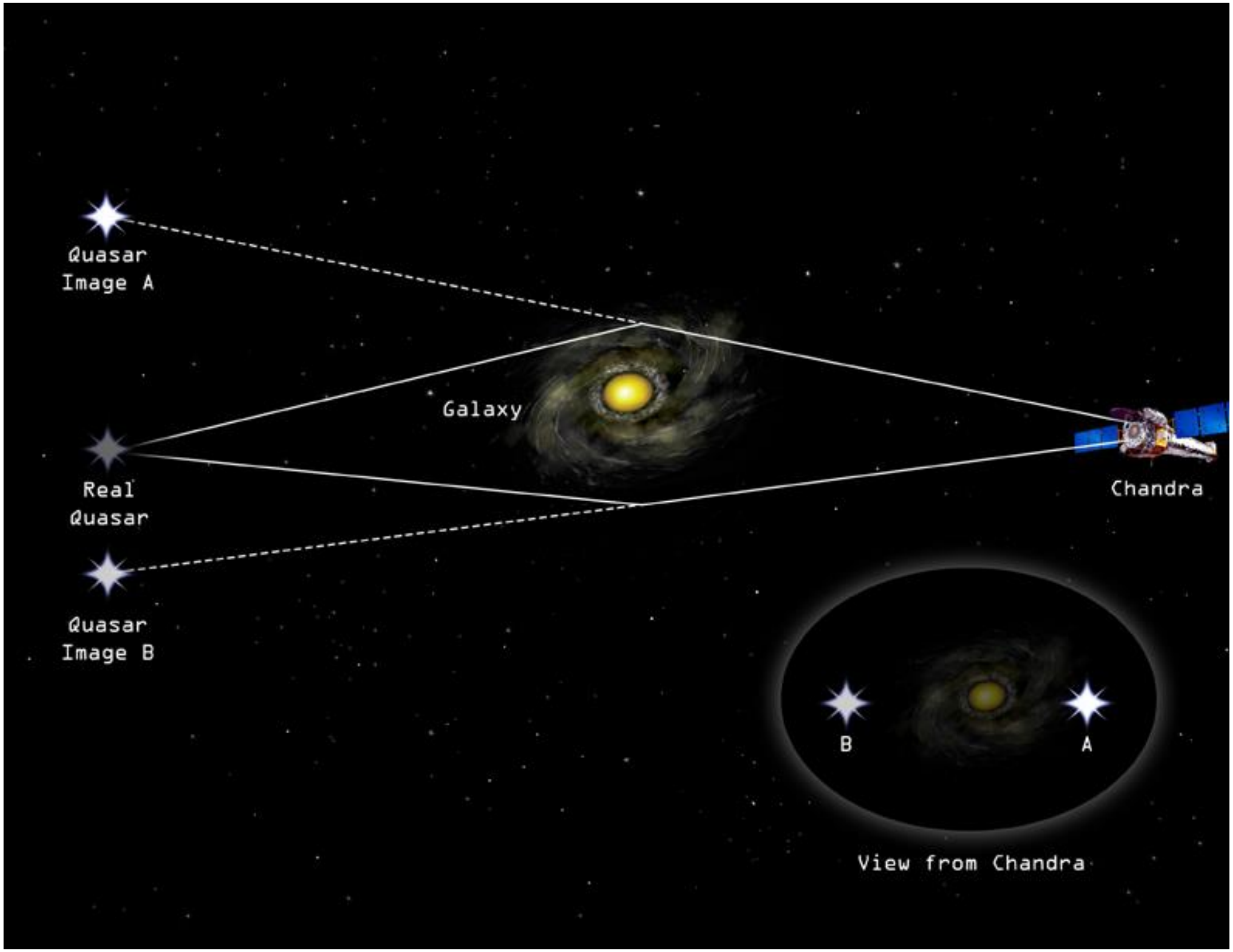
of the black hole?

Still, don't know!

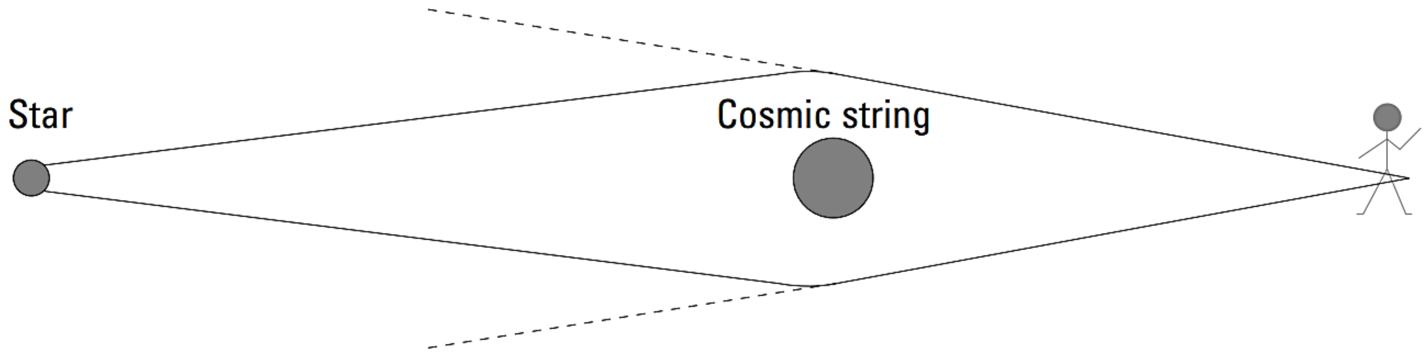
Andrew Strominger

Cumrun Vafa

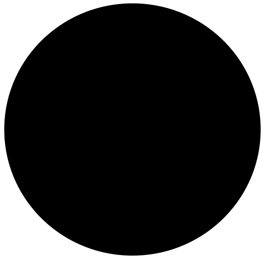
- **The Real World:** Cosmology
  - Cosmic Strings



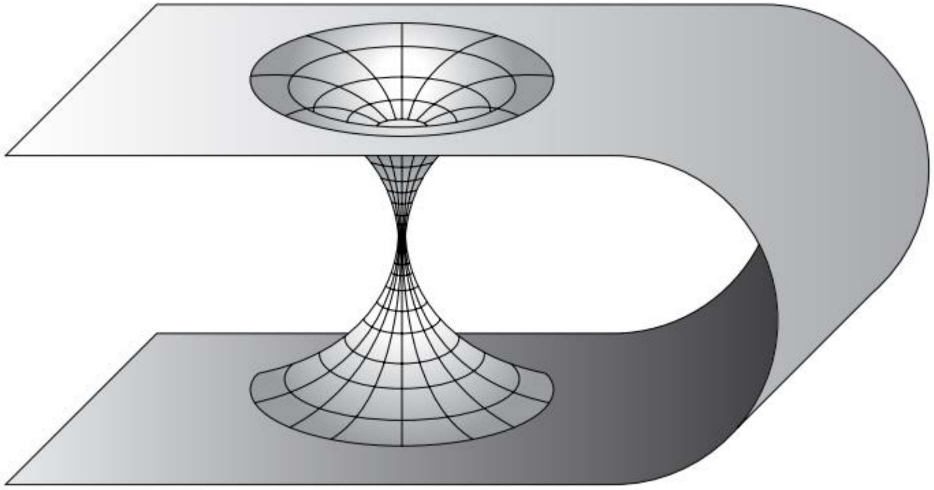
- **The Real World:** Cosmology
  - Cosmic Strings



  - Black Hole and Wormholes

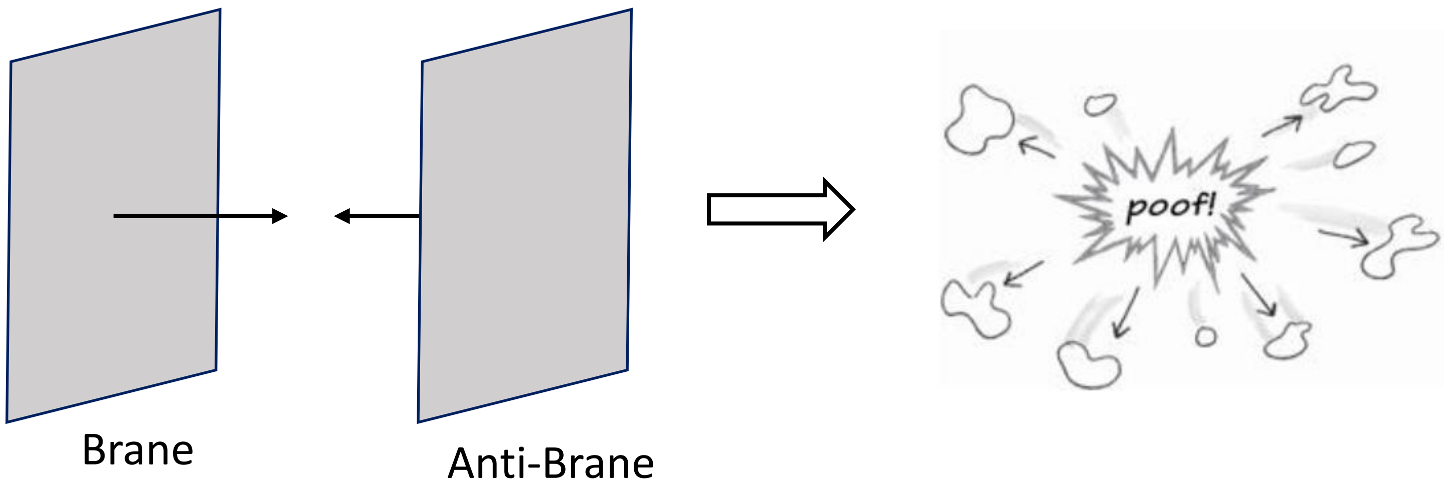


Strong Coupling



- **The Real World:** Cosmology

  - Big bang theory

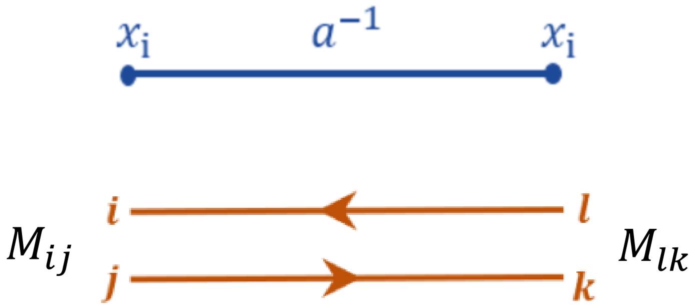


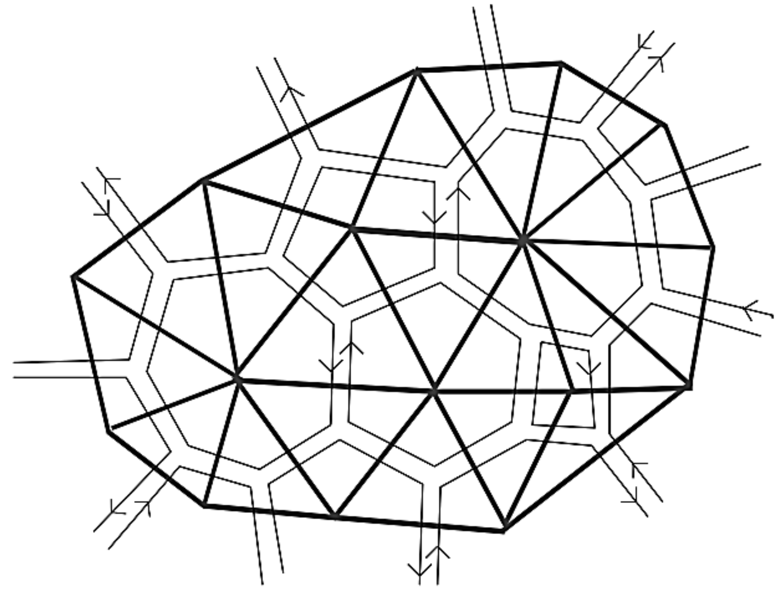
  - Other Universes

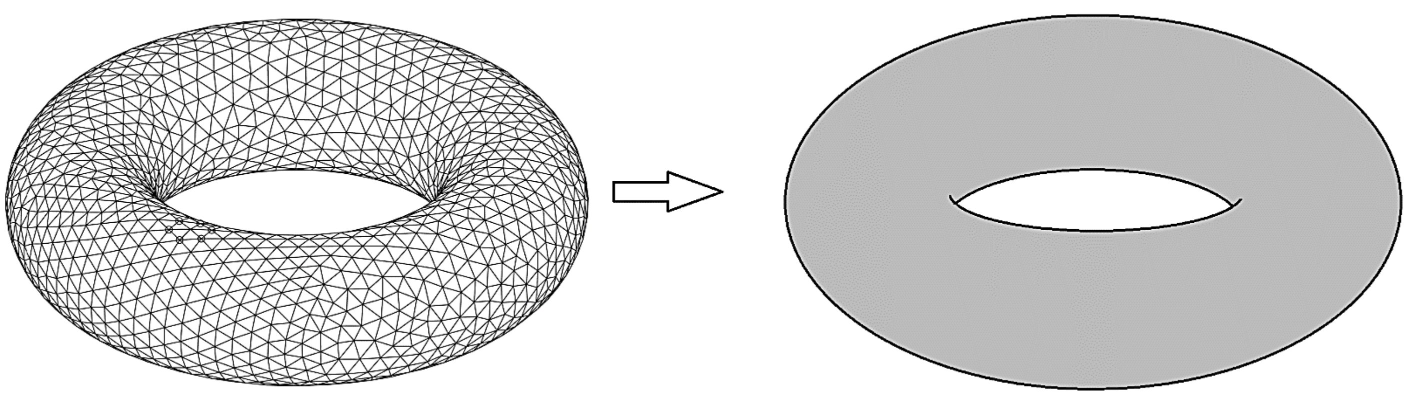
  - String theory predicts the existence of a huge number of universes

  - To solve this, physicists proposed "**Swampland**" scenario (Cumrun & others)

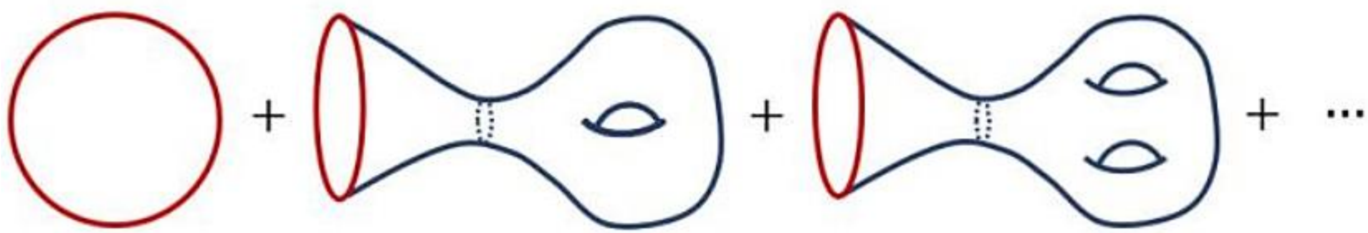
- **The Real World:** Mathematics
  - Relation to Matrix Models







- **The Real World:** Mathematics
  - Relation to volumes
    - There are also string theories in dimensions lower than D=26 and D=10
    - They are called "**non-critical**" string theories
    - Consider non-critical string in D=2 (e.g. Liouville theory)
    - The partition function of this theory is related to the sum over volumes:



    - It diverges as **2g!**
    - This is possible through "Mirzakhani's Recursion"
    - It is directly related to 2d quantum gravity

M. Mirzakhani

Conclusion

Failure or Victory?!

Failures

- Strings can’t be observed experimentally yet, due to the requirement of tremendous amount of energy

- Still couldn’t provide a full description for the Standard Model

- The supersymmetry has not been discovered yet

- It predicts ~10^500 number of universes as a solution!

- Its solutions require a **non-perturbative** formulation (not understood)!

Victories

- It’s a **Renormalizable** theory
- In the **<u>low-energy limit</u>**, It describes General Relativity alongside its higher order corrections/derivatives
- AdS/CFT or Holography is a concept that first extracted from string theory
- It can accurately count the number of black hole microstates
- Helped mathematicians to develop their work in topology & diff. geometry


Thank
you


Any
Question?!

Questions?!