



String theory and its relation to particle physics

-a review on string theory-

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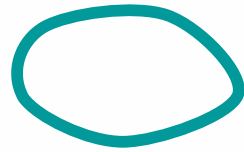
Overview of string theory

- String theory: fundamental object is **string**
 - mathematical **consistency** determines the theory
 - **supersymmetry** and **10 dimensions** are needed
 - (quantum) unification of **gravity** and **gauge** interactions
 - consistency leads **dualities** (open/closed, T-dual, S-dual,...)
- Ingredients
 - closed string
~**graviton** 
 - D-brane and open string
~**gauge** fields 
 - others (Orientifold plane, NS5 brane, etc)

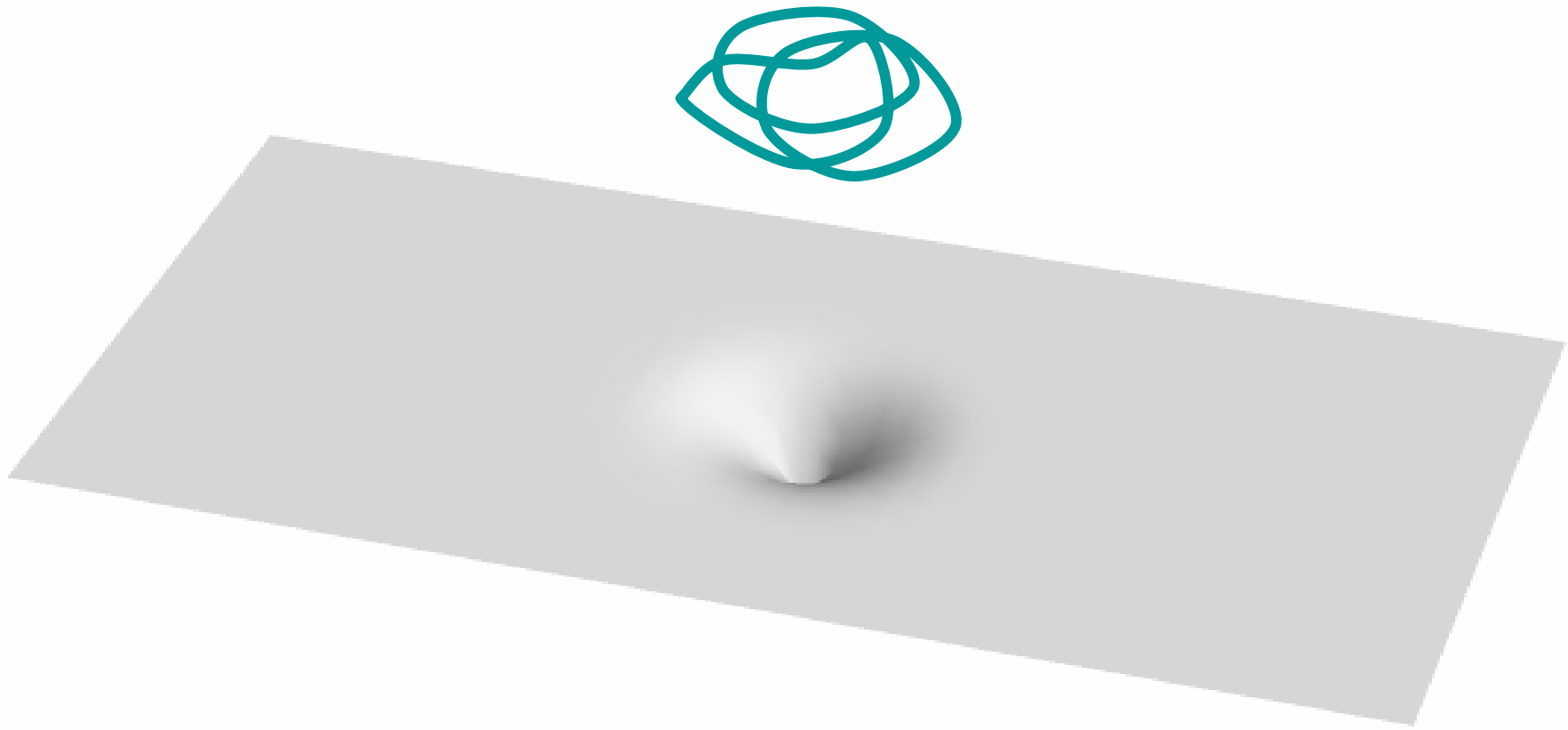
Closed string, Open string and D-brane

Closed string

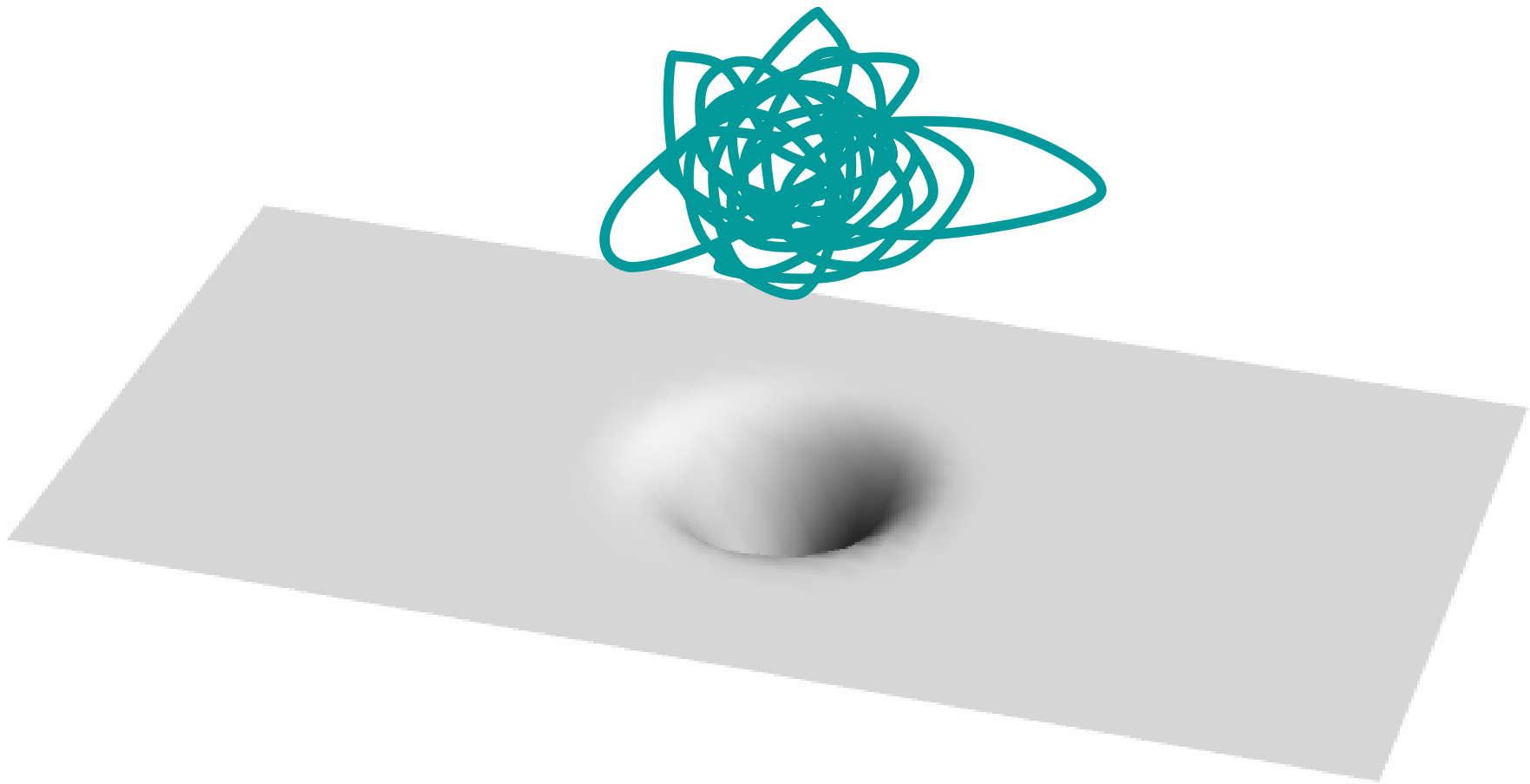
Closed string ~ graviton, dilaton, flux
~ supergravity



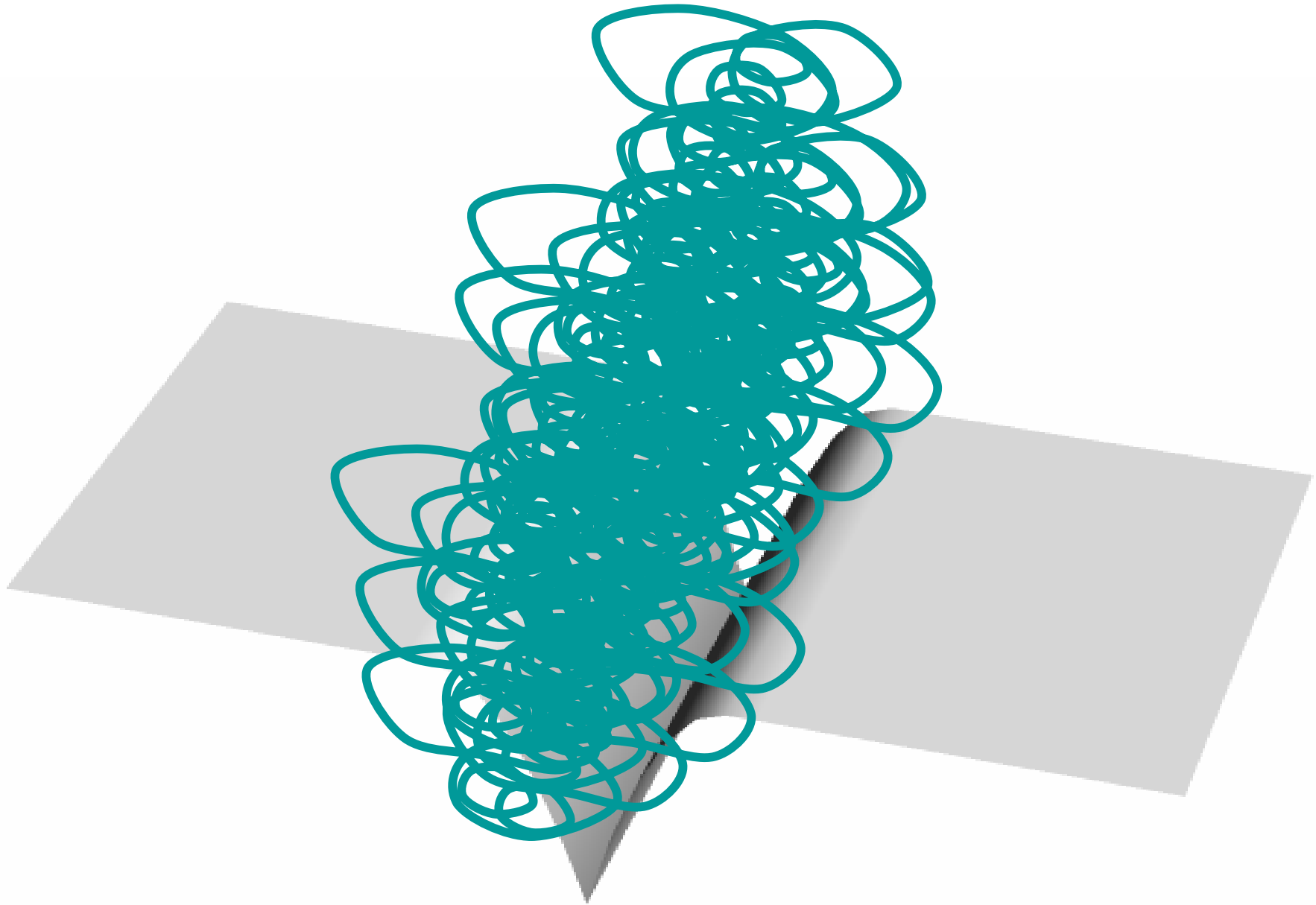
Adding more Closed Strings



Making Black Hole

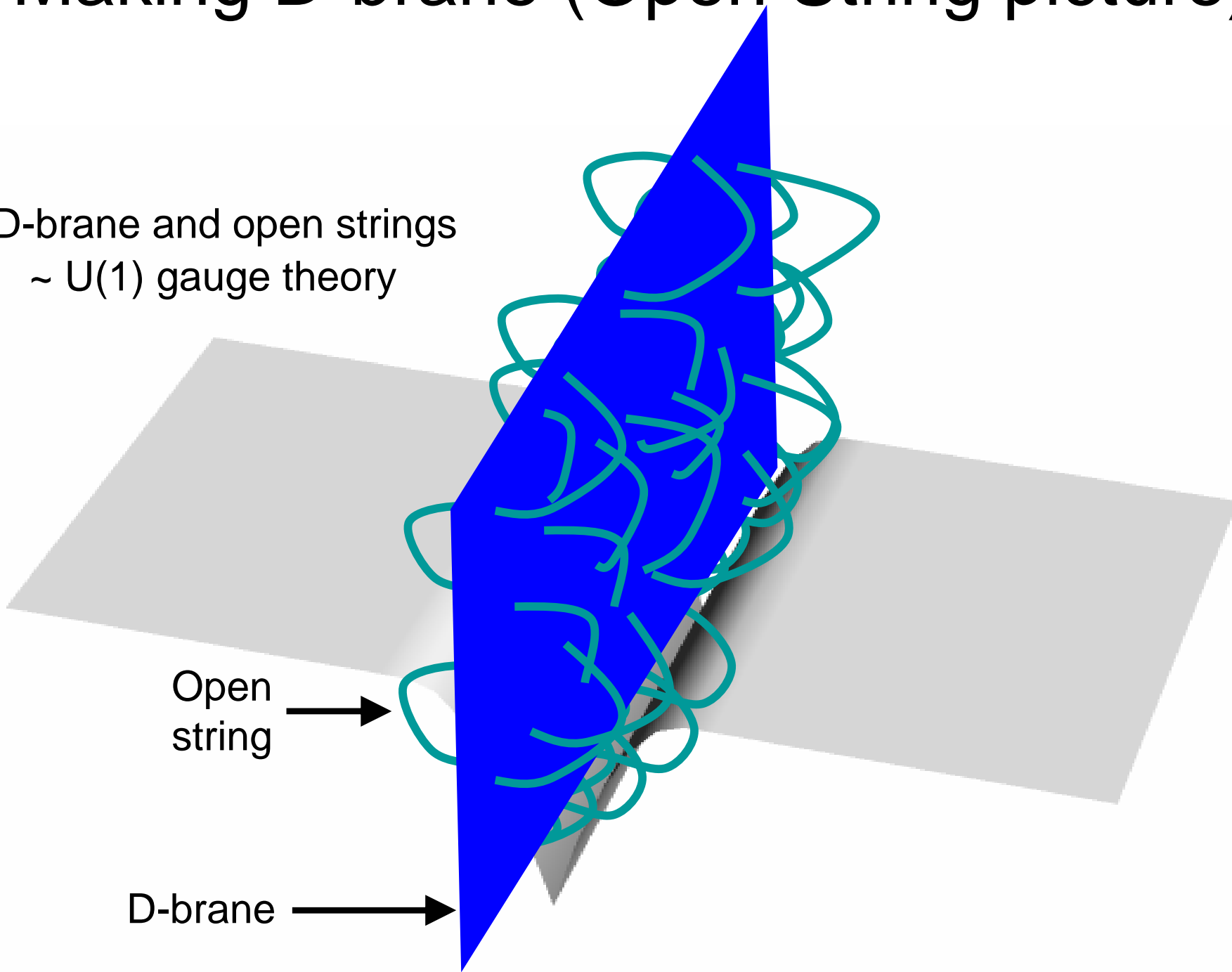


Making D-brane (Closed string picture)



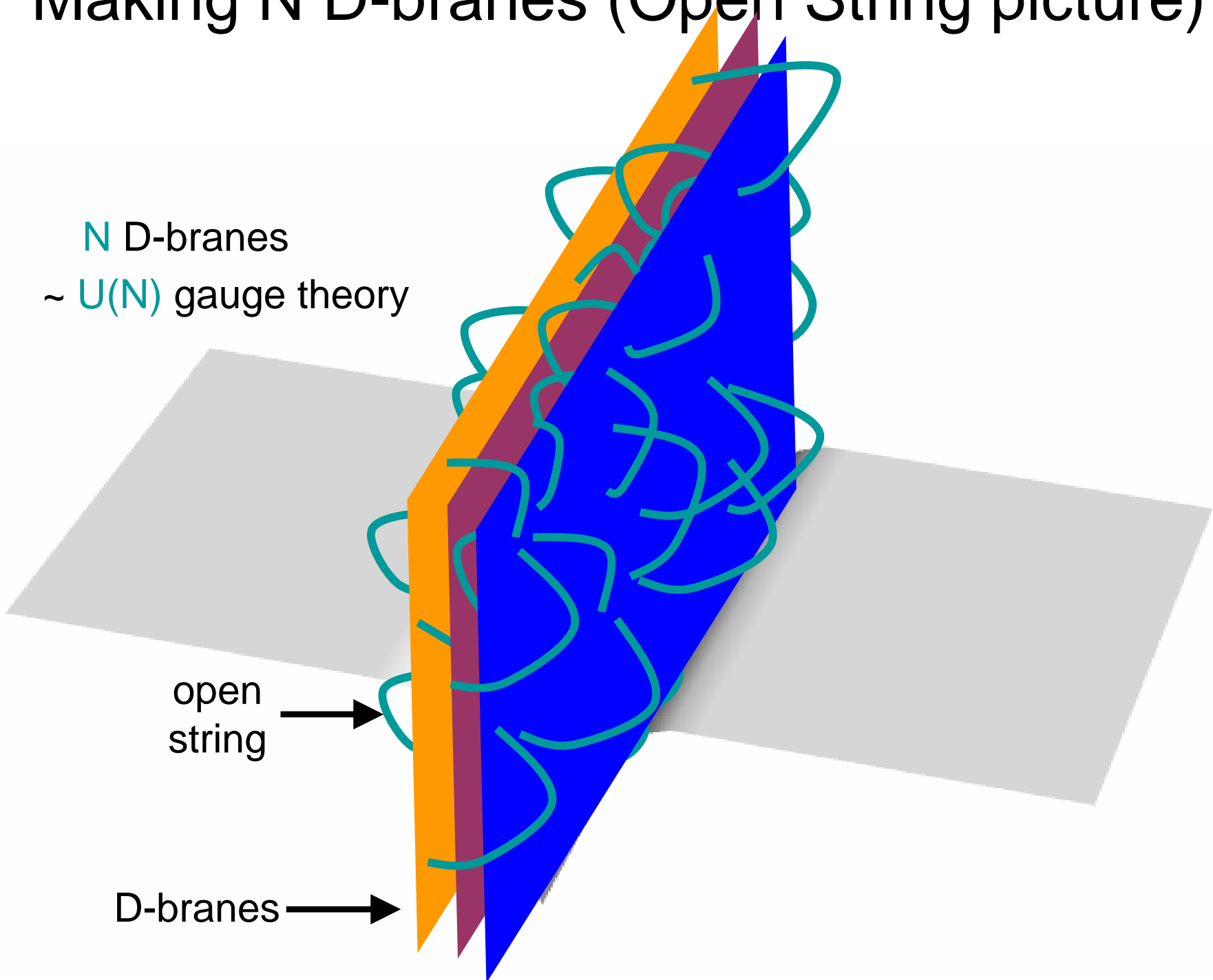
Making D-brane (Open String picture)

D-brane and open strings
~ U(1) gauge theory



Making N D-branes (Open String picture)

N D-branes
~ $U(N)$ gauge theory



Many directions in string theory

- Non-perturbative formulations of string theory
 - M-theory, Matrix Models, String Field Theory, AdS/CFT...
- Calculable toy models of string theory
 - Topological String, Non-critical String...
- Stringy physics
 - Black hole microstates, Tachyon condensation, NC geometry...
- Dualities
 - AdS/CFT, Mirror symmetry...
- String “phenomenology” ← today’s focus
 - String model building, “AdS/QCD”, cosmology, landscape...

However, these are related to each other!

Relation to particle theory

- Strings and particles look same at low energy
 - effective field theory is enough for many purposes
 - 10D supergravity + super Yang-Mills gauge theories
(closed string) (D-brane and open string)
- Compactification (10D=our 4D + small extra 6D)
 - origin of rich structures in 4D effective theory
 - depends on details of 6D background (Calabi-Yau manifold)
 - SUSY may or may not exist in 4D effective theory
(depends on how symmetric 6D background is)

As a result, (perturbative) string theory selects a subset of 4D effective field theories

Variety of string model building

Approach is not unique!

- **Starting point** may be different
 - heterotic string, type IIA(B) string, heterotic M-theory...
- **Building blocks** may be different
 - closed string, D-brane and open string, flux, orientifold plane...
 - Calabi-Yau manifold, warped geometry...
- **Target** may be different
 - MSSM, GUTs, SM itself, any other beyond SM...

The number of possible approaches may increase more and more with developments of string theory and particle physics

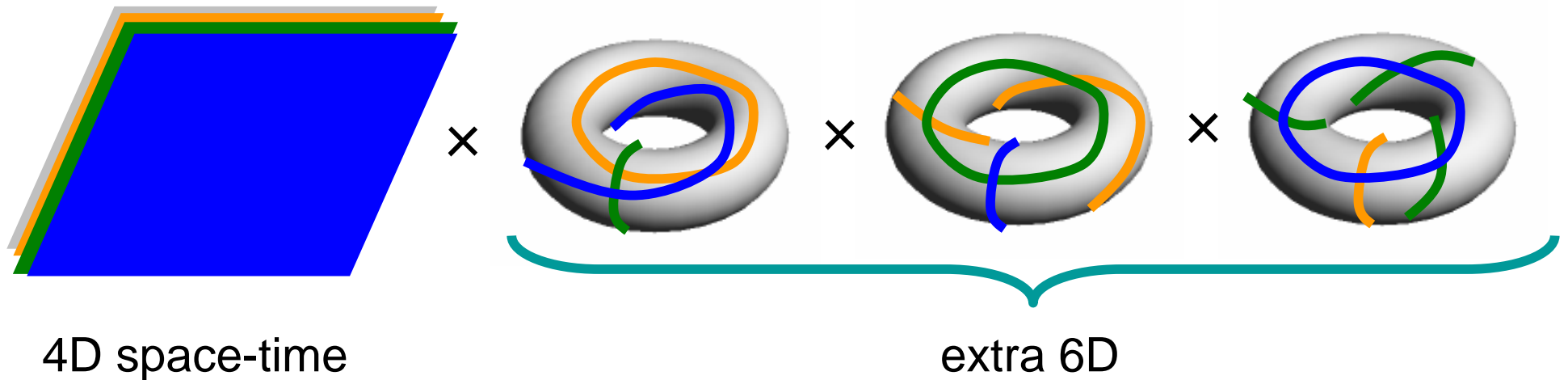
An example

-Intersecting D-brane scenario-



Intersecting D-brane scenario

- 10D space-time compactified into our 4D + extra 6D
- Consider D6-brane which is (1+6)Dim object
- D6-branes cover our (1+3)D space-time
- D6-branes also wrap 3D in extra 6D



Intersecting D-brane scenario

Open string connecting
same brane

||

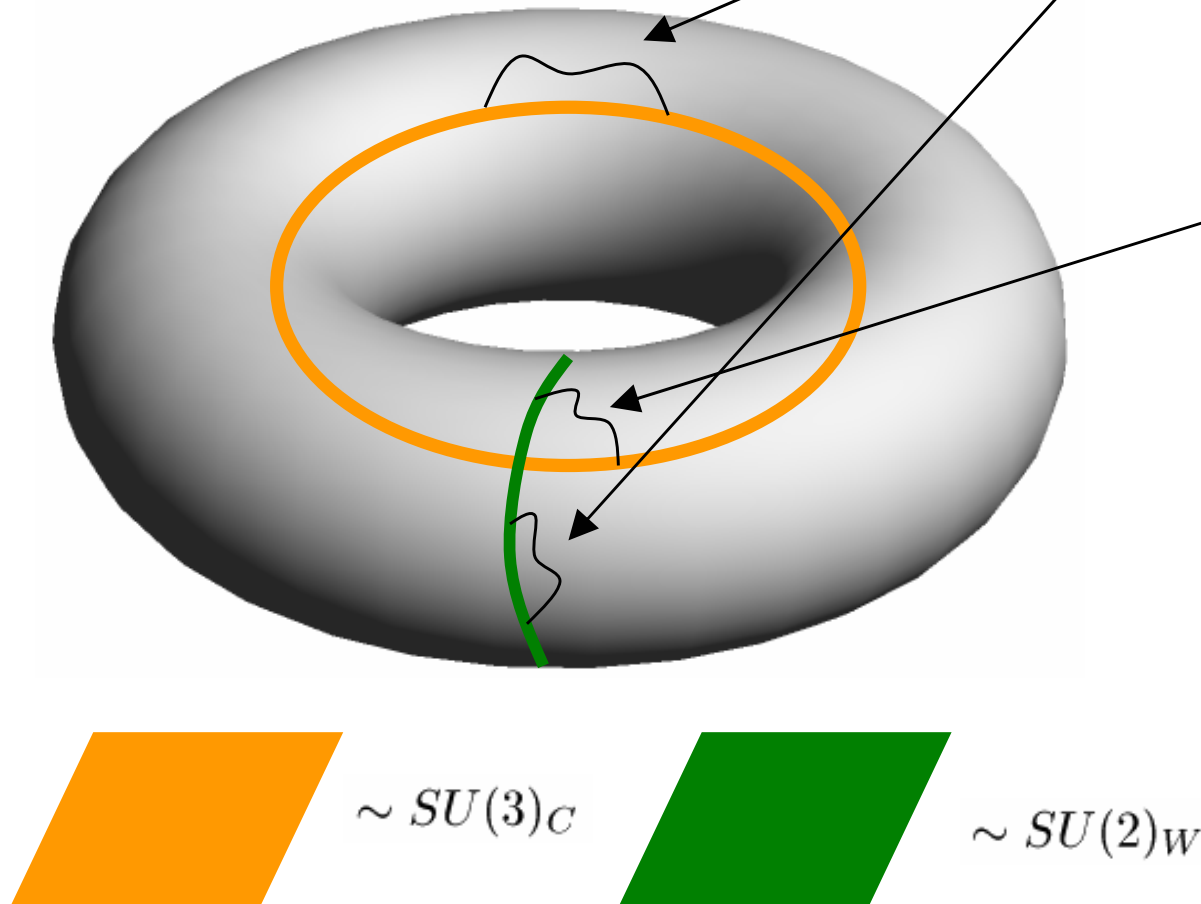
Gauge boson

Open string
at the intersecting point

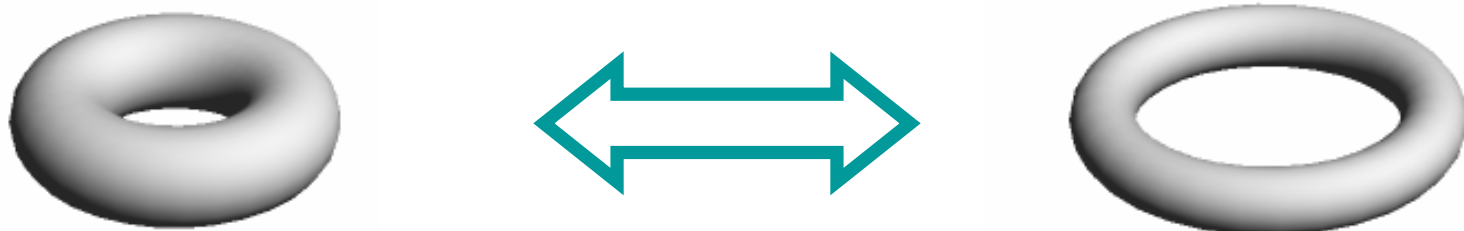
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Chiral fermion with $(3, \bar{2})$
representation

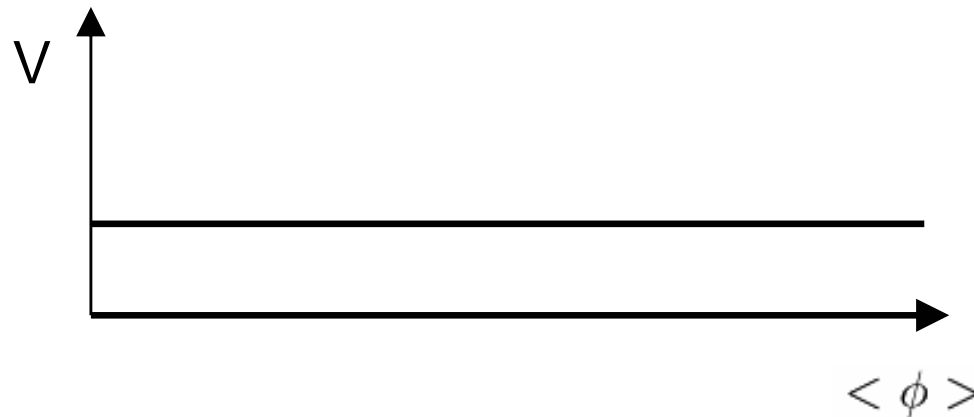
One may construct his/her
favorite models in this way



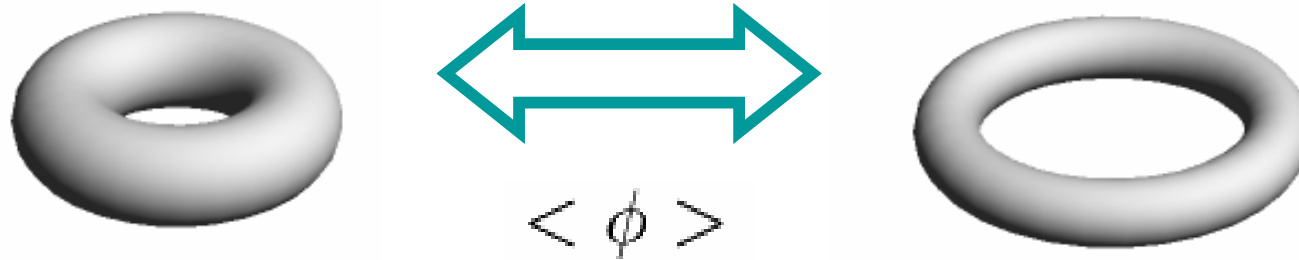
A generic problem -moduli stabilization-



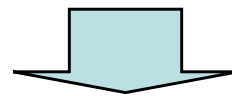
$\langle \phi \rangle$



Moduli stabilization

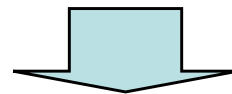


In general, compact manifold can **change their shape**

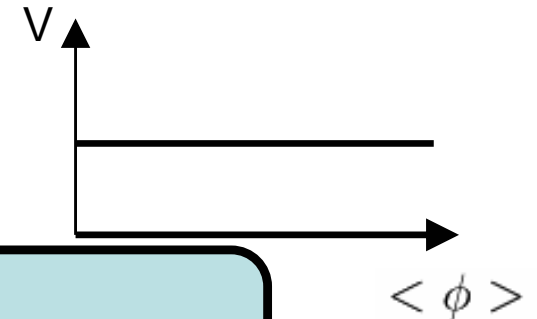


~Moduli degrees of freedom

Especially, if the manifold is symmetric enough to keep SUSY,
no energy cost deformations (=flat directions) do exist



Unwanted massless scalars ϕ
(must be stabilized!)



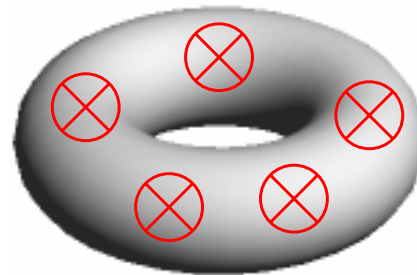
This is a generic problem
for higher dimensional effective field theory

How to address this problem
in the framework of string theory?

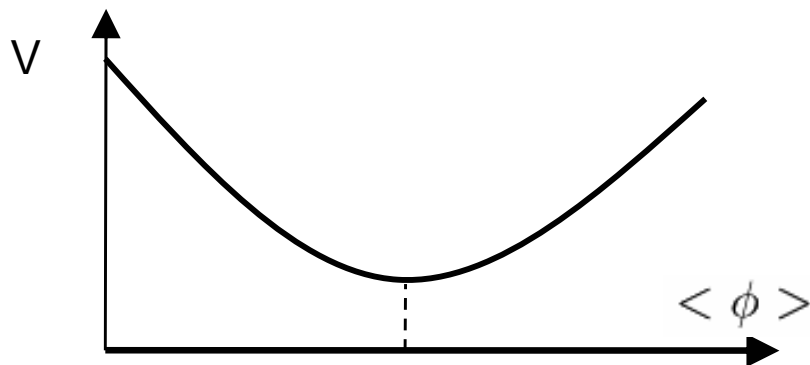
An answer: Flux compactification

Flux compactification

- String theory predicts extra **higher rank gauge fields** $C_{\mu\nu}$
 - Flux $F = dC$
- One can turn on non-trivial flux in the compact manifold



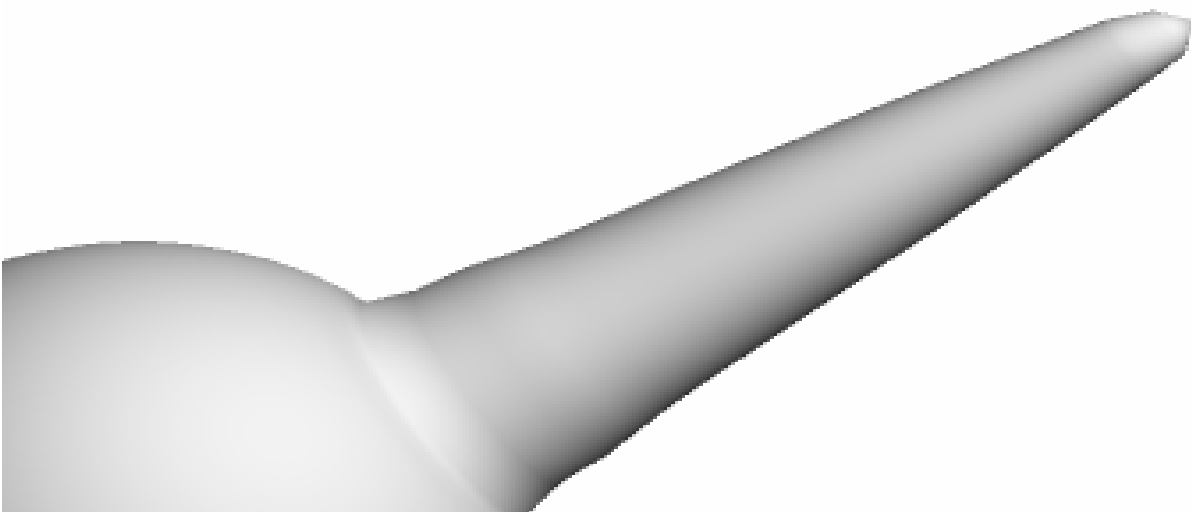
- Total amount of flux is **quantized** and **fixed**
- Shape will be determined by minimal energy condition
 - **Moduli stabilization** → ϕ acquires mass!



- # of vacua is estimated by # of typical cycle and flux $\sim 10^{500}$
“string landscape”

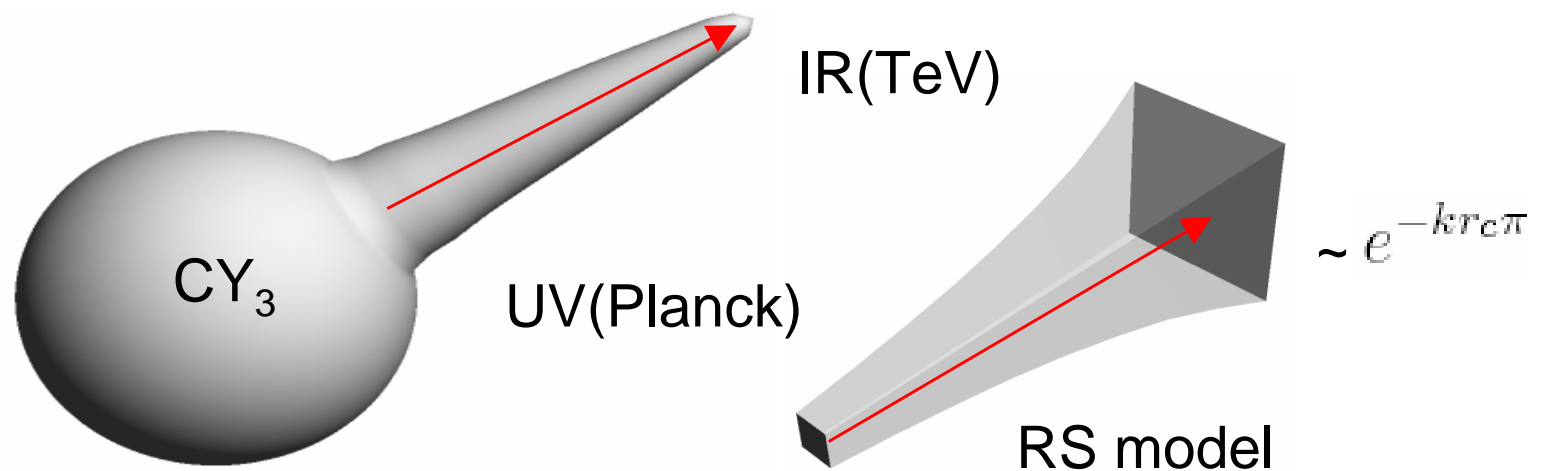
Another benefit of flux

“Throat”



Warped throat

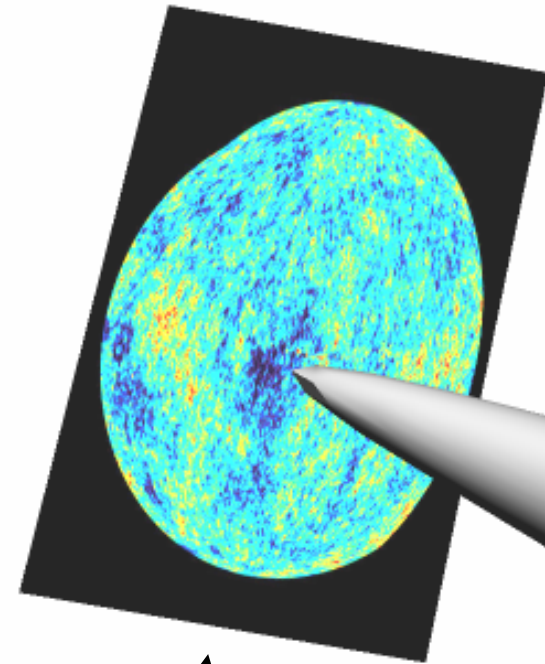
- Turn on flux in 6D manifold
- Back reaction can change the geometry into “throat”



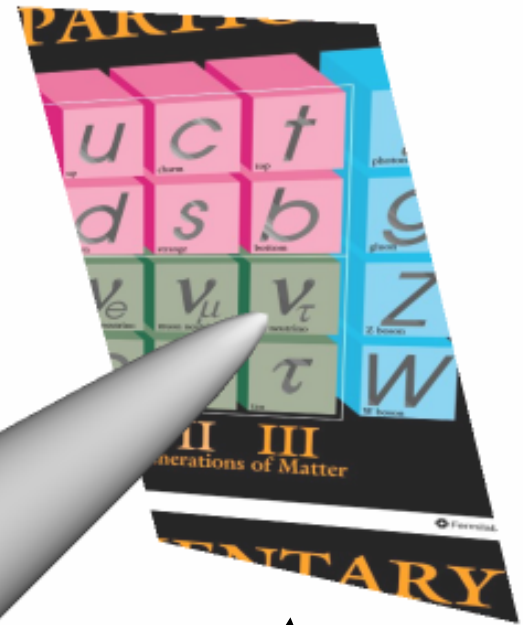
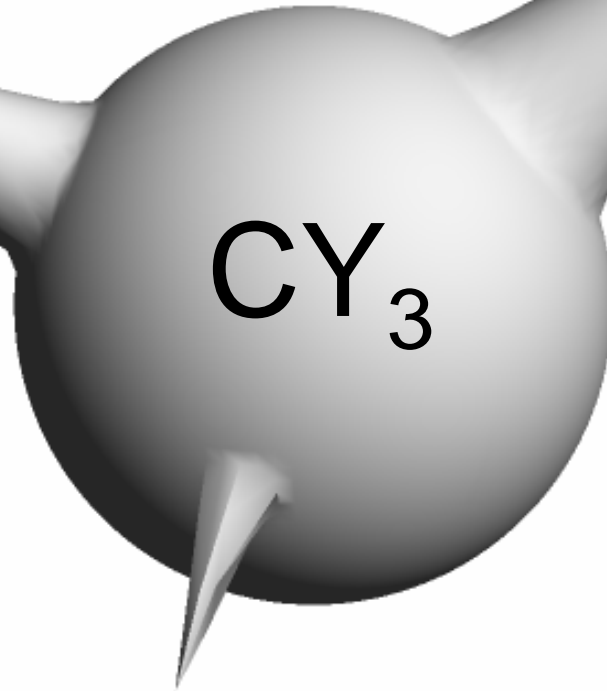
- Throat gives warped geometry like Randall-Sundrum model
- If you put brane at the tip of throat, physical scale on the brane depends on the size of throat



A solution for hierarchy problem



Brane-anti brane
inflation



Branes
for SM sector

One may use different throats
with different scales for different purposes!

Yet another connection to particle physics

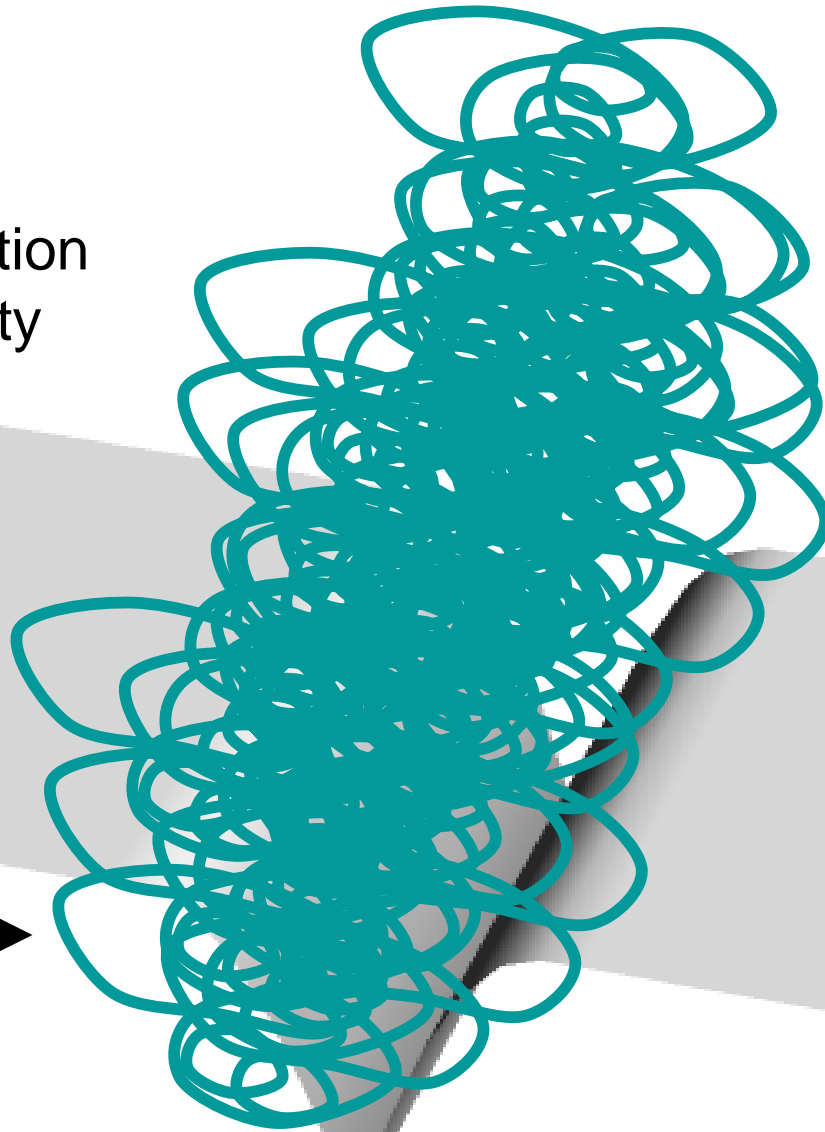
AdS/CFT duality

-gravitational description of gauge theory-

Making D-brane (Closed string picture)

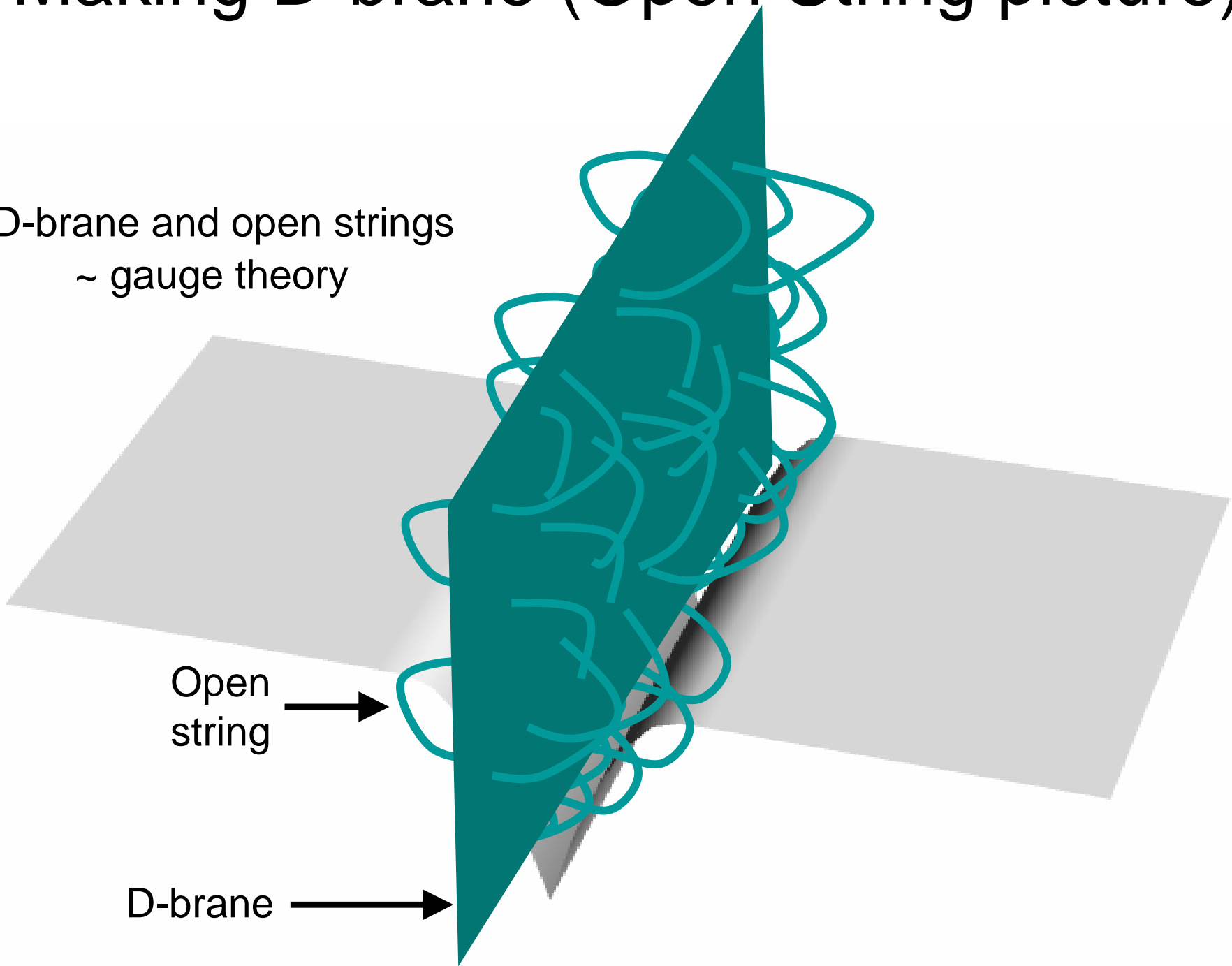
Brane like solution
of supergravity

Closed
string



Making D-brane (Open String picture)

D-brane and open strings
~ gauge theory



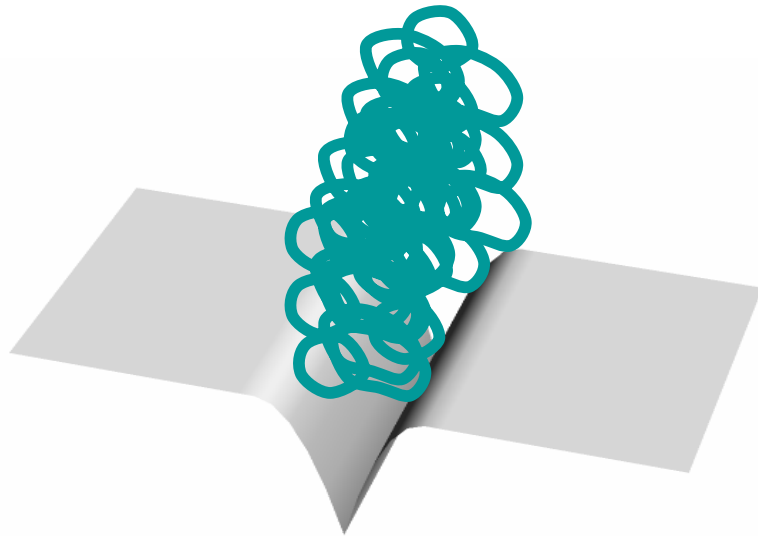
Open string →

D-brane →

AdS/CFT correspondence

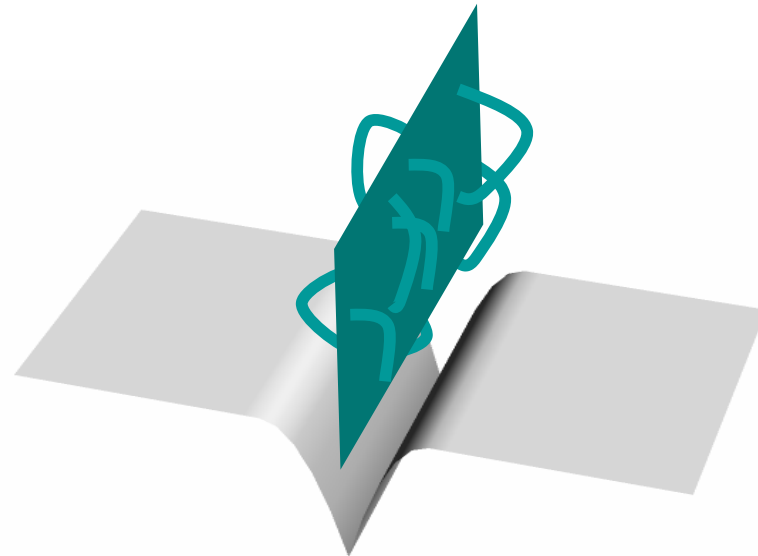
We have two different descriptions for same object!

Closed string
description



=

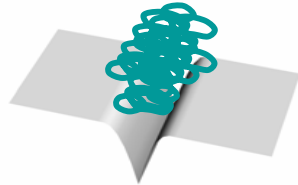
Open string
description



Especially, in the case of **D3-brane**, at low energy these two description will be approximated by

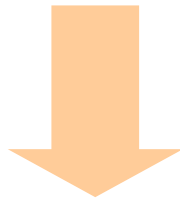
AdS/CFT correspondence

Closed string
description



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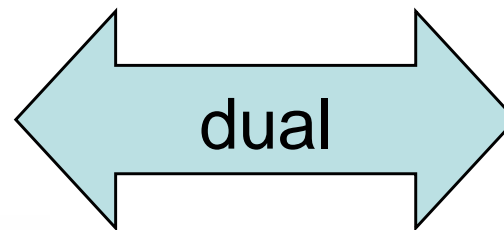
Open string
description



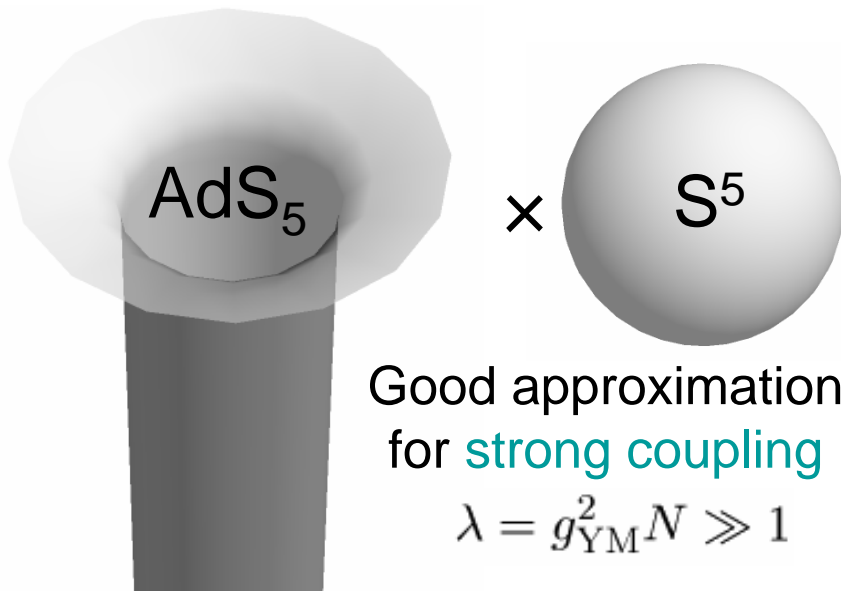
Low energy limit
with large N



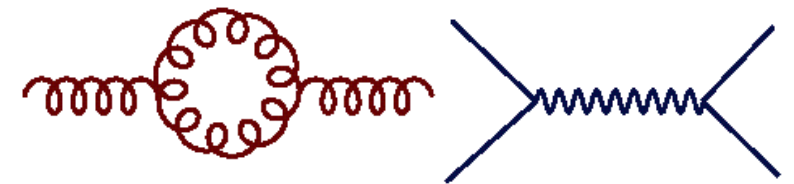
Supergravity
on $\text{AdS}_5 \times S^5$



$D=4$ $\mathcal{N}=4$ $U(N)$
Super Yang-Mills



Good approximation
for strong coupling
 $\lambda = g_{\text{YM}}^2 N \gg 1$



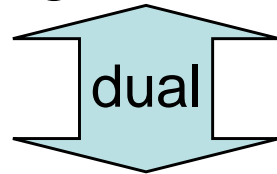
Good approximation
for weak coupling
 $\lambda = g_{\text{YM}}^2 N \ll 1$

Strong coupling region of gauge theory
can be described by classical gravity!

Can we apply this idea to
QCD physics?

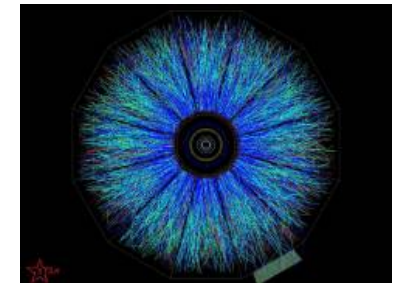
Application to QCD physics

- Quark-Gluon plasma might be mimicked by Super Yang-Mills theory at **finite temperature**

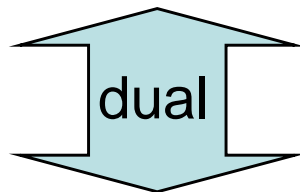


AdS geometry with **black hole**

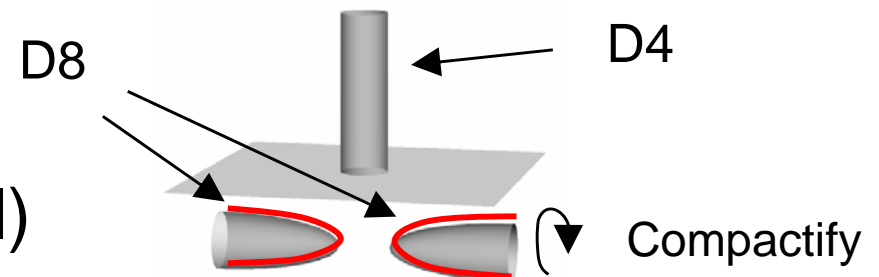
RHIC
experiment



- Compactified N_C D4 with probe N_f D8 brane system
~ $SU(N_C)$ QCD with N_f flavor @ low energy



Holographic QCD
(Sakai-Sugimoto model)



Summary

- String model building
 - 4D physics depends on extra 6D background (CY, brane, flux)
 - Ex. Intersecting D-brane scenario
 - Moduli problem can be solved by flux compactification
 - Randall-Sundrum like geometry can be realized by throat
 - Inflaton might be in another throat
 - Many consistency conditions must be satisfied
- AdS/CFT
 - Strong coupling region of gauge theory can be described by classical gravity on $AdS_5 \times S^5$
 - Application to QCD might be possible by changing the geometry

Comments

- AdS/QCD vs. string model building
 - AdS/CFT correspondence is a **mathematical relation**.
 - Even **if** string theory as theory of everything was totally **wrong**, AdS/CFT would be **still OK**.
 - On the other hand, even if string theory gives unified theory of our world, it is **not clear** whether we have gravitational description of strongly coupled region of QCD or not.
- How string vacuum should be chosen?
 - Non-perturbative dynamics determines a unique vacuum? (Traditional)
 - All possible backgrounds are realized by eternal inflation? (Landscape)
 - ??? c.f talk by G. Kribs
- String **“phenomenology”** and **other areas** of string theory are **strongly coupled**.

References

- For string model building and cosmology,
The 20th Taiwan Spring School on Particles and Fields
Gary Shiu: *String Phenomenology (Video)*
 - <http://www.phys.sinica.edu.tw/~ss2007/>
- For AdS/QCD,
The 7th Particle Physics Phenomenology Workshop
Yi Yang: *Status of AdS/QCD (Live)*
 - [Next talk](#)
- For general topics in string theory,
String seminars of string theory group in Taiwan
 - [Every Friday](#) with black board