Current Trends In String Theory

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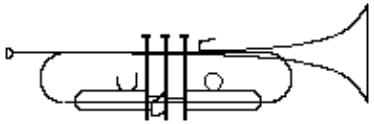
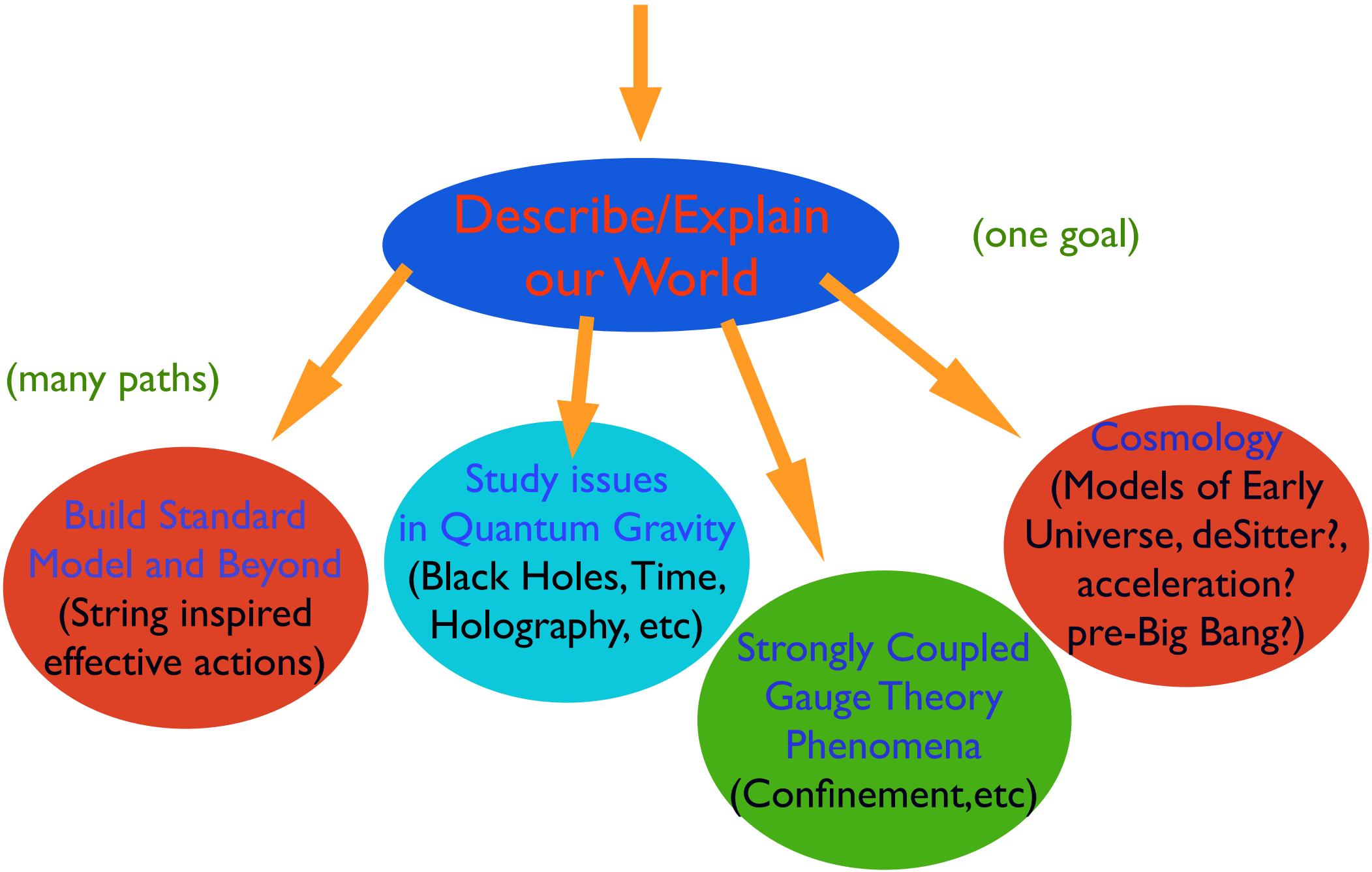
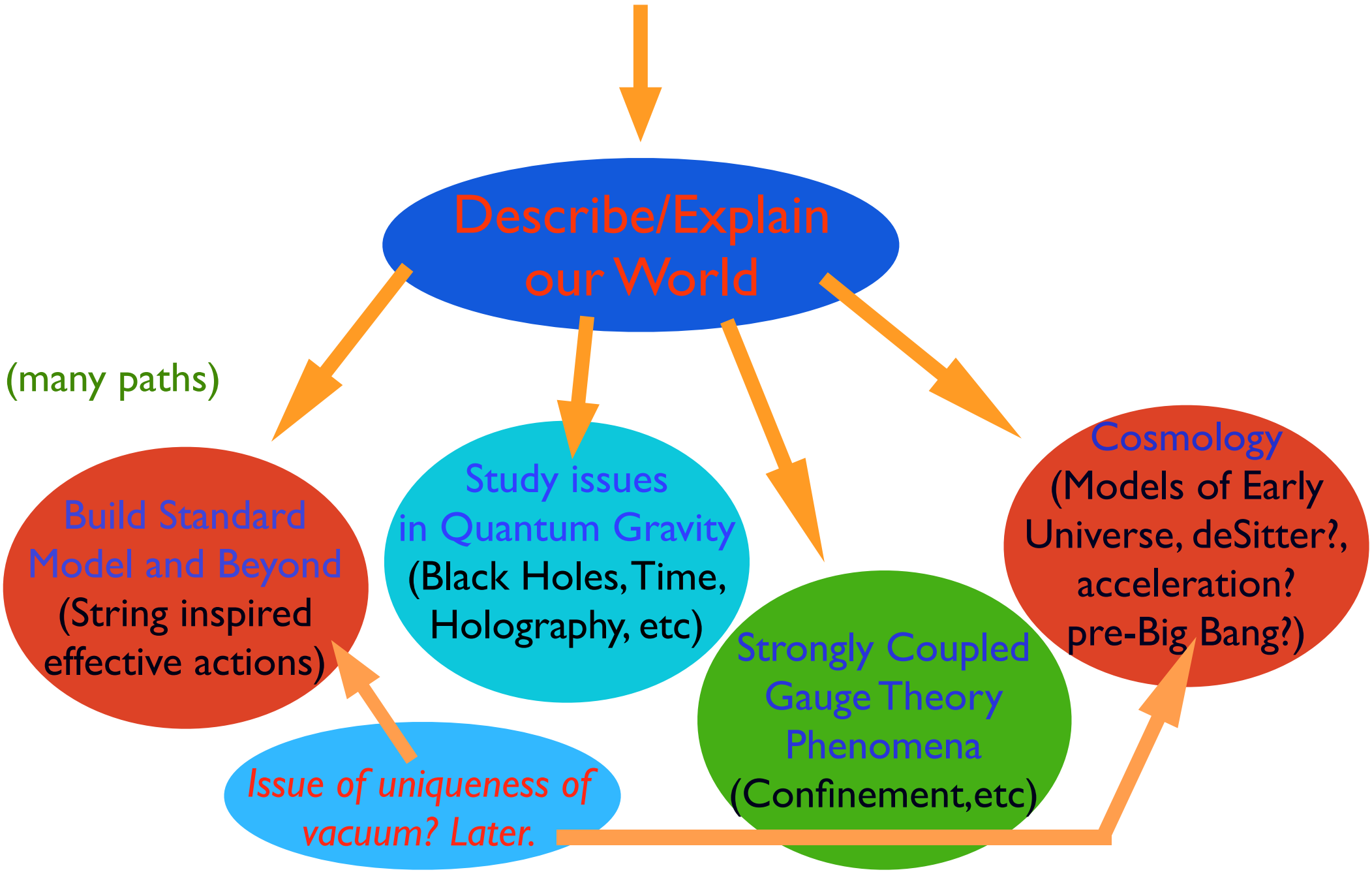


String Theory's Goals?

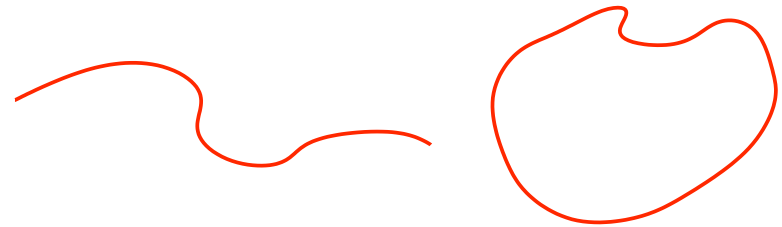


String Theory's Goals?



The Tools (I)

Open and Closed Strings:



Type I

Type IIA
Type IIB
Heterotic

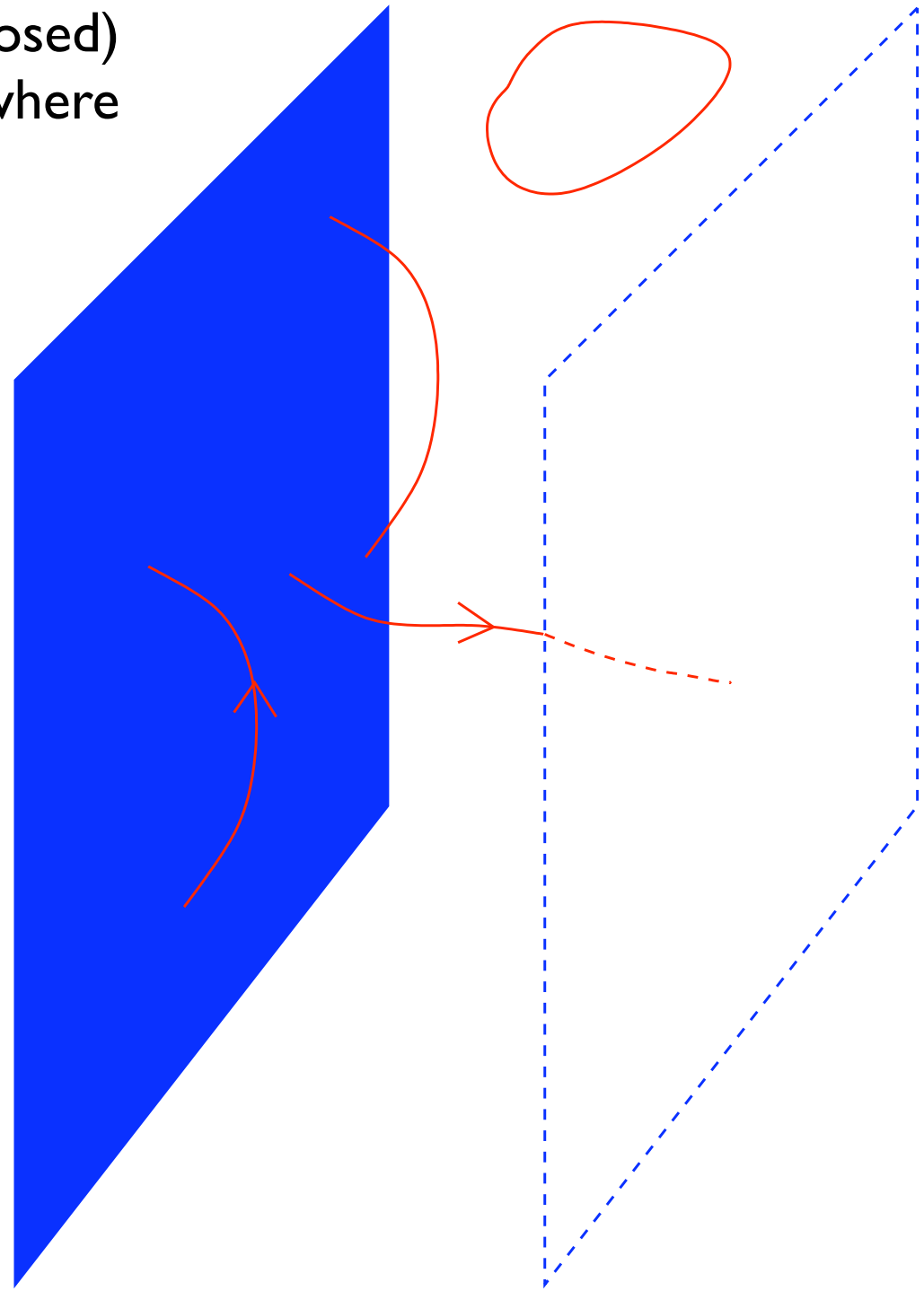
$SO(32)$

$E_8 \times E_8$

11D Supergravity

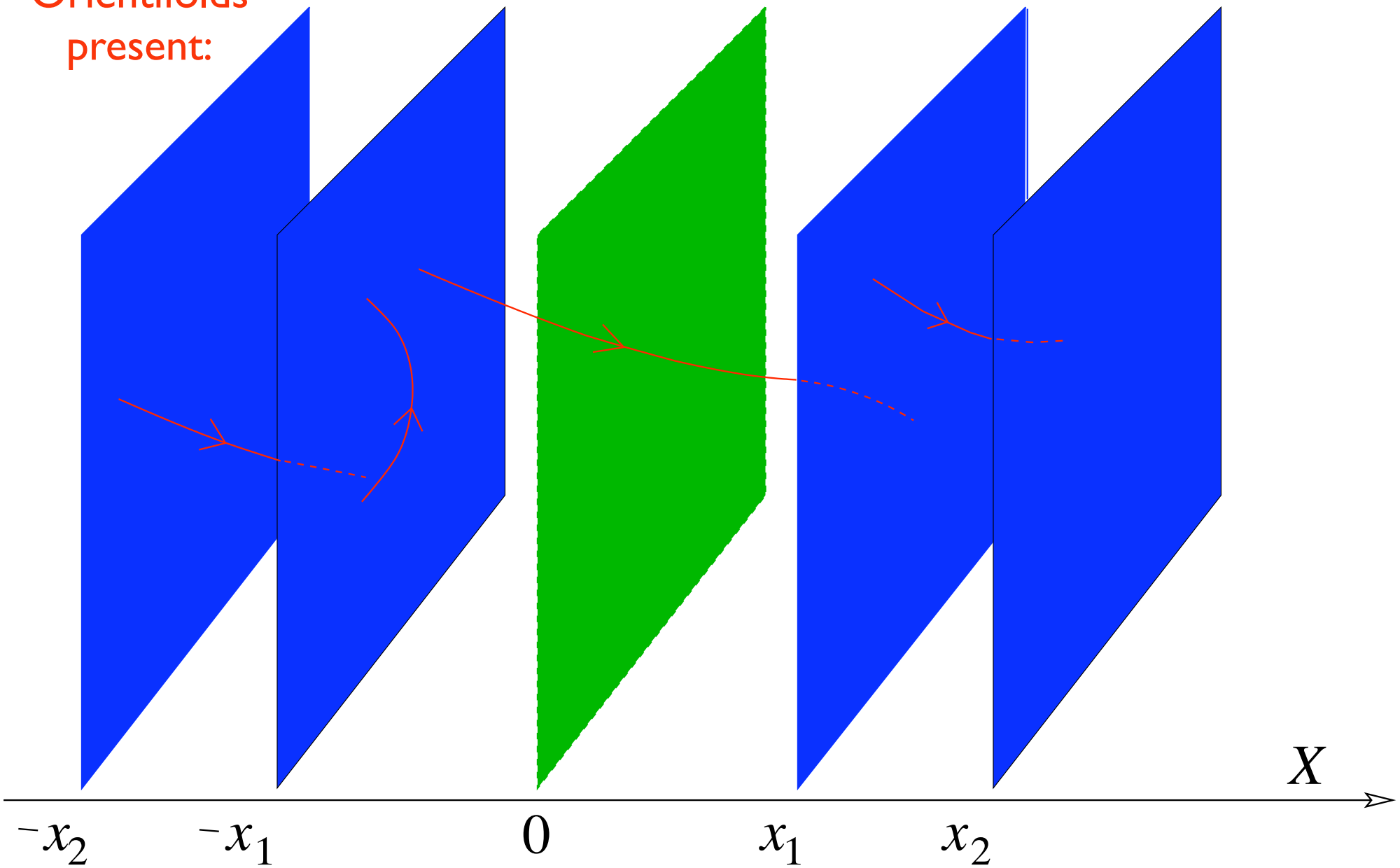
Put all together in the language of extended objects....

Think of open string sectors as existing within a type II (closed) string theory, as D-branes, where the endpoints lie.

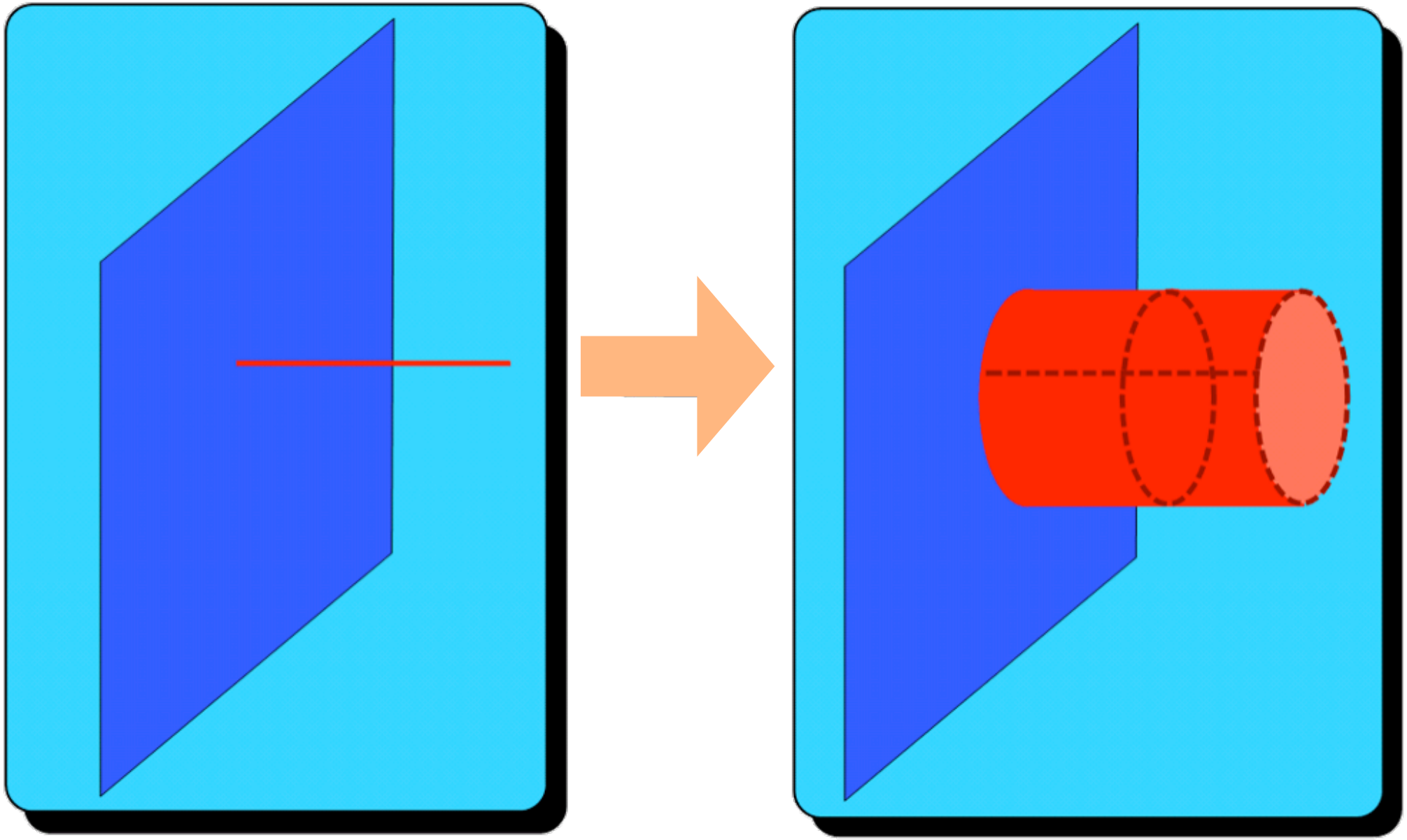


p extended directions: **Dp-brane**

Sometimes with Orientifolds present:



p extended directions: **Op-plane**

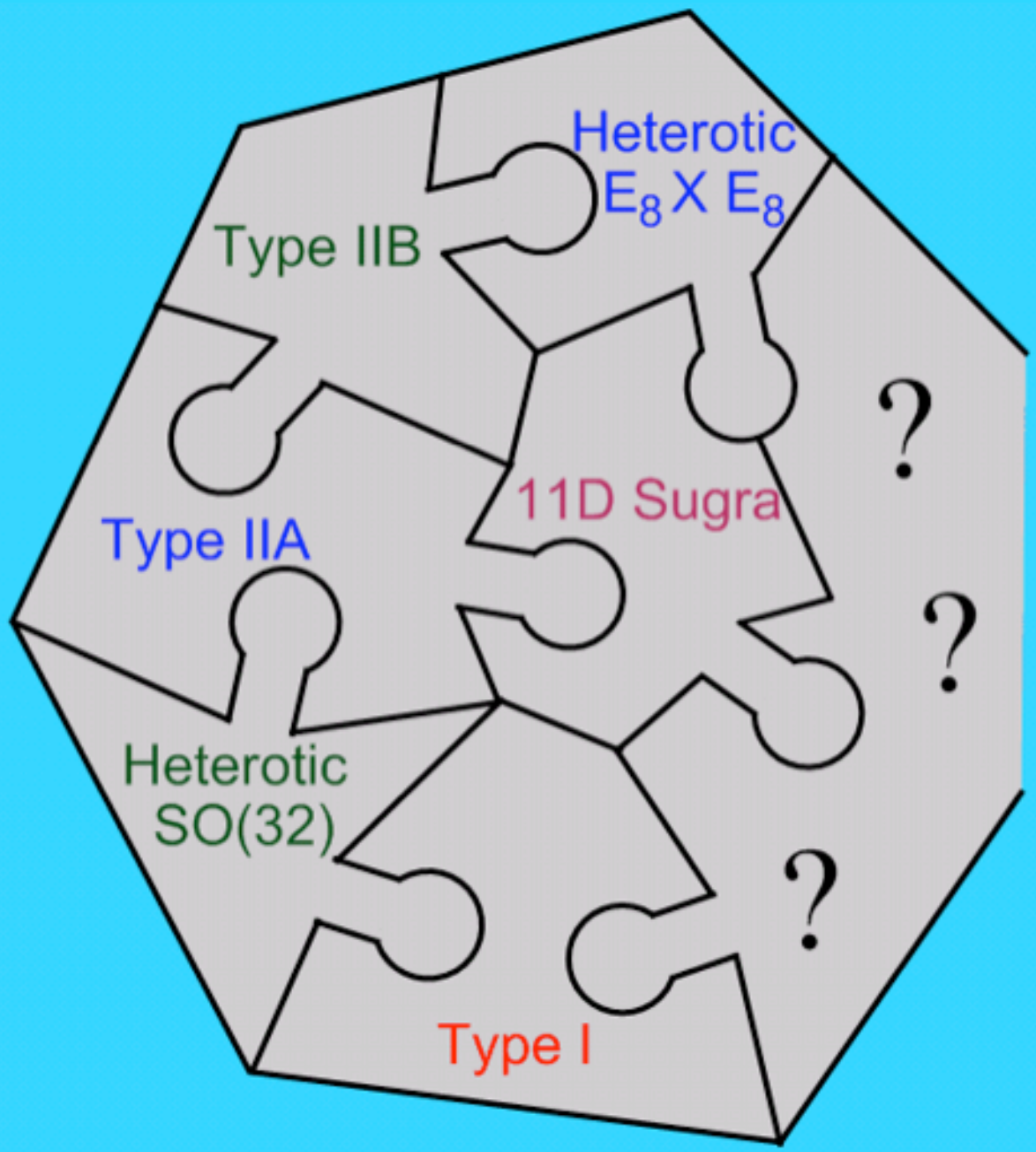


Within the open/closed description, one can describe the D-branes' natural sourcing of closed string fields

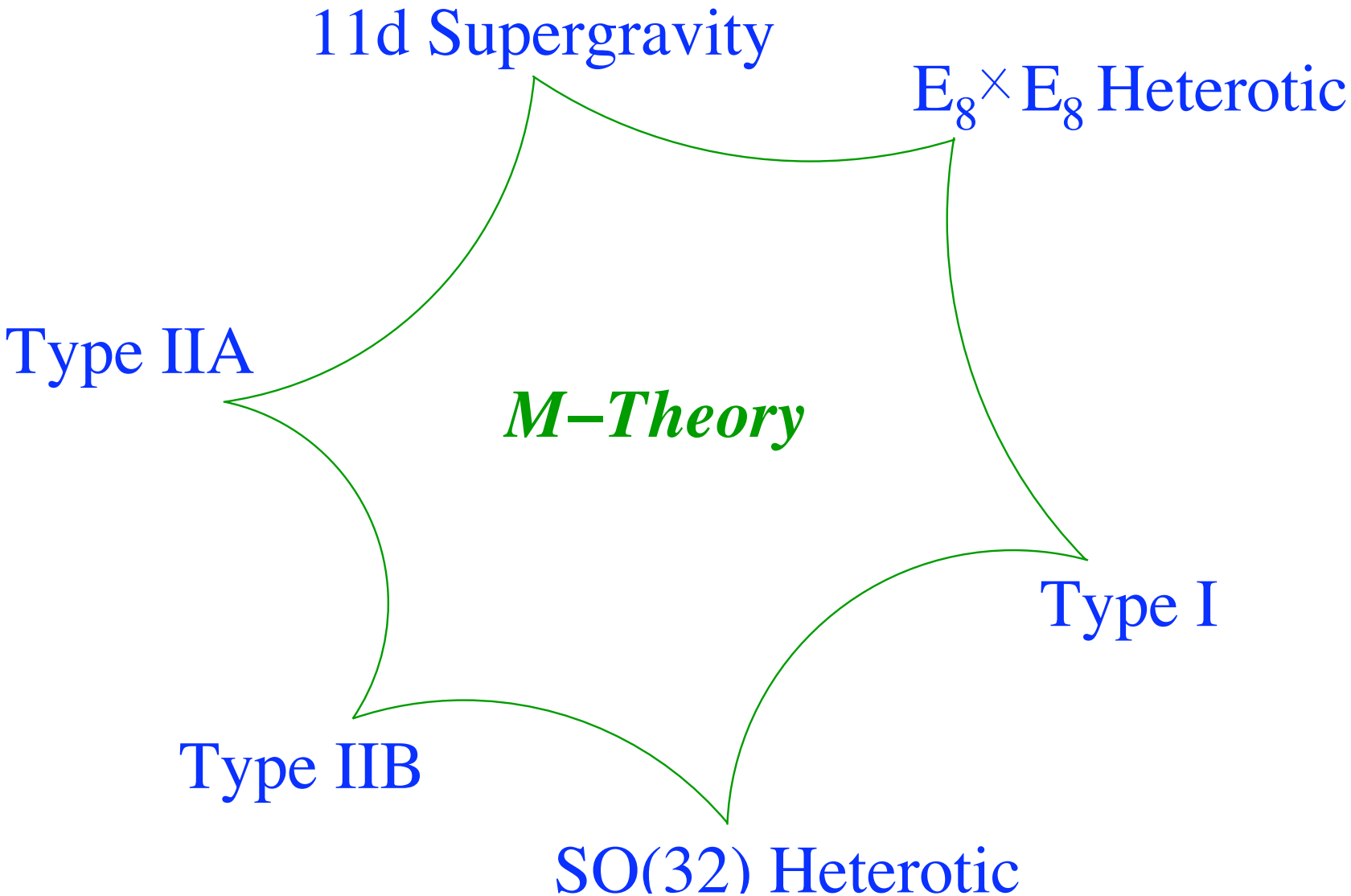
NS-NS: $\longrightarrow$ $G_{\mu\nu}, \Phi$

R-R: $\longrightarrow$ $C_{\mu_0\mu_1\cdots\mu_p}$

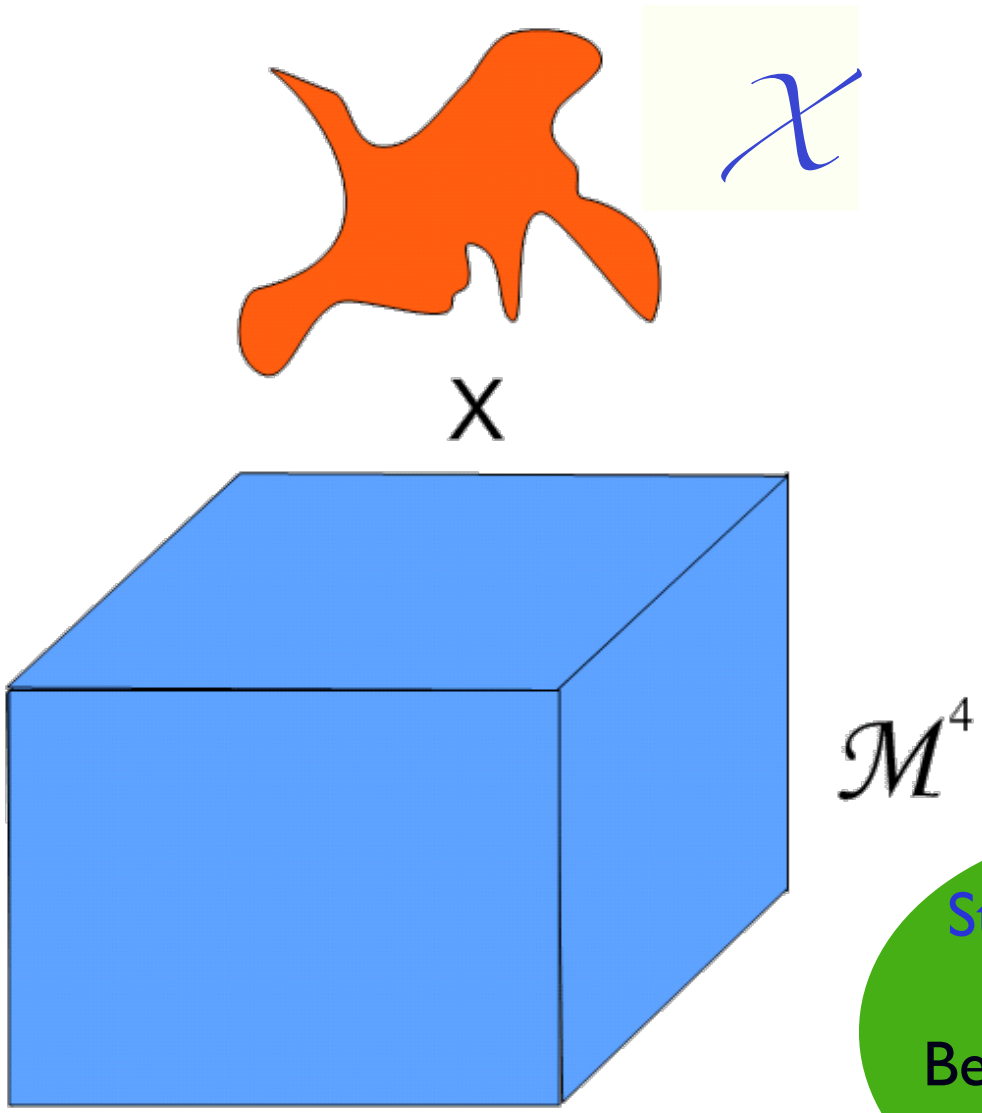
The various theories all fit together into a larger picture.



What is the full "M-Theory" ?


11d Supergravity
$E_8 \times E_8$ Heterotic
Type IIA
M–Theory
Type I
Type IIB
SO(32) Heterotic

Uniqueness of Vacuum?



As usually presented, strings are expected to give a unique answer which will be our universe.

Found increasing number of ways of describing numerous vacua

There are two main approaches now

Still looking for dynamics
Better control of vacuum selection

Assume there's no unique vacuum
Take another approach altogether

What Brought Us to This?

Data

Observations that our universe is accelerating have produced an upheaval:

Cosmological Constant?
$\Lambda > 0$

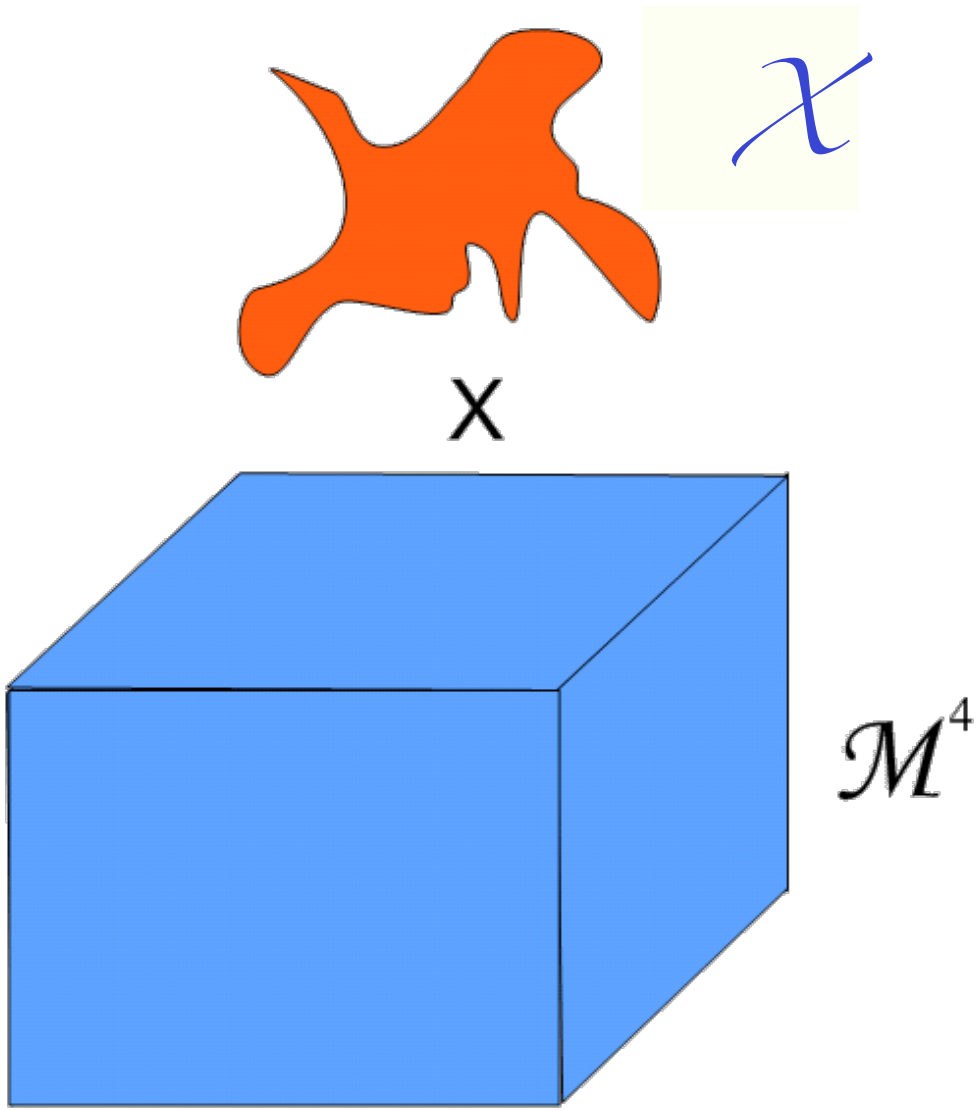
Scalar Fields?

We've developed powerful technology for:

Cosmological constant:
Study of spacetimes with $\Lambda < 0$
Taught us about holography, black holes, gauge theory....

Scalars:
Very good at studying the many massless scalars which appear
Moduli space problems have taught us a lot about M-theory, black holes, gauge theory
All helped by Supersymmetry

Where do the Scalars come from?



Size of $\mathcal{X}$? Shape of $\mathcal{X}$?

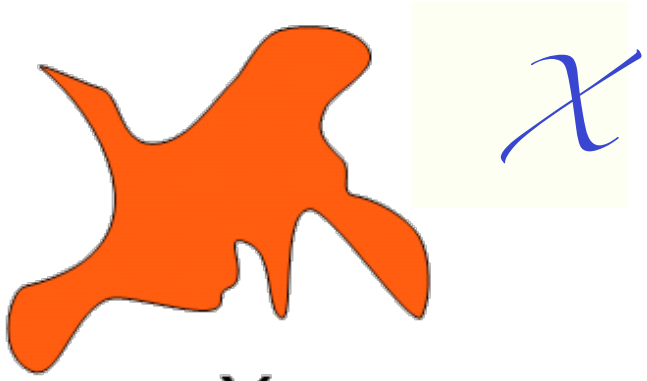
Susy does not restrict these

Locally adjustable parameters

Scalar Fields in *D=4*

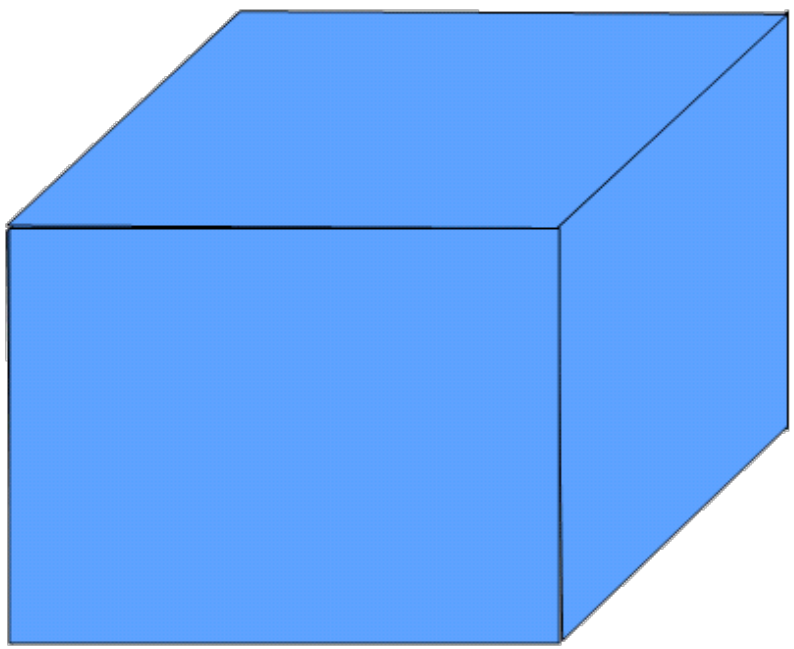
Where do the Scalars come from?

Size? Shape?

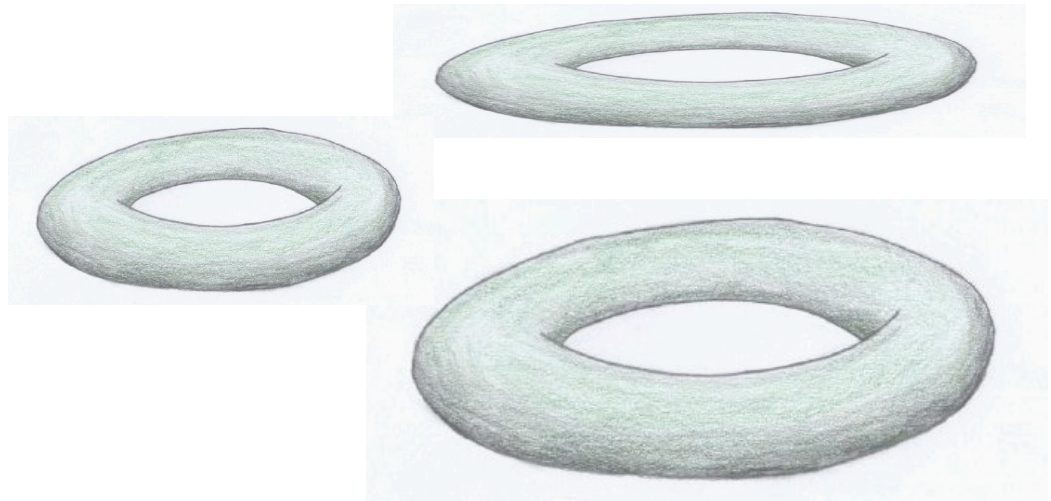


$\mathcal{X}$

X



$\mathcal{M}^4$



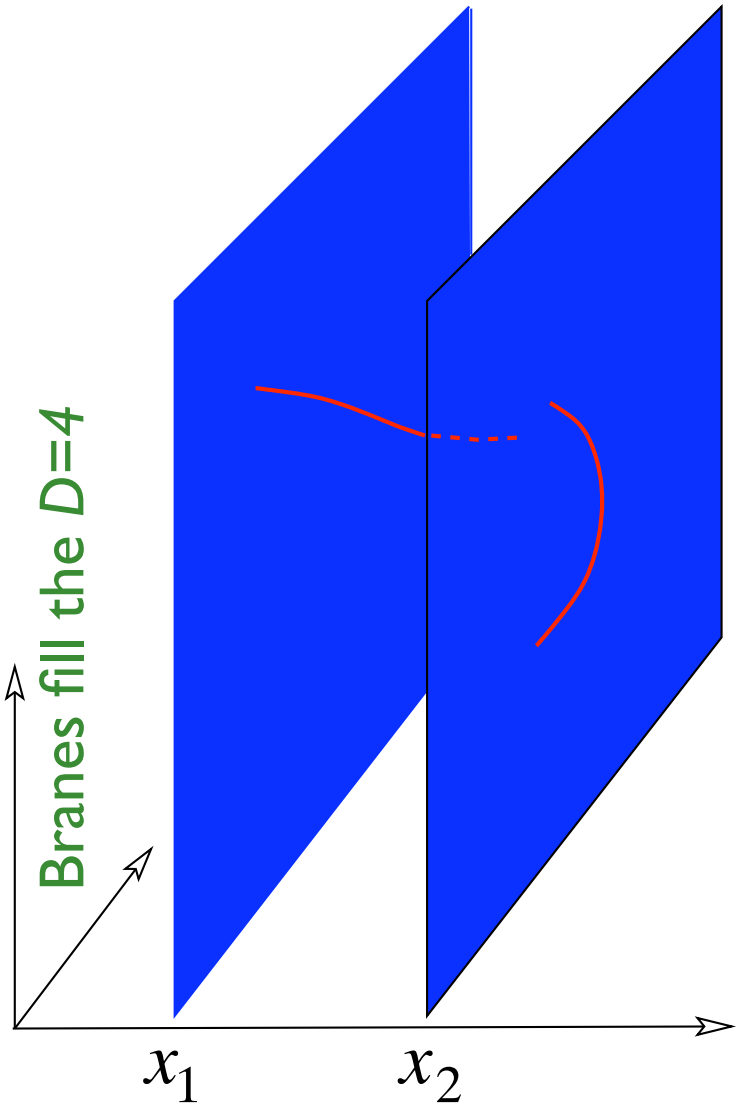
This is also true for subspaces "cycles" of $\mathcal{X}$

Kahler Moduli

Complex Moduli

Many Scalar Fields in $D=4$

Where do the Scalars come from?



Positions of branes?
Relative angle?

D-branes are BPS states.

Susy does not restrict these

(depending upon space in which they're embedded.)

Locally adjustable parameters

Scalar Fields in $D=4$

This is also true for larger branes wrapping various subspaces "cycles" of $\mathcal{X}$

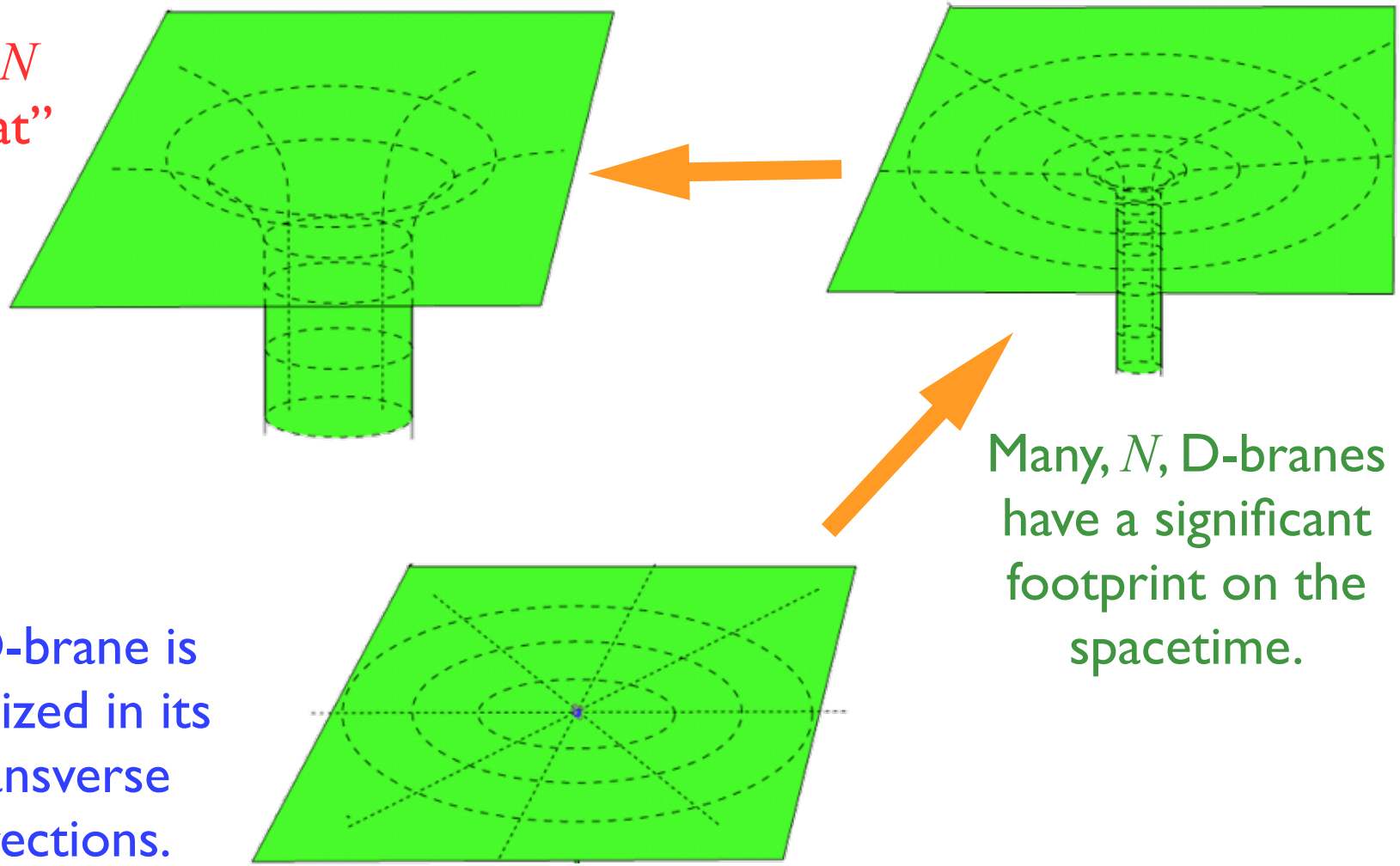
Many Scalar Fields in $D=4$

What happens to all these scalars when Susy broken?

Generate potentials for all?
Physics of these potentials?

Negative CC in String Theory

In the large N limit, a "throat" opens up.

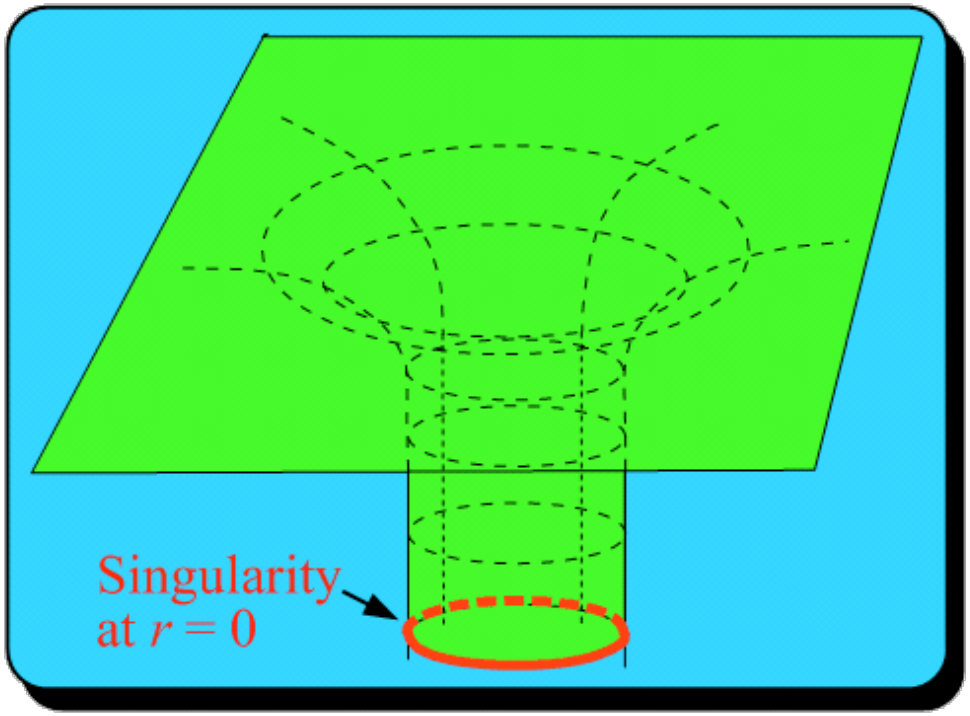


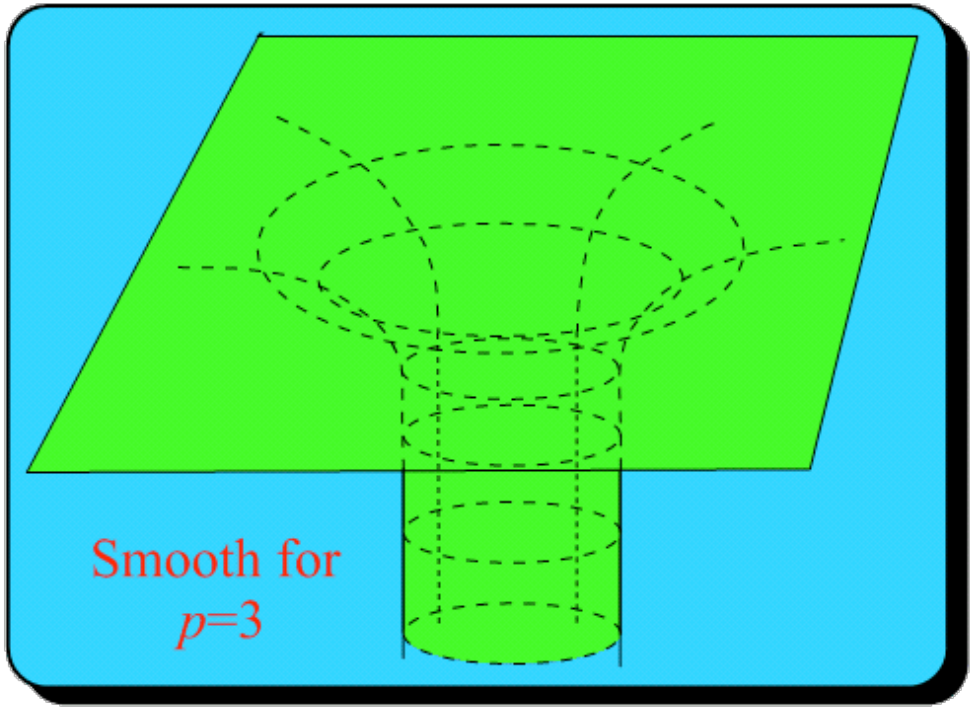
Many, N, D-branes have a significant footprint on the spacetime.

A D-brane is localized in its transverse directions.

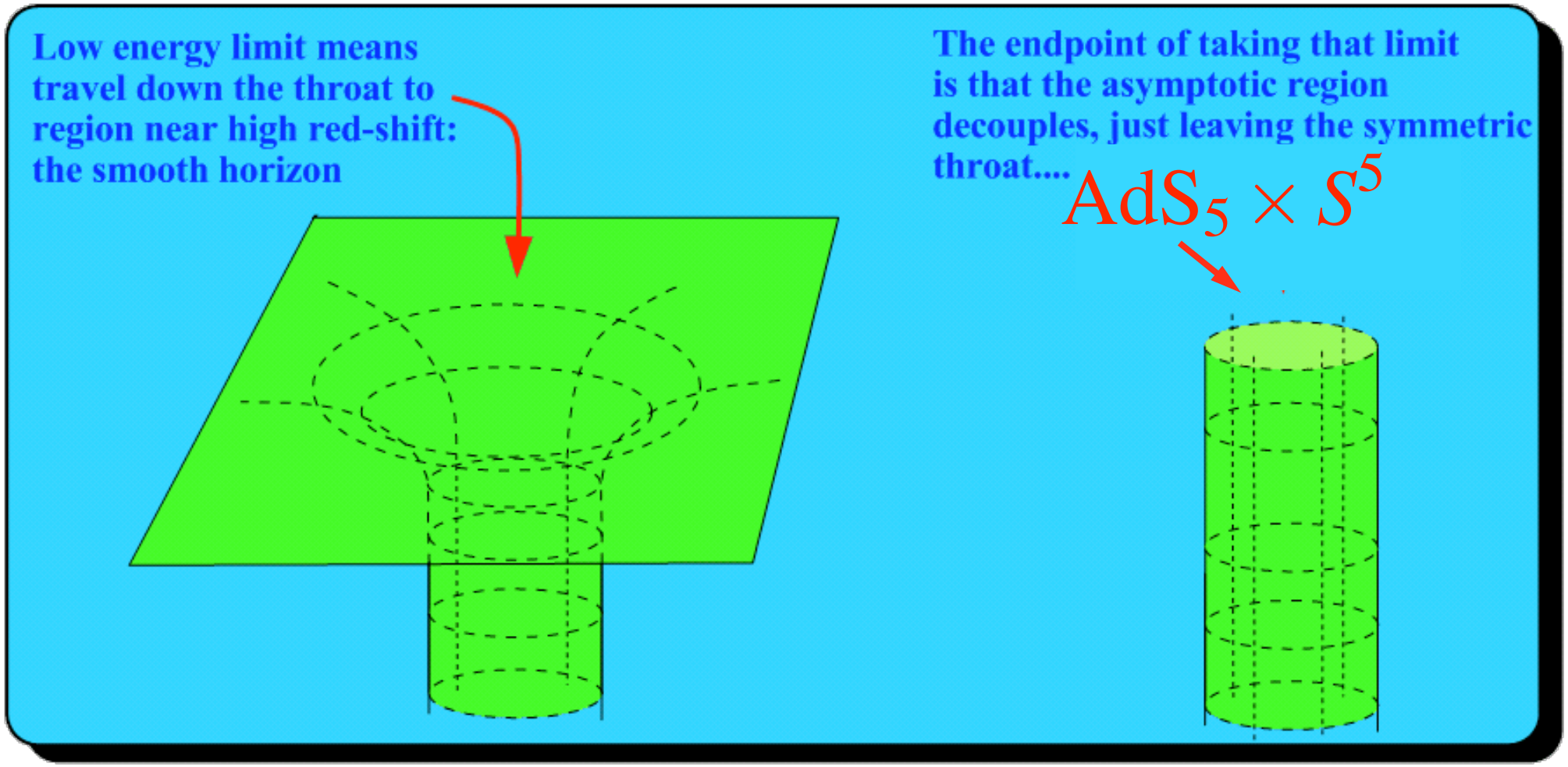
A D3-brane is special.

It also naturally fills a *D=4* spacetime...



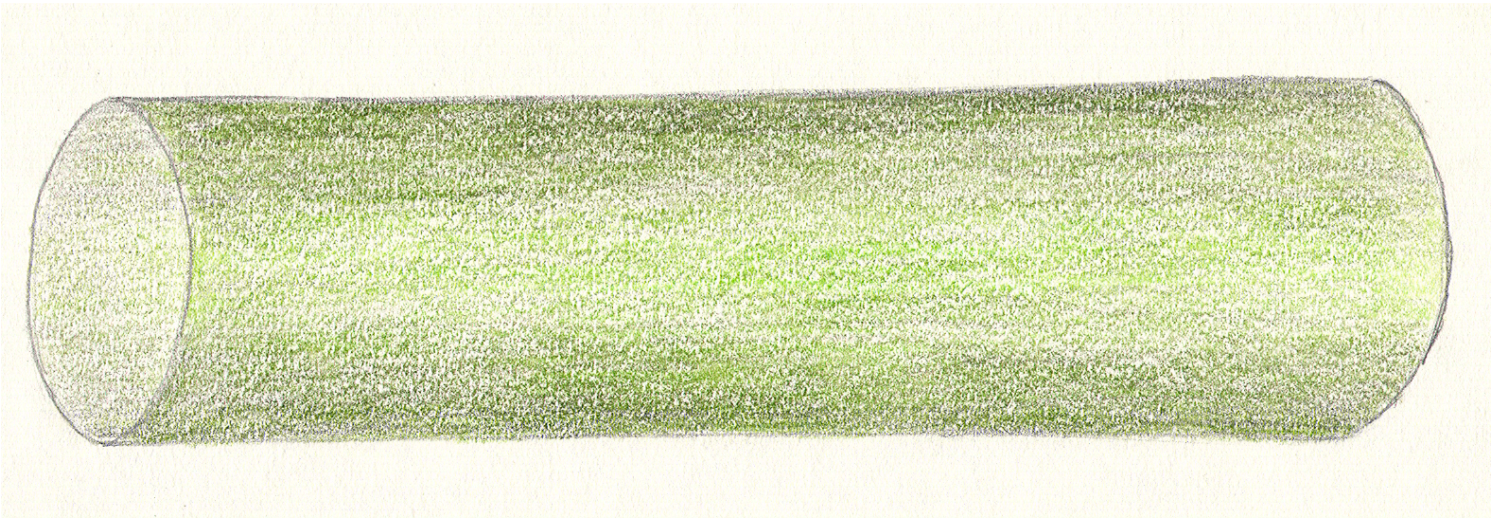


A D3-brane is special.



This is the same limit in which the *D=4* theory is *SU(N)* Yang-Mills Theory

The Usefulness of Throats

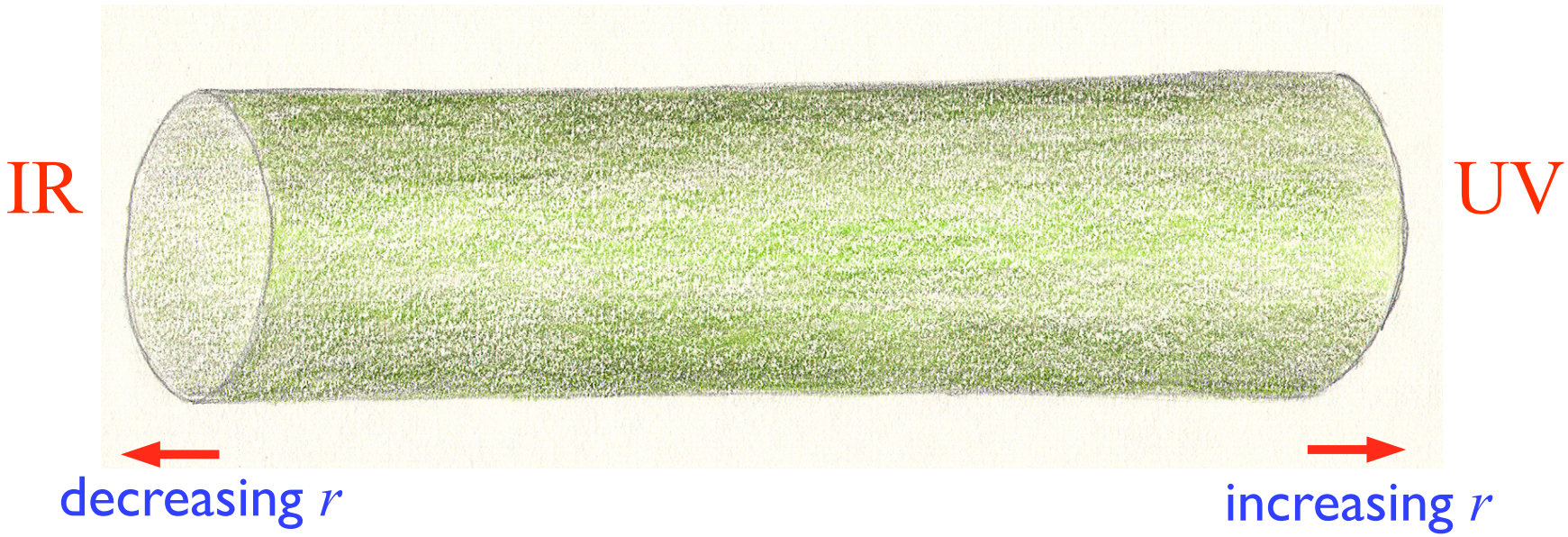


Metric of a cross-section

$$ds^2 = e^{2A(\perp)} \overbrace{g_{\mu\nu} dx^\mu dx^\nu} + ds_\perp^2$$

"warp factor"

The Usefulness of Throats



$$ds^2 = e^{2A(\perp)} g_{\mu\nu} dx^\mu dx^\nu + ds_\perp^2$$

AdS_5 :

$$A(\perp) = \frac{r}{\ell}$$

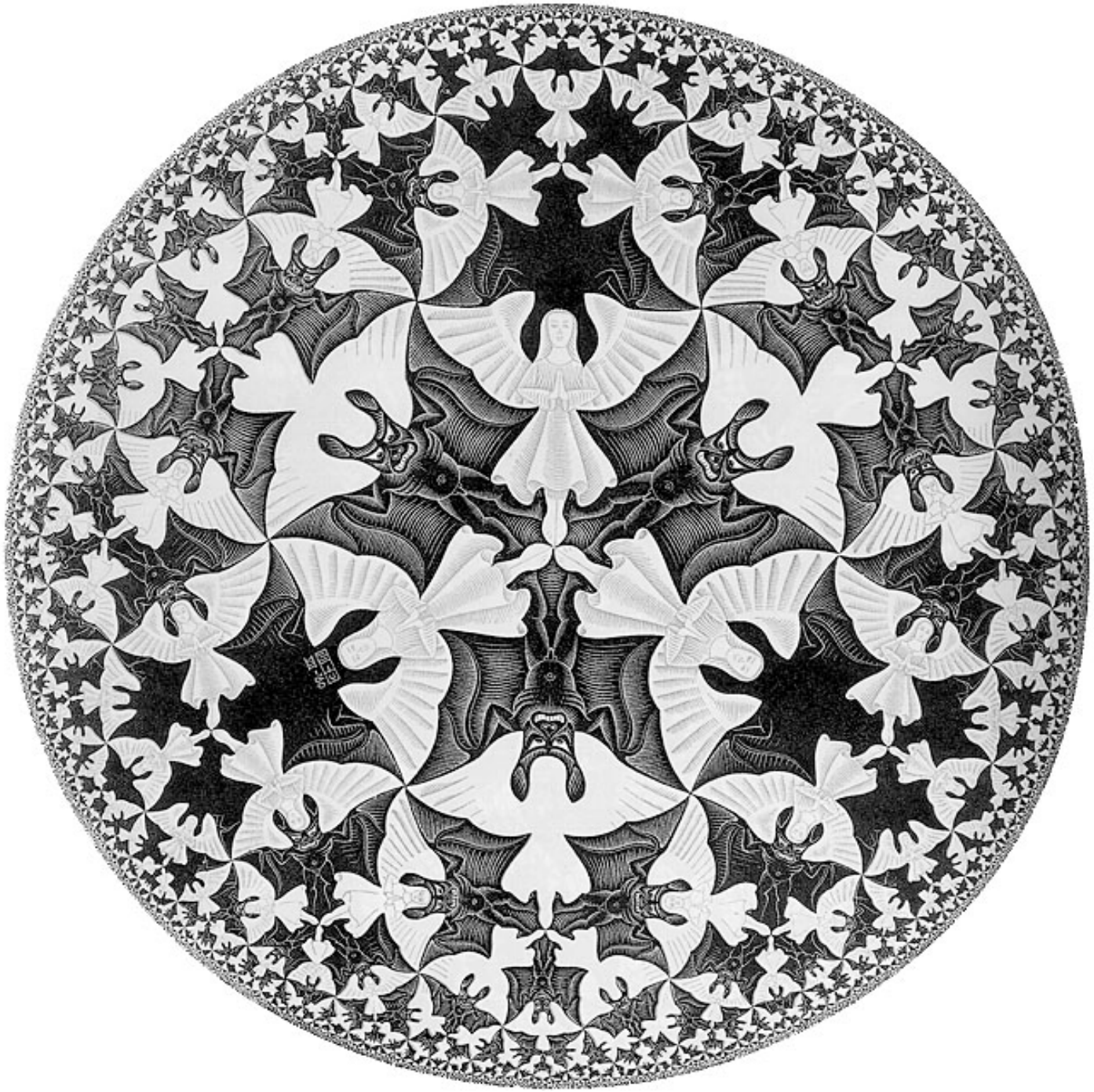
$$ds_\perp^2 = dr^2$$

$$g_{\mu\nu} = \eta_{\mu\nu}$$

At some value of r: $L_{10}^2 = e^{2A(r)} L_4^2$

So the warp factor gives small *D=4* scales for large r and vice-versa!

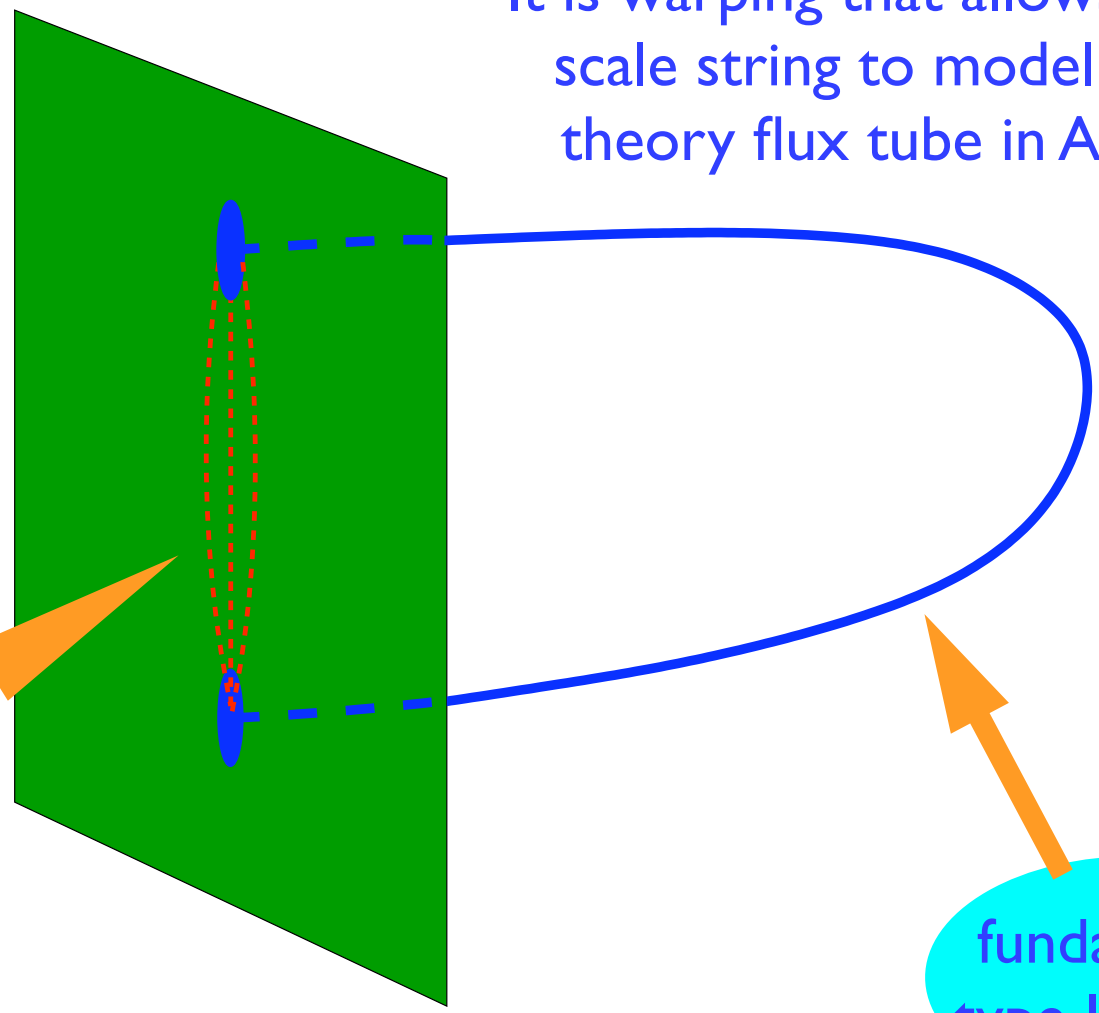
The Usefulness of Throats



Everybody knows an example!

The Usefulness of Throats

It is warping that allows a Planck scale string to model a gauge theory flux tube in AdS/CFT



quarks connected by flux tube in D=4 gauge theory

fundamental type IIB string

This will be useful in cosmological scenarios, later....

Thinking about $\mathrm{AdS}_5 \times S^5$

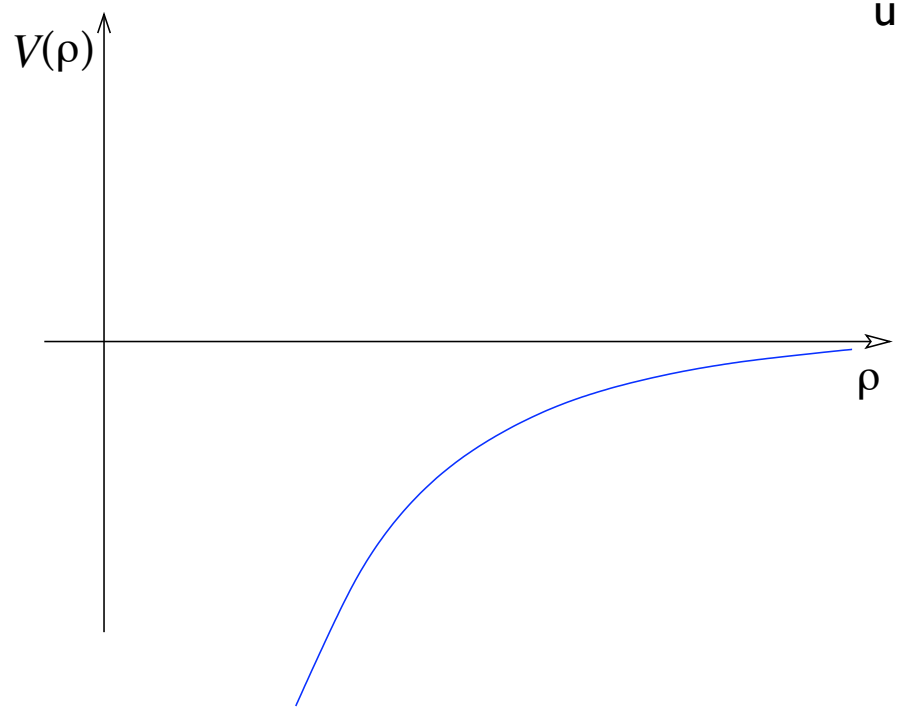
Compactifying on the sphere gives a *D=5* scalar representing its radius.

$$V_{\mathrm{Sph}}(\rho) \sim -\frac{g_s^{p/4}}{\rho^p}$$

positive curvature gives negative potential

$$R = \rho \ell_{\mathrm{Pl}}$$

radius in *D=5* Planck units



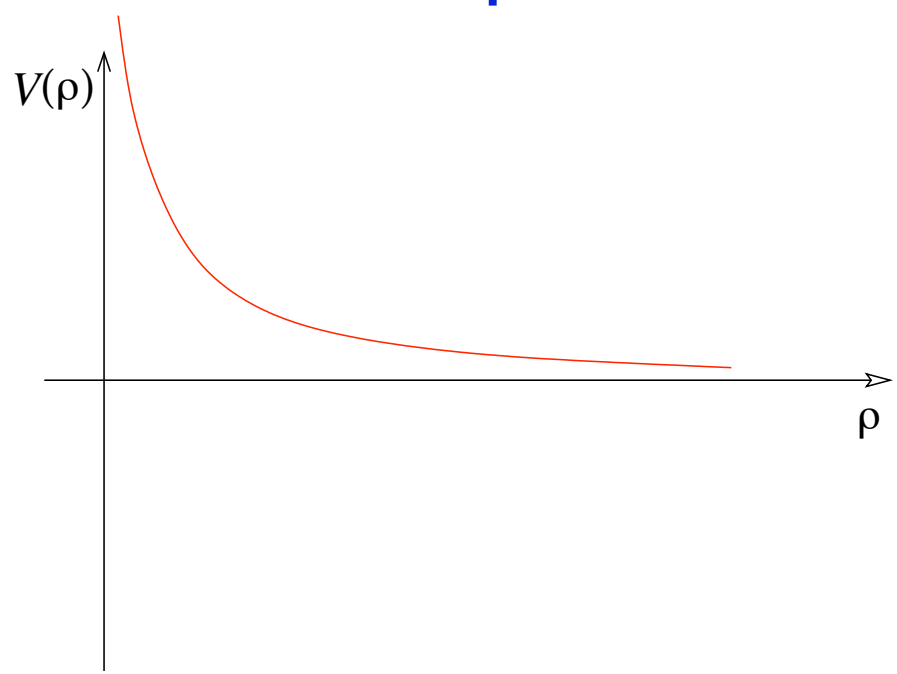
Sphere wants to shrink away...

Thinking about $\mathrm{AdS}_5 \times S^5$

There are N units of R-R 5-form flux through the sphere

$$V_{\mathrm{Flu}}(\rho) \sim \frac{N^2 g_s^{q/4}}{\rho^q}$$

Reduce energy by growing the sphere...



Thinking about $AdS_5 \times S^5$

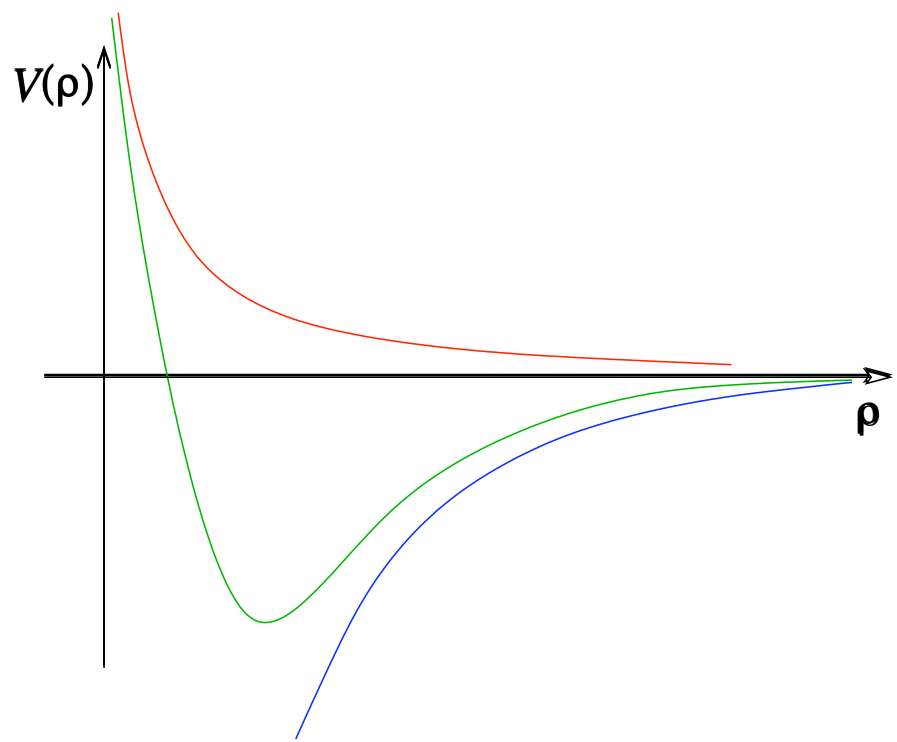
minimum at: $\rho^{q-p} = \frac{q}{p} N^2 g_s^{\frac{q-p}{4}}$

$$\frac{q}{p} = \frac{5}{2}$$

$$q - p = 8$$

$$\rho \sim (g_s N)^{1/4}$$

$$V(\rho) \sim -\frac{g_s^{p/4}}{\rho^p} + \frac{N^2 g_s^{q/4}}{\rho^q}$$



Thinking about $AdS_5 \times S^5$

So a combination of geometry and R-R flux can stabilize a modulus.

Size of sphere set by units of flux. Can make it large so that supergravity valid.

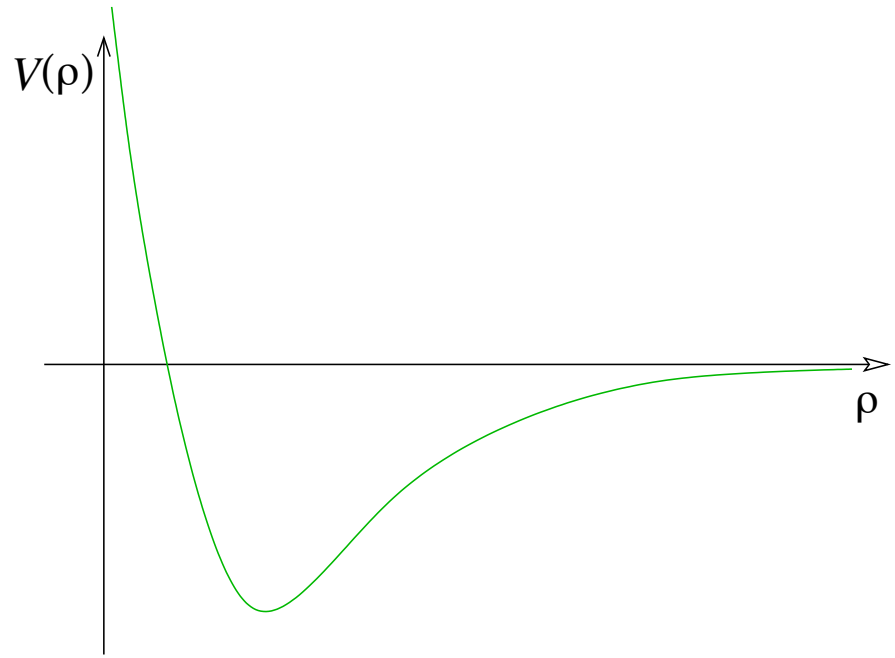
$$\rho \sim (g_s N)^{1/4}$$

Naturally get negative CC this way.

Naturally have reliable control over computations

(Supersymmetry still present)

Can one get positive CC using same tools?



Will need to break Supersymmetry...

Thinking about $\mathrm{AdS}_5 \times S^5$

Can one get positive CC using same tools?

Need to break Supersymmetry

But need reliable computational control

Tools to obtain positive CC

Content of the Type II theories

NS-NS: $\longrightarrow$ $G_{\mu\nu}, \Phi, B_{\mu\nu}$

R-R: $\longrightarrow$ $C_{\mu_0\mu_1\cdots\mu_p}$

$$F = dC$$
$$H = dB$$

Flux Compactifications are of great interest

$H - \text{flux}$

Thread these fluxes through 3-cycles in the transverse geometry.

$F - \text{flux}$

Play off the different sectors against each other

Tools to obtain positive CC

Focus on Type IIB theory

$$\frac{\mu_3}{2}\int_{\mathcal{X}} H\wedge F - \frac{1}{4}(N_{O3}-N_{\overline{O3}}) + N_{D3} - N_{\overline{D3}} = 0$$

("tadpole" consistency constraint)

(*D=4* filling branes and planes)

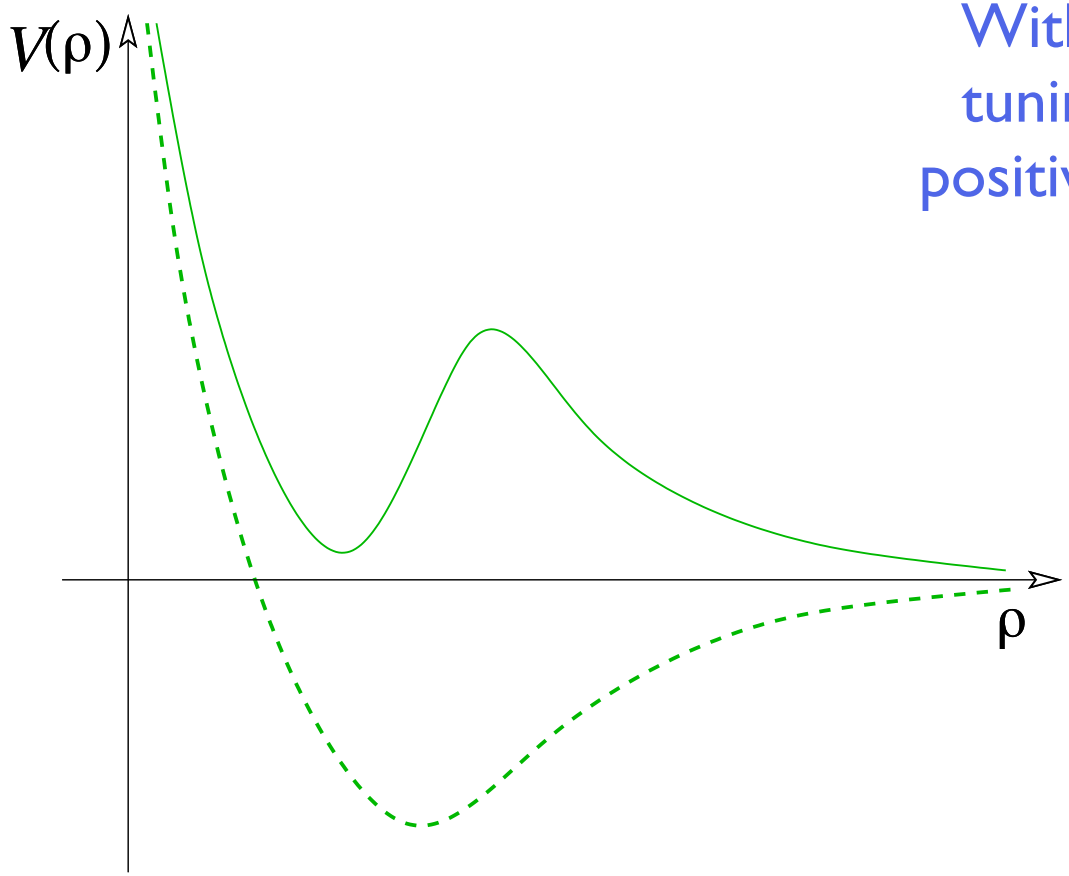
(1-loop contrib'n to h)

The Players from different sectors

D-Branes **O-Planes** **Geometry** **Fluxes**

$$V(\Phi,\rho_i) = Ae^{4\Phi}\left(-fe^{-2\Phi} + ge^{-2\Phi} + ne^{-\Phi} + h\right)$$

Tools to obtain positive CC

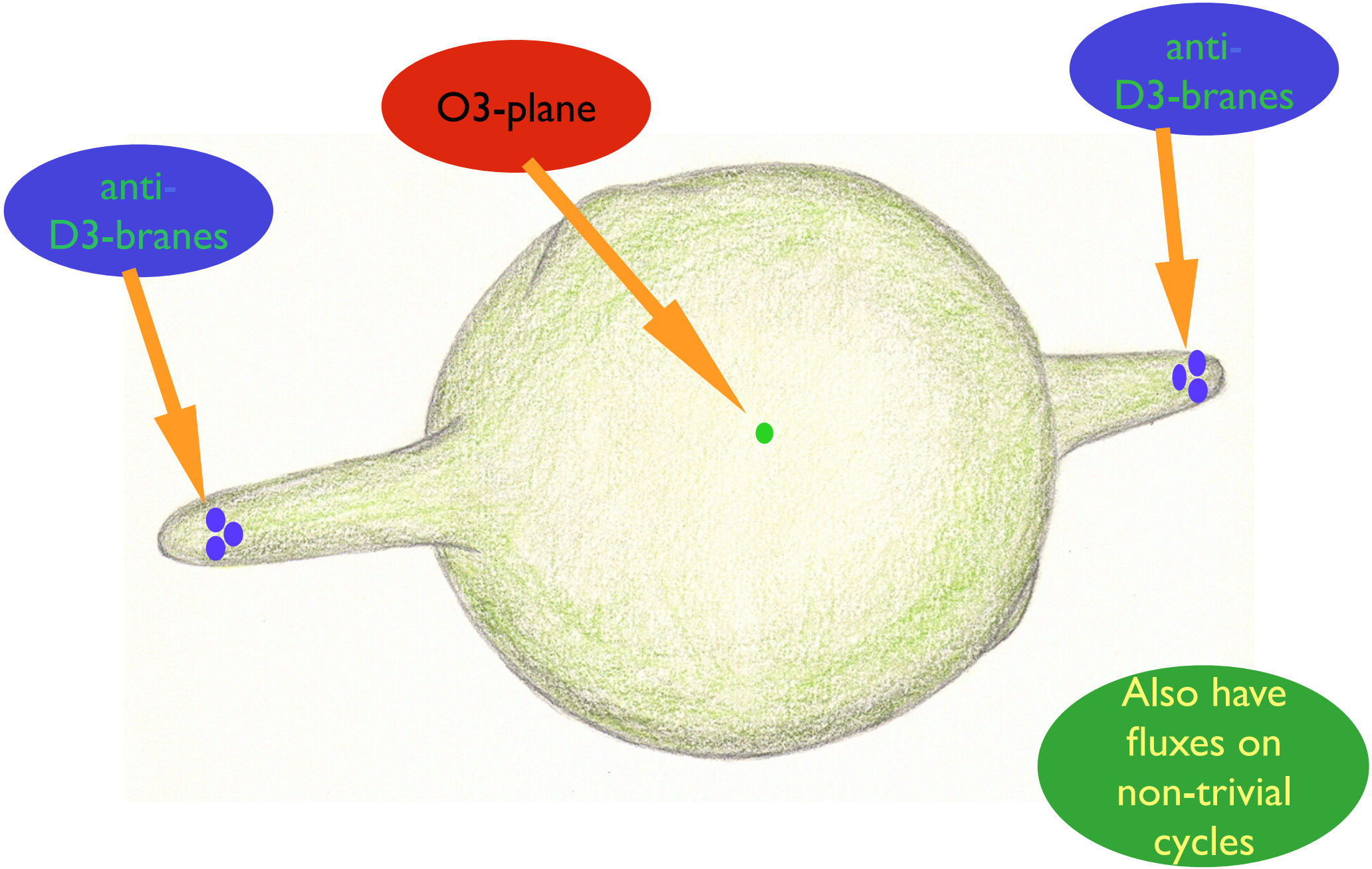


With appropriate tuning, can obtain positive (meta)stable minimum

The KKLT Scenario

The manifold $\mathcal{X}$ with all ingredients.....

The KKLT Scenario



The KKLT Scenario

Worry:
Non-perturbative effects under control?

world-sheet instantons

$e^{-\frac{A}{\alpha'}}$ effects

D3-branes can wrap non-trivial 4-cycles

e^{-V} effects

Hard to stabilize Kahler moduli especially

D7-branes can wrap non-trivial 4-cycles

$e^{-\frac{V}{gs}}$ effects

Stabilize at weak coupling and low curvature?

Viable Scenario?

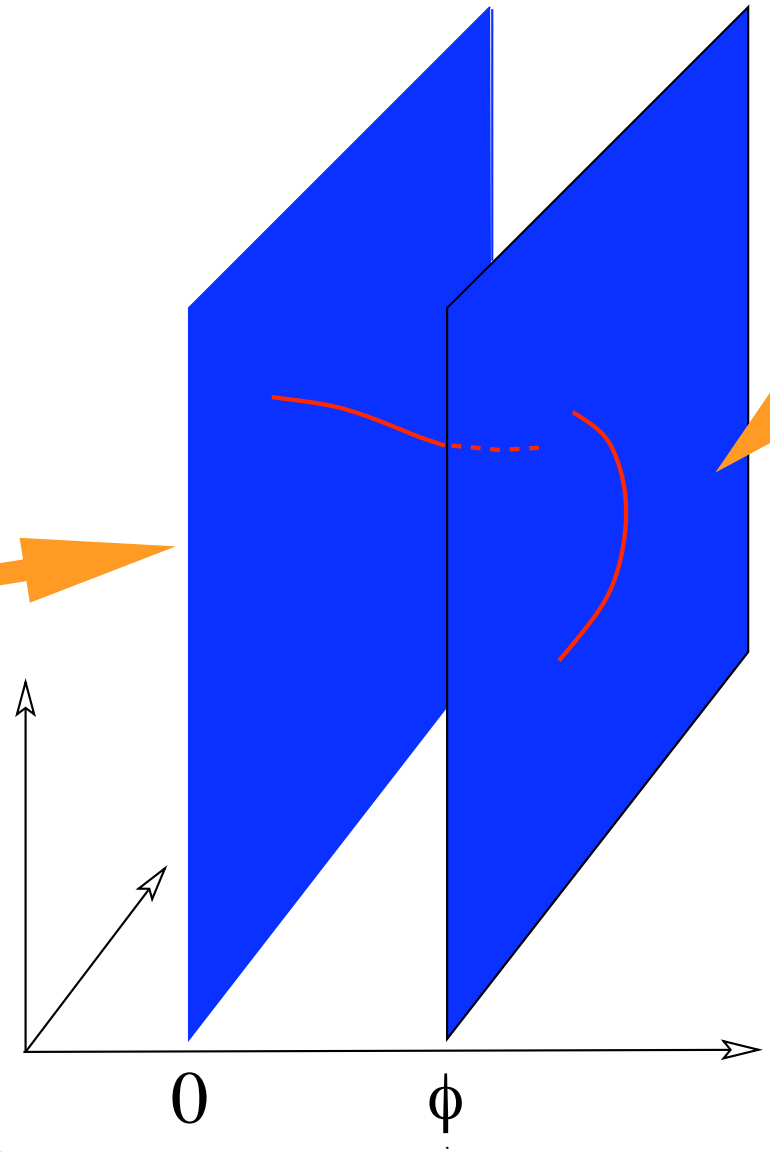
It is generally believed that it is possible that many such solutions exist

There is considerable disagreement about whether any have been found!

Evidently a problem of great interest and a subject of heated debate

Brane-AntiBrane Inflation: DT Scenario

Revisit the brane scalars



anti-D3-brane

D3-brane

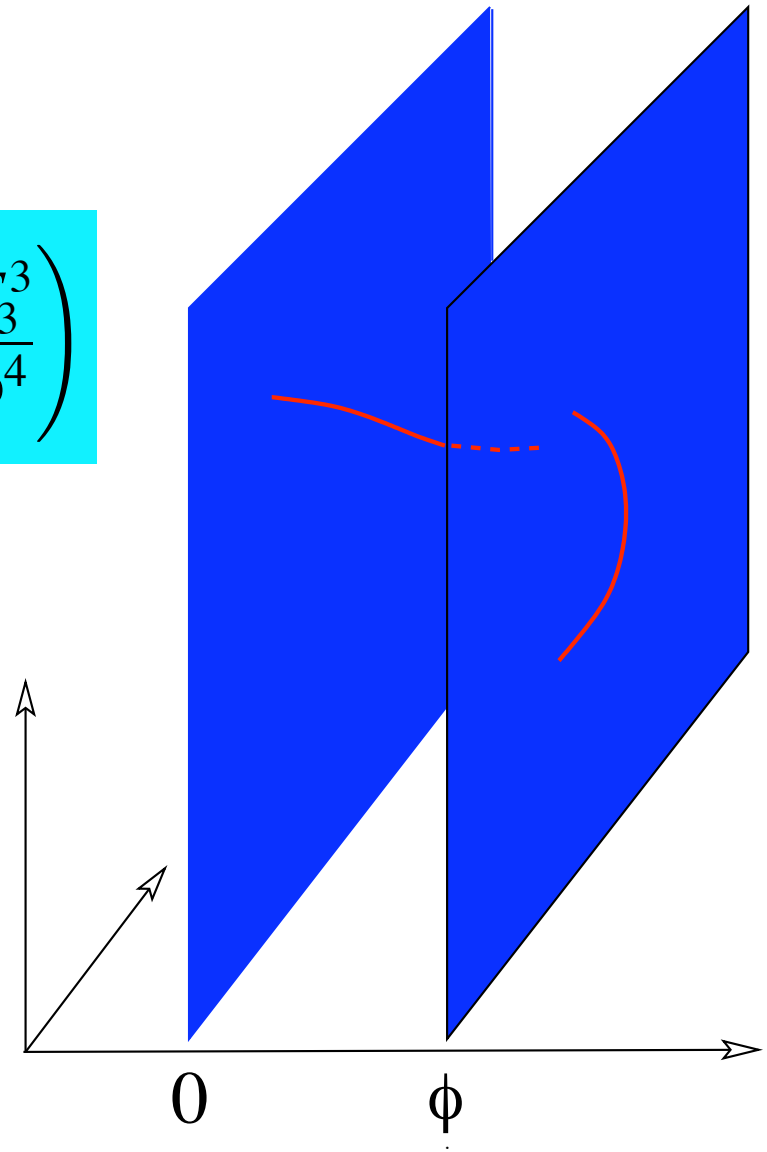
distance between them is a *D=4* scalar

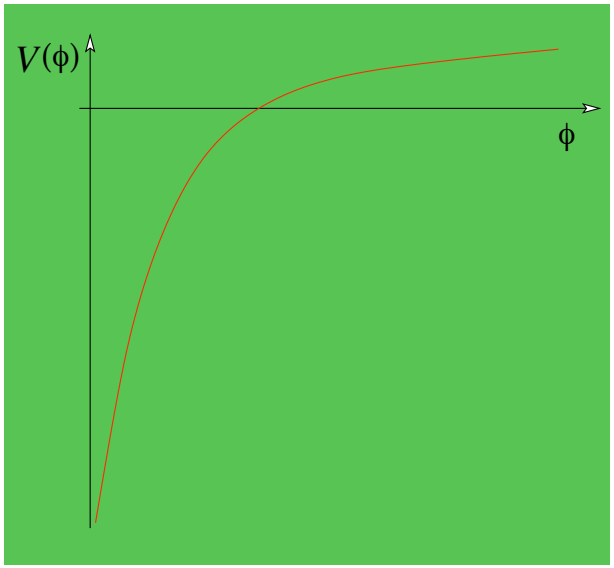
possible inflaton?

examine form of potential, look at slow roll conditions

Brane-AntiBrane Inflation: DT Scenario

$$V(\phi) = 2T_3\left(1 - G_N^{10}\frac{T_3^3}{\phi^4}\right)$$

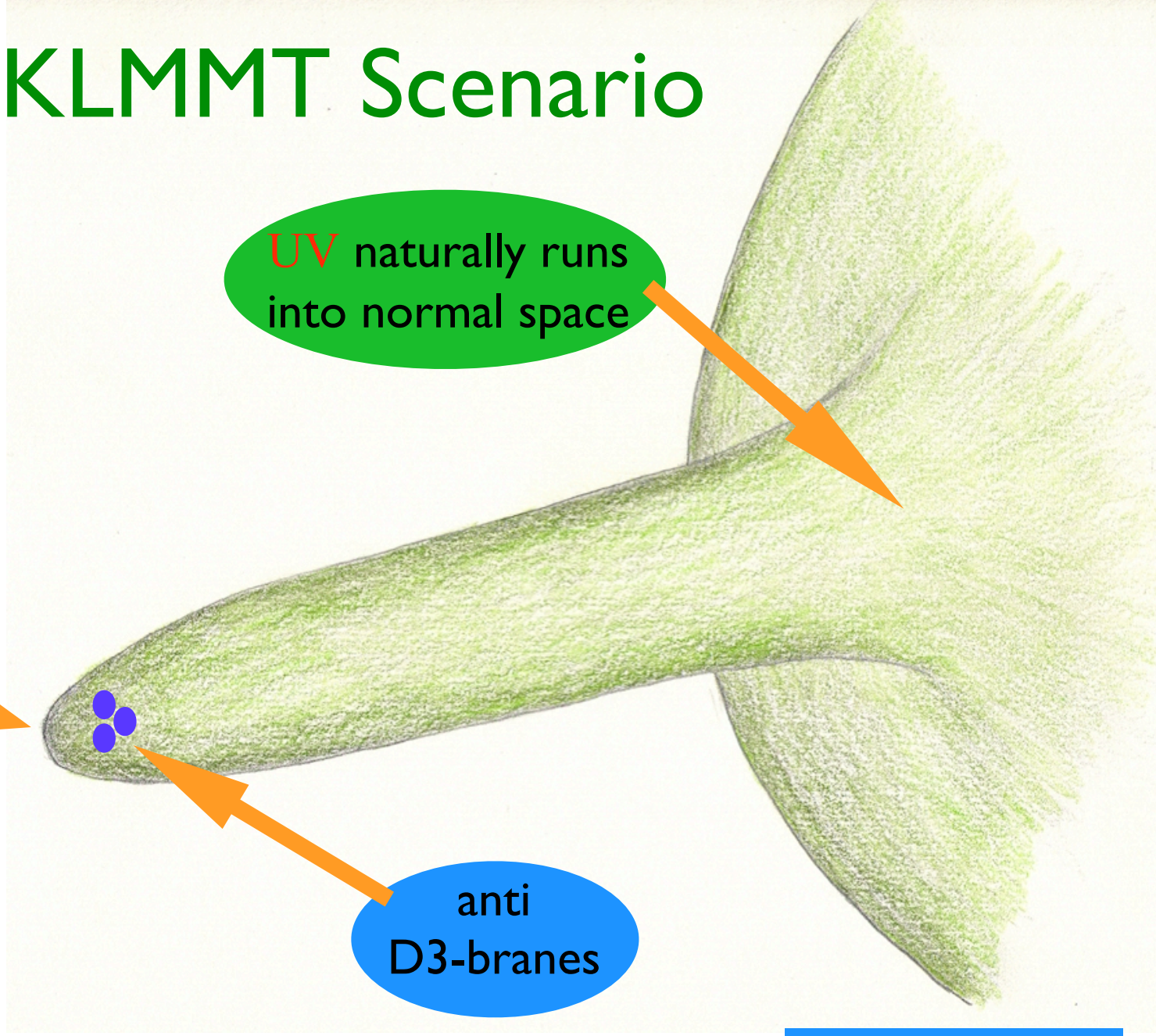




It does not work. Slow roll needs the branes to be separated by a size bigger than the space they're in

KKLMMT Scenario

KKLT Scenario has natural throats with warped geometry

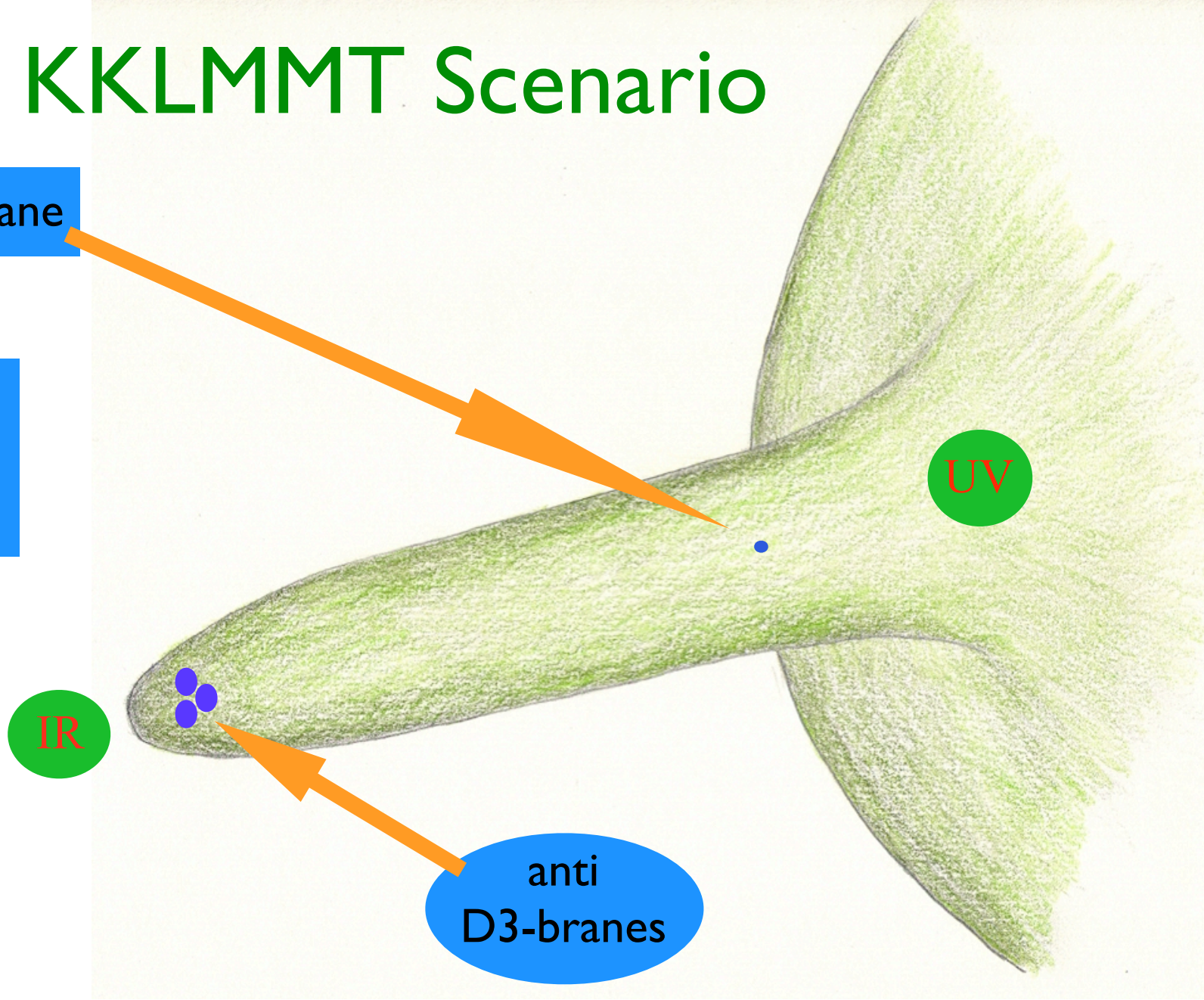


Natural realization of RS scenario

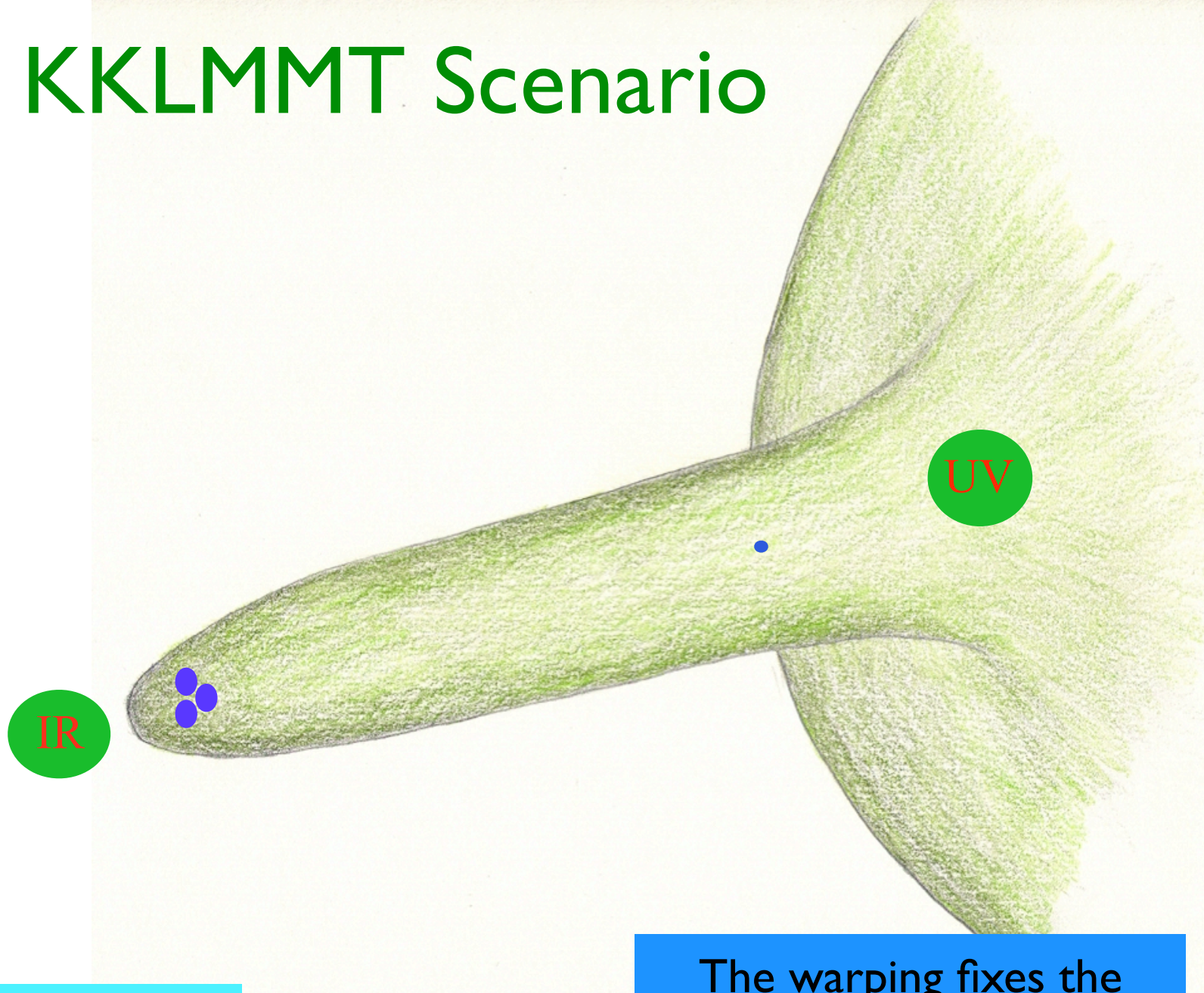
KKLMMT Scenario

Now add a D3-brane

It will roll down to annihilate with the anti-branes.



KKLMMT Scenario



recompute potential

$$e^{2A(UV)} \sim 1$$
$$e^{2A(IR)} << 1$$

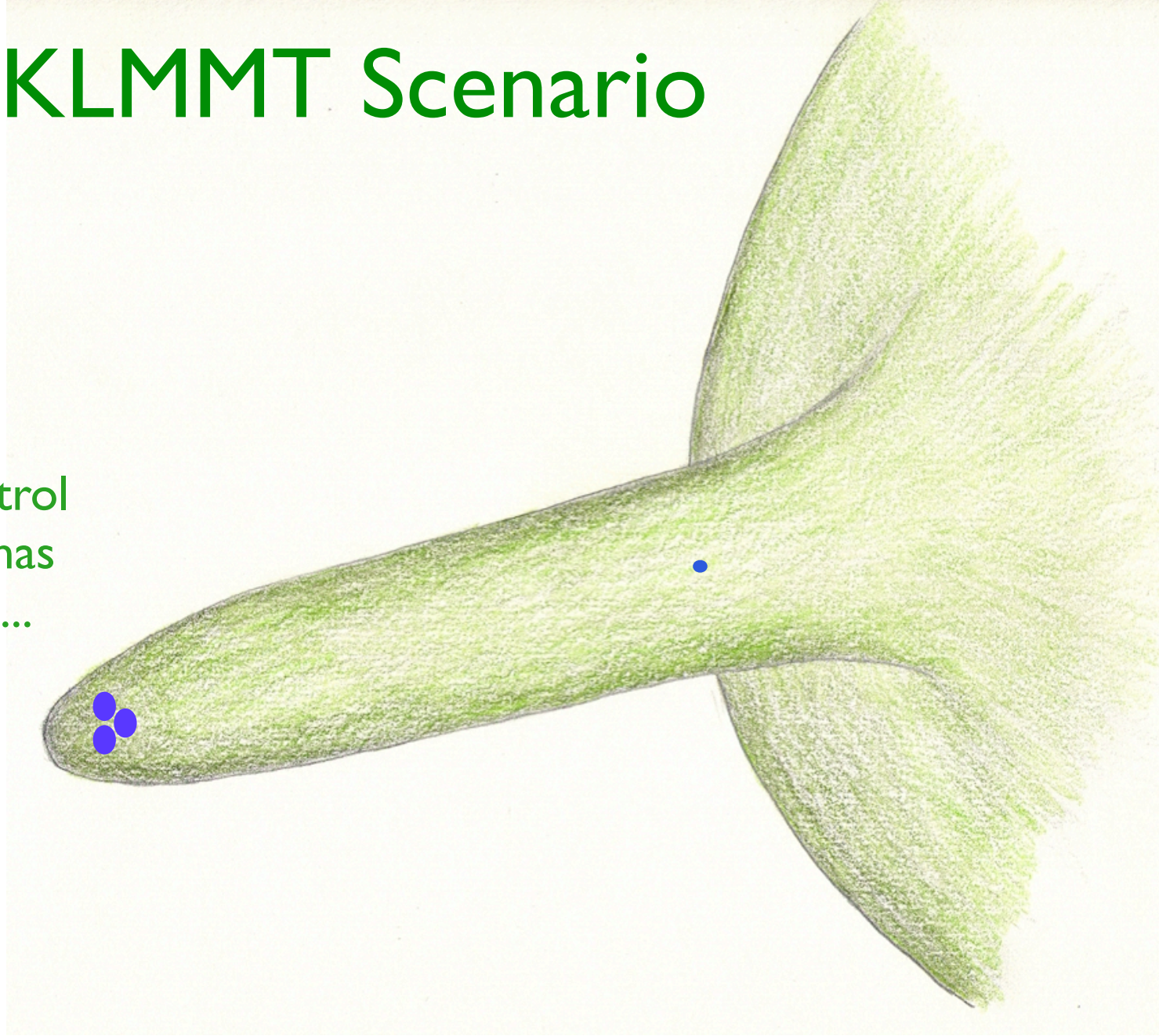
The warping fixes the problem of scales in the brane-antibrane inflation scenario

KKLMMT Scenario

This is a very natural scenario.

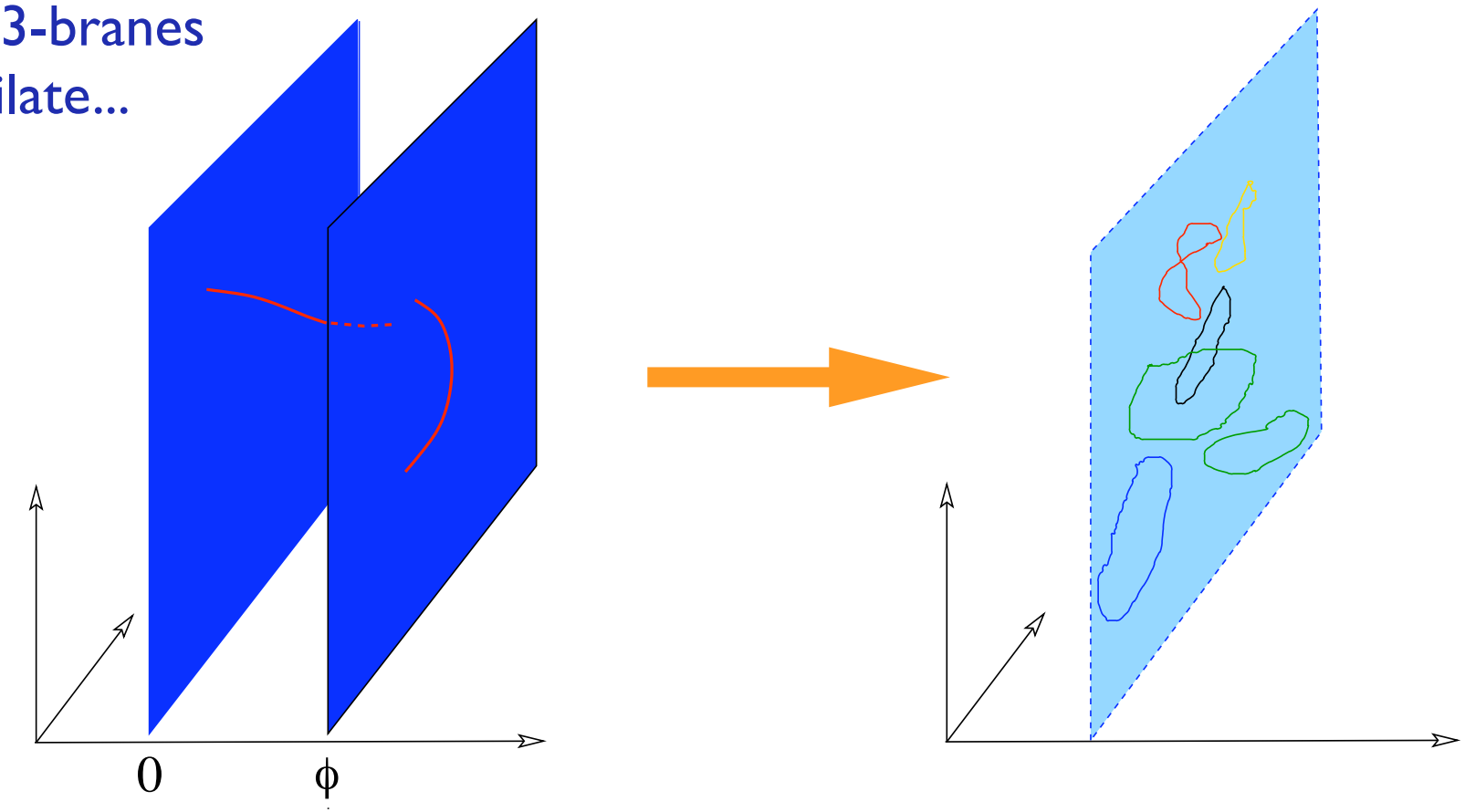
It suffers from same control problems as KKLT, and has new control problems....

...but it offers a very exciting framework.



Cosmic D and F Strings: CMP Scenario

When D3-branes annihilate...



The strings are topological structures in the "tachyon" field

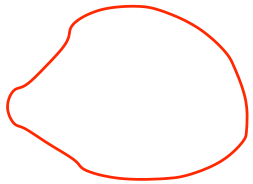
...they can leave strings behind.

Cosmic D and F Strings: CMP Scenario

What type of string?

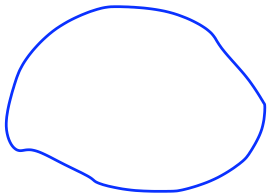
F-string

$(1,0)$



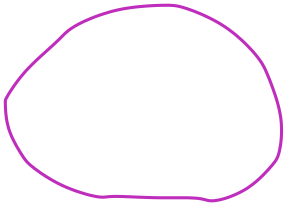
D-string

$(0,1)$



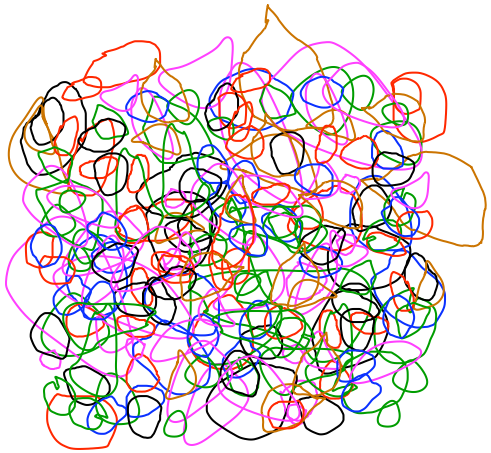
Most importantly, these strings can form bound states:

$(1,1)$



(p,q) in general

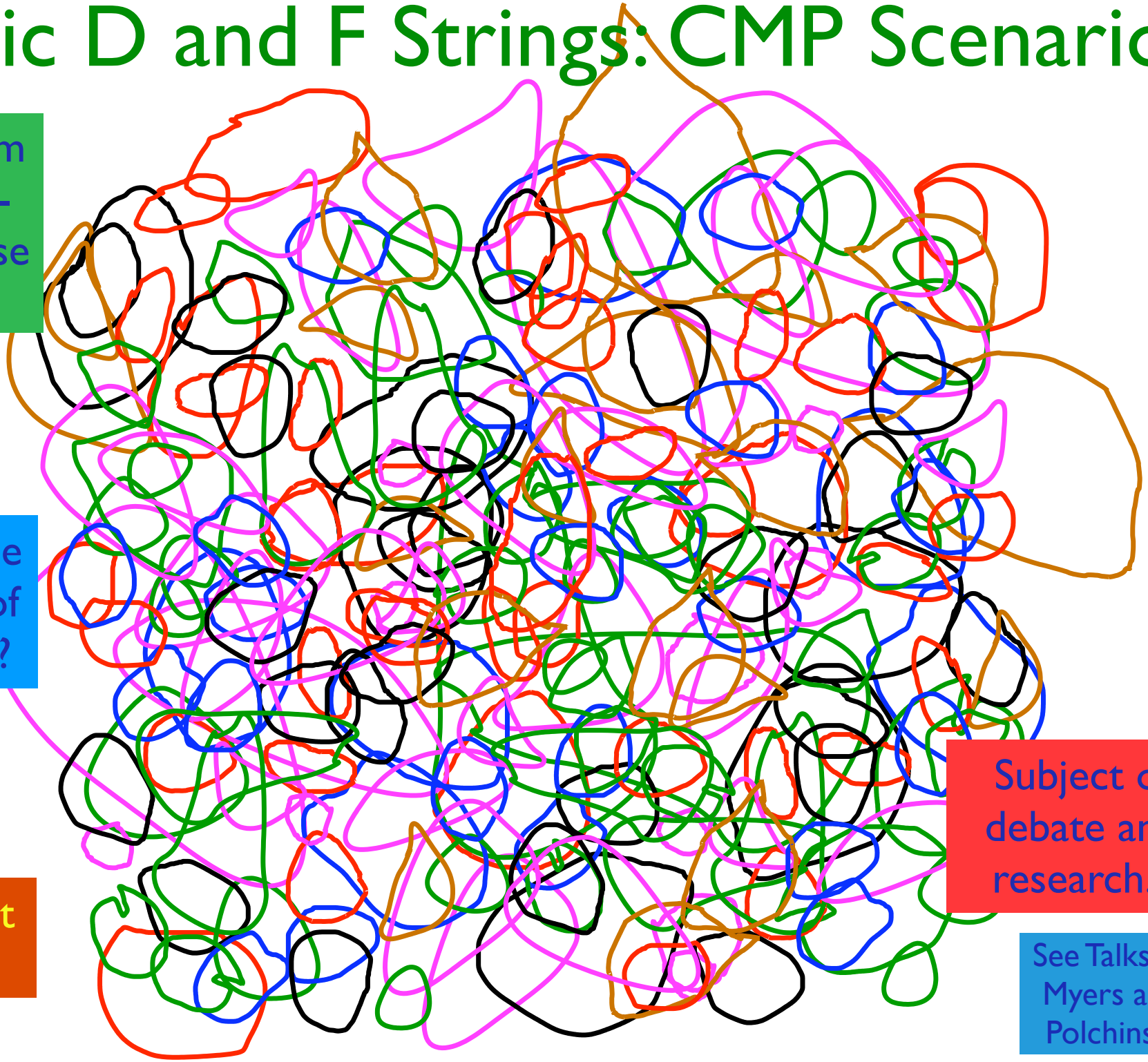
...they can form networks



They will form and get inflated.... are their effects visible in our universe?

Cosmic D and F Strings: CMP Scenario

Strings seem to be long-lived in these scenarios



What are the properties of the netwok?

How does it evolve?

Subject of debate and research...

See Talks by Myers and Polchinski

The Landscape

GKP, KKLT, and BP: Very large number of flux vacua consistent with small positive cc.

Makes more urgent the need to search for mechanism for selecting vacuum dynamically

Perhaps there is no such mechanism!

Susskind: Perhaps we need to appeal to an anthropic argument for the properties of our universe?

Douglas et. al.: Seek to gain better understanding of the landscape by doing statistics of vacua with various properties.

Tackles head on the issue of whether we can make testable detailed predictions in string/M-theory at all.

All approaches being pursued right now. Much to be done.

Brief Overview of The Rest

There is a lot of diverse activity!

Much of the technology described earlier was manufactured and developed in various other contexts.

Some Key Foci:

Tachyon Condensation

As means of following fate of unstable vacua

As means of constructing D-branes

As means of better understanding open vs closed string descriptions

Got inflation from brane annihilation this way

Used this to make cosmic D- and F-strings

Brief Overview of The Rest

There is a lot of diverse activity!

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Some Key Foci:

Tachyon Condensation

Which technology used?

String Field Theory
(Many new developments)
Matrix Models
(New ideas, several examples)

Made concrete many ideas of Sen

Brief Overview of The Rest

There is a lot of diverse activity!

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Some Key Foci:

de Sitter Spacetime

Holographic description of positive CC?

Lessons from AdS/CFT? New type of brane? S-brane?

Ideas about what the finite entropy of de Sitter means....

How to write quantum theory in accelerating universes?

Brief Overview of The Rest

There is a lot of diverse activity!

Much of the technology described earlier was manufactured and developed in various other contexts.

Some Key Foci:

de Sitter Spacetime

Which technology used?

Conformal Field Theory
(Some new developments)
(Super)gravity
(New ideas....)

Brief Overview of The Rest

There is a lot of diverse activity!

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Some Key Foci:

Black Hole Microstates

Revisiting this story. Strominger-Vafa and others developed a successful picture

Remarkable success in matching microstates for certain BPS holes.

Is picture complete? Mathur: Does a black hole really form?

Brief Overview of The Rest

There is a lot of diverse activity!

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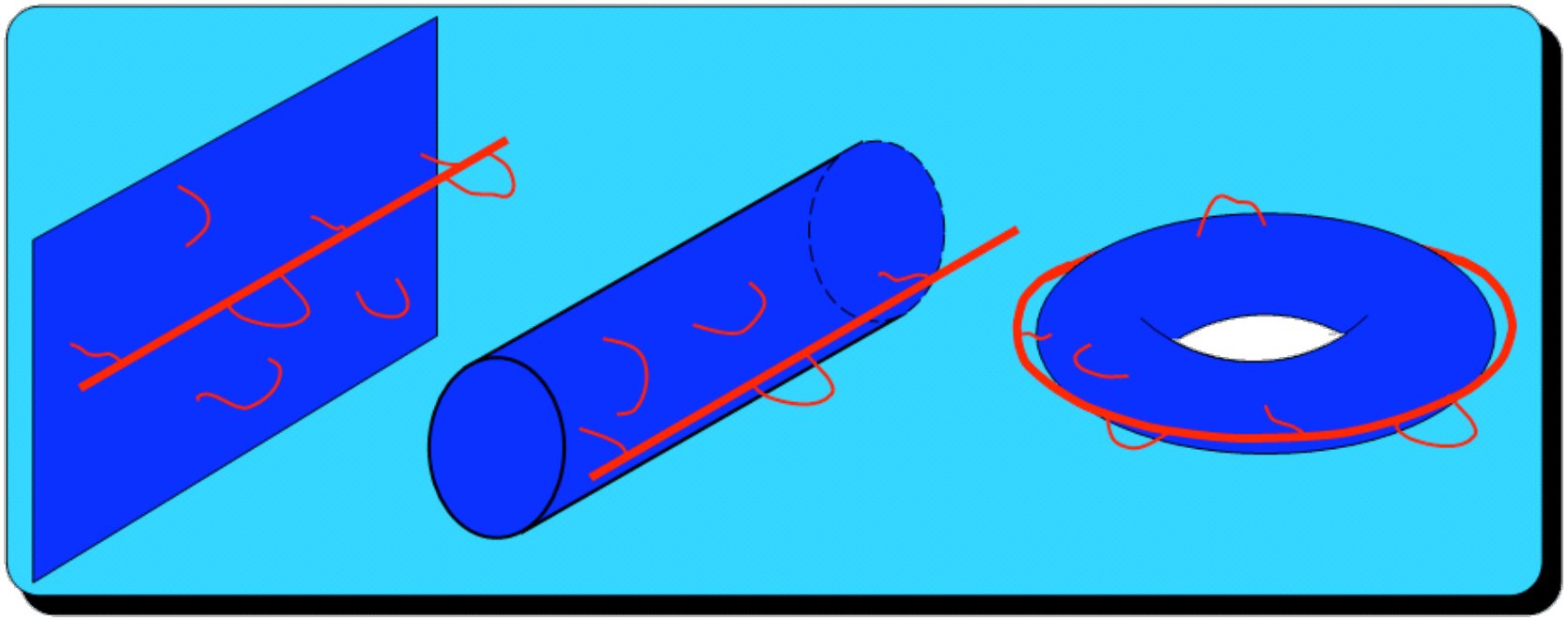
Some Key Foci:

Black Hole Microstates

Is there only one geometry for all microstates?

D1-D5 wrapped on torus and circle with momentum



Brief Overview of The Rest

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Some Key Foci:

Black Hole Microstates

Or does every microstate have a distinct geometry?

Black hole is then a "fuzzy" combination of all the geometries

Radical new picture if true!

Brief Overview of The Rest

There is a lot of diverse activity!

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Some Key Foci:

Black Hole Microstates

Which technology used?

(Super)gravity
(Many new solutions sought. See talk by Warner in parallel sessions.)

Brief Overview of The Rest

There is a lot of diverse activity!

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Some Key Foci:

AdS/CFT and Beyond

The story continues. Better understanding on many fronts.

More complicated gauge/gravity duals constructed and understood

Large R-charge operators.. spinning strings....plane waves....

N=1 theories, meson dynamics...

e.g. Klebanov-Strassler geometry part of KKLT scenario

Brief Overview of The Rest

There is a lot of diverse activity!

Much of the technology described earlier was manufactured and developed in various other contexts.

Some Key Foci:

AdS/CFT and Beyond

Which technology used?

(Super)gravity
Field Theory
Integrable Systems
Sigma Models
(Very long list...)

Brief Overview of The Rest

There is a lot of diverse activity!

Much of the technology described earlier was manufactured and developed in various other contexts.

Some Key Foci:

Strings and Gravity

Continued studies of fate of various GR phenomena in strings

Black Holes, Closed Timelike Curves, Singularities, etc.

Often teaches us about many of the other systems mentioned herein

Many new phenomena and examples....

Brief Overview of The Rest

There is a lot of diverse activity!

Much of the technology described earlier was manufactured and developed in various other contexts.

Some Key Foci:

Matrix Models

Dijkgraaf-Vafa breakthrough: Matrix Models compute N=1 superpontential terms

Relation to topological string studies also

McGreevy-Verlinde: Return to D=2 and D<2 Strings from Matrix models

Toy models of holography, tachyon condensation...etc!

Brief Overview of The Rest

There is a lot of diverse activity!

Much of the technology described earlier was manufactured and developed in various other contexts.

Some Key Foci:

Topological Strings and Twistors

Considerable activity on topological strings on CYs (Relation to matrix models)

New breakthrough! Witten: (N=4 pure) Yang-Mills amplitudes rewritten as a twistor space string!

This may signal another rich vein of progress..... much activity

Conclusion

- Since the Revolution, a large number of tools have been developed.
- We are beginning to put these tools together to learn more about how string theory might relate to our world.
- Tantalizing glimpses of a mature picture emerging.
- Might even make contact with data!
- Lots to do... It is an exciting time.