The Search For Nature

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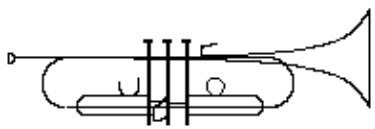


This Section's Goal

To see what people are up to in trying to find "the" vacuum:
- to understand the concerns and some current techniques
- to see how the techniques we learned might help us do this

(This will only be a sketch, unfortunately.)

To enable you to:
- follow current events....
- make your own contributions....

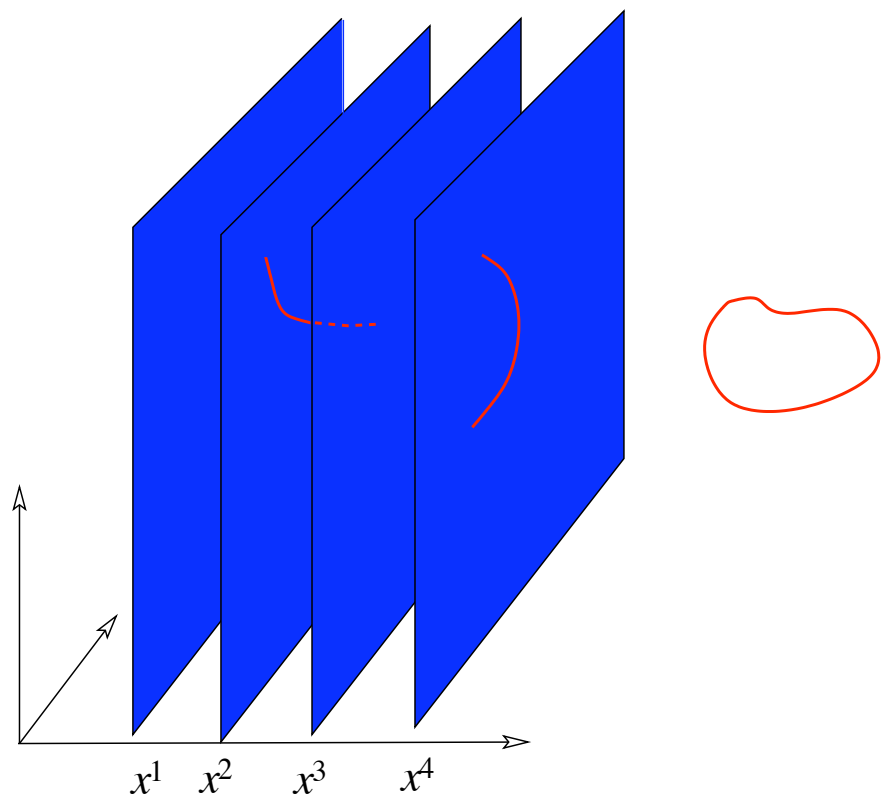
The Tools

Type I

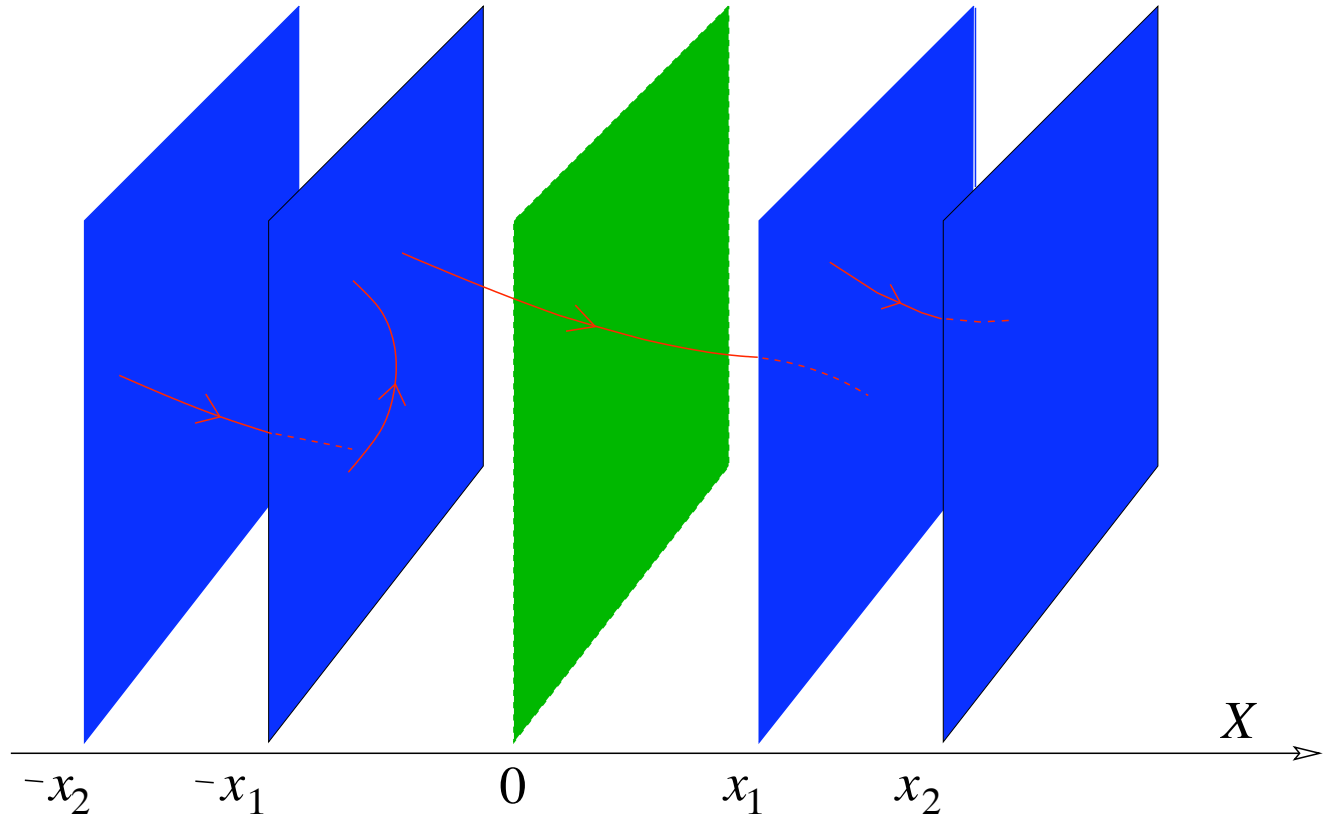
Type IIA
Type IIB

1 1D Supergravity

Branes



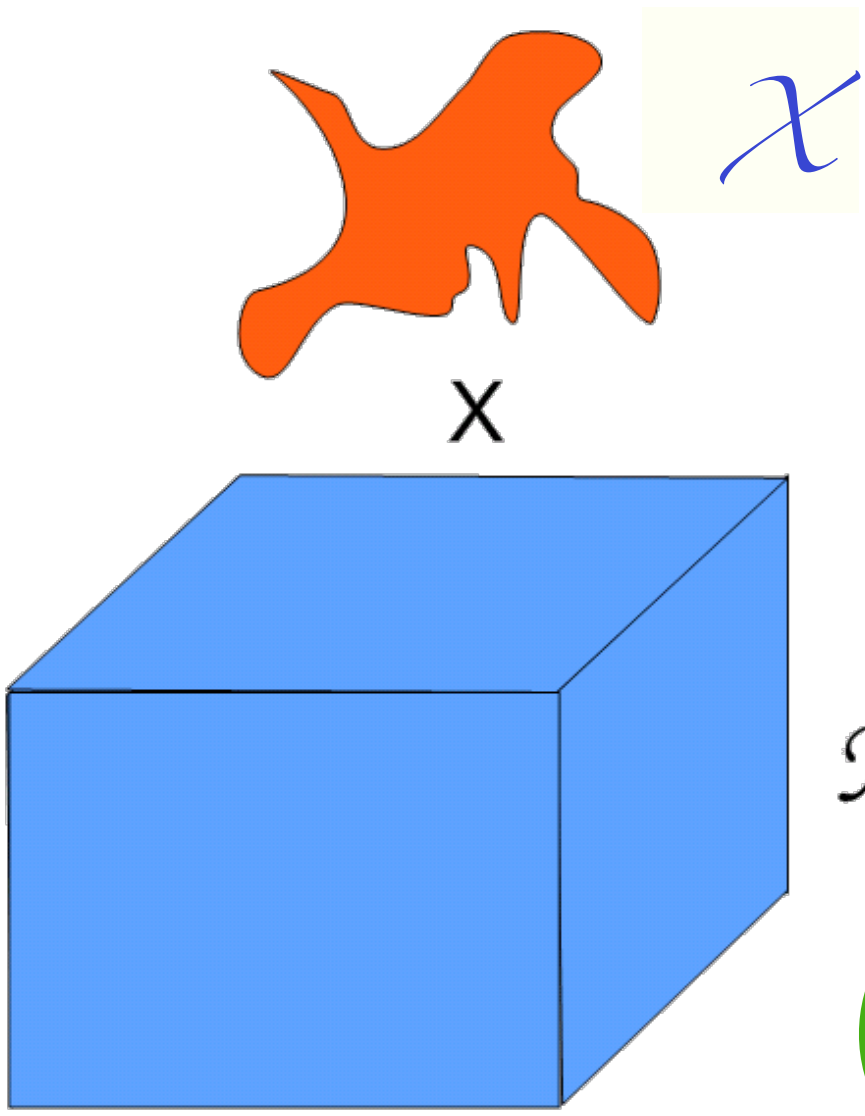
Sometimes with Orientifolds present:



p extended directions: **Op-plane**

They are non-dynamical planes with negative tension

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?

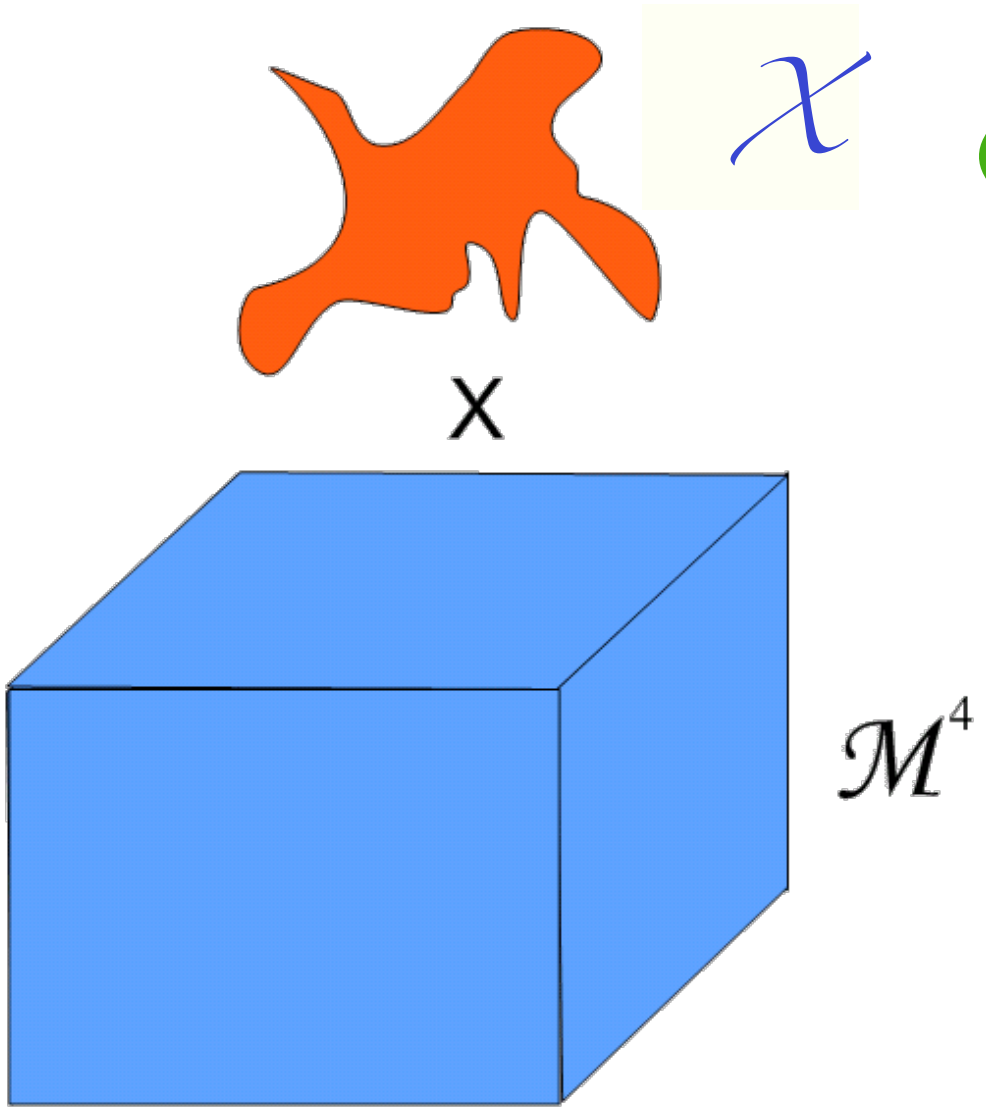
Observations that our universe is accelerating have produced an upheaval:

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 $\mathcal{X}$?

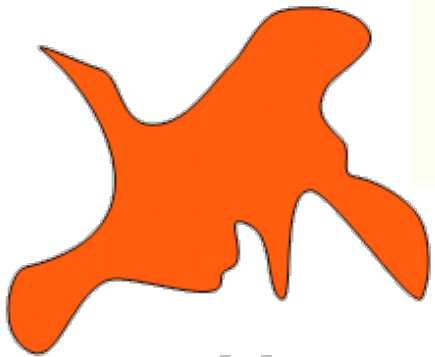
Susy does not restrict these

Locally adjustable parameters

Scalar Fields in *D=4*

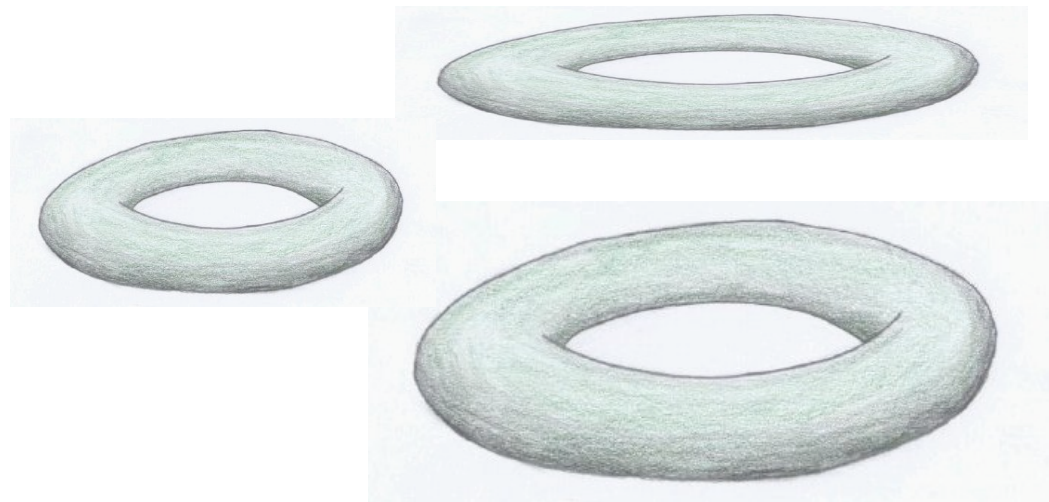
Where do the Scalars come from?

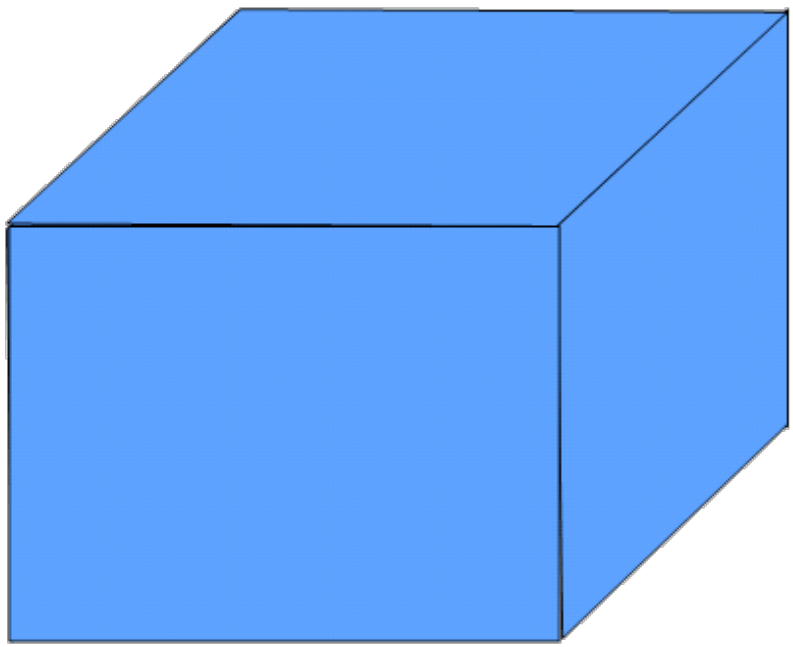
Size? Shape?



$\mathcal{X}$

X





$\mathcal{M}^4$

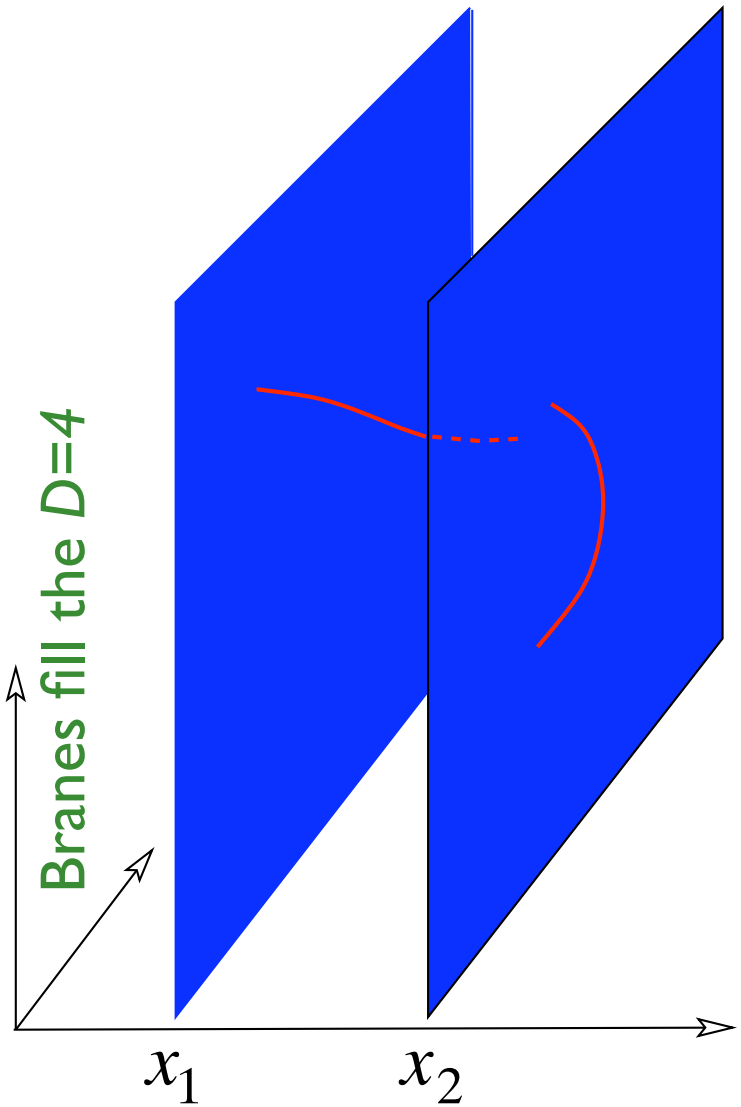
This is also true for subspaces "cycles" of $\mathcal{X}$

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?

Thinking about $AdS_5 \times S^5$

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

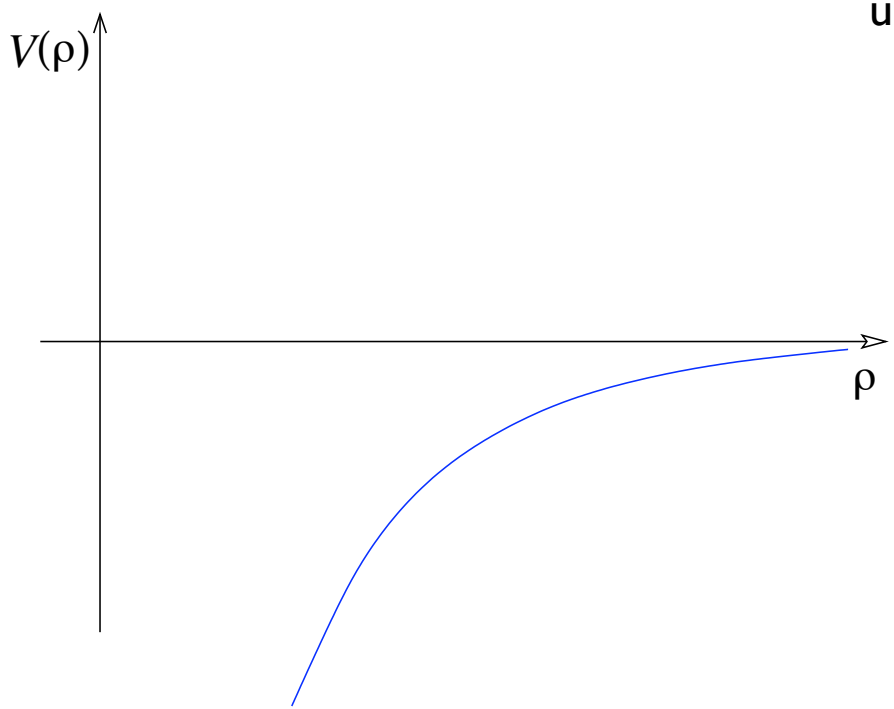
$$V_{\mathrm{Sph}}(\rho) \sim -\frac{g_s^{p/4}}{\rho^p}$$

positive curvature gives negative potential

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

radius in *D=5* Planck units

(Measuring things in *D=5* Einstein frame, so got to be careful of powers of dilaton and hence string coupling, right? Check them!)



Sphere wants to shrink away...

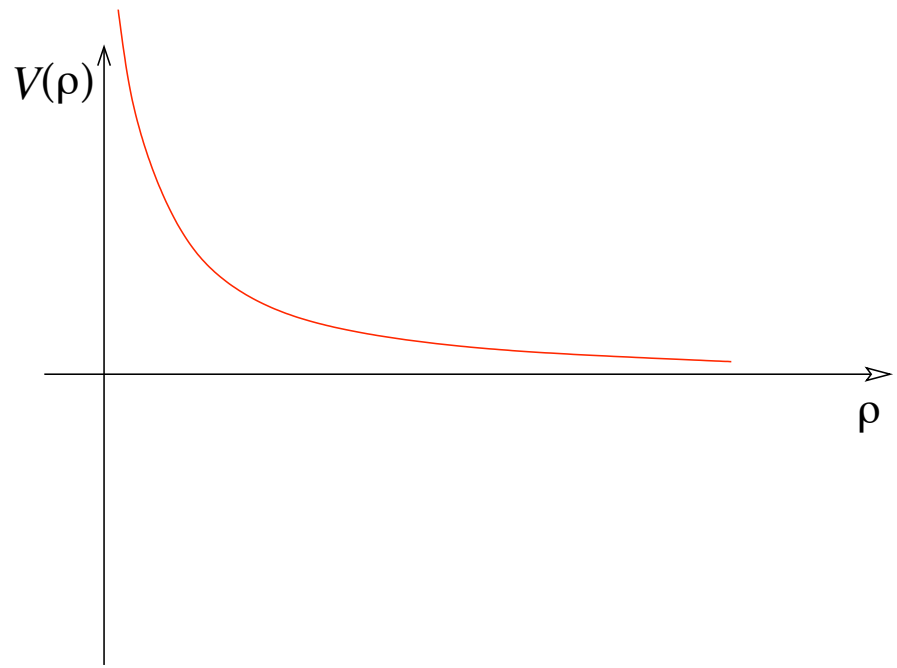
See nice notes by E. Silverstien, hep-th/0405068

Thinking about $AdS_5 \times S^5$

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

Reduce energy by growing the sphere...

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



See nice notes by E. Silverstien, hep-th/0405068

Thinking about $AdS_5 \times S^5$

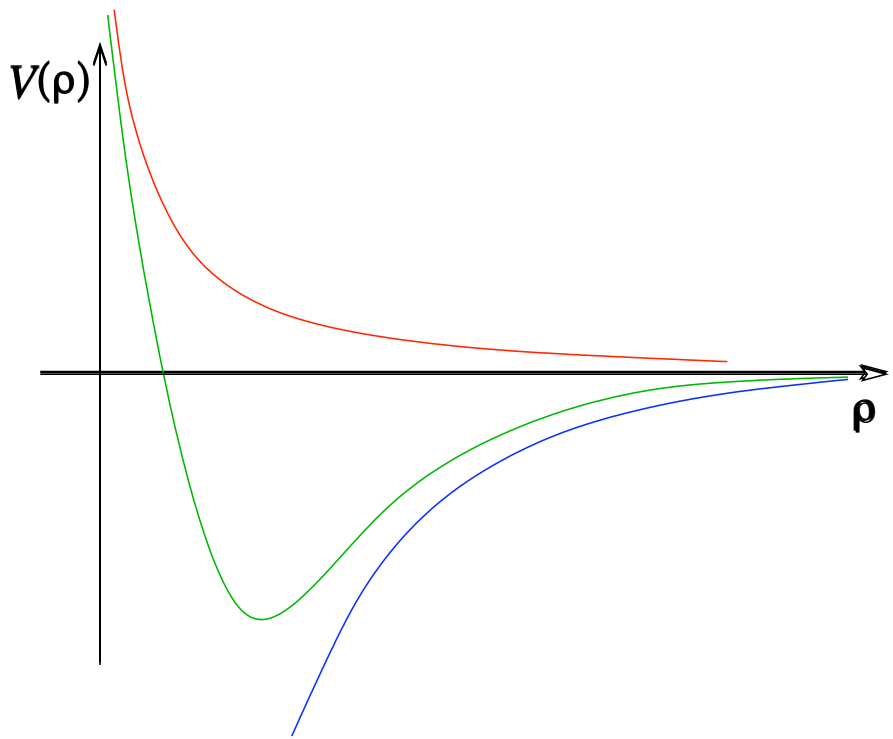
minimum at: $\rho^{q-p} = \frac{q}{p} N^2 g_s^{\frac{q-p}{4}}$

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

$$q - p = 8$$

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

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



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.

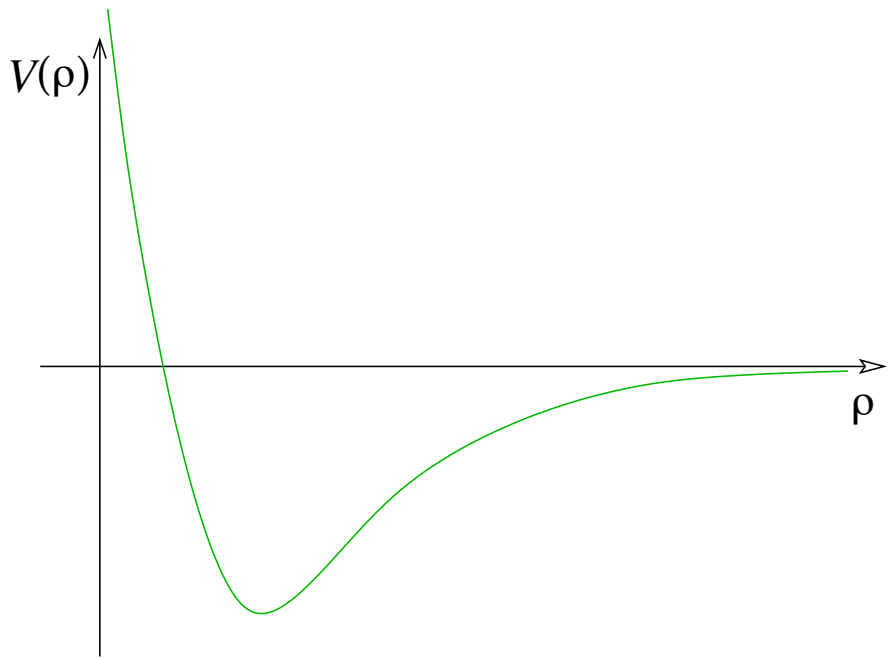
$$\rho \sim (g_s N)^{1/4}$$

Naturally get negative CC this way.

Naturally have reliable control over computations

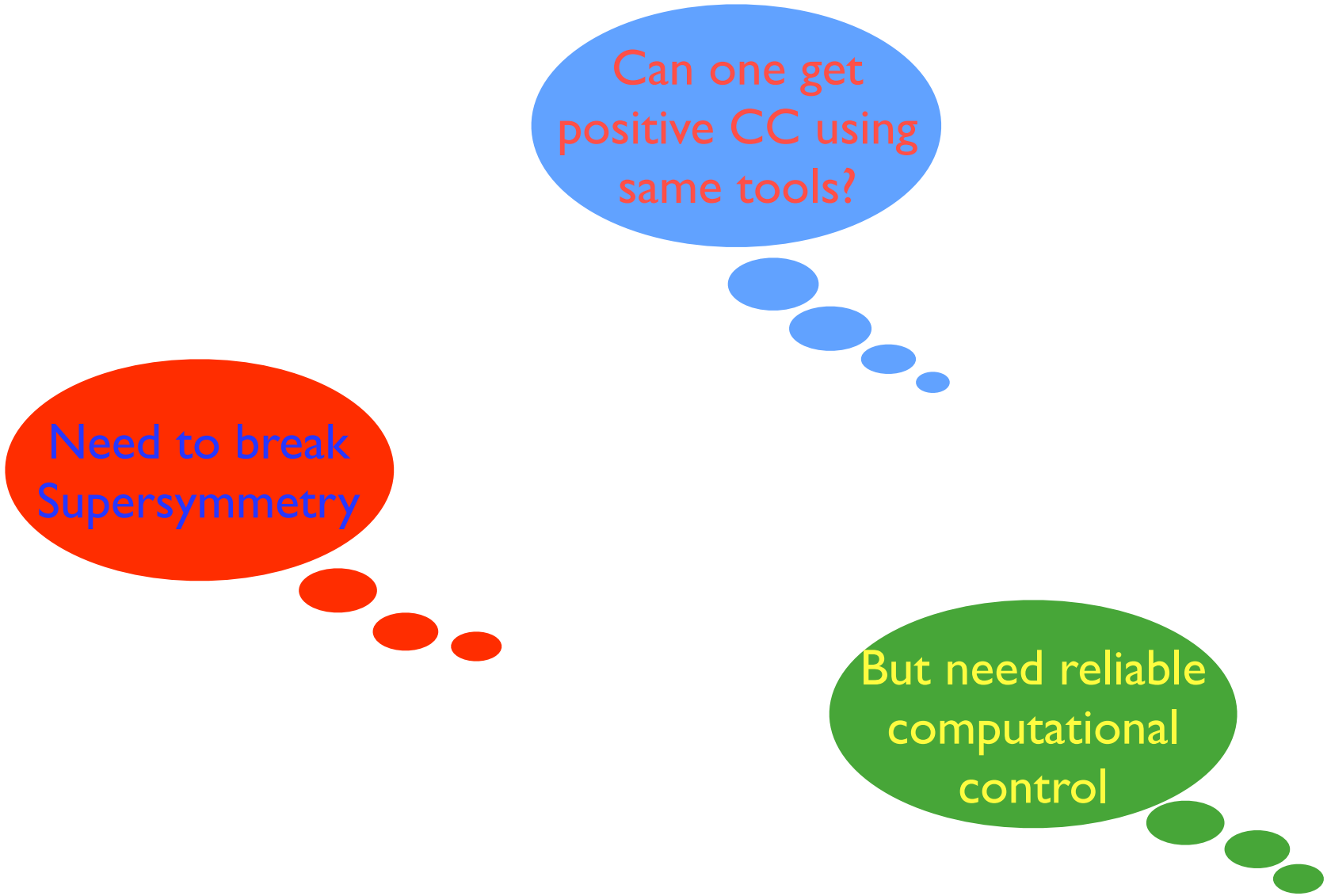
(Supersymmetry still present)

Can one get positive CC using same tools?



Will need to break Supersymmetry...

Thinking about $AdS_5 \times S^5$



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

$H-$ flux

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

$F-$ 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)

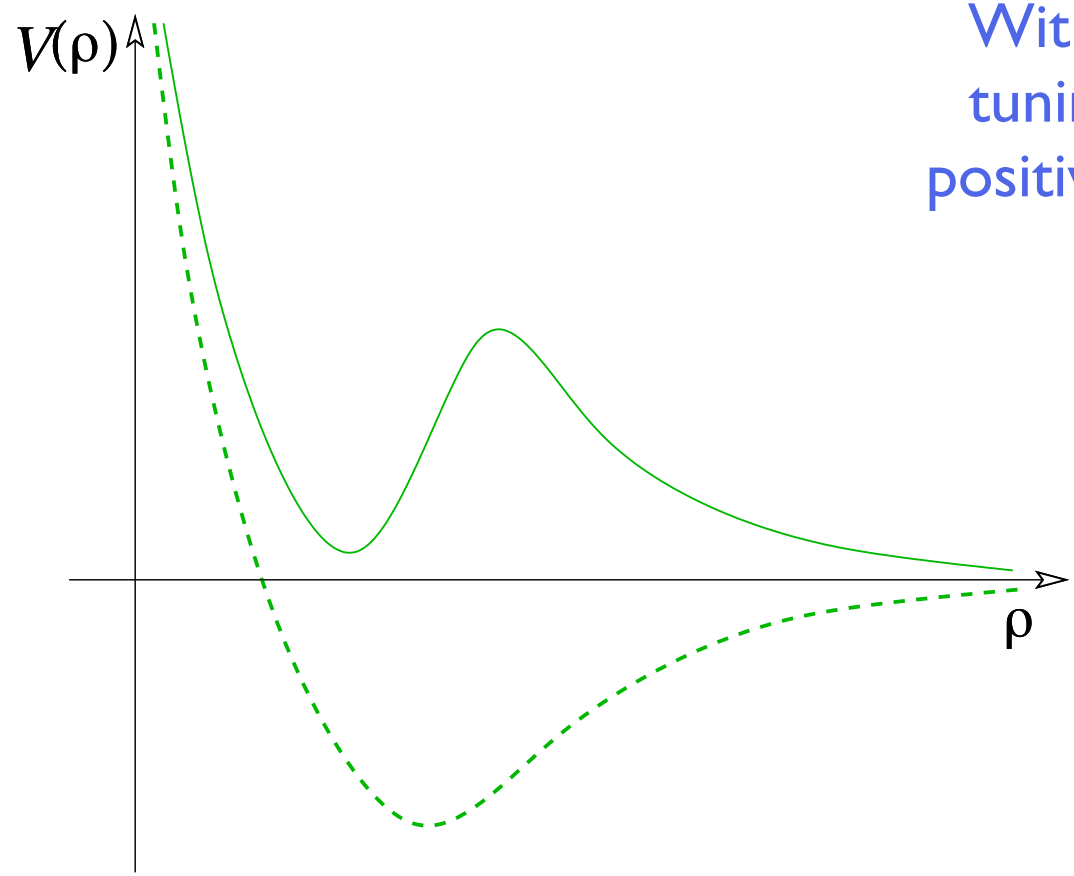
(1-loop contrib'n to h)

The Players from different sectors

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

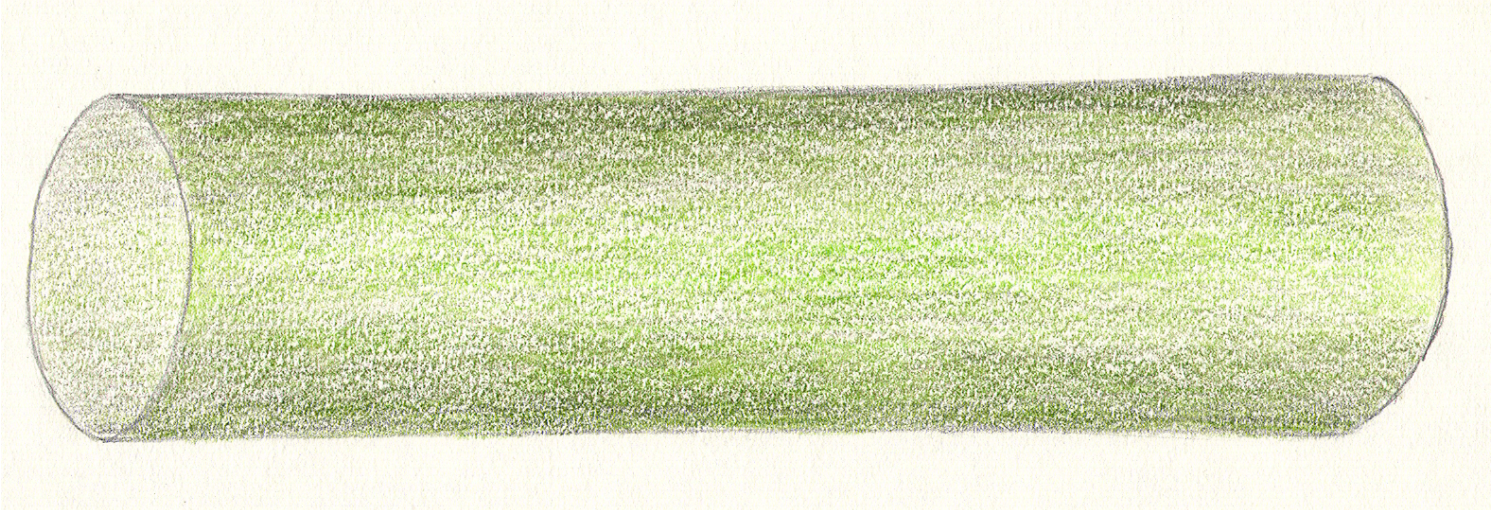
$$V(\Phi,\rho_i)=Ae^{4\Phi}\left(-fe^{-2\Phi}+ge^{-2\Phi}+ne^{-\Phi}+h\right)$$

Tools to obtain positive CC



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

The Usefulness of Throats

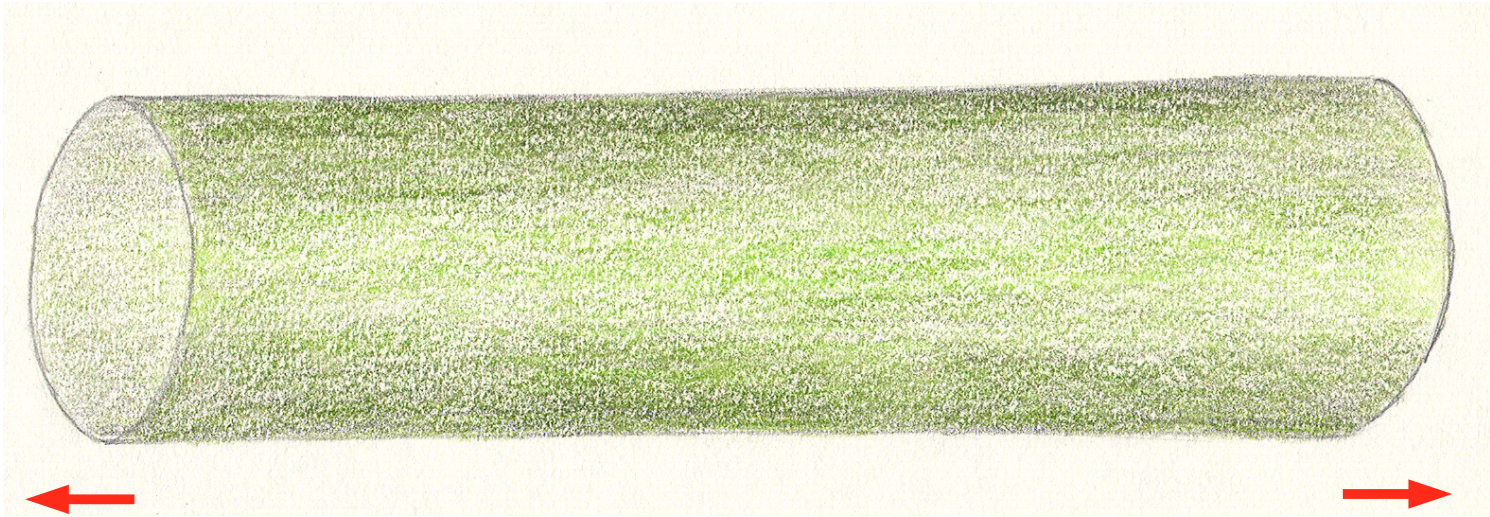


Metric of a cross-section

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

"warp factor"

The Usefulness of Throats



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

AdS_5 :

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

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

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

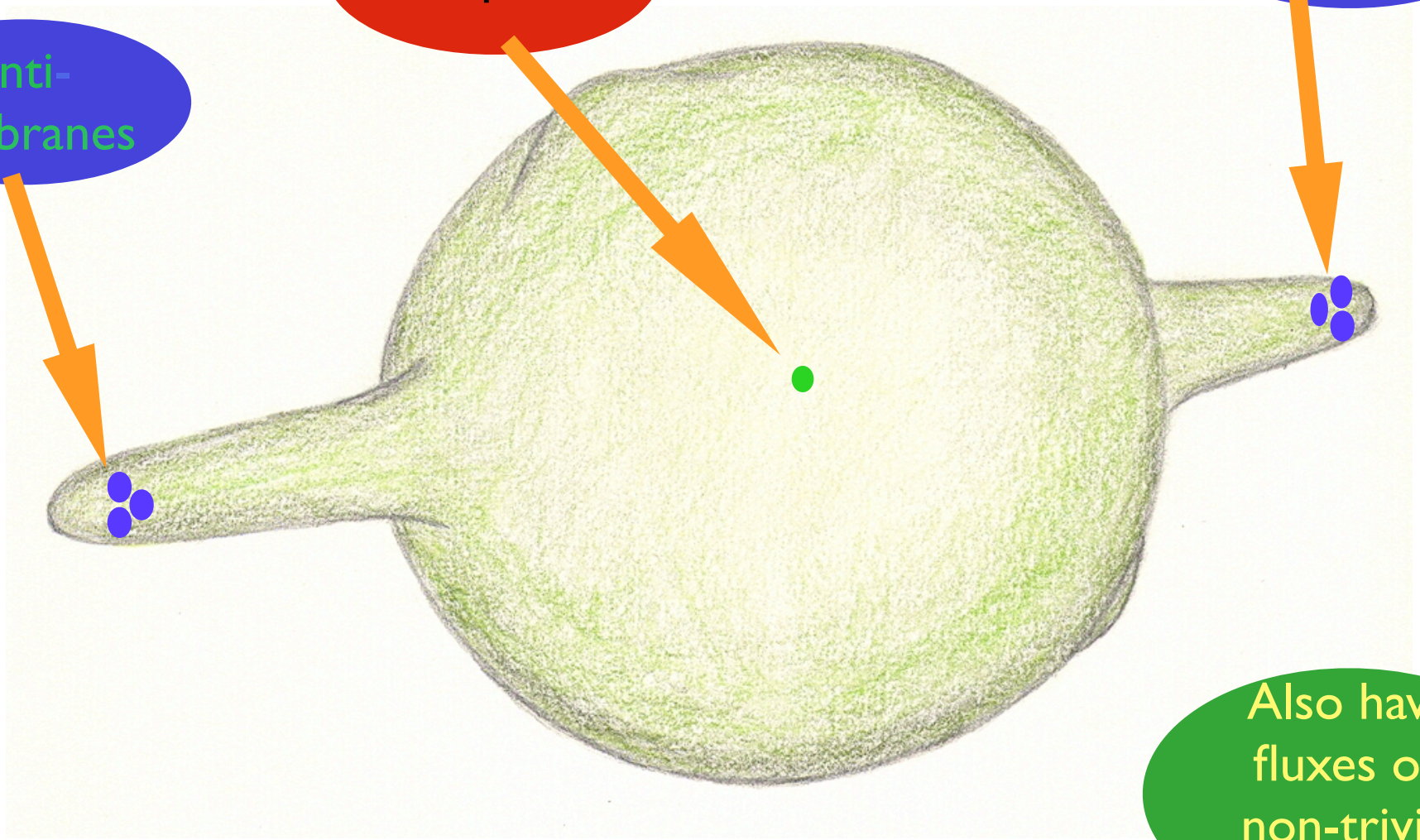
At some value of r: $L_{10}^2 = e^{2A(r)} L_4^2$

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

The KKLT Scenario

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

The KKLT Scenario



Also have fluxes on non-trivial cycles

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?

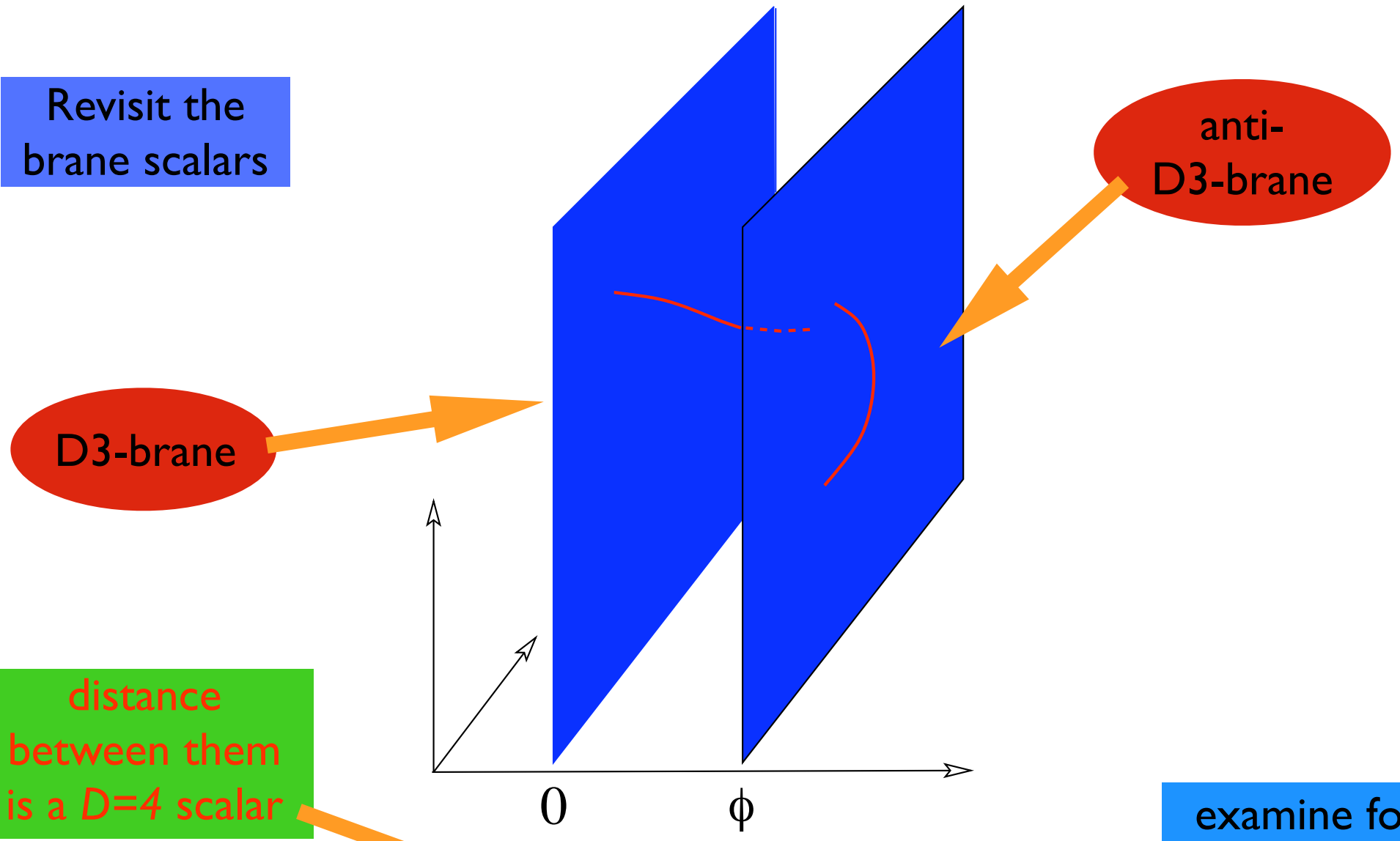
It is generally believed that it is possible that many such solutions exist

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



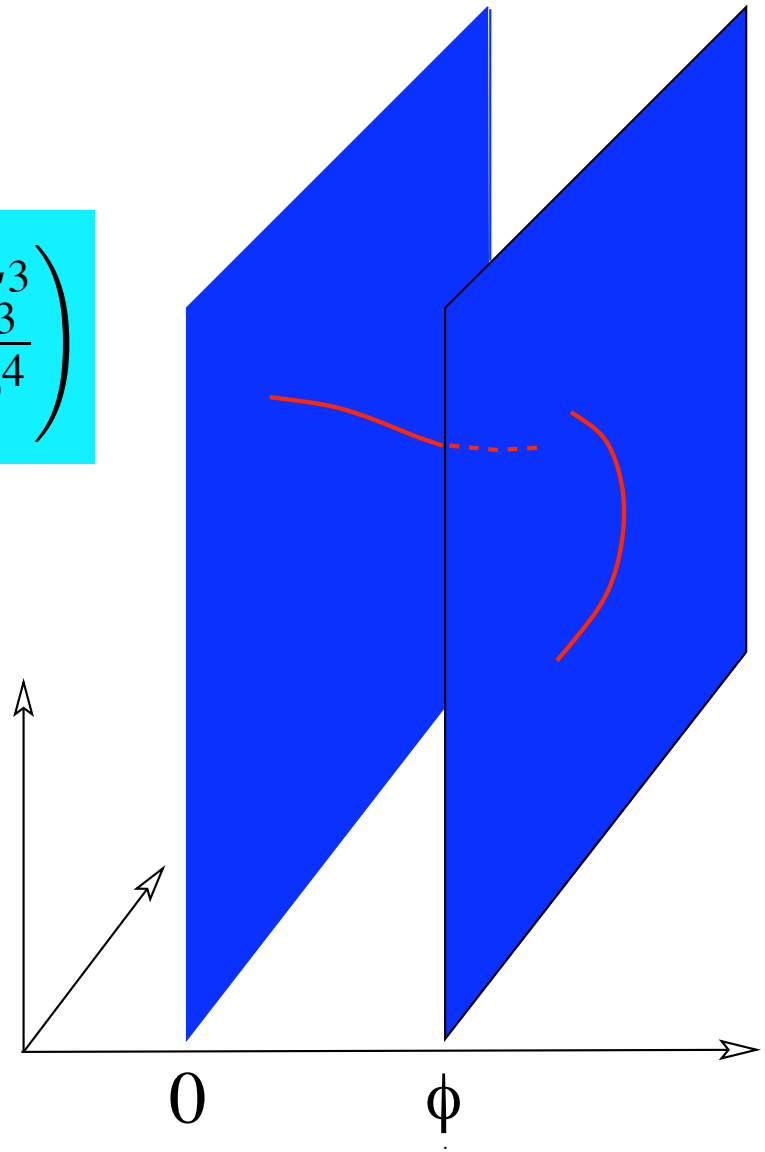
distance between them is a *D=4* scalar

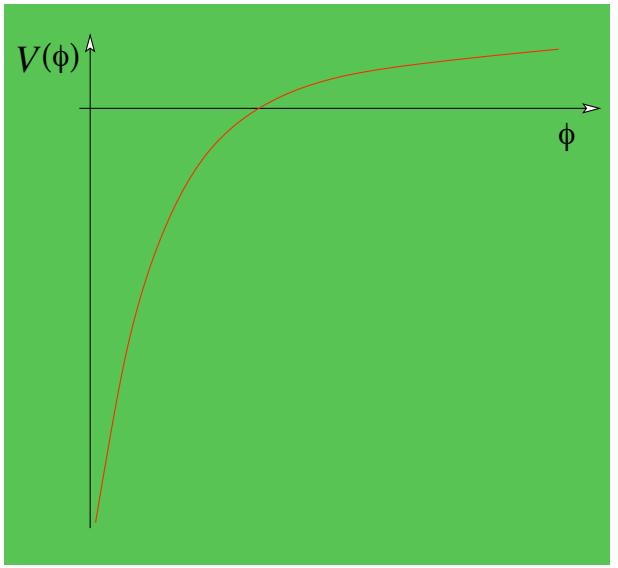
possible inflaton?

examine form of potential, look at slow roll conditions

Brane-AntiBrane Inflation: DT Scenario

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

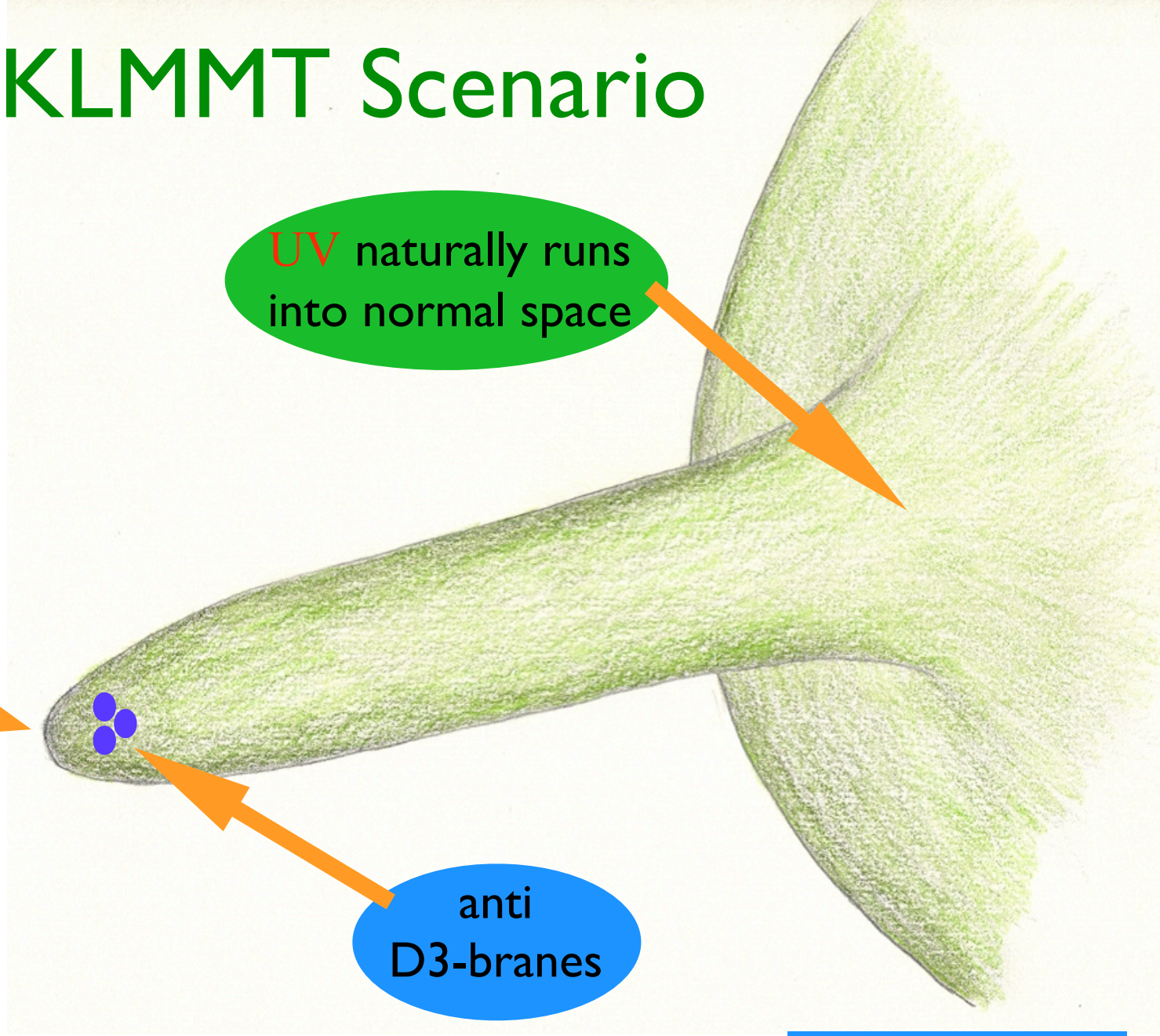




It does not work. Slow roll needs the branes to be separated by a size bigger than the space they're in

KKLMMT Scenario

KKLT Scenario has natural throats with warped geometry

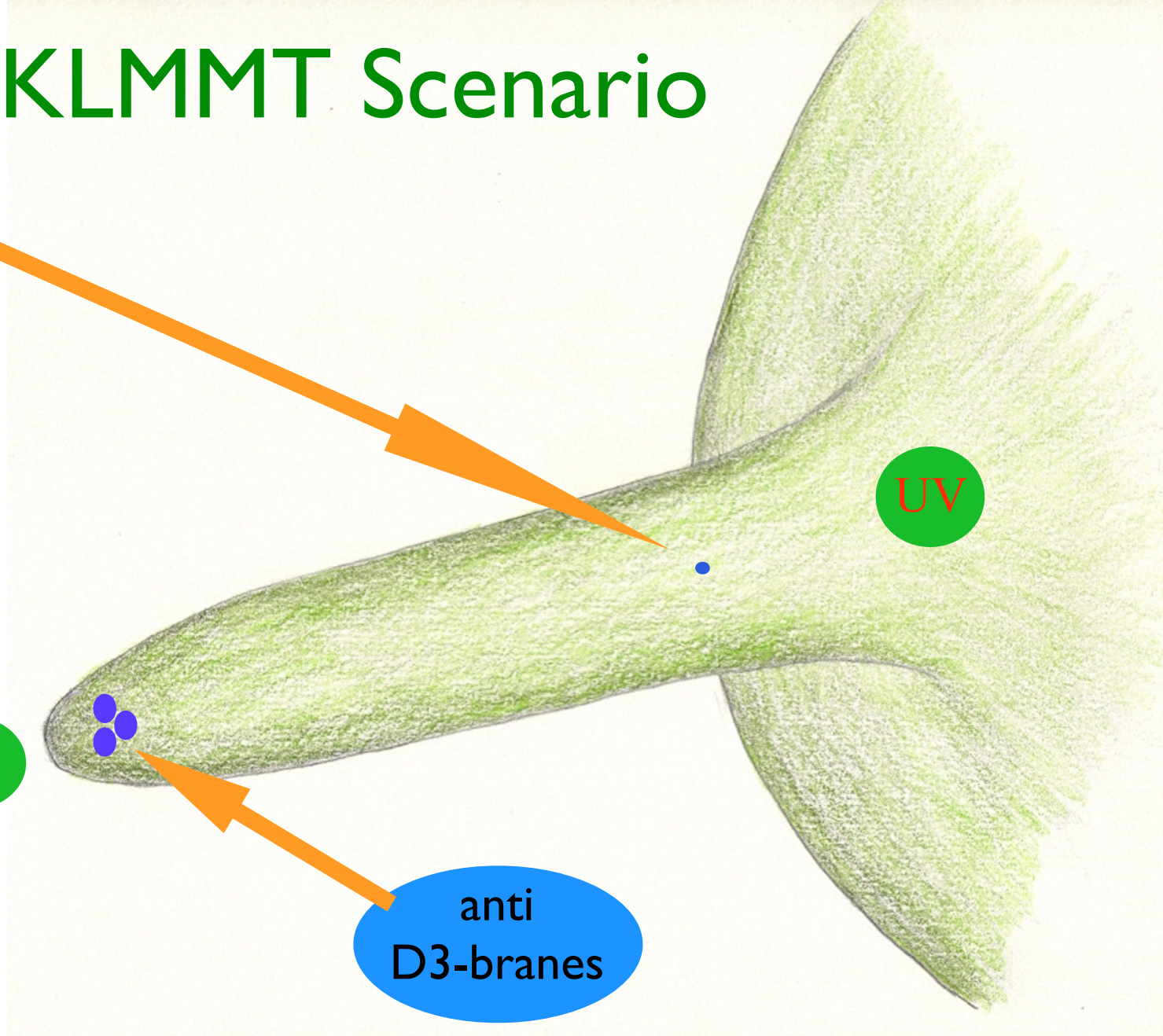


Natural realization of RS scenario

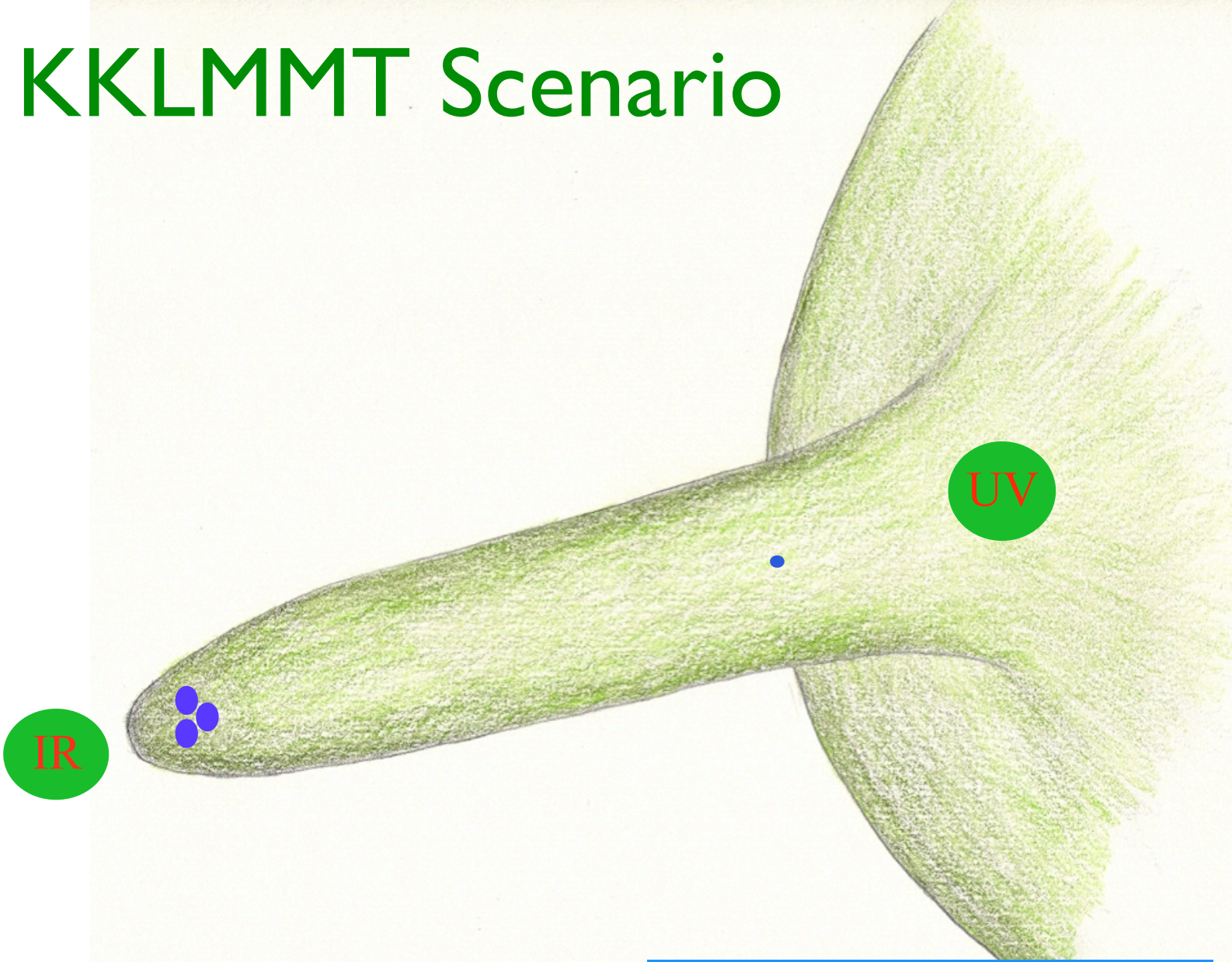
KKLMMT Scenario

Now add a D3-brane

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



KKLMMT Scenario



recompute potential

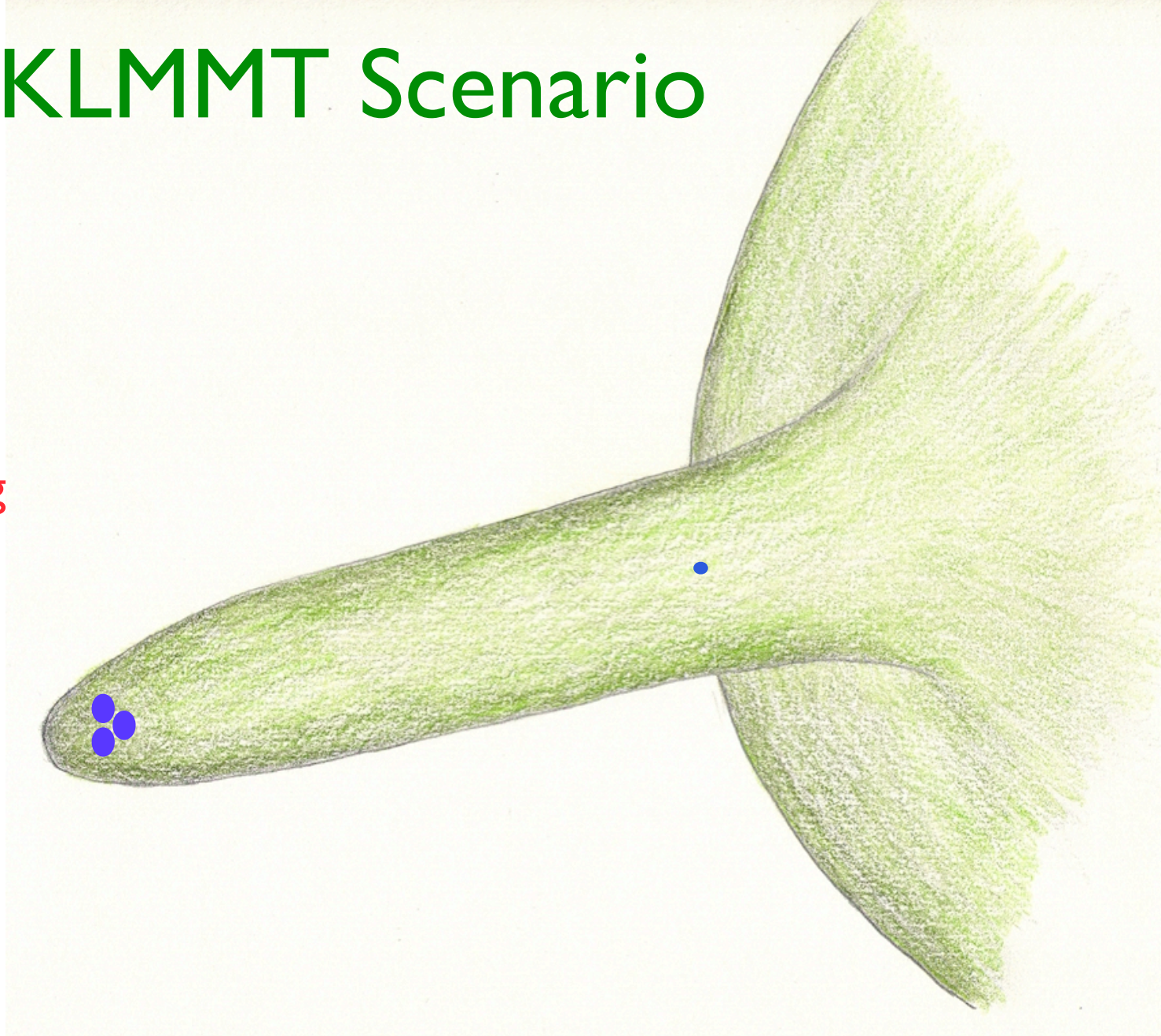
$$e^{2A(UV)} \sim 1$$
$$e^{2A(IR)} << 1$$

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

KKLMMT Scenario

This is a very natural scenario.

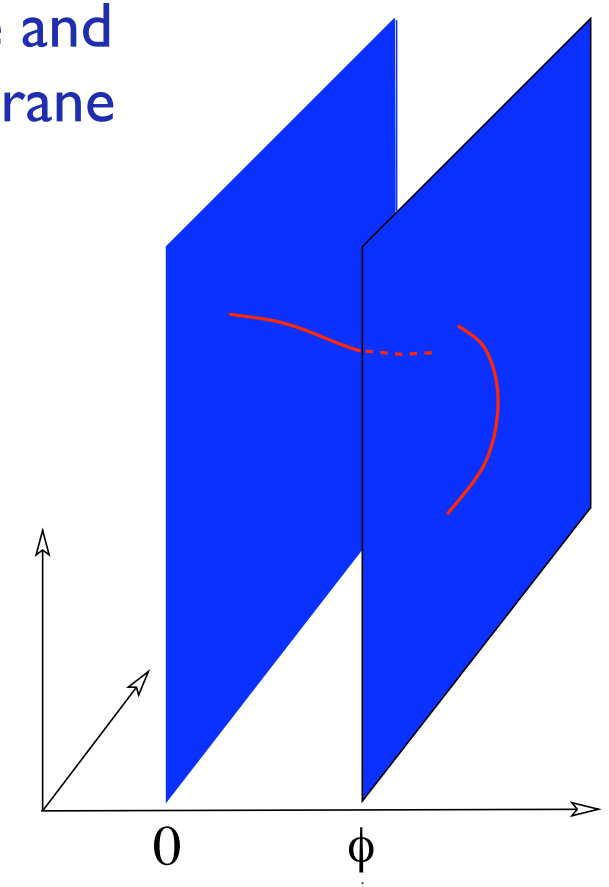
...it offers a very exciting framework.



if it can be kept under reliable control.

Cosmic D and F Strings: CMP Scenario

D3-brane and anti-D3-brane

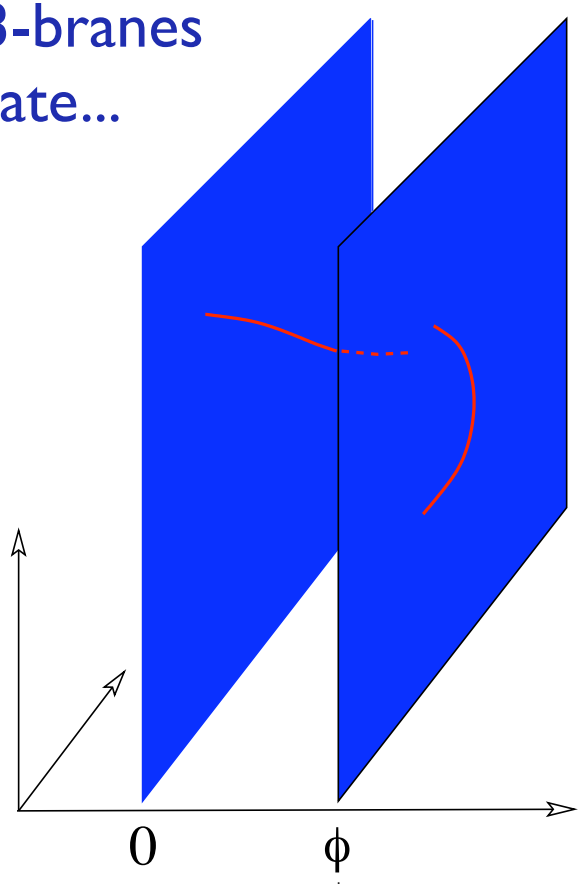


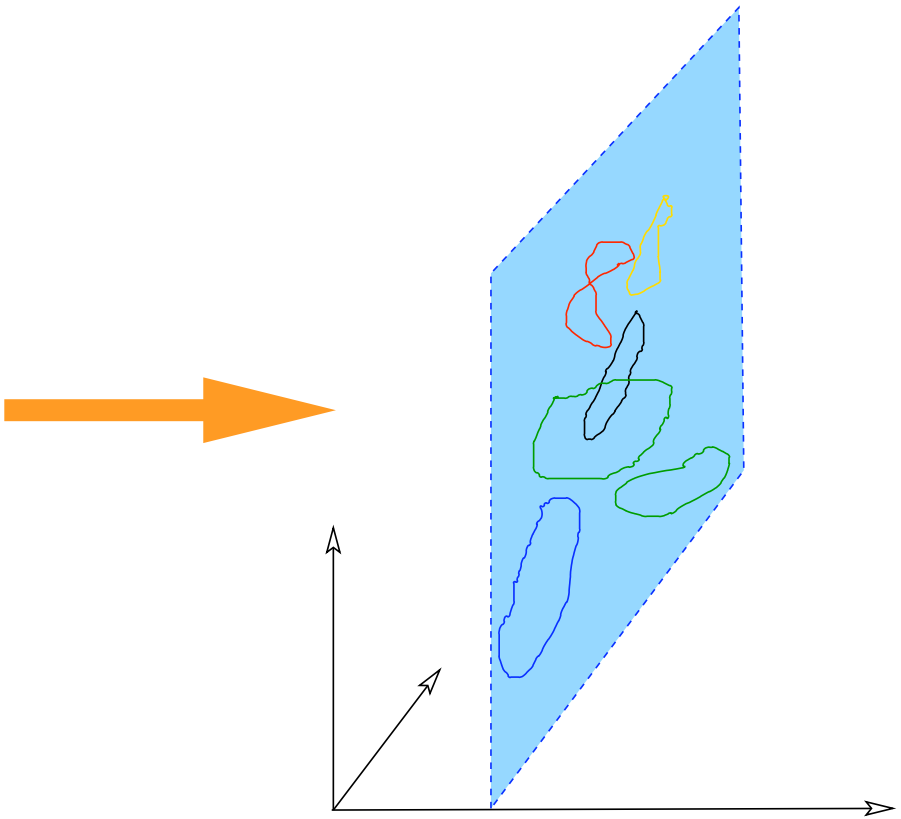
Study of open string sector reveals a tachyon in the spectrum.

That's ok... it is just the mode telling you that they attract each other.....

Cosmic D and F Strings: CMP Scenario

When D3-branes annihilate...





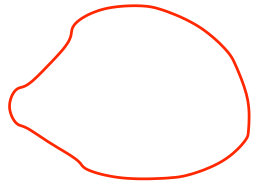
The strings are topological structures in the "tachyon" field

...they can leave strings behind.

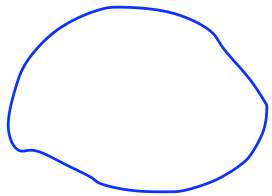
Cosmic D and F Strings: CMP Scenario

What type of string?

F-string $(1,0)$

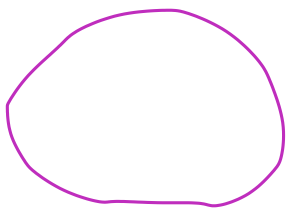


D-string $(0,1)$



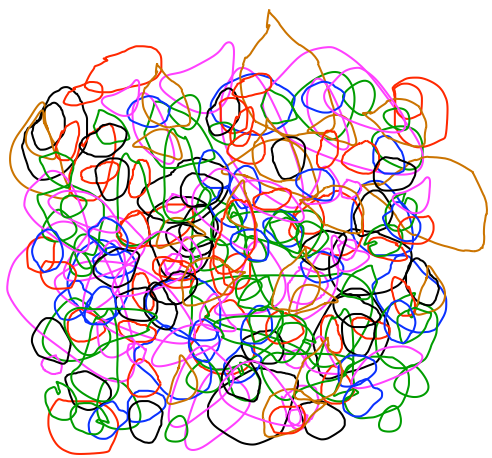
Most importantly, these strings can form bound states:

$(1,1)$



(p,q) in general

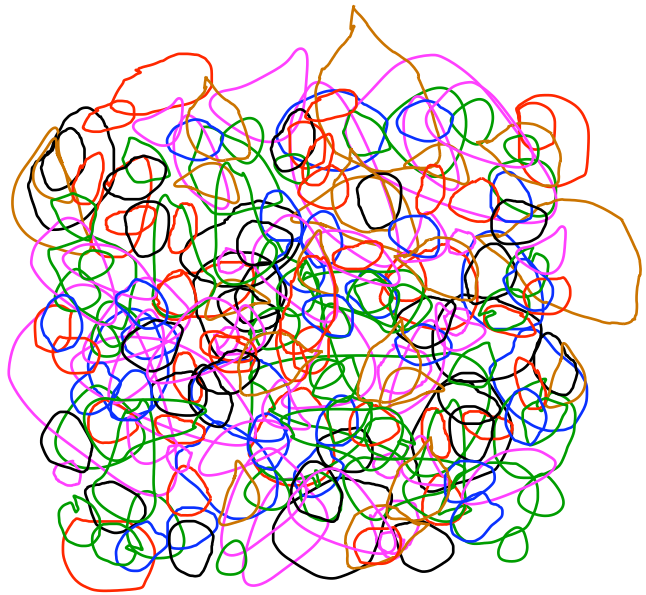
...they can form networks



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...

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.

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.