Title: Holographic Systematics of D-Brane Inflation

Date: May 20, 2009 09:00 AM

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Abstract:

D-brane Potentials via AdS/CFT

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Cornell

Effective Field Theories in Inflation

PI

May 20, 2009

Based on:

D. Baumann, A. Dymarsky, S. Kachru, I. Klebanov, & L.M., 0808.2811.
D. Baumann, A. Dymarsky, S. Kachru, I. Klebanov, & L.M., in preparation.
S. Gandhi & L.M., in preparation.

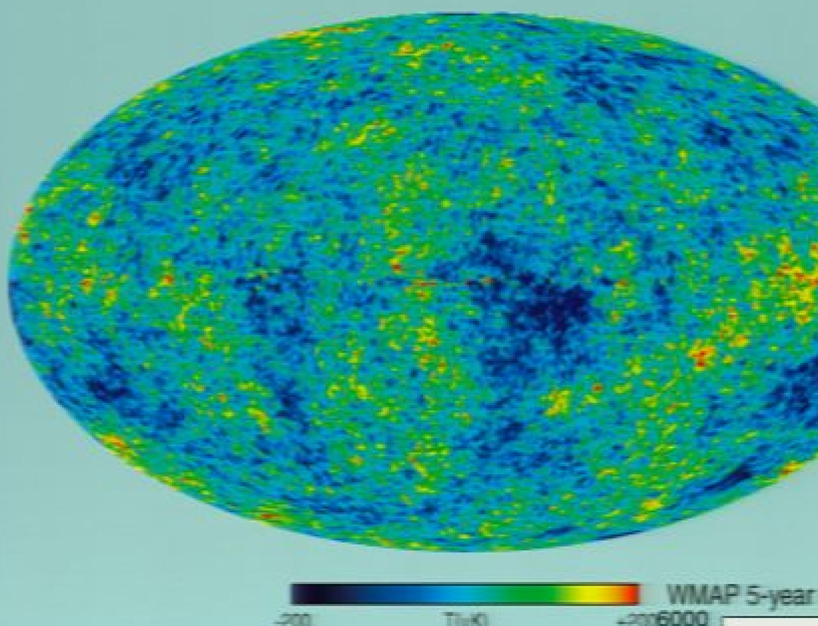
Building on:

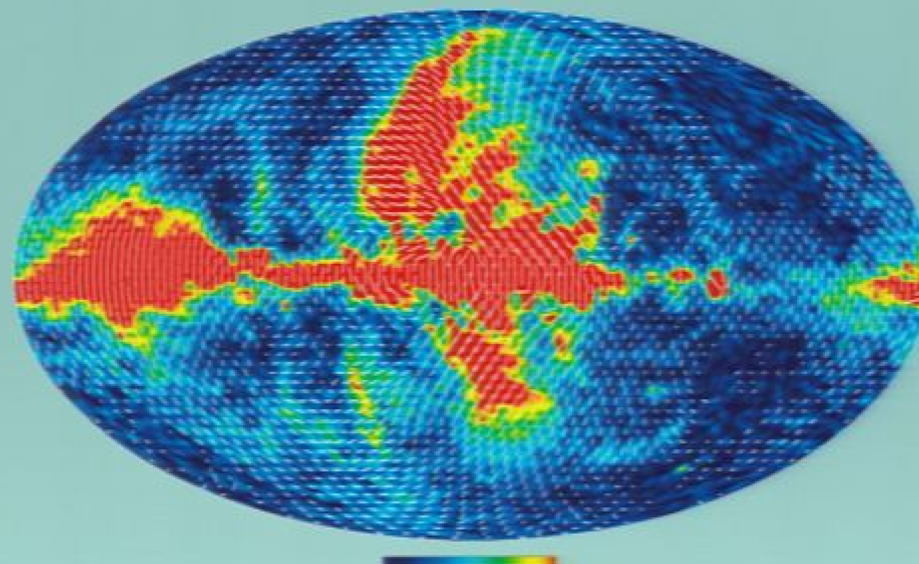
D. Baumann, A. Dymarsky, I. Klebanov, J. Maldacena, L.M., & A. Murugan, hep-th/0607050.
D. Baumann, A. Dymarsky, I. Klebanov, L.M., & P. Steinhardt, 0705.3837.
D. Baumann, A. Dymarsky, I. Klebanov, & L.M., 0706.0360.

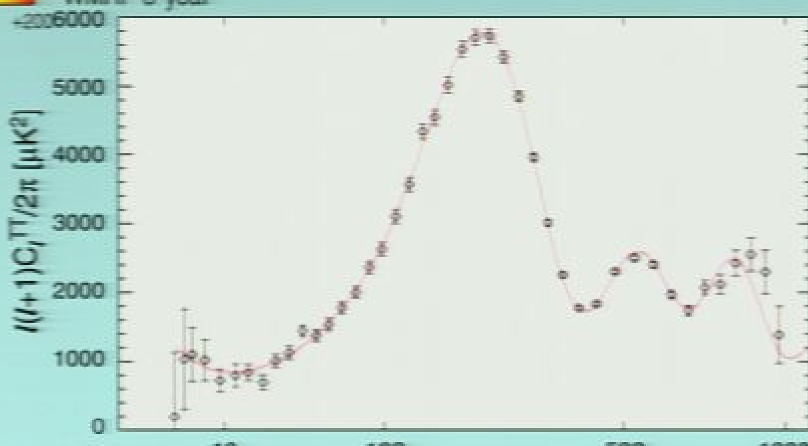
See also:

C. Burgess, J. Cline, K. Dasgupta, & H. Firouzjahi, hep-th/0610320.
O. DeWolfe, L.M., G.Shiu, & B. Underwood, hep-th/0703088.
A. Krause & E. Pajer, 0705.4682.

Goal: develop theoretical models of the early universe suitable for an era of precision cosmology.







NASA/WMAP Science Team

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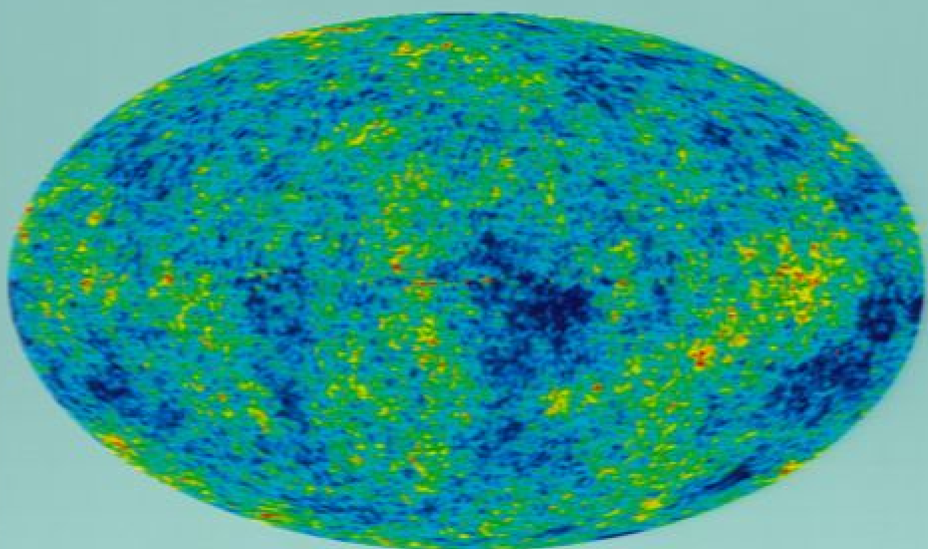

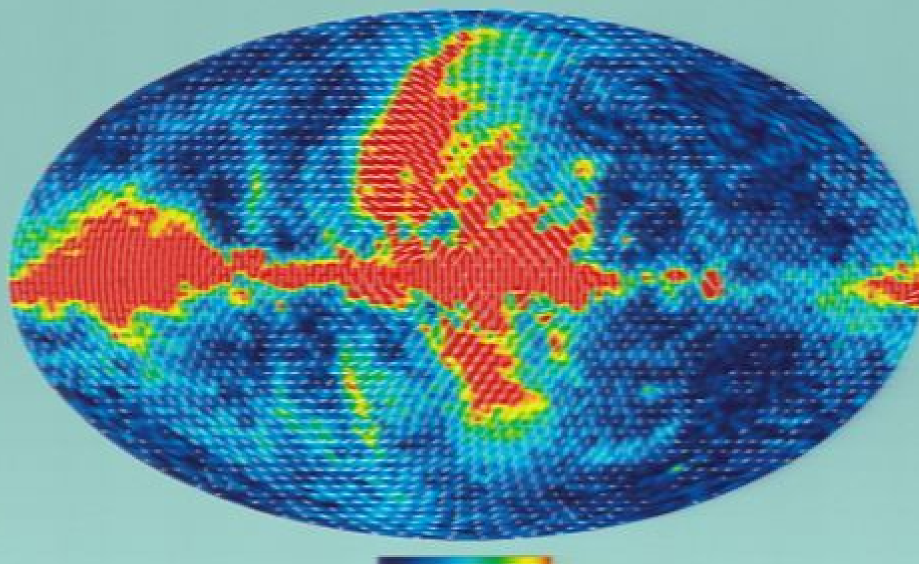

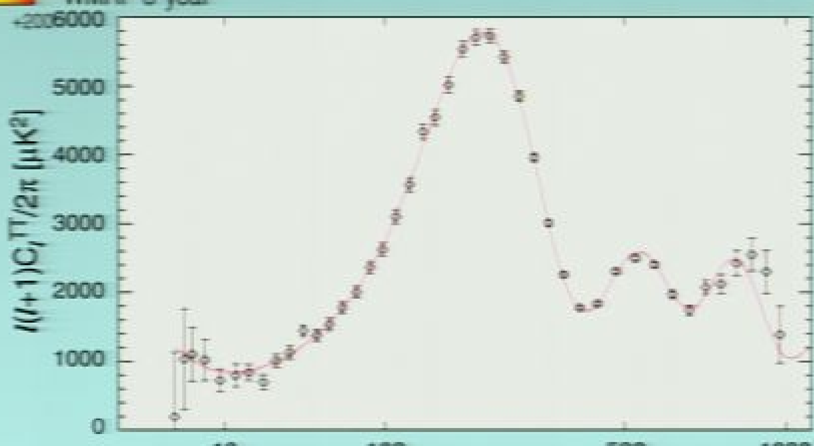

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Propose and constrain mechanisms for inflation in string theory.

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Derive inflaton action in string compactifications with stabilized moduli.

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e.g. for D3-brane inflation.

Dvali&Tye 1998
Dvali,Shafi,Solganik 2001
Burgess,Majumdar,Nolte,Quevedo,Rajesh,Zhang 2001
Kachru, Kallosh, Linde, Maldacena, L.M., Trivedi, 2003

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Challenge:

Common approximation schemes often fail to incorporate relevant effects of massive moduli.

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Challenge:

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Method:

Study D-branes probing compact warped throats, where noncompact approximations and AdS/CFT are applicable, and compactification effects can be included systematically.

Plan

I. Brief review of the problem.
II. Systematic method:
    I. Gravity side: leading solution to 10d equations of motion
    II. Gauge theory side: enumeration of contributing operators
III. Implication: D7-brane superpotentials source fluxes
IV. Conclusions

I.
The problem

Inflation is sensitive to Planck-scale physics.

- Inflationary Lagrangian generically receives critical contributions from $\Delta \lesssim 6$ Planck-suppressed operators.
  - Very generally, we expect contributions from integrating out massive degrees of freedom to which the inflaton couples.
  - The key point is that for inflation, even Planck-mass degrees of freedom are important. Moreover, we know that some new degrees of freedom must appear at (or well below) the Planck scale.

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  - The key point is that for inflation, even Planck-mass degrees of freedom are important. Moreover, we know that some new degrees of freedom must appear at (or well below) the Planck scale.
  - One important contribution:

$$V \to V + \frac{\varphi^2}{M_P^2} V \Rightarrow \delta m_\varphi^2 = 6H^2 \Rightarrow \delta\eta = 2 \qquad \eta \equiv \frac{m_\varphi^2}{3H^2} \ll 1$$

- Problem persists even for small-field, low-scale inflation.
- Clear in effective field theory; corroborated by essentially all string inflation models.

Options for dealing with the sensitivity to Planck-scale physics.

I. Invoke a symmetry strong enough to forbid all such contributions.
   - i.e., forbid the inflaton from coupling to massive d.o.f.

Freese, Frieman, Olinto 90;
Kallosh, Hsu, Prokushkin 04;
Dimopoulos, Kachru, McGreevy, Wacker 05;
Conlon & Quevedo 05;
L.M., Silverstein, Westphal 08

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II. Enumerate all relevant contributions and determine whether fine-tuned inflation can occur.
   - i.e., arrange for cancellations.

Baumann, Dymarsky, Klebanov, L.M., 07;
Haack, Kallosh, Krause, Linde, Lust, Zagermann, 08;
Baumann, Dymarsky, Kachru, Klebanov, L.M., 08

Moduli stabilization and the eta problem

- In string inflation, the Planck-suppressed contributions take various forms (string loop and α' corrections, both perturbative and nonperturbative; Euclidean D-brane contributions; backreaction effects; ...)
- In practice, most of these contributions may be understood as arising from integrating out massive moduli.
- Knowing (and controlling) the inflaton potential therefore requires detailed information about moduli stabilization, i.e., one needs the full effective action in a stabilized vacuum.
- This talk: use AdS/CFT to systematically enumerate these compactification effects.

Why should you care?

- Inflation is highly compelling.
- Sensitivity to Planck-scale physics provides a rare opportunity to probe processes at high energies.
- Inflation in string theory provides added value
  - New mechanisms (e.g. DBI, monodromy)
  - Constraints on parameters (e.g. tensors in some classes of models but not in others)
  - Framework for dealing with Planck-sensitive problems

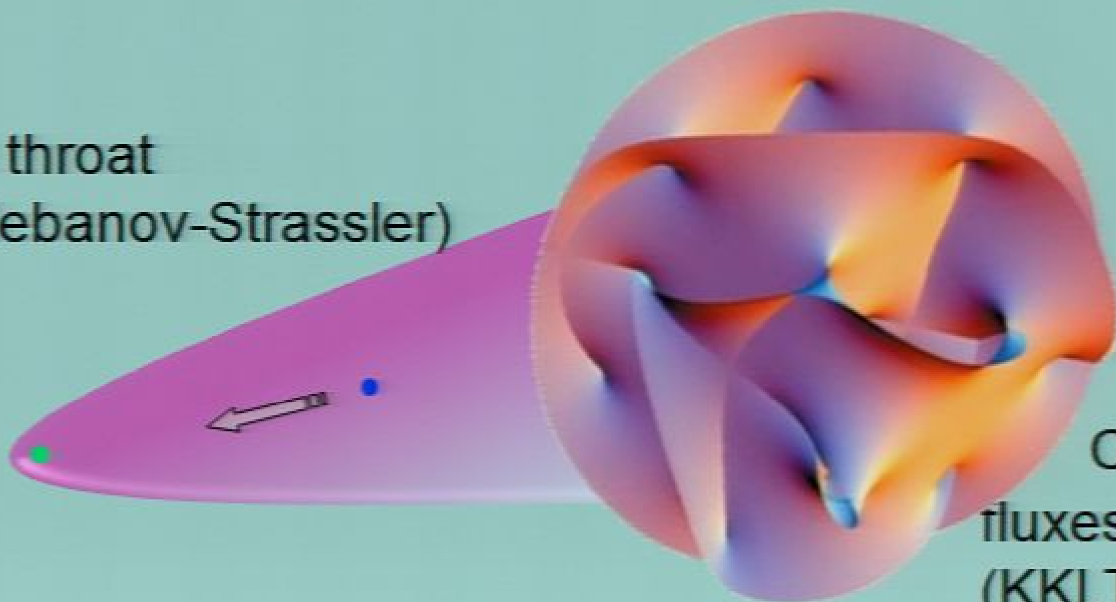
  …. but only if done carefully enough to expose the novel content.
  - in particular, requires rather thorough dimensional reduction.
- Therefore, we should study one or more models for long enough to get everything right!
  - D3-brane inflation is well-studied and admits a large toolkit.

Today's talk

- Focus on a D3-brane in a warped throat.
- Determine form of D3-brane potential, including all relevant contributions.
- Concretely, I will compute the potential for a D3-brane in a compact Klebanov-Strassler throat attached to a general bulk whose Kahler moduli are assumed to be stabilized nonperturbatively.
- In practice, will use Klebanov-Witten SCFT for most of the computation.
- Result leads to interesting ten-dimensional perspective on nonperturbative effects.

Warped D-brane inflation

warped throat
(e.g. Klebanov-Strassler)



CY orientifold, with
fluxes and nonperturbative W
(KKLT 2003)

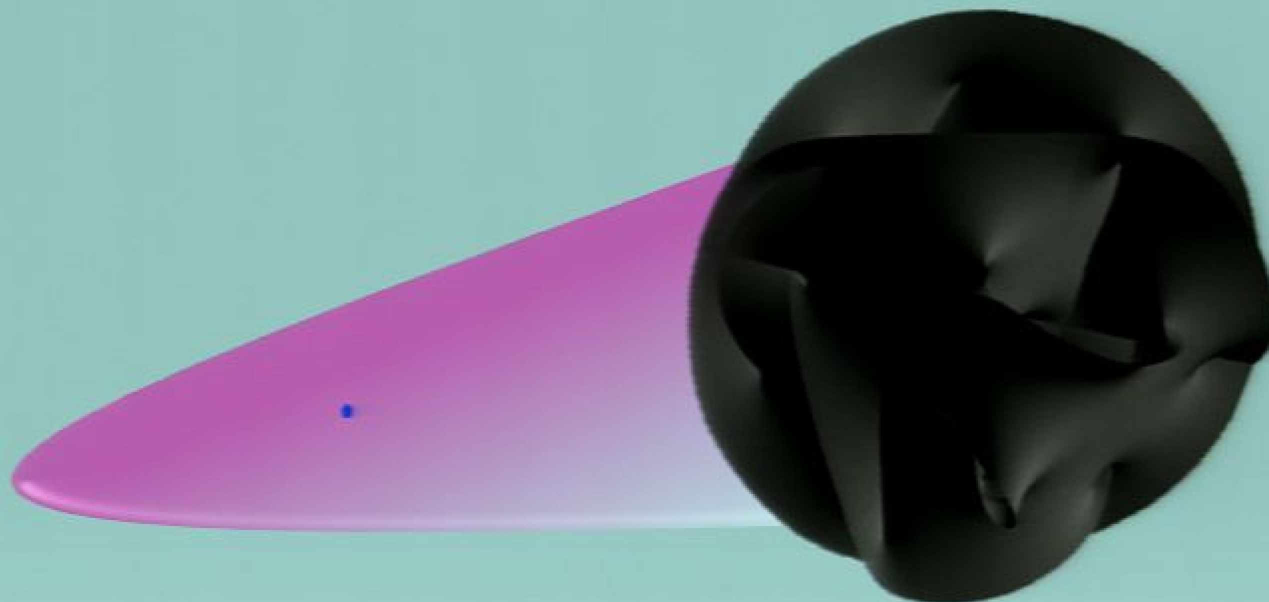
D3-brane

anti-D3-brane

warped throat gives:
- weak Coulomb potential
- control of energy scales
- **explicit local geometry**
- **dual CFT**

Kachru, Kallosh, Linde, Maldacena, L.M., Trivedi, 2003

What is the D3-brane potential?



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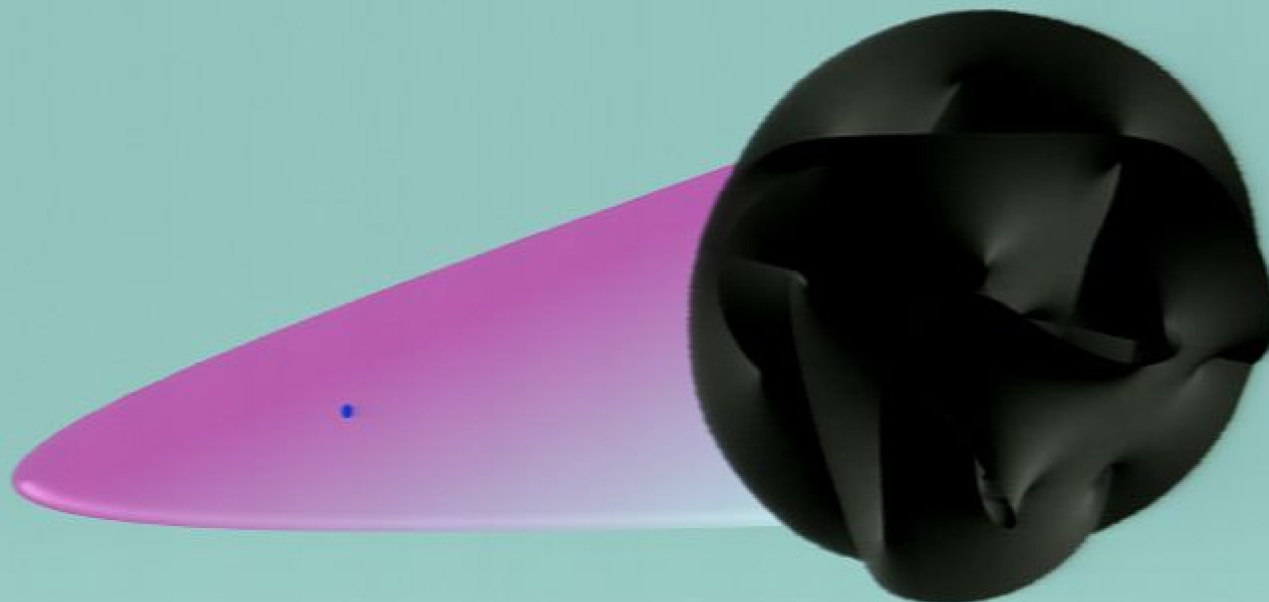

Specifically, what is the leading effect of moduli stabilization on the potential for a D3-brane in a throat?

D3-branes in flux compactifications

$$ds^2 = e^{2A(y)} g_{\mu\nu} dx^\mu dx^\nu + e^{-2A(y)} \tilde{g}_{mn}(y) dy^m dy^n$$

$$\tilde{F}_5 = (1 + \star_{10}) \left[d\alpha(y) \wedge dx^0 \wedge dx^1 \wedge dx^2 \wedge dx^3 \right]$$

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$$\Phi_\pm \equiv e^{4A} \pm \alpha$$

$$G_\pm \equiv (i \pm \star_6) G_3$$

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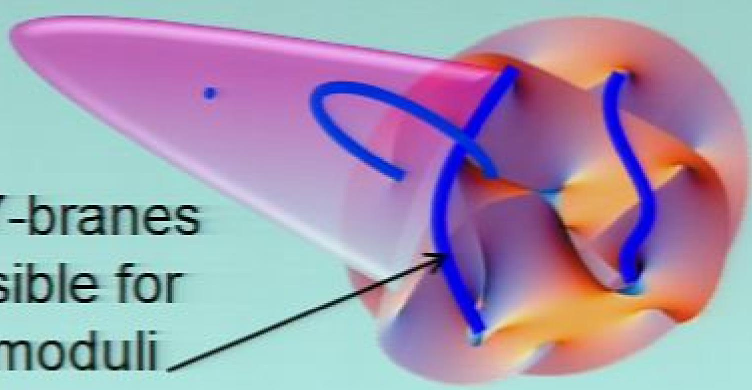
D3-branes feel no potential in ISD solutions ('no-scale'),
but
nonperturbative stabilization of Kahler moduli will spoil this.

D3-branes in KKLT compactifications

$$W = \int G_3 \wedge \Omega + A(y) e^{-a\rho}\,, \qquad \mathcal{K} = -3\,\log\Big(\rho + \bar{\rho} - k(y,\bar{y})\Big)$$



ED3/D7-branes responsible for Kahler moduli stabilization

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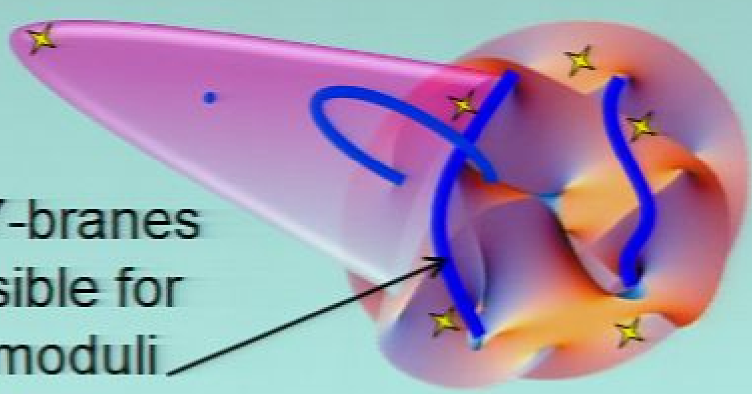
For generic A(y), solutions to $D_\rho W = D_y W = 0$

i.e., supersymmetric D3-brane vacua, are **isolated**. But where are they, and what is the potential in between?



ED3/D7-branes responsible for Kahler moduli stabilization

DeWolfe, L.M., Shiu, & Underwood, hep-th/0703088.

Options:

- Compute A(y) in a special case.

  Berg, Haack, Kors, hep-th/0404087

  Baumann, Dymarsky, Klebanov, Maldacena, L.M., & Murugan, hep-th/0607050.

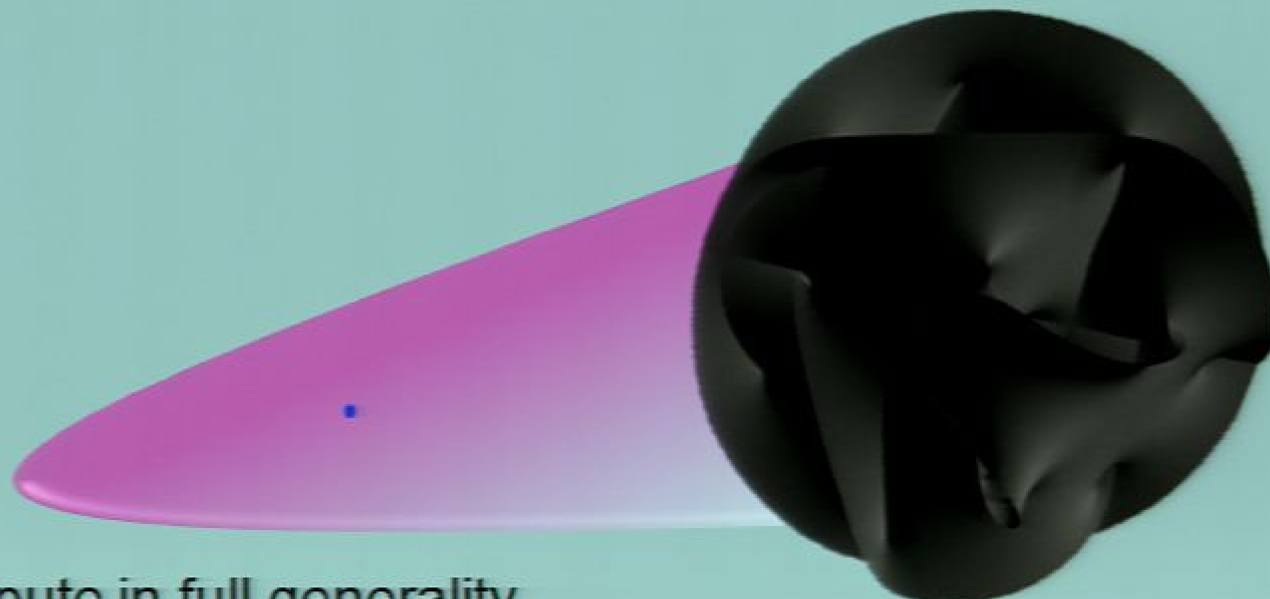
- Characterize the structure of the potential more generally.

  Baumann, Dymarsky, Kachru, Klebanov, & L.M., 0808.2811.

  Baumann, Dymarsky, Kachru, Klebanov, & L.M., in preparation.

Today: understand the leading term both ways.

General structure of the D3-brane potential?



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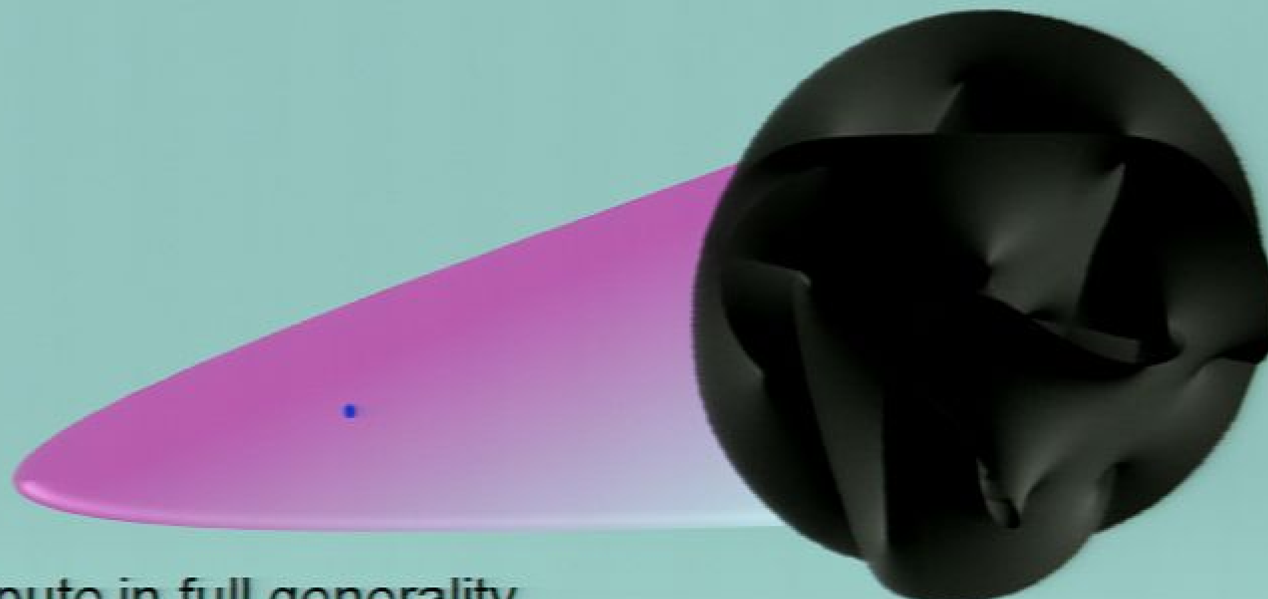

Clearly hard to compute in full generality.

Idea: for a D3-brane well inside a warped throat, leading effects captured by structure of throat + some information about boundary conditions in UV.

Intuitive in CFT: leading terms in the potential on the Coulomb branch captured by perturbations by the handful of most relevant operators.

$$\mathfrak{L} \to \mathfrak{L} + \sum c_i \mathcal{O}_i$$

II.
The potential in 10D supergravity

A Simple Idea

The D3-brane potential comes from Φ_- alone. So we are interested in the profile of Φ_-.

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Arbitrary compactification effects can be represented by specifying boundary conditions for Φ_- in the UV of the throat, i.e. by allowing arbitrary non-normalizable Φ_- profiles.

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Filtering in the throat

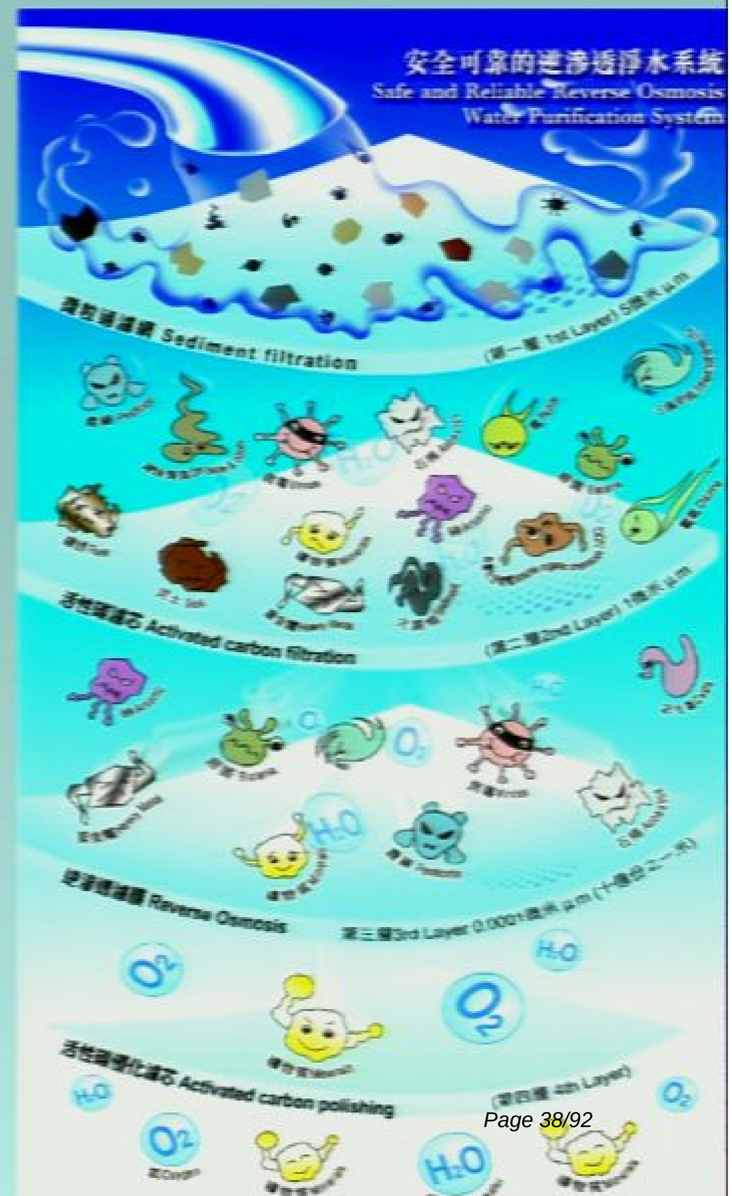
The warped geometry filters the compactification effects; in gauge theory variables,

$$V(\Lambda) \propto \sum_i c_i \left(\frac{\Lambda}{\Lambda_{UV}} \right)^{\Delta_i}$$

The leading contributions are those that diminish least rapidly towards the IR, i.e. the most relevant operators in the gauge theory.

By determining the spectrum of dimensions Δ_i we can extract the leading terms in the potential.

$$V(r) = \sum_i c_i r^{\Delta_i} f_i(\Psi)$$



Concrete example, gravity side

Consider linearized Φ_- perturbations around a finite-length KS throat, which we approximate by $AdS_5 \times T^{1,1}$.

$$ds^2 = h^{-1/2}\eta_{\mu\nu}dx^\mu dx^\nu + h^{1/2}(dr^2 + r^2 ds^2_{T^{1,1}})$$

$$h(r) = \frac{27\pi g_s}{4r^4}\alpha'^2 N$$

In general, many other modes are turned on, but at the *linear* level they do not couple to D3-branes.

EOM linearized around ISD compactifications

$$ds^2 = e^{2A(y)} g_{\mu\nu} dx^\mu dx^\nu + e^{-2A(y)} \tilde{g}_{mn}(y) dy^m dy^n$$

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$$\widetilde{\nabla}^2 \Phi_\pm = \frac{e^{8A+\phi}}{24} |\widetilde{G_\pm}|^2 + e^{-4A} |\widetilde{\nabla} \Phi_\pm|^2 + \mathrm{local}$$

Linearization around ISD compactifications

$$\mathrm{d}s^2 = e^{2A(y)} g_{\mu\nu} \mathrm{d}x^\mu \mathrm{d}x^\nu + e^{-2A(y)} \tilde{g}_{mn}(y) \mathrm{d}y^m \mathrm{d}y^n$$

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Linearity + absence of sources.

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If $G_- = 0$, this is the Laplace equation in the conifold.
Warmup: let's solve the Laplace equation.

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Warmup: let's solve the Laplace equation.
Caution: we'll see that G_ sources (inhomogeneous solution) actually give the leading effect.

Linearization around ISD compactifications

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But first, let's solve the Laplace equation in the conifold.

Solution:

Kim, Romans, & van Nieuwenhuizen, 1985.
Gubser, 1998.
Ceresole, Dall'Agata, D'Auria, Ferrara, 1999.

$$\Phi_-(r,\Psi) = \sum_{L,M} \Phi_{LM} \left(\frac{r}{r_{\rm UV}}\right)^{\Delta(L)} Y_{LM}(\Psi) + c.c.$$

$$\Box_5 Y_{LM} = -\Lambda Y_{LM}$$

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$$L \equiv \{J_1, J_2, R\} \quad \Longleftrightarrow \quad SU(2)\times SU(2)\times U(1)_R$$

$$\Lambda \equiv 6\left[J_1(J_1+1) + J_2(J_2+1) - R^2/8\right]$$

$$\Delta \equiv -2 + \sqrt{6\left[J_1(J_1+1) + J_2(J_2+1) - R^2/8\right] + 4}$$

$$V(r) = \sum_i c_i r^{\Delta_i} f_i(\Psi)$$

What are the lowest modes?

$$\{J_1, J_2, R\} = \{\tfrac{1}{2}, \tfrac{1}{2}, 1\} \qquad \Phi_-^{(3/2)}$$

Δ=3/2 chiral mode

$$\{J_1, J_2, R\} = \{1,0,0\} \text{ and } \{0,1,0\}$$

Δ=2 nonchiral mode $\qquad \Phi_-^{(2)}$

$$V(r) = c_{3/2} r^{3/2} + c_2 r^2 + \ldots$$

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Are these the leading terms?

We've found the leading contributions from the homogeneous solution for Φ_-,

$$V(r) = c_{3/2} r^{3/2} + c_2 r^2 + \dots$$

i.e. ignoring IASD flux as a source in

$$\widetilde{\nabla}^2 \Phi_\pm = \frac{e^{8A+\phi}}{24} |\widetilde{G_\pm}|^2$$

We should check this.

The potential from IASD flux

We should solve $$\widetilde{\nabla}^2\Phi_\pm = \frac{e^{8A+\phi}}{24}|\widetilde{G_\pm}|^2$$ incorporating a source.

$$G_- = \sum_\lambda r^\lambda f_\lambda(\Psi)$$

To do this, one of us (A.Dymarsky) finds the spectrum of G_- turns on a general G background, and extracts the leading term in Φ_-.

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Solution:

Kim, Romans, & van Nieuwenhuizen, 1985.
Gubser, 1998.
Ceresole, Dall'Agata, D'Auria, Ferrara, 1999.

$$\Phi_{-}(r,\Psi) = \sum_{L,M} \Phi_{LM} \left(\frac{r}{r_{\rm UV}}\right)^{\Delta(L)} Y_{LM}(\Psi) + c.c.$$

$$\Box_5 Y_{LM} = -\Lambda Y_{LM}$$

$$L \equiv \{J_1, J_2, R\} \quad \Longleftrightarrow \quad SU(2)\times SU(2)\times U(1)_R$$

$$\Lambda \equiv 6\left[J_1(J_1+1) + J_2(J_2+1) - R^2/8\right]$$

$$\Delta \equiv -2 + \sqrt{6\left[J_1(J_1+1) + J_2(J_2+1) - R^2/8\right] + 4}$$

$$V(r) = \sum_i c_i r^{\Delta_i} f_i(\Psi)$$

Linearization around ISD compactifications

$$\mathrm{d}s^2 = e^{2A(y)} g_{\mu\nu} \mathrm{d}x^\mu \mathrm{d}x^\nu + e^{-2A(y)} \tilde{g}_{mn}(y) \mathrm{d}y^m \mathrm{d}y^n$$

$$\tilde{F}_5 = (1 + \star_{10}) \left[\mathrm{d}\alpha(y) \wedge \mathrm{d}x^0 \wedge \mathrm{d}x^1 \wedge \mathrm{d}x^2 \wedge \mathrm{d}x^3 \right]$$

$$G_\pm \equiv (i \pm \star_6) G_3$$

$$V = T_3 \, \Phi_-$$

$$\Phi_\pm \equiv e^{4A} \pm \alpha$$

$$\widetilde{\nabla}^2 \Phi_\pm = \frac{e^{8A+\phi}}{24} |\widetilde{G_\pm}|^2$$

But first, let's solve the Laplace equation in the conifold.

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The leading terms, gravity side

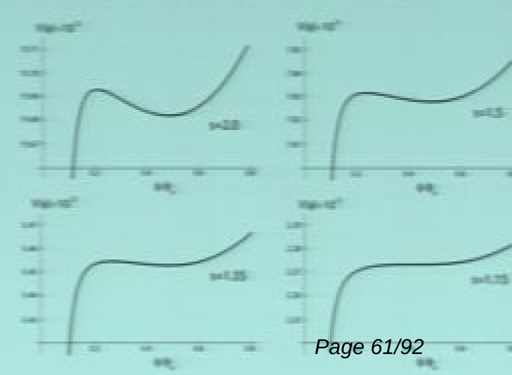
Recap: after solving $\widetilde{\nabla}^2 \Phi_\pm = \frac{e^{8A+\phi}}{24} |\widetilde{G_\pm}|^2$

with a general G background, the D3-brane potential is

$$V(r) = c_1 r^1 + c_{3/2} r^{3/2} + c_2 r^2 + \ldots$$

supported by $G_- \neq 0$ from homogeneous solution

So the D3-brane potential originates in UV perturbations of G_- and Φ_-.



For a better understanding, let's try another perspective.

III.
The potential in the dual gauge theory

Gauge theory version

Normalizable perturbations in supergravity correspond to perturbations of the state of the dual CFT. These IR contributions typically decouple from the compactification, and hence are easily included.

$$\varphi(r) = \alpha r^{-\Delta} + \beta r^{\Delta-4}$$

Non-normalizable perturbations in supergravity correspond to perturbations of the Lagrangian of the dual CFT. These UV contributions originate in the compact region.

Maldacena, 1997
Gubser, Klebanov, & Polyakov, 1998
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Gauge theory version

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$$\mathcal{L}_0 + \delta\mathcal{L} = \int d^2\theta d^2\bar{\theta}\,(K_0 + \delta K) + \int d^2\theta\,(W_0 + \delta W) + h.c.$$

$$\delta K = \sum c_i \mathcal{O}_{\Delta_i} \qquad \delta W = \sum d_i \mathcal{O}^{chiral}_{\Delta_i}$$

(In general, these operators may involve 4D curvature or hidden sector fields.)

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The RG flow filters these effects; the leading contributions are those that diminish least rapidly towards the IR, i.e. the most relevant contributions.

The structure of the potential on the Coulomb branch is therefore determined by the lowest-dimension operators in the CFT.

Concrete example, CFT side

Klebanov-Witten SCFT:

SU(N) x SU(N) gauge group

SU(2) x SU(2) x $U(1)_R$ global symmetry

bifundamentals A_i, B_i

Klebanov & Witten, hep-th/9807080

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contributing chiral operators:

$$\mathcal{O}_\Delta = \mathrm{Tr}\left(A^{(i_1} B_{(j_1} A^{i_2} B_{j_2} \dots A^{i_R)} B_{j_R)} \right) + c.c.$$

most relevant chiral operators:

$$\mathcal{O}_{3/2} = \mathrm{Tr}\left(A_i B_j \right) + c.c.$$

Leading perturbations, CFT side

$$\delta K = c_{3/2}\mathcal{O}_{3/2} X^\dagger X \qquad \delta W = d_{3/2}\mathcal{O}_{3/2}$$

most relevant perturbation:

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The potential that results is

$$V = c_1 r^1$$

One can check that the higher terms also match the gravity side.

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- We have one more perspective to try: 4D supergravity.

We can try to compute A(y) and plug into

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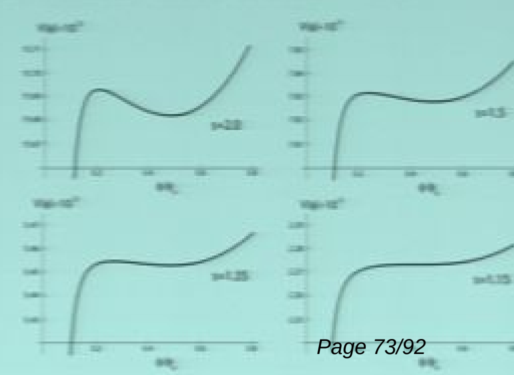

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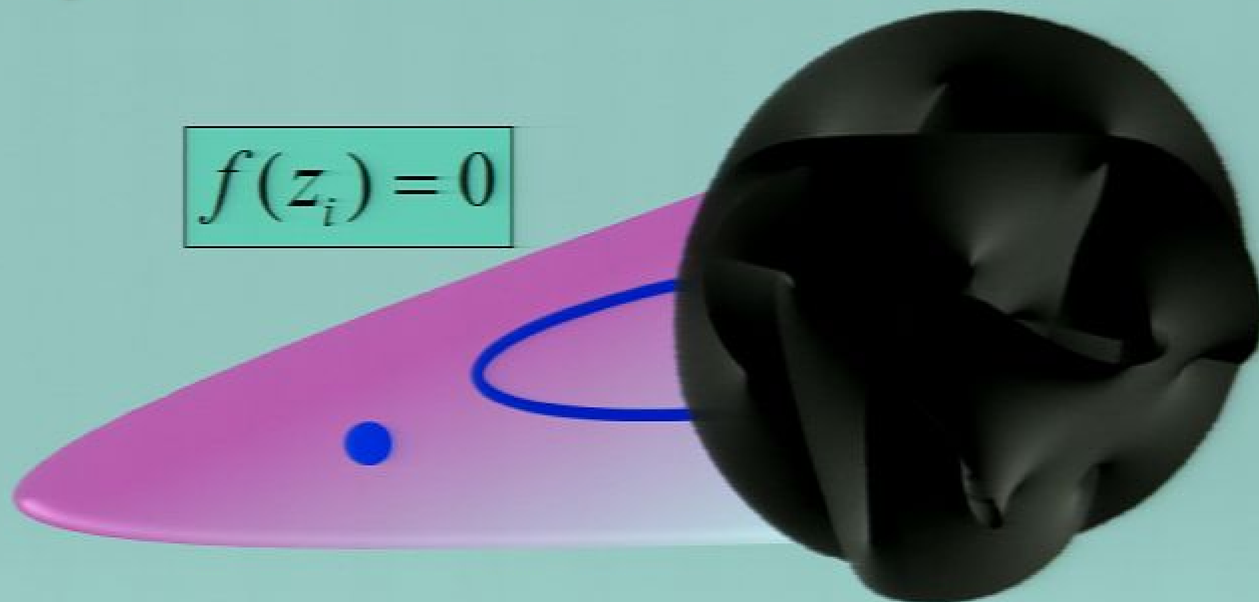
A background for computing A(y): a four-cycle embedded in the throat

$$f(z_i) = 0$$

$$\sum_{i=1}^{4} z_i^2 = \varepsilon^2$$



D3-brane is a source for a perturbation of the warped metric.

It corrects the warped volume of the four-cycle Σ_4 and hence corrects the nonperturbative superpotential.

$$W_{NP} = \exp(-T_3 V^{w}_{\Sigma_4})$$

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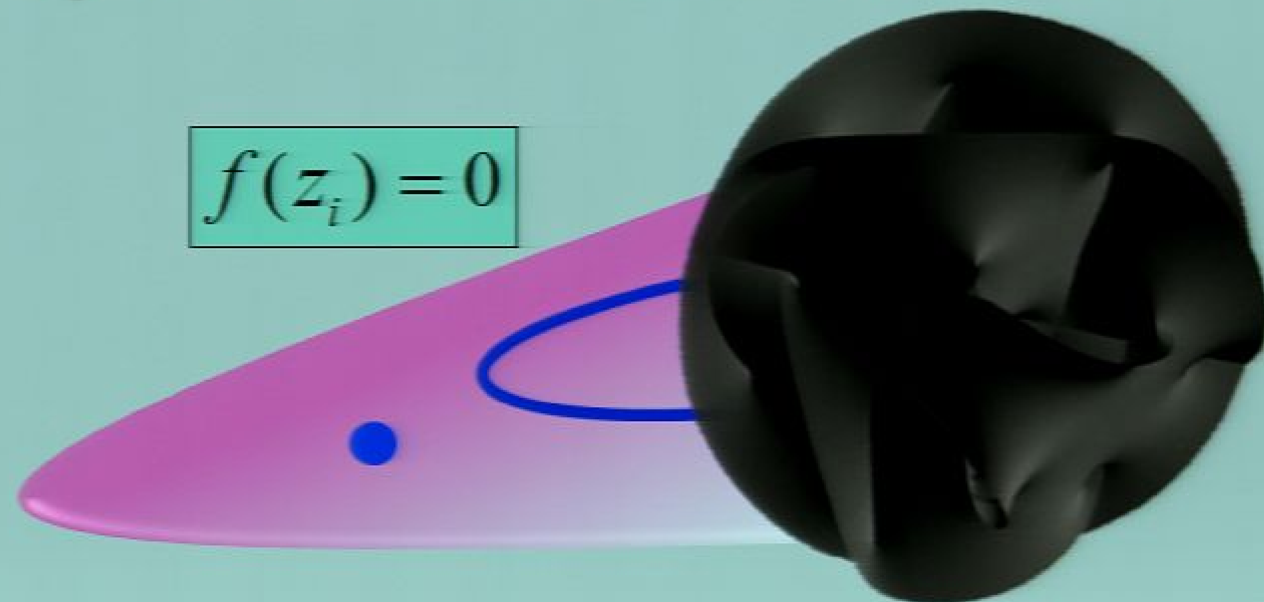

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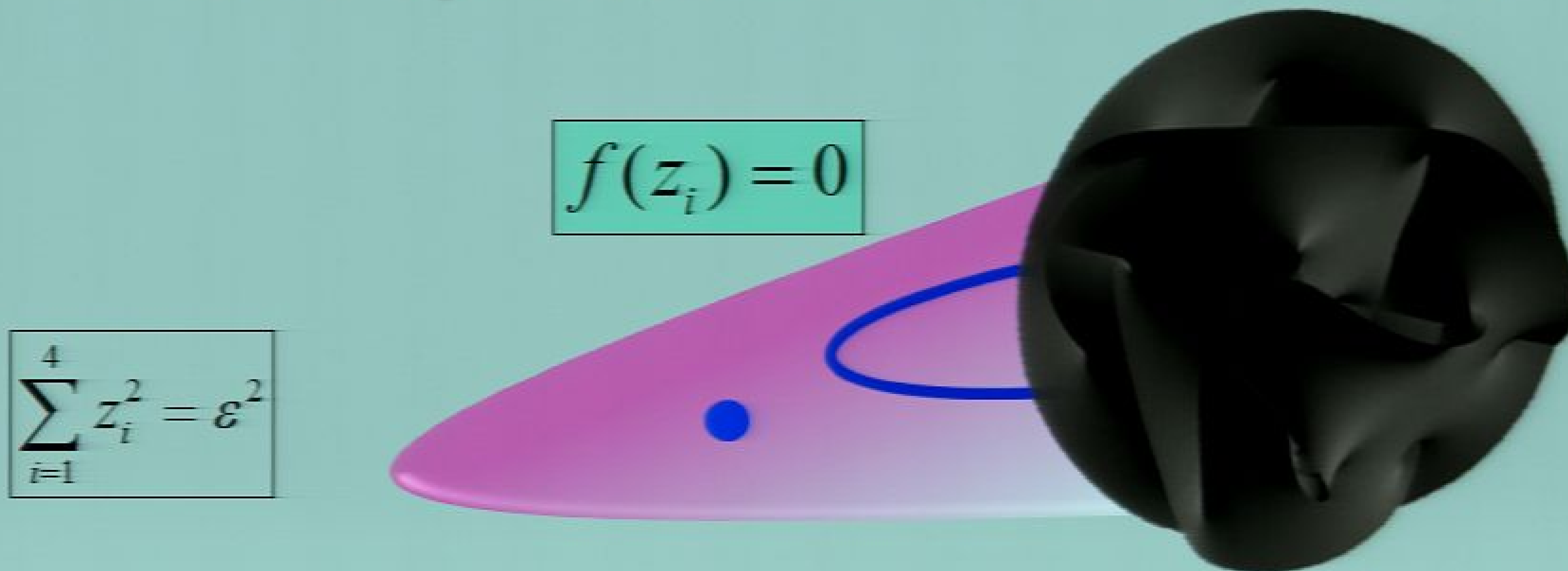

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Result for a general warped throat

Ganor, hep-th/9612007
Baumann, Dymarsky, Klebanov, Maldacena, L.M., & Murugan, hep-th/0607050.

If N wrapped branes are embedded along

$$f(z_i) = 0$$

then the superpotential correction is

$$A = A_0 f(z_i)^{1/N}$$

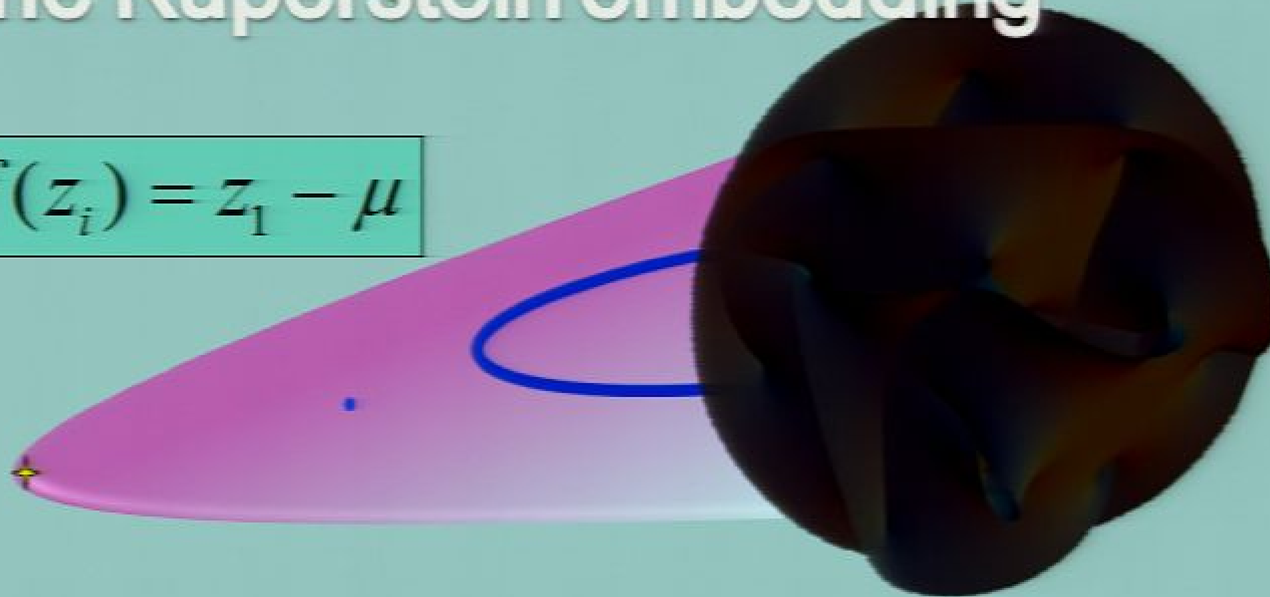
so the superpotential is

$$W_{KKLT} = \int G \wedge \Omega + A_0 f(z_i)^{1/N} e^{-a\rho}$$

Example: the Kuperstein embedding

Kuperstein,
hep-th/0411097

$$f(z_i) = z_1 - \mu$$



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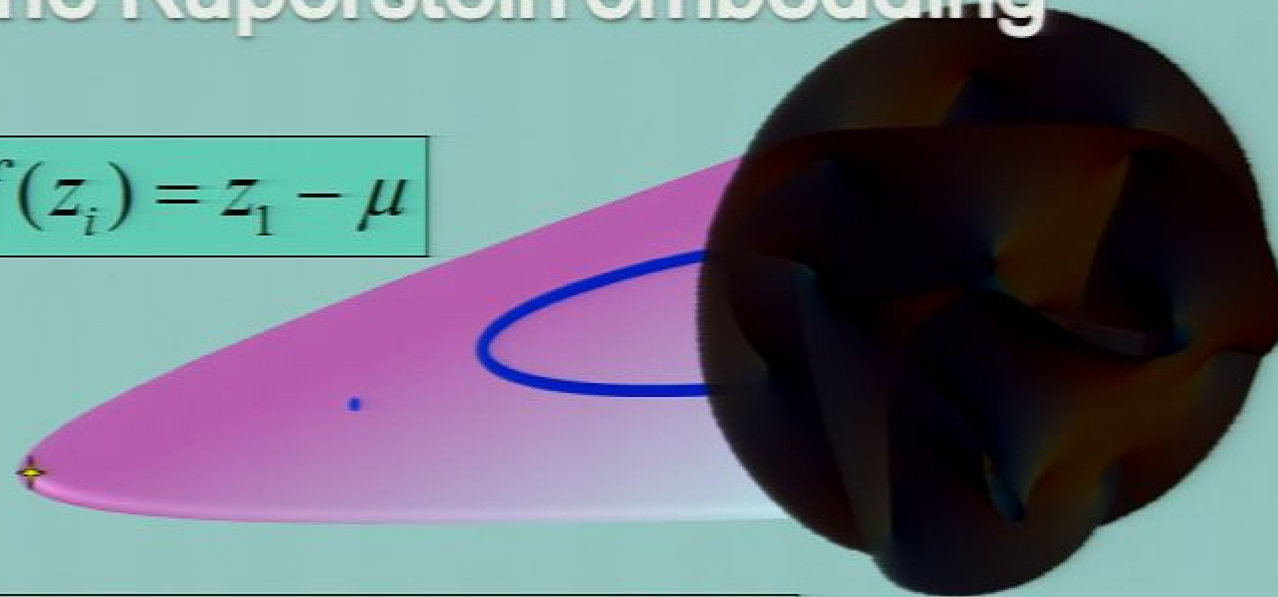

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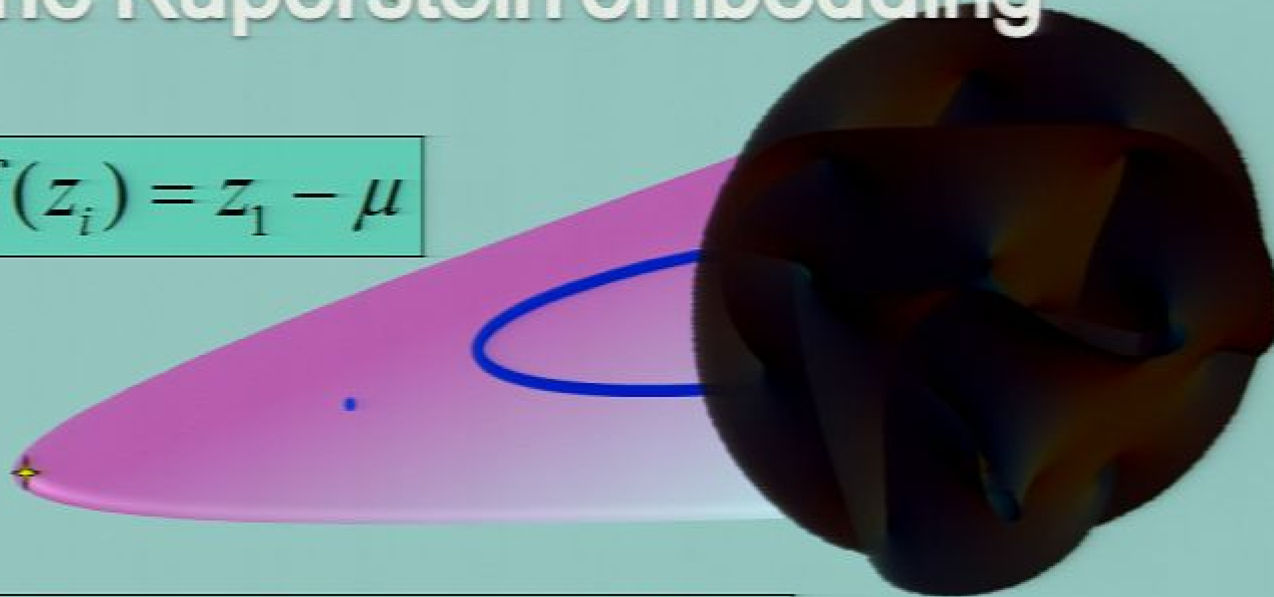

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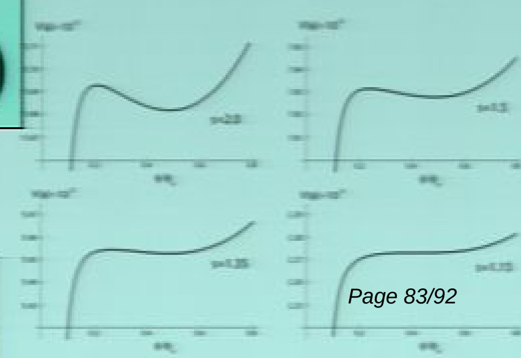

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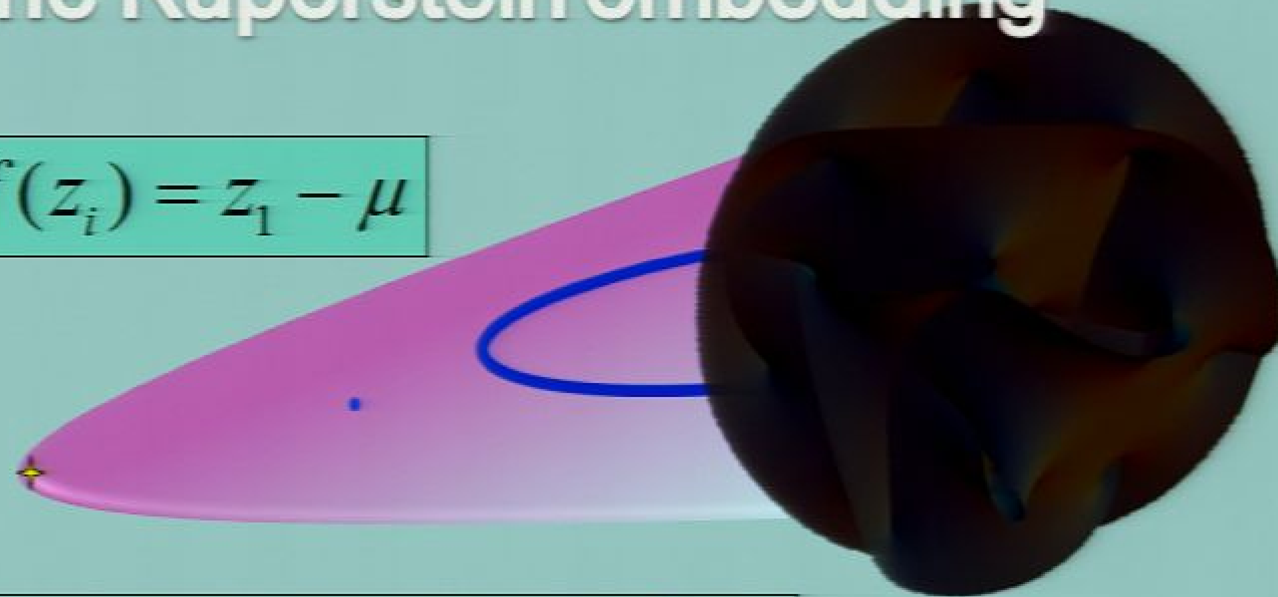

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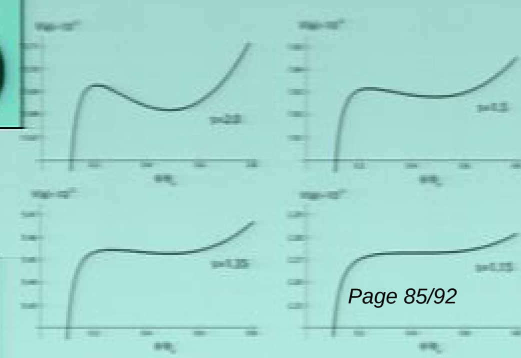

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Phenomenology:
Inflection point inflation

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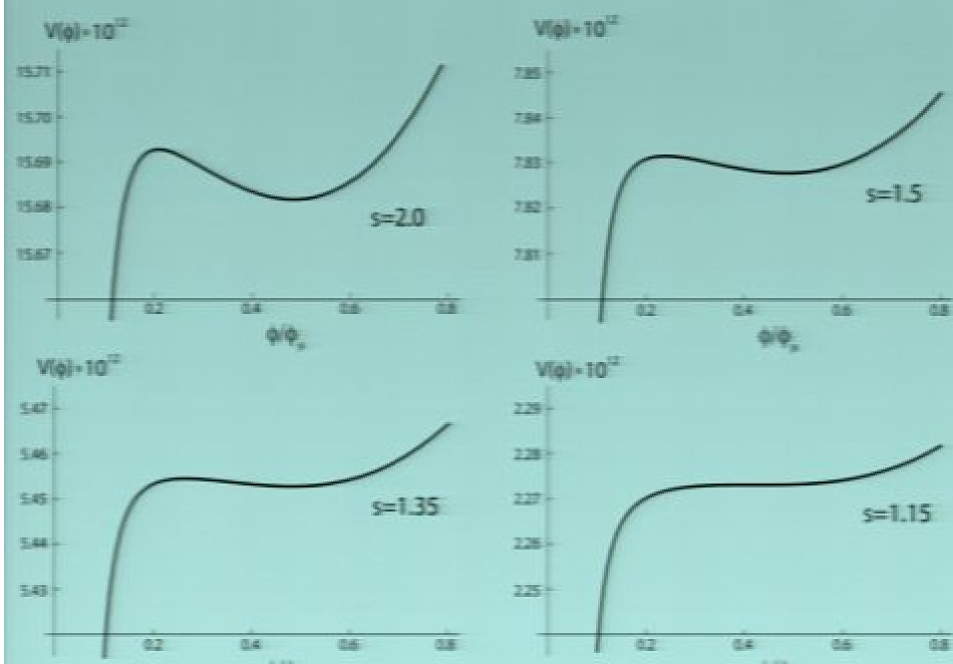
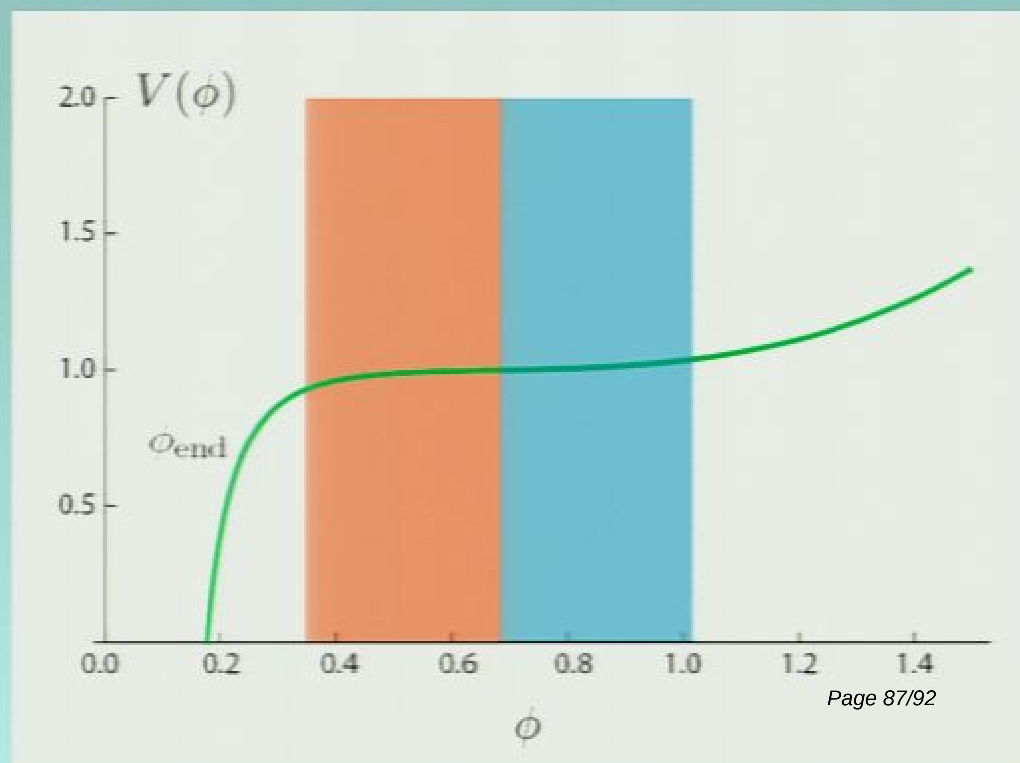
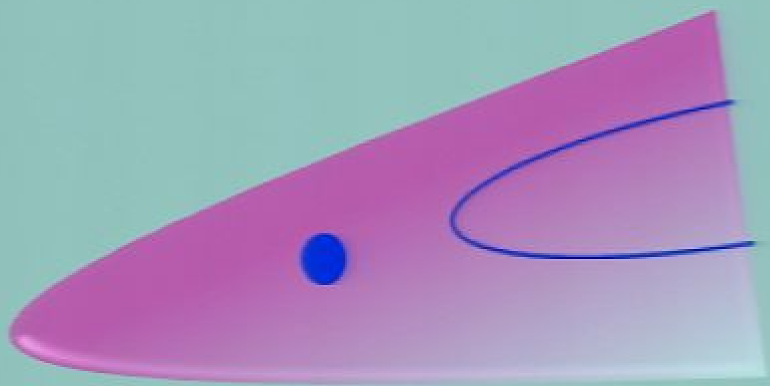




Q. What sources the IASD flux?



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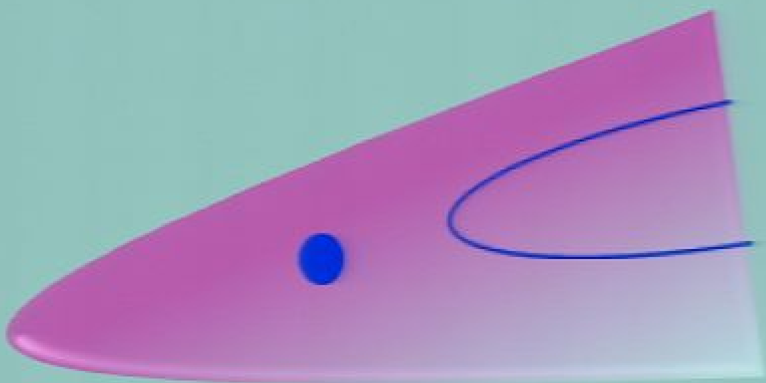

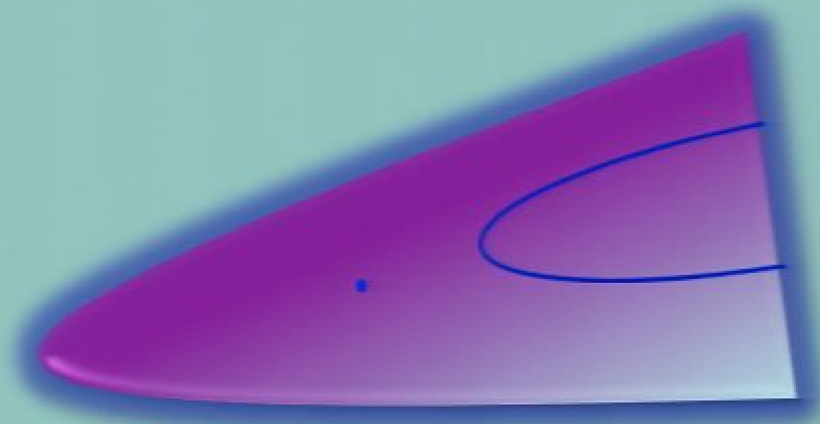

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Potential of probe D3-brane is then computed via 10D supergravity:

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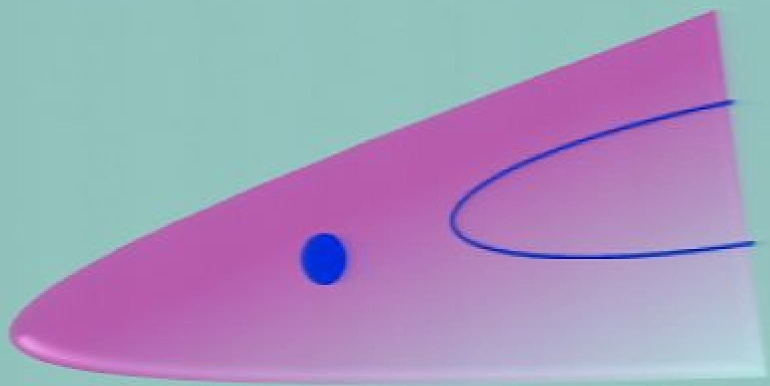
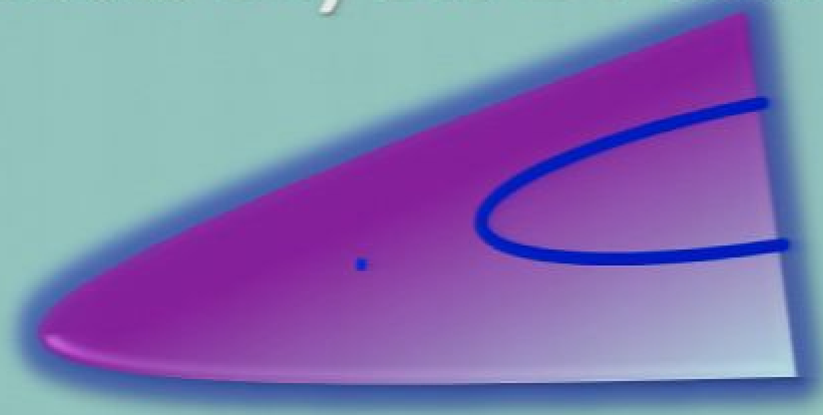
A. (Nonperturbative effects on) the D7 branes.





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What coupling sources the flux?

$$W_{NP} = A_0 g(z_i)^{1/N} e^{-a\rho} = \exp\left(-\frac{f_{D7}}{N}\right)$$

$$f_{D7} \propto 2\pi\rho - \log g(z_i)$$

superspace completion:

$$\int d^2\theta\, \Phi\, W^\alpha W_\alpha = (2\pi\rho - \log g(z_i)) F^{\mu\nu} F_{\mu\nu} + F_\Phi \lambda^\alpha \lambda_\alpha$$

auxiliary component: $F_z \propto C - i g_s^{-1} B$

implies a gaugino coupling:

$$\left(C - i g_s^{-1} B\right) \lambda^\alpha \lambda_\alpha$$

Conclusions

- We have a systematic approach to computing the structure of the inflaton potential in warped brane inflation.
- Method: consider generic perturbations of ultraviolet region, and focus on most relevant terms.
- Equivalently, perturb dual CFT by most relevant operators.
- Our approach reproduces, extends, and simplifies the results of direct computation of W from wrapped D7-branes.
- We capture general effects of compactification, provided that the D3-brane is far from the top and from the tip.
- Leading effect comes from IASD flux sourced by D7-brane superpotential.
- Phenomenology: inflection-point inflation.