Decay of False Vacuum via Fuzzy Monopole in String Theory

1) Aya Kasai (Kyushu U.), Yutaka Ookouchi (Kyushu U.).
arXiv:1502.01544[hep-th] Phys. Rev. D 91, 126002

2) Aya Kasai (Kyushu U.), Yuichiro Nakai (Harvard U.), Yutaka Ookouchi (Kyushu U.). arXiv:1508.04608 [hep-th]

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2015/12/08 @Osaka U.

Big Picture: Multiverse

Semi-classical vacuum decay

Soliton (Impurity) causes semi-classical inhomogenous vacuum decay

P. J. Steinhardt, Nucl. Phys. B 190, 583 (1981)
Y. Hosotani, Phys. Rev. D27 789 (1983)
U. Yajnik, Phys. Rev D34, 1237 (1986)

Let me demonstrate this idea by using cosmic string

Phenomenological Study

(Not string theory yet)

Eto, Hamada, Kamada, Kobayashi, Ohashi, YO: 1211.7237 [hep-th]

Originating from SUSY model building

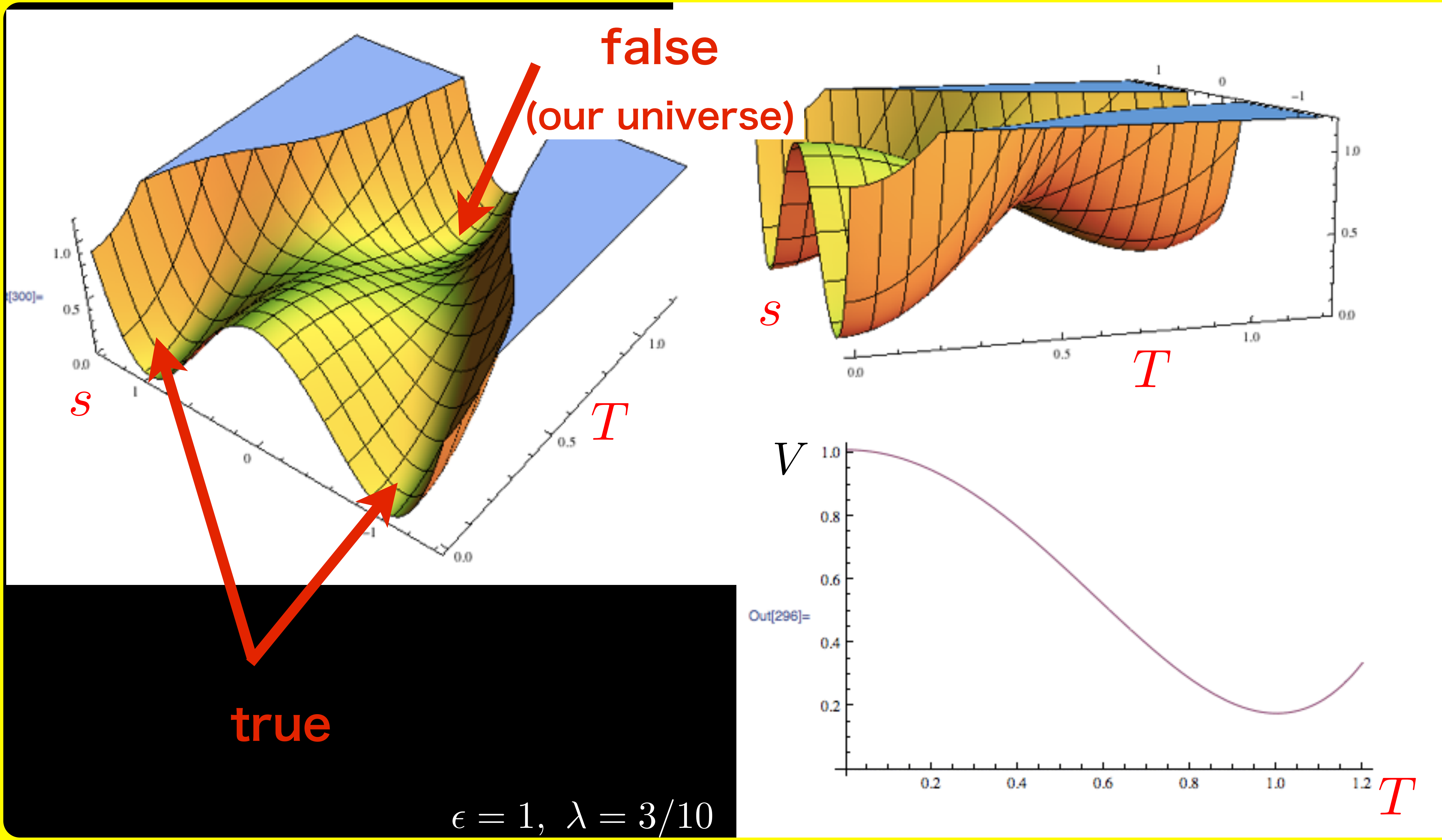
$$\mathcal{L} \;=\; \mu^4 \left[\frac{1}{\mathcal{V}(T)} \left|\tilde{\partial}_\mu T\right|^2 + \epsilon^2 \left|\tilde{\partial}_\mu s\right|^2 - \mathcal{V}(T)|s^2-1|^2 - \frac{4}{\epsilon^2}|T|^2|s|^2 \right].$$

mass dim

$$\mathcal{V}(T) \equiv 1 - \frac{|T|^2}{2\lambda} + \frac{|T|^4}{4\lambda}.$$

- 2 dim-less fields $T,\ s$
- 2 dim-less parameters $\lambda,\ \epsilon$

Landscape of vacua



Symmetries of the model

$$\mathcal{L} \;=\; \mu^4 \left[\frac{1}{\mathcal{V}(T)} \left|\tilde{\partial}_\mu T\right|^2 + \epsilon^2 \left|\tilde{\partial}_\mu s\right|^2 - \mathcal{V}(T)|s^2-1|^2 - \frac{4}{\epsilon^2}|T|^2|s|^2\right].$$

$$\mathcal{V}(T) \equiv 1 - \frac{|T|^2}{2\lambda} + \frac{|T|^4}{4\lambda}.$$

$$U(1): \quad T \to e^{i\alpha} T$$

$$Z_2: \quad s \to -s$$

- false $\quad T \neq 0,\ s = 0$

  cosmic string is formed by U(1) breaking

- true $\quad T = 0,\ s \neq 0$

Cosmic R-string (R-tube) solution

$$T = f(\rho)e^{in\theta}, \quad s = \gamma\, h(\rho),$$

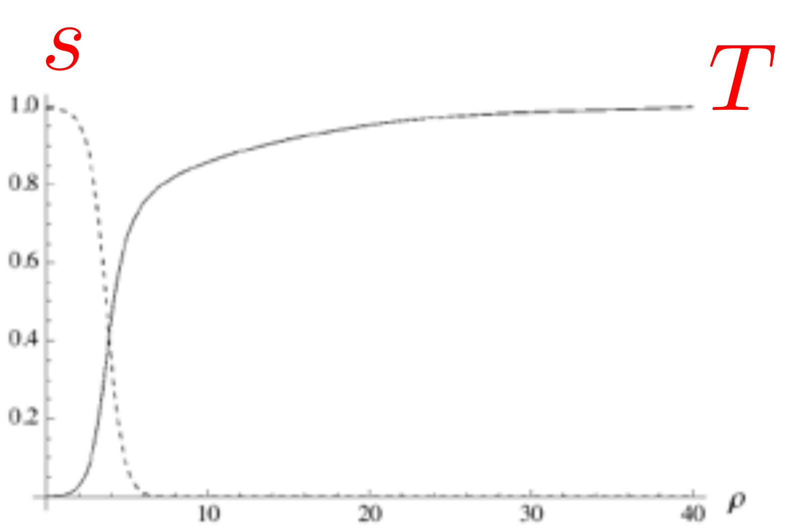
winding number

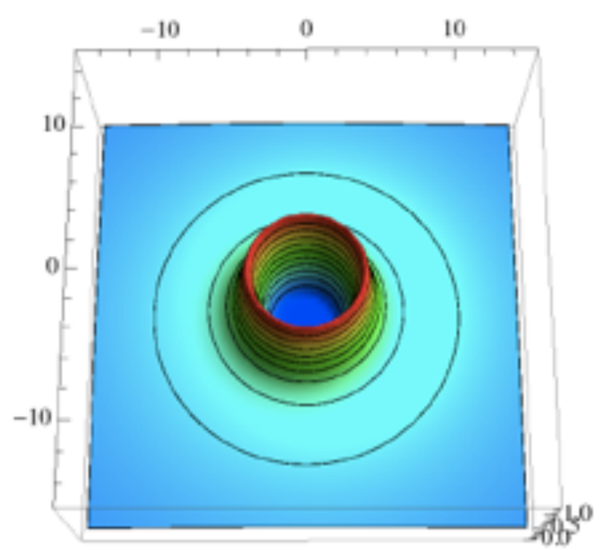
two vacua

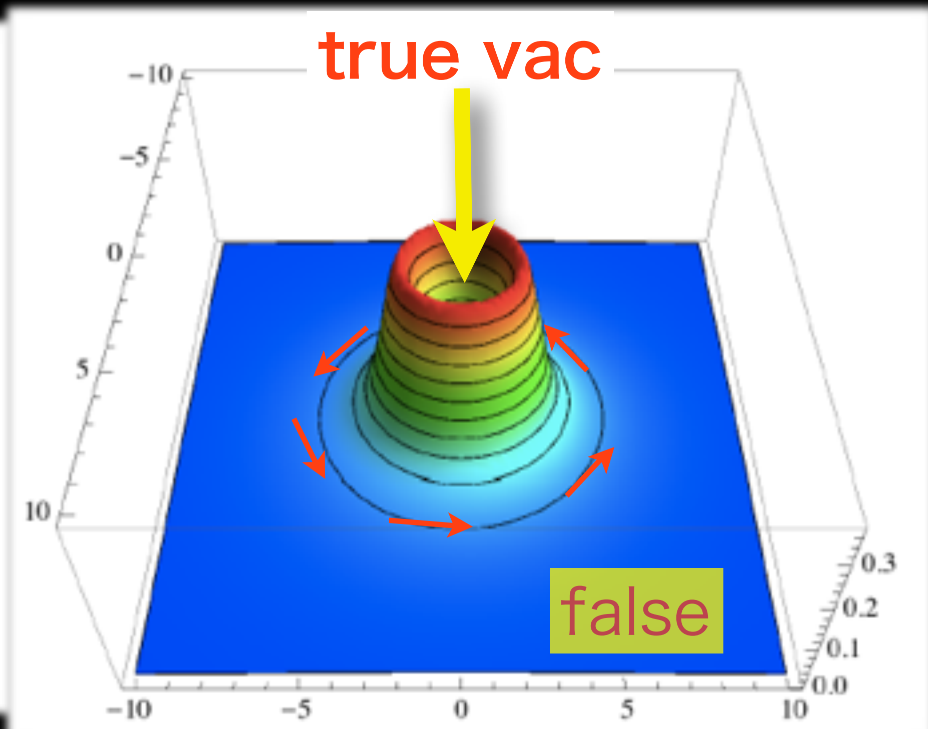
Instability depends on parameters,

In a wide range of parameter space, it is unstable

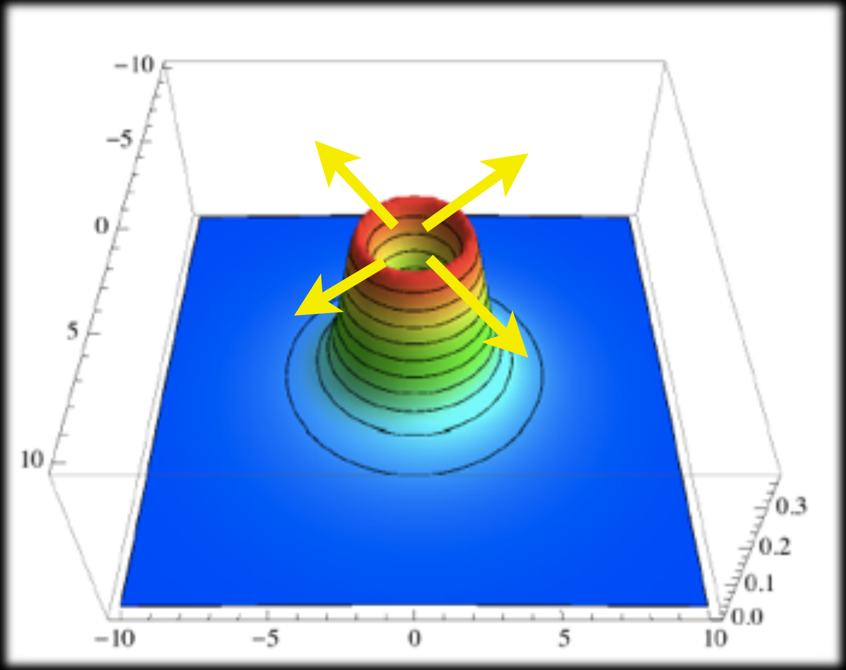
$\epsilon = 1, \quad \lambda = 27/100$







Semi-classical vacuum decay



Spontaneous U(1) break

String → Tube →

Expansion of radius →

our universe is filled out by true vacuum

Now, we are ready to discuss our project

What we will show is an
application of catalysis to string theory

Import the idea into string theory

Can we see a similar effect in string theory?

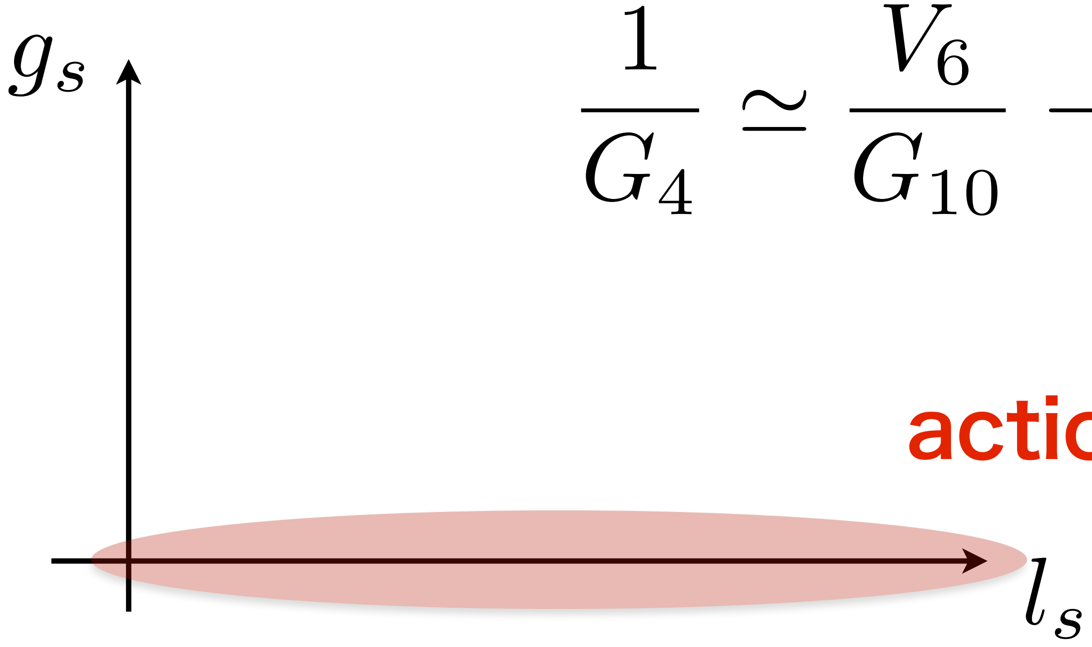
Mini string landscape

$$g_s \ll 1,\ l_s = \mathrm{finite}$$

non-compact 6D internal manifold

$\rightarrow$ 4D gravity can be ignored

$$\frac{1}{G_4} \simeq \frac{V_6}{G_{10}} \rightarrow \infty$$



action is Dirac-Born-Infeld (DBI)

Our Goal

1）D3 brane (impurity) makes the life-time of a metastable vacuum drastically shorter

2）A new way to construct dielectric brane without using background flux nor angular momentum

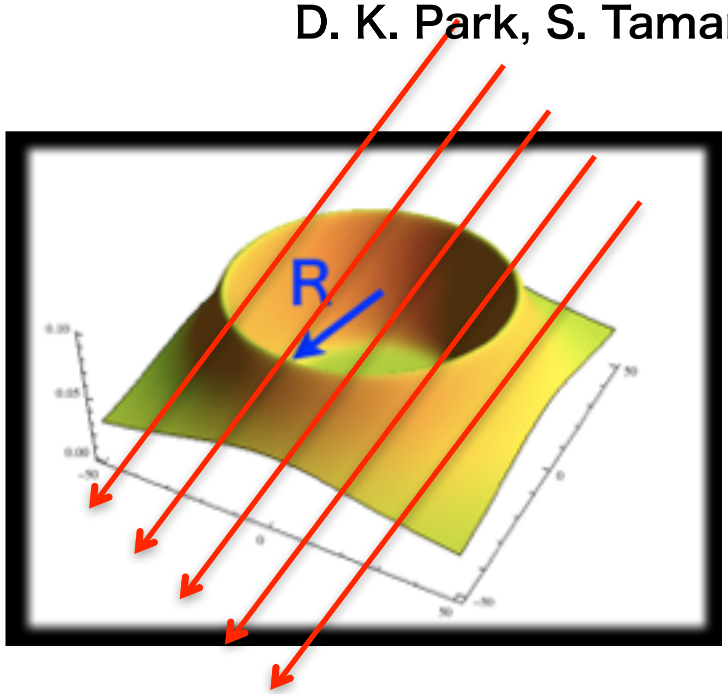
R. Emparan, Phys. Lett. B423, 71 (1998)

R. Myers, JHEP 9912 022 (1999)

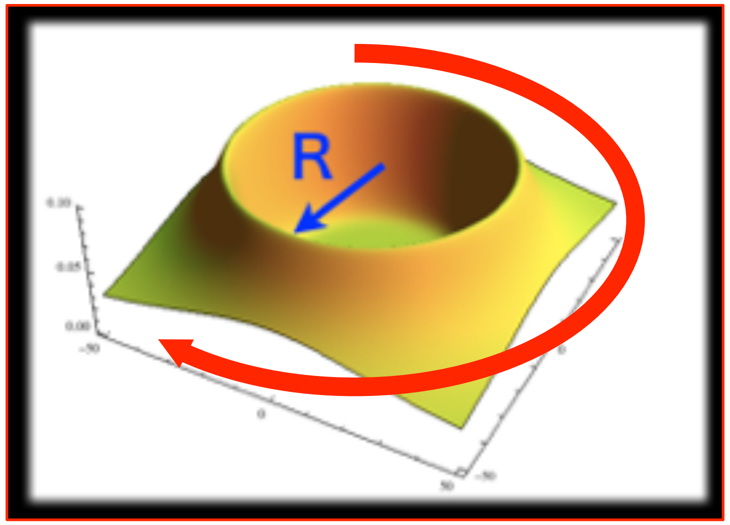
K. Hashimoto, JHEP 0207, 035 (2002)

D. Mateos and P. K. Townsend, Phys. Rev. Lett. 87, 011602 (2001)

D. K. Park, S. Tamarian and H. J. W. Muller-Kirsten, JHEP 0205, 009 (2002)



Background flux



Angular momentum

Set up of geometry

M. Aganagic, C. Beem, J. Seo and C. Vafa, Nucl. Phys. B 789, 382 (2008)

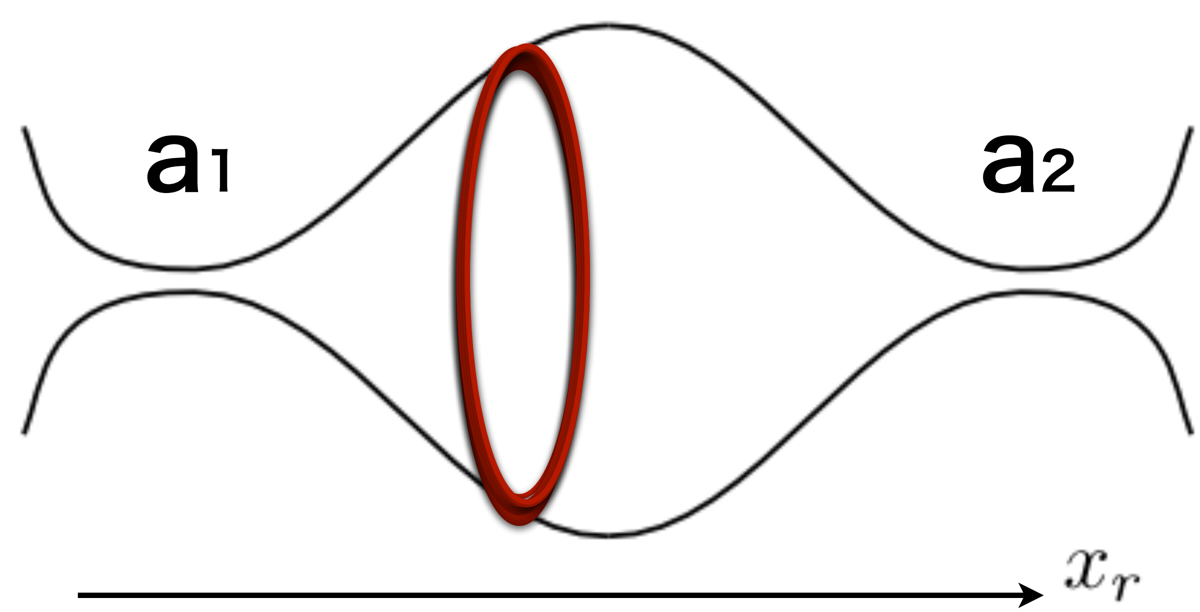
Use the Calabi-Yau manifold

$$W'(x)^2 + y^2 + z^2 + w^2 = 0 \qquad W'(x) = g(x - a_1)(x - a_2).$$

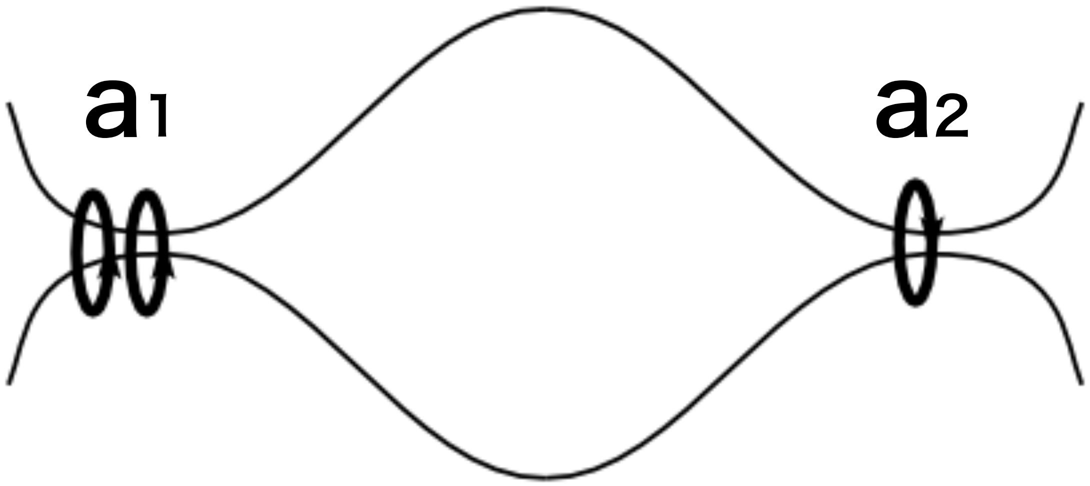
Important 3-dim sub-manifold

$$y_i^2 + z_i^2 + w_i^2 = g^2(x_r - a_1)^2(x_r - a_2)^2$$

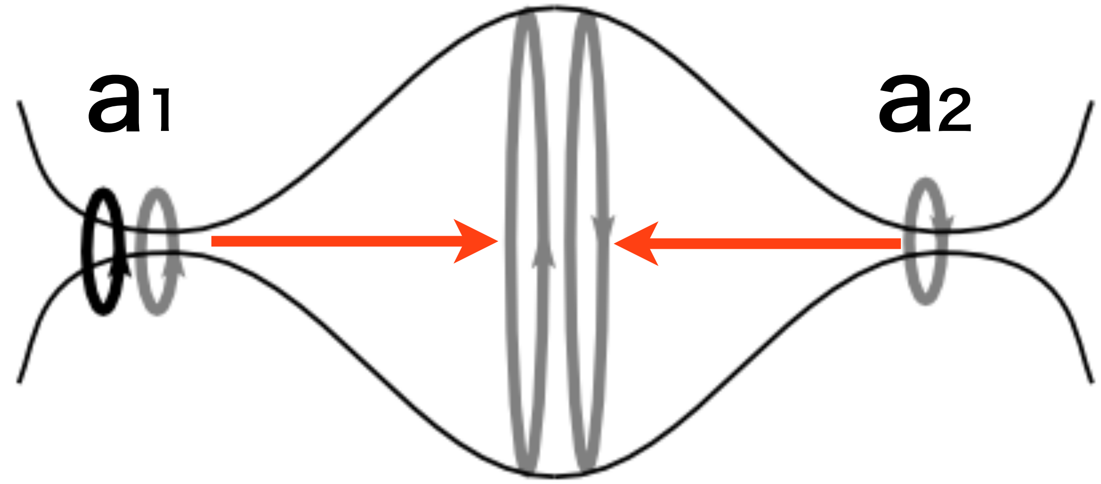
3-cycle=set of S^2



True and false vacua



false vacuum



true vacuum

Wrapping n D5 at a_1

Wrapping n anti-D5 at a_2

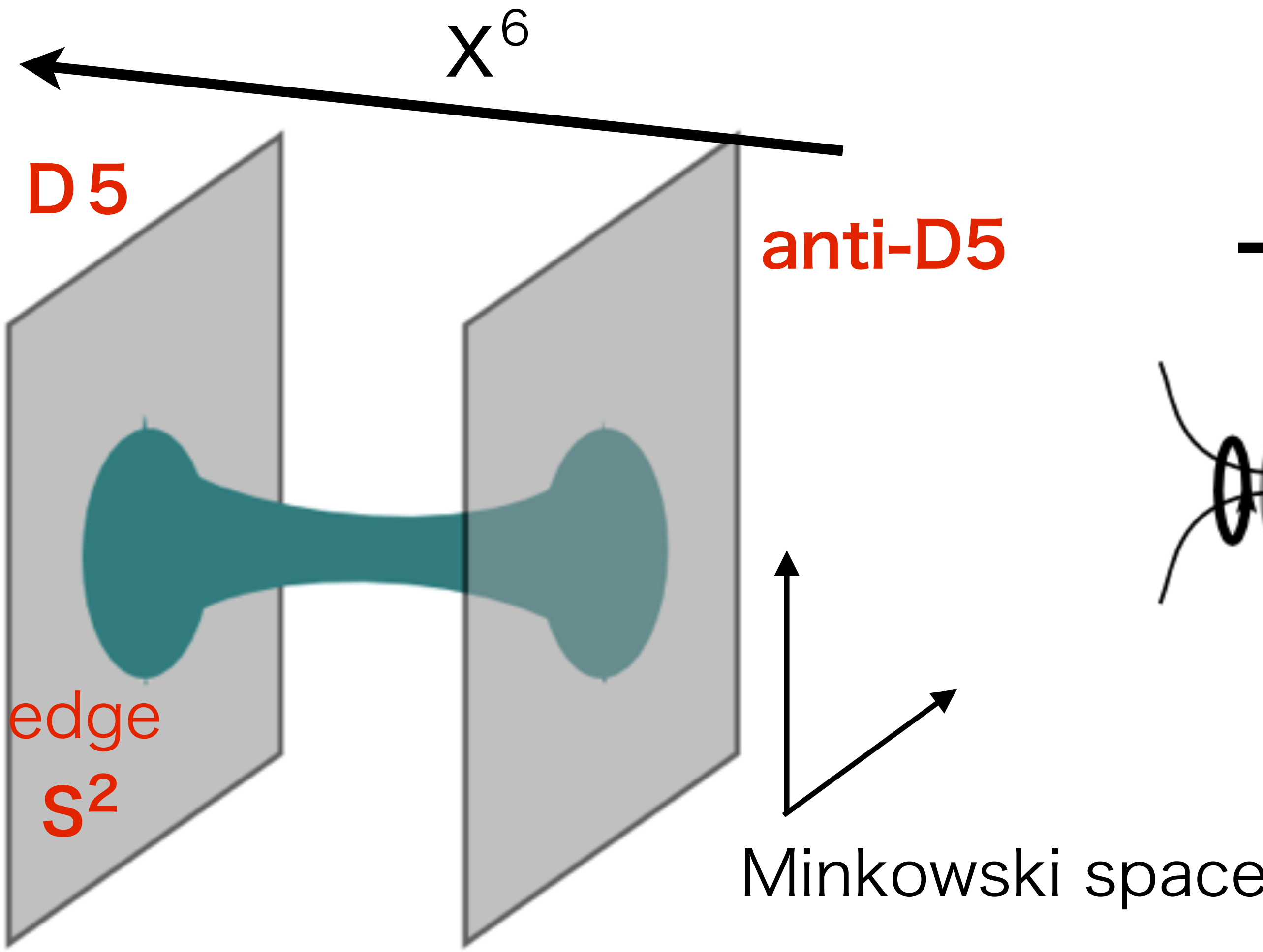
→ D5/anti-D5 annihilation

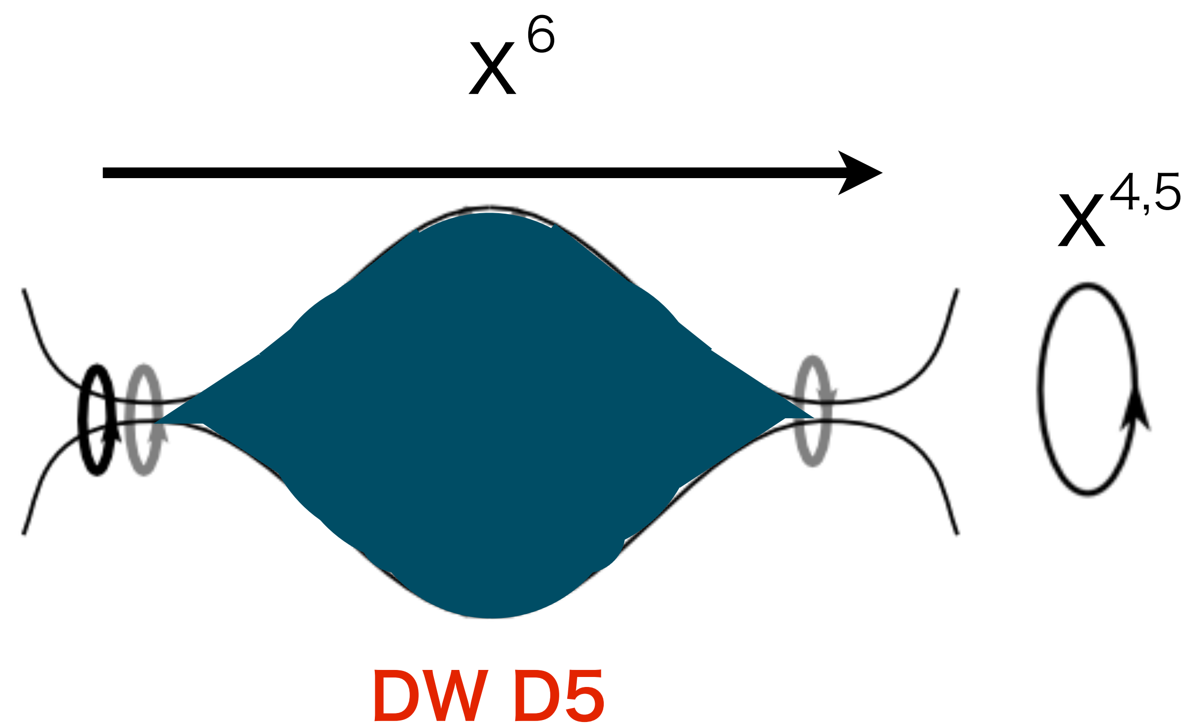
energy (density) gap

$$\Delta V = 2\frac{|r|}{g_s l_s^4} n \qquad r = \int_{C_i} B$$

Annihilation process

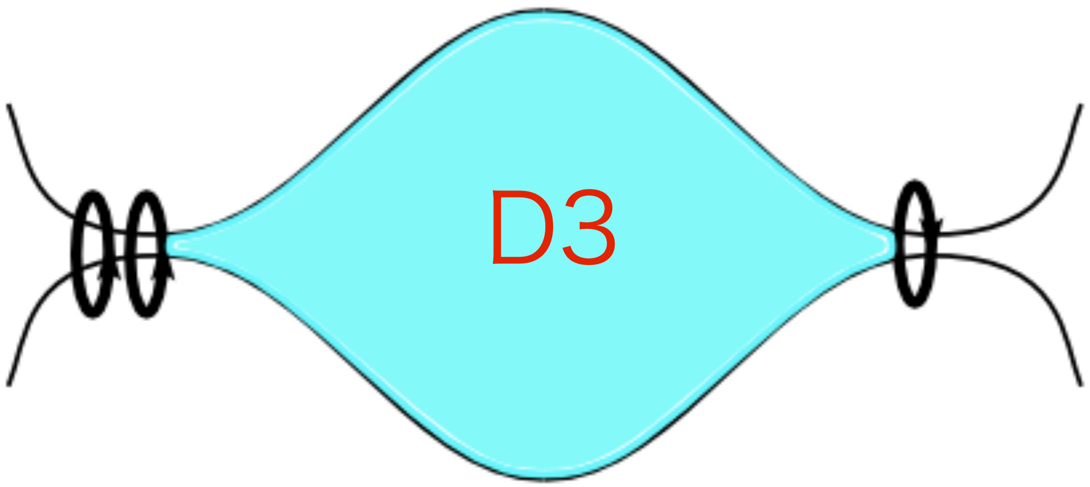
Partial annihilation of D5 and antiD5 branes





	0	1	2	3	4	5	6	7	8	9
			S^2							
DW	○	△	△	△	○	○	○	×	×	×

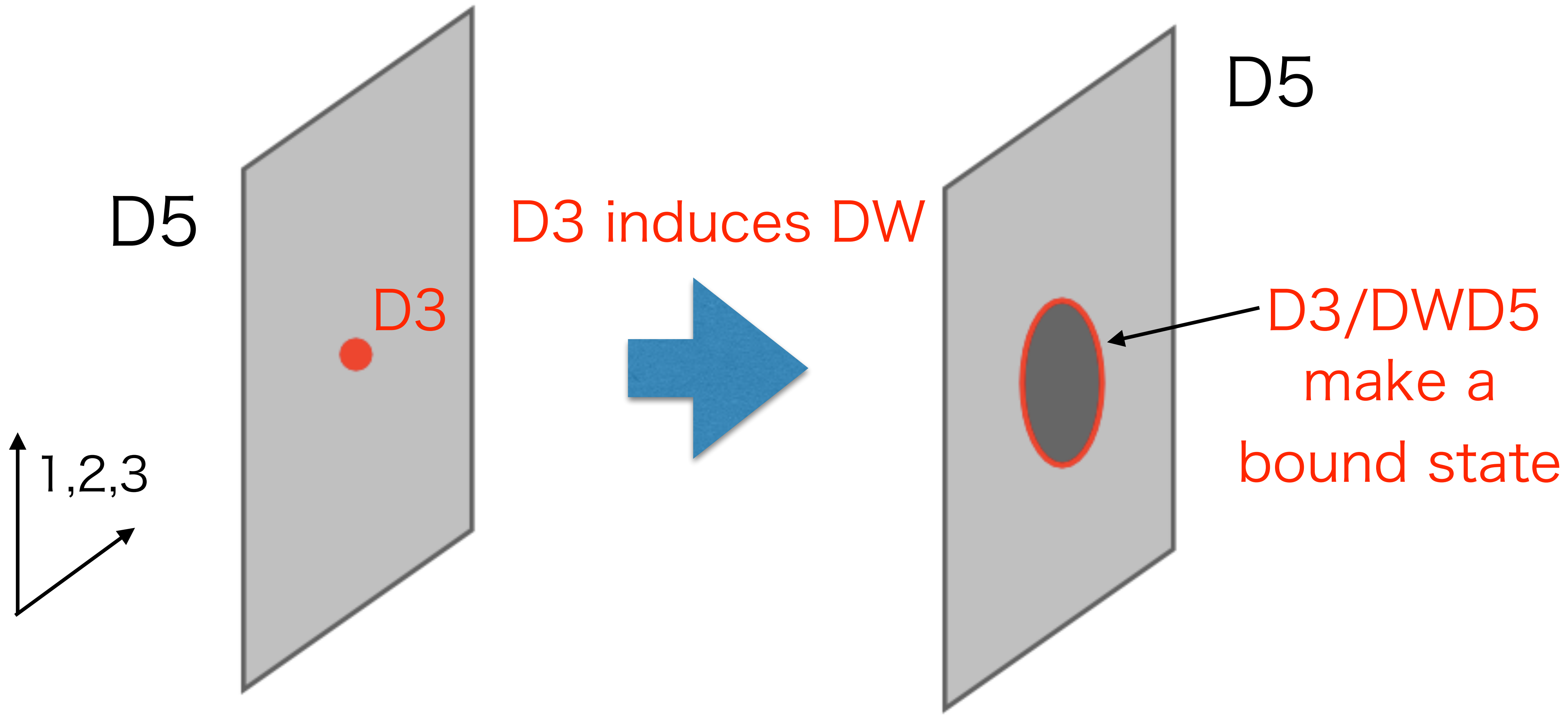
Add D3 brane as an impurity



D3 plays a role of monopole

	0	1	2	3	4	5	6	7	8	9
D3	○	×	×	×	○	○	○	×	×	×
DW	○	△	△	△	○	○	○	×	×	×

Process of the vacuum decay



	0	1	2	3	4	5	6	7	8	9
D5	○	○	○	○	○	○	×	×	×	×
D3	○	×	×	×	○	○	○	×	×	×
DW	○	△	(2) △	△	○	○	○	×	×	×

Bound state of D3/DWD5

bound state energy

$$E_{D5/D3} = \sqrt{(T_{D5}4\pi R^2 V_3)^2 + (n_{D3}T_{D3}V_3)^2}.$$

total energy of system

$$E_{\rm total} = \sqrt{(T_{D5}4\pi R^2 V_3)^2 + (n_{D3}T_{D3}V_3)^2} - \frac{4\pi}{3}\Delta V R^3 + {\rm const},$$

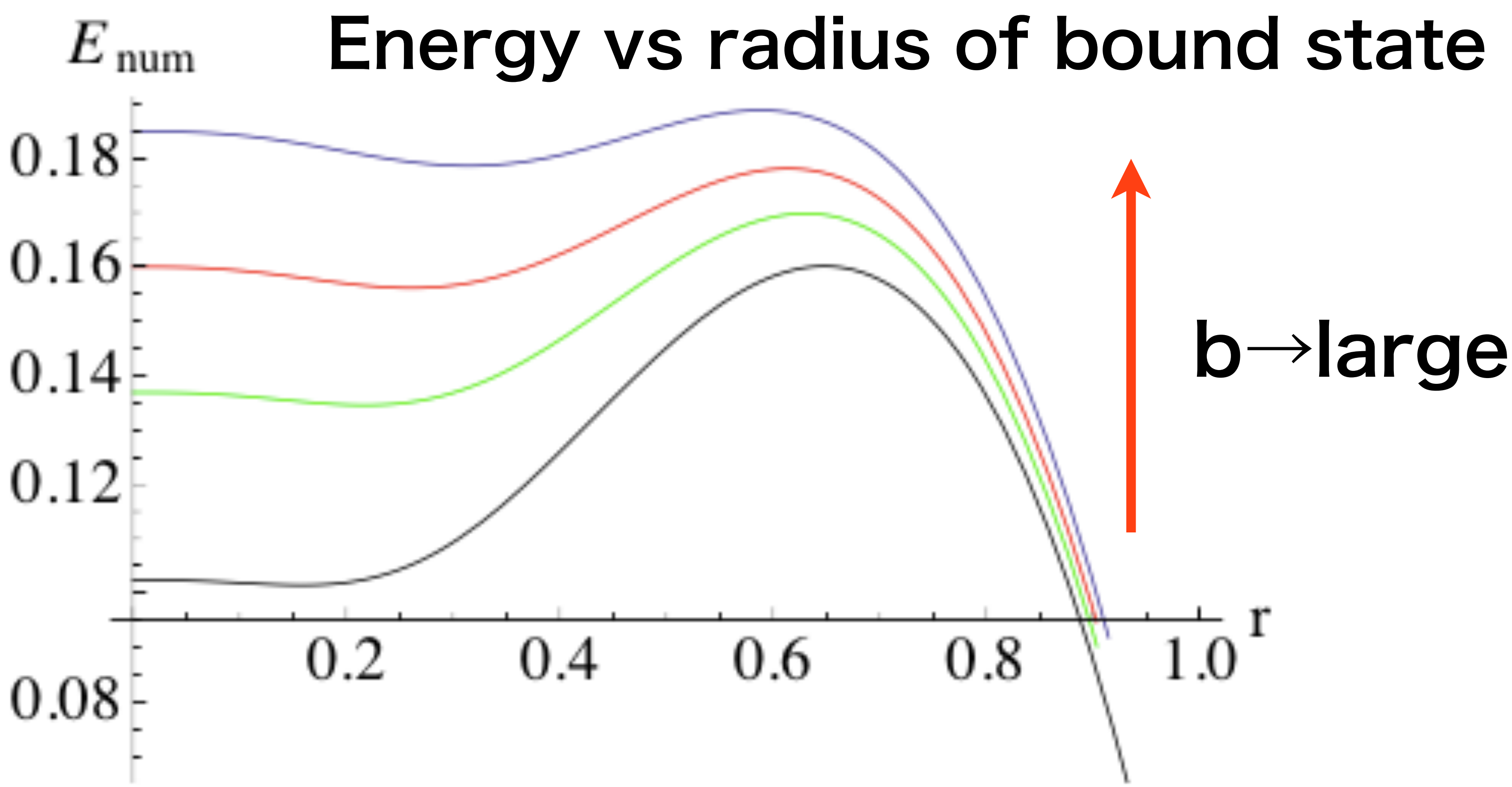
c.f. K. Hashimoto, JHEP 0207, 035 (2002)

winding number of monopole

dimensionless parameters

$$r = \frac{\Delta V}{3T_{DW}}R, \qquad b^4 = \left(\frac{\Delta V}{3T_{DW}}\right)^4 \left(\frac{T_{D3}n_{D3}}{4\pi T_{D5}}\right)^2.$$

Bound state of D3/DWD5



1) When b is large, the bubble is unstable

$$b > \frac{\sqrt{2}}{3} \qquad \text{(unstable).}$$ → bubble expand without bound

2) When b is small, the bubble is metastable

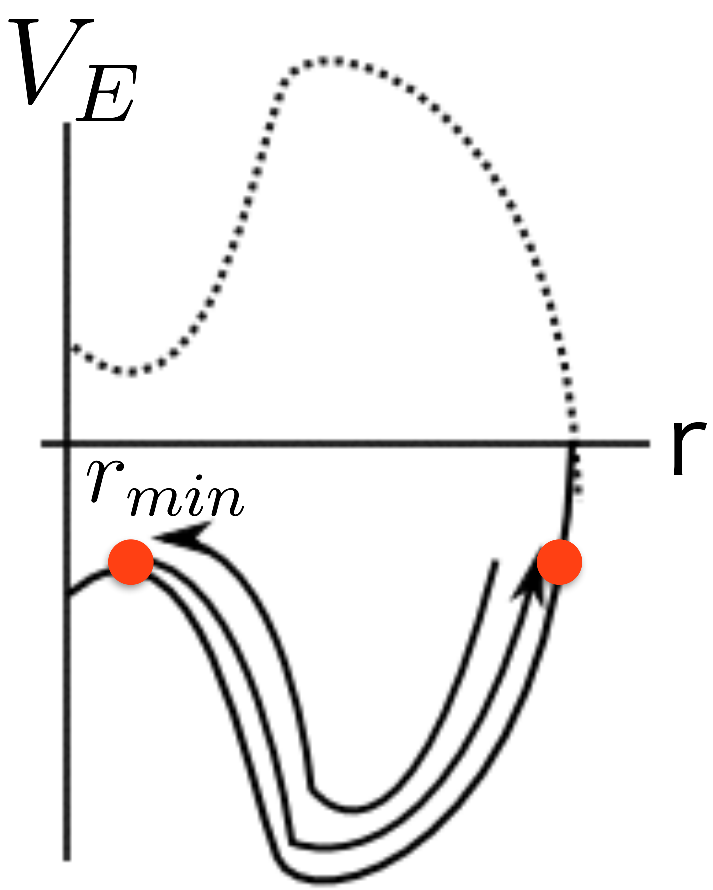
$$r_{\rm min} = \frac{1}{3}\sqrt{2 - \sqrt{4 - 81 b^4}}.$$

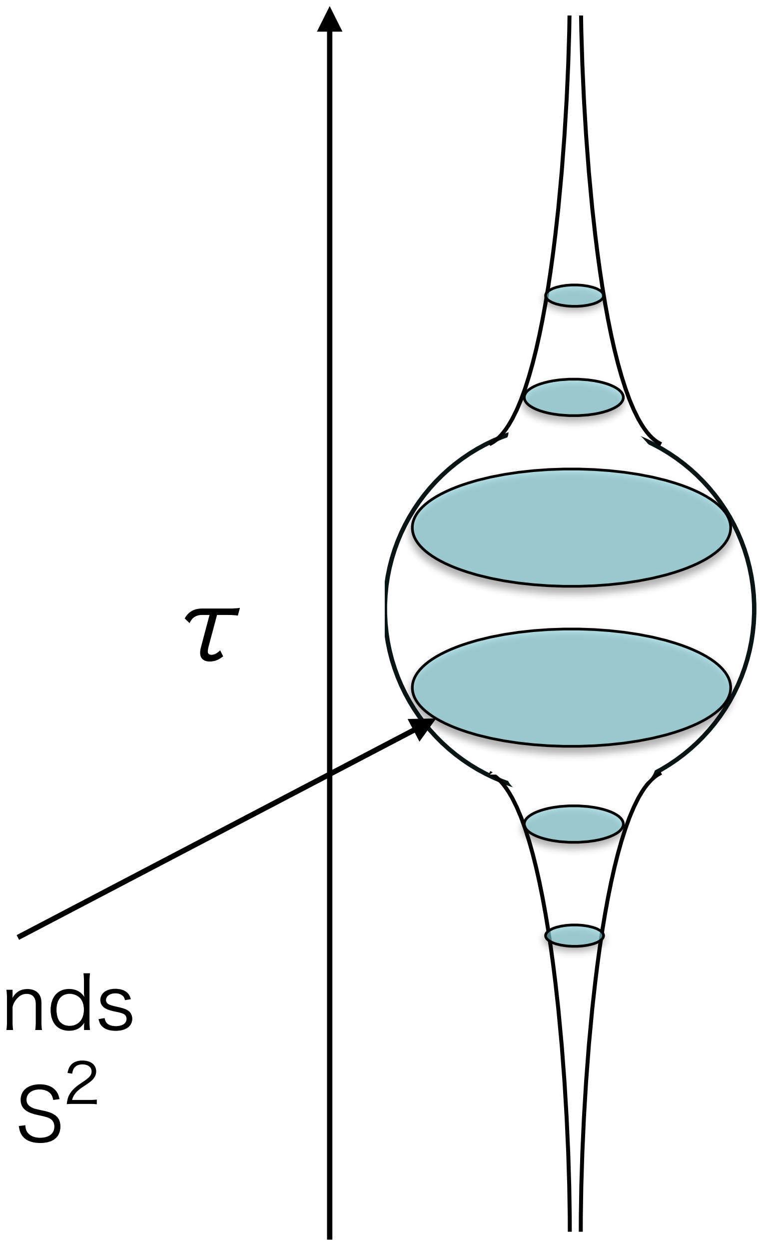
a new dielectric brane supported by true vacuum

Bounce action

bounce solution =a solution of
Euclidean action

S. R. Coleman, Phys. Rev. D 15, 2929 (1977)



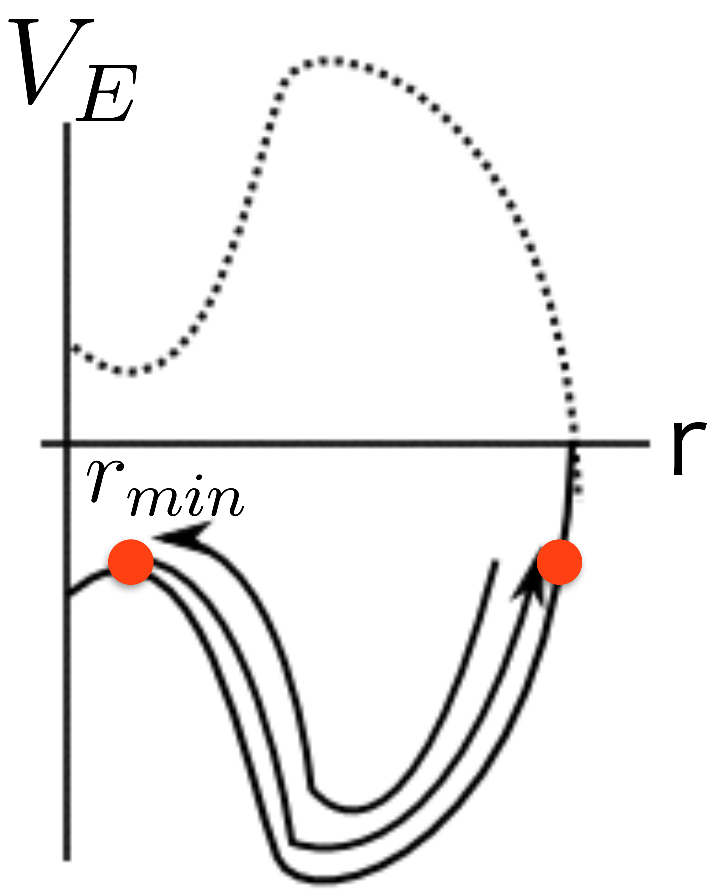


Circle corresponds
to the size of S^2

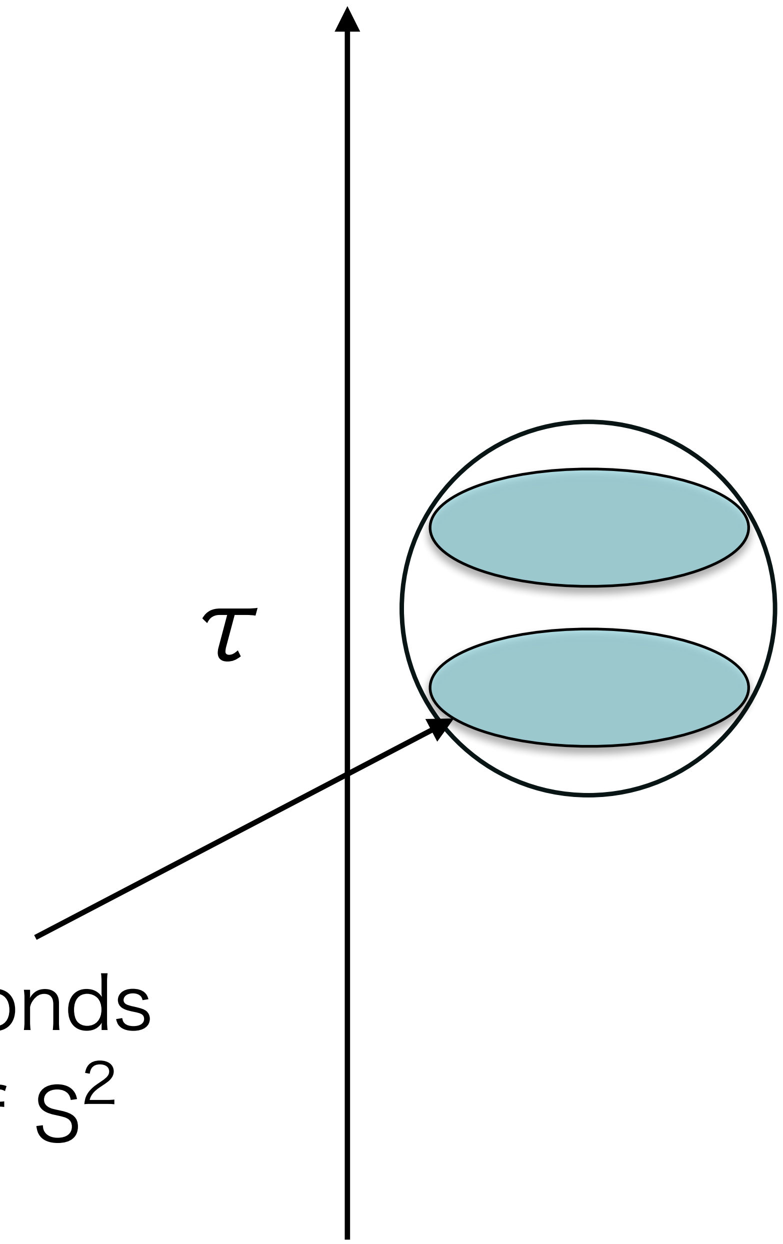
Symmetry of bounce $\left\{ \begin{array}{l} \text{1)without monopole - O(4) sym.} \\ \text{2) with monopole - O(3) sym.} \end{array} \right.$

Bounce action

bounce solution =a solution of Euclidean action



S. R. Coleman, Phys. Rev. D 15, 2929 (1977)

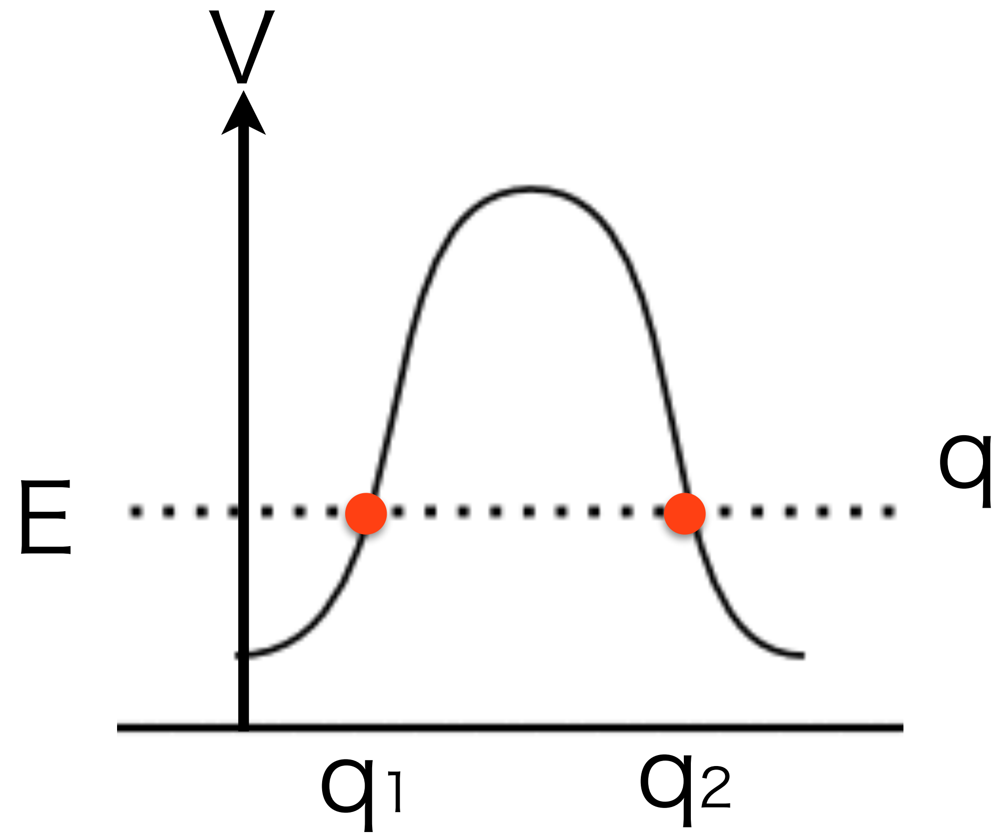


Circle corresponds to the size of S^2

Symmetry of bounce
- 1)without monopole - O(4) sym.
- 2) with monopole - O(3) sym.

Why bounce action?

One-dimensional tunneling



Tunneling rate by WKB approximation

$$\Gamma = \exp\left(-2B/\hbar\right)$$

$$B = 2\int_{q_1}^{q_2} dq\sqrt{2m(V(q)-E)}$$

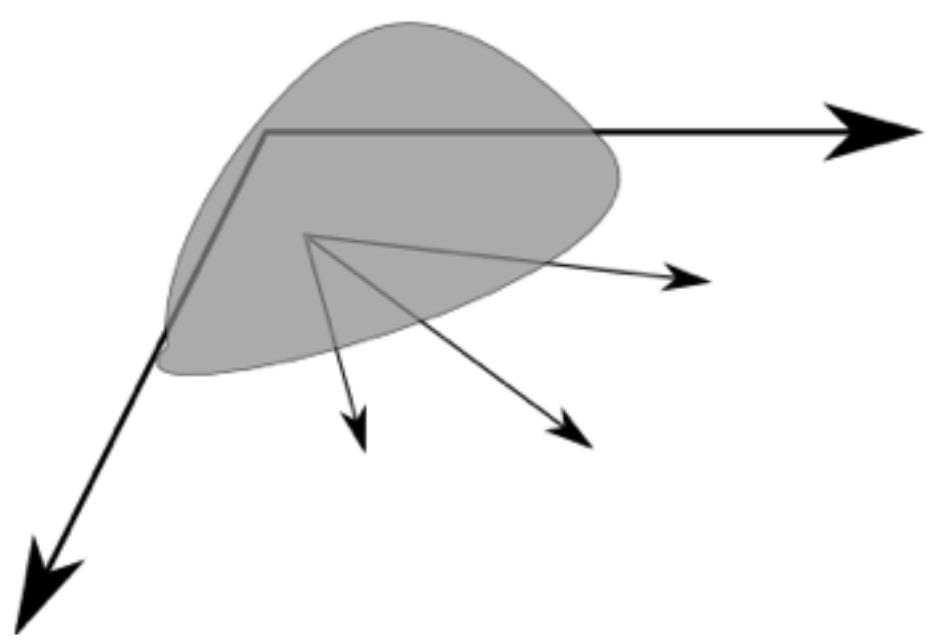
Why bounce action?

Multi-dimensional case, the decay rate depends on the path

$$\Gamma = \exp\left(-2B/\hbar\right)$$ **"q={qi}"**

$$B[\text{path}] = 2\int_0^{s_f} ds \sqrt{2(V(q) - E)}$$

We want to know the path which gives the smallest value of B



the bounce solution gives a nice way to find the path

Why bounce action?

Plugging the solution into Euclidean action we get

$$S_E = \underbrace{\int_{\tau_0}^{\tau_f} ds \sqrt{2[V(q) - E]}}_{\text{Minimized B}} + \int_{\tau_0}^{\tau_f} d\tau E$$

Minimized B

$$B[\mathrm{path}] = 2\int_0^{s_f} ds \sqrt{2(V(q) - E)}$$

by subtracting the second extra term from the bounce action, we get the minimized B

With monopole O(3) symmetric

R. Emparan, Phys. Lett. B423, 71 (1998)

K. Hashimoto, JHEP 0207, 035 (2002)

D. K. Park, S. Tamarian and H. J. W. Muller-Kirsten, JHEP 0205, 009 (2002)

Spherical ansatz for bubble

$$X^0 = t, \quad X^1 = R(t)\sin\theta\cos\varphi, \quad X^2 = R(t)\sin\theta\sin\varphi, \quad X^3 = R(t)\cos\theta.$$

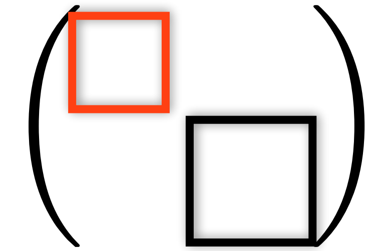
Dissolving monopole leaves magnetic field on DWD5 brane

$$B\sin\theta \equiv 2\pi\alpha' F_{\theta\varphi}$$

The action of the bound state is

$$S = -T_{D5}\int d^6\xi\sqrt{-\det(\partial_\alpha X^\mu \partial_\beta X_\mu + 2\pi F_{\alpha\beta})} + \int dt \frac{4\pi}{3}R^3\Delta V$$

With monopole O(3) symmetric

det is given by Minkowski and internal parts 

$$
\begin{aligned}
-\det(\partial_\alpha X^\mu \partial_\beta X_\mu + 2\pi\alpha' F_{\alpha\beta}) &= -\det(\partial_a X^\mu \partial_b X_\mu + 2\pi\alpha' F_{\alpha\beta}) \cdot \det(\partial_A X^I \partial_B X_I) \\
&= \left[(1-\dot{R}^2)R^4 + B^2(1-\dot{R}^2)\right] \cdot \det(\partial_A X^I \partial_B X_I),
\end{aligned}
$$

With monopole O(3) symmetric

$$
\begin{aligned}
-\det(\partial_\alpha X^\mu \partial_\beta X_\mu + 2\pi\alpha' F_{\alpha\beta}) &= -\det(\partial_a X^\mu \partial_b X_\mu + 2\pi\alpha' F_{\alpha\beta}) \cdot \det(\partial_A X^I \partial_B X_I) \\
&= \left[(1-\dot{R}^2)R^4 + B^2(1-\dot{R}^2)\right] \cdot \det(\partial_A X^I \partial_B X_I),
\end{aligned}
$$

$$
= -\int dt \left[4\pi T_{D5} V_3 \sqrt{(1-\dot{R}^2)R^4 + B^2(1-\dot{R}^2)} - \frac{4\pi}{3} R^3 \Delta V\right]
$$

$$
\boxed{\begin{gathered} V_3 = \int d^3\xi^A \sqrt{\det(\partial_A X^I \partial_B X_I)}. \\ T_{DW} = T_{D5} V_3 \end{gathered}}
$$

Now let's estimate the decay rate

With monopole O(3) symmetric

Introduce the dimension less variable

$$r = \frac{\Delta V}{3T_{DW}} R, \qquad b^4 = \left(\frac{\Delta V}{3T_{DW}}\right)^4 \left(\frac{T_{D3} n_{D3}}{4\pi T_{D5}}\right)^2 . \qquad s = \frac{\Delta V}{3T_{DW}} \tau .$$

Eucledianize the action

Factor out $B_{O(4)}$ for comparison

$$S_E = \left(\frac{27\pi^2 T_{DW}^4}{2\Delta V^3}\right) \frac{8}{\pi} \left[\int ds \left(\sqrt{(r^4 + b^4)(1 + \dot{r}^2)} - r^3 \right) \right]$$

$$\equiv B_{O(4)} \frac{8}{\pi} S_{\rm num}^{O(3)}$$

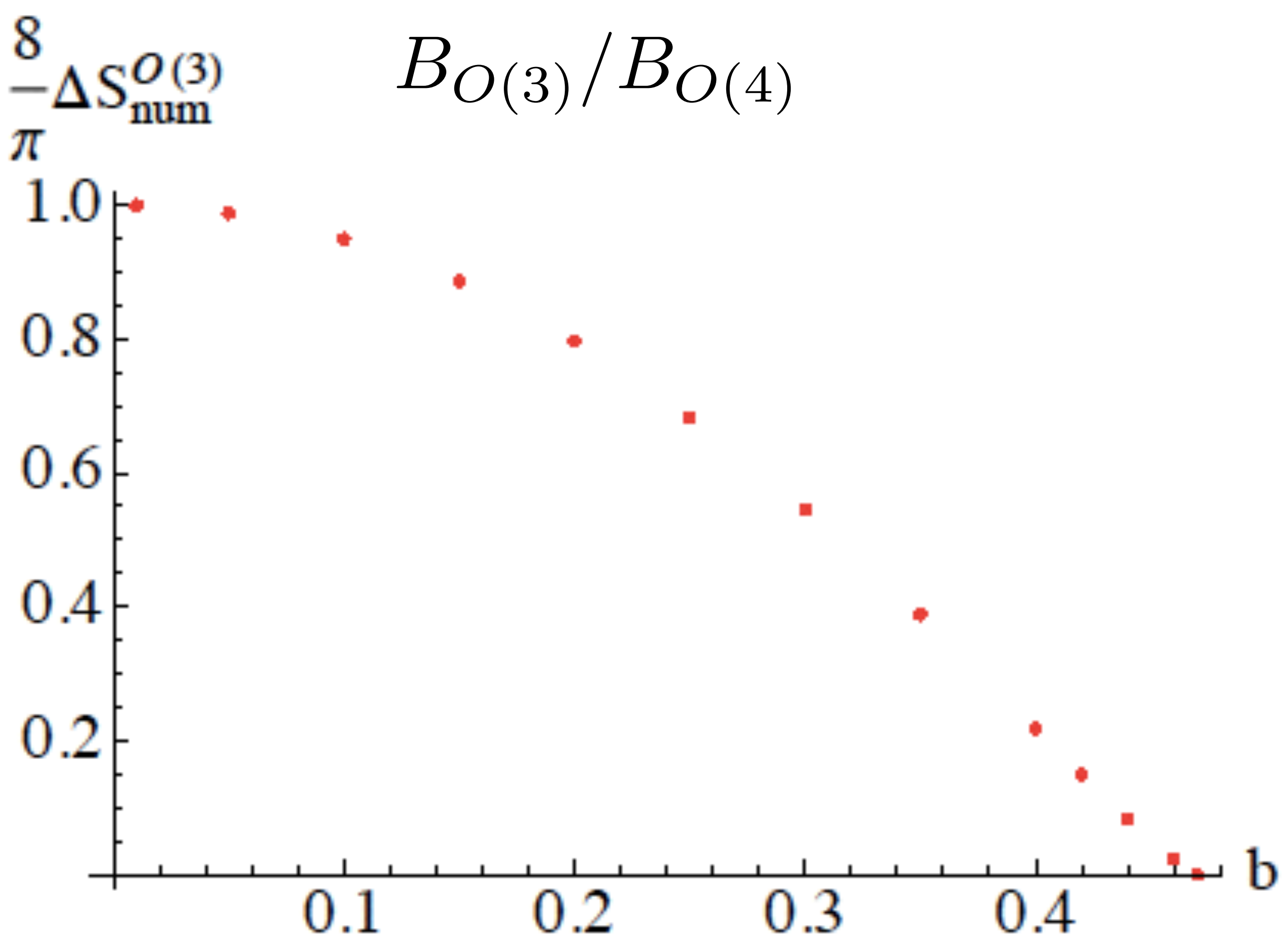
So the decay rate is

$$B_{O(3)} = B_{O(4)} \frac{8}{\pi} \left[S_{\rm num}^{O(3)}(r_{\rm bounce}) - S_{\rm num}^{O(3)}(r_{\rm min}) \right] = B_{O(4)} \boxed{\frac{8}{\pi} \Delta S_{\rm num}^{O(3)}}$$

With monopole O(3) symmetric

Numerical results

$B_{O(3)}/B_{O(4)}$



$b \neq 0$ smaller than 1

$\rightarrow \; B_{O(3)} < B_{O(4)}$

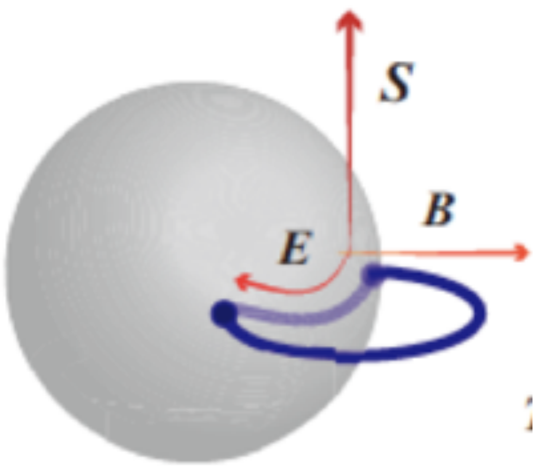
$\rightarrow \; \Gamma_{O(3)} > \Gamma_{O(4)}$

By the monopole, the life-time of the false vacuum becomes drastically shorter

Topology change of bubble

Adding F1-string to the bubble induces a topology change

cf Nishioka, Takayanagi JHEP 0810(2008)082



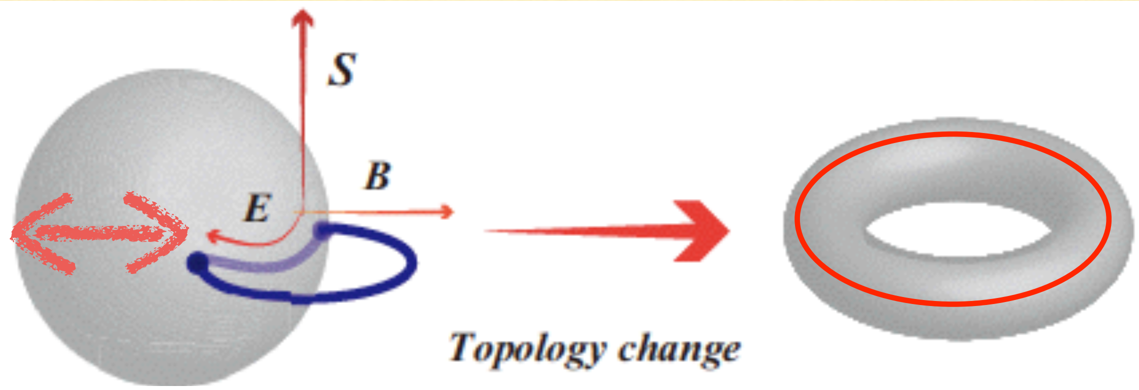
Dissolving F1 string induces an electric field

$$E_\theta = 2\pi\alpha' F_{t,\theta}$$

Pointing vector generates angular momentum and the action of spherical anzats becomes ill-defined

→ indication of topology change

Before/After Topology Change



$$R_{\rm monopole} = \frac{3T_{\rm DW}}{\Delta V} r_{\rm min}. \qquad l \equiv \frac{L}{R_{\rm monopole}}.$$

Compare the bounce with the one with less-symmetry

$$B_{O(2)} = B_{O(3)} \frac{2r_{\rm min}\Delta S_{\rm num}^{O(2)}}{9\Delta S_{\rm num}^{O(3)}}$$

$$l > \frac{9\Delta S_{\rm num}^{O(3)}}{2r_{\rm min}\Delta S_{\rm num}^{O(2)}} \sim \mathcal{O}(1)$$

In typical parameter choice, bubble has longer life-time

Dissolved F1 string makes the life-time of the bubble longer

Warped geometry and Catalysis

Warping without impurity

$$ds^2 = e^{2A(y)} g_{\mu\nu} dx^\mu dx^\nu + e^{-2A(y)} g_{mn} dy^m dy^n. \qquad \boxed{e^{2A} \ll 1,}$$

For simplicity, we assume that the warp factor is almost constant

Volume of internal space and tension and energy gap are

$$V^{\mathrm{warp}} = V(e^{-2A})^{3/2}, \qquad T_{\mathrm{DW}}^{\mathrm{warp}} = T_{D5} V^{\mathrm{warp}} e^{3A} \qquad \Delta V^{\mathrm{warp}} = \Delta V e^{4A}$$

$$\boxed{B_{O(4)} = \frac{27\pi^2}{2} \frac{T_{\mathrm{DW}}^4}{(\Delta V)^3}. \qquad \to \qquad B_{O(4)}^{\mathrm{warp}} = B_{O(4)} e^{-12A}}$$

Without monopole, the warping makes the life-time of the false vacuum much longer

Warped geometry and Catalysis

Warping with an impurity

DBI action for the bound state is modified as follows

$$-T_{DW}^{\mathrm{warp}} \int d^3\xi \sqrt{-\det(\partial_\alpha X^\mu \partial_\beta X_\mu) + e^{-4A} B^2}$$

We use the formula shown before by simply replacing

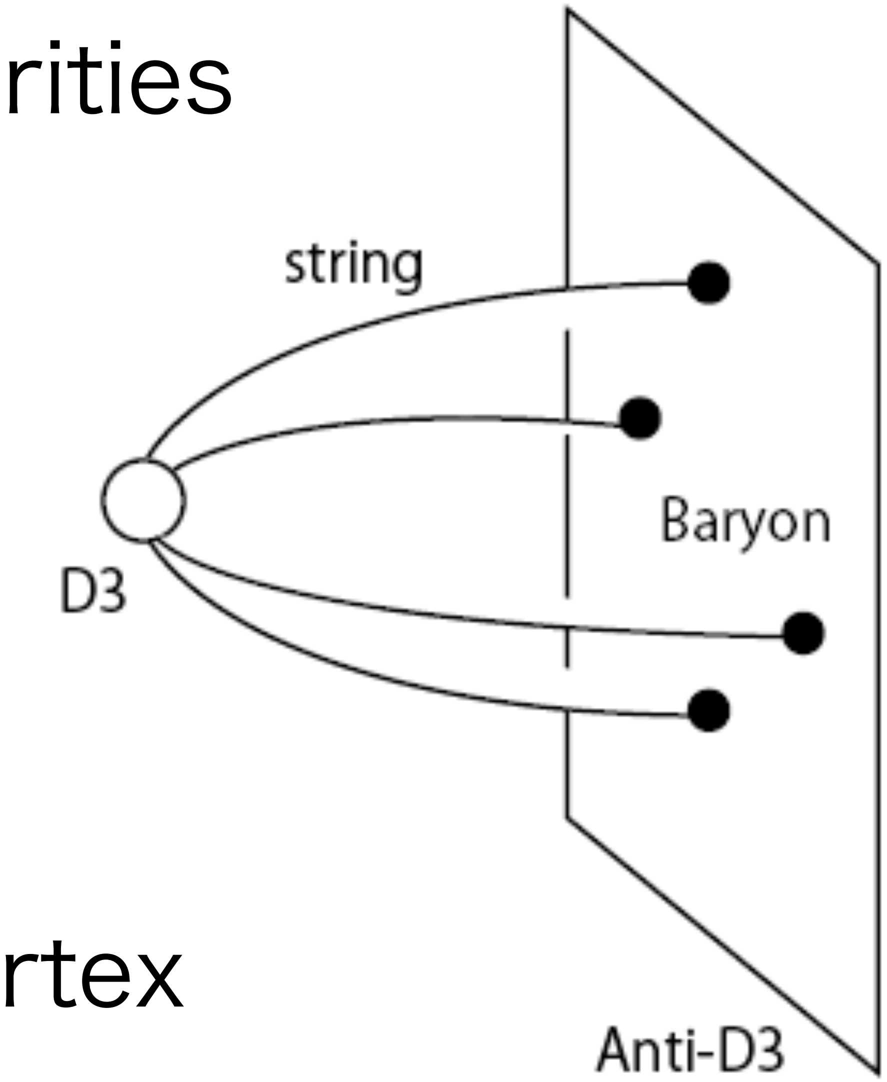
$$T_{DW} \to T_{DW}^{\mathrm{warp}}, \quad B^2 \to B^2 e^{-4A}$$

unstable condition $\quad e^{-2A} b > \frac{\sqrt{2}}{3} \quad \text{(unstable)}$

With an impurity, the warping effect makes the life-time much shorter!

Baryon as an impurity

So far, we studied solitons as impurities



In flux compactification, the baryon can be seed for the effect

2) Aya Kasai, Yuichiro Nakai, Y. O. arXiv:1508.04608 [hep-th]

D3-brane with RR-flux =Baryon vertex

We showed that baryon can catalyze the brane/flux annihilation

Stability in KKLT

In progress

1. Catalysis by baryon
2. Warping, together with the catalysis,
   drastically shorten the life-time

If we naively apply these results to KKLT model, the successful de Sitter vacua becomes unstable!

Summary

Claim 1) Vacuum instability by catalysis plays crucial role in string landscape

Claim 2) Bubble can be a giant monopole

Claim 3) Topology of a bubble is not necessarily sphere

Summary

Claim 4) The warp factor, together with the catalysis, drastically shorten the life-time

Claim 5) Baryon can be a seed for catalysis

Claim 6) KKLT de Sitter vacuum may be unstable

Claim 7) In estimating the life-time of vacua, the shape of the potential is not enough information

Claim 8) In discussing the attractor point in string landscape, the catalysis can play important role.