

# Cobordism Conjecture and new objects in string theory

Based on 2205.09782 and 2208.01656 with R. Blumenhagen, N. Cribiori, C. Kneißl

Andriana Makridou

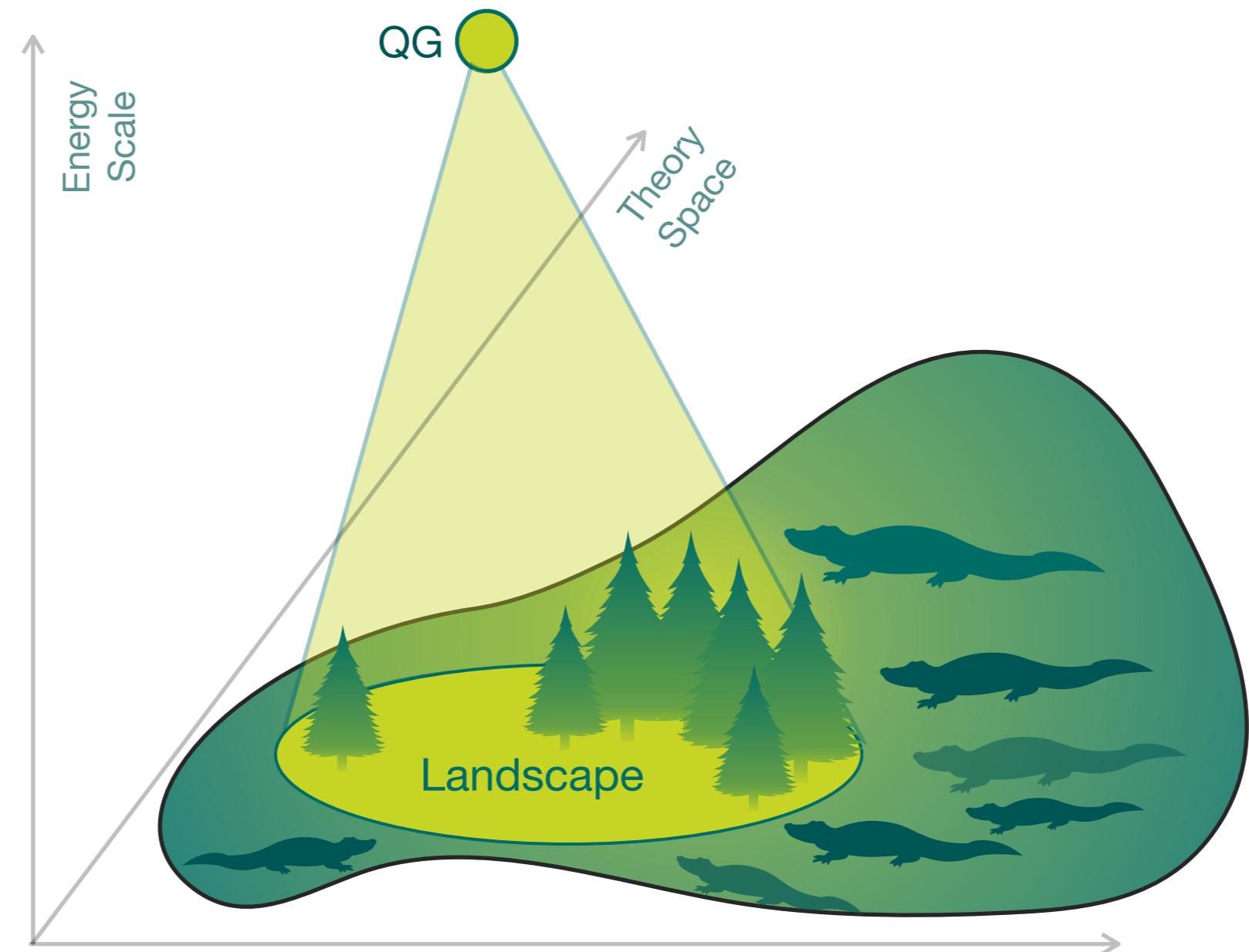
Xmas Theoretical Physics Workshop @Athens 2022

December 21st, 2022

# The Swampland Program

[Reviews: 1903.06239, 2102.01111, 2212.06187]

Idea: Not all consistent-looking low-energy EFTs can be UV-completed to Quantum Gravity

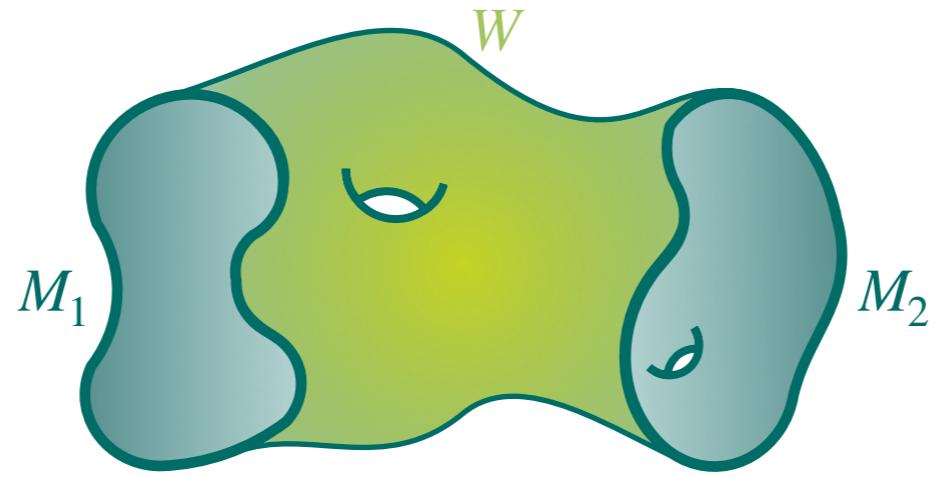


Goal: Differentiate Landscape from Swampland - via Swampland Conjectures

# Outline

- Cobordism and the Cobordism Conjecture
- Gauging Cobordism charges: Background fixing and Tadpole conditions
- Breaking Cobordism charges: Dynamical Cobordism and a new 8d defect

# Cobordism

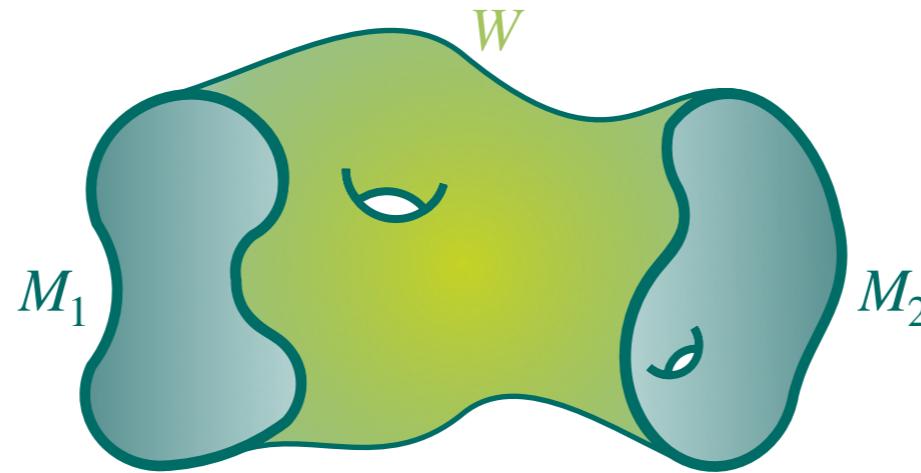


$$M_1 \sim M_2 \Leftrightarrow \exists W \text{ s.t. } \partial W = M_1 \sqcup M_2$$

$$\Omega_k^\xi = \{\text{compact, closed, } k\text{-dimensional manifolds}\} / \sim$$

Allowed topology  
changes  
(Encoded in  $\xi$ )

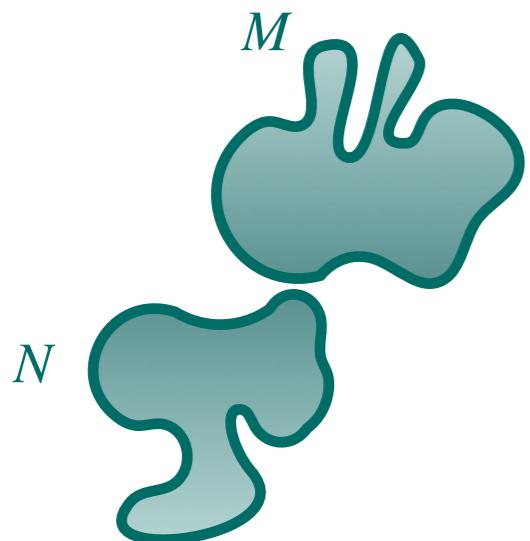
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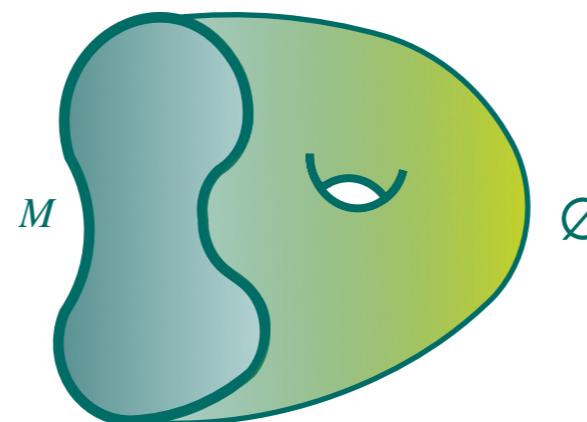
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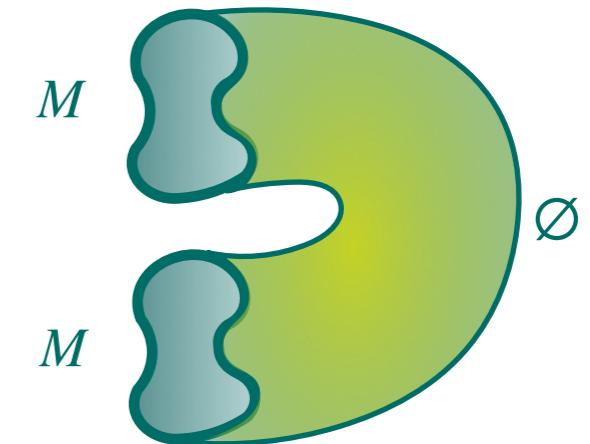
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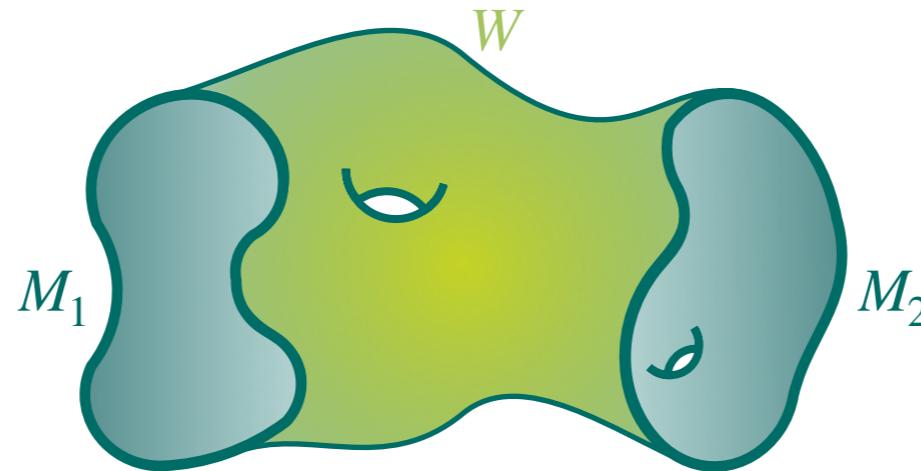


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$$[M] + [M] = [M \sqcup M] = 0$$

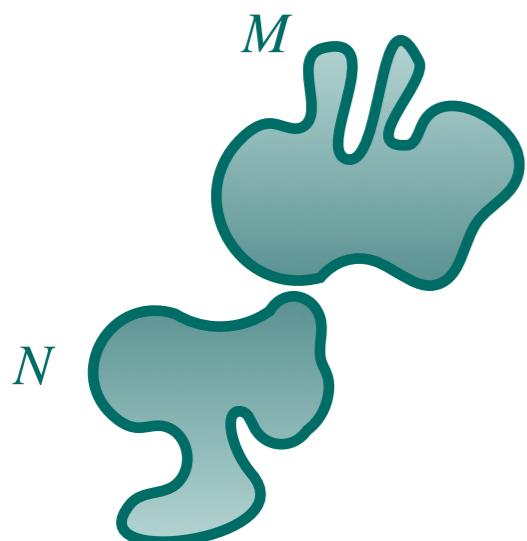
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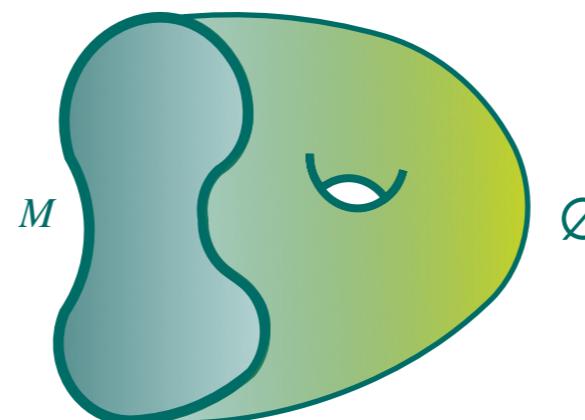
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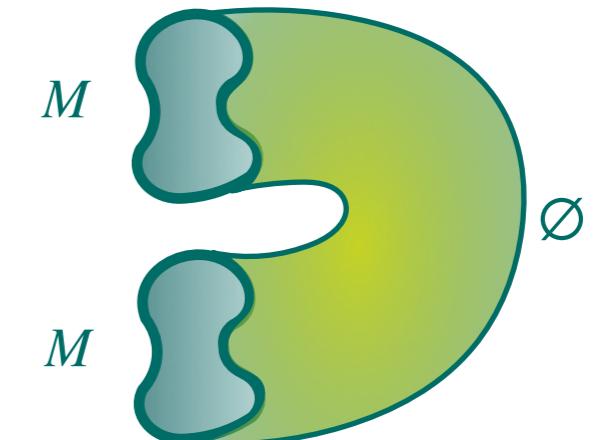
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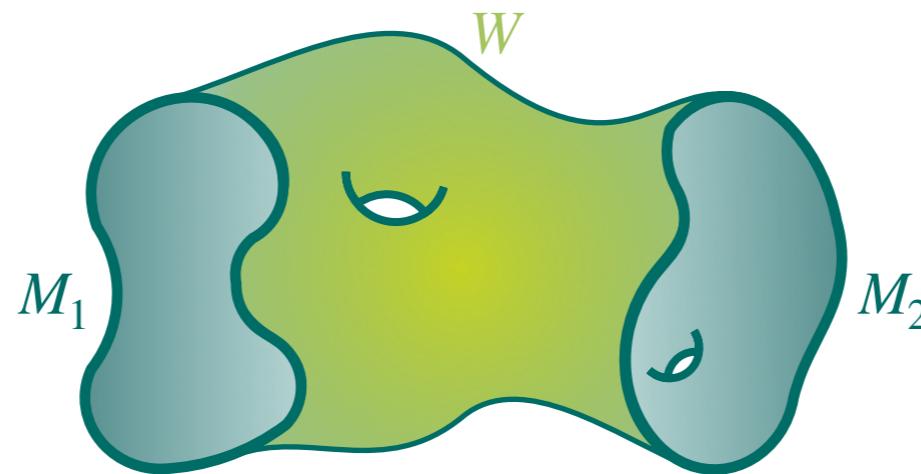
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For oriented manifolds:  $[M] + [\bar{M}] = 0, [M] + [N] = [M \sqcup \bar{N}]$

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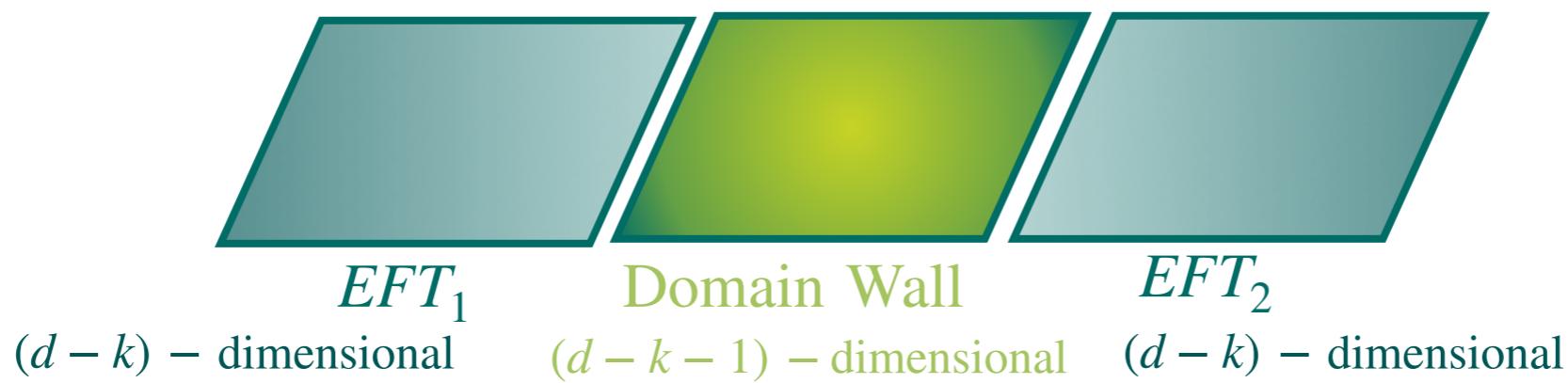


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Compactify  $d$ -dimensional theory on  $M^k$  down to  $D=d-k$  dimensions:



→ *Finite-energy transition between EFTs*

→ *Domain walls detected by cobordism can be well-known objects, e.g. D-branes*

# Cobordism Conjecture

Cobordism Group  $\Omega_k^\xi \leftrightarrow$  Cobordism Invariant  $\mu_k$

For empty set:  $\mu_k[\emptyset] = 0$

If cobordism class  $[M] \neq 0 \leftrightarrow$  obstruction to decay into “nothing”

$\Omega_k^\xi \neq 0 \Leftrightarrow$   $(d - k - 1)$ -dim. global symmetry  
with charges labelled by classes  $[M] \in \Omega_k^\xi$

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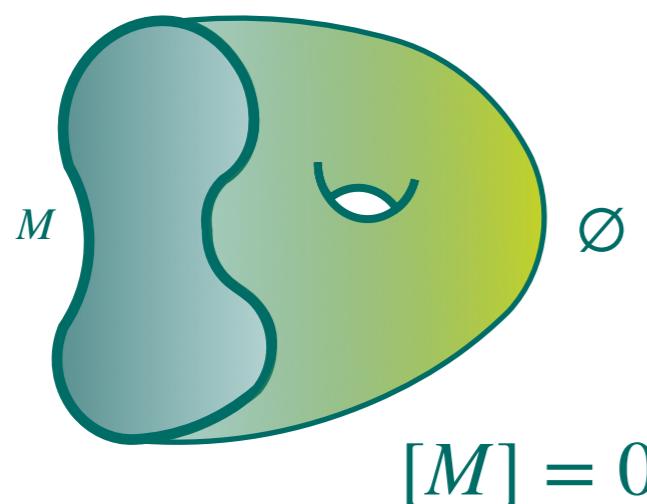
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But: No global symmetries in quantum gravity  $\rightarrow$  Cobordism Conjecture  
e.g. [ Banks, Seiberg '10]



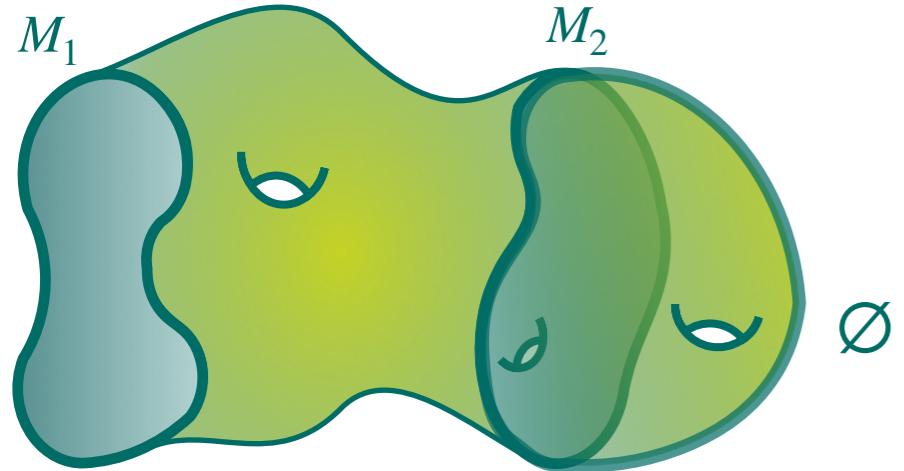
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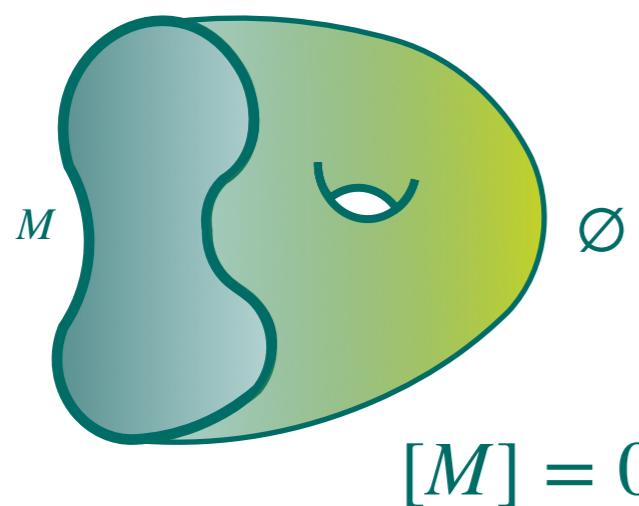


In  $D=d-k$  dimensions:



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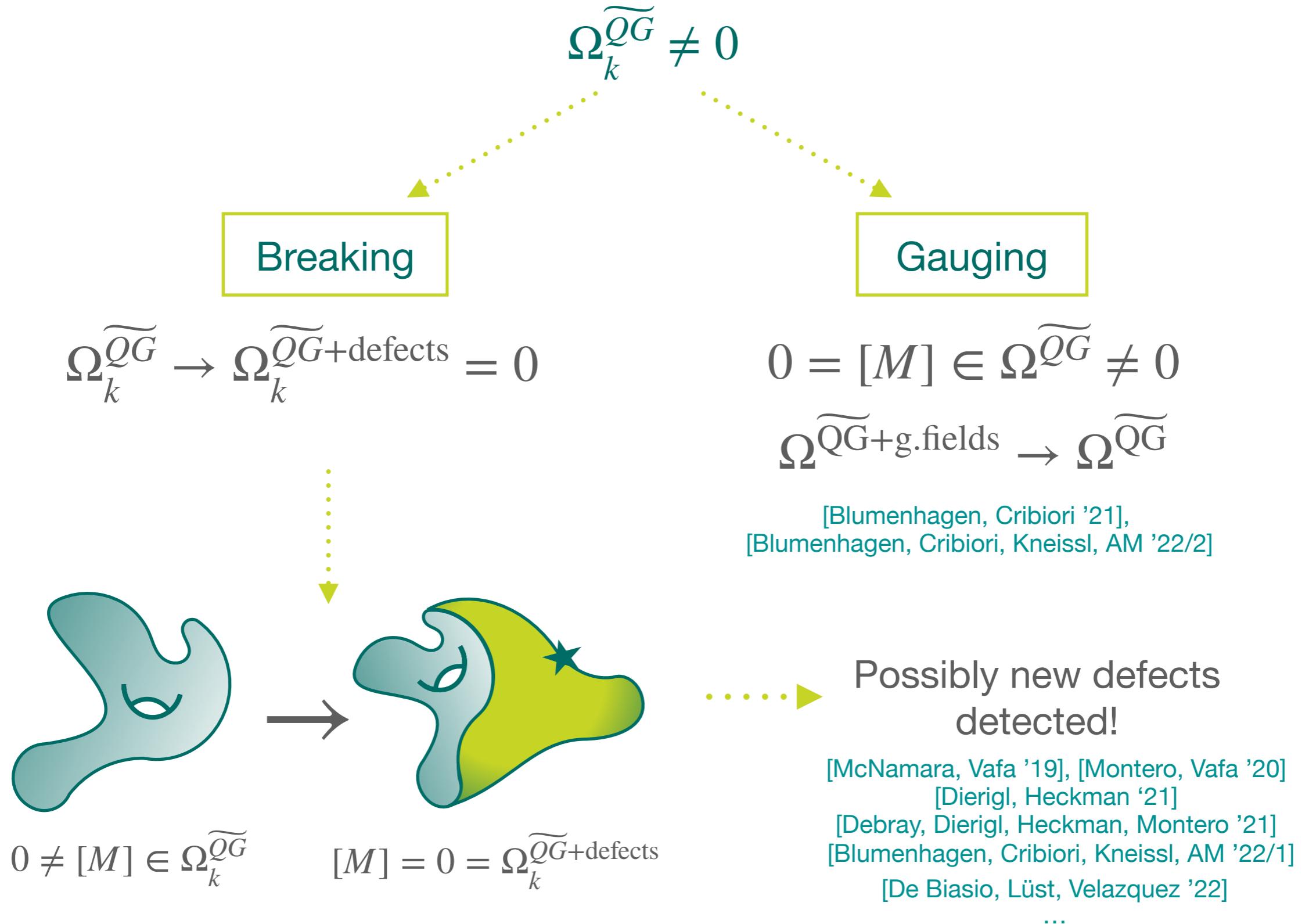
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# Cobordism Conjecture Consequences



# Cobordism and String Theory

What are the relevant structures for String Theory? Type I  $\leftrightarrow \xi = \text{Spin}$ , Type II  $\leftrightarrow \xi = \text{Spin}^c$

[see also Andriot, Carqueville, Cribiori]

$n$	0	1	2	3	4	5	6	7	8	9	10
$\Omega_n^{\text{Spin}}$	$\mathbb{Z}$	$\mathbb{Z}_2$	$\mathbb{Z}_2$	0	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	$2\mathbb{Z}_2$	$3\mathbb{Z}_2$
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→ Type I, II brane classification [Witten '98]

Not an accident! → Atiyah-Bott-Shapiro orientation  $\alpha^c : \Omega_*^{\text{Spin}^c}(pt) \rightarrow K_*(pt)$ .

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For fixed  $k$ , i.e.  $[M] \in \Omega_k^{\text{Spin}^c}$ , we have  $\alpha^c([M]) = Td([M])$ .

$\alpha^c$ : cobordism invariant, surjective  $\rightarrow \Omega_n^{\text{Spin}^c}/\ker(\alpha^c) \cong K^{-n}$ .

# Gauging Cobordism Charges

[Blumenhagen, Cribiori '21]

K-theory charges are gauged [Freed '00]

Gauged symmetries accompanied by tadpole conditions:  $0 = \int_M dF_{n-1} = \int_M J_n$

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In practice: add K-theory + cobordism contributions

$$0 = \int_M dF_{n-1} = \sum_{j \in \text{def}} \int_M Q_j \delta^{(n)}(\Delta_{10-n,j}) + \sum_{i \in \text{inv}} a_i \mu_{n,i}$$

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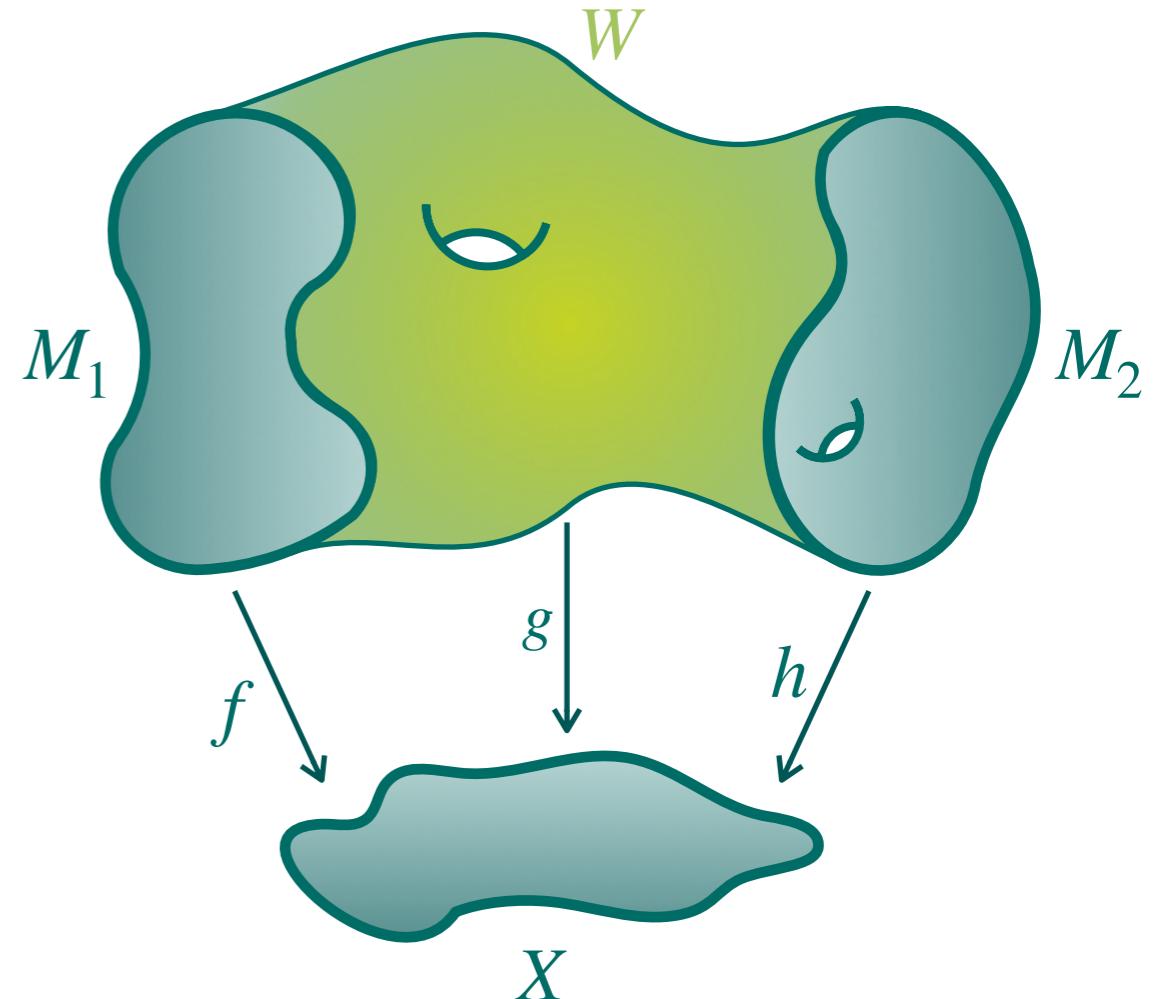
This procedure reproduces known string theory tadpoles!

# Background fixing

$\Omega_k^\xi(X)$  : cobordism groups relative to manifold  $X$

For  $X = pt$  :  $\Omega_k^\xi(pt) \equiv \Omega_k^\xi$ .

In general:  $\Omega_k^\xi(X) = \Omega_k^\xi(pt) \oplus \tilde{\Omega}_k^\xi(X)$ .



→ How does the cobordism conjecture generalise upon fixing the background?

[Blumenhagen, Cribiori, Kneissl, AM '22/1]

Cobordism Conjecture Refinement:  $\Omega_k^{QG}(X) = 0$

→ Need to compute  $\Omega(X), K(X) \rightarrow$  Atiyah-Hirzebruch Spectral Sequence

# K-theory general results

We compute for  $X = \{S^k, T^k, K3, CY_3\}$ , with  $k = \dim(X)$ ,  $n \geq 0$ :

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$K^{-n}(X)$ : (BPS) D-branes of codimension n in flat space  $\mathbb{R}^{1,d-k-1}$

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## Extra info:

No Freed-Witten anomaly in appearing branes

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Reminder: Cobordism group of  $X$  related to continuous map  $f: M \rightarrow X$ ,  $M$  ( $n+k$ )-dim.

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**Relation to K-theory:**

$n \geq 0 : \Omega_{n+k}^{\text{Spin}^c}(X)$  related to  $K_{n+k}(X) \cong K^{-n}(X)$

$-k \leq n < 0 : \Omega_{n+k}^{\text{Spin}^c}(X)$  has no *physical* K-theory counterpart.

# Example: IIB on Calabi-Yau $CY_3 = X$

$$\begin{aligned} K^0(X) &= b_6 K^0(pt) \oplus b_4 K^{-2}(pt) \oplus b_2 K^{-4}(pt) \oplus b_0 K^{-6}(pt) \\ &= b_6 \mathbb{Z} \oplus b_4 \mathbb{Z} \oplus b_2 \mathbb{Z} \oplus b_0 \mathbb{Z} \end{aligned}$$

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All branes of codimension 0 in  $\mathbb{R}^{1,3}$  and wrapping:

entire  $CY_3 \rightarrow$  D9-branes     $b_4$  4-cycles  $\rightarrow$  D7-branes     $b_2$  2-cycles  $\rightarrow$  D5-branes

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$(b_6 + b_4 + 2b_2 + 2b_0) = (3b_2 + 3)$ -dim. lattice of  $\mathbb{Z}$ -valued 3-form global charges

# Plugging everything together: tadpoles

Example -  $n = 0$ :

$$K^0(pt) = \mathbb{Z} \quad \text{and} \quad \Omega_0^{\text{Spin}^c}(pt) = \mathbb{Z}$$

9-form symmetry gauged  
by D9-branes

global 3-form symmetry in 4d  
magnetic current:  $\tilde{J}_0(M_6) = td(M_6) = 1$

$$N\delta^{(0)}(M_6) + a^{(1)}td_0(M_6) = 0$$

For  $a^{(1)} = 0, -32$  : Type I/IIB D9-tadpole cancellation condition

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→ Can also reproduce:

F-theory D7-brane cancellation condition

Type I on  $K3 \times T^2$  D5 tadpole cancellation condition

Type IIB orientifold with O5 cancellation condition

F-theory D3-brane cancellation condition

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Cobordism       $\Omega_4^{\text{Spin}^c}(X) = b_4 \Omega_0^{\text{Spin}^c}(pt) \oplus b_2 \Omega_2^{\text{Spin}^c}(pt) \oplus \Omega_4^{\text{Spin}^c}(pt)$

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*Not a priori irrelevant!*

Proposed resolution, for  $X = CY_3$  and  $n \leq 6$ :

For  $\Omega_n^{\text{Spin}^c}(X)$ ,  $n$  odd  $\rightarrow$  breaking of symmetry necessary

For  $\Omega_n^{\text{Spin}^c}(X)$ ,  $n$  even  $\rightarrow$  gauging possible, new contributions to known tadpoles

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# A systematic view

$$\Omega_6^{\text{Spin}^c}(X) = b_6 \Omega_0^{\text{Spin}^c}(pt) \oplus b_4 \Omega_2^{\text{Spin}^c}(pt) \oplus b_2 \Omega_4^{\text{Spin}^c}(pt) \oplus b_0 \Omega_6^{\text{Spin}^c}(pt)$$

O9 contribution to  $F(CY_4)_{c_1(M_6)}$  contr. to  $\mathcal{C}_{10}$  - tadpole

$F(CY_4)_{c_1(M_6)}$  contr. to  $\mathcal{C}_8$  - tadpole

$tr(R \wedge R)_{D9,O9}$  contr. to  $\mathcal{C}_6$  - tadpole

$F(CY_4)_{c_1 c_2, c_1^3}$  contr. to  $\mathcal{C}_4$  - tadpole

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$$tr(R \wedge R)_{D9,O9} \text{ contr.}$$
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 $C_{10}$  - tadpole      to  $C_8$  - tadpole      to  $C_6$  - tadpole      to  $C_4$  - tadpole

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O7 contribution to $C_8$ - tadpole	$N7_{c_1(M_4)}$ contr. to $C_6$ - tadpole	$tr(R \wedge R)_{D7,O7}$ contr. to $C_4$ - tadpole
---------------------------------------	--	---

$$\Omega_2^{\text{Spin}^c}(X) = b_2 \Omega_0^{\text{Spin}^c}(pt) \oplus b_0 \Omega_2^{\text{Spin}^c}(pt)$$

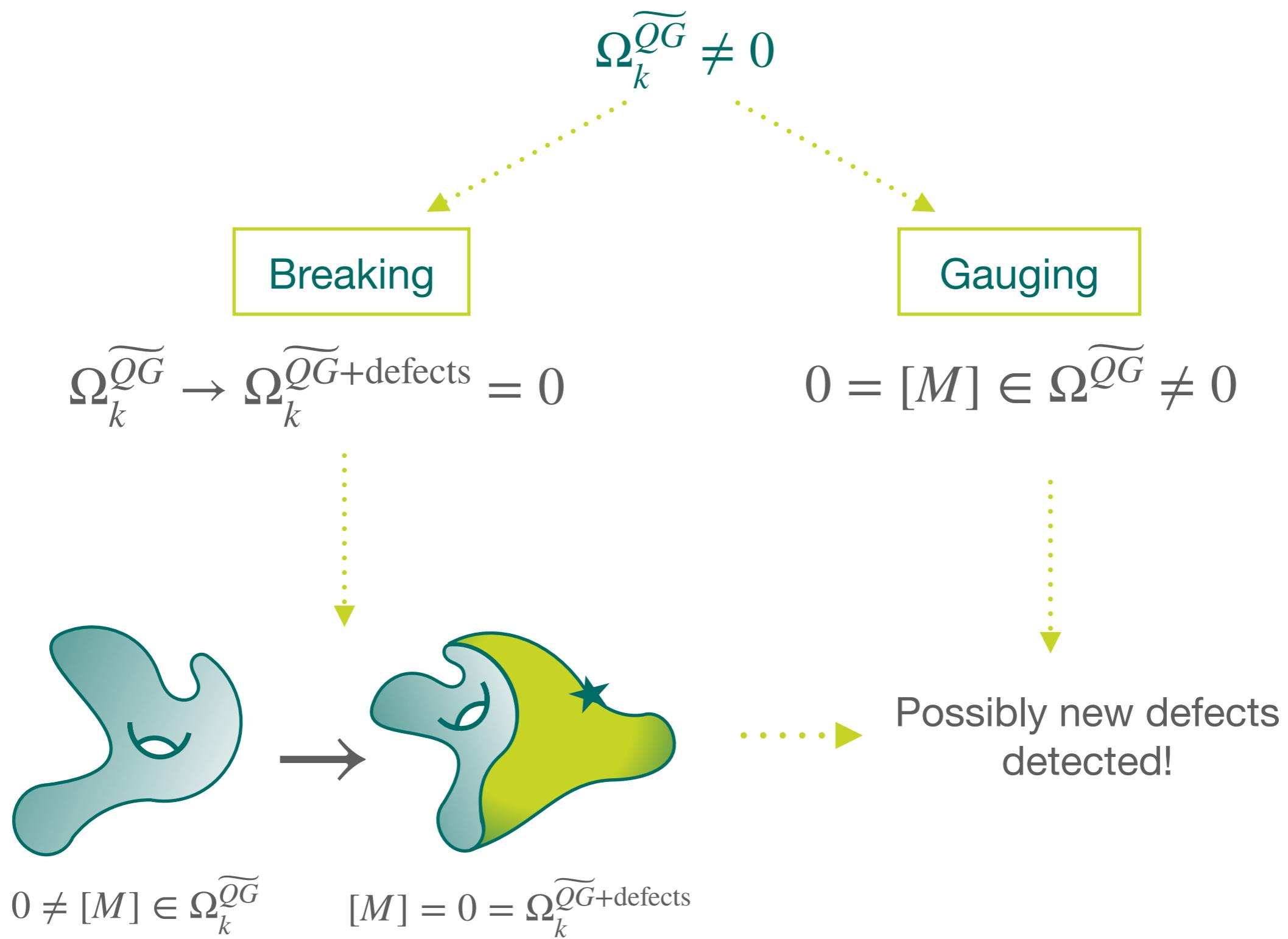
O5 contribution to  $N5_{c_1(M_2)}$  contr. to  
 $C_6$  - tadpole  $C_4$  - tadpole

$$\Omega_2^{\text{Spin}^c}(X) = b_0 \Omega_0^{\text{Spin}^c}(pt)$$

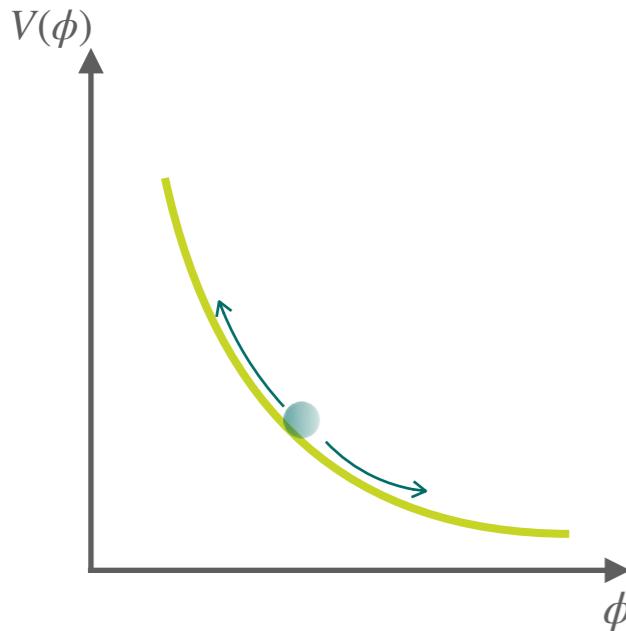
O5 contribution to  
 $C_4$  - tadpole

$N7_{c_1(M_4)}$ ,  $N5_{c_1(M_2)}$  possible new contributions!

# Cobordism Conjecture Consequences



# Tadpoles & Dynamical Cobordism



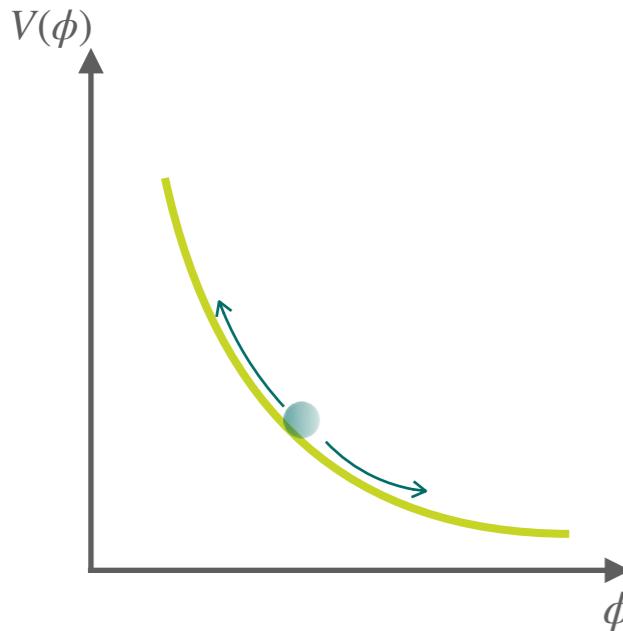
Dynamical tadpoles (vs RR tadpoles)

Naturally occurring in supersymmetry-breaking potentials

Indicate lack of maximally-symmetric vacuum

[Sugimoto '99]  
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## Reinterpretation in Cobordism Terms

[ Buratti, Delgado, Uranga '21]

[ Buratti, Calderon-Infante, Delgado, Uranga '21]

[ Angius, Calderon-Infante, Delgado, Huertas, Uranga '22]

[ Angius, Delgado, Uranga '22]

Solution extends in finite spacetime distance  $\Delta$ , with  $\Delta \sim \mathcal{T}^{-n}$

Mechanism: “apparent singularity” = cobordism defect.

 Tadpole

For field distance  $D \rightarrow \infty$  at singularity: Wall of Nothing/End-of-the-world brane

Cobordism distance conjecture:  $\Delta \sim e^{-\frac{1}{2}\delta D}$ ,  $|\mathcal{R}| \sim e^{\delta D}$

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**Goal:** Backreaction of gauge neutral, non-supersymmetric 9-dimensional object w/  
brane-like dilaton coupling

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**Physical realisation:** non-BPS  $\widehat{D8}$ -brane, non-SUSY stack of  $16 \times \bar{D}8 + O8^{++}$

**Action:** 
$$S = \frac{1}{2\kappa_{10}^2} \int d^{10}x \sqrt{-G} \left( \mathcal{R} - \frac{1}{2}(\partial\Phi)^2 \right) - T \int d^{10} \sqrt{-g} e^{\frac{5}{4}\Phi} \delta(r).$$

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**Solution Ansatz:**  $ds^2 = e^{2\mathcal{A}(r,y)} ds_8^2 + e^{2\mathcal{B}(r,y)} (dr^2 + dy^2).$

$$\mathcal{A} = A(r) + U(y)$$

$$\mathcal{B} = B(r) + V(y)$$

$$\Phi = \chi(r) + \psi(y)$$

**Solutions  $I, II^\pm$ :** Both periodic in  $r$  - trigonometric dependence    [Blumenhagen, Font '00]  
 $\rightarrow$  spontaneous compactification on  $S^1$

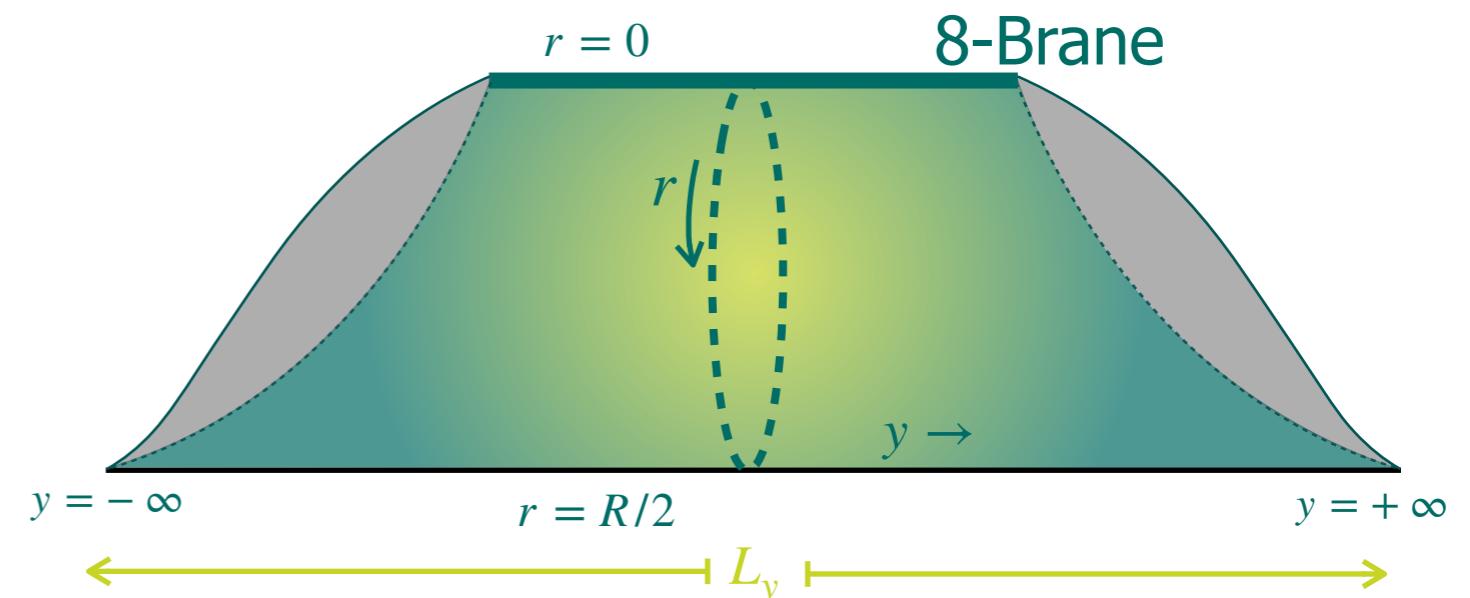
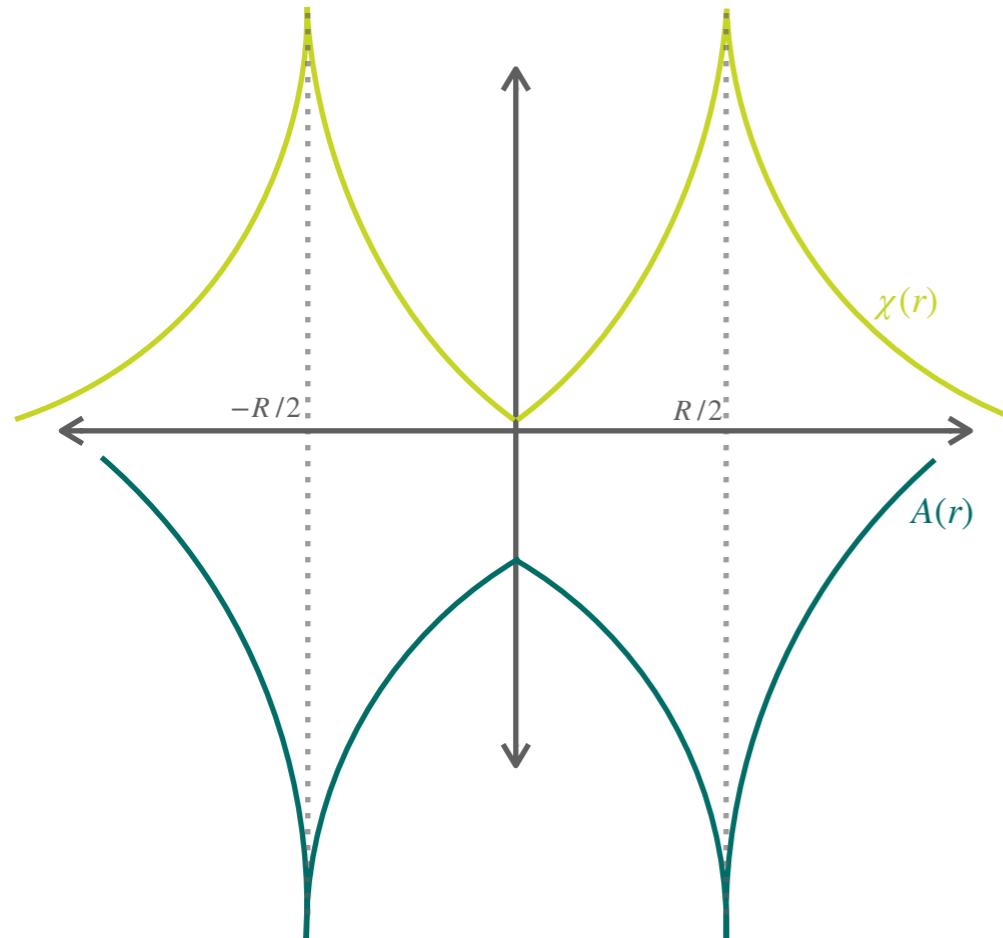
# Qualitative behaviour

r-direction spontaneously compactified on  $S^1$  with radius R:  $e^{\frac{5}{4}\phi_0} \sim \frac{1}{\lambda R}$

Logarithmic singularities at  $r = \pm \frac{R}{2}$ , string coupling diverges

$$\uparrow \kappa_{10}^2 T$$

y-direction: infinite length in sols  $I, II^-$ , becomes finite interval in sol  $II^+$



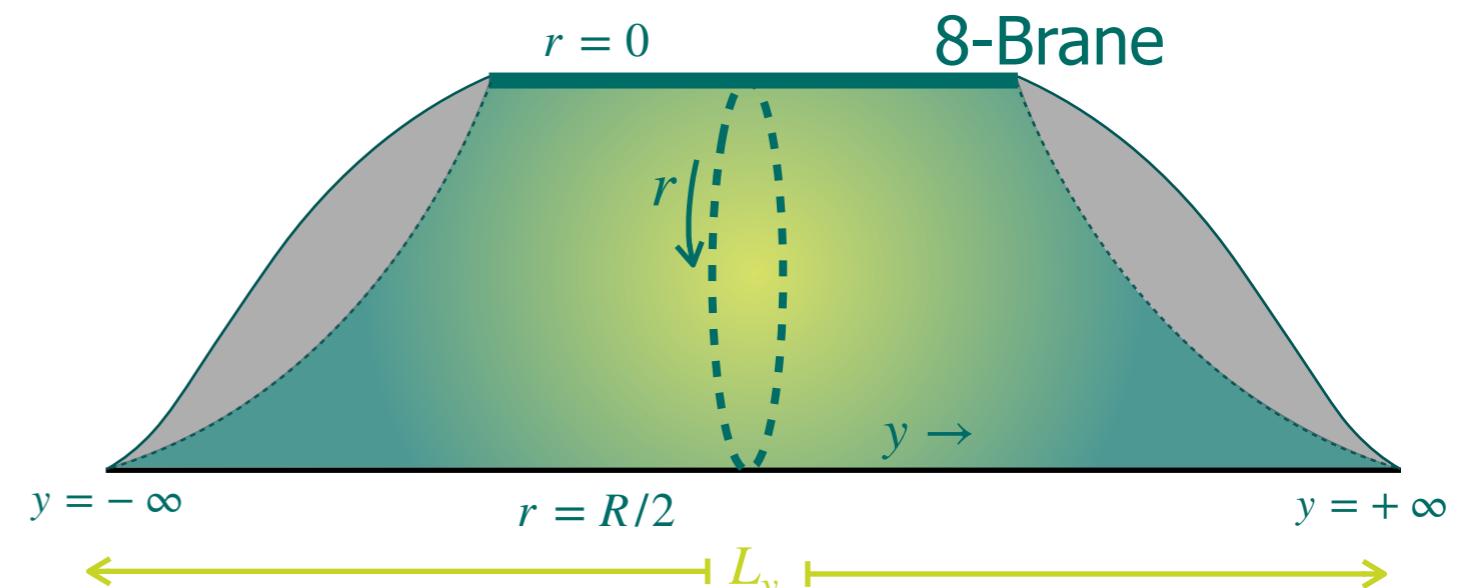
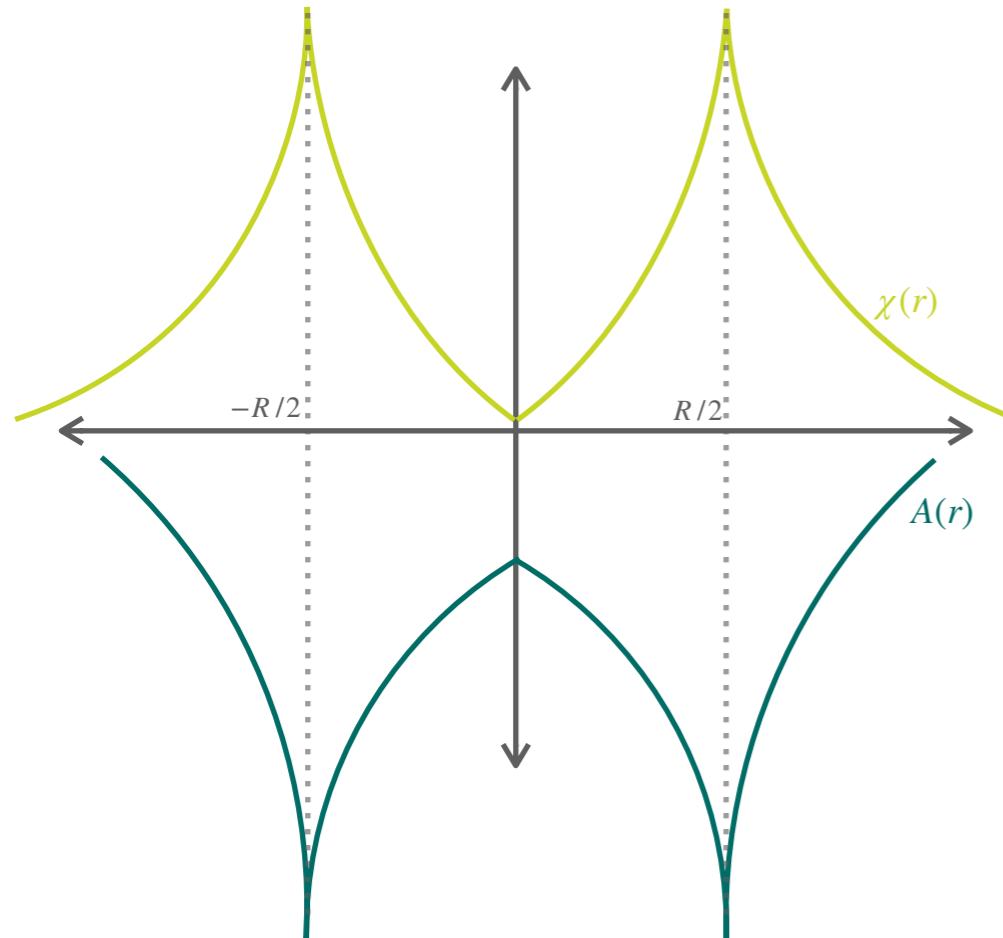
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$$\Delta \sim L_y \sim \mathcal{T}^{-1}$$

$$\Delta \sim e^{-\sqrt{2}D}$$

$$|\mathcal{R}| \sim e^{2\sqrt{2}D}$$

# ETW Defects

**Input:** 8-dimensional defect : log-singularity,  $S^1$  direction capped off  
Poincaré symmetry along the “brane” preserved  
2d transversal rotational symmetry broken

**Non-Isotropic Solution Ansatz:**  $ds^2 = e^{2\hat{\mathcal{A}}(\rho,\phi)}ds_8^2 + e^{2\hat{\mathcal{B}}(\rho,\phi)}(d\rho^2 + \rho^2 d\phi^2)$ .

The diagram illustrates the separation of variables in the metric ansatz. It shows a horizontal dotted line with two vertical arrows pointing upwards from below it, one on each side. The text "Separation of variables" is centered between the arrows.

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..... Separation .....  
of variables

**Solutions  $ETW7^\pm$ :**

Logarithmic singularities at  $\rho = 0$ , string coupling diverges

For appropriate parameter selection same scaling as 9d defect

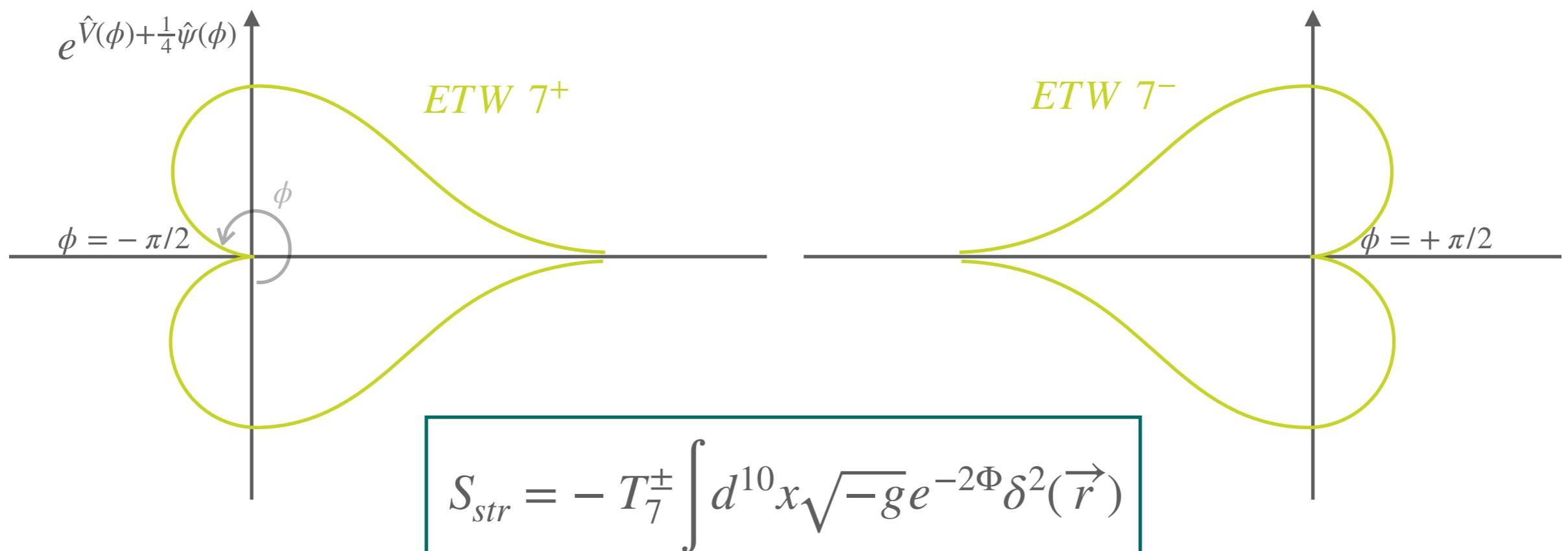
Dynamical Cobordism scaling satisfied:  $\Delta \sim e^{-\sqrt{2}D}$ ,  $|\mathcal{R}| \sim e^{2\sqrt{2}D}$

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..... Separation .....  
of variables



with  $\kappa_{10}^2 T_7 = 2\pi$

# Summary and Outlook

The Cobordism Conjecture holds more generally:  $\Omega_n^{\text{QG}}(X) = 0$

Cobordism and K-theory charges combine, respectively giving geometrical and localised contributions to tadpole cancellation conditions

The Cobordism Conjecture is consistent with dimensional reduction

Tadpole conditions can be systematically constructed from bottom-up, possibly including new terms coming from cobordism contributions

We provided a concrete example for physical realisation of dynamical cobordism

Eom for defect solved  $\rightarrow$  new 7-brane defect, predicted by cobordism breaking

# Summary and Outlook

## Future directions:

Reconstruction of tadpole conditions with minimal string theory input

Independent verification of cobordism-predicted objects

Clarification of cases with torsion

Extension to more complicated cobordism groups

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Thank you!

# Extra Slides

# Cobordism Conjecture Consequences

$$\Omega_k^{\widetilde{QG}} \neq 0$$

Breaking

Gauging

$$\Omega_k^{\widetilde{QG}} \rightarrow \Omega_k^{\widetilde{QG}+\text{defects}} = 0$$

$$0 = [M] \in \Omega^{\widetilde{QG}} \neq 0$$

$$\Omega_k \neq 0 \leftrightarrow dJ_k = 0 : J_k \text{ magnetic current}$$

Breaking

Gauging

$$dJ_k = \delta^{(k+1)}(\Sigma) \neq 0$$

$$J_k = dF_{k-1}$$

# Computation of $\Omega_k^\xi(X)$ - General technique

Tool: (Homological) Atiyah - Hirzebruch Spectral Sequence (AHSS)

Start with fibration:  $F \rightarrow E \rightarrow B$ ,      use AHSS to determine  $G_n(E)$  from  $G_n(B)$ .

Spectral sequence data: pages  $E^r$ , differentials  $d^r$ .

$$E^{r+1} \cong H(E^r) = \frac{\ker d^r : E^r \rightarrow E^r}{\text{Im } d^r : E^r \rightarrow E^r}$$

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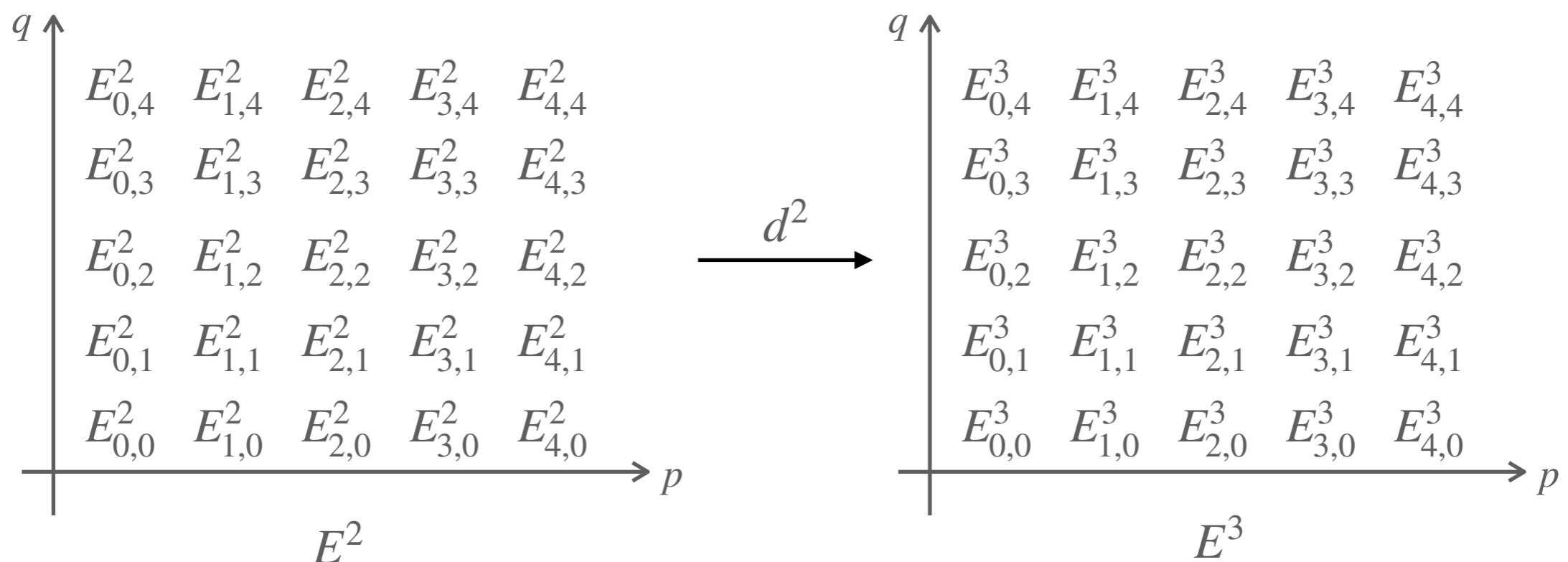
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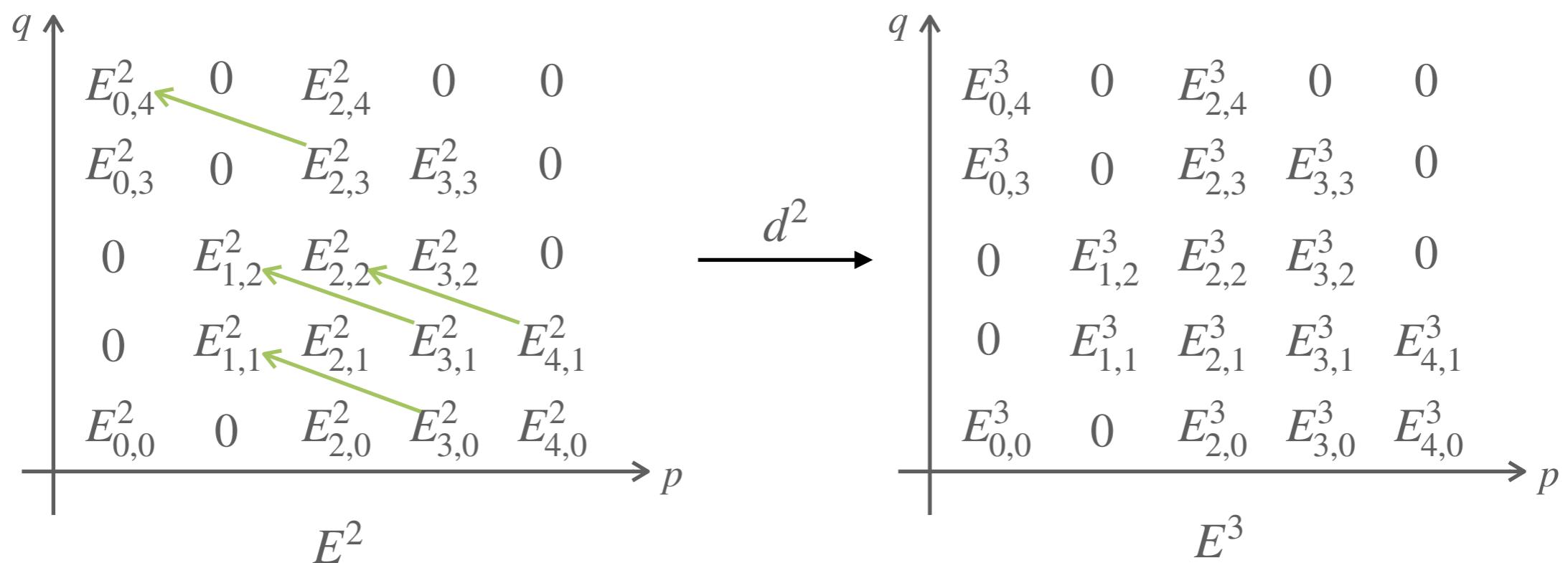
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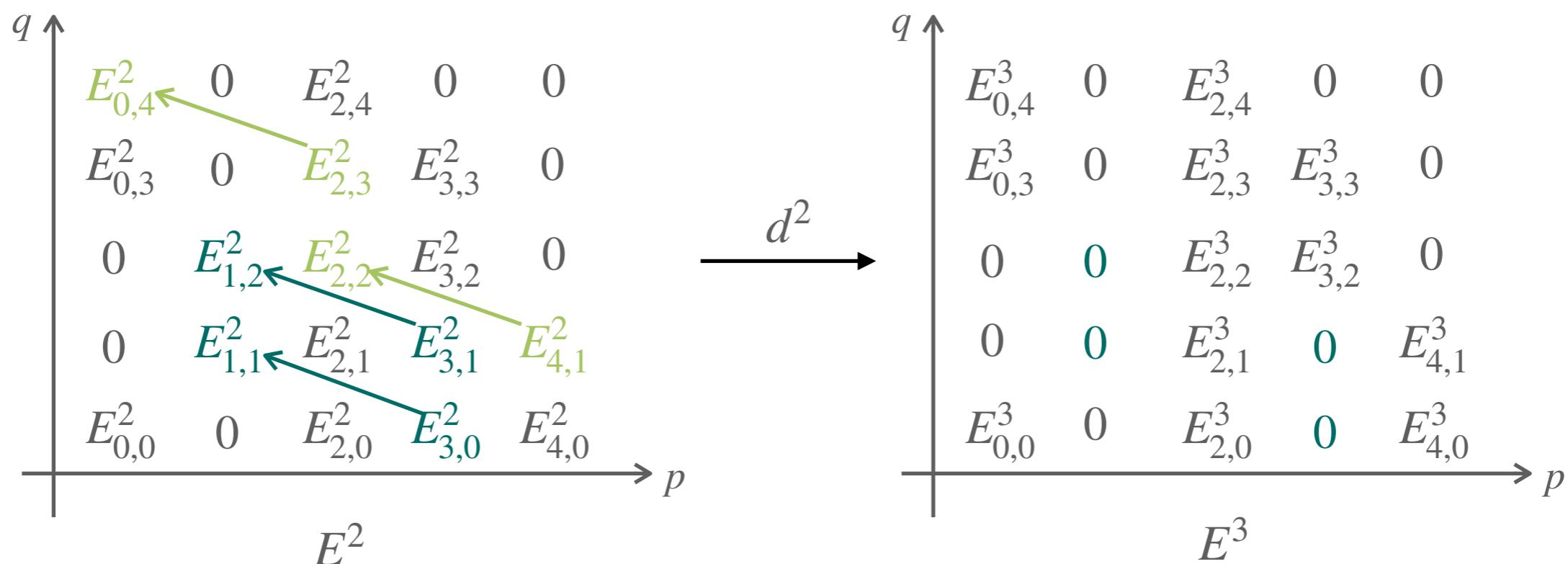
Tool: (Homological) Atiyah - Hirzebruch Spectral Sequence (AHSS)

Start with vibration:  $F \rightarrow E \rightarrow B$ , use AHSS to determine  $Gr(G_n(E))$  from  $G_n(F)$ .

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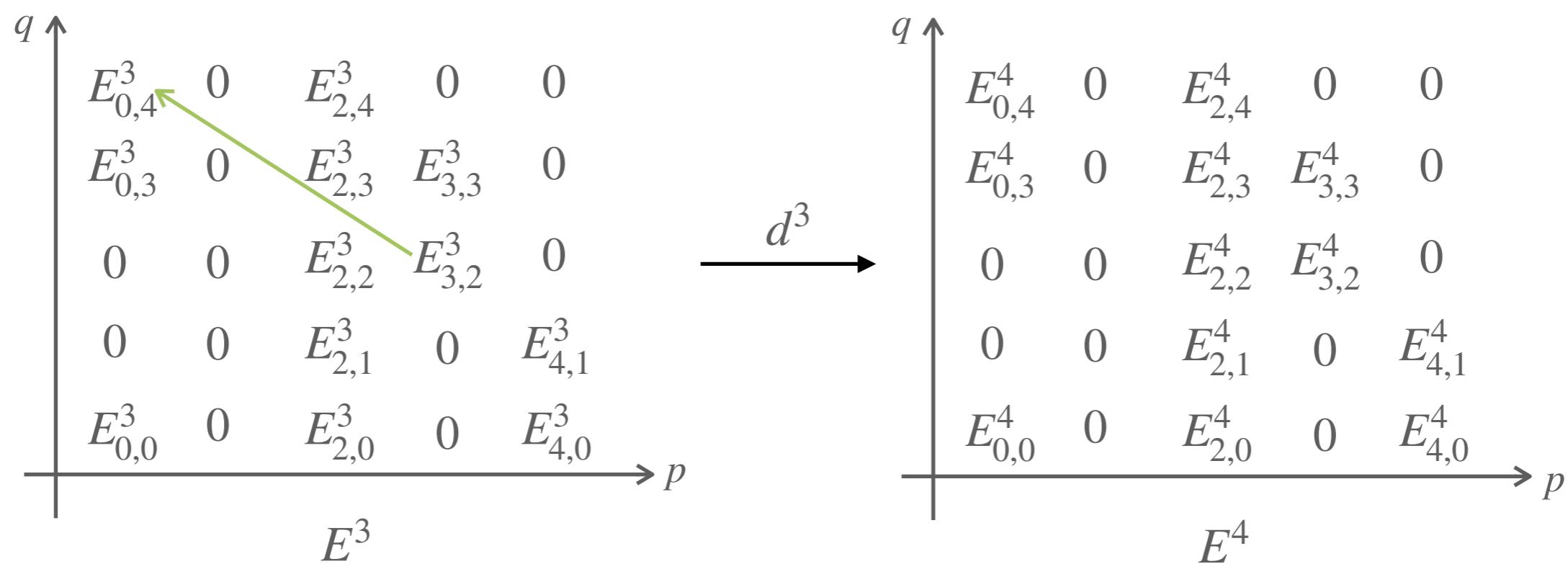
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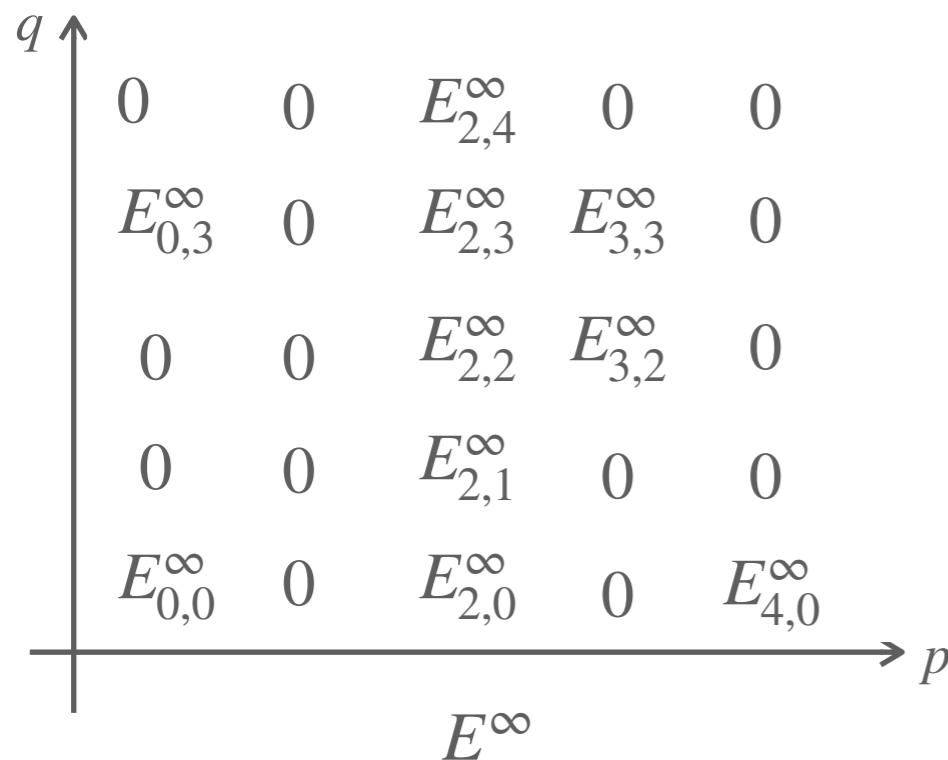
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# Computational Algorithm and challenges:

Compute second page →      Act with  $d^r$ , until  $E^\infty$ -page →      Read off  $Gr(G_n(E))$

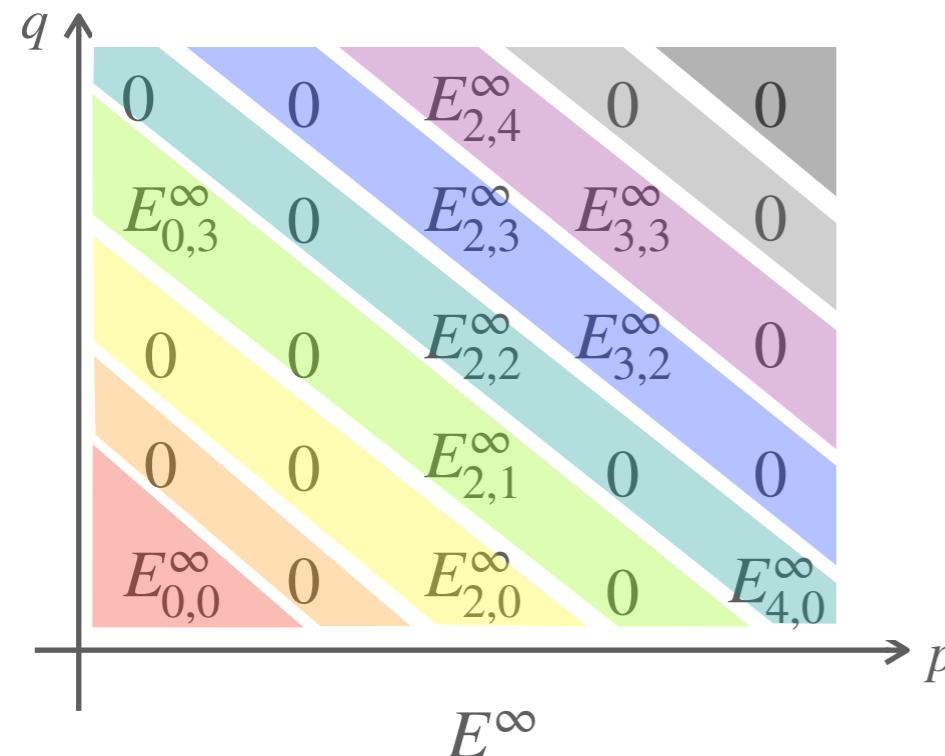


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$$G_0(E) = E_{0,0}^\infty$$

$$G_1(E) = 0$$

$$G_2(E) = E_{2,0}^\infty$$

$$G_3(E) = e(E_{0,3}^\infty, E_{2,1}^\infty)$$

$$G_4(E) = e(E_{2,2}^\infty, E_{4,0}^\infty)$$

$$G_5(E) = e(E_{2,3}^\infty, E_{3,2}^\infty)$$

$$G_6(E) = e(E_{2,4}^\infty, E_{3,3}^\infty)$$

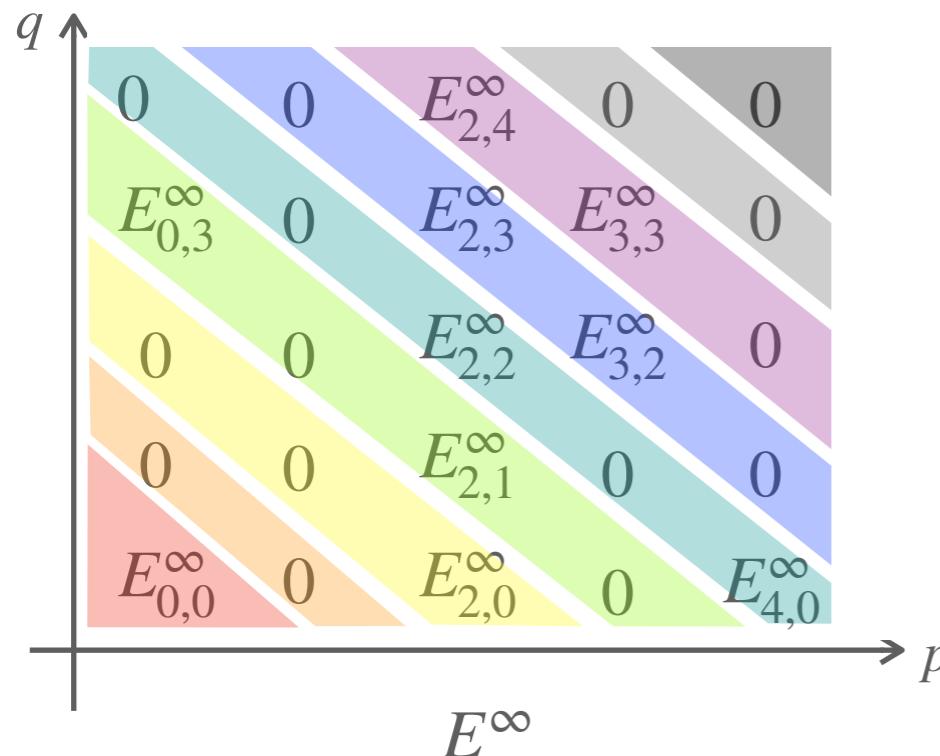
$$G_7(E) = 0$$

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$$G_6(E) = e(E_{2,4}^\infty, E_{3,3}^\infty)$$

$$G_7(E) = 0$$

Common Difficulties:

Determination of differentials, Extension problem

There is physical info in both types of mathematical problems!

e.g.[Diaconescu, Moore, Witten '00, Maldacena, Moore, Seiberg '01]

# Gauging Cobordism Charges

[Blumenhagen, Cribiori '21]

K-theory charges are gauged [Freed '00]

Gauged symmetries accompanied by tadpole conditions:  $0 = \int_M dF_{n-1} = \int_M J_n$

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In practice: add **K-theory** + **cobordism** contributions

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↑  
D-brane contributions      ↑  
Geometric contributions

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Example:

$$0 = \sum_i \int_M N_i \delta^{(6)}(\Delta_{4,i}) + a_1^{(6)} \frac{c_2(M)c_1(M)}{24} + a_2^{(6)} \frac{c_1^3(M)}{2}.$$

For  $a_1^{(6)} = -12$ ,  $a_2^{(6)} = -30$ ,  $M = B_3$ : D3-tadpole of F-theory

# Plugging everything together: tadpoles

Tadpole 1:

$$K^0(pt) = \mathbb{Z} \quad \text{and} \quad \Omega_0^{\text{Spin}^c}(pt) = \mathbb{Z}$$

9-form symmetry gauged by D9-branes 

global 3-form symmetry in 4d magnetic current:  $\tilde{J}_0(M_6) = td(M_0) = 1$  

$$N\delta^{(0)}(M_6) + a^{(0)}td_0(M_6) = 0$$

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Tadpole 2:

$(\times b_4)$

$$K^{-2}(pt) = \mathbb{Z} \quad \text{and} \quad \Omega_2^{\text{Spin}^c}(pt) = \mathbb{Z}$$

7-form symmetry gauged by D7-branes  $\rightarrow$  global 3-form symmetry in 4d:

$$\tilde{J}_2^{(a)}(M_6) = \sum_{a=1}^{b_4} j_0^{(2)a} \wedge \omega_{(2)a}$$

$$\sum_{j \in \text{def}} N_j \delta^{(2)}(\mathbb{R}^{1,3} \times \Sigma_{4,j}) + a^{(2)} c_1(M_6) = 0$$

For  $a^{(2)} = -24$  and  $M_6$  base of elliptically fibered  $CY_3$  :  
F-theory D7-cancellation condition

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↑  
transverse  
direction

Solution Ansatz: 
$$ds^2 = e^{2\mathcal{A}(r,y)} ds_8^2 + e^{2\mathcal{B}(r,y)} (dr^2 + dy^2).$$

$$\mathcal{A} = A(r) + U(y)$$

$$\mathcal{B} = B(r) + V(y)$$

$$\Phi = \chi(r) + \psi(y)$$

# 9-dimensional Domain Wall

**Goal:** Backreaction of gauge neutral, non-supersymmetric 9-dimensional object w/  
brane-like dilaton coupling

[Blumenhagen, Font '00]

**Physical realisation:** non-BPS  $\widehat{D8}$ -brane, non-SUSY stack of  $16 \times \bar{D}8 + O8^{++}$

Action:  $S = \frac{1}{2\kappa_{10}^2} \int d^{10}x \sqrt{-G} \left( \mathcal{R} - \frac{1}{2}(\partial\Phi)^2 \right) - T \int d^{10} \sqrt{-g} e^{\frac{5}{4}\Phi} \delta(r).$

↑  
transverse  
direction

**Solution Ansatz:**  $ds^2 = e^{2\mathcal{A}(r,y)} ds_8^2 + e^{2\mathcal{B}(r,y)} (dr^2 + dy^2).$

$$\mathcal{A} = A(r) + U(y)$$

$$\mathcal{B} = B(r) + V(y)$$

$$\Phi = \chi(r) + \psi(y)$$

**Solution I**

$$A(r) = \frac{1}{8} \log \left| \sin \left( 8K(|r| - \frac{R}{2}) \right) \right|$$

$$\chi(r) = -\frac{3}{2} \log \left| \tan \left( 4K(|r| - \frac{R}{2}) \right) \right| + \phi_0$$

$$\vdots$$

$$U(y) = -Ky$$

**Solutions II $^\pm$**

$$A(r) = \frac{1}{8} \log \left| \sin \left( 8K(|r| - \frac{R}{2}) \right) \right|$$

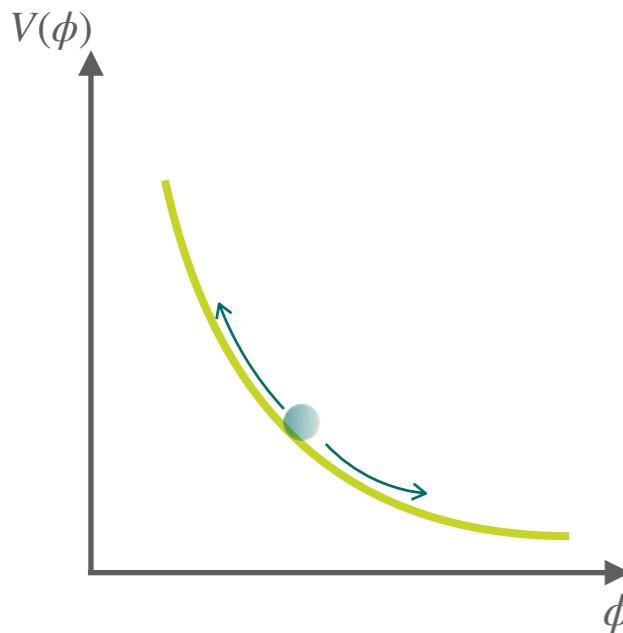
$$\chi(r) = \frac{\alpha^\pm}{8} \log \left| \sin \left( 8K(|r| - \frac{R}{2}) \right) \right| + \log \left| \tan \left( 4K(|r| - \frac{R}{2}) \right) \right| + \phi_0$$

$$\vdots$$

$$U(y) = \frac{1}{8} \log (\cosh(8Ky))$$

[Blumenhagen, Font '00]

# Tadpoles & Dynamical Cobordism



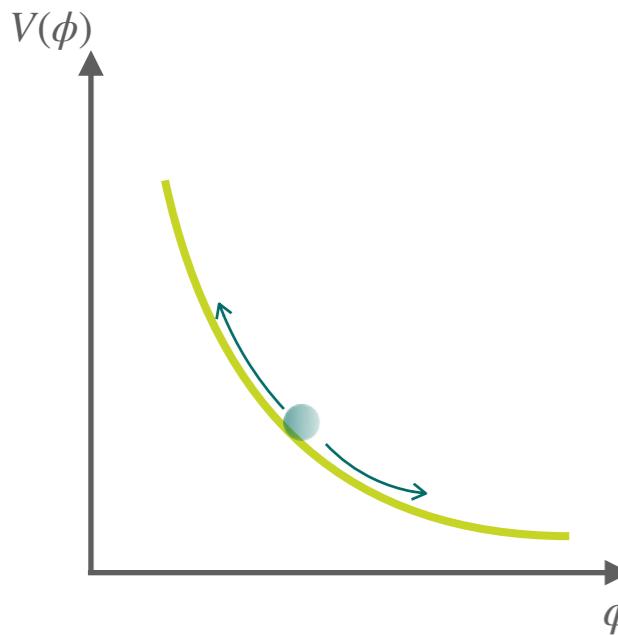
Dynamical tadpoles (vs RR tadpoles)

Naturally occurring in supersymmetry-breaking potentials

Indicate lack of maximally-symmetric vacuum

[Sugimoto '99]  
[Antoniadis, Dudas, Sagnotti '99]  
[Angelantonj '99]  
...  
recently : [Raucci '22]

# Tadpoles & Dynamical Cobordism



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Example: Sugimoto Model ( USp(N) Type I with N  $\bar{D}9$  and N  $O9_-$  )

[Sugimoto '99]

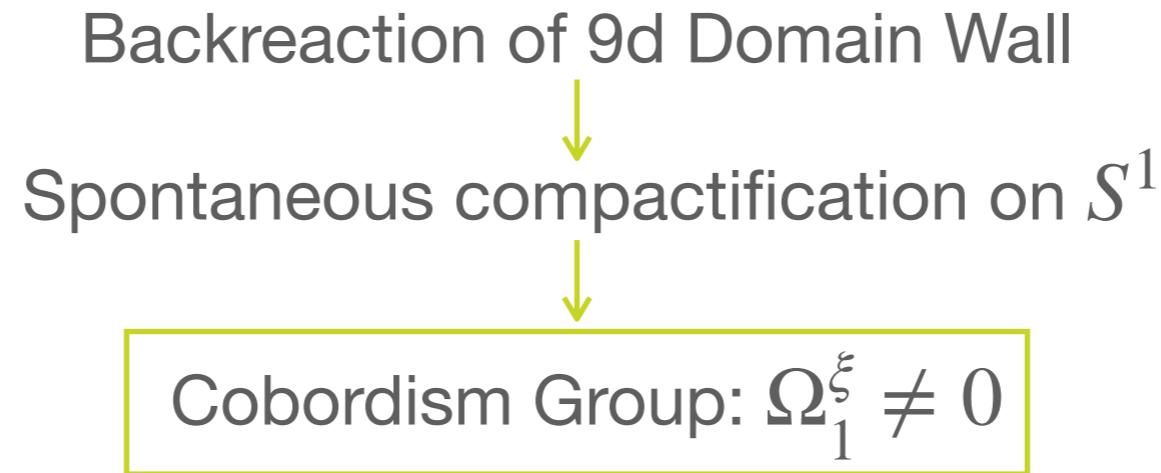
Action:

$$S = \frac{1}{2\kappa_{10}^2} \int d^{10}x \sqrt{-G} \left( \mathcal{R} - \frac{1}{2}(\partial\Phi)^2 \right) - T_9 \int d^{10}x \left( (N+32)\sqrt{-G} e^{\frac{3}{2}\Phi} - (N-32)A_{10} \right) + \dots$$

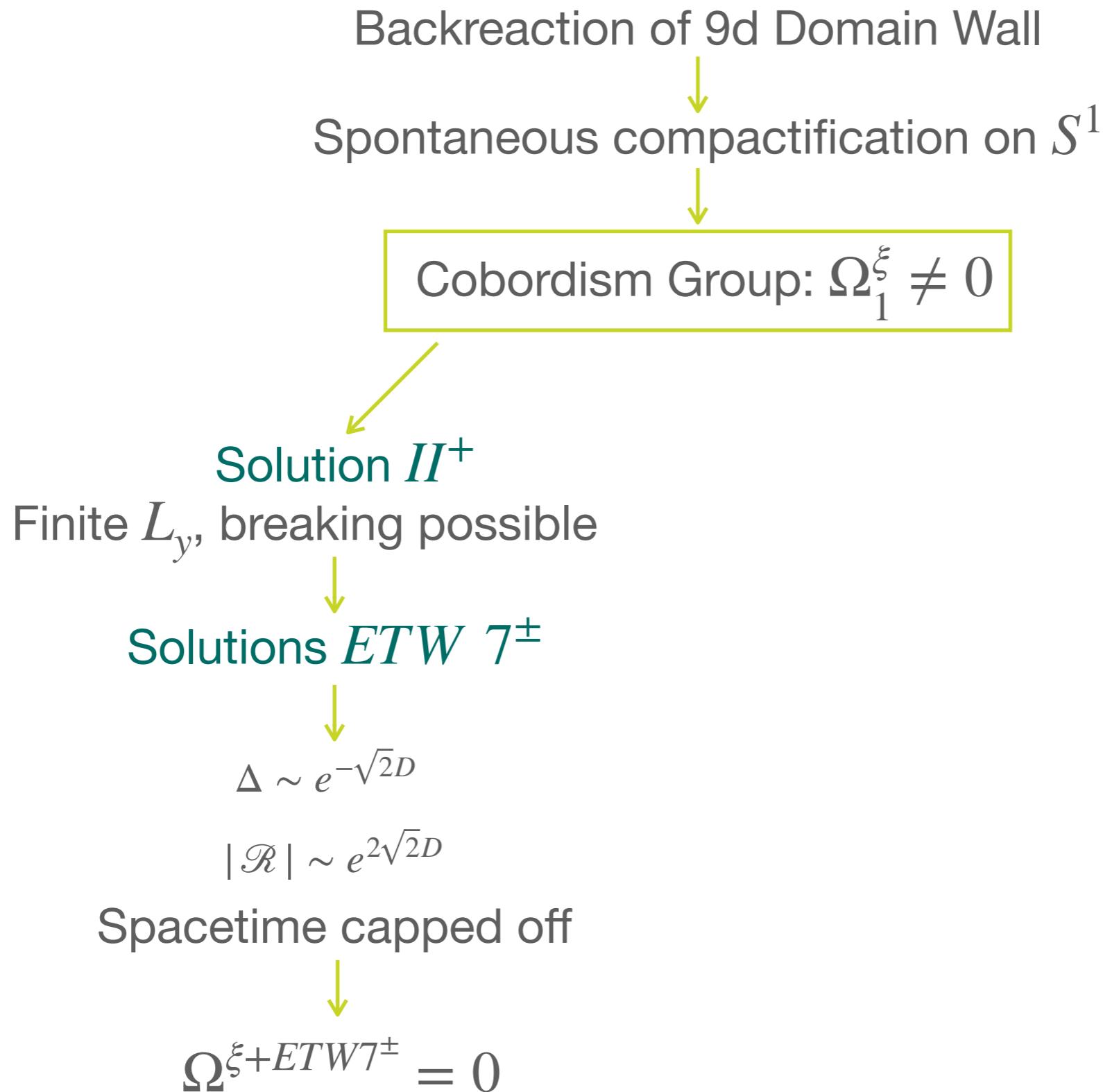
→ Solution preserving 9d Poincaré invariance [Dudas, Mourad '00]

→ singularities at finite spacetime distance, spontaneous compactification to 9d

# Cobordism Interpretation



# Cobordism Interpretation



# Cobordism Interpretation

