

# *Multigravity from string theory*

## **SUSY 2022, Ioannina**

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*based on hep-th:*

1711.11372, 1807.00591    CB, I. Lavdas  
1905.05039, 2207.xxxxx    CB

# 1. Introduction

A deep question about (the boundary between) landscape & swampland:

*Can 4D gravity be modified in the IR ?*

other than  
scalar-tensor

	Spin 1 gauge bosons	Spin 2 graviton
Localized ?	<i>D-branes</i> ✓	?
massive ?	<i>BEH</i> ✓	?

The question came to front-stage at the turn of the millenium, in particular with the **Randall-Sundrum-Karch** & **Dvali-Gabadadze-Porrati** bottom-up **brane-world** models

Then, over the next decade people completed the program of writing down a **ghost-free non-linear** extension of the **Fierz-Pauli** theory of massive gravity:

*the **dRGT** Effective Field Theory*

Boulware-Deser '72

...  
Arkani-Hamed, Georgi, Schwartz '02

...  
**de Rham, Gabadadze, Tolley '10**  
Hassan, Rosen '11  
Mukhanov, Chamseddine '11

Is this EFT part of the string-theory landscape ?  
(or is there a BEH mechanism for gravity ?)

Simple massive gravity is actually almost ruled out by astro/cosmo + laboratory data:

astro/cosmo:  $m \sim H \sim 10^{-32} \text{eV}$

Dvali, Gruzinov, Zaldarriaga '02; . . .  
see de Rham, Deskins, Tolley, Zhou '16

weak lensing, lunar ranging; LIGO, . . .

breakdown of dRGT  $\Lambda_3 \sim (m^2 m_{\text{Planck}})^{1/3} \sim (100 \text{ km})^{-1}$

Vainshtein non-linearities:  $r_{\odot} \sim \left( \frac{M_{\odot}}{\Lambda_3 m_{\text{Planck}}} \right)^{1/3} \sim \text{galactic}$

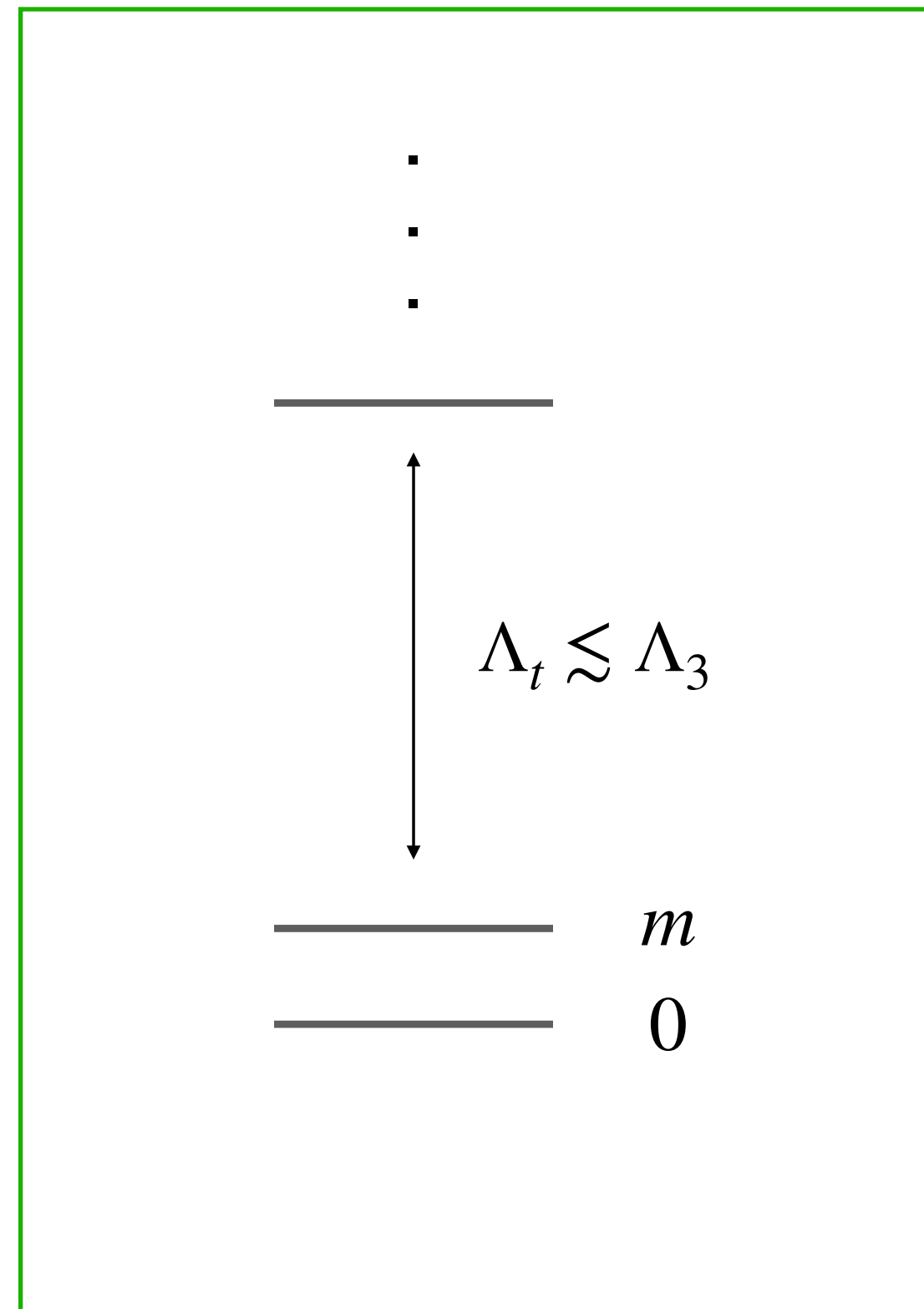
So laboratory tests impossible, and solar-system tests require 'acrobatics'

**Little incentive to replace Einstein's theory**

But bigravity EFT is much less constrained



*mass*



Babichev et al '16

Akrami, Hassan, König, Schmidt-May '16

'dark graviton'

mass and coupling can  
be tuned

For theory: not very different (m-gravity is a limit)

**so focus on bigravity**

The embedding of bigravity stumbles a priori on two crucial problems:

We want bigravity EFT in **de Sitter background** with mass obeying **Higuchi** bound:

$$m^2 \geq \frac{2}{\ell_{\text{dS}}^2}, \quad \text{where } \ell_{\text{dS}} = H^{-1}$$

We want **scale separation**, i.e. if dS is uplift of AdS vacuum:  $m\ell_{\text{AdS}} \ll 1$

These go against two key swampland conjectures:

### No stable dS vacua

Danielsson, Van Riet '18  
Obied, ooguri, Spondyneiko, Vafa '18  
Andriot '18  
.....

### No scale separation

Tsimpis '12  
.....  
D. Luest, Palti, Vafa '19  
Font, Herraez, Ibanez '19  
S. Luest, Vafa, Wiesner, Xu '22

The fate of scale separation will decide whether multigravity is in landscape or swampland

but if scale separation can be achieved, so will EFTs of massive AdS gravity

**In the rest of this talk I will try to convince you about this using holography**

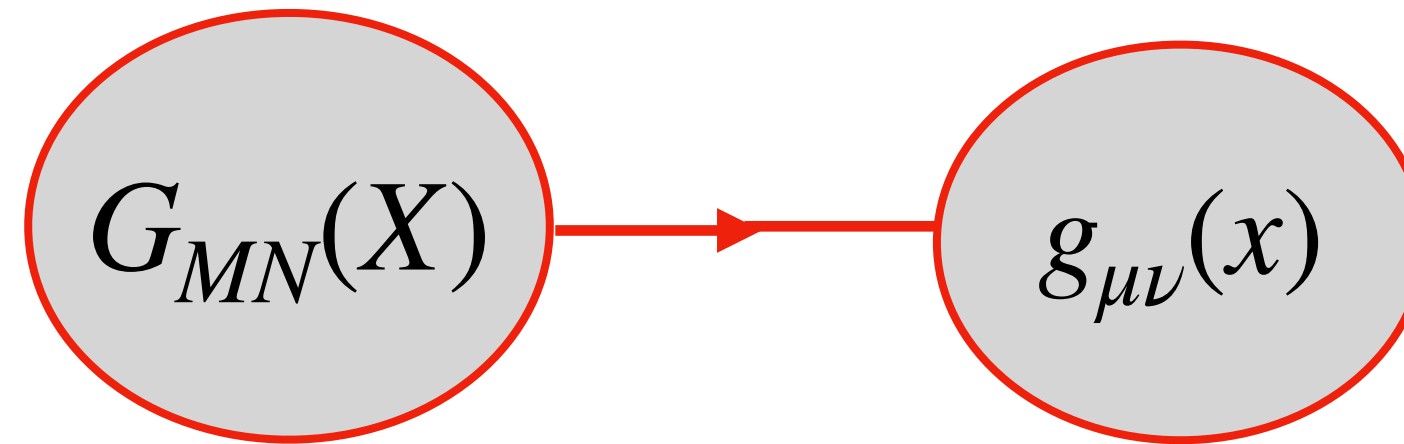
**speculation:**

If stable dS solutions do not exist, this may even actually help since removing the Higuchi bound may reduce the tension on the AdS to dS lift

## 2. Bigravity EFT

An EFT exists:

*Pauli, Fierz '39 . . . .*  
*Arkani-Hamed, Georgi, Schwartz '02*  
*. . . .*



*mapping:*  $X^M = \Phi^M(x)$

Stueckelberg, or  
 would-be Goldstone bosons

*diffeo-invariant  
 local action:*

$$S_{\text{bigrav}} = -\frac{1}{2\kappa_1^2} \int d^4X \sqrt{G} [R(G) + \Lambda_1] - \frac{1}{2\kappa_2^2} \int d^4x \sqrt{g} [R(g) + \Lambda_2] \\
+ \frac{m^2}{2(\kappa_1^2 + \kappa_2^2)} \int d^4x \sqrt{g} F(g_{\mu\nu}, \hat{G}_{\mu\nu})$$

*pullback:*  $\hat{G}_{\mu\nu} = \partial_\mu \Phi^M \partial_\nu \Phi^N G_{MN}$

But 4 would-be g.b., one (potential **ghost**) must decouple *Boulware, Deser '72*

Possible with 3-parameter choice of  $F(g_{\mu\nu}, \hat{G}_{\mu\nu})$  *de Rham, Gabadadze, Tolley '10*  
*Hassan, Rosen '11*

Mixed volumes in 1st-order formalism *Hinterblicher, Rosen '12*

$$\sqrt{g} F = \epsilon_{a_1 a_2 a_3 a_4} \sum_{n=1}^3 \beta_n \int e^{a_1} \wedge \cdots \wedge e^{a_n} \wedge \hat{E}^{a_{n+1}} \wedge \cdots \wedge \hat{E}^{a_4}$$

$$\hat{E}^a = E_M^a \partial_\mu \phi^M dx^\mu$$

dRGT

$\kappa_1 \rightarrow 0$  freezes  $G_{MN}(X)$  and leaves a massive  $g_{\mu\nu}(x)$

Like Einstein gravity, this is EFT but it breaks down much earlier :

*breakdown scales:*

$$\Lambda_3 \sim \left( \frac{m^2}{\kappa} \right)^{1/3} \quad \text{Minkowski}$$

smaller of  $\Lambda_2 \sim \left( \frac{m}{\kappa} \right)^{1/2}$  and  $\Lambda_3 \sim \left( \frac{m}{\kappa \ell_{\text{AdS}}} \right)^{1/3} \quad \text{AdS}$

*de Rham, Hinterblicher, Johnson '18*

cf. with massive spin-1 :  $\Lambda \sim \frac{m}{g}$  (Higgs or strong coupling before this scale)

But for spin-2, no particles of lower spin can save the day !

*Bonifacio, Hinterblicher, Rosen '19*

### 3. Holographic mechanism(s)

The problem has an interesting "translation" in terms of the dual CFT:

Start with two decoupled theories, CFT & CFT'  
each with its own conserved em tensor and central charge

$$\partial^a T_{ab} = \partial^a T'_{ab} = 0 \qquad \begin{aligned} \langle TT \rangle &\sim c \\ \langle T'T' \rangle &\sim c' \end{aligned}$$

The dictionary is:  $c = \left(\frac{2\ell}{\pi K}\right)^2$       and       $\Delta(\Delta - 3) = (m\ell)^2$

conserved em tensor has canonical  $\Delta = 3 \quad \implies m = 0$

Now turn on a 'small coupling'  $\mathcal{L}_{\text{tot}} = \mathcal{L}_{\text{CFT}} + \mathcal{L}_{\text{CFT}'} + \Delta\mathcal{L}$

conserved

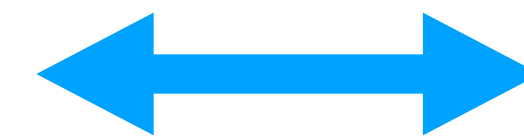
$$T^{\text{tot}} = T + T' + \Delta T^{\text{tot}}$$



massless

spin-2 primary,  
not conserved

$$T^{\text{rel}} = c'T - cT' + \Delta T^{\text{rel}}$$



$$\Delta - 3 = \epsilon \simeq (m\ell)^2$$

$$\partial^a T_{ab}^{\text{rel}} = V_b$$

Stueckelberg

In terms of superconformal reps:

$$\lim_{\epsilon \rightarrow 0} D(3 + \epsilon, 2) = D(3, 2) \oplus D(4, 1)$$

long

short

Porrati '01

Superconformal : *likewise but*

$$\mathcal{N} \leq 4 \quad \text{in} \quad \text{AdS}_4$$

$$\mathcal{N} \leq 2 \quad \text{in} \quad \text{AdS}_5$$

CB '19

Cordova, Dumitrescu, Intriligator '16

NB: in maximal susy case

Stueckelberg multiplet has 4 spin 3/2

Massive graviton multiplet same as massless N=8

Deformation of gauged N=8 ?

CB, S. Luest

## Key question: what type of interaction ?

### DOUBLE TRACE:

$$\Delta \mathcal{L} = \lambda \mathcal{O} \mathcal{O}'$$

marginal

single-trace

Kiritsis '06

Aharony, Clark, Karch '06

Kiritsis, Niarchos '08

calculate:

$$\epsilon = \frac{\lambda^2}{10} \left( \frac{1}{c} + \frac{1}{c'} \right) \delta \delta' + \mathcal{O}(\lambda^4)$$

But problem:

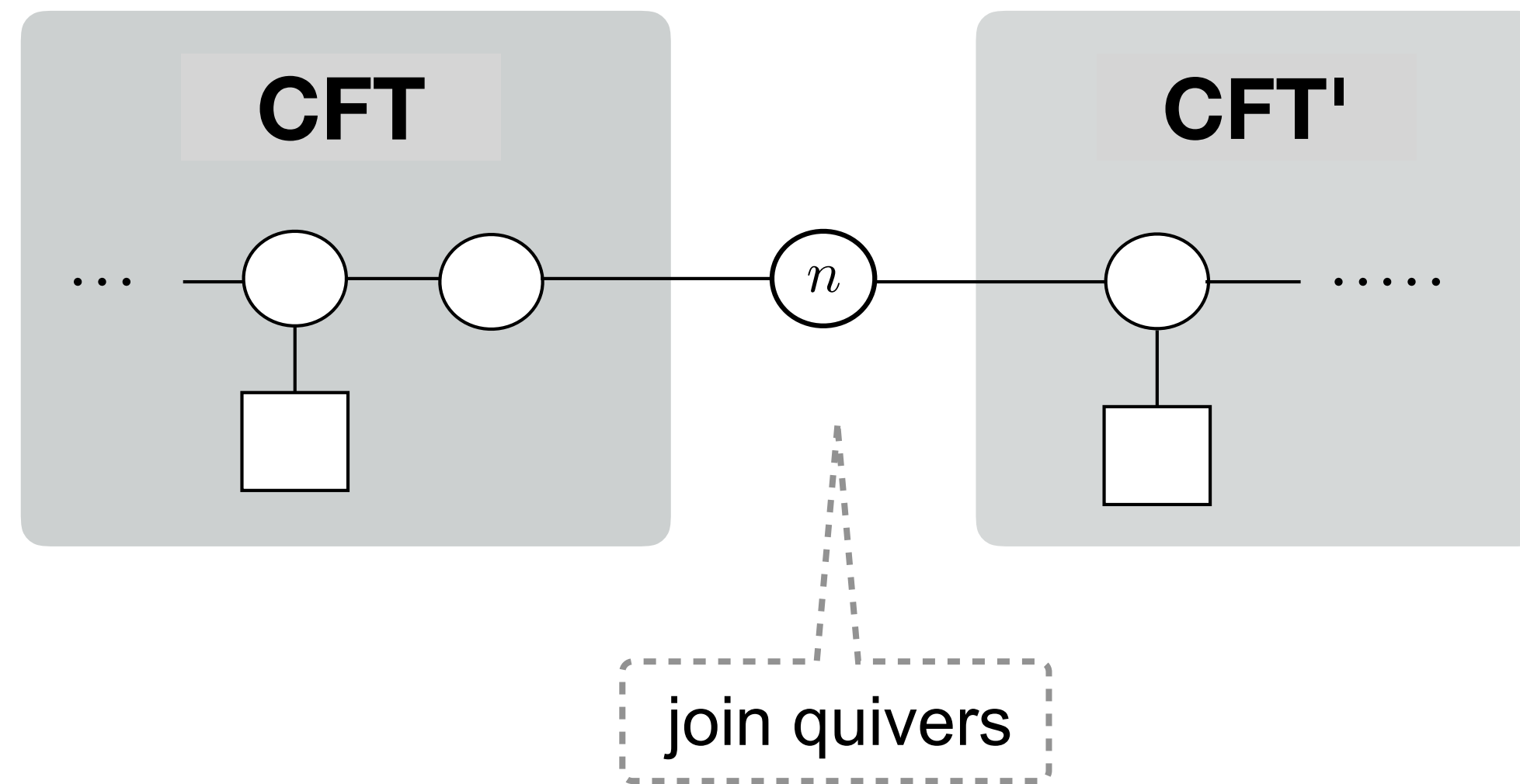
effect is one-loop in gravity

longitudinal modes are 2-particle bound states

EFT is unlikely

## MEDIATION

gauge common  
global symmetry



CB, Lavdas '18

but 3d gauge coupling strong in IR, how can the mixing be small ?

"Secret": **very few mediators**  $\frac{n^2}{c}, \frac{n^2}{c'} \ll 1$

That this works shown with exact dual IIB-string solutions  
(though these have N=4 susy and hence no scale separation)

## 4. Gravity dual

The IIB AdS4 solutions:

General local form found by the UCLA group     D'Hoker, Estes, Gutperle '07

Global consistency, and 1-to-1 correspondence with **good Gaiotto-Witten** SCFTs

Assel, CB, Estes, Gomis '11, '12

Aharony, Berdichevsky, Berkooz, Shamir '11

NB: *One of very few solns with fully-localized 5-brane sources*

Superconformal **isometries** force the geometry to have the fibered form

$$(AdS_4 \times S^2 \times \hat{S}^2) \times_w \Sigma$$

Riemann  
surface

$$\frac{4}{\alpha'} ds^2 = \rho_4^2 ds_{\text{AdS}}^2 + \rho_1^2 ds_{(1)}^2 + \rho_2^2 ds_{(2)}^2 + 4\rho^2 dz d\bar{z}$$

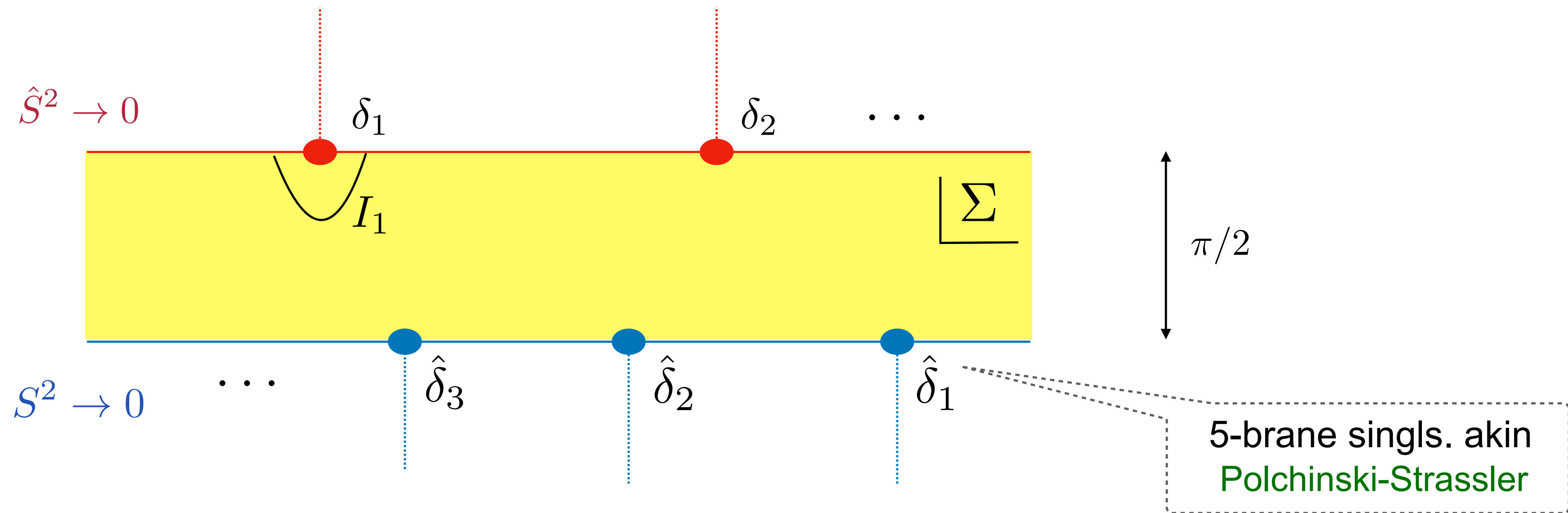
There are also 3-form, 5-form and dilaton backgrounds that I don't exhibit

$$F_3, H_3, F_5 \quad e^\Phi$$

All backgrounds expressed in terms of **two non-negative harmonic functions** on the Riemann surface  $\Sigma$  = infinite strip.

$$W = \partial_z \partial_{\bar{z}} (h_1 h_2) , \quad \mathcal{U}_i = 2h_1 h_2 |\partial_z h_i|^2 - h_i^2 W$$

$$\rho_4^8 = 16 \frac{\mathcal{U}_1 \mathcal{U}_2}{W^2} , \quad \rho_1^8 = 16 h_1^8 \frac{\mathcal{U}_2 W^2}{\mathcal{U}_1^3} , \quad \rho_2^8 = 16 h_2^8 \frac{\mathcal{U}_1 W^2}{\mathcal{U}_2^3} , \quad \rho^8 = \frac{\mathcal{U}_1 \mathcal{U}_2 W^2}{h_1^4 h_2^4} .$$



$$h_1 = \sum_{a=1}^p m_a \log \left( \frac{1 + ie^{z-\delta_a}}{1 - ie^{z-\delta_a}} \right) + c.c.$$

$$h_2 = \sum_{\hat{a}=1}^{\hat{p}} \hat{m}_{\hat{a}} \log \left( \frac{1 + e^{-z+\hat{\delta}_{\hat{a}}}}{1 - e^{-z+\hat{\delta}_{\hat{a}}}} \right) + c.c.$$

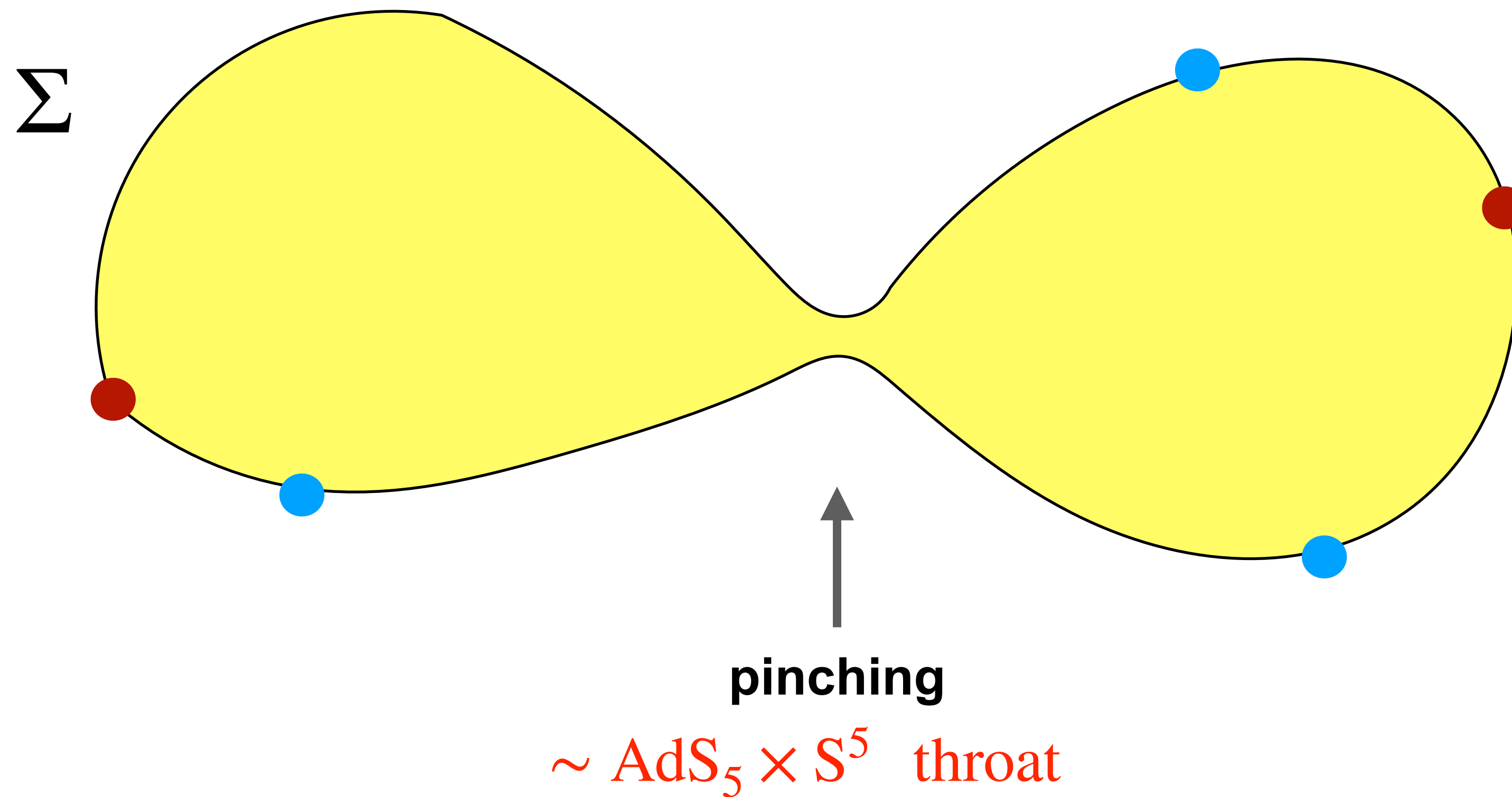
$$I_1 \times \hat{S}^2 \sim S^3$$

carries  $m_1$  units of D5  
charge

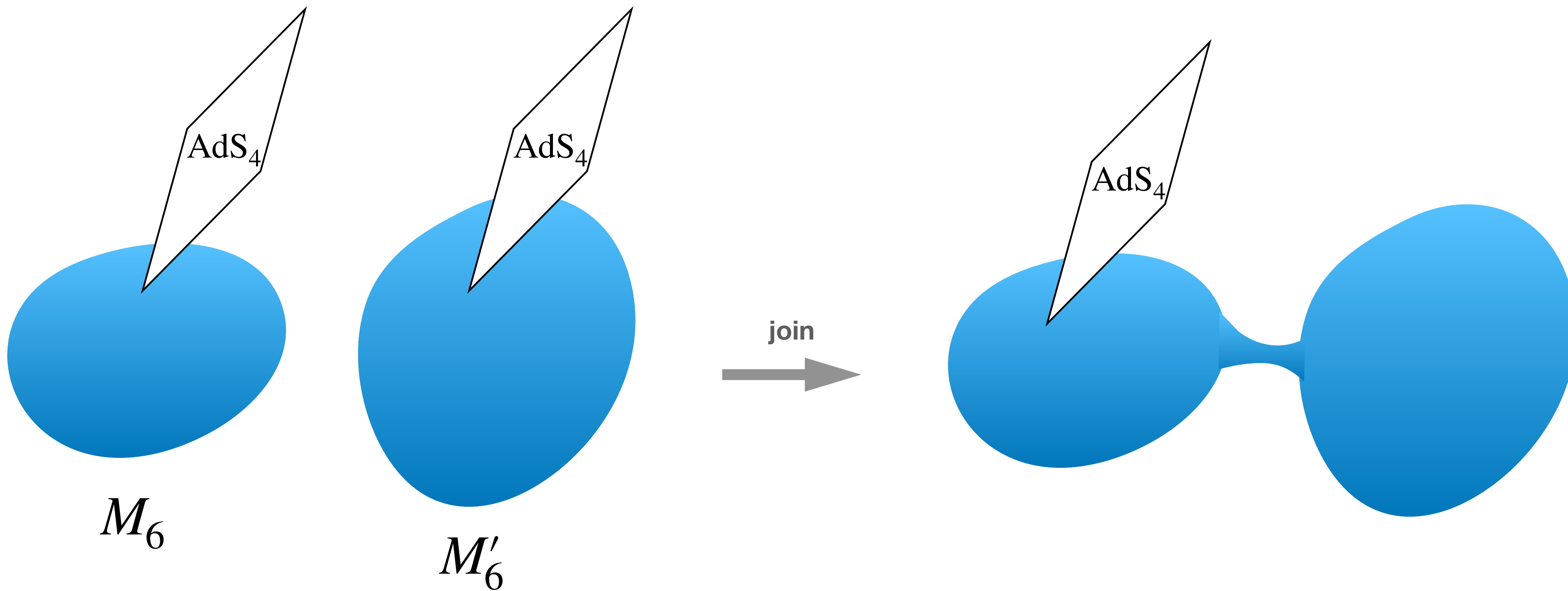
$$S^3 \times S^2$$

carries  $l_1$  units of D3  
charge

The decoupling limit of the CFTs corresponds to pinching the Riemann surface



# 10d geometry



Convenient: *the spin-2 spectrum depends **only on geometry**, not fluxes*

Csaki, Erlich, Hollowood, Shirman '00

CB, Estes '11

$$\Delta_{\text{BE}} \psi = m^2 \psi, \quad \Delta_{\text{BE}} = -\frac{1}{\sqrt{g}} e^{-2A} \partial_m \sqrt{g} g^{mn} e^{4A} \partial_n$$

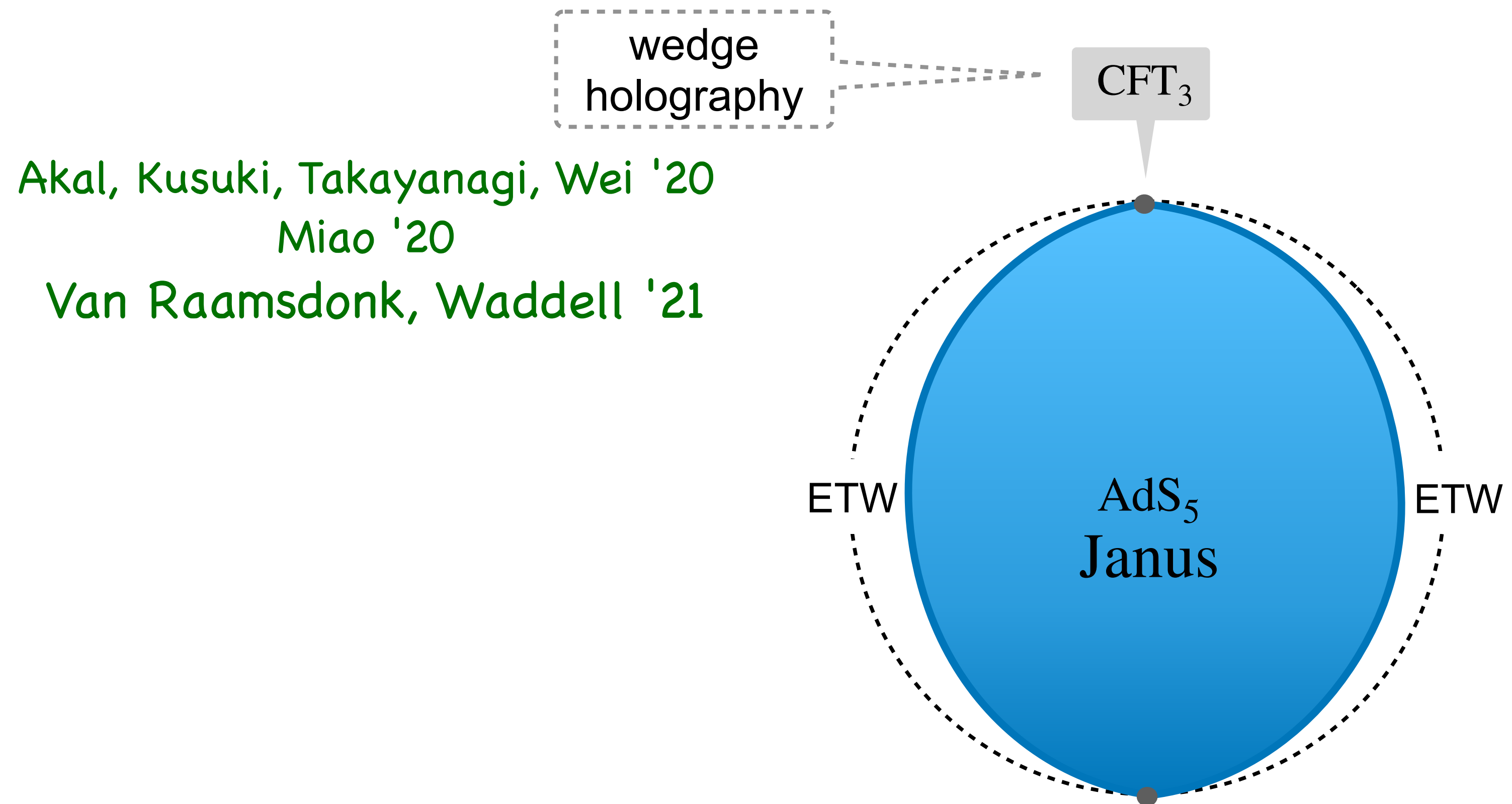
Bakry - Emery operator, cf De Luca, De Ponti, Mondino, Tomasiello '21

This is a Schödinger-like problem with norm  $\langle \psi | \psi' \rangle = \int \sqrt{g} g^{mn} e^{2A} \partial_m \psi \partial_n \psi'$

(see Stelle '20

for alternative self-adjointness)

The low-lying spectrum is **determined by the geometry of the throat** with appropriate boundary conditions at the two **`EOW Planck branes'**



cf. **Randall-Sundrum-Karch**  
bottom-up model

Janus IIB solution  
(dilaton varies)      Bak, Gutperle, Hirano '03  
D'Hoker, Estes, Gutperle '06

$$\epsilon \simeq \boxed{\frac{n^2}{4\pi^4} \frac{\tanh^3 \delta\phi}{|\delta\phi - \tanh \delta\phi|}} \times \frac{1}{c}$$

$\lambda_{\text{eff}}^2$

CB, Lavdas '18

Two factors suppress the mixing:

◆  $\frac{n^2}{c} \ll 1$

few mediators

◆  $\delta\phi \rightarrow \infty$

Janus parameter

hidden in dual CFT

The string coupling  $g_s$  has **no obvious translation** in SCFT<sub>3</sub>

In Gaiotto-Witten theories it is roughly the ratio of NS5 to D5 branes, so joining a small -  $g_s$  theory with its mirror suppresses the mixing

This should be so, because in the limit  $c' \rightarrow \infty$  the CFT couples effectively to 4d  $\mathcal{N} = 4$  SYM, which becomes a free theory when  $g_s \rightarrow 0$

NB: We expect this phenomenon to persist for  $\mathcal{N} < 4$  SCFTs

Last question: If this is UV embedding of (massive) multigravity, how to see the **EFT breakdown** in the limit  $\epsilon \rightarrow 0$  ?

**The throat grows an extra fifth dimension**

for  $\frac{n^2}{c} \rightarrow 0$  throat tends to  $\text{AdS}_5$

for  $\delta\phi \rightarrow \infty$  : Janus throat tends to  $\text{AdS}_4 \times \text{interval} [-\delta\phi, \delta\phi]$

KK modes on interval condense

## 5. Conclusion

Recipy for UV completion of multi-gravity EFT :

- ① Find scale-separated AdS4 flux vacua, dual to 3d large-N CFTs ( $\mathcal{N} < 2$  susy)
- ② Gauge a common global symmetry  $G$  of two such CFTs;  
rank of  $G$  must be  $\ll N$  & large Janus variation also helps

Have shown that ② works; real question is whether ① in landscape or swampland

Some related recent work:

Like KK modes, **open-string** spin-2 Regge excitations  $\in$  long (Weyl) supermultiplet;  
Interesting computation of their coupling to gravity, but no EFT ?

D. Luest, Markou, Mazloumi, Stieberger '21

Gapped spectrum expected in KR model with two Planck branes

Also arises in linear-dilaton bottom-up model in

Antoniadis, Dimopoulos, Giveon '11

Antoniadis, Markou, Rondeau '21

***Thank you for your attention***