50 Years of the Veneziano Model

Galileo Galilei Institute, May 11-15

$$A(s,t,u) = \frac{\bar{\beta}}{\pi}\left[B(1-\alpha(t), 1-\alpha(s)) + B(1-\alpha(t), 1-\alpha(u)) + B(1-\alpha(s), 1-\alpha(u))\right] \quad (3)$$

where we have introduced the Euler B-function $B(x,y) = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)}$.

Scanned from the original manuscript of the paper "Construction of a crossing symmetric, Regge behaved amplitude for linearly rising trajectories" by Gabriele Veneziano, 1968

A `magic' formula

by a superb scientist and man

D-branes* — a tribute to Joe

1954 - 2018

Thinking out of (or deep inside ?) the box

Constantin Bachas
Ecole Normale Sup, Paris

* *a personnal recollection*

In March of 1995 I wrote a paper on some advantages of compactifications of type I theory with magnetic fluxes

(viz intersecting-brane models)

Soon thereafter I received an email from Joe inviting me to participate in the workshop on Unification: From the Weak Scale to the Planck Scale that was being held in Santa Barbara this same Fall

I arrived there a few days after the posting of Joe's famous paper:

Dirichlet Branes and Ramond-Ramond Charges

Joseph Polchinski*
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106-4030
(Received 10 October 1995)

We show that D-branes, extended objects defined by mixed Dirichlet-Neumann boundary conditions, break half the supersymmetries of the type II superstring and carry a complete set of electric and magnetic Ramond-Ramond charges. The product of the electric and magnetic charges is a single Dirac unit, and the quantum of charge is that required by string duality. This is strong evidence that D-branes are intrinsic to type II string theory and are the Ramond-Ramond sources needed for string duality. Also, we find in the IIa string a 9-form potential, which gives an effective cosmological constant.

$$\mu_p^2 = 2\pi(4\pi^2\alpha')^{3-p}$$

$$\mu_p\mu_{6-p} = 2\pi$$

hep-th/9510017

This short note was an instant revelation, one of these rare moments when many seemingly disjoint pieces of a puzzle fall magically in place !

To put it in context, one should first realize that at this time **open strings** were something of a backwater of string theory, despite the fact that the Veneziano amplitude and the Green-Schwarz mechanism both refered to them

The heterotic string, more economical (modular invariance) and phenomenologically appealing (E8xE8, semirealistic vacua), was monopolizing the interest

One of the few groups working on open strings was the Roma II group of Augusto Sagnotti, with his students and later collaborators Bianchi, Pradisi & Angelantonj

They had understood several key ingredients, in particular **orientifolds**, and the necessity to cancel closed-string **tadpoles**

At about the same time, Joe with students Dai&Leigh had recognized that D-branes are dynamical **soliton-like** excitations of string theory :

New Connections Between String Theories

UTTG-12-89

To summarize, the dual theory to a theory of open plus closed oriented strings is a theory of closed strings coupled to a new dynamic object, the « D-brane" (short for Dirichlet-brane). The perpendicular U(l) gauge boson becomes the collective coordinate for motion of the D-brane. The remaining perpendicular gauge bosons, of SU(N), do not appear to have any such collective interpretation. The extension of the low energy effective action (15) to the full set of massless fields . . . is under study . . .

. . . . . However, as far as we are aware, the present work is the first interpretation of a Dirichlet hyperplane as an actual dynamical object, which can couple in a consistent way to closed strings

Some other premonitory indights

Shenker, Horava, Green . .

e^{-1/g_s}

T-duality

instantons

But the `declics' were (i) the advent of **string dualities,** (ii) Witten's **Strings'95** talk, and (iii) one (a posteriori simple) calculation

Hull+Townsend
Witten

from *Memories of a Theoretical Physicist* **arXiv:1708.09093**

Witten seemed astonished, and said that I should write this up . . . . . So I dropped everything and wrote . . . The paper took just a little over a week to write.

Most of it was a careful presentation of what was in the papers with Cai, and Dai and Leigh. But there was one new calculation that I felt was needed.

And so I began to realize that I had finally, at the ripe old age of 41, done something that had changed the direction of science . . . I had been living with D-branes for eight years, but never taking it too seriously because of the lack of heterotic D- branes

Those that got their physics education in the late 70's grew with **non-perturbative QFT, solitons and instantons.** Studying a soliton like the 't Hooft-Polyakov monopole required a series of steps:

- Solve the non-linear field eqns (often numerically)
- Find the spectrum of perturbative fluctuations
- Compute the low-E effective action

D-branes did all of that in a magic stroke !

They solved exactly the unkown closed-string field-theory equations, and had an effective action that was **non-abelian Yang-Mills**

Neveu, Scherk '72
`Connection between Yang-Mills fields and dual models'

As soon as I read Joe's paper, I decided this was the thing to work on.

I computed the scattering of D-branes, reprocessing a '92 paper with Massimo Porrati. Being in Santa Barbara I was talking to Joe and offered him to cosign the paper; he refused saying that he would not sign a paper unless he contributed to its calculations.

D-branes were a **Pandora's box,** allowing to reprocess all sorts of things in a totally new light. From the **Veneziano amplitude** one could extract for instance the α' corrections to D-brane actions

Tseytlin; Bain, CB, Green; Garousi . . .

D-branes changed the face of string theory, inspired/influenced most of the post-95 developments including Strominger-Vafa's microscopic derivation of **BH entropy**, and the advent of quantitative **Holography**

A small partial list:

- Dualities, dualities, . . . — cf Eliezer's talk
- New phenomenology — Arkani-Hamed, Dimopoulos, Dvali; Munich, Madrid, UPenn groups . . . cf Fernando's talk
- D-instanton calculations — Green et al; Torino group; cf Angel Uranga's talk
- D-brane engineering & 3D gauge theory — Hanany-Witten; . . .
- Tachyon condensation in SFT — Sen; . . .

Almost everyone in the room has/is probably worked/ing on some aspect of D-branes, and like with Gabriele's famous formula the fall offs keep coming in.

It would be inappropriate to try to summarize in few minutes

Subject: Re: wishes
From: "Joseph Polchinski" <joep@kitp.ucsb.edu>
Date: Sat, January 30, 2016 6:31 pm
To: bachas@lpt.ens.fr
Priority: Normal
Options: View Full Header | View Printable Version | Download this as a file | View Message Details | Add to Address Book

Dear Costas,

Thank you! I expect the best. I want to be there, and contributing, when we sort our quantum gravity.

Best,
Joe

> On Jan 29, 2016, at 11:49 PM, bachas@lpt.ens.fr wrote:
>
>
> Dear Joe,
>
>   I wish you all the best for your upcoming surgery, and look forward
> to many
> many exciting Polchinski papers   soon thereafter.
>
>   I am confident that this latest hacking attempt will fail !
>
> Cheers,
>
> Costas
>

Life does not always follow one's wishes . . . .

But I want to leave you with a **forward-looking** note:
a computation seeded (once more!) in D-branes

Not **History** but history still

Massive AdS gravity from String Theory

CB, Lavdas 1711.11372; 1805.xxxxx

An old question: **Can gravity be `higgsed' (become massive) ?**

Extensive (recent & less recent) literature:

Pauli, Fierz, Proc.Roy.Soc. 1939 . . . . .

Reviews: Hinterblicher 1105.3735; de Rham 1401.4173
Schmidt-May & von Strauss 1512.00021

A classical ghost-free theory exists, but is it an effective theory ?
and with what range of validity ?

de Rham, Gabadadze, Tolley '11
Hasan, Rosen '11

To answer such questions useful to have UV-completion of massive gravity, which is what I will describe here.

Note: AdS background is special: no **vDVZ** discontinuity & ensuing strong non-linearities within **Vainshtein** radius

Porrati '00;
Kogan, Mouslopoulos, Papazoglou '00

but still threat of **Boulware-Deser** ghost.

AdS/CFT holographic dictionary

graviton of AdS_4

$g_{\mu\nu}$

$\longleftrightarrow$

energy-momentum of CFT_3

T_{ab}

mass

$$m^2 = \Delta(\Delta - 3)$$

scaling dimension

Conserved e-m tensor has $\Delta = 3$

this follows from representation theory of the conformal group $SO(2,3)$

$D(\Delta, j = 2)$ must be short rep since $\partial^a T_{ab} = 0$ gives null state

$\therefore$ massive graviton $\longleftrightarrow$ dissipative energy-momentum

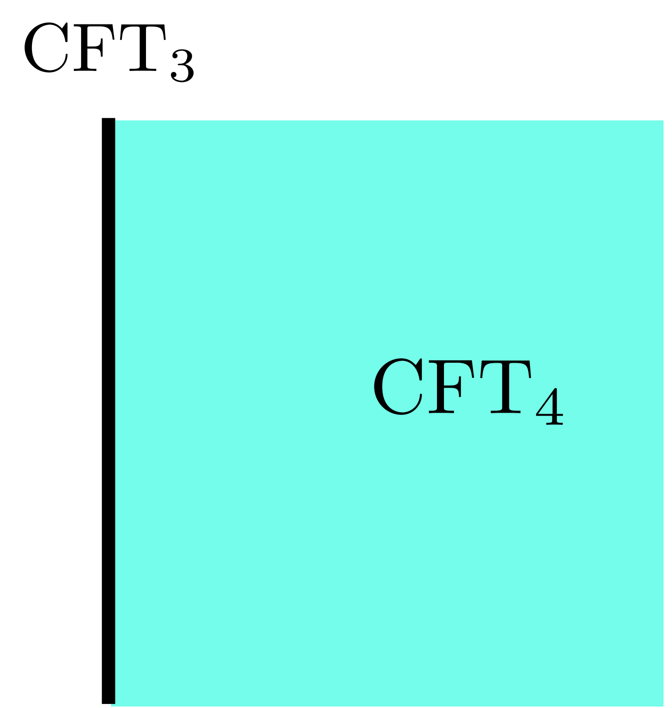
For dissipation one needs new degrees of freedom :

- another CFT_3 , but since total e-m tensor is conserved there exists <u>both</u> a massless and a massive graviton

bimetric

- a `bulk' CFT_4

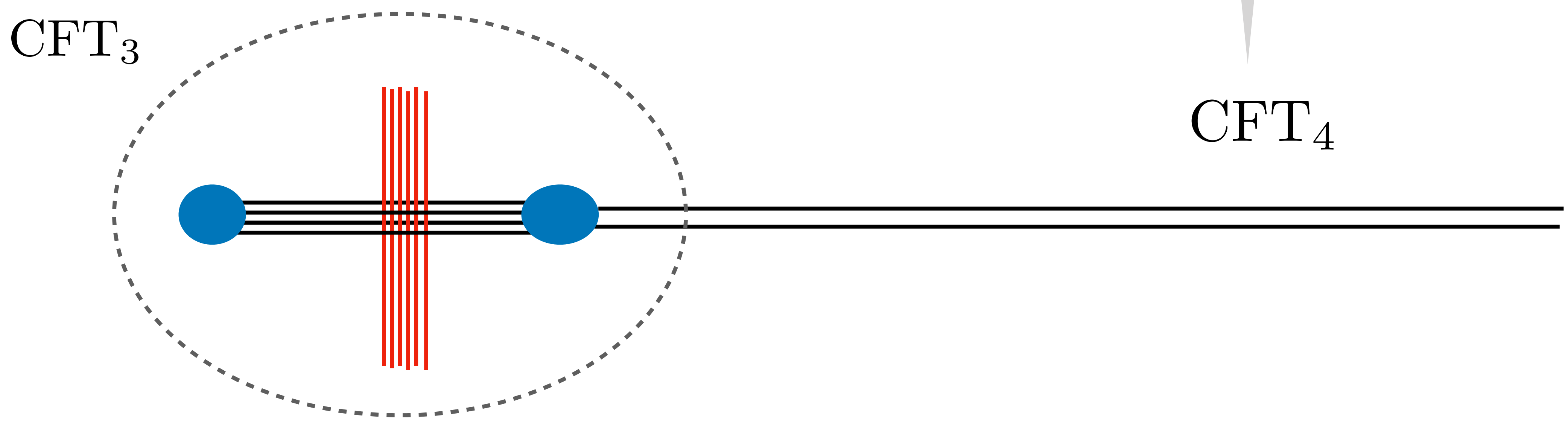
$\partial^a T_{ab} = T_{b\perp}$ is not null



decoupling

small AdS mass $\longleftrightarrow$ small CFT energy leakage

Setup: **boundary** N=4 d=4 $SU(n)$ super Yang-Mills



Hanany-Witten '96

Gaiotto-Witten '08

	012	3	456	789
D3	x	x		
D5	x		x	
NS5	x			x

'Fat CFT3' contains most degrees of freedom

But strongly-coupled, & Δ is not a priori susy protected

so how to compute it in field theory ?

<u>Our result</u>: a computation on the gravity side

$$3(\Delta - 3) \simeq \quad m^2 = \frac{3}{16\pi^2}\,\kappa_4^2\,n^2$$

CB, Lavdas 1711.11372

no dilaton jump

$$\times F(\Delta\phi, n)$$

with dilaton jump: in progress

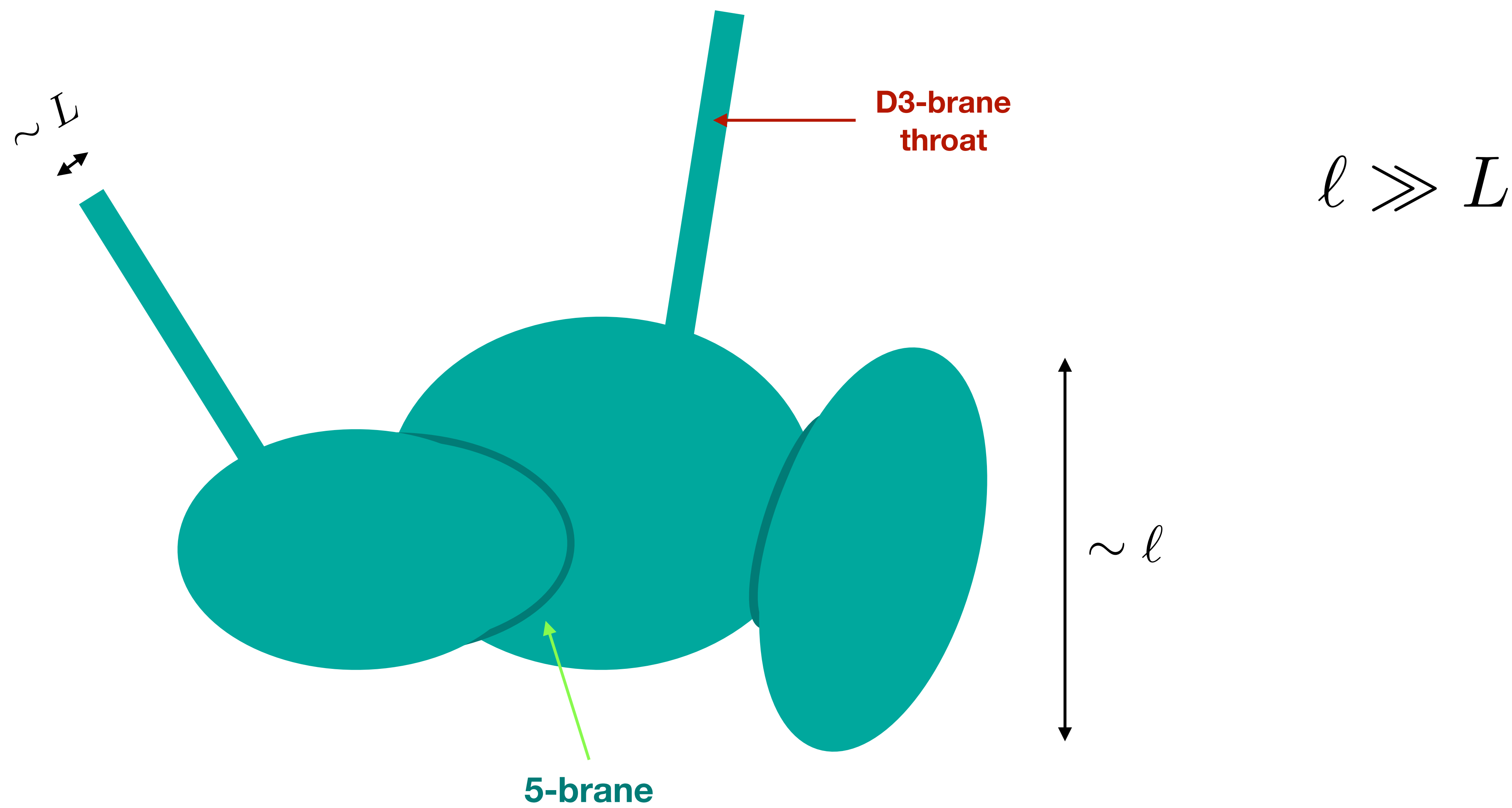
How is it computed ?

Find dual near-horizon geometries (N=4 AdS4xM6 solutions of IIB sugra)

D'Hoker, Estes, Gutperle 0705.0022 ; 0705.0024 **general local**

Assel, CB, Estes, Gomis 1106.4253 ; 1210.2590 **global**

(see also CB, Estes 1103.2800;
Aharony, Berdichevsky, Berkooz, Shamir 1106.1870;
CB, Bianchi, Hanany arXiv: 1711.06722)



The non-compact `compactification' manifold looks like scottish **Bagpipes:**

pipe: cutoff $\mathrm{AdS}_5 \times \mathrm{S}^5$ throat of radius $L^4 = 4\pi n \alpha'^{\,2}$

bag: compact manifold $\tilde{M}_6$, eff. gravity coupling κ_4

The graviton mass is the minimum (over normalized wavefunctions) of

$$\int_{M_6} \sqrt{g} e^{4A} |\partial\psi|^2$$

CB, Estes 1103.2800

The optimal wavefunction minimizes this quantity inside the AdS5 throat

$$ds^2 \sim L^2[dx^2 + (\cosh x)^2 ds^2_{\mathrm{AdS}_4}] + ds^2_{S^5}$$

with boundary conditions:

$\psi \simeq \psi_0 = \#\kappa_4$	$\psi \simeq 0$
$x \to -\infty$	$x \to \infty$
bag	semiinfinite **pipe**

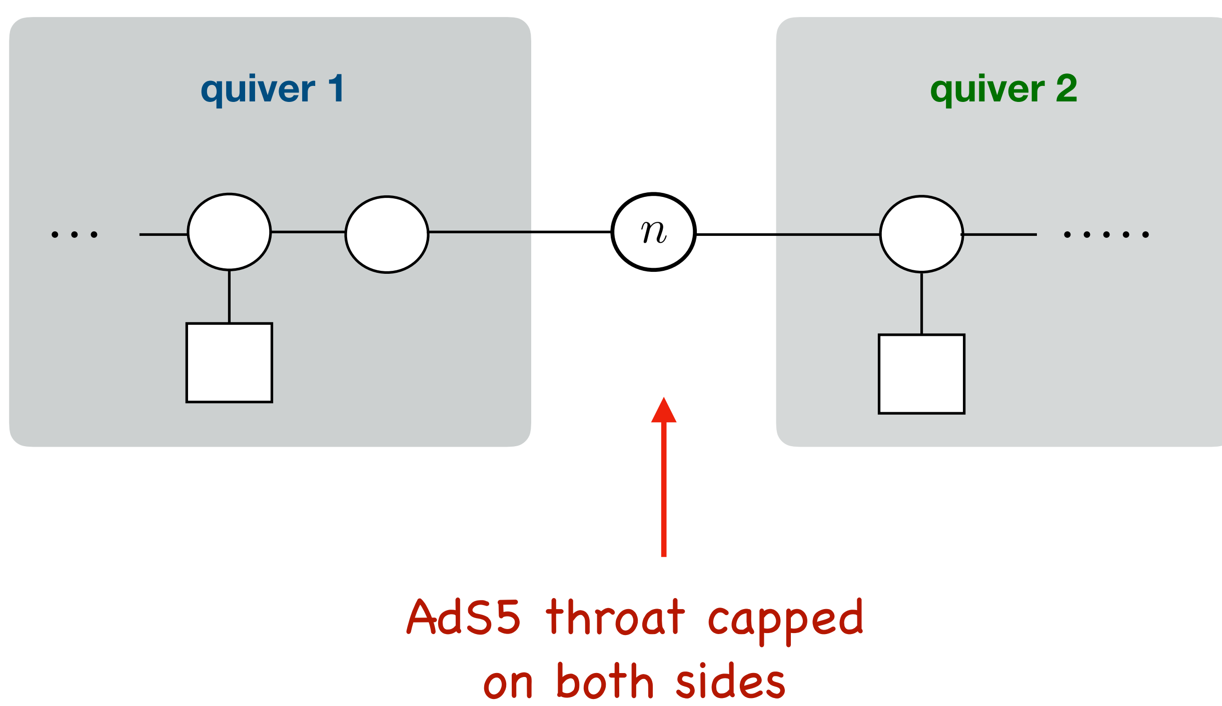
normalizable because of bag cutoff

Remarks

— String embedding of toy (`thin brane') model of Karch+Randall '00

— Result only depends on bnry via κ_4 (and dilaton jump)

— Closely-related **bi-gravity** model:



Compare with double-trace deformation of two disjoint CFTs:

$$m^2 \simeq h^2\left(\frac{1}{c_1} + \frac{1}{c_2}\right)$$

coupling → h; central charge → c_2

Aharony, Clark, Karch '06 ;
Kiritsis, Niarchos

Looks similar in nature, but in our case: conformal invariance guaranteed,
& string theory manifestly local

Can the comparison be made precise ?

Thank you for your

attention