Massive AdS (Super)Gravity & Holography

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September 2019

Based on arXiv: **1711.11372 ; 1807.00591** with **Ioannis Lavdas**

& arXiv: **1905.05039**

Collaborators on closely related work:

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Amihay **Hanany** & Bruno **Le Floch**

A Higgs mechanism for Gravity ?

A question with a long history:

Fierz - Pauli 1939

. . . .

Van Dam, Veltman, Zakharov 1970

Vainshtein 1972

Boulware, Deser 1973

. . . .

Arkani-Hamed, Georgi, Schwartz 2002

't Hooft; Chamseddine, Mukhanov; . . .

de Rham, Gabadadze, Tolley 2011

Hassan, Rosen 2011

cf. (spin-1) gauge theory:

$$\mathcal{L} = \mathrm{tr}\left[-\frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu} + v^2(A_\mu - U^\dagger\partial_\mu U)(A^\mu - U^\dagger\partial^\mu U)\right]$$

U : three [for SU(2)] scalar Stueckelberg fields

Breakdown of perturbative unitarity at $E \sim v = m/g$

Restore with Higgs particle:

$$\Phi = U\begin{pmatrix} v + h \\ 0 \end{pmatrix}$$

For (spin-2) gravity:

Stueckelberg fields :

massless vector + scalar
$\|\|$
massive vector

Geometric interpretation from **bimetric** theories (two Universes + interaction):

$$S_{\rm bm} \sim m^2_{\rm Planck} \int d^4x \sqrt{g}[R(g) + \lambda] \quad + \quad M^2_{\rm Planck} \int d^4X \sqrt{G}[R(G) + \Lambda]$$

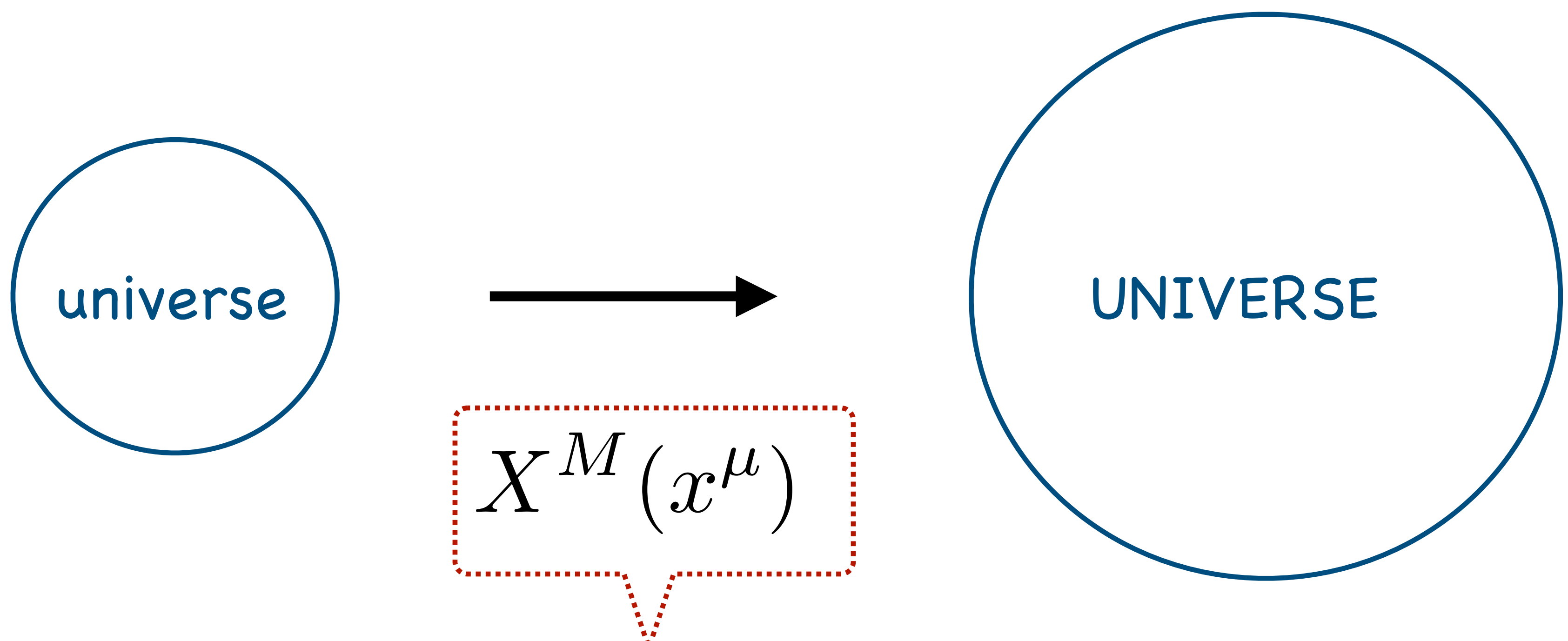
$$+ \boxed{m^2 m^2_{\rm Planck} \int d^4x \sqrt{g}\, f(g^{\mu\nu} \hat{G}_{\mu\nu})}$$

where $\quad \hat{G}_{\mu\nu} = G_{MN}(X) \partial_\mu X^M \partial_\nu X^N$

Mixing two massless gravitons : one massless & one massive

In the limit $M_{\text{Planck}} \to \infty$ the massless one decouples

and we are left with **massive gravity.**



Four Stueckelberg scalars

In consistent effective theory one of these should drop out.

This happens in the **dRGT** [3 parameter] action

Ultimate breakdown scale in Minkowski : $E_\star = (m^2 m_{\text{Planck}})^{1/3}$

Tension with GW data:	LIGO quotes $m \leq 10^{-23}\, eV$ $E_\star \sim 10^{-6}\, eV$

Analog of 'Higgs particle' ? Need quantum (UV) embedding

Have found one (but) for **AdS** (super)gravity

technical control ?

Massive AdS supergravities

Particle states in AdS_{d+1} form representations of the

conformal group $\mathrm{SO}(2,d) \supset \mathbb{R} \times \mathrm{SO}(d)$

energy ang.mom.

Lowest-lying (in $d=3$): spin s , energy Δ

Corresponding unitary representation denoted $[s]_\Delta$

Massless particles for $s > \frac{1}{2}$: $\Delta = s+1$

$[s]_\Delta$ is a **short** representation

At the unitarity threshold, $\Delta \to s+1$

$$\boxed{[s]_\Delta} \to \boxed{[s]_{s+1}} \oplus \boxed{[s-1]_{s+2}}$$

Long **Short** **Stueckelberg**

For spin 2 : $[2]_{3+\epsilon} \to [2]_3 \oplus [1]_4$ Stueckelberg = massive vector

Massless graviton + `Goldstone' → **Massive** graviton

Porrati 2001, 2003

Supersymmetry:

Conformal group ⟶ **Super**conformal group

$$d \leq 6$$

e.g. $\mathrm{SO}(2,3) \rightarrow \mathrm{Osp}(4|N)$

Nahm 1978

Goldstone multiplet ⟶ Goldstone **super**multiplet

includes spin 3/2

Absolutely protected massless supergravitons

[short spin-2 supermultiplets]

$$\Longrightarrow \quad d \leq 4 \qquad N \leq \frac{1}{2}\mathrm{max}$$

Cordova, Dumitrescu, Intriligator 1612.00809

ruled out

$$\mathrm{AdS}_{D>5}$$

$$N > \frac{1}{2}\max$$

	Susy	$\mathfrak{g}$	Massless graviton
AdS_7	$\mathcal{N}$=(2,0)	$\mathfrak{osp}(8^*\|4)$	$D_1[0,0,0]_4^{(0,2)}$
	$\mathcal{N}$=(1,0)	$\mathfrak{osp}(8^*\|2)$	$B_3[0,0,0]_4^{(0)}$
AdS_6	$\mathcal{N}=1$	$\mathfrak{f}(4)$	$B_2[0,0]_3^{(0)}$
AdS_5	$\mathcal{N}=4$	$\mathfrak{psu}(2,2\|4)$	$B_1\bar{B}_1[0;0]_2^{(2,0,2)}$
	$\mathcal{N}=3$	$\mathfrak{su}(2,2\|3)$	$B_1\bar{B}_1[0;0]_2^{(1,1;0)}$
AdS_4	$\mathcal{N}=8$	$\mathfrak{osp}(8\|4)$	$B_1[0]_1^{(0,0,0,2)\ \text{or}\ (0,0,2,0)}$
	$\mathcal{N}=7$	$\mathfrak{osp}(7\|4)$	$B_1[0]_1^{(0,0,2)}$
	$\mathcal{N}=6$	$\mathfrak{osp}(6\|4)$	$B_1[0]_1^{(0,1,1)}$
	$\mathcal{N}=5$	$\mathfrak{osp}(5\|4)$	$B_1[0]_1^{(1,0)}$

Table 1: The AdS_D supergravities for which the massless graviton is in an absolutely protected representation. We list the number of supersymmetries, the superconformal algebra $\mathfrak{g}$, and the absolutely protected representation in the notation of ref. [9]. The list includes all cases in $D > 5$ dimensions, and all cases with more than half-maximal supersymmetry for reasons explained in the main text. The table has redundancies: when the massless graviton is protected for given $(D, \mathcal{N}_0)$ it is also protected for all $(D, \mathcal{N} > \mathcal{N}_0)$.

kinematically allowed Msugras

	Susy	Multitrace	Massless graviton	Stueckelberg
AdS_5	$\mathcal{N}=2$	no	$A_2\bar{A}_2[0;0]_2^{(0;0)}$	$B_1\bar{B}_1[0;0]_4^{(4;0)} \oplus \left(A_2\bar{B}_1[0;0]_3^{(2;2)} \oplus \mathrm{cc}\right)$
	$\mathcal{N}=1$	yes	$A_1\bar{A}_1[1;1]_3^{(0)}$	$L\bar{A}_2[1;0]_{7/2}^{(1)} \oplus \mathrm{cc}$
AdS_4	$\mathcal{N}=4$	no	$A_2[0]_1^{0,0)}$	$B_1[0]_2^{(2,2)}$
	$\mathcal{N}=3$	no	$A_1[1]_{3/2}^{(0)}$	$A_2[0]_2^{(2)}$
	$\mathcal{N}=2$	yes	$A_1\bar{A}_1[2]_2^{(0)}$	$L\bar{A}_1[1]_{5/2}^{(1)} \oplus \mathrm{cc}$
	$\mathcal{N}=1$	yes	$A_1[3]_{5/2}$	$L[2]_3$

Table 2: The AdS supergravities for which the graviton multiplet can obtain a mass by gauging a global symmetry of the dual SCFT. The alternative 'multi-trace mechanism' is only possible for $N_Q \leq 4$ supercharges. The superconformal algebras are $\mathfrak{su}(2,2|\mathcal{N})$ in $d=4$ and $\mathfrak{osp}(\mathcal{N}|4)$ in $d=3$. The two right-most columns list the massless graviton and the Stueckelberg multiplets in the notation of ref. [9]. The massive graviton multiplets contain 2^{N_Q-1} bosonic and 2^{N_Q-1} fermionic states.

3.3 Stueckelberg multiplets

Case of N=4, D=4 supergraviton :

$$L[0]_{1+\epsilon}^{(0;0)} \xrightarrow{\epsilon\to 0} A_2[0]_1^{(0;0)} \oplus B_1[0]_2^{(1;1)}$$

massive supergraviton

graviton supermultiplet
(6 vectors, 2 scalars)

Goldstone mode
112 bosonic d.o.f.
& 4 **spin-3/2 fermion**

bosons : $[0]_1^{(0;0)} \oplus [0]_2^{(0;0)} \oplus [1]_2^{(1;0)\oplus(0;1)} \oplus [2]_3^{(0;0)}$

fermions : $[1/2]_{\frac{3}{2}}^{(\frac{1}{2};\frac{1}{2})} \oplus [3/2]_{\frac{5}{2}}^{(\frac{1}{2};\frac{1}{2})}$

bosons : $[0]_2^{(1;1)} \oplus [1]_3^{(1;1)\oplus(1;0)\oplus(0;1)} \oplus [0]_3^{(2;0)\oplus(0;2)\oplus(1;0)\oplus(0;1)\oplus(1;1)\oplus(0;0)}$
$\oplus [1]_4^{(0;0)\oplus(1;0)\oplus(0;1)} \oplus [0]_4^{(1;1)\oplus(0;0)} \oplus [0]_5^{(0;0)}$

fermions : $[1/2]_{\frac{5}{2}}^{(\frac{3}{2};\frac{1}{2})\oplus(\frac{1}{2};\frac{3}{2})\oplus(\frac{1}{2};\frac{1}{2})} \oplus [3/2]_{\frac{7}{2}}^{(\frac{1}{2};\frac{1}{2})} \oplus [1/2]_{\frac{7}{2}}^{(\frac{3}{2};\frac{1}{2})\oplus(\frac{1}{2};\frac{3}{2})\oplus 2(\frac{1}{2};\frac{1}{2})} \oplus [1/2]_{\frac{9}{2}}^{(\frac{1}{2};\frac{1}{2})}$

A technical challenge :

Construct N=4, D=4 massive AdS supergravity

$$m \ll \frac{1}{\ell_{\rm AdS}}$$

NB1: The extra spin-3/2 Goldstones **NOT** part of 4d gauged supergravity

But part of (gauged) N=8 sugra

CB, Severin Luest in progress

NB2: Massive N=4 supergravity in Minkowski with higher-R terms by

Ferrara, Kehagias, Dieter Luest 2018

Holographic duals

DICTIONARY:

CFT	**gravity**
energy-momentum tensor t_{ij}	graviton $h_{\mu\nu}$
dimension Δ	mass m

$$\boxed{\Delta(\Delta-3) \;=\; m^2\ell^2_{\rm AdS}}$$

conserved	$\partial^i t_{ij} = 0$	massless
leaking	$\partial^i t_{ij} = V_j$	Stueckelberg

BIMETRIC DUAL :

$$\mathcal{L} = \mathcal{L}_{\rm cft} + \mathcal{L}_{\rm CFT} + \delta\mathcal{L}$$

$\delta\mathcal{L} = 0$ (decoupled) $\Longrightarrow$ $t_{ij}\,, T_{ij}$ separately conserved

$\Longrightarrow$ two massless gravitons

`small' coupling $\Longrightarrow$

$\dfrac{t_{ij} + T_{ij}}{\sqrt{c + C}}$	total conserved
$\dfrac{C t_{ij} - c T_{ij}}{\sqrt{C^2 c + c^2 C}}$	$\Delta = 3 + \epsilon, \quad \epsilon \ll 1$

$C \to \infty$ limit of massive gravity

TWO `MECHANISMS' :

1. Double trace $\delta\mathcal{L} = \lambda\,\mathrm{tr}(o)\mathrm{tr}(\mathcal{O})$ `quantum' in gravity

CFT perturbation theory:

$$\epsilon \;=\; \#\lambda^2(\frac{1}{c} + \frac{1}{C})$$

Kiritsis 2006

Aharony, Clark, Karch 2006

Kiritsis, Niarchos 2008

Relevant/marginal deformations $\Longrightarrow$ $$N \leq \frac{1}{4}\max$$

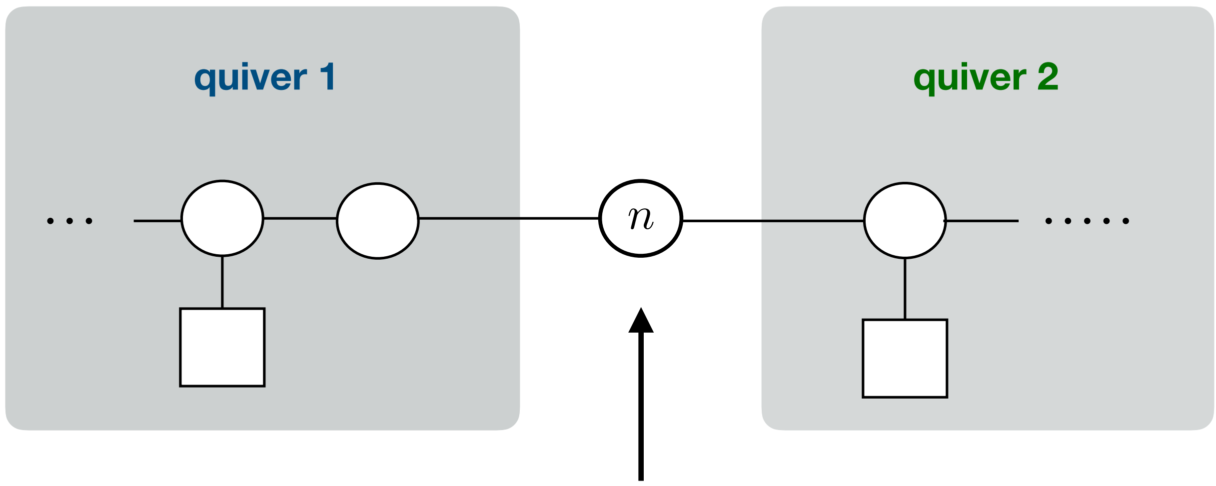
Superpotential deforms $\delta W = \phi\Phi$

Stueckelberg superfield $\phi D_\alpha \Phi - \Phi D_\alpha \phi$

CB 1905.05039

2. Gauge mediation

gauge common global symmetry



low-n or **weakly-coupled**
U(n) messenger gauge field

Allowed by $\boxed{N = \frac{1}{2}\max}$

$N = 2, d = 4$
$N = 4, d = 3$

Stueckelberg in $(\text{conserved current}) \otimes (\text{free vector})$ multiplet

String theory embedding

The embedding uses a well-studied class of

$N = 4 \;\; \mathrm{AdS}_4/\mathrm{SCFT}_3$ dual pairs

<u>On CFT side</u>: \`good linear-quiver' theories with IR fixed points

Hanany, Witten 1996

Gaiotto, Witten 2008

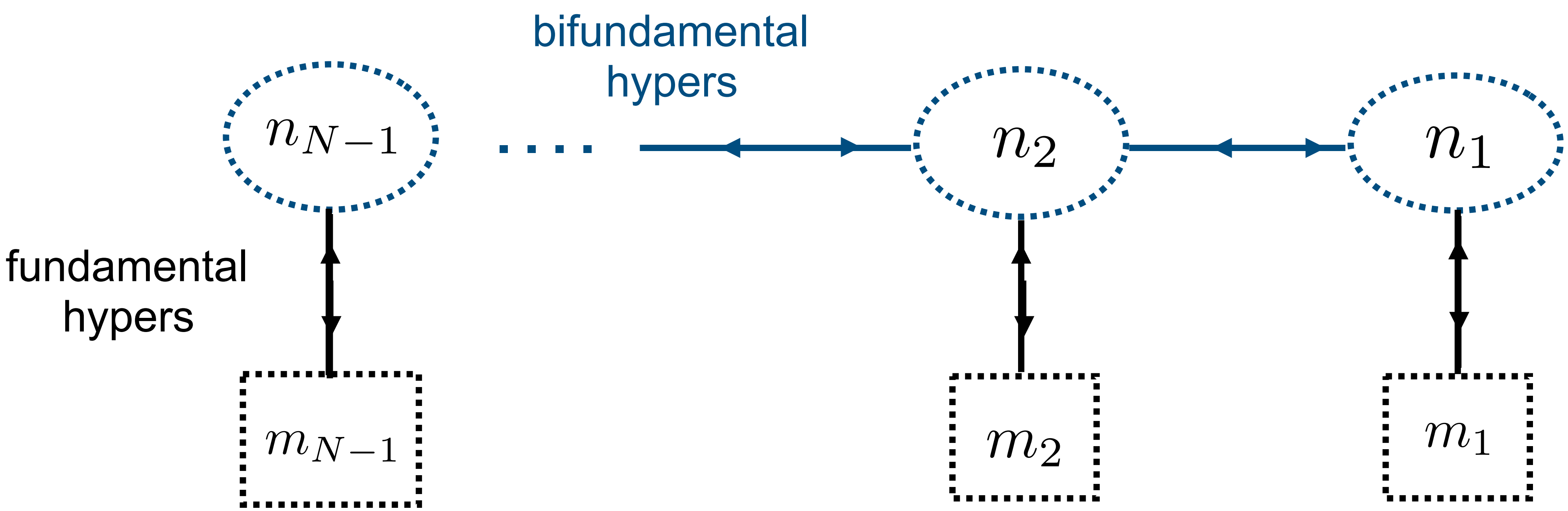
The quiver describes the gauge group and hypermultiplet content

masses = FI terms = 0; gauge couplings flow to ∞

no other free parameters

The field content of the (Lagrangian) theory is determined by a **quiver diagram:**

A-type quiver



Gauge group: $U(n_1) \times U(n_2) \times \cdots \times U(n_{N-1})$

Flavor symmetry: $\left[U(m_1) \times U(m_2) \times \cdots \times U(m_{N-1})\right] / U(1)$

On gravity side: Exact IIB solutions and holographic dictionary known

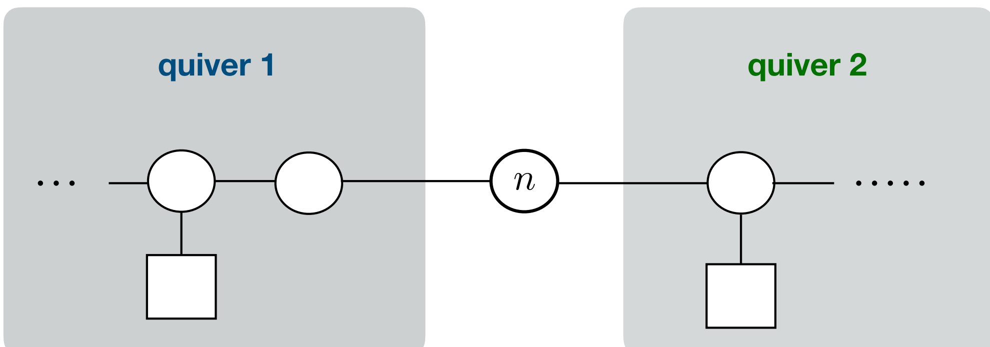
D'Hoker, Estes, Gutperle 2007

Aharony, Berdichevsky, Berkooz, Shamir 2011

Assel, CB, Estes, Gomis 2011

Gauge-group ranks = f(brane charges) $\longrightarrow$ continuous in supergravity

Step 1: Compute the geometry in the degeneration limit $n \to 0$



Step 2: Compute the spin-2 Kaluza-Klein spectrum cf CB, Estes 2011

Graviton mass

$$\epsilon \simeq \frac{1}{3} m^2 \ell^2_{\rm AdS} = \lambda^2_{\rm eff} (\frac{1}{c} + \frac{1}{C})$$

$$\lambda^2_{\rm eff} = \frac{n^2}{4\pi^4} \frac{\tanh^3 \delta\phi}{|\delta\phi - \tanh \delta\phi|}$$

$\delta\phi$: dilaton variation of two universes

$$\frac{n^2}{c} \sim \frac{\text{d.o.f. mediator}}{\text{d.o.f. universe}}$$

$m\ell_{\rm AdS}$ can be made parametrically small

Breakdown of Stueckelberg theory: $$E_\star \sim \left(\frac{m\, m_{\rm Planck}}{\ell_{\rm AdS}} \right)^{\frac{1}{3}}$$

Spins < 2 do not help (?)

Tower of spin-2 or more must come down in $m \to 0$ limit

Non BPS spin-2 modes (in Janus throat) shown indeed to condense

visible in CFT ? bootstrap ?

Similar phenomenon for double-trace coupling ?

Conclusions & Outlook

- Massive AdS N=4, D=4 supergravity can be UV completed

  (part of the landscape)

- Construct the Lagrangian; deform N=8 ?

- Embedding for D=5 ? (class-S theories)

- Minkowski ? Phenomenology ?