Massive Gravity: Landscape or Swampland?

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Conference on "**Strings, Geometry and the Swampland**"

Schloss Ringberg *(November 8-12, 2021)*

Relevant papers :

CB, I. Lavdas arXiv: 1711.11372; arXiv: 1807.00591

CB, B. Le Floch, I. Lavdas arXiv: 1905.0697 + in progress

CB, S. Lüst in progress

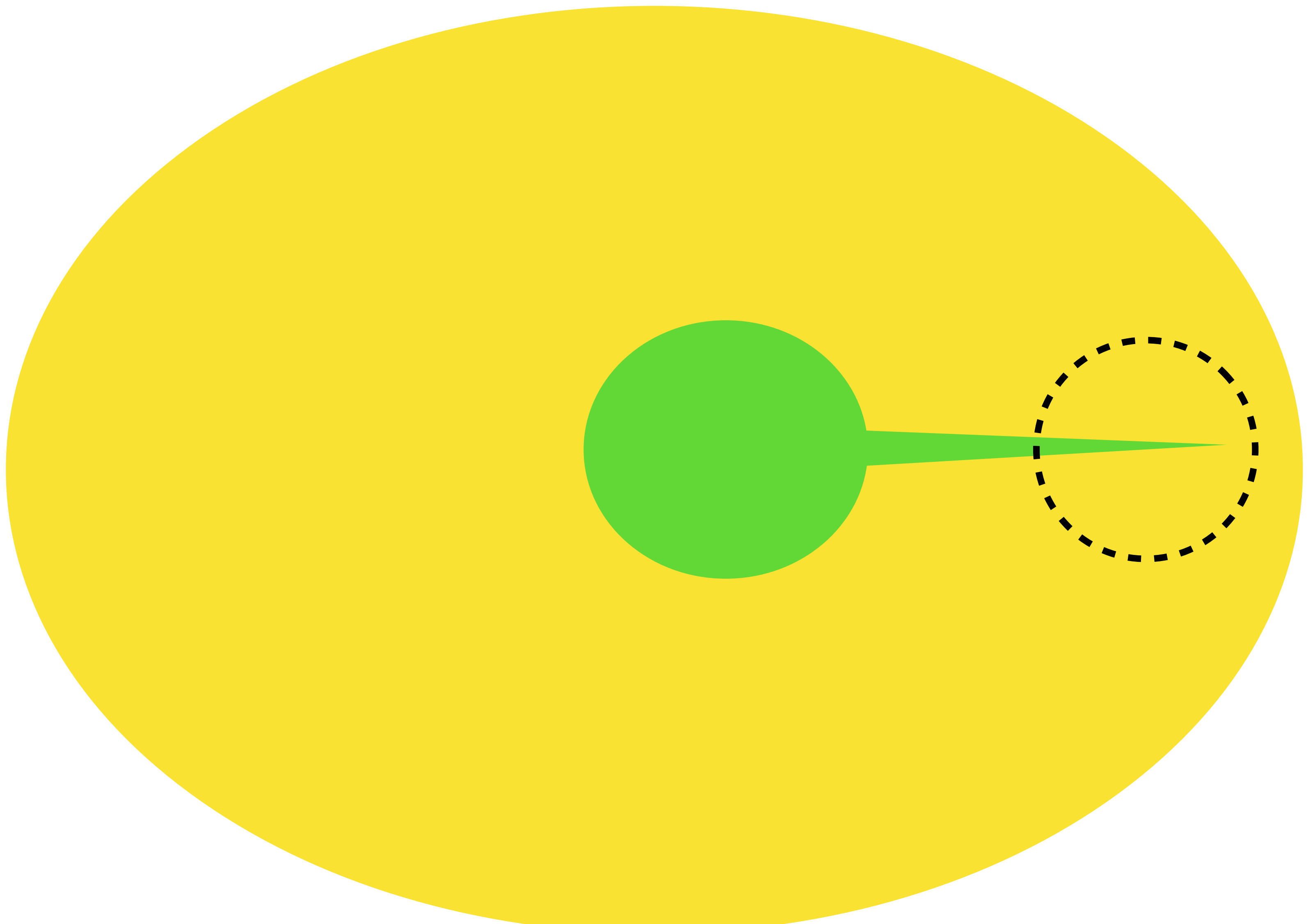
Today I will mainly rely on: CB **arXiv: 1905.05039**

and try to review more broadly the issue:

Are massive-gravity and bigravity EFTs in the string landscape or in swampland ?

Massive gravity & bigravity:

An unfamiliar corner of the Landscape/Swampland



bottom-up models ???

Randall, Sundrum, Karch
Dvali, Gabadadze, Porrati

ghost-free EFTs ??

de Rham Gabadadze, Tolley
Hassan, Rosen

particular IIB AdS embedding

CB, Lavdas

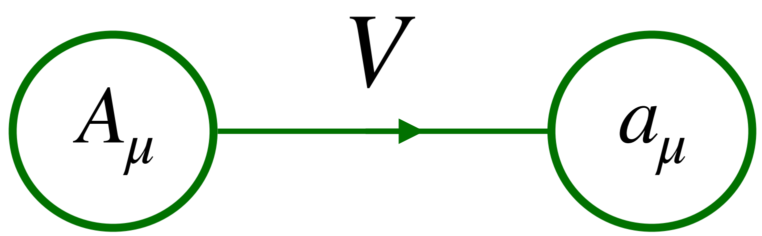
Plan

1. EFTs for bigravity and massive gravity
2. AdS and supersymmetry
3. Holographic mechanisms
4. String theory embeddings
5. A (wild) conjecture

Brout-Englert-Higgs mechanism for interacting spin-1 fields:

Spontaneous breaking $\quad G \times G \to G_{\text{diag}}$

Stückelberg or "Goldstones" $\quad G \ni V \to u V \mathcal{U}^\dagger$



non-linear sigma model

$$S_{\text{YM}} = \int d^4x \left[-\frac{1}{4g_1^2} \sum_a F^a_{\mu\nu} F^{\mu\nu,a} - \frac{1}{4g_2^2} \sum_a f^a_{\mu\nu} f^{\mu\nu,a} + \frac{m^2}{2(g_1^2 + g_2^2)} \mathrm{tr}\Big((D_\mu V)^\dagger D^\mu V \Big) \right]$$

gauge-invariant mass term

$g_2 \to 0$ decouples one set of gauge bosons

Scales: m , $\Lambda = \frac{m}{g_1}$

cutoff of EFT

New particles or strong coupling

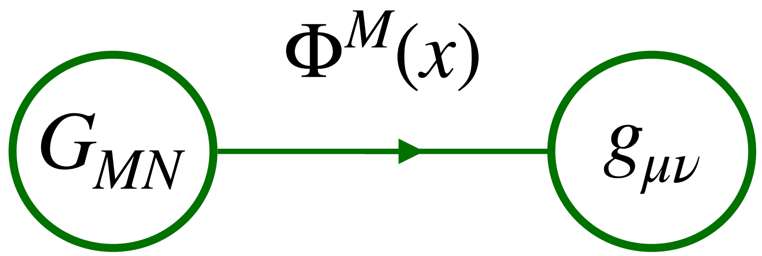
For weak interactions LHC has settled the issue in favour of Higgs

Unless $m \ll \Lambda$ there is no EFT

NB in passing: $\mathrm{WGC} \Leftrightarrow \Lambda < M_{\mathrm{Planck}}$

A similar reasoning applied to gravity:

Arkani-Hamed, Georgi, Schwartz



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

Scalar under X-diffeo
Tensor under x-diffeo

$$S_{\text{bigrav}} = -\frac{1}{2\kappa_1^2}\int d^4X\sqrt{G}\,\left[R(G)+\Lambda_1\right] - \frac{1}{2\kappa_2^2}\int d^4x\sqrt{g}\,\left[R(g)+\Lambda_2\right]$$

$$+\frac{m^2}{2(\kappa_1^2+\kappa_2^2)}\int d^4x\sqrt{g}\,F(g_{\mu\nu},\hat{G}_{\mu\nu})$$

$\kappa_1 \to 0$ decouples one graviton, freezes G_{MN} to a fiducial metric $\longrightarrow$ massive gravity

Up to here same as for spin 1

But crucial difference:

$\Phi^M(x)$ has 4 degrees of freedom,

3 missing polarizations + a ghost

Choosing F to be `mixed volume elements' decouples the ghost

e.g. $\int e_{abcd}\, e^a \wedge e^b \wedge \hat{E}^c \wedge \hat{E}^d$

Hinterblicher, Rosen

Fierz, Pauli

de Rham, Gabadadze, Tolley

Hassan, Rosen

By analogy one could have expected a cutoff scale $\Lambda_2 \sim \sqrt{\frac{m}{\kappa}}$

Analysis of dRGT in Minkowski gives instead $\Lambda_3 \sim \left(\frac{m^2}{\kappa}\right)^{1/3}$

Although specific to dRGT, this seems to be an "ultimate breakdown scale"

- No choice of F does better

- No spins < 2 can improve the bad high-E behavior

Bonifacio, Hinterblicher, Rosen

- Analyticity + improved unitarity of 4-point scattering indicates lower cutoff Λ_4

Cheung, Remmen;
Bellazzini et al;
de Rham, Melville, Tolley

Can dRGT or any variant EFT of massive gravity be in the Landscape ?

The **strong spin-2 swampland conjecture** says **NO** Kläwer, Lüst, Palti

cutoff: $\Lambda_1 \sim m$

$\exists$ evidence favouring this in Minkowski background see end

But the story looks different in AdS

Disclaimer:

The low cutoff limits the phenomenological viability of m-gravity, though observations test the theory in cosmological bakgrounds and with massive sources

Dvali; . . .

But the question is of theoretical interest in its own right since IR modifications of gravity are **rare**

2. AdS & supersymmetry

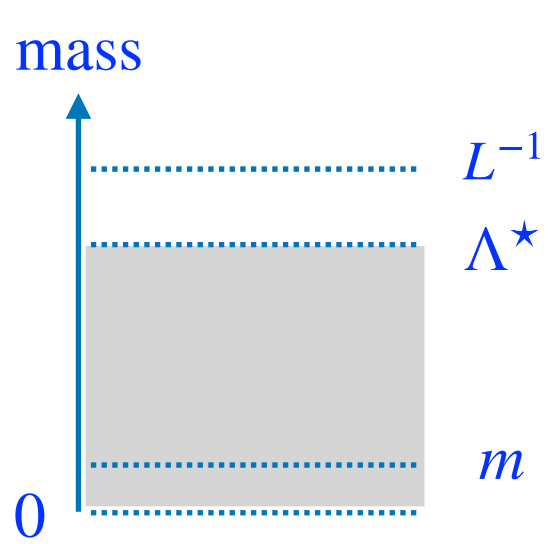
Why AdS ?

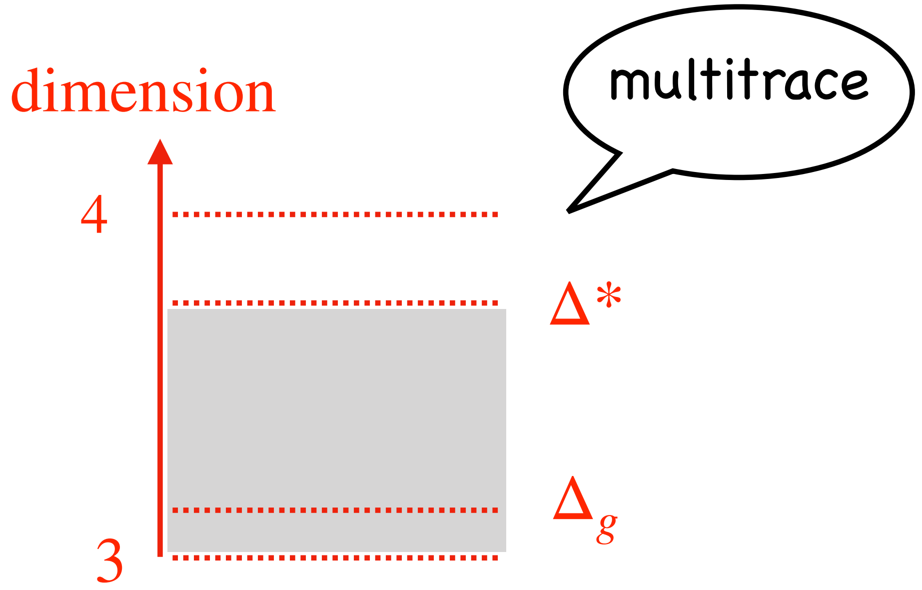
- because $\exists$ IIB string embedding
- because the dual CFT question is very interesting

Main difference in AdS dRGT : cutoff

$$\Lambda^\star \sim \left(\frac{m}{L\,\kappa}\right)^{1/3}$$

For "EFT" need $mL \ll 1$; $m \ll \Lambda^\star$





Why susy ?

For technical convenience

Actually even N=1 susy ghost-free theory not yet constructed

Zinoviev; . . .

But IIB embedding indicates that **maximal, N=4** extension exists

If so it should be a very special theory, like the conventional maximal supergravities

Superconformal representation theory narrows down possibilities

Consider to start BEH of spin S in D=4 dimensions:

This converts a short rep into a long rep of $SO(2,3)$

Mass $m^2 \sim \Delta - s - 1$ Scaling dimension

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

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

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

With $\mathcal{N}=4$ supersymmetry the particles belong to reps of $\mathrm{Osp}(4\,|\,4)$

These are classified

Dolan

Cordova, Dumitrescu, Intriligator

BEH of the supergraviton amounts to

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

massive supergraviton

graviton supermultiplet
(6 vectors, 2 scalars)

Stückelberg :

112 bosonic d.o.f.
& four **spin 3/2 fermions**

2^8 = helicity states = 128 bosons + 128 fermions

This is not possible for superconformal symmetries where the graviton supermultiplet is separated from continuum by mass gap

	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	$\mathcal{N}=8$	$\mathfrak{osp}(8\|4)$	$B_1[0]_1^{(0,0,0,2)\ \text{or}\ (0,0,2,0)}$
	$\mathcal{N}=7$	$\mathfrak{osp}(7\|4)$	$B_1[0]_1^{(0,0,2)}$
	$\mathcal{N}=6$	$\mathfrak{osp}(6\|4)$	$B_1[0]_1^{(0,1,1)}$
	$\mathcal{N}=5$	$\mathfrak{osp}(5\|4)$	$B_1[0]_1^{(1,0)}$

$D > 5$

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

ruled out

fits nicely with M-theory expectations of possible bnrs + defects

kinematically allowed m-sugras

		Susy	Multitrace	Massless graviton	Stueckelberg
m-ads5	AdS_5	$\mathcal{N}=2$	no	$A_2\bar{A}_2[0;0]_2^{(0;0)}$	$B_1\bar{B}_1[0;0]_4^{(4;0)} \oplus \left(A_2\bar{B}_1[0;0]_3^{(2;2)} \oplus \text{cc}\right)$
		$\mathcal{N}=1$	yes	$A_1\bar{A}_1[1;1]_3^{(0)}$	$L\bar{A}_2[1;0]_{7/2}^{(1)} \oplus \text{cc}$
m-ads4	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	$A_1\bar{A}_1[2]_2^{(0)}$	$L\bar{A}_1[1]_{5/2}^{(1)} \oplus \text{cc}$
		$\mathcal{N}=1$	yes	$A_1[3]_{5/2}$	$L[2]_3$

In all cases the Stückelberg multiplet includes (extra) spin-3/2 gravitinos

Can these massive supergravities be constructed ? Do they exist ?

Remark

N=4 D=4 compatible with BEH of spin 2

but not of spin 1

because massless spin-1 multiplets are absolutely protected

Louis, Triendl '14
Corodova et al '16

Global symmetries of dual $SCFT_3$ cannot break under marginal deformations; but em conservation can

3. Holographic BEH mechanisms

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

$$\Delta(\Delta - d) = m^2 \ell_{\rm AdS}^2$$

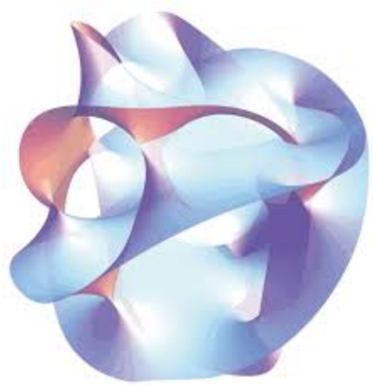
$$< tt > \sim c \sim (m_{\rm Pl} \ell_{\rm AdS})^{d-1}$$

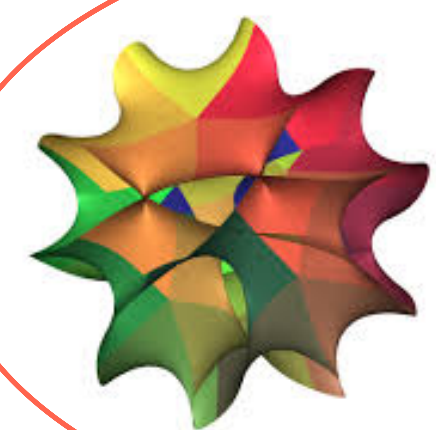
conserved $\quad \partial^i t_{ij} = 0 \quad$ massless

\`leaking' $\quad \partial^i t_{ij} = V_j \quad \longleftarrow \quad$ Stückelberg

DUAL of BIMETRIC TH:

$\mathrm{ads}_4 \times_w$





${}_w\times\ \mathrm{ADS}_4$

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

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

$\Longrightarrow$ two massless gravitons

'weak' coupling $\Longrightarrow$

$$T^{\text{tot}}_{ij} = \frac{t_{ij} + T_{ij}}{\sqrt{c + C}} \quad \text{conserved}$$

$$T^{\text{rel}}_{ij} = \frac{C t_{ij} - c T_{ij}}{\sqrt{C^2 c + c^2 C}} \quad \Delta = d + \epsilon$$

$\epsilon \ll 1$ & all other spin-2 ops have $\Delta = d + o(\epsilon)$

gap

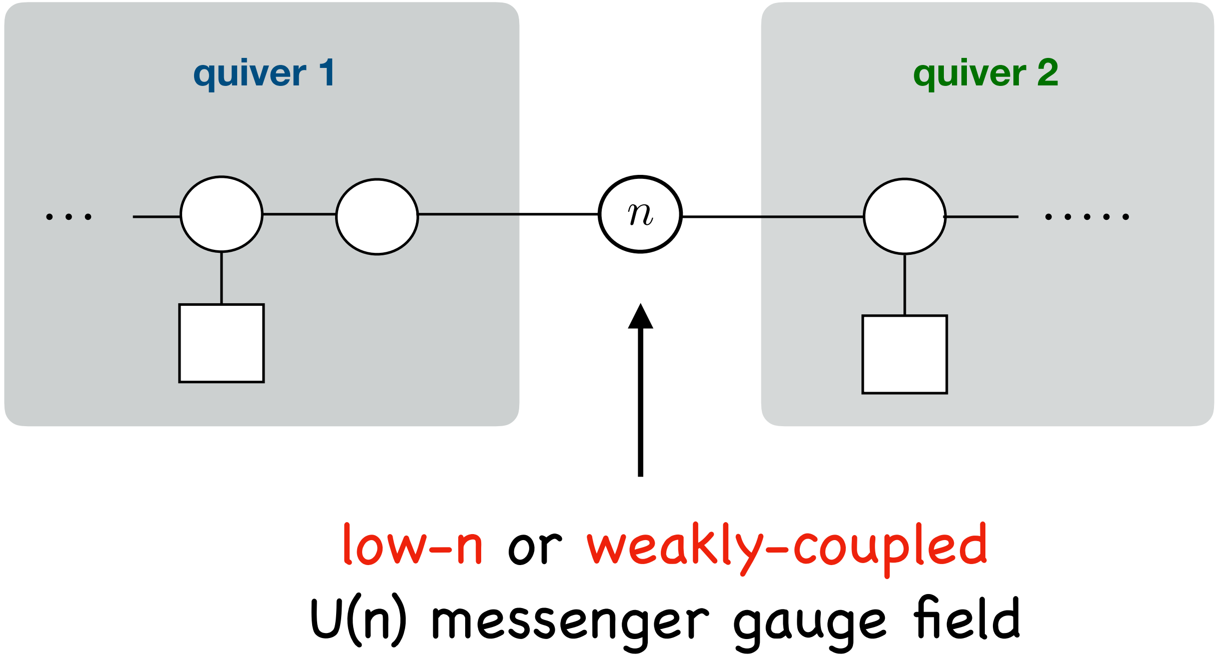
NB limit of massive gravity: $C \to \infty \Longrightarrow T^{\text{tot}}_{ij} \simeq 0$

Two dual BEH mechanisms

1. **Double trace** $\delta\mathcal{L} = \lambda\,\mathrm{tr}(o)\mathrm{tr}(\mathcal{O})$ — Poratti; Kiritsis; Aharony, Clark, Karch

$\lambda \ll 1$

2. **Gauge mediation** gauge common global symmetry — CB, Lavdas



- Double trace can at most preserve $\frac{1}{4}$ max susy

so it cannot be holographic-dual to mads4 or mads5

Proof: no marginal supermultiplet factorizes into a product of supermultiplets except for free fields

e.g. N=2, d=4 only marginal parameters are gauge couplings; while N=1, d=4 has also cubic superpotentials

- Double trace is non-geometrical, corresponds to 2-particle bacground

4. String-theory embeddings

With this much susy the relevant dual SCFTs are

d=3 (conjectured) IR fixed point of good Hanany-Gaiotto-Witten theories

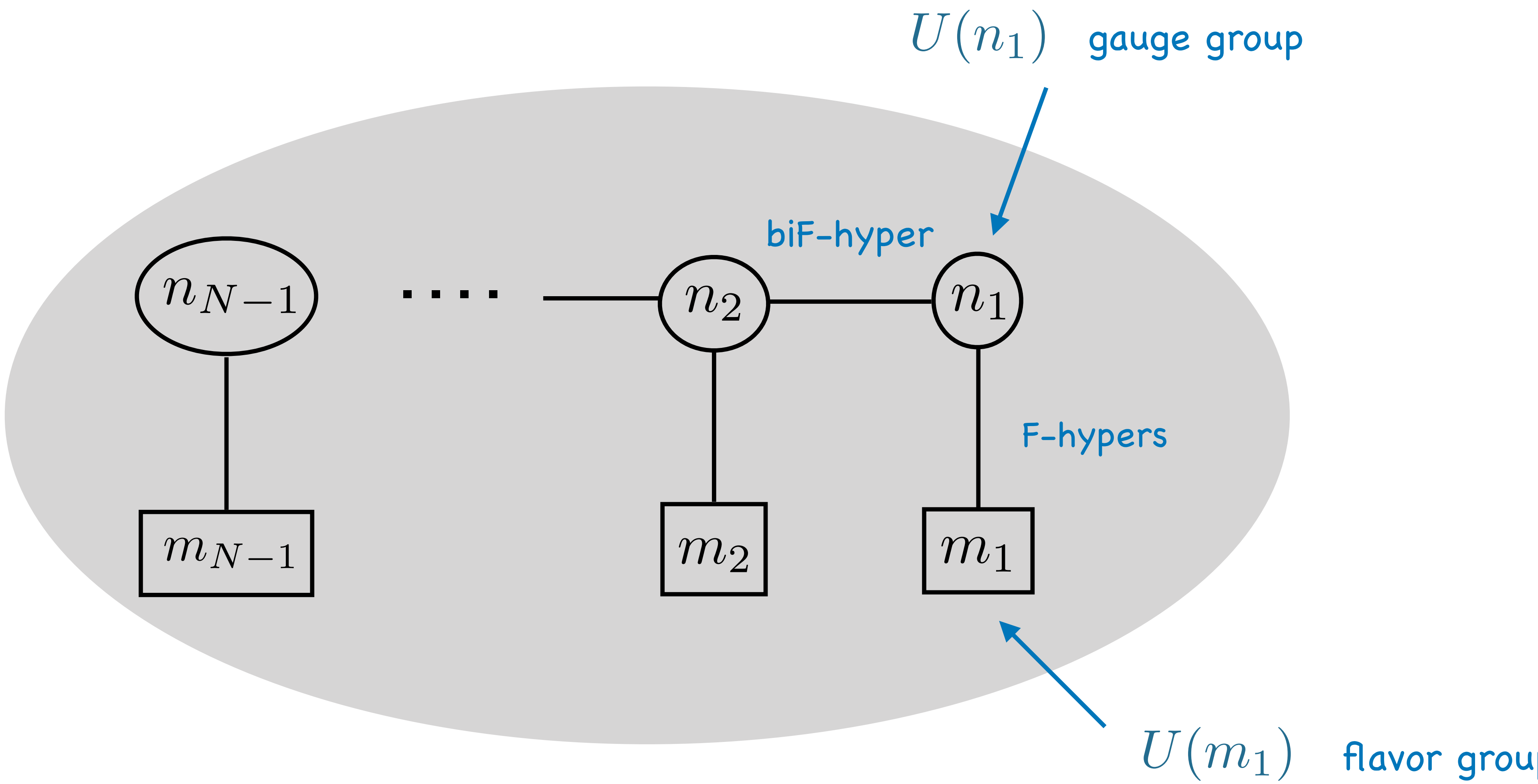
d=4 class-S Gaiotto N=2 SCFT theories

The supergravity solutions are explicitly known

D=4 IIB of the form $(\mathrm{AdS}_4 \times \mathrm{S}_2 \times \mathrm{S}_2') \times_w \Sigma_2$ Assel, CB, Estes, Gomis; D'Hoker, Estes, Gutperle

D=5 M-theory of the form $(\mathrm{AdS}_5 \times \mathrm{S}_2 \times \mathrm{S}_1) \times_w \Sigma_3$ Gaiotto, Maldacena; Maldacena, Nunez

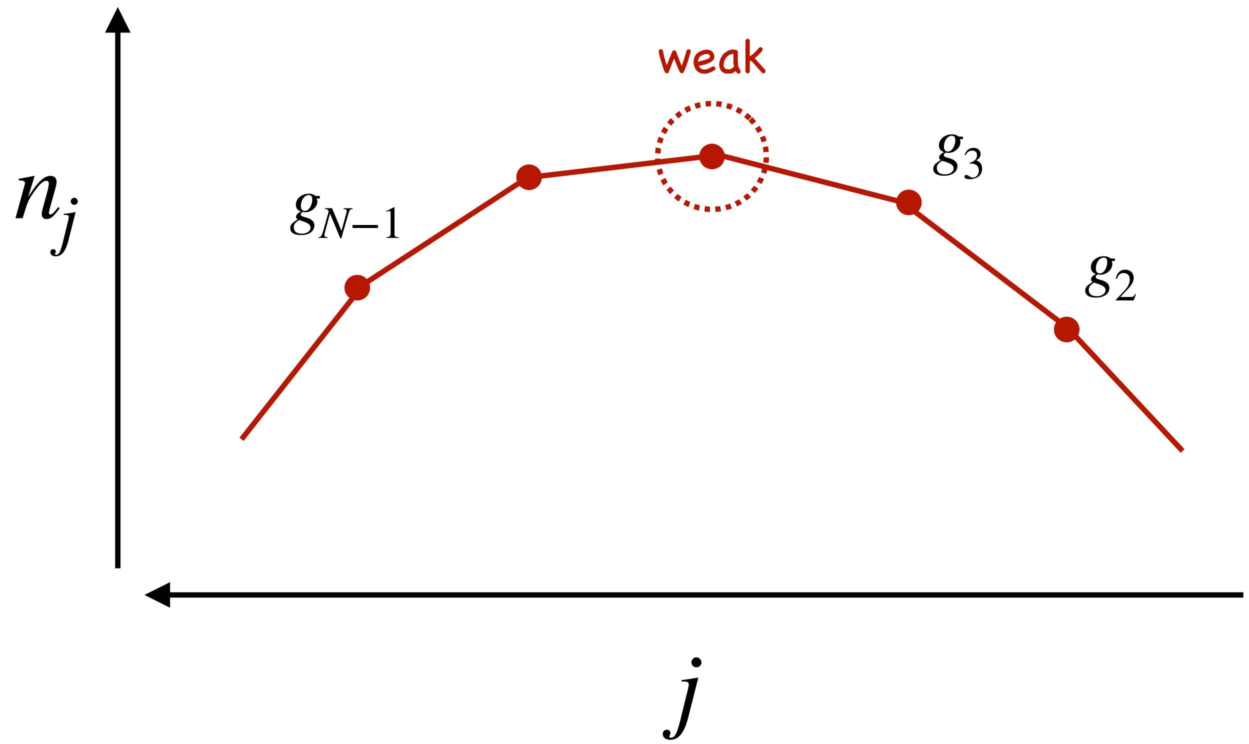
Both SCFT types are described by quiver gauge theories



but there are some key differences when one tries to cut

the chain continuously in two disjoint quivers

In d=4 vanishing of beta functions implies concave rank curve

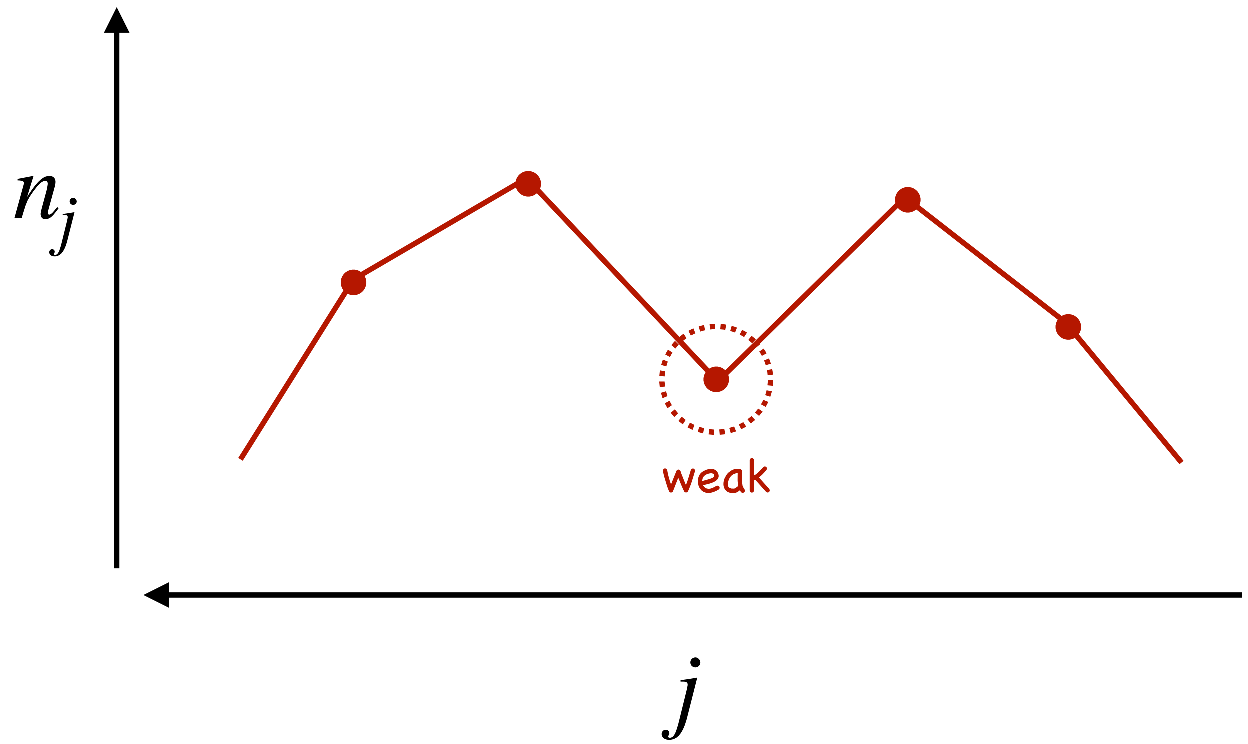


So one cannot cut the chain by lowering the rank of a "weak node"

One can take $g_{\text{weak}} \to 0$; no (known) smooth geometry of the bridge

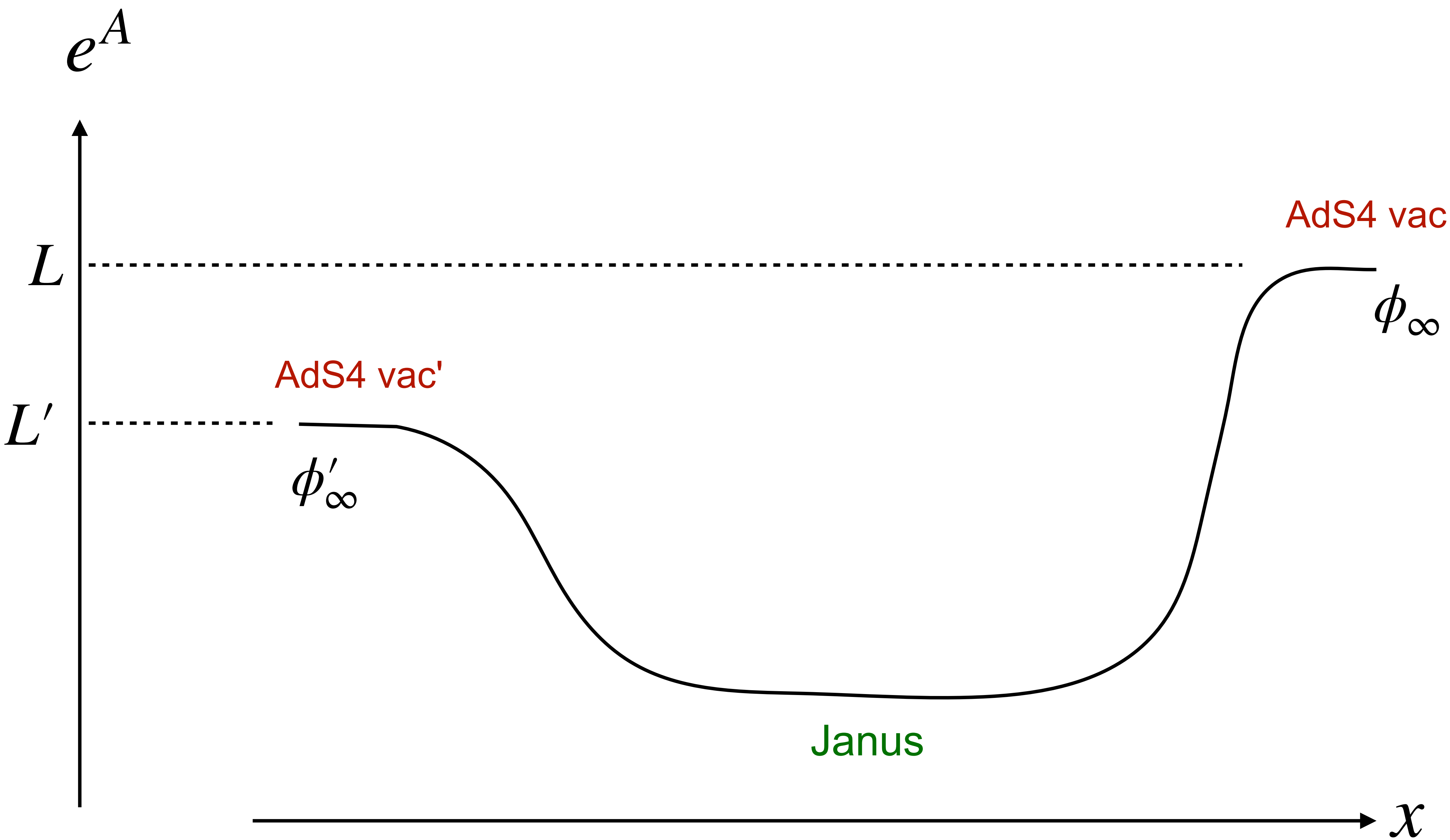
must study degeneration in string theory

In d=3 there are no continuous parameters, but ranks not concave so can cut chain by taking $\frac{n_{\rm weak}}{n_j} \to 0$



In the dual geometry the bridge is a cutoff $AdS_5 \times S_5$ throat, or more generally its Janus deformation

$$ds^2 = dx^2 + e^{2A(x)} ds^2_{\text{AdS4}} + d\tilde{s}^2_5 \ , \quad \phi(x)$$

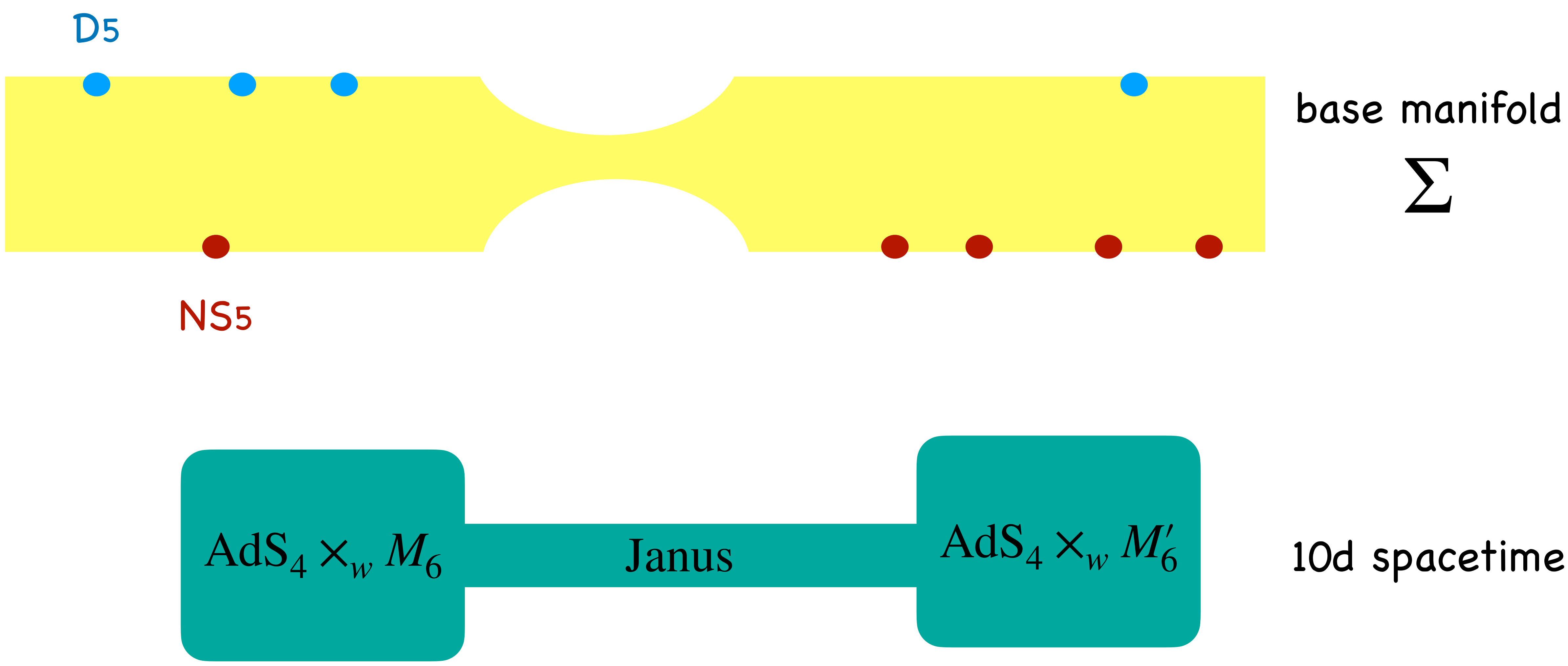


(Obscure in QFT) Janus parameter $\Delta\phi = \phi_\infty - \phi'_\infty$

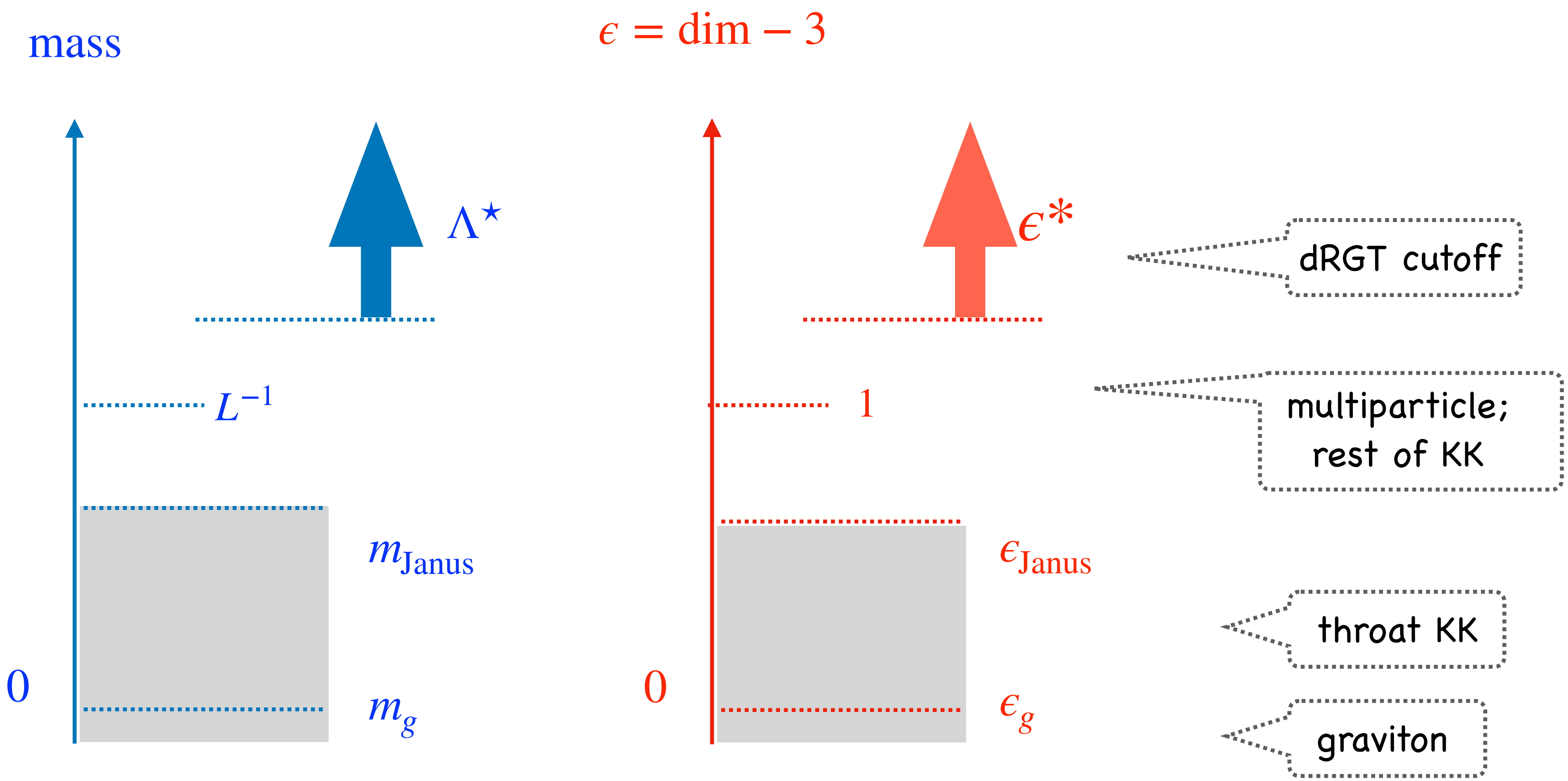
Taking to infinity also decouples the theories and sends $\epsilon_{\text{gr}} \to 0$

5. An EFT N=4 D=4 m-supergravity ?

Now to the punchline of this talk:



spin-2 spectrum in this IIB background is:



$$\epsilon_g = \# \frac{n^2}{c_{3d}\,|\Delta\phi|} \ll 1 \; ; \quad \epsilon^\star \sim (\epsilon_g c_{3d})^{1/3} \; ; \quad \epsilon_{\mathrm{Janus}} \sim |\Delta\phi|^{-2}$$

strings ; D-branes

Is there an N=4 EFT for the lightest massive spin-2 mode ?

Caveats:

(i) $\exists$ also massless gauge bosons on 5-branes dual to flavour currents

(ii) validity of "EFT" in AdS should be defined through conformal bootstrap

If yes it should involve an unusual N=4 Stückelberg multiplet

Closed string;
flavour neutral

$$\psi_\mu \,, A_\mu \,, \cdots$$

$$4 \quad 10+6$$

A hitherto unknown deformation of N=8 ?

some unchartered territory for
Gianguido's next book !

Note added:

Interesting recent work by De Luca, De Ponti, Mondino, Tomasiello

extends Cheeger bounds to spin-2 KK mass operator in generic

A(dS) or Mink compactifications.

If $m_1 \gtrsim 1/L$ then $m_2 \sim m_1$

(in line with strong spin-2 swampland conjecture in flat background)

Kläwer, Lüst, Palti

$m_1 \ll 1/L$ no useful upper bounds

For and even counterexamples with non-singular $m_1 \to 0$

Tomasiello (private)

breakdown of EFT should come from stringy/brane states

Vielen Dank