Applications of the holographic duality

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Basics of AdS-CFT duality

Addition of flavor to the gauge/gravity duality

Summary and outlook

Fundamental interactions, microscopic world: How to?

• Fundamental interactions (strong, weak, electromagnetic forces) are addressed by Quantum Field Theories (QFT)

• QFT: particles are excited states of quantum fields

• QFTs are treated perturbatively with an expansion in Feynman diagrams of increasing order. Each vertex is associated to a coupling constant factor g, perturbatively small

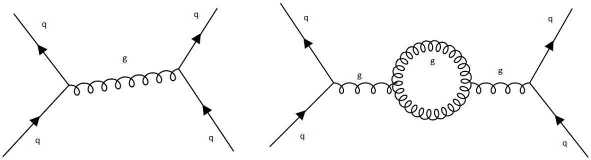

Figure: Schematic example of a Feynman diagram for QCD with no loops (left) and 1 loop (right)

• What if g is large? $\Rightarrow$ Perturbative expansion breaks $\Rightarrow$ QFT's become intractable

Gravity: How to?

• Theories to describe largest scales in the universe. 'Why macroscopic objects fall?'

• General Relativity (GR), theories of supergravity, string theory, etc

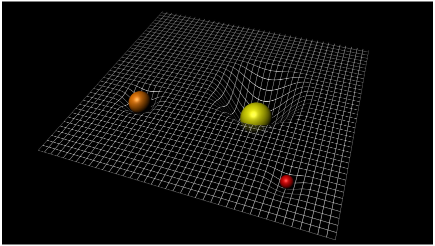

Figure: Schematic drawing of the curvature of spacetime due to matter. Figure taken from www.esa.int

• 'Roughly' : $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$ (GR)

What is the holographic duality?:

(AdS/CFT, or gauge/gravity duality)

• AdS/CFT is a conjecture of the existence of a relation of duality between certain classes of QFTs with certain classes of theories of gravity

• 1st version of the gauge/gravity duality (Maldacena '97):

$$\{\mathcal{N} = 4 \text{ SYM}, SU(N)\} \Leftrightarrow \{\text{type IIB strings on } AdS_5 \times S^5\}$$

• Why is it useful? It relates 'opposite' regimes in both gravity and field theory sides. When the QFT is non-tractable (strong coupling, $g \gg 1$) the gravity theory becomes easily tractable, and viceversa

$\Rightarrow$ It allows to make predictions in QFT at ($g \gg 1$)! Cons: testing them is difficult

Basics of AdS-CFT duality

$$CFT_d \text{ 'boundary theory'} = \text{quantum theory of gravity in asymptot. } AdS_{d+1}$$

$$\text{Boundary theory operators} \longleftrightarrow \textit{Fields in the bulk}$$

$$\begin{gathered} T_{\mu\nu} \longleftrightarrow g_{\mu\nu} \\ J_\mu \longleftrightarrow A_\mu \\ \Phi \longleftrightarrow \varphi \end{gathered} \tag{1}$$

- Define: $Z[J]$: bdy theory partition function, J: sources, $\mathcal{O}$: operators
- Coupling of $J, \mathcal{O}$ through: $S_{\mathcal{O}} = \int d^d x J \mathcal{O}$

AdS-CFT: 'the bdy theory partition function = bulk partition function with bdy condition that fields asymptote sources' $\rightsquigarrow$ At large N, λ:

$$Z_{boundary}[J] = e^{iS_{bulk}[\varphi_0]}|_{\varphi_0 \sim J r^{d-\Delta} + \langle\Phi\rangle r^\Delta} \tag{2}$$

My research: **addition of flavor to the gauge-gravity duality**

The original version of the gauge/gravity duality has only adjoint matter.
Electrons in condensed matter, QCD quarks... are fundamental fields!!!

Fundamentals? $\Rightarrow$ Add N_f flavor D-branes (Karch '01)

- N_f small $\rightarrow$ Flavors as probes $\rightarrow$ Non-dynamical, infinitely massive quarks
- N_f large $\rightarrow$ Backreaction of flavor branes! $\rightarrow$ $S_{SUGRA} + S_{branes}$

• Flavor branes = sources to sugra eoms $\rightarrow$ violation of Bianchi id. for supergravity fluxes $dF \neq 0$

• If sources are localized $\rightarrow$ $dF \sim \delta(x)$. Challenging equations!

$\Rightarrow$ Use smeared sources: a continuous distribution of branes $\rightarrow$ avoids $\delta(x)$ (easier problem)

An interesting example of QFT with flavors: the **D3-D5** intersection

• We add D5-flavor branes according to the array:

	0	1	2	3	4	5	6	7	8	9
D3	x	x	x	x	-	-	-	-	-	-
D5	x	x	x	-	x	x	x	-	-	-

• Used to model quantum Hall effect (Kristjansen, Semenoff [1212.5609]), (Kristjansen, Pourhasan, Semenoff [1311.6999])

• Holographic model of graphene (Evans, Jones [1407.3097]), (Gran, Jokela, Musso, Ramallo, Tornsö [1909.01864])

• Magnon excitations in a ferromagnet (Filev, Johnson, Shock [0903.5345])

This setup was known in the probe approximation

- D5's create a defect in (x^0, x^1, x^2) where fundamentals live
- (2+1)-d fundamental matter coupled to gauge theory in (3+1)-d

My work along this line? Construct geometries accounting for backreaction of the D5s and use them to model interesting systems

- Addition of flavor to the gauge/gravity duality: the D3-D5 setup

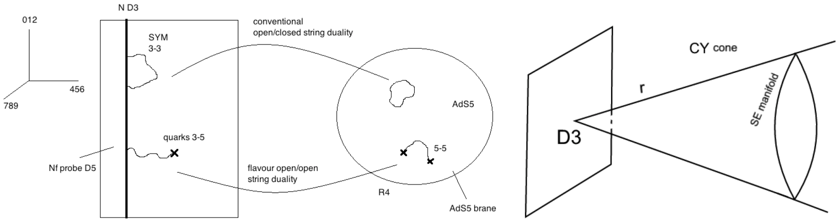

Figure: Left: the D3-D5 setup and matter content. Right: schematic view of D3-geometry

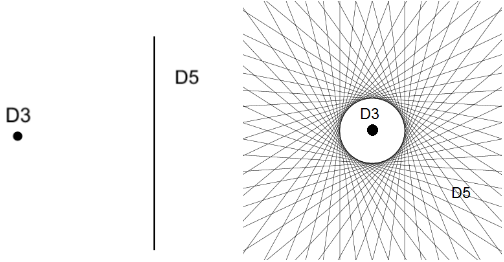

Figure: Left: Localized D5 flavors. Right: smeared D5 flavors. Radius of circle = position of cavity (= quark mass)

Some works

1. (Conde, Lin, J. M. P., Ramallo, Zoakos [1607.04998]): Construction of massless anisotropic background. Scaling solution:

$$ds^2 = \frac{r^2}{R^2}\left[dx_{1,2}^2 + \left(\frac{4Q_f}{3}\right)^{\frac{4}{3}} \frac{(dx_3)^2}{r^{\frac{4}{3}}}\right] + R^2\frac{dr^2}{r^2} + \bar{R}^2\left[ds_{KE}^2 + \frac{9}{8}(d\tau + A)^2\right] \quad (3)$$

2. (J. M. P., Ramallo, Zoakos [1710.00548]): Massless black hole (QFT at $T \neq 0$):

$$ds^2 = \frac{r^2}{R^2}\left[-\left(1-\frac{r_h^{\frac{10}{3}}}{r^{\frac{10}{3}}}\right)(dx^0)^2 + (dx^1)^2 + (dx^2)^2 + \left(\frac{4Q_f}{3}\right)^{\frac{4}{3}}\frac{(dx_3)^2}{r^{\frac{4}{3}}}\right]$$
$$+R^2\left(1-\frac{r_h^{\frac{10}{3}}}{r^{\frac{10}{3}}}\right)^{-1}\frac{dr^2}{r^2} + \bar{R}^2\left[ds_{KE}^2 + \frac{9}{8}(d\tau + A)^2\right] \quad (4)$$

3. (Jokela, J. M. P., Ramallo, Zoakos [1901.02020]): Massive background. Massive profile $p(r)$ characterized by a cavity inside which $p(r) = 0$. Cavity $\sim$ quark mass

• We compute: Wilson loops, entanglement entropy, thermodynamics of probe D5's etc and determine κ-symmetric embeddings for the D5 branes in the bckg

4. (Hoyos, Jokela, J. M. P., Ramallo [2001.08218]): D3-D5 with non-monotonic 'flavor' profiles. This creates holographic duals to anisotropic states

5. (Garbayo, Hoyos, Jokela, J. M. P., Ramallo [2208.04958]): The BH in (4) and the solution (3) is non-analytic in $Q_f \to 0$. Here we obtain a solution regular if $Q_f \to 0$ and also with backreacted finite quark density μ

• We compute: thermodynamics, transport coefficients, Wilson loops and entanglement entropies

Related works...

6. (Hoyos, Jokela, J. M. P., Ramallo, Tarrío [2104.11749]): We extend the study of non-monotonic profiles and their effect in the null energy conditions in ABJM, D2-D6 and D3-D7

D3-D3' setup

7. (Jokela, J. M. P., Rigatos [2112.14677]): we construct the backreacted intersection of the D3-D3' setup along a (1+1)-d defect with smeared D3' branes. System dual to a (1+1)-d QFT

Flavor effects in entanglement entropy

8. (Jokela, Kastikainen, J. M. P., Ruotsalainen [2401.07905]): we study Liu-Mezei renormalization group monotones in flavored ABJM, $\mathcal{N} = 1$ Klebanov-Witten and $\mathcal{N} = 4$ SYM theories. We use Ryu-Takayanagi prescription in these geometries and demonstrate the matching with a probe computation for the limit of few flavors

To summarize

• Holography is a successful tool to address problems in quantum field theory

• Holography has many applications: QCD, cosmology, condensed matter, hydrodynamics, astrophysics...

• With simple holographic models one can predict many experimental results. Holography has still much to teach us!

• One of my research lines is in the addition of flavor to AdS/CFT, in which I have made an extensive study of the effects of incorporating the backreaction of flavors. $\Rightarrow$ There are several directions to follow along this line of research:

Future directions

• Add 4-d flavors with probe D7-branes to our geometry in [2208.04958] as done in (Gran, Jokela, Musso, Ramallo, Tornso [1909.01864]), to study the anisotropic physics of layered materials in condensed matter, more promising towards finding a plasmon

• Construct a version of the D3-D3' geometry in [2112.14677] at $T \neq 0$

• Construct a cigar-like geometry in the D3-D3' system, interesting to study confinement

• Construct equations of state of neutron stars in D3-D5 anisotropic geometry. Apply them to study no-hair relations for compact stars

• ...

Thank you for your attention