Holographic Graphene in a Cavity

Durham YTF - 17th December 2014

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Based on arXiv:1407.3097 (Phys. Rev. D 90, 086008) in collaboration with Nick Evans

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- One way to drive graphene to stronger coupling is to place it in a **cavity** e.g. placing a sheet between two mirrors. The separation **length scale** enters into the effective coupling.
- Graphene-like systems can be realised holographically using particular **probe-brane** constructions that give rise to **defect QFTs**. We would like to put such systems in a cavity.

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  where note that $\mathcal{N} = 4$ SYM is a **conformal field theory**, hence the name AdS/CFT.
- Terminology: "QFT side" vs. "gravity side".

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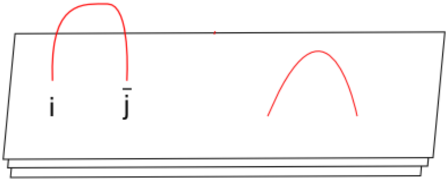

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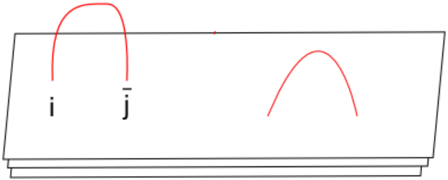

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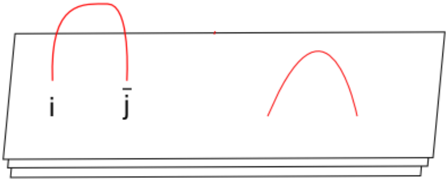

- E.g. worldvolume theory on stack of N_c D3-branes in IIB is $\mathcal{N} = 4$ SYM with gauge group $SU(N_c)$.
- Near-brane geometry of a stack of N_c D3-branes is $AdS_5 \times S^5$!

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- The correspondence is a **weak/strong duality** - makes holography very useful!
- In fact, the form in which holography is most commonly used and in which we will use it is:

$$\boxed{\text{QFT at Strong Coupling} \ \Leftrightarrow \underline{\text{Classical}} \ \text{Gravity in (A)AdS}}$$

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- AdS_{d+1} isometries SO(2,d) $\Leftrightarrow$ conformal group in $\mathbb{R}^{1,d-1}$.
- AdS space has a **boundary**. AdS_{d+1} can be written:

$$ds^2 = \frac{R^2}{u^2}(du^2 + \eta_{\mu\nu} dx^\mu dx^\nu)$$

where $\mu = 0, 1, ..., d-1$, and R is the **AdS radius**. The boundary is at $u = 0$, and is a copy of Minkowski space $\mathbb{R}^{1,d-1}$. This is where the dual QFT lives!

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Adding Flavour to the Correspondence

- Original correspondence only contains **adjoint DoF** in the gauge theory i.e. vector multiplet $(A_\mu^a, \lambda^a, \phi^a)$. We want 'matter' or quarks ψ^i i.e. **fundamental DoF**.

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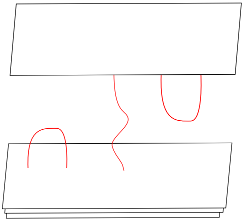

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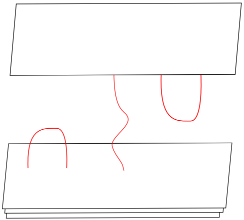

- The **probe limit** is $N_f \ll N_c$ and means there is **no backreaction** on the geometry. Very useful approximation!

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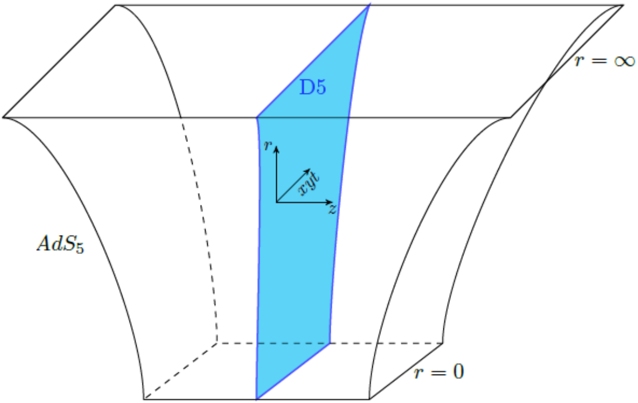
- This gives rise to a **defect QFT** i.e. the matter is confined to a 2+1-dim. defect within the spacetime of the 3+1-dim. QFT.
- The picture is thus that of 2+1-dim. matter interacting via gauge DoF that propagate in 3+1-dim. c.f. the low-energy effective field theory of **graphene**.

Illustration of Probe Brane and Defect QFT



[Semenoff et. al. 2014]

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- Would now like to study this from the gravity side!

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- The gravity dual for $\mathcal{N} = 4$ SYM on a compact space is given by the **AdS Soliton**:

$$ds^2 = \frac{1}{u^2}(h(u)^{-1}du^2 + \eta_{ij}dx^i dx^j + h(u)dz^2) + d\Omega_5^2$$

where $i = 0, 1, 2$, the compact direction is z, and:

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- Note that the space closes off smoothly at the horizon $u = u_0$ where $h(u)$ vanishes.

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Putting in a Single Graphene Sheet

- Use a different coordinate system when putting the probe brane in:

$$ds^2 = (\rho^2 + L^2)(g_x dx_{2+1}^2 + g_z dz^2) + \frac{1}{(\rho^2 + L^2)}(d\rho^2 + \rho^2 d\Omega_2^2 + dL^2 + L^2 d\tilde{\Omega}_2^2)$$

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- Recall:

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  The transverse directions are $(z, L, \tilde{\Omega}_2)$ - note the transverse $SO(3)$ symmetry (important later!).

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$$S_{DBI} \sim -T \int d\xi^6 \sqrt{-\det \left[g_{MN} \frac{dX^M}{d\xi^a} \frac{dX^N}{d\xi^b} \right]}$$

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  where ξ^a are the coordinates on the 6-dimensional worldvolume of the D5-brane.
- Fixing a gauge, plugging in the ansatz $L(\rho)$ and taking g_{MN} as above, the action becomes:

$$S \sim - \int d\rho \left(1 + \frac{1}{(\rho^2 + L^2)^2} \right)^{3/2} \rho^2 \sqrt{1 + L'^2}$$

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- Chiral condensate in graphene is a condensate of **excitons** - bound state of an electron and a hole.
- Non-zero c for zero m signals **chiral symmetry breaking** (c.f. QCD - confinement, mass gap etc).

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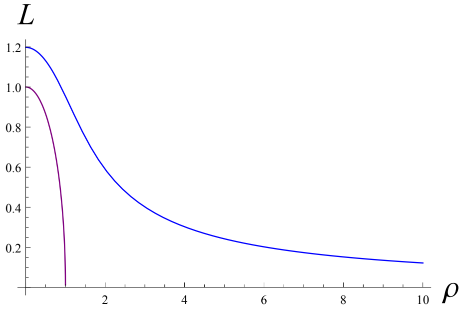

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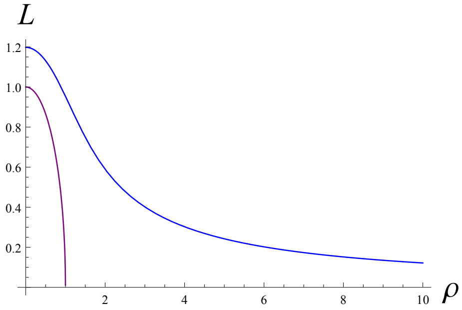

- Clearly have $c \neq 0 \to$ chiral symmetry breaking!

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- The non-zero value of $L(0)$ can be interpreted as a dynamically generated **mass gap** - for example, gives rise to massive mesons.
- So putting in a single graphene sheet leads to χSB - doesn't happen in pure AdS case.

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Joined Configurations

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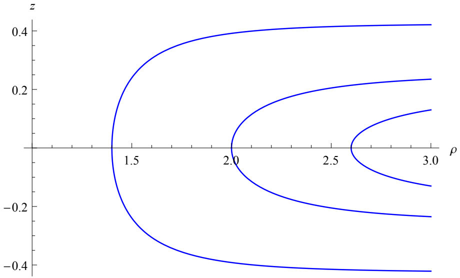
- Proceed as before. Action is independent of z explicitly so there is a constant of motion $\Pi_z \equiv \partial \mathcal{L} / \partial z'$. Thus, problem reduces to a first order ODE:

$$z' = \pm \frac{\sqrt{2}\Pi_z \rho^2}{\sqrt{(1 + 1/\rho^4)(\rho^4 - 1)^4 - \Pi_z^2 \rho^4 (\rho^4 + 4/(1 + \rho^4) - 3)}}$$

Example Solutions and Properties

- Plot the joined configurations for various values of the turning point ρ_0:



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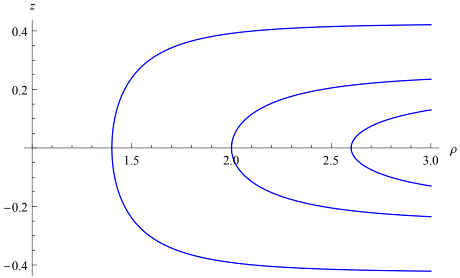
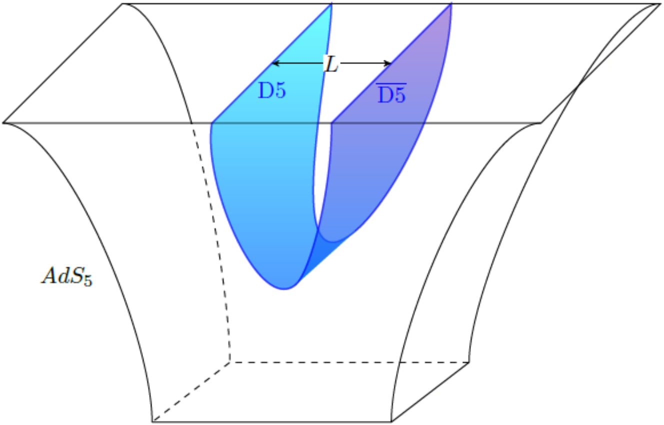


- **Maximum separation** is given by $\pi/2$ (i.e. half the width of the space) - corresponds to the branes extending right down to the horizon.

Illustration of Joined Configurations



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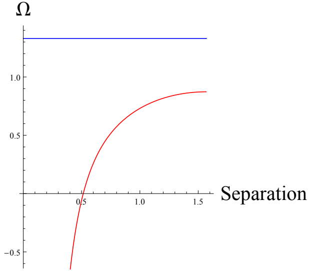

Vacuum Alignment for 2 sheets

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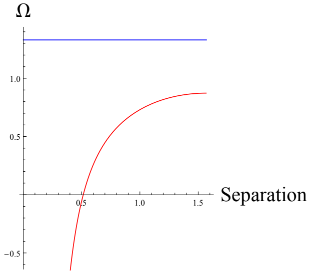

- The joined configuration is always favourable - condensation across the sheets is the vacuum configuration for all separations!

Overview

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  for extrinsic curvature K.
- Have also added a boundary matter Lagrangian $\mathcal{T}$ which is taken to be constant and interpreted as the **tension** of the boundary.

Gravity Dual of Strip

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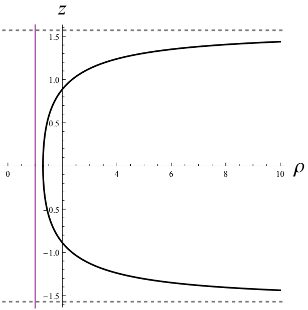

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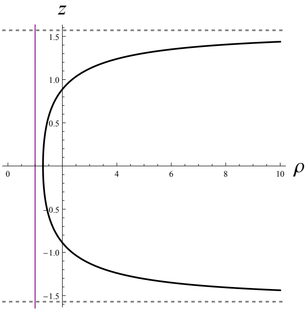

- However, we find that the brane embedding does not close off before hitting this new boundary!

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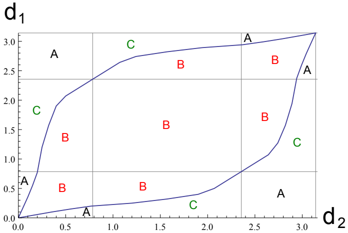
- Result is a complicated phase diagram:



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- Including mirror images, there are additional possible phases where one or more sheets condenses with its mirror image. The resulting phase diagram is then somewhat more interesting.
- Hope is that these qualitative predictions could be looked for experimentally.