AdS/Condensed Matter

Supergravity helps Condensed Matter Physics. A first example: Holographic Superconductors

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9 April 2013

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Supergravity helps Condensed Matter Physics. A first example: Holographic Superconductors

In collaboration with Jorge Russo, Diederik Roest, Andrea Borghese, Aldo Dector
Based on [1104.4473] [1206.5827] [1205.2087]

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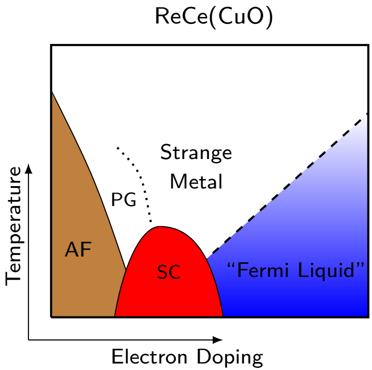
Summary

Motivations



Non Fermi Liquid/ Non BCS
some unconventional features

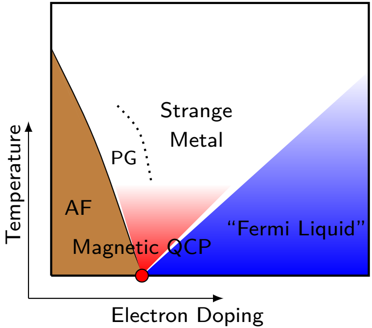
Strange Metal phase, examples:

- $\rho \approx T^n$ with n function of the doping and varying in $[1, 2]$.
- Drude tail falls off with non integer power law, example $w^{2/3}$.

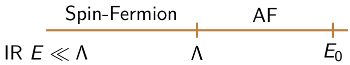
High T_c SuperC phase, examples:

- d-wave order parameter
- T_c around $100K$
- $C_e \approx T^n$ for $T < T_c$.

ReCe(CuO)



The Spin Fermion Model



$$\mathcal{L}_{sf} = g\ c^{\dagger}_{w,\mathbf{k}} \vec{\sigma} c_{w-\Omega,\mathbf{k}-\mathbf{q}}\ \vec{S}_{\Omega,\mathbf{q}}$$

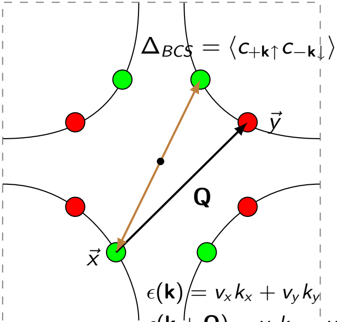
$$\mathcal{L}_f = c^{\dagger}_{w,\mathbf{k}} G_0^{-1}(w,\mathbf{k}) c_{w,\mathbf{k}}$$

$$\mathcal{L}_s = \chi_0^{-1}(\mathbf{q},\Omega)\ S_{\Omega,\mathbf{q}} S_{\Omega,\mathbf{q}}$$

$$G_0(w,\mathbf{k})^{-1} = w - \epsilon(\mathbf{k})$$

$$\chi_0(\Omega,\mathbf{q})^{-1} = \left(\xi^{-2} + (\mathbf{q}-\mathbf{Q})^2 - (\Omega/v_s)^2\right)$$

Motivations [1005.1288, Sachdev and Metlitski]



$\epsilon(\mathbf{k}) = v_x k_x + v_y k_y$

$\epsilon(\mathbf{k}+\mathbf{Q}) = v_y k_y - v_x k_x$

$v_F^2 = v_x^2 + v_y^2$

Hot spot: point $\vec{x} \in$ FS such that $\exists\ \vec{y}$ with

the property: $\vec{x} - \vec{y} = \mathbf{Q}$

Loop contr. organized in powers of $\lambda \sim \dfrac{g^2}{v_f \xi^{-1}}$

Results

- d-wave from BCS at H.S : $\Delta_{\mathbf{k}} = -\Delta_{\mathbf{k}+\mathbf{Q}}$.
- NFL from Loop corrections:

$$G^{-1}_{H.S.} \sim \mathrm{sign} w \sqrt{i|w|} - \vec{v}\vec{k}$$

Limitations

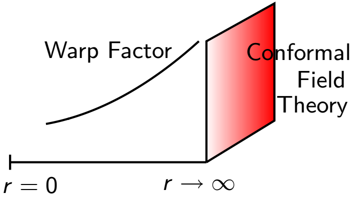
- strong coupling
- No quasiparticle at H.S.
- Large N exp. not under control

Summary

AdS/CFT minimal structure

Large N gauge theory d dimensions	Classical gravity $d+1$ dimensions
aAdS_{d+1} spacetime	$ds^2 = \frac{r^2}{L^2}(-dt^2 + d\vec{x}^2) + \frac{L^2}{r^2}dr^2$

scalars $m^2 = \Delta(\Delta - d)$



$$\phi(r, x_\mu) = \begin{cases} \phi_0 / r^{\Delta_-} & \text{source} \\ \mathcal{O}/r^{\Delta_+} & \text{vev} \end{cases}$$

$AdS \quad \{t, \vec{x}\} \to \lambda\{t, \vec{x}\} \quad r \to r/\lambda$

$CFT \quad \{t, \vec{x}\} \to \{t, \vec{x}\}/s \quad E \to s\,E$

$$\left\langle \exp \int \phi_0 \mathcal{O} \right\rangle_{CFT} = \mathcal{Z}_{\mathrm{Grav}}(\phi_0)$$

Large N gauge theory d dimensions	Classical gravity $d+1$ dimensions

aAdS$_{d+1}$ spacetime

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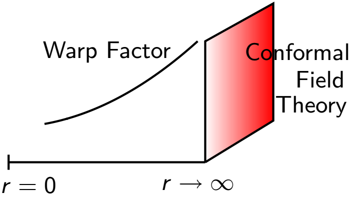

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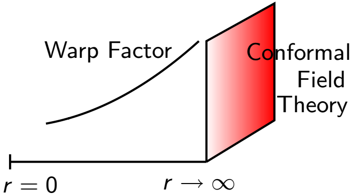
AdS	$\{t, \vec{x}\} \to \lambda\{t, \vec{x}\}$	$r \to r/\lambda$
CFT	$\{t, \vec{x}\} \to \{t, \vec{x}\}/s$	$E \to s\ E$

$$\left\langle \exp \int \phi_0 \mathcal{O} \right\rangle_{CFT} = e^{-N^2 \mathcal{S}_{class}(\phi)}$$

AdS/CFT MINIMAL STRUCTURE

Large N gauge theory d dimensions	Classical gravity $d+1$ dimensions
AdS$_{d+1}$ spacetime	$$ds^2 = \frac{r^2}{L^2}(-dt^2 + d\vec{x}^2) + \frac{L^2}{r^2}dr^2$$

gauge boson $A = A_\mu dx^\mu$



$$A(r, x_\mu) = \begin{cases} \mathcal{S}_0 & \text{source} \\ \mathcal{J}/r^{d-2} & \text{vev} \end{cases}$$

AdS $\{t, \vec{x}\} \to \lambda\{t, \vec{x}\}$ $\quad r \to r/\lambda$

CFT $\{t, \vec{x}\} \to \{t, \vec{x}\}/s$ $\quad E \to s\, E$

$$\left\langle \exp \int (\mathcal{S}_0^\mu \mathcal{J}_\mu) \right\rangle_{CFT} = e^{-N^2 \mathcal{S}_{class}(A)}$$

Basic Lagrangian density

$$\mathcal{L}[g_{\mu\nu}, A_\mu, \zeta] = \frac{1}{2\kappa^2}\left[\mathcal{R} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}D_\mu\zeta\overline{D^\mu\zeta} - V(|\zeta|)\right]$$

The ansatz

$$ds^2 = -g(r)e^{-\chi(r)}dt^2 + \frac{dr^2}{g(r)} + r^2\ d\vec{x}_d^2,$$

$$A_\mu dx^\mu = \Phi(r)dt$$

$$|\zeta| = \eta(r)$$

$g(r_h)$	Eq. I order for g
$\chi(r_h)$	Eq. I order for χ
$\Phi(r_h), \Phi'(r_h)$	Eq. II order for Φ
$\eta(r_h),\ \eta'(r_h)$	Eq. II order for η
	$\longrightarrow 6+1$ parameters

Basic Lagrangian density

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$$|\zeta| = \eta(r)$$

Eq. I order for g
Eq. I order for χ
Eq. II order for Φ
Eq. II order for η

$\longrightarrow 6+1$ parameters

$7 - 2 = 5$

2 scalings

- fix the value of r_h
- $\chi(r_h) = \chi_0$

Basic Lagrangian density

$$\mathcal{L}[g_{\mu\nu}, A_\mu, \zeta] = \frac{1}{2\kappa^2}\Big[\mathcal{R} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}D_\mu\zeta\overline{D^\mu\zeta} - V(|\zeta|)\Big]$$

The ansatz

$$ds^2 = -g(r)e^{-\chi(r)}dt^2 + \frac{dr^2}{g(r)} + r^2\ d\vec{x}_d^2, \qquad A_\mu dx^\mu = \Phi(r)dt \qquad |\zeta| = \eta(r)$$

Eq. I order for g

Eq. I order for χ

Eq. II order for Φ

Eq. II order for η

$\longrightarrow 6+1$ parameters

$5-2=3$

because $g(r) \sim (r-r_h)$

- $\Phi(r) \sim \Phi_0(r-r_h)$
- $\eta'(r_h) \propto \eta(r_h) \equiv \eta_0$

Basic Lagrangian density

$$\mathcal{L}[g_{\mu\nu}, A_\mu, \zeta] = \frac{1}{2\kappa^2}\Big[\mathcal{R} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}D_\mu\zeta\overline{D^\mu\zeta} - V(|\zeta|)\Big]$$

The ansatz

$$ds^2 = -g(r)e^{-\chi(r)}dt^2 + \frac{dr^2}{g(r)} + r^2\ d\vec{x}_d^2,$$

$$A_\mu dx^\mu = \Phi(r)dt$$

$$|\zeta| = \eta(r)$$

Eq. I order for g

Eq. I order for χ

Eq. II order for Φ

Eq. II order for η

$\longrightarrow 6 + 1$ parameters

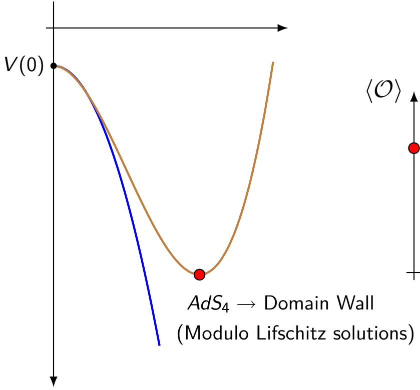
$3 - 1 = 2$

$g'(r_h)$ gives the Temperature and depends on (η_0, Φ_0)

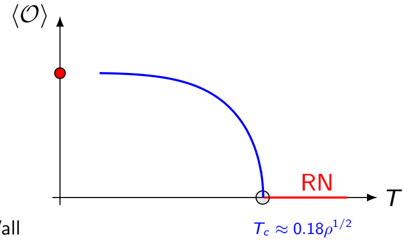
(η_0, Φ_0) to set the source $= 0$.

Two Simple Potentials

$$V = -6 - m^2|\zeta|^2$$

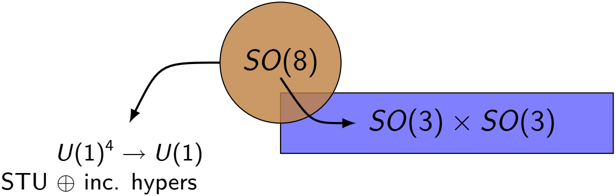


$$V = -6 - m^2|\zeta|^2 + \lambda|\zeta|^4$$



Scalar Manifold from $\mathcal{N} = 8$ $d = 4$

$$\mathcal{L}_{scalar} = \frac{1}{2}\partial^\mu \eta \partial_\mu \eta - \mathcal{J}(\eta) A_\mu A^\mu - V(\eta)$$



$\mathcal{J}_1 = \sinh^2\left(\frac{\eta}{2}\right)$

$V_1 = -2(2 + \cosh\eta)$

Unexpected condensation

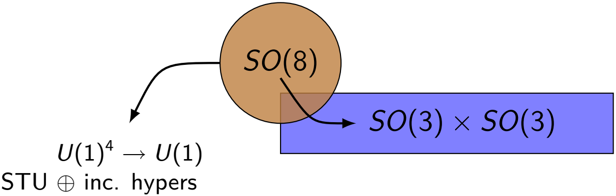
$\mathcal{J}_2 = \frac{1}{4}\sinh^2(\eta)$

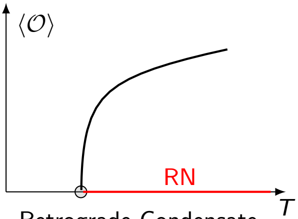
$V_2 = \frac{1}{2}\sinh^4\left(\frac{\eta}{2}\right) + V_1$

Similar to the Abelian Higgs model

Scalar Manifold from $\mathcal{N} = 8$ $d = 4$

$$\mathcal{L}_{scalar} = \frac{1}{2}\partial^{\mu}\eta\partial_{\mu}\eta - \mathcal{J}(\eta)A_{\mu}A^{\mu} - V(\eta)$$





Retrograde Condensate

$$\mathcal{J}_2 = \tfrac{1}{4}\sinh^2(\eta)$$

$$V_2 = \tfrac{1}{2}\sinh^4\left(\tfrac{\eta}{2}\right) + V_1$$

Similar to the Abelian Higgs model

Summary

The $\mathcal{N} = 2$ supergravity setup: Bosonic Sector

- graviton multiplet = { gravity $\oplus$ graviphoton }.
- Hyperscalars q^u parametrize a $\mathcal{Q}$ Kahler manifold: $(J^x)_u^v$, H_{uv}
- The $SU(2)$ group of R-symmetry acts on the hyperscalars.
- The gauge group is introduced by gauging compact isometries (Killing vectors K_λ^u) of $\mathcal{Q}$.

As a consequence of the gauging procedure, the Lagrangian gets a unique scalar potential.

$$V = 2g^2\Big(4H^{uv}\partial_u\mathcal{W}\partial_v\mathcal{W} - 3\mathcal{W}^2\Big), \qquad \mathcal{W} = \sqrt{\tfrac{2}{3}P^x P^x}$$

$$2n_H P_\lambda^x = (J^x)_u^v \, \nabla_v K_\lambda^u = (J^x)_u^v \, (\partial_v K_\lambda^u - \Gamma^u_{vp} K_\lambda^p)$$

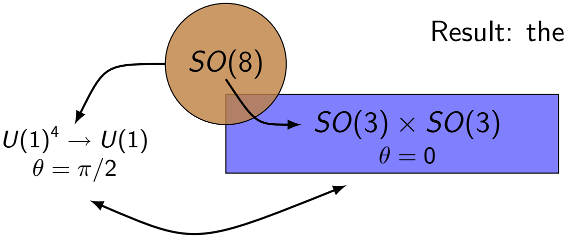
The Universal Hypermultiplet $SU(2,1)/U(2)$

$\dim_{\mathbb{R}} SU(2,1)/U(2) = 4$. The coset space is top. a ball in $\mathbb{C}^2$

$$\zeta_1 = \tau \cos\frac{\theta}{2} e^{i(\varphi+\psi)/2} \qquad \zeta_2 = \tau \sin\frac{\theta}{2} e^{-i(\varphi-\psi)/2}$$

$$H_{uv} dq^u dq^v = \frac{d\tau^2}{(1-\tau^2)^2} + \frac{\tau^2}{4(1-\tau^2)}(\sigma_1^2 + \sigma_2^2) + \frac{\tau^2}{4(1-\tau^2)^2}\sigma_3^2$$

Isotropy group is $U(2) = SU_R(2) \times U(1)$ with $U(1)_3 \subset SU_R(2)$



Result: the gauging of $U(1)_3$ builds the bridge

$$R[\zeta_1] = +1$$
$$R[\zeta_2] = -1$$
$$\tau = \tanh\frac{\eta}{2}$$

THE UNIVERSAL HYPERMULTIPLET $SU(2,1)/U(2)$

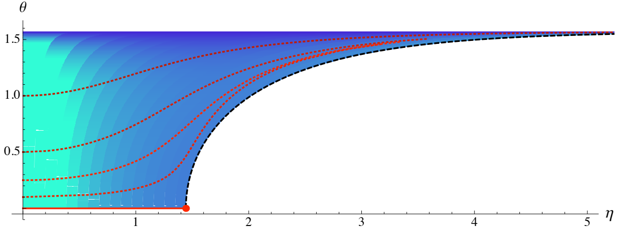
Idea: If θ can be fixed arbitrarily in the range $[0, \pi/2]$ we find a new family of solutions interpolating between $1-2$.

...from this point of view the retrograde condensate can be used as a clue to detect the existence of a bigger family of sol. $\rightarrow d = 5\ \mathcal{N} = 8$

UV Asymptotics η : $d = 4$ and $m^2 L^2 = -2 \rightarrow \Delta_- = 1$ and $\Delta_+ = 2$

$$\eta(r) = \frac{\mathcal{O}_1}{r} + \frac{\mathcal{O}_2}{r^2} + \dots, \qquad \theta(r) = \theta_\infty + \frac{\xi}{r} + \dots;$$

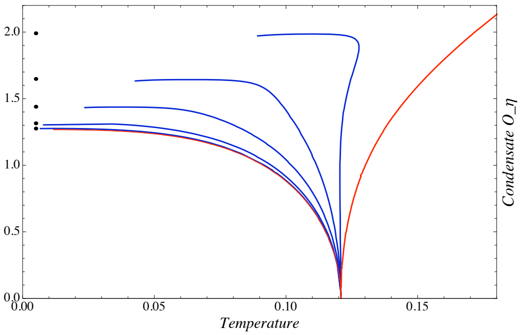
$\mathcal{O}_2 = 0 \rightarrow \Delta = 1$ Condensate



- The red dot is the saddle point $\theta = 0$, $\eta = 2\ \mathrm{arccosh}\sqrt{5}$.
- The red lines, are the horizon values of the functions $\theta(r)$ and $\eta(r)$.
- The value of θ_∞ can be read on the vertical axis.

$\theta_\infty \neq 0$ the superconductor is driven towards $\theta(r_h) = \pi/2$ as $T \to 0$.

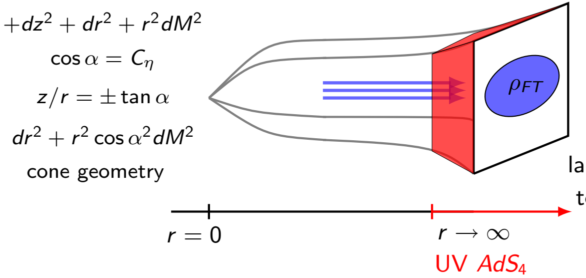
$\Delta = 1$ Condensates: Numerics



- From bottom to top $\theta_\infty = 0, 0.1, 0.25, 0.5, 0.75, 1$
- First order phase transitions for $\theta_\infty > \theta_{cr} \approx .95$.

(the curves should be represented in a 3d space according to their value of θ_∞)

Extremal solutions for $\theta_\infty \neq 0$: Phase II



2 Hints:

- $\theta(r_h) \to \pi/2$
- Solitons with large mass converge to extremal Hol.SC.

$$ds^2 = r^2(-dt^2 + d\vec{x}^2) + \frac{dr^2}{r^2 + C_\eta^2}, \qquad \eta(r) = 2 \operatorname{arcsinh} \frac{C_\eta}{r}$$

$$\theta(r) = \frac{\pi}{2} + \delta_\theta r \qquad \Phi(r) = \delta_\Phi r$$

Extremal solutions for $\theta_\infty \neq 0$: Phase II

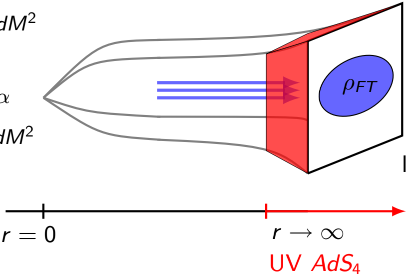
$-dz^2 + dr^2 + r^2 dM^2$

$\cosh\alpha = C_\eta$

$z/r = \pm\tanh\alpha$

$dr^2 + r^2\cosh\alpha^2 dM^2$

cone geometry



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$$ds^2 = r^2(-dt^2 + d\vec{x}^2) + \frac{dr^2}{r^2 + C_\eta^2}, \qquad \eta(r) = 2\ \mathrm{arcsinh}\ \frac{C_\eta}{r}$$

$$\theta(r) = \frac{\pi}{2} + \delta r \qquad \Phi(r) = \delta r$$

Summary

1 Motivations

2 AdS/CFT and Hol. Superconductors: minimal structure

3 $\mathcal{N} = 2$ sugra coupled to $SU(2,1)$ hypermultiplet

4 Probing the IR geometry: EE

5 Dual Field Theory and Marginal Deformations

Probing the IR geometry

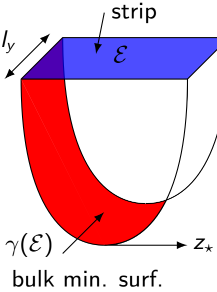
- Entangled Entropy

$$S(\mathcal{E}) = -\mathrm{Tr}\rho_{\mathcal{E}} \log \rho_{\mathcal{E}}\,, \quad \rho_{\mathcal{E}} = \mathrm{Tr}_{\overline{\mathcal{E}}}|gs\rangle\langle gs|$$

- Excitations $\begin{cases} \textit{vector type} \\ \textit{conductivity} \\ \\ \textit{fermionic type} \end{cases}$

Probing the IR geometry

- Entanglement Entropy



$$ds_{sp}^2 = \frac{L^2}{z^2}(dx^2 + dy^2 + U(z)dz^2)$$

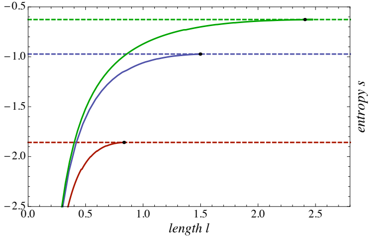
$$S(\mathcal{E}) = \frac{2\pi L^2}{\kappa^2}\mathrm{Area}(\gamma_{\mathcal{E}})$$

$$S(\mathcal{E}) = \frac{4\pi L^2}{\kappa^2} l_y \left(s + \frac{1}{\epsilon}\right)$$

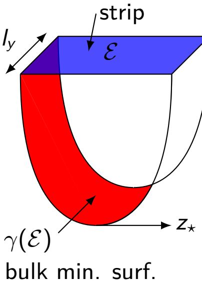
$$s = 2L^2 l_y \int_\epsilon^{z_\star} \frac{dz}{z^2}\sqrt{U(z) + x'(z)^2}$$

$$\frac{l_x}{2} = \int_\epsilon^{z_\star} dz\, \frac{z^2}{z_\star^2}\sqrt{\frac{U(z)}{1-(z/z_\star)^4}}$$

Probing the IR geometry: EE at $T = 0$



From top to bottom
$\theta_\infty = 0.5, 1., 1.4.$



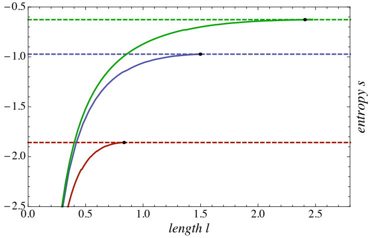
$z_\star \gg 1/C_\eta$

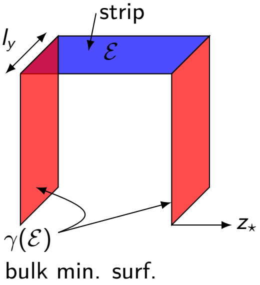
$U(z) \approx (C_\eta z)^{-2}$

$$\frac{l_x}{2} = z_\star \int_\epsilon^1 dz \; \frac{z^2}{\sqrt{1 - z^4}} U(z z_\star)^{1/2}$$

$$\frac{l_x}{2} \sim const \frac{1}{C_\eta}$$

Probing the IR geometry: EE at $T = 0$





From top to bottom
$\theta_\infty = 0.5, 1., 1.4.$

$$s = 2L^2 l_y \int_\epsilon^{z_\star} \frac{dz}{z^2}\sqrt{U(z)}$$

$$z_\star \gg \frac{1}{C_\eta}$$

Summary

$$\eta(r) = \frac{\mathcal{O}}{r} + \ldots, \qquad \theta(r) = \theta_\infty + \frac{\xi}{r} + \ldots$$

$\Delta = 1$ Condensate

$$\zeta_1(r) = \tanh\frac{\eta(r)}{2}\cos\frac{\theta(r)}{2}, \qquad \zeta_2(r) = \tanh\frac{\eta(r)}{2}\sin\frac{\theta(r)}{2}$$

Dual Field theory

$$\eta(r) = \frac{\mathcal{O}}{r} + \ldots, \qquad \theta(r) = \theta_\infty + \frac{\xi}{r} + \ldots$$

$\Delta = 1$ Condensate

$$\zeta_1(r) = \frac{\mathcal{O}_1^{(1)}}{r} + \frac{\mathcal{O}_1^{(2)}}{r^2} + \ldots, \qquad \zeta_2(r) = \frac{\mathcal{O}_2^{(1)}}{r} + \frac{\mathcal{O}_2^{(2)}}{r^2} + \ldots$$

$$\mathcal{O}_1^{(1)} = \frac{1}{2}\mathcal{O}\cos\frac{\theta_\infty}{2} \qquad \mathcal{O}_1^{(2)} = -\frac{1}{4}\mathcal{O}\xi\sin\frac{\theta_\infty}{2}$$

$$\mathcal{O}_2^{(1)} = \frac{1}{2}\mathcal{O}\sin\frac{\theta_\infty}{2} \qquad \mathcal{O}_2^{(2)} = \frac{1}{4}\mathcal{O}\xi\cos\frac{\theta_\infty}{2}$$

Dual Field theory

The dictionary is $\begin{array}{l} \zeta_1 \to \Delta = 1 \text{ Op.} \\ \zeta_2 \to \Delta = 2 \text{ Op.} \end{array}$ i.e. opposite quant.

- Double trace deformation! $\mathcal{O}_2^{(1)} = \lambda \mathcal{O}_1^{(1)}$ and $\mathcal{O}_1^{(2)} = -\lambda \mathcal{O}_2^{(2)}$

The marginal coupling is $\lambda = \tanh \frac{\theta_\infty}{2}$

$$\mathcal{O}_1^{(1)} = \frac{1}{2} \mathcal{O} \cos \frac{\theta_\infty}{2} \qquad \mathcal{O}_1^{(2)} = -\frac{1}{4} \mathcal{O} \xi \sin \frac{\theta_\infty}{2}$$

$$\mathcal{O}_2^{(1)} = \frac{1}{2} \mathcal{O} \sin \frac{\theta_\infty}{2} \qquad \mathcal{O}_2^{(2)} = \frac{1}{4} \mathcal{O} \xi \cos \frac{\theta_\infty}{2}$$

Dual Field theory

The dictionary is $\begin{array}{l} \zeta_1 \to \ \Delta = 1 \text{ Op.} \\ \zeta_2^\dagger \to \ \Delta = 2 \text{ Op.} \end{array}$ i.e. opposite quant.

- Double trace deformation! $\mathcal{O}_2^{(1)\dagger} = \lambda \mathcal{O}_1^{(1)}$ and $\mathcal{O}_1^{(2)} = -\bar{\lambda} \mathcal{O}_2^{(2)\dagger}$

Taking into account the charges $\zeta_1 \leftrightarrow \zeta_2^\dagger$. Then, $\lambda = \tanh \frac{\theta_\infty}{2} e^{-i\psi}$

$$\mathcal{O}_1^{(1)} = \frac{1}{2} \mathcal{O} \cos \frac{\theta_\infty}{2} e^{i(\phi+\psi)/2} \qquad \mathcal{O}_1^{(2)} = -\frac{1}{4} \mathcal{O} \xi \sin \frac{\theta_\infty}{2} e^{i(\phi+\psi)/2}$$

$$(\mathcal{O}_2^{(1)})^\dagger = \frac{1}{2} \mathcal{O} \sin \frac{\theta_\infty}{2} e^{i(\phi-\psi)/2} \qquad (\mathcal{O}_2^{(2)})^\dagger = \frac{1}{4} \mathcal{O} \xi \cos \frac{\theta_\infty}{2} e^{i(\phi-\psi)/2}$$

Dual Field theory

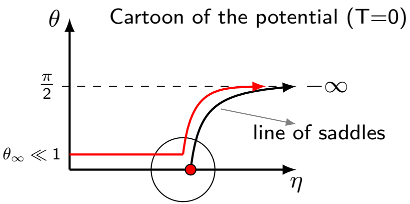
Marginal deformation

$$\int d^3x \left(\lambda \mathcal{O}_1 \mathcal{O}_2 \; + \; \overline{\lambda} \mathcal{O}_1^\dagger \mathcal{O}_2^\dagger\right) \qquad \mathcal{O}_2^{(2)\dagger} = \frac{1}{2}\xi \mathcal{O}_1^{(1)} e^{-i\psi} \; .$$

We interpret $\theta(r)$ in an RG fashion:

$\theta_\infty \neq 0$ in the UV, drives the theory to $\theta(0) = \pi/2$ in the IR.

This value is associated to the confining background $\rightarrow$ Issue on λ!



λ exactly marginal but the confining IR phase has to be associated to a relevant def.

$$\theta(r) = \theta_\infty + \frac{\xi}{r} + \ldots$$

$$\xi = 0 \leftrightarrow \theta(r) = const.$$

Dual Field theory

Marginal deformation

$$\sim \int d^3x \, \left(\xi \mathcal{O}_1^\dagger \mathcal{O}_1\right) \qquad \mathcal{O}_2^{(2)\dagger} = \frac{1}{2}\xi \mathcal{O}_1^{(1)} e^{-i\psi} \, .$$

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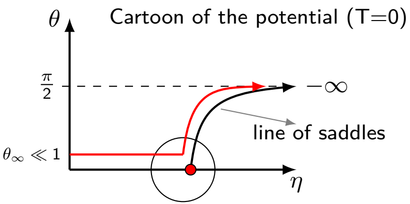

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Conclusions

We have find new holographic superconductor solutions in $\mathcal{N} = 8$ sugra where:

- The topology of the underling $\mathcal{N} = 2$ model plays an important role
- The back-reaction changes the IR physics of the solutions and this IR physics is geometrically understood

It may be that a similar story holds for the $5D$ $\mathcal{N} = 8$.

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We have find new holographic superconductor solutions in $\mathcal{N} = 8$ sugra where:

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Thanks for the attention!!