Holographic studies of ABJM theory at finite density

OSCAR HENRIKSSON

NORDITA WORKSHOP, OCTOBER 5 2017

UNIVERSITY OF HELSINKI

Based on work mainly from...
1609.07186 with O. DeWolfe, S. Gubser, C. Rosen
1612.06823 with C. Rosen

Top-down vs. bottom-up holography

Gauge/gravity dualities can be derived from string theory

Top-down dualities are difficult to deal with
→ can postulate gravity theory, assume duality

Bottom-up is flexible – too flexible?

Top-down imposes tight constraints, allows for more precise statements

...especially regarding fermionic response

$$
\begin{aligned}
\mathscr{L} = & -\tfrac{1}{2}eR(e,\omega) - \tfrac{1}{2}\varepsilon^{\mu\nu\rho\sigma}(\bar{\psi}^i_\mu \gamma_\nu D_\rho \psi_{\sigma i} - \bar{\psi}^i_\mu \overleftarrow{D}_\rho \gamma_\nu \psi_{\sigma i}) \\
& - \tfrac{1}{12}e(\bar{\chi}^{ijk}\gamma^\mu D_\mu \chi_{ijk} - \bar{\chi}^{ijk}\overleftarrow{D}_\mu \gamma^\mu \chi_{ijk}) - \tfrac{1}{96}e\mathscr{A}_\mu{}^{ijkl}\mathscr{A}^\mu{}_{ijkl} \\
& - \tfrac{1}{8}e[F^+_{\mu\nu IJ}(2S^{IJ,KL} - \delta^{IJ}_{KL})F^{+\mu\nu}{}_{KL} + \text{h.c.}] \\
& - \tfrac{1}{2}e[F^+_{\mu\nu IJ}S^{IJ,KL}O^{+\mu\nu KL} + \text{h.c.}] \\
& - \tfrac{1}{4}e[O^+_{\mu\nu}{}^{IJ}(S^{IJ,KL} + u^{ij}{}_{IJ}v_{ijKL})O^{+\mu\nu KL} + \text{h.c.}] \\
& - \tfrac{1}{24}e[\bar{\chi}_{ijk}\gamma^\nu\gamma^\mu\psi_{\nu l}(\hat{\mathscr{A}}_\mu{}^{ijkl} + \mathscr{A}_\mu{}^{ijkl}) + \text{h.c.}] \\
& - \tfrac{1}{2}e\bar{\psi}^{[i}_\mu \psi^{j]}_\nu \bar{\psi}^\mu_i \psi^\nu_j \\
& + \tfrac{1}{4}\sqrt{2}e[\bar{\psi}^i_\lambda \sigma^{\mu\nu}\gamma^\lambda \chi_{ijk}\bar{\psi}^j_\mu \psi^k_\nu + \text{h.c.}] \\
& + e[\tfrac{1}{144}\eta\varepsilon_{ijklmnpq}\bar{\chi}^{ijk}\sigma^{\mu\nu}\chi^{lmn}\bar{\psi}^p_\mu \psi^q_\nu \\
& + \tfrac{1}{8}\bar{\psi}^i_\lambda \sigma^{\mu\nu}\gamma^\lambda \chi_{ikl}\bar{\psi}_{\mu j}\gamma_\nu \chi^{jkl} + \text{h.c.}] \\
& + \tfrac{1}{864}\sqrt{2}\eta e[\varepsilon^{ijklmnpq}\bar{\chi}_{ijk}\sigma^{\mu\nu}\chi_{lmn}\bar{\psi}^r_\mu \gamma_\nu \chi_{pqr} + \text{h.c.}] \\
& + \tfrac{1}{32}e\bar{\chi}^{ikl}\gamma^\mu \chi_{jkl}\bar{\chi}^{jmn}\gamma_\mu \chi_{imn} - \tfrac{1}{96}e(\bar{\chi}^{ijk}\gamma^\mu \chi_{ijk})^2 .
\end{aligned}
$$

Outline

1) ABJM theory and 4D SUGRA

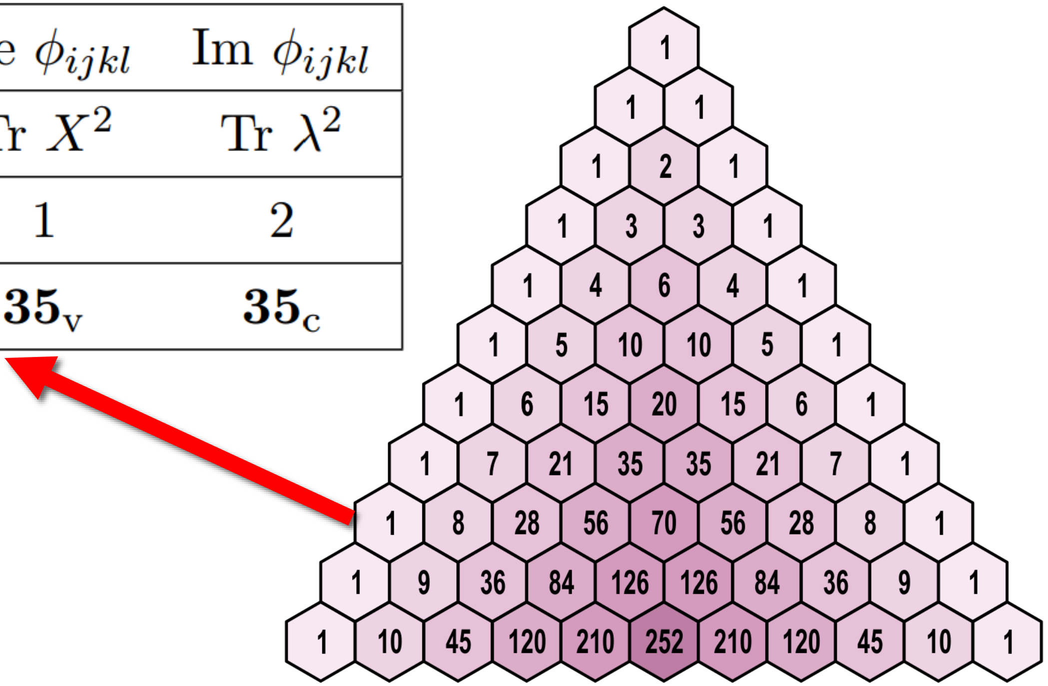
Top-down fermionic linear response

2) …in superconducting phases
3) …compared to bosonic response
4) Summary & outlook

4D $\mathcal{N} = 8$ gauged supergravity

Large field content:

SUGRA mode	$g_{\mu\nu}$	ψ^i_μ	A^{IJ}_μ	χ_{ijk}	Re ϕ_{ijkl}	Im ϕ_{ijkl}
Dual operator	$T^{\mu\nu}$	$\mathcal{S}^{\mu i}$	$J^{\mu IJ}_R$	Tr $X\lambda$	Tr X^2	Tr λ^2
Conformal dimension	3	5/2	2	3/2	1	2
$SO(8)$ rep	$\mathbf{1}$	$\mathbf{8}_\mathrm{s}$	$\mathbf{28}$	$\mathbf{56}_\mathrm{s}$	$\mathbf{35}_\mathrm{v}$	$\mathbf{35}_\mathrm{c}$



$SO(8)$ gauge symmetry

70 scalars parametrize coset space $\mathrm{E}_7/SU(8)$

ABJM theory

A 3D superconformal Chern-Simons-matter QFT

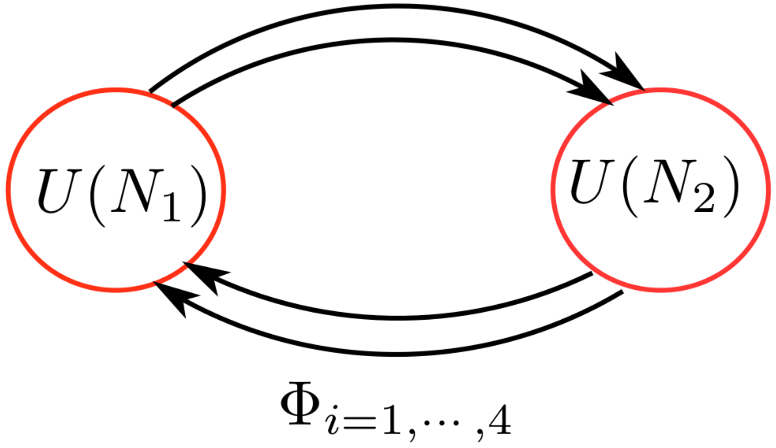
Two vector multiplets with gauge group $U(N) \times U(N)$

Global $SO(8)$ symmetry

Matter supermultiplets in bifundamental representation

Gauge invariant operators (schematic):

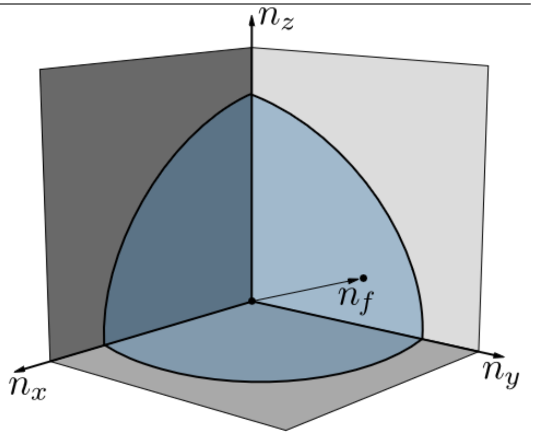
- $Tr\, X^2$ and $Tr\, X\, \Lambda$ and $Tr\, \Lambda^2$



Has classical gravity dual when $N \gg 1$

ABJM at finite density

Turn on chemical potential for one or more $U(1) \subset SO(8)$



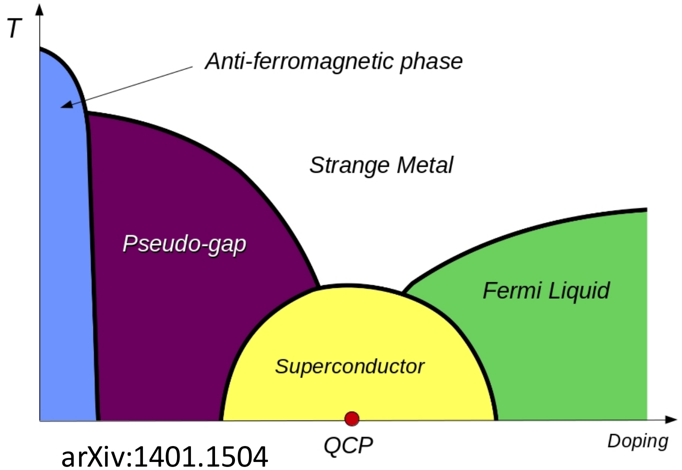
Expectations for finite density?

→ Fermi surfaces

→ Symmetry breaking (superconductivity)

→ Exciting new phases?

Will compute fermionic & bosonic two-point functions, leading to spectral weights, Fermi surfaces, susceptibilities…



arXiv:1401.1504

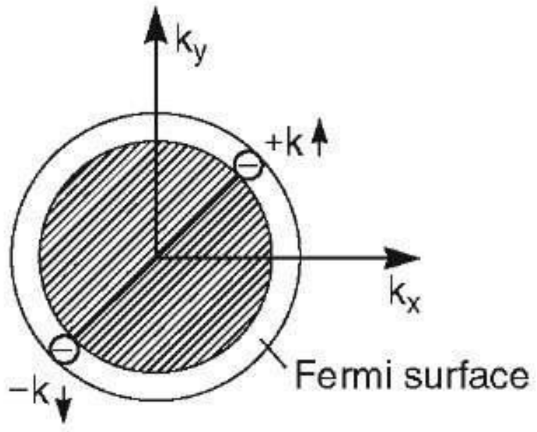
Conventional superconductors

Superconductivity $\Leftrightarrow$ Spontaneous breaking of $U(1)$ symmetry

a Higgs mechanism!

BCS: Electron-phonon interactions → Cooper pairing

→ gapped fermion spectrum



Dealing with maximal supergravity

SUGRA has many fields, complicated!

To isolate a more manageable sector of full SUGRA, perform **consistent truncation**

This can be done using group theory:

→ pick subgroup $H \subset SO(8)$

→ keep only fields invariant under that subgroup

→ guaranteed to be consistent

(Decouple spin-1/2 from spin-3/2 using related group theory)

Supergravity truncations

We use two such subgroups of $SO(8)$:

→ $SO(3) \times SO(3)$ and $SU(4)$ ⇨ $$2e^{-1}\mathcal{L} = R - \mathcal{F}^2 - \frac{3}{2}\frac{|\mathcal{D}\xi|^2}{(1-\frac{3}{4}\xi^2)^2} - \frac{24}{(1-\frac{3}{4}\xi^2)^2}(-1+\xi^2)$$

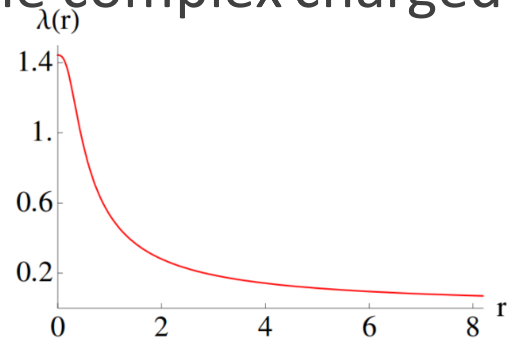
⇩

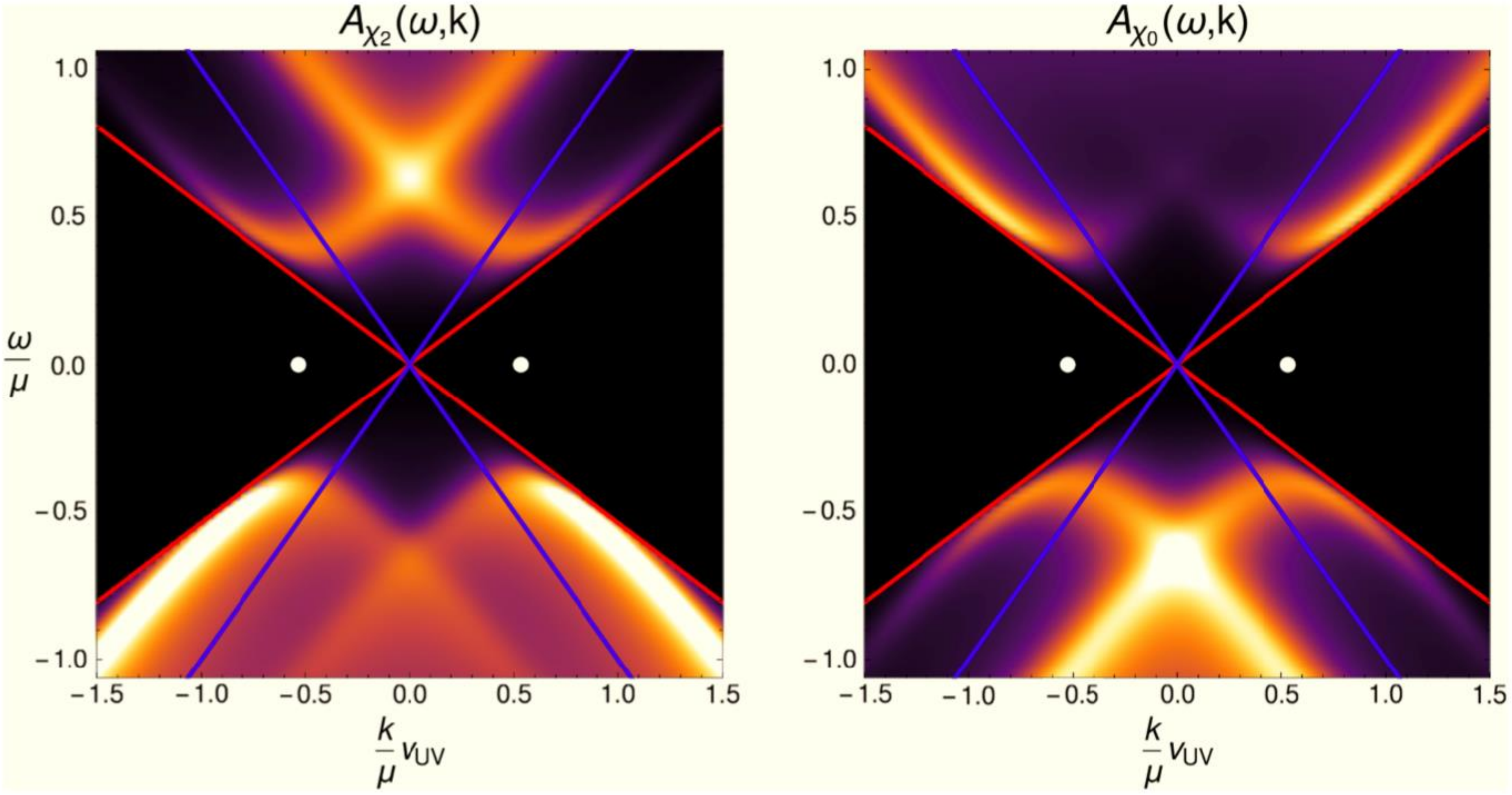
$$e^{-1}\mathcal{L} = \frac{1}{2}R - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \partial_\mu\lambda\partial^\mu\lambda - \frac{\sinh^2(2\lambda)}{4}\left(\partial_\mu\alpha - gA_\mu\right)\left(\partial^\mu\alpha - gA^\mu\right) - \mathcal{P}$$

$$\mathcal{P} = \frac{g^2}{2}\left(s^4 - 8s^2 - 12\right) \qquad \text{with} \qquad s \equiv \sinh\lambda$$

In both cases, left with metric, one U(1) gauge field, and one complex charged scalar

→ Three different T=0 symmetry breaking **domain walls**





Results: Exclusively **GAPPED** fermion spectra

…in three different top-down domain walls

Why gapped?

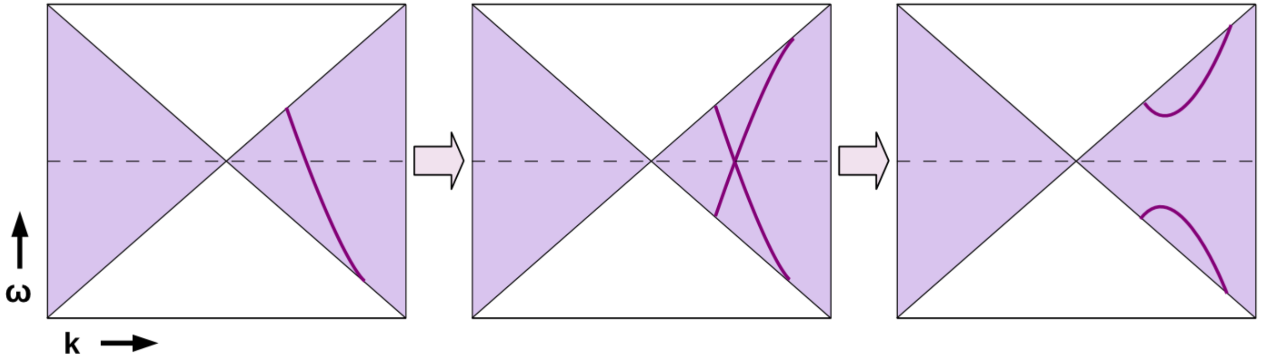
Operator mixing → level repulsion

$$\left(i\Gamma^\mu \nabla_\mu \mathbf{1} + \mathbf{S}\right)\vec{\chi} = 0$$

$$\begin{pmatrix} -\frac{1}{4}\not{A}(\cosh 2\lambda + 3) & 0 & \Gamma_5 \sinh\lambda & -\sinh\lambda \\ 0 & \frac{1}{4}\not{A}(\cosh 2\lambda + 3) & -\sinh\lambda & -\Gamma_5 \sinh\lambda \\ -\Gamma_5 \sinh\lambda & -\sinh\lambda & \frac{i}{2\sqrt{2}}\not{F} & \frac{1}{2}\left(\not{A} - \sqrt{2}\right)\Gamma_5 \sinh^2\lambda \\ -\sinh\lambda & \Gamma_5 \sinh\lambda & \frac{1}{2}\left(\not{A} + \sqrt{2}\right)\Gamma_5 \sinh^2\lambda & -\frac{i}{2\sqrt{2}}\not{F} \end{pmatrix}$$

Mixing looks ≈ generalized BCS

Faulkner et al. 0911.3402



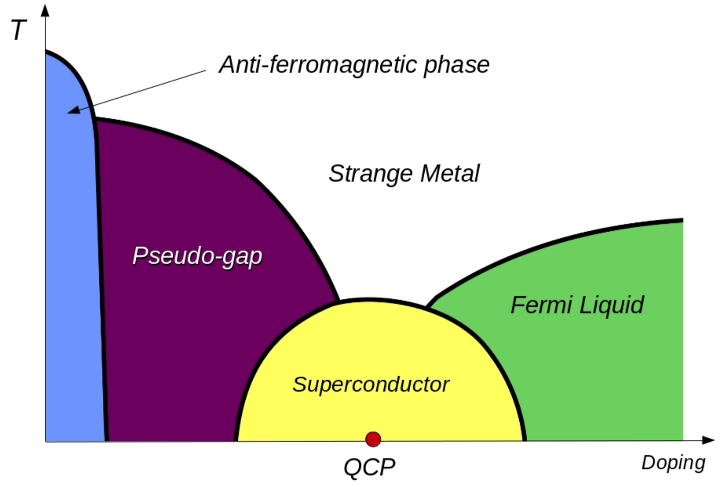
Results so far…

Studying ABJM theory with holography, we found…

“normal” phase Fermi surfaces with non-FL fermions

…which upon symmetry breaking become…

gapped through a “holographic BCS mechanism”



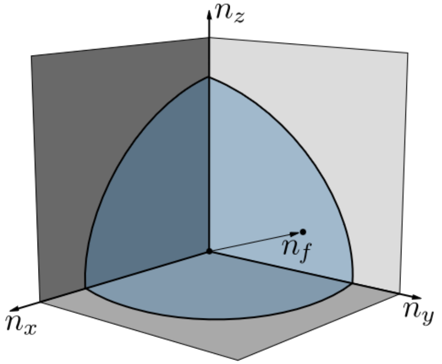
Important question: Does the fermion response give information about $O(N^2)$ physics, or does it only involve a subleading sector?

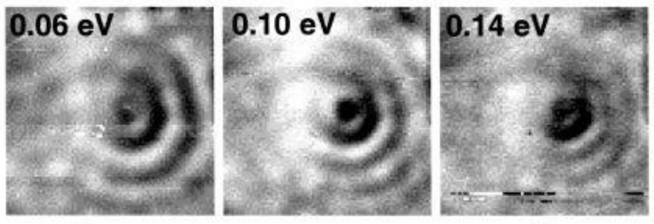
Correlated Correlators

⇨ **Related question:** Do Fermi surfaces leave footprints in bosonic observables?

At weak coupling: **YES!**

$2k_F$ singularities → *Friedel oscillations*





Correlated Correlators

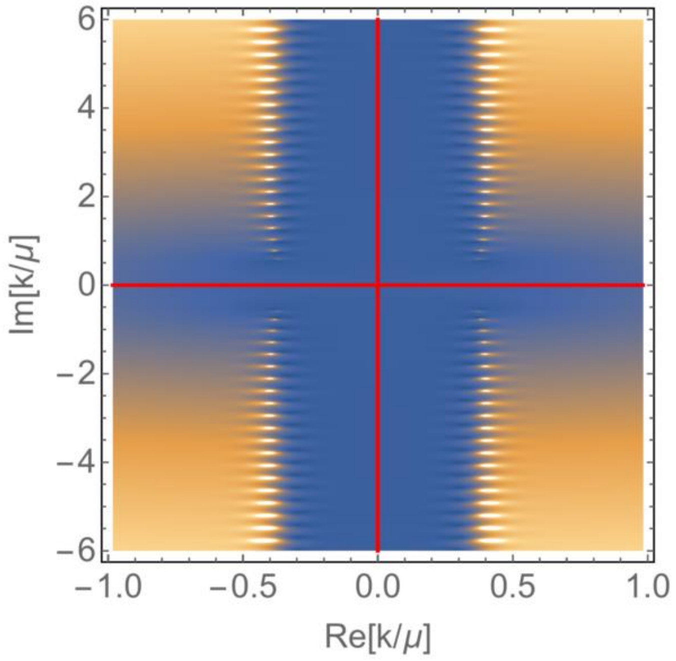
⇨ **Related question:** Do Fermi surfaces leave footprints in bosonic observables?

At strong coupling: **???** – Holographic states: No...?

→ in AdS-RN, singularities at complex momenta

(Blake, Donos, Tong 1412.2003)

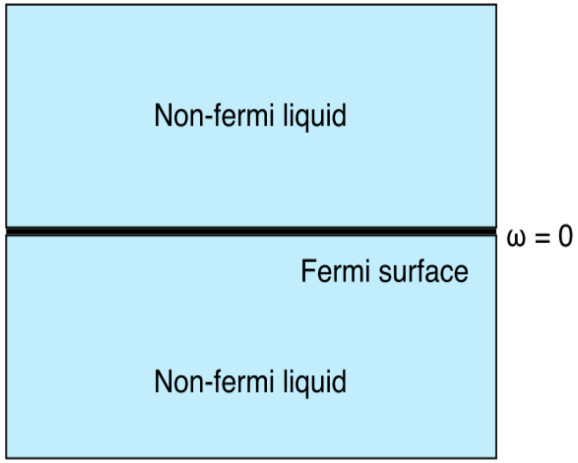
→ no "conventional" FS signature

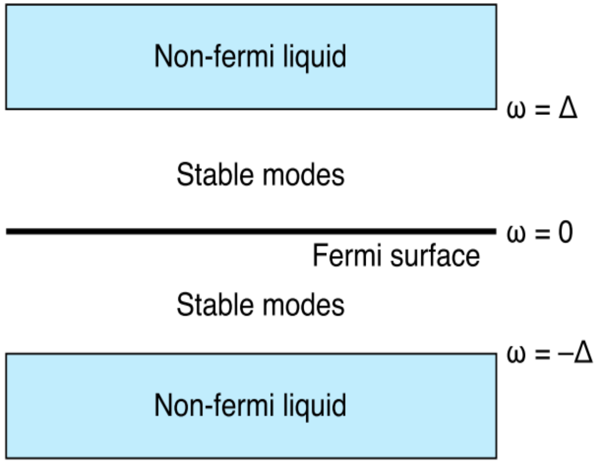


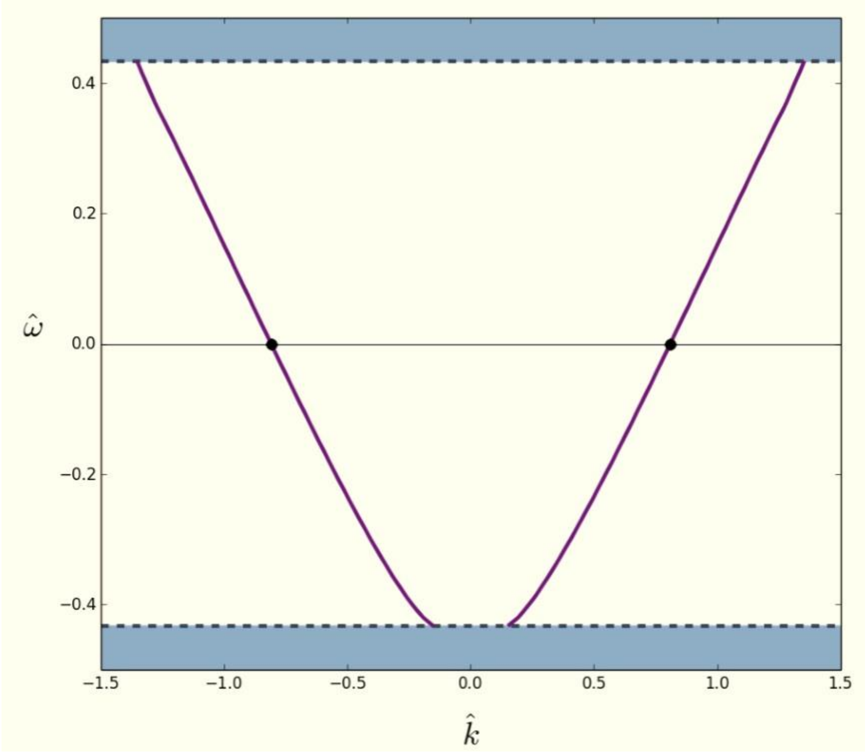
Susceptibility in the 3-charge black brane

A special top-down geometry

IR is an “η-geometry”







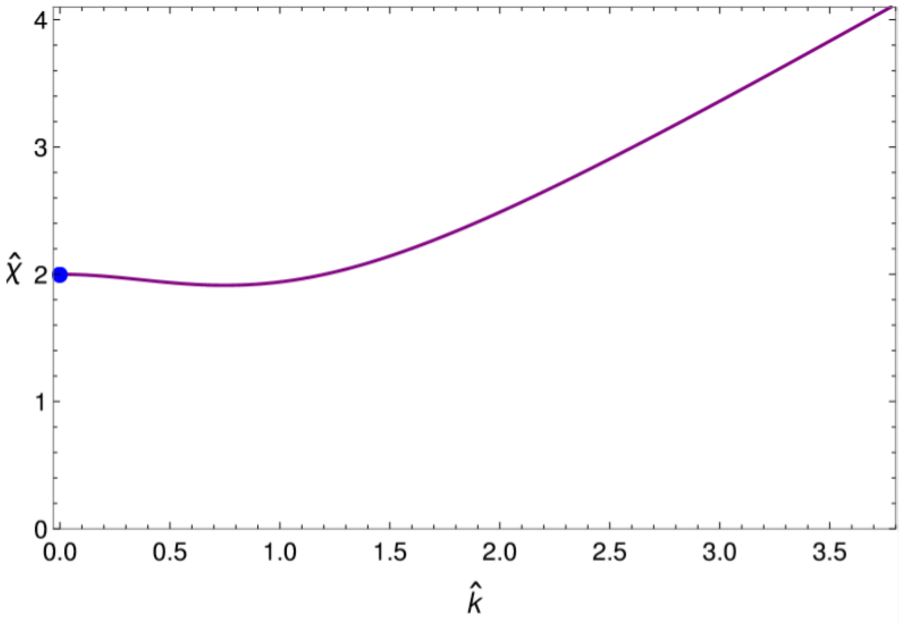
Stable interval in fermion spectral weights

Susceptibility in the 3-charge black brane

Need to solve linearized Maxwell equations for A_0

→ couples to metric and scalar

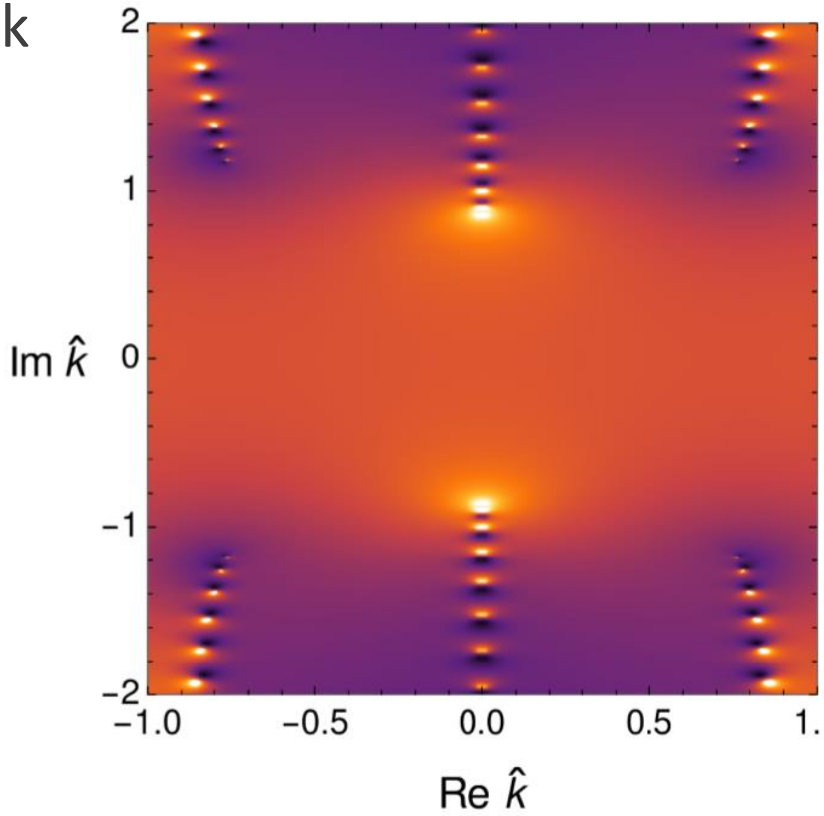
Matching to $\frac{\partial \rho}{\partial \mu}$ at $k = 0$ requires finite, SUSY-preserving counterterms!



Susceptibility in the 3-charge black brane

Again, singularities at complex momenta

→ different from weak coupling – no *clear* mark of Fermi surfaces



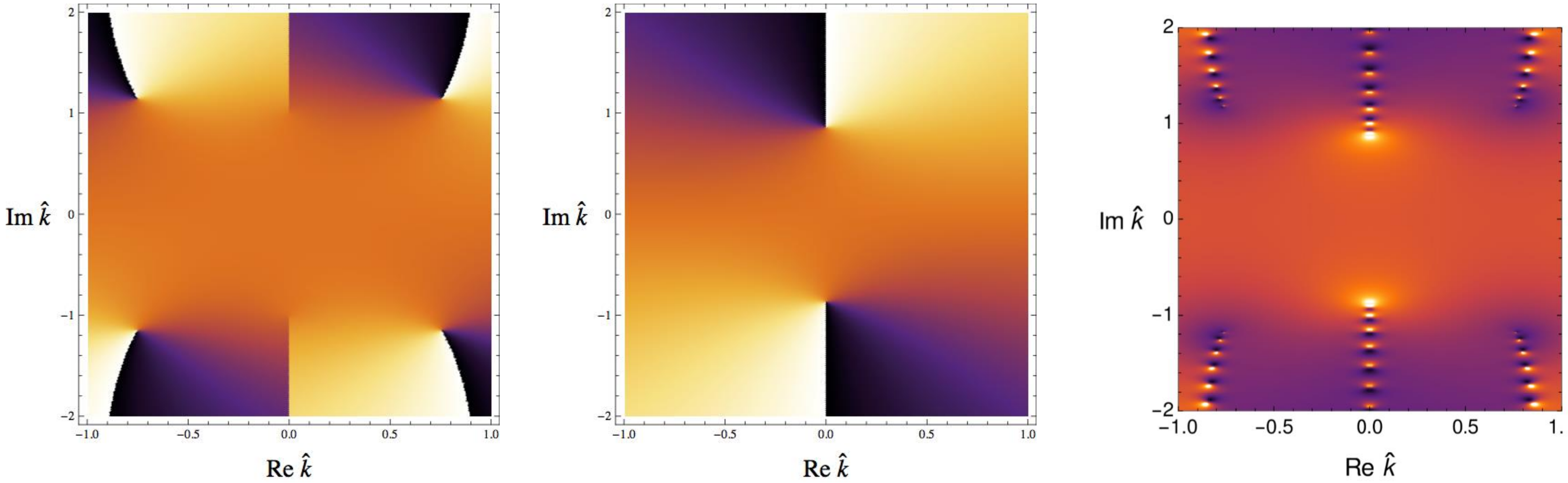
In both AdS-RN and here, we find

$$Re(k^*) \approx 1k_F$$

→ conspiracy or coincidence?

Susceptibility in the 3-charge black brane

IR conformal to $AdS_2 \times R^2$ ⇨ zero-temperature controlled by set of IR scaling exponents (Anantua et al. 1210.1590)



Takeaways

Studied ABJM/$\mathcal{N} = 8$ SUGRA duality

Top-down imposes strong constraints...

→ Fermi surfaces with **non-Fermi liquid** behavior

→ upon symmetry breaking ⇨ **gapped** fermions ($\approx$ "holographic BCS")

→ quantitative comparisons between fermionic and bosonic response meaningful ⇨ fermions results relevant at leading order in N?

Future directions:

- Compare fermionic/bosonic response in more general backgrounds
- Study how spectra in SUSY states changes upon adding finite density

Thank you!