Holographic Plasmons

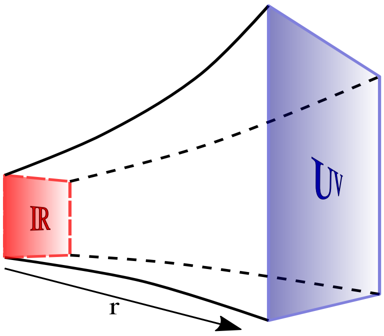
E. Mauri and H. T. C. Stoof
Institute for Theoretical Physics, Utrecht University

Gauge/Gravity Duality

Classical gravity in d + 1 dimensions

$$Z_{\mathrm{QFT}}[J(x)] = \int \mathcal{D}\phi \, e^{iS_{\mathrm{gravity}}[\phi(x,r)]}\Big|_{\phi(x,r=\infty)=J(x)}$$

d-dimensional **strongly-coupled** field theory



The extra dimension on the (asymptotically AdS) gravity side encodes the energy scale of the QFT.

Holographic dictionary

QFT boundary		Gravity bulk
Nonzero temperature T	$\longleftrightarrow$	Black hole
Global conserved current $J^\mu(x)$	$\longleftrightarrow$	Maxwell field $A_\mu(x,r)$
Energy-momentum tensor $T^{\mu\nu}(x)$	$\longleftrightarrow$	Metric field $g_{\mu\nu}(x,r)$

Useful for computing **real-time response functions** $\chi^{\alpha\beta}(\omega,k)$ of strongly-interacting systems, and the associated spectral functions

$$A_{\alpha\alpha}(\omega,k) = -\mathrm{Im}\left[\chi^{\alpha\alpha}(\omega,k)\right]$$

The **Reissner-Nordström black hole** is the simplest gravitational theory dual to a QFT with nonzero temperature and chemical potential:

$$S_{\mathrm{gravity}} = \int \mathrm{d}^{d+1}x\,\sqrt{-g}\left(R - 2\Lambda - \frac{1}{4\lambda}F_{\mu\nu}F^{\mu\nu}\right)$$

$$\mathrm{d}s^2 = -f(r)\mathrm{d}t^2 + \frac{1}{f(r)}\mathrm{d}r^2 + r^2\mathrm{d}\boldsymbol{x}^2$$

Charged holographic metals

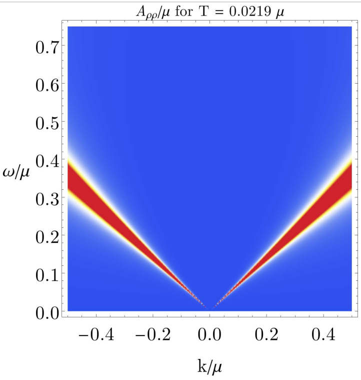
Conventional holographic models describes **neutral** systems, with low energy **sound** modes. We want to **add Coulomb interactions** to model charged matter, with low energy **plasmon** excitations. We do this by deforming the boundary theory with the Maxwell action:

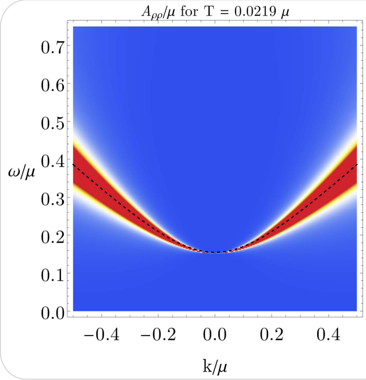
$$S_{\mathrm{Maxwell}} = -\frac{1}{2}\int \frac{\mathrm{d}^d k}{(2\pi)^d}\alpha^2 \langle J^\mu(k)\rangle \left[\frac{\eta_{\mu\nu} - (1-\xi)k_\mu k_\nu/k^2}{k^2}\right]\langle J^\nu(-k)\rangle$$

$$S_{\mathrm{gravity}}$$

$$\chi^{\rho\rho}(\omega,k) = G^{00}(\omega,k)$$

Sound: $\omega^2 = v_s^2 k^2$





$$S_{\mathrm{gravity}} + S_{\mathrm{Maxwell}}$$

$$\chi^{\rho\rho}(\omega,\boldsymbol{k}) = \frac{G^{00}(\omega,\boldsymbol{k})}{1 - \frac{\alpha^2}{\boldsymbol{k}^2}G^{00}(\omega,\boldsymbol{k})}$$

Plasmon: $\omega_p^2 \propto \alpha^2 \dfrac{\langle\rho\rangle^2}{\langle\epsilon\rangle}$

This procedure gives rise to a holographic response function of the form expected from traditional condensed-matter calculations in the **RPA approximation**, with $V(\boldsymbol{k}) = \alpha^2/\boldsymbol{k}^2$ the Coulomb potential.

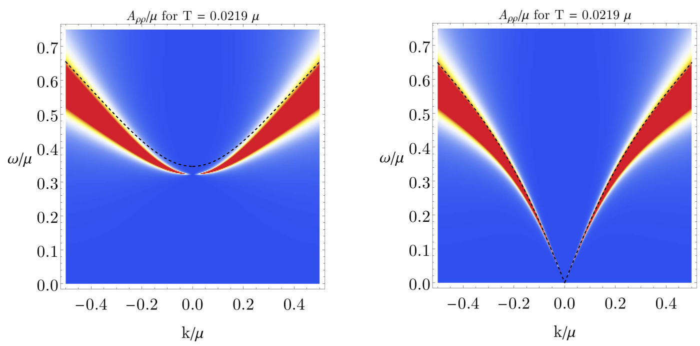
Layered system

Introducing interactions among charges, allows us to model a stack of (2+1)-dimensional layers at distance ℓ with **strong in-plane short-range interactions, coupled by** a **long-range Coulomb interaction.**

The coupling generates a potential of the form:

$$V(k,p) = \alpha^2 \frac{\ell}{2|k|}\frac{\sinh(|k|\ell)}{\cosh(|k|\ell) - \cos(p\ell)}$$

that gives rise to a dispersion relation for the low-energy plasmon excitations that changes from a **gapped mode** (a) to linear "**acoustic plasmon**" (b) as a function of the out-of-plane Bloch momentum $p \in [0, 2\pi/\ell)$.



(a) $p\ell = 0$ (b) $p\ell = \pi$

Outlook: the addition of Coulomb interactions to holographic models of strongly-interacting matter gives rise to features expected in the response of charged matter, and it therefore allows for a description of the properties of strongly-interacting materials, such as **strange metals** and **high-temperature superconductors,** that can more closely reproduce experimental results.

References: E. Mauri and H. T. C. Stoof, Screening of Coulomb interactions in Holography, arXiv: 1811.11795 (2018)