**References and further reading**

For more details on the holographic approach to condensed matter systems (AdS/CMT), see the review by Hartnoll [78]. Other useful reviews for specific areas of AdS/CMT include [119], [120] and [118]. The gravity dual Galilean and Schrödinger symmetry was described by Son [103] and Balasubramanian and McGreevy [104]. The gravity dual of Lifshitz symmetry was described by Kachru, Liu and Mulligan [102]. The Lifshitz gravity dual was obtained in Horava-Lifshitz gravity in [105]. The string theory embedding was obtained in [106], [107], [108]. The recipe for calculation of correlation functions in AdS/CFT at finite temperature was proposed in [111]. The calculation of viscosity over entropy density is described in the review [110]. It was first found in [112] for $\mathcal{N} = 4$ SYM, and in [113] it was shown to be valid for a large class of models with gravity duals involving black holes. The calculation of transport properties in the ABJM model (2+1 dimensions) from dual black holes was described in [115]. The model of holographic superconductor described here was first proposed by Gubser in [114], and developed by Hartnoll, Herzog and Horowitz [109]. The applications of the ABJM model to condensed matter physics are reviewed in [116]. The reduction of the ABJM to the Landau-Ginzburg model was found in [117].

# Exercises, Chapter 25.

1) Prove explicitly the invariance of the metric in (25.12) under the (finite) symmetries generated by $D, P_i, H, M_{ij}, K_i, N$ and $C$.

2) Calculate holographically the spectral function for the Green's function for a scalar operator with $\Delta = 3$ in $d = 4$.

3) Find the Kubo formula for the bulk viscosity $\zeta$.

4) Fill in the details leading to (25.82).

5) Calculate the entropy and the temperature of the black hole solution in (25.93).

6) Consider the further reduction $\chi_1 = \phi_2 = 0$ in (25.121). Find the reduced action and show that the reduction is consistent.

- The requirement to have $m_n^2 \propto n$ at large $n$ implies that $\Phi - A \propto z^2$ at large $z$ (IR) (and $\Phi - A \propto -\log z$ at small $z$, in the UV).
- The requirement that also $m_S^2 \propto S$ at large $S$ implies that $\Phi \propto z^2$ at large $z$ and $A \sim -\log z$ at small $z$, solved by $\Phi = z^2/z_m^2$ and $A = -\log z$, when $m_{n,S}^2 = 4(n+S)/z_m^2$.
- In improved holographic QCD, from the known perturbative beta function of QCD, written as $\beta(\lambda)$, where $\lambda = N_c e^{\Phi}$, one extracts the perturbative form of the dilaton potential in the gravity dual $V(\lambda) = \sum_n V_n \lambda^n$, and of a corresponding expansion of the metric $e^{2A}$ as an expansion in the UV in $\log(z\Lambda)$.
- If we also want an expansion in the IR, in order to describe low energy physics, we need to make an ansatz for the exact beta function $\beta(\lambda)$ in QCD, and use it, together with the Einstein's equations, to determine the gravity dual.

**References and further reading**

The extended "hard-wall" model was introduced in [99] and the "soft-wall model" of AdS/QCD was introduced in [100]. The improved holographic QCD model was introduced in [101].

## Exercises, Chapter 24.

1) Calculate the mass of the pion, $m_\pi$, in the hard wall model.

2) Calculate the $\rho - \pi - \pi$ coupling in the hard wall model.

3) For the soft wall model with $A = -\log z$ and $\Phi = z^2/z_m^2$, calculate the $\rho - \rho - \pi - \pi$ coupling.

4) For the soft wall model with $A = -\log z$ and $\Phi = z^2/z_m^2$, calculate the mass of the pion.

5) Prove that the equations of motion (24.43) reduce on the conformal coordinates (24.16) to (24.44).

6) Propose an ansatz for $\beta(\lambda)$ that agrees with $b_0$ and $b_1$ and can be used at large $\lambda$.