Thermodynamics and Bosonic Excitations of Holographic Metals

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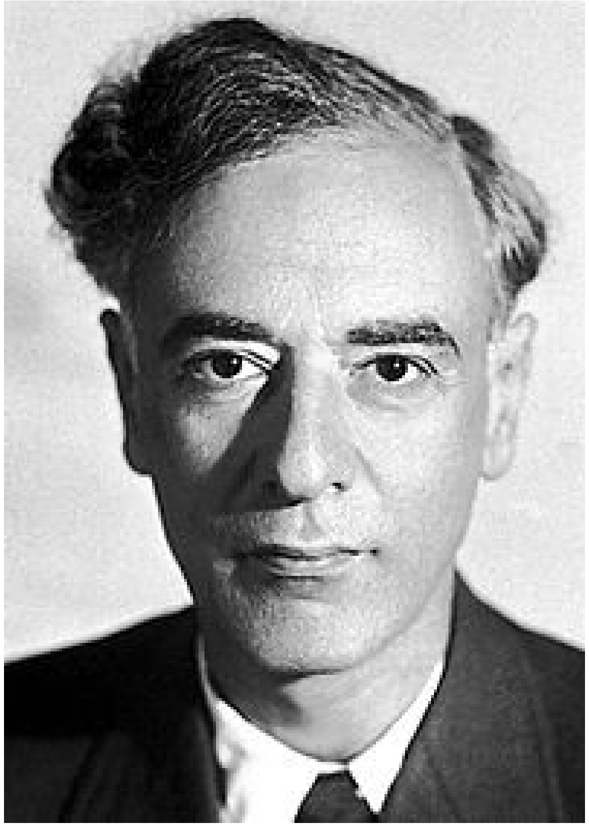
A Panorama of Holography
Cracow School of Theoretical Physics

Motivation

- Understanding physics of many body, strongly coupled fermions is very difficult.
- For low T, most metals can be described by Landau Fermi Liquid Theory (LFL), a phenomenological model governed by quasiparticle excitations of a Fermi surface.
  - Unclear if model can be derived from first principles.
- Holography provides natural framework for studying strongly coupled systems.
  - Is it possible to recover features of a LFL in a holographic context?
    - Yes! Sort of...



LFL in Holography: Thermodynamics

- The first problem to arise comes from thermodynamics. LFL predicts:

$$C_v \sim T$$

  - For a general, conformally invariant theory, T is completely determined from symmetries and dimensionality.

- Work around: Relax asymptotic symmetries and construct dualities where boundary theory is scale invariant but not conformally invariant.

  - Gives boundary theories with either Schrodinger or Lifshitz symmetries. They are invariant under:

$$t \to \lambda^z t, \quad \vec{x} \to \lambda \vec{x}$$

    and have:

$$C_v \sim T^{d/z}$$

Near equilibrium dynamics: Zerosound

- Characteristic property of LFL: Gapless excitation in the longitudinal current-current correlator known as the **zerosound** mode (ZS).

$T \to 0$

$$\bar{\omega} = \pm v_s \bar{k} - i\Gamma_0 \bar{k}^2 + \mathcal{O}(\bar{k}^3)$$

- In the context of holography, the existence of a ZS mode has been established/studied for several models. Generically:

$$\mathrm{Re}\,(\bar{\omega}) \sim \bar{k}$$

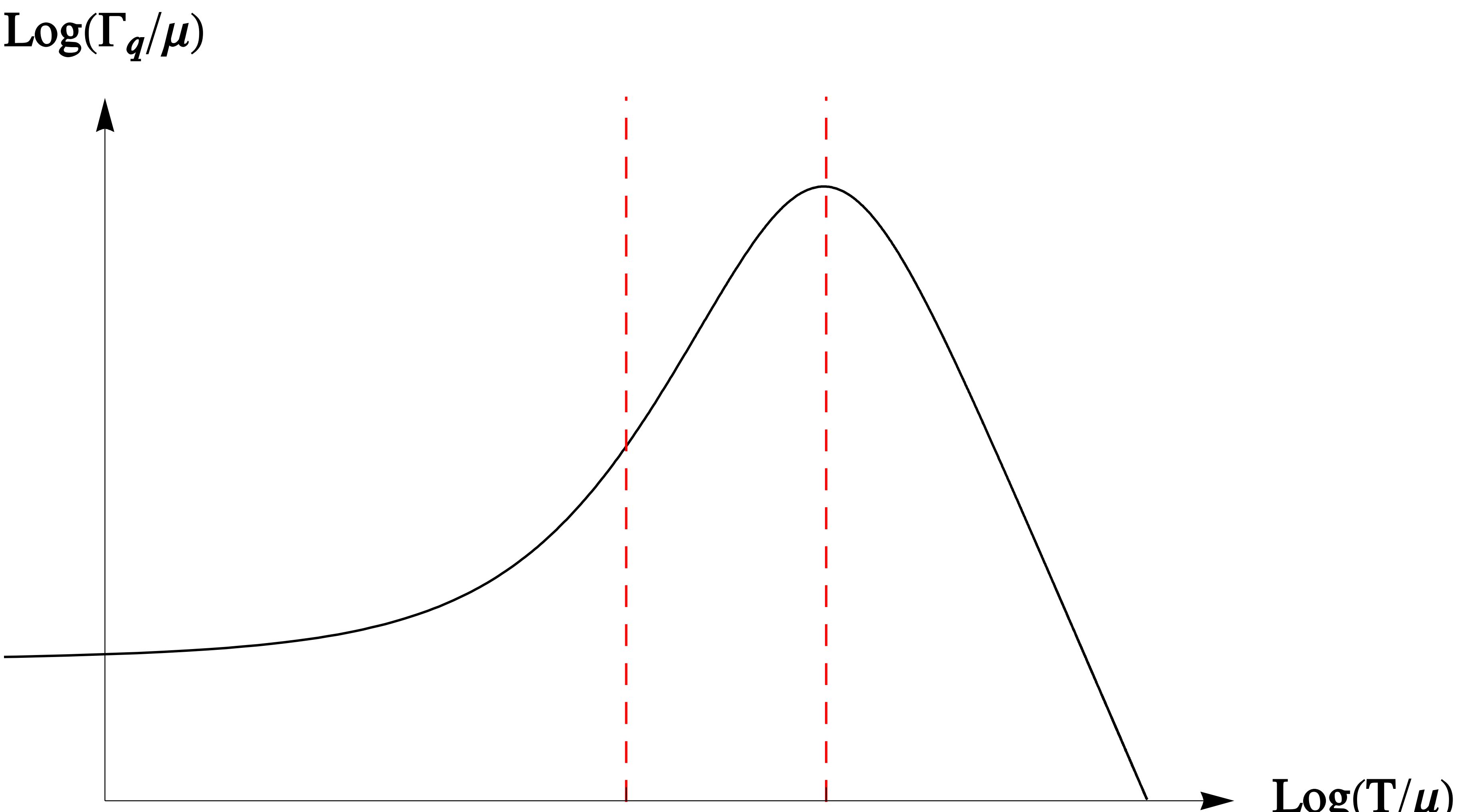
The imaginary part is sensitive to the details of the model.

- For Lifshitz theories,

$$\mathrm{Im}\,(\bar{\omega}) \sim \bar{k}^{2/z}$$

- LFL theory also predicts low T behavior of ZS, expected to hold for weakly interacting systems. Three regimes:
  - $0 \leq T \leq \bar{\omega}$ Collisionless Quantum Regime
  - $\bar{\omega} \leq T \leq \sqrt{\bar{\omega}}$ Collisionless Thermal Regime
  - $T > \sqrt{\bar{\omega}}$ Hydrodynamic Regime

Properties of zerosound



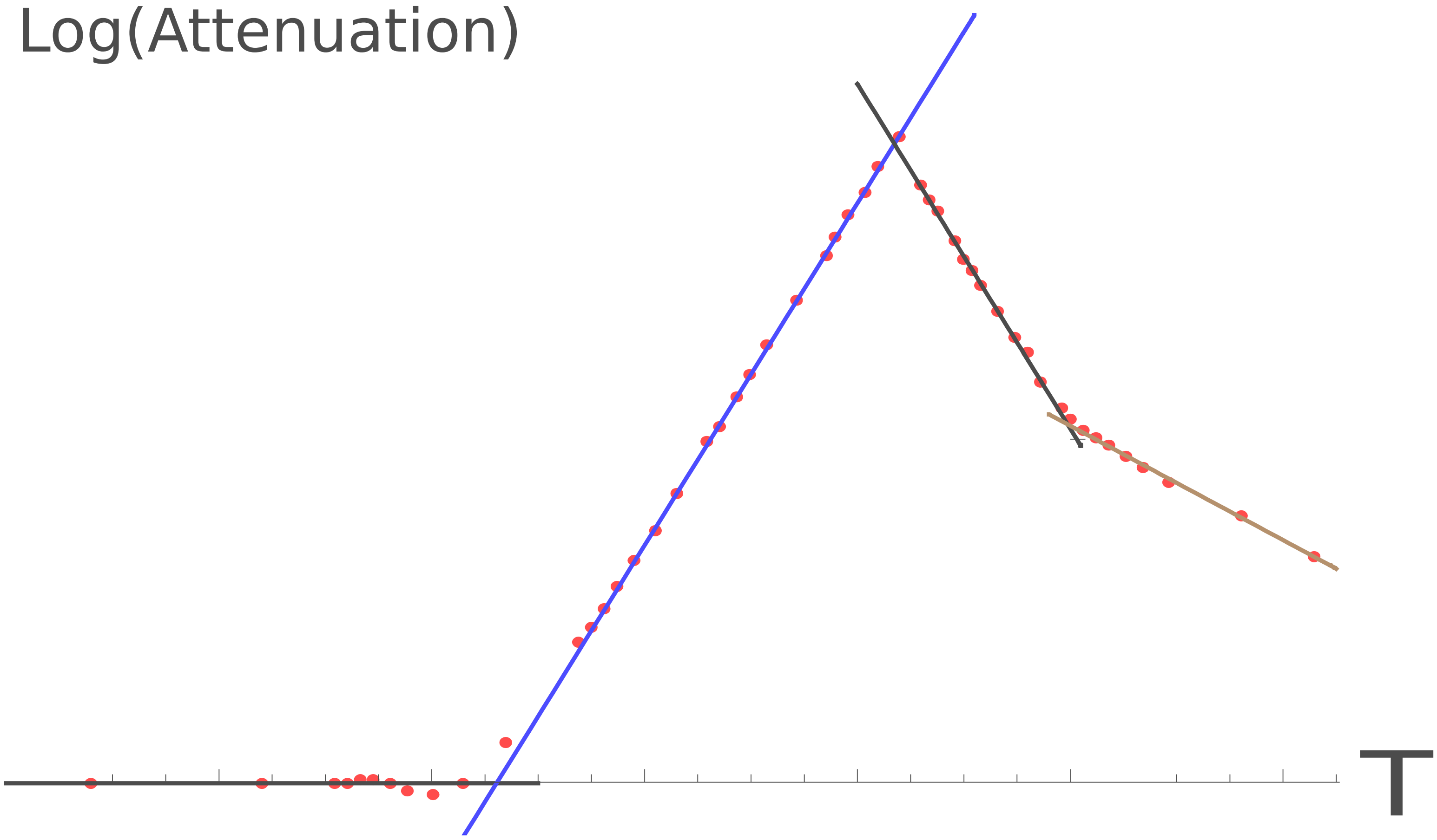
[1109.6343]

Holography and LFL: Probe theories

- These regimes are expected to hold for weakly interacting FL, but probe brane theories capture similar features!
  - D3/D7: Davison et. al. [1109.6343]
    - Found same three regimes with same T dependence
    - $C_v \sim T^6$
    - No evidence of sharp Fermi surface.
  - Sakai-Sugimoto Model: B.D.,M.I., N.J., J.P. [1403.1827]
    - Found similar regime split, but with additional regime between collisioness thermal and hydrodynamic regimes.
    - $C_v \sim T$
    - No evidence of sharp Fermi surface.

      No de Haas-van Alphen Oscillations [0906.3892]

Sakai-Sugimoto Model



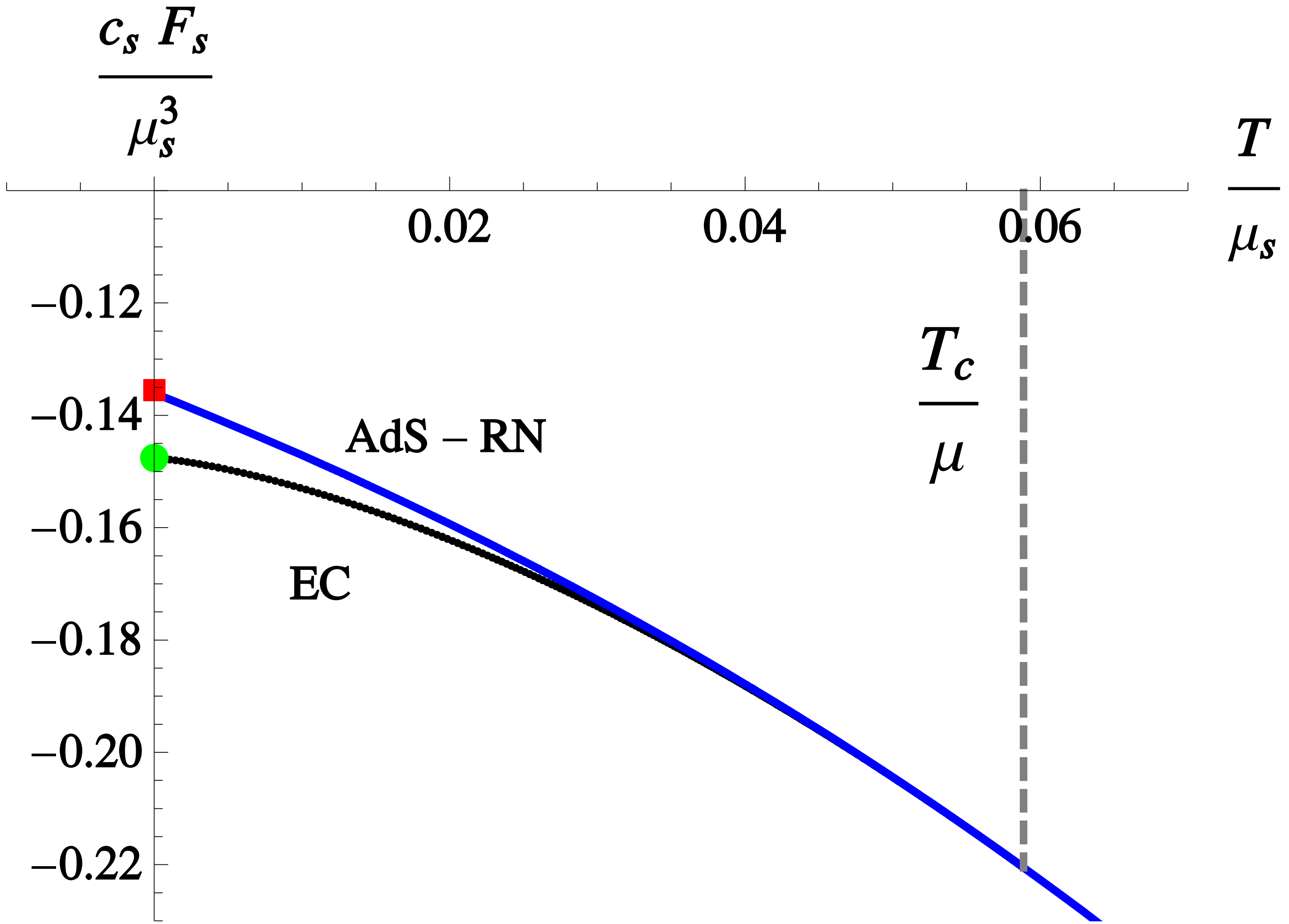
Holography and LFL: EMΛ - theories

- Proper zerosound T dependence has not been found in EMΛ theories, where gauge fluctuations couple to metric fluctuations.
  - Only tested in AdS-RN (Davison et. al.) [1111.0660]
- Can we find the T-separation of regimes and proper T-dependence of the zerosound in models which include backreaction?

Electron Cloud

- Explicity include charged fermions directly in the bulk, using Thomas-Fermi approximation
  - T = 0:
    Hartnoll et. al. [1008.2828]
    Finite T
    Puletti et. al. [1011.6261]
  - Presence of “smeared” Fermi surface [1011.2502]
  - de Haas-van Alphen oscillations observed[1501.06459]
  - Lifshitz scaling in IR
  - Thermodynamically favored over AdS-RN

Electron Cloud



[1011.6261]

Electron Cloud

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \frac{3}{L^2}g_{\mu\nu} = \kappa^2\left(T^{\text{EM}}_{\mu\nu} + T^{\text{PF}}_{\mu\nu}\right)$$

$$\nabla_\mu F^{\nu\mu} = e^2 J^\nu \qquad T^{\text{EM}}_{\mu\nu} = \frac{1}{e^2}\left(F_{\mu\rho}F_\nu{}^\rho - \frac{1}{4}g_{\mu\nu}F_{\rho\sigma}F^{\rho\sigma}\right)$$

$$T^{\text{PF}}_{\mu\nu} = (\rho + p)\,u_\mu u_\nu + p g_{\mu\nu} \qquad \mathbf{T}_{\mu\nu} = T^{\text{EM}}_{\mu\nu} + T^{\text{PF}}_{\mu\nu}$$

$$J_\mu = \sigma(v)u_\mu \qquad \nabla_\mu \mathbf{T}^{\mu\nu} = 0 \qquad u^2 = -1$$

$$ds^2 = L^2\left(-f(v)dt^2 + \frac{1}{v^2}\left(dx^2 + dy^2\right) + g(v)dv^2\right)$$

$$u^\mu = \frac{1}{L\sqrt{f}}\delta^\mu_0 \qquad A_\mu = \frac{eL}{\kappa}h(v)\delta^0_\mu$$

$$\mu_{\text{loc}} = A_t/L\sqrt{f} \sim h/\sqrt{f}$$

$$\rho = \beta\int_m^{\mu_{\text{loc}}} \epsilon^2\sqrt{\epsilon^2 - m^2}d\epsilon \qquad \sigma = \beta\int_m^{\mu_{\text{loc}}} \epsilon\sqrt{\epsilon^2 - m^2}d\epsilon$$

$$\rho + p = \mu_{\text{loc}}\sigma$$

Fluctuation Analysis

$$y \to -y$$

$$\delta g_{v\mu} = \delta A_v = 0$$

Shear Channel $(\delta g_{xy}, \delta g_{ty}, \delta A_y, \delta u_y)$

Sound Channel $(\delta g_{tt}, \delta g_{tx}, g_{xx}, \delta g_{yy}, \delta A_t, \delta A_x, \delta u_t, \delta u_x, \delta u_v)$

Gauge Invariant Variables:

$$\delta A_\mu \to \delta A_\mu - \partial_\mu \Lambda$$

$$\delta g_{\mu\nu} \to \delta g_{\mu\nu} - \nabla_\mu \xi_\nu - \nabla_\nu \xi_\mu$$

$$\delta A_\mu \to \delta A_\mu - \xi^\alpha \nabla_\alpha A_\mu - A_\alpha \nabla_\mu \xi^\alpha$$

Fluctuation Analysis

$$X_1(\omega, k, v) = \delta A_y(v)$$

$$X_2(\omega, k, v) = \omega \delta g_{xy}(v) + k \delta g_{ty}(v)$$

$$Y_1(\omega, k, v) = \omega \delta A_x(v) + k \delta A_t(v) + \frac{ekv^3 h'(v)}{2\kappa} \delta g_{yy}(v)$$

$$Y_2(\omega, k, v) = 2k\omega v^2 \delta g_{tx}(v) + \omega^2 v^2 \delta g_{xx}(v) + k^2 v^2 \delta g_{tt}(v) - \frac{1}{2} v^2 \left(2\omega^2 + k^2 v^3 f'(v)\right) \delta g_{yy}(v)$$

Fluctuation Analysis: QNM spectra

$$Y_1'' + C_1 Y_1' + C_2 Y_2' + C_3 Y_1 + C_4 Y_2 = 0$$
$$Y_2'' + D_1 Y_2' + D_2 Y_1' + D_3 Y_2 + D_4 Y_1 = 0$$

$$Y_{1,2} = (1-v)^{-\frac{2i\omega}{6-q^2}} R_{1,2}$$

$$R^1_{1,2} = (0,1) \qquad 0 = \det \begin{pmatrix} R_1^1 & R_1^2 \\ R_2^1 & R_2^2 \end{pmatrix}\Bigg|_{\text{boundary}}$$
$$R^2_{1,2} = (1,0)$$

Results and Future Work

- Results:
  - [Not yet published]
- Future work:
  - [Not yet published]