Holographic Plasmons

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Talk based on the following papers

Outline

• Introduction to plasmons
• Holographic electromagnetism
• Screened vs physical response
• Collective modes and BCs
• Bulk plasmons - exotic dispersion - momentum dissipation
• Transverse modes - momentum dissipation
• 2D plasmons (e.g. graphene)
• Electron cloud - ‘acoustic’ plasmons
• Work in progress
Plasmons 101

- Plasma oscillations: Collective excitation in the charge density when perturbed at the resonant frequency.

- Dynamical polarisation key as it provides the restoring force.

- Plasmon: Quantum of plasma oscillation, or the whole collective excitation.

- Used for staining church windows during the Middle Ages.

- Many applications: Biosensing, fast communication within circuits etc.
Plasmons in Strange Metals

- Common strange metal phases:
  1. Normal phase of many high temperature superconductors.
  2. Dirac fluid phase in graphene.

- Difficult to measure plasmon dispersion due to \textit{wave localisation}.

- Can be up to $\alpha^{-1} \sim 100$ in graphene, allowing for a miniaturisation of circuits.

- New technique applicable for strange metals: momentum-resolved electron energy-loss spectroscopy (M-EELS)

- Recently used to analyse Bi$_{2.1}$Sr$_{1.9}$CaCu$_2$O$_{8+x}$ (BSCCO) where plasmons are found for small wave vectors [Mitrano et al. 2018].
How to study plasmons

- Dielectric function $\varepsilon(\omega,k)$ relevant quantity to study as takes into account the dynamical polarisation.

- Plasmon modes are longitudinal solutions to $\varepsilon(\omega,k) = 0$, the ‘plasmon condition’.

- Or equivalently poles in the density-density response function to an external field, i.e. a collective mode.

- “A collective mode always corresponds to a possible oscillation of the system in the absence of an external field” [D. Pines and P. Nozières, 1966]

- In QFT one has to resort to various approximations, e.g. RPA.

- For systems without quasiparticles, or for strongly coupled systems, QFT is not applicable.

- For these systems holography is the ideal framework, yielding exact results, i.e. no approximations made.
Holographic Electromagnetism

- The holographic dictionary
  \[ \mathcal{F} = F|_{\partial M}, \quad \mathcal{J} = \nu_n W, \]

- Boundary induction tensor
  \[ \mathcal{J} = -\langle \rho \rangle \, dt + j = *^{-1} d * (\mathcal{F} - \mathcal{W}) \]

- Maxwell’s equation on the boundary
  \[ d\mathcal{F} = 0, \quad d * \mathcal{W} = *\mathcal{J}_{ext}, \]

- Standard decomposition
  \[ \mathcal{F} = \mathcal{E} \wedge dt + *^{-1}(\mathcal{B} \wedge dt), \]
  \[ \mathcal{W} = \mathcal{D} \wedge dt + *^{-1}(\mathcal{H} \wedge dt), \]

- Conductivity and dielectric functions
  \[ j = \sigma \cdot \mathcal{E}, \quad \mathcal{D} = \varepsilon \cdot \mathcal{E}. \]
  (Ohm’s law)
Screened vs Physical response


- Distinguish between:
  - *Screened* response functions describing the response to the screened electric field $\mathcal{E}$ inside the material.
  - *Physical* response functions describing the response to an external electric displacement field $\mathcal{D}$.

- $\mathcal{D}$ is the quantity that is actually being tuned directly in an experimental setup.

- Relation between screened and physical response encoded in the dielectric function

$$
\chi = \frac{\chi_{sc}}{\epsilon_L} \quad \chi_{sc} = \langle \rho \rho \rangle = \frac{G_{00}}{i\omega}
$$

- Collective modes = poles of the physical response function $\chi$. 
Screened vs Physical response

• Relations that hold for (holographic) electromagnetism

\[ \chi_{sc} = \langle \rho \rho \rangle = \frac{G_{00}}{i\omega} \]

Continuity equation

\[ \sigma_{ij} = -\frac{\langle j_i j_j \rangle}{i\omega} = -\frac{G_{ij}}{i\omega}, \]

• Conductivity and dielectric function related

\[ \varepsilon_L = 1 - \frac{\sigma_L}{i\omega} \]

• Equivalent to

\[ \chi = \frac{\chi_{sc}}{1 - V_k\chi_{sc}} \quad \text{with} \quad V_k = \frac{\lambda}{k^2} \]

• Poles in \( \sigma_L \) give poles in \( \varepsilon_L \), and no pole in \( \chi \), i.e. QNMs do not yield collective modes.

• Hence all collective modes are given by the ‘plasmon’ condition

\[ \varepsilon(\omega, k) = 0. \]

• There can also be ‘trivial’ solutions given by \( A = J = 0 \) i.e. modes purely within the gravity sector.
Collective modes and boundary conditions


- Dirichlet conditions gives poles in $\sigma_L$ corresponding to QNMs.
- Can we find modified boundary conditions for the bulk fields that yields solutions to the ‘collective mode’ condition on the boundary?

- Start from $\varepsilon(\omega, k) = 0$ with a harmonic perturbation in the x-direction, and in the absence of external fields
  \[\omega^2 \delta A_x + \delta J_x = 0.\]
  \[\left(\sigma_L \propto \frac{1}{i\omega} \frac{\delta A'_x}{\delta A_x}\right)\]

- NB: Collective modes $\mathcal{D} = 0$ vs QNMs $\mathcal{E} = 0.\quad (j = \sigma \cdot \mathcal{E})$

- Modified BC is equivalent to a double trace deformation of the field theory and is related to an RPA form of the Green’s function.

Bulk Plasmons


- Co-dimension zero.
- Toy model: A Reissner-Nordström metal.
- For uncharged systems we see the standard sound mode.
- Turning on charge, this mode becomes gapped and can be identified with the (optical) plasmon mode.
- Note the damping of the plasmon mode for small $k/T$, in contrast to the Fermi liquid result, consistent with Mitrano et al. (2018).
Collective modes vs QNMs

- The lowest modes in each sector for $\mu/T = 5$ (real parts dashed, imaginary parts solid).
- Plasmon mode $\leftrightarrow$ sound mode
- Why this is a purely holographic non-hydro result will be explained on the next slide.
Exotic Dispersion


[c.f. Mitrano et al. (2018)]

[A. Romero-Bermúdez, A. Krikun, K. Schalm and J. Zaanen (2019)]
Lattice Effects

• The atomic lattice breaks translational invariance, implying that momentum is no longer conserved.

• With an eye towards the cuprate strange metal we focus on ‘weak momentum relaxation’.

• We study two models for including momentum relaxation without explicitly adding the lattice (c.f. the relaxation rate in the Drude model).
  ▶ Explicit breaking: Linear axion model
  ▶ Spontaneous symmetry breaking (SSB)

• Plasmons strongly damped already without breaking translational invariance, now additional contribution from momentum relaxation.

• First class of model also studied in [A. Romero-Bermúdez, Density response of holographic metallic IR fixed points with translational pseudo-spontaneous symmetry breaking, JHEP 07 (2019) 153]

Results

- Plots for symmetry breaking strength $\alpha^3/T = (0.1, 3.75, 5, 10, 25)$ [red-blue]
- The gapped plasmon smoothly approaches the ungapped sound mode
- Goes through the ‘exotic’ transition, including negative dispersion at low $k$. 
Transverse collective modes


- First study of the transverse sector including Coulomb interactions and dynamical EM.
- Transverse polarisation field but no transverse charge density fluctuations.
- We study three cases:
  1. A holographic plasma with conserved momentum
  2. A holographic (dirty) plasma with finite momentum relaxation
  3. A holographic viscoelastic plasma spontaneously broken translational symmetry.
- The Fermi-Liquid case (Pines & Nozières)
  - CM only exists for $F_1^S > 6$
Transverse collective modes


• Results:

‣ Reproduce the results from Pines & Nozières for a quasiparticle system, including the damping of the transverse collective mode at small $k$.

‣ NB: photon mode damped even at $k = 0$ as for the bulk plasmon.
2D Plasmons


- Co-dimension one.
- Adjust the BCs to force the boundary current to be confined to 2+1 dims, while the electric field lives in 3+1 dims.
- Real part describes the expected $\omega \propto \sqrt{k}$ dispersion, linear imaginary part agrees with Lucas and Das Sarma [Phys. Rev. B 97, 115449 (2018)].
- Generalized to an infinite stack to by Mauri & Stoof [JHEP 04 (2019) 35].
The Electron Star

[S. A. Hartnoll, A. Tavanfar, “Electron stars for holographic metallic criticality”]

• The RN black hole can become unstable at low temperatures.

• This generically happens for $\mu/T > 1$.

• NB: This is the same order of magnitude of $\mu/T$ for which the ‘exotic’ dispersion appears.

• If the bulk supports charged fermions we get an electron star for $T=0$.

• Mechanism: Schwinger pair production for sufficiently low mass of the fermions.

\[ \mu_{\text{loc}} > m \]
The Electron Cloud

[V. G. M. Puletti, S. Nowling, L. Thorlacius, T. Zingg, “Holographic metals at finite temperature”]

- What happens if we turn on a temperature in the electron star?
- Temperature $\leftrightarrow$ horizon
- There will now be a cloud with an inner and outer radius, and a RN geometry outside the cloud.
- NB: The charge of the RN solution differs in the two regions due to the charge in the cloud.
Holographic response of Electron Clouds

Main results:

• The ‘exotic’ dispersion persists

• There is a new collective mode due to oscillations in the charged cloud

• Linear for small $k/T$ - ‘acoustic’ plasmon

• This mode also displays ‘exotic’ dispersion for a range of parameter values
• Cuprate high $T_c$ superconductors - stacked conducting CuO$_2$ planes.

• Normal phase: quasi-2D physics, i.e. out-of-plane charge dynamics incoherent.

• Superconducting phase: 3D coherence.

• In-plane charge dynamics dominated by optical plasmons.

• Out-of-plane charge dynamics dominated by acoustic plasmons.

• Essential mechanism: poorly screened interplane Coulomb interactions.

• Aim: Create realistic holographic models for layered strongly correlated systems.

Interface plasmons (SPPs)

[S. Maier, Plasmonics: Fundamentals and applications, 2007]

• By far the most common experimental realisation of plasmons.
• Why is this not the type of plasmon showing up in the study of strange metals using M-EELS?
• Damped plasmon only present at small k seems consistent with the data [Mitrano et al. 2018].

[Gran et al., in preparation]

[Maier]
[Johnson & Christy, 1972]
Conclusions

• Generic framework for holographic modelling of boundary theories with dynamic electromagnetism.

• Collective modes, including plasmons, require mixed BCs.

• These new BCs are related to an RPA form of the Green’s function and are equivalent to a double trace deformation of the boundary field theory.

• Dispersion for bulk and 2D plasmons can be computed.

• For bulk plasmons, both in RN and EC, we obtain an exotic dispersion in a region difficult to analyse using standard techniques.

• We have also added the effects of an atomic lattice for bulk plasmons.

• Transverse sector, including dynamical EM and momentum dissipation, was recently explored.
Outlook

• Add a magnetic field - relevant experimental setup

• Extend to interface plasmons (SPP) and realistic models for high $T_C$ superconductors - work in progress

• Study other phenomena where the dynamical polarisation can not be neglected, e.g. in connection to charged impurities

• Experimental challenges (hydrodynamic flow and (pre-)turbulent phenomena)
Thanks!