Holographic Plasmons

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(Marcus Tornsö, Tobias Zingg)

Talk based on the following three papers

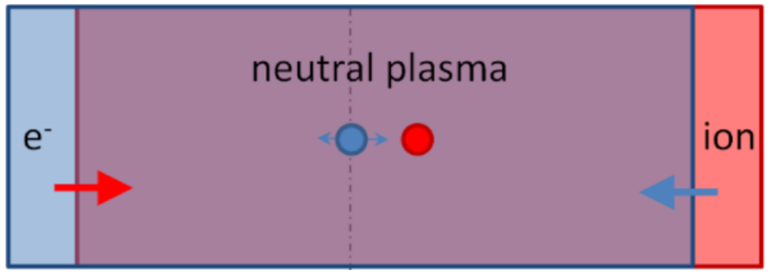
- U. Gran, M. Tornsö, and T. Zingg, *Holographic Plasmons*, arXiv:1712.05672
- U. Gran, M. Tornsö, and T. Zingg, *Plasmons in Holographic Graphene*, arXiv:1804.02284
- U. Gran, M. Tornsö, and T. Zingg, *Exotic Holographic Dispersion*, arXiv:1808:05867

Outline

- Introduction to plasmons
- Holographic electromagnetism
- Screened vs Physical response
- Physical modes and BCs
- Bulk plasmons
- 2DEG plasmons (e.g. graphene)
- Exotic dispersion

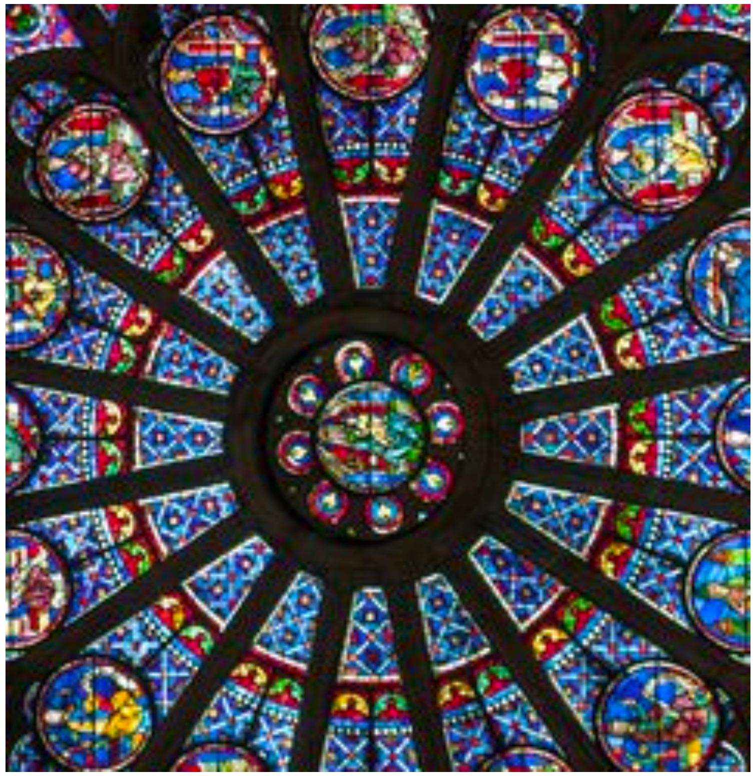
Plasmons 101

- 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

- Strange metal: A phase without quasiparticle excitations.

    1. Normal phase of many high temperature superconductors.

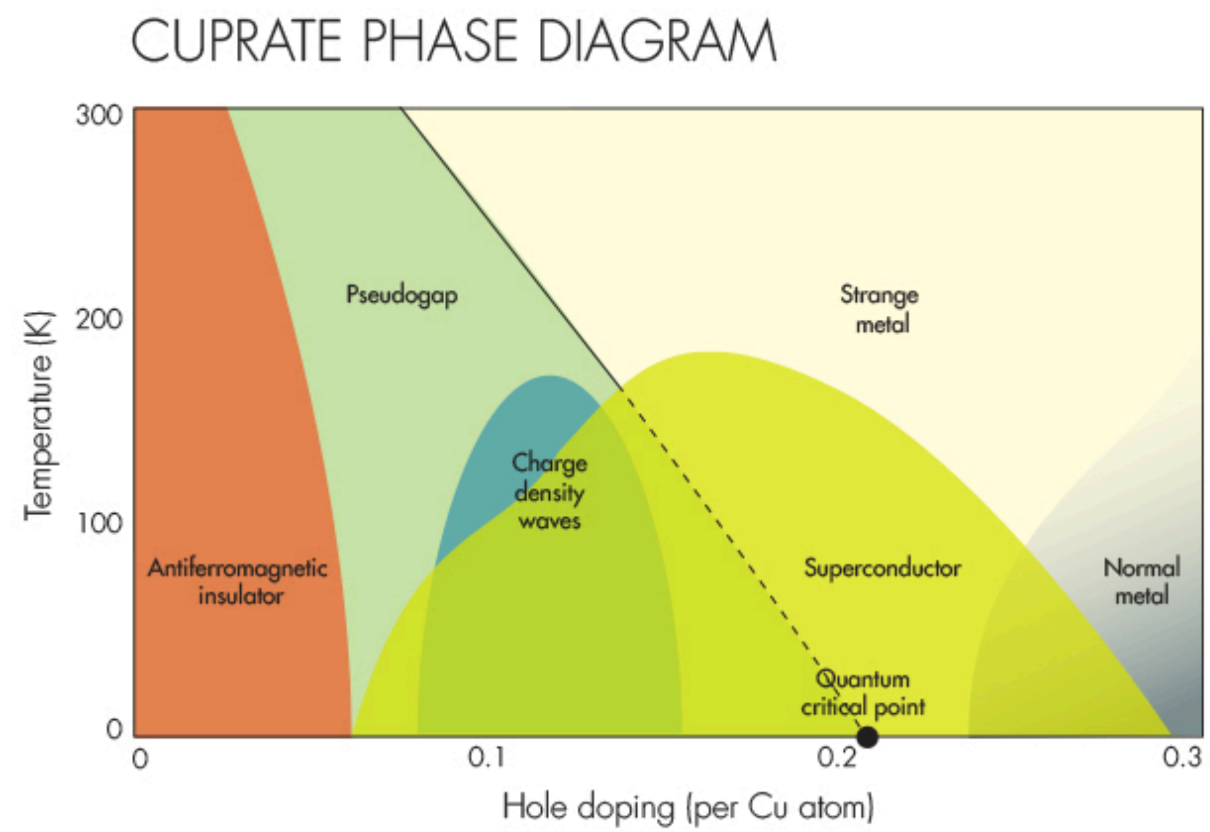
    2. Dirac fluid phase in graphene.

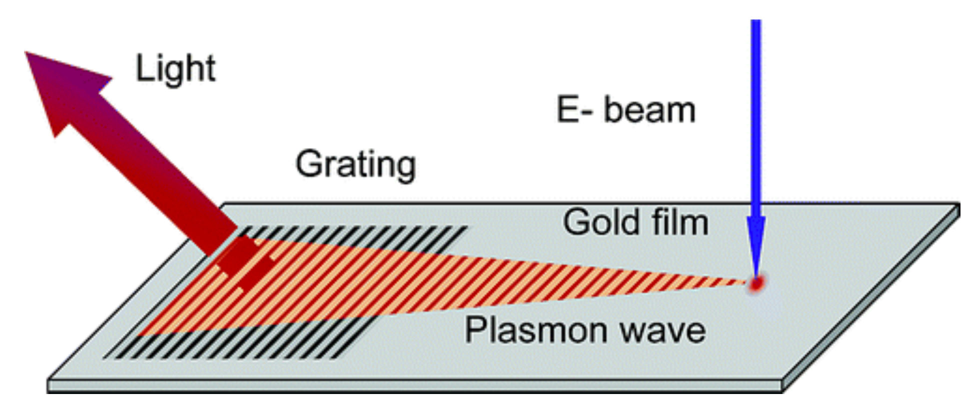
- Difficult to measure plasmon dispersion due to *wave localisation.*

- 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)

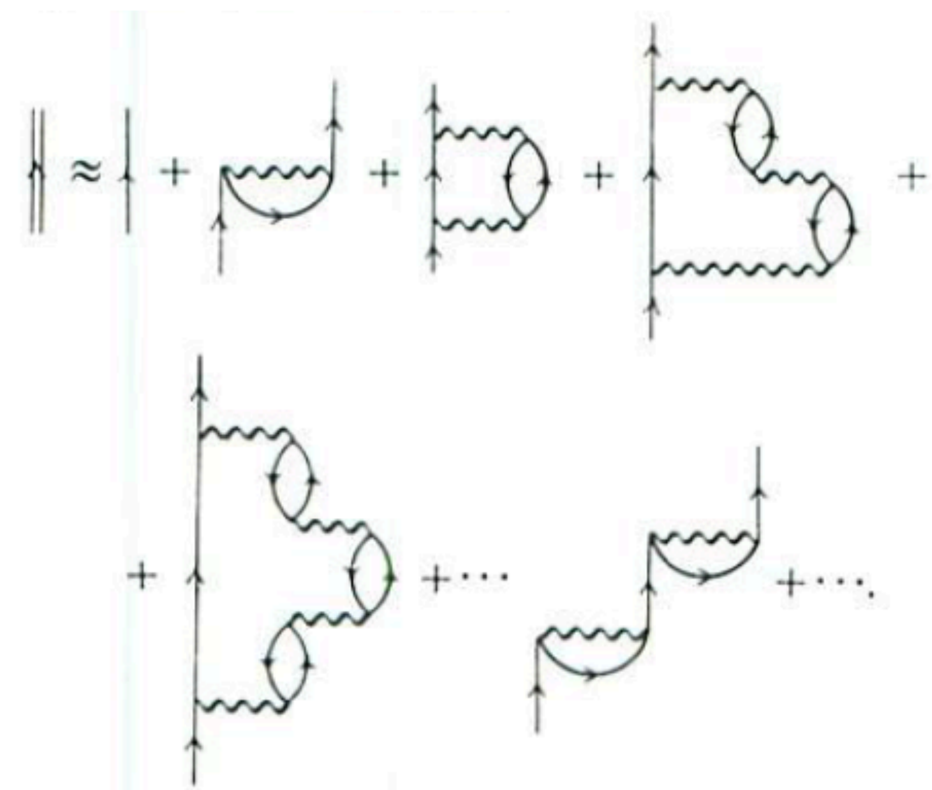
- Recently used to analyse $Bi_{2,1}Sr_{1,9}CaCu_2O_{8+x}$ (BSCCO).





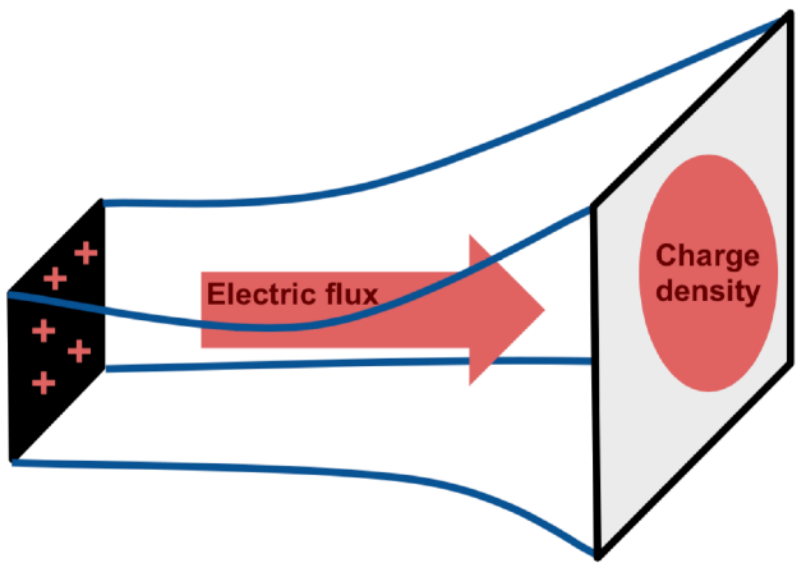
How to study plasmons

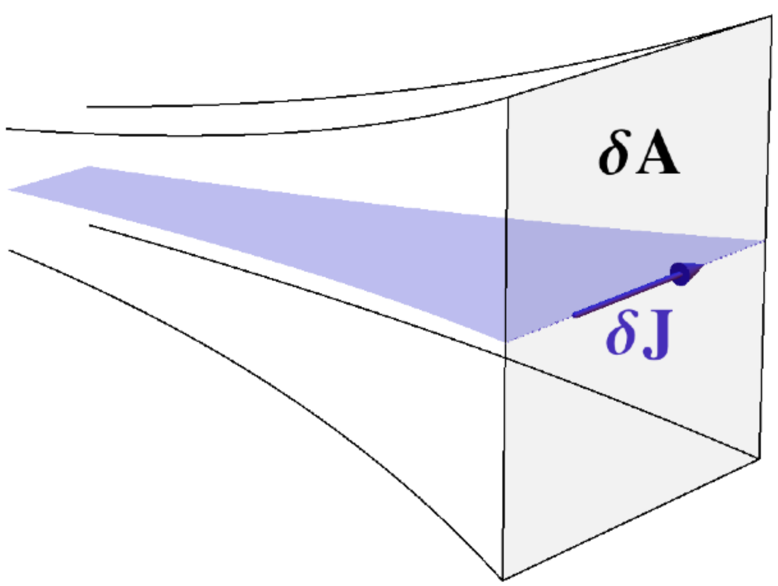
- Dielectric function ε(ω,k) relevant quantity to study as takes into account the dynamical polarisation.
- Plasmon modes are longitudinal solutions to ε(ω,k) = 0, the ‘plasmon condition’.
- Or equivalently poles in the density-density response function to an *external* field.
- In QFT one has to resort 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, and yields results valid to all orders of perturbation theory.



Holography in a Nutshell

- Gravity theory in the bulk, QFT on the boundary.
- Renormalisation group scale has been geometrised and provide the radial direction (an "energy" dimension).
- Temperature in the QFT $\Longleftrightarrow$ Hawking temperature of the black hole.
- Charge density in the QFT $\Longleftrightarrow$ charge of the black hole (Reissner-Nordström).
- Gauge fields in the bulk couple to conserved currents on the boundary.
- Equating the partition functions in the bulk and on the boundary gives the gauge/gravity duality.
- Relates weakly coupled bulk physics to strongly coupled boundary physics, and vice versa.
- Original motivation from string theory, but is believed to hold much more generally.





Holographic Electromagnetism

- The holographic dictionary $$\mathcal{F} \;=\; F\big|_{\partial M}\,, \quad \mathcal{J} \;=\; \imath_n W\,,$$
- Boundary induction tensor $$\mathcal{J} \;=\; -\langle\rho\rangle\, dt + \boldsymbol{j} \;=\; \star^{-1} d\star(\mathcal{F} - \mathcal{W})$$
- Maxwell's equation on the boundary $$d\mathcal{F} \;=\; 0\,, \quad d\star\mathcal{W} \;=\; \star\mathcal{J}_{ext}\,,$$
- Standard decomposition $$\mathcal{F} = \boldsymbol{\mathcal{E}}\wedge dt + \star^{-1}(\boldsymbol{\mathcal{B}}\wedge dt)\,,$$ $$\mathcal{W} = \boldsymbol{\mathcal{D}}\wedge dt + \star^{-1}(\boldsymbol{\mathcal{H}}\wedge dt)\,,$$
- Conductivity and dielectric functions $$\boldsymbol{j} \;=\; \sigma\cdot\boldsymbol{\mathcal{E}}\,, \qquad \boldsymbol{\mathcal{D}} \;=\; \varepsilon\cdot\boldsymbol{\mathcal{E}}\,.$$

Screened vs Physical response

[D. Pines and P. Nozières, The Theory of Quantum Liquids, 1966]

- Distinguish between:
  - *Screened* response functions describing the response to the screened electric field $\mathcal{E}$.
  - *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

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

- Physical modes = poles of the physical response function χ.

Screened vs Physical response

- Physical response function $\chi \;=\; \dfrac{\chi_{sc}}{\epsilon_L}$ $\qquad \chi_{sc} \;=\; \langle \rho\, \rho \rangle = \dfrac{G_{00}}{i\omega}$

- Relations that hold for (holographic) electromagnetism

$$\sigma_{ij} \;=\; -\frac{\langle \boldsymbol{j}_i\, \boldsymbol{j}_j \rangle}{i\omega} = -\frac{G_{ij}}{i\omega}\ , \qquad \chi_{sc} \;=\; \frac{k^2}{i\omega}\sigma_L$$

- Conductivity and dielectric function related

$$\varepsilon_L = 1 - \frac{\sigma_L}{i\omega}$$

- Poles in σ_L give poles in ε_L .

- Hence all physical modes are given by the ‘plasmon’ condition

$$\varepsilon(\omega, k) = 0\ .$$

Physical modes and boundary conditions

- Dirichlet conditions gives poles in σ_L corresponding to QNMs.

- Can we find modified boundary conditions for the bulk fields that yields solutions to the ‘physical 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

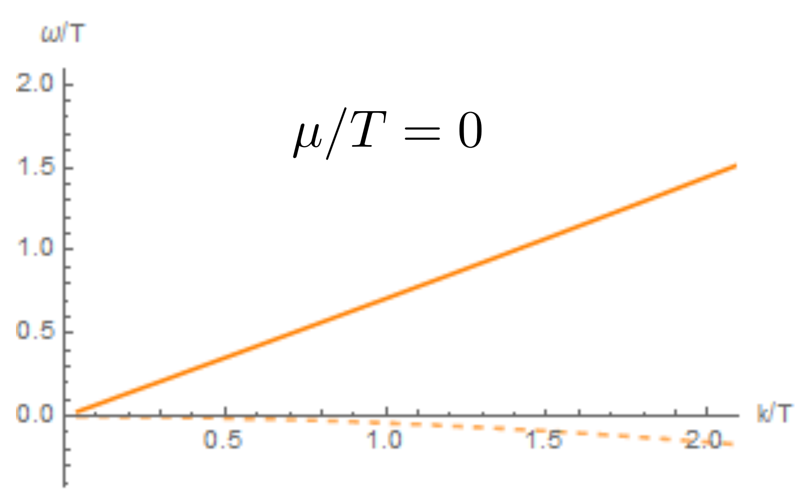
$$\omega^2 \delta\mathcal{A}_x + \delta\mathcal{J}_x = 0 \, .$$

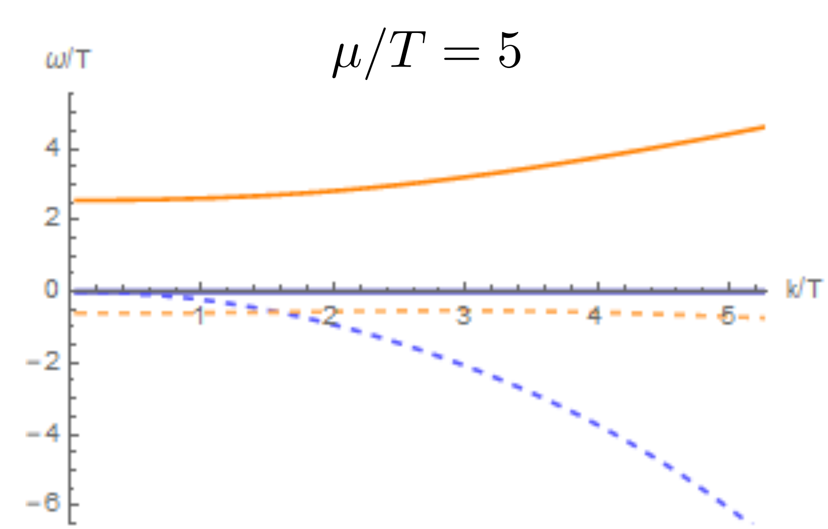
- NB: Physical modes $\boldsymbol{\mathcal{D}} = 0$ vs QMNs $\boldsymbol{\mathcal{E}} = 0$. $(\boldsymbol{j} \; = \; \sigma \cdot \boldsymbol{\mathcal{E}})$

- The new BC is related to an RPA form of the Green’s function.

Bulk Plasmons

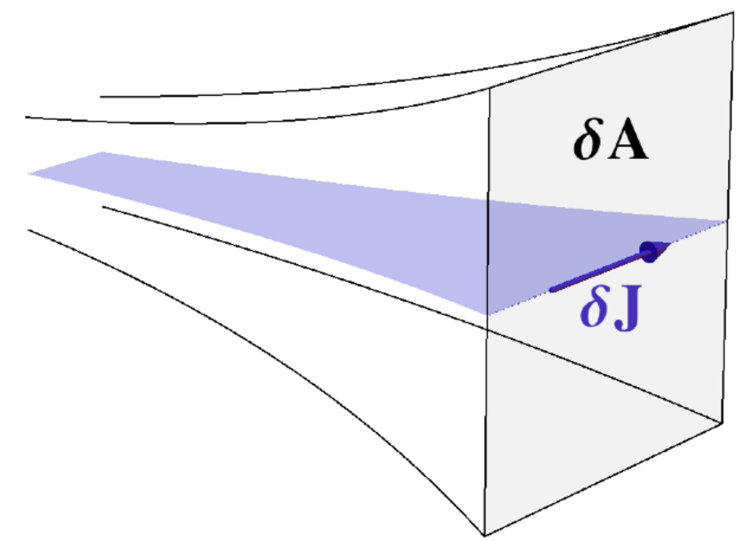
- Co-dimension zero.
- Toy model: A Reissner-Nordström metal.
- For uncharged systems we see the standard (zero) sound mode.
- Turning on charge, this mode becomes gapped and can be identified with the plasmon mode.
- For small k, the dominant mode (least negative imaginary part) is the diffusion mode.
- For larger k, the plasmon is the dominant mode.

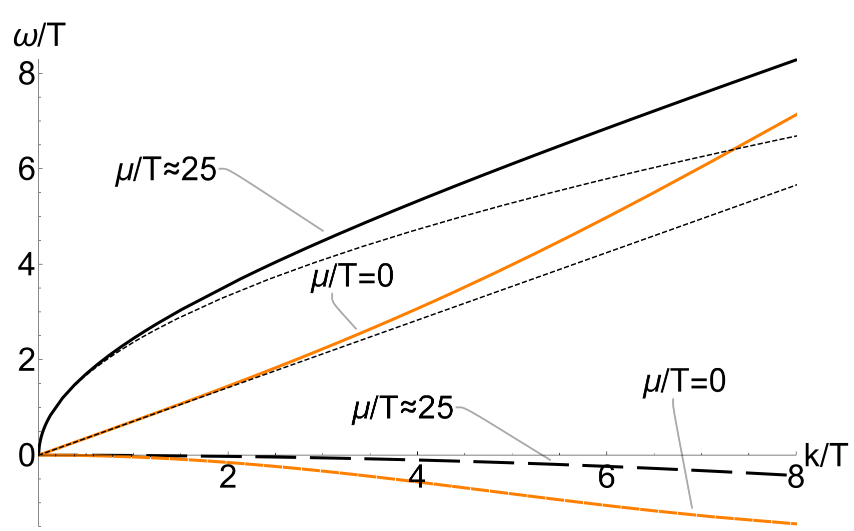


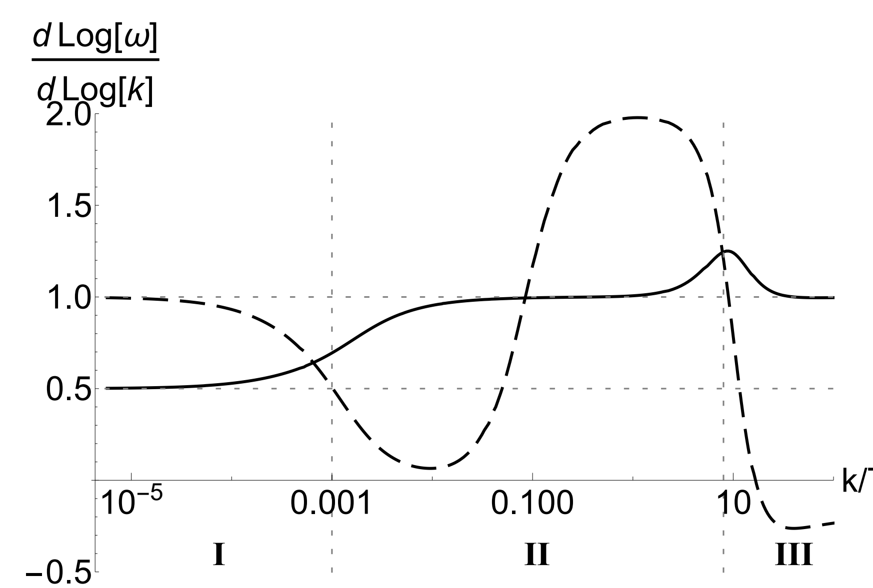


2DEG Plasmons

- 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.
- Preferable to have a top-down model, but must include back reaction so probe-brane models will not work.
- Real part describes the expected $\omega \propto \sqrt{k}$ dispersion, linear imaginary part agrees with Lucas and Das Sarma [arXiv:1801:0149].





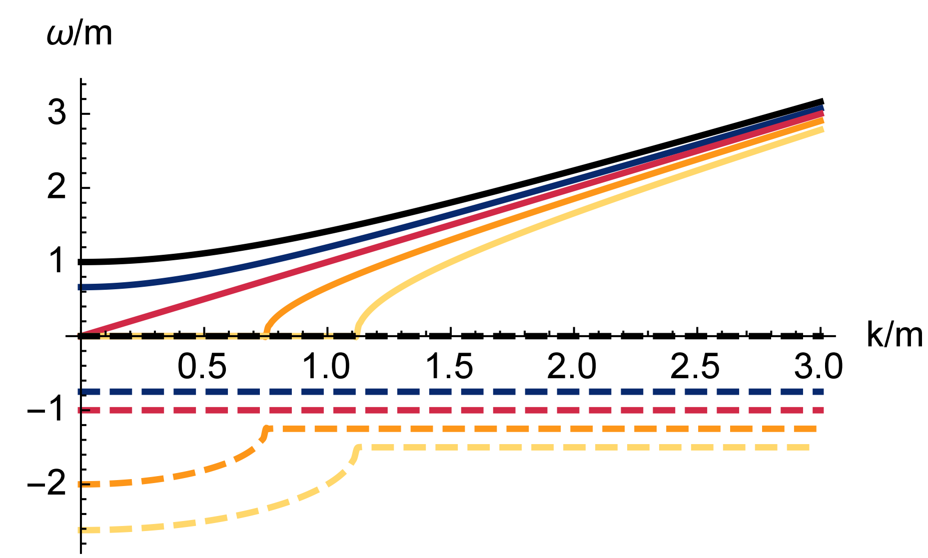


Exotic Dispersion

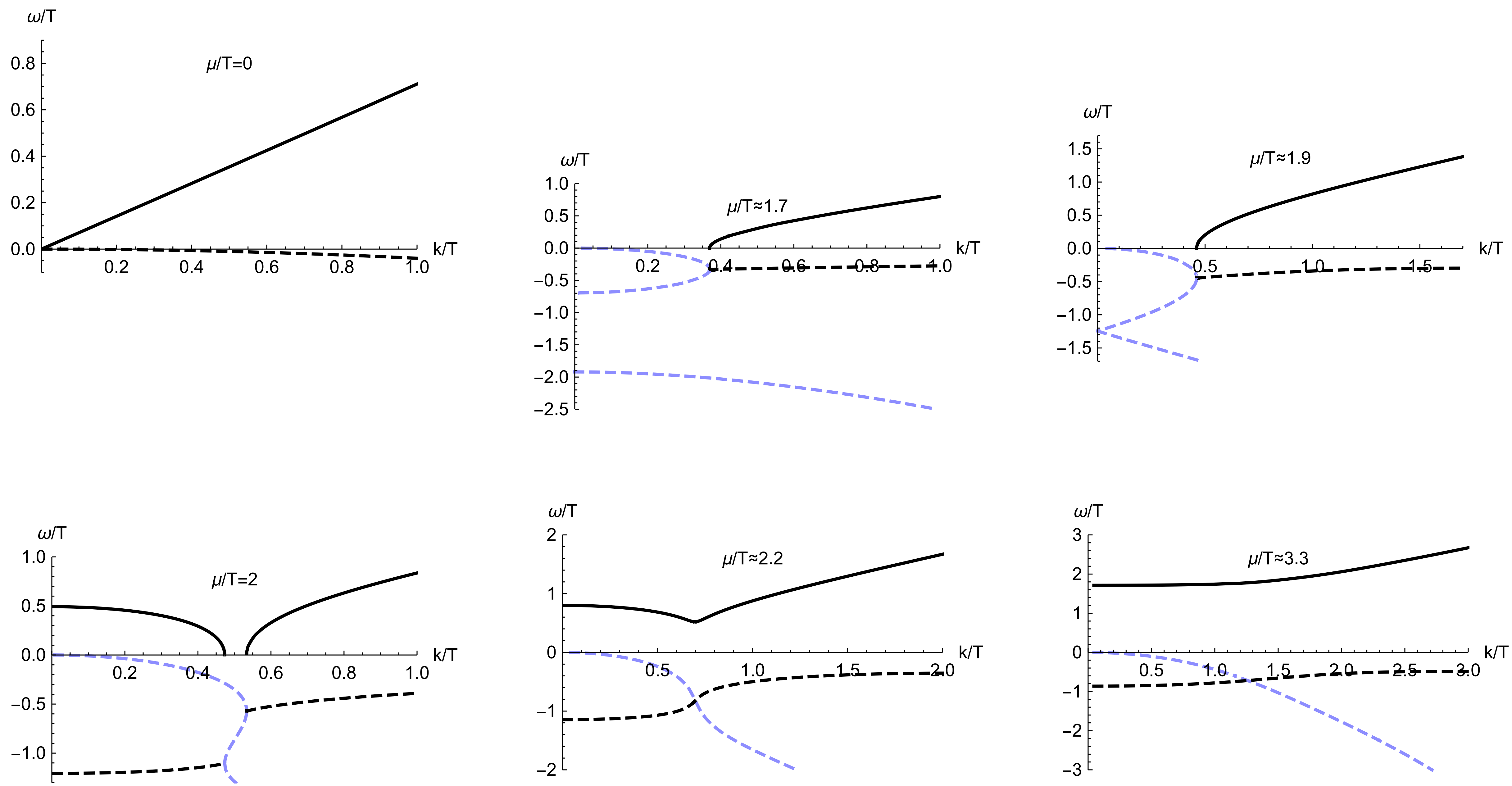
- Caldeira-Leggett model of quantum dissipation.
- Allows for an exact quantum treatment of dissipation (adiabaticity, 1st order perturbation theory)
- Damping term due to dissipation.
- Qualitatively, this leads to a toy model for a bulk plasmon

$$\omega^2 - c^2k^2 + i\omega\eta - v = 0$$

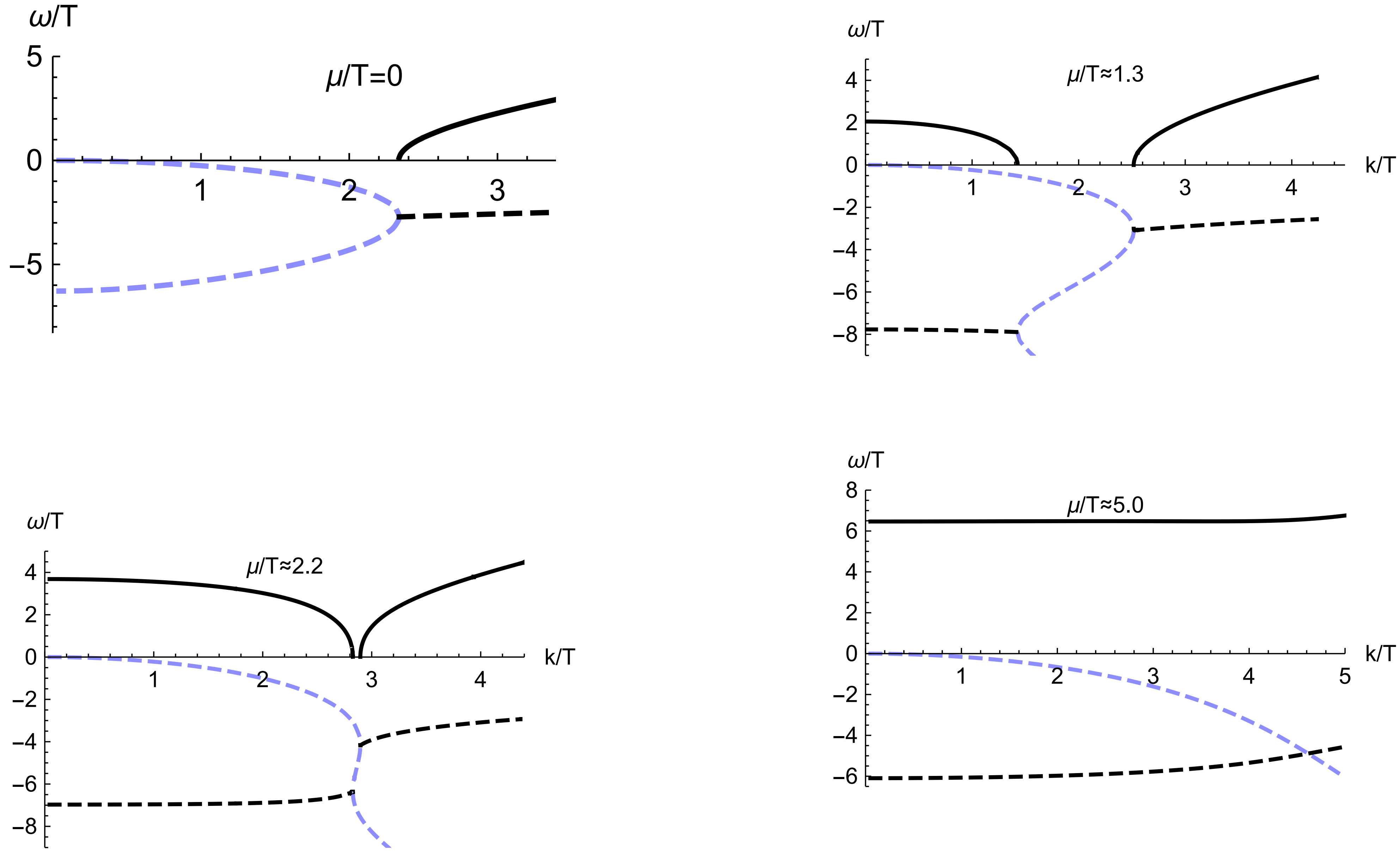
- Standard case, $v = m^2$.



Exotic Dispersion - Plasmon modes



Exotic Dispersion - QNMs



Conclusions

- Holographic model of strongly coupled electromagnetism.
- Physical modes, including plasmons, require mixed BCs.
- These new BCs are related to an RPA form of the Green's function.
- Dispersion for bulk and 2DEG plasmons can be computed.
- For bulk plasmons we obtain an exotic dispersion in a region difficult to analyse using standard techniques.