Collective modes in holographic plasmas with momentum dissipation

Marcus Tornsö

Acknowledgements

Supervisor Ulf Gran and collaborators Matteo Baggioli, Tobias Zingg, Amadeo Jimenez Alba

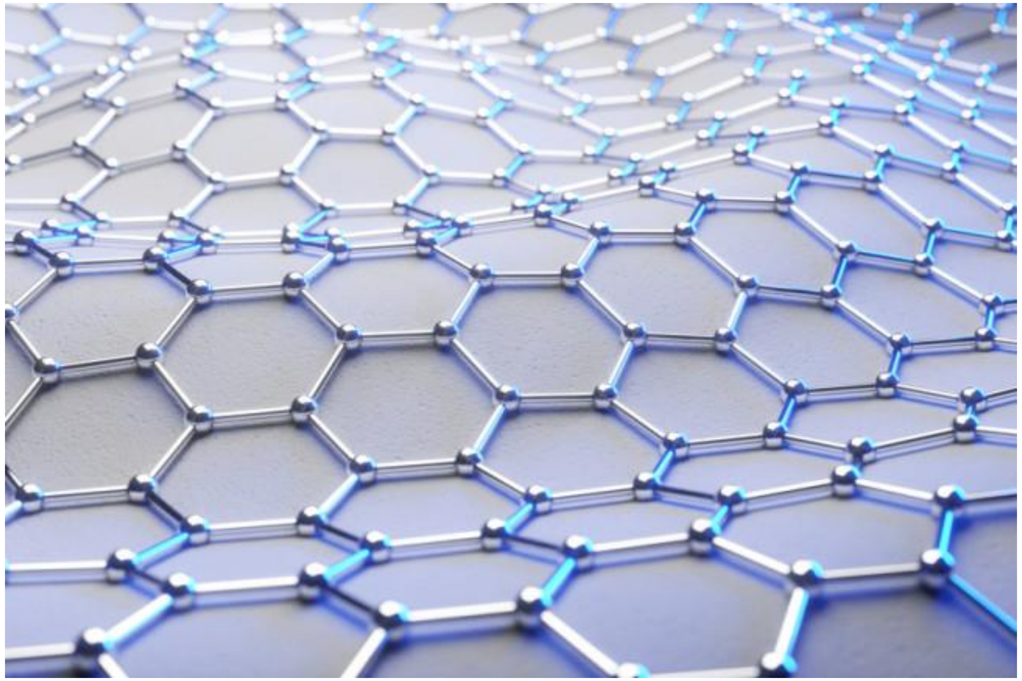
Talk is mostly based on

- M. Baggioli, U. Gran, A. Jimenez Alba, M. Tornsö, T. Zingg arXiv:1905.00804
- M. Baggioli, U. Gran, M. Tornsö arXiv:1912.07321

and some previous work

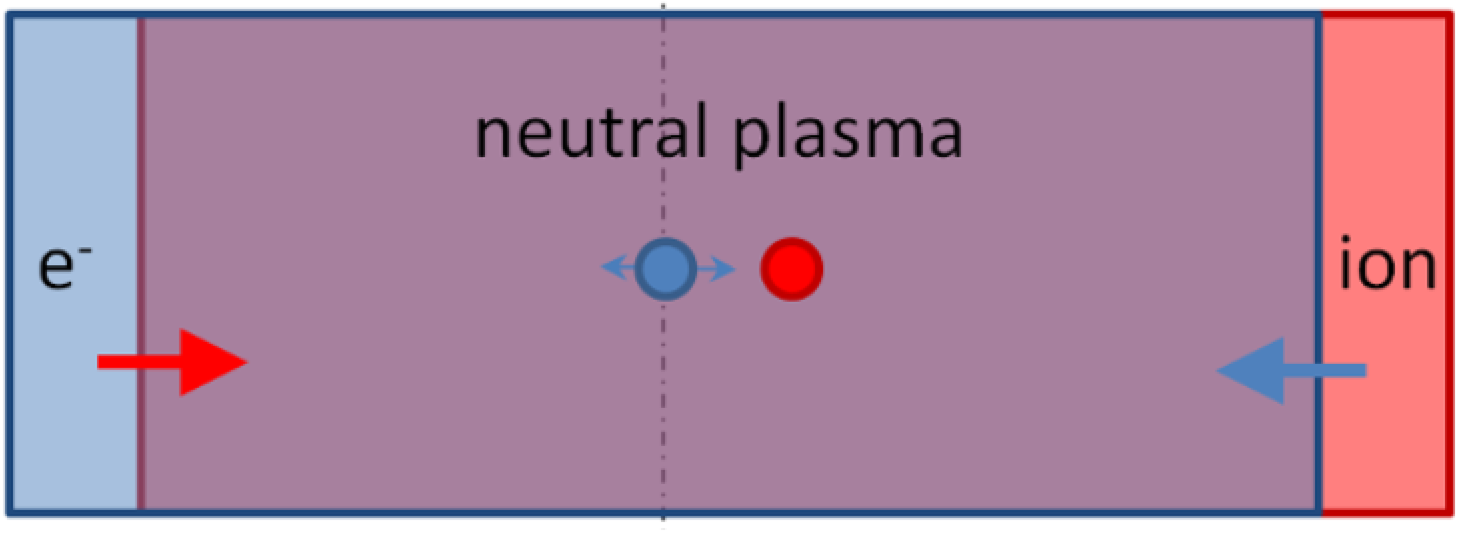
Outline

- Plasmons and collective modes
- Holographic electromagnetism
- Collective modes and BCs
- Our findings
- Conclusions



Plasmons – What are they?

- Collective excitations of a charge density → plasma frequency
- Dynamical polarization behind the restoring force
- Quanta (or the whole excitations) are called plasmons



Different types of plasmons

- Longitudinal
- Transverse

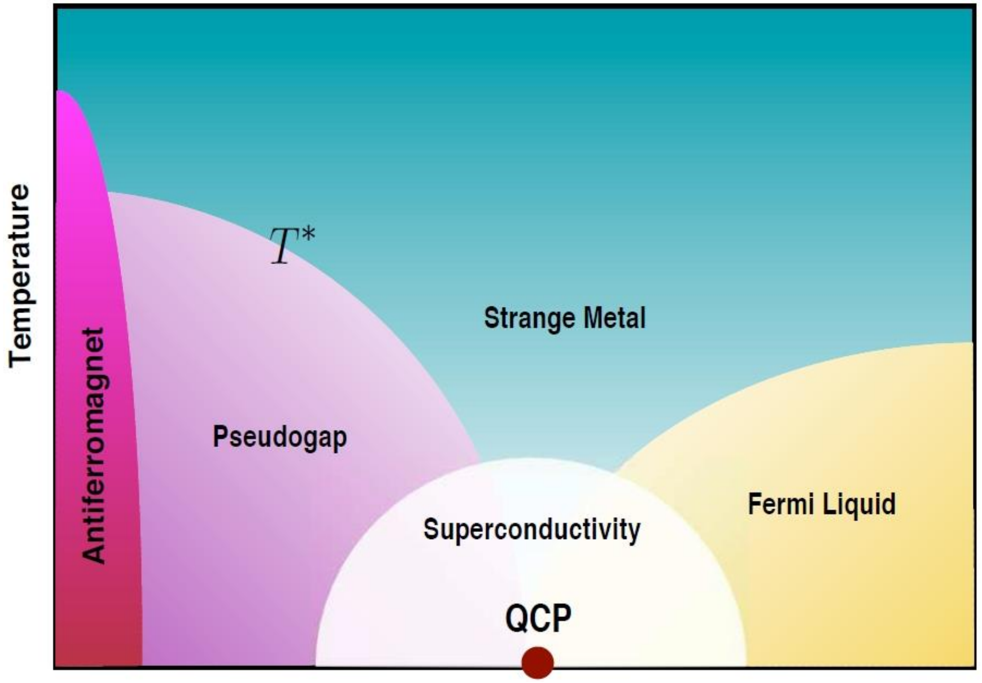
- Bulk
- Codimension-1
- Surface

Plasmons – Why do we care?

- History – Roman cups, stained windows
- Modern uses – Plasmonics, nanosensing, miniaturization

Plasmons and Strange Metals

- Strange metals are phases of matter without quasiparticle excitations.
- High-Tc superconductors.
- Dirac fluid phase of graphene.
- Experimentally difficult to measure due to wave localization
- Recently with M-EELS on BSCCO

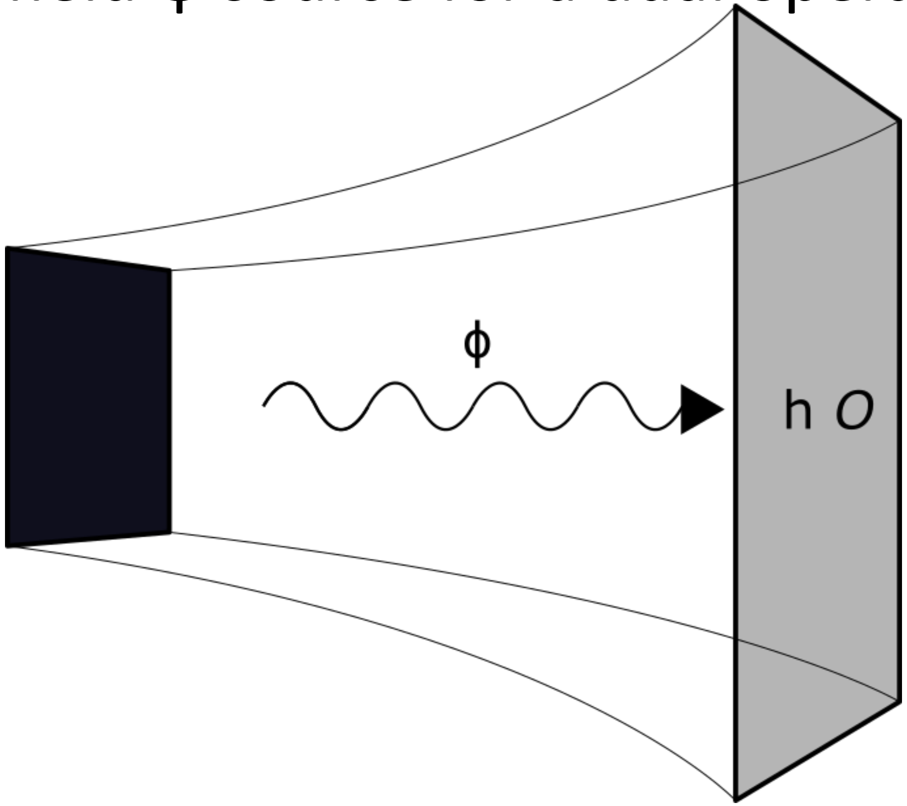


Plasmons – How do we study them?

- Solutions to Maxwell’s equations where the dielectric function, ε, has a key role.
- For ‘standard’ plasmons, the condition is $\varepsilon(\omega,k) = 0$
- Or alternatively, as poles to the density-density response function, χ, to an external field
- QFT resorts to various approximations, e.g. RPA, which are not applicable for strongly coupled systems
- This is where holography comes in!

Holographic Dictionary – relating bulk and boundary

- The partition functions in the bulk and boundary theories are the same
- Boundary value of a field ϕ source for a dual operator.



Electrical conductivity

- From the partition functions, we can compute Green's functions defining electrical and thermal conductivities.
- Near the boundary we have

$$\delta A_x = \delta A_x^{(0)} + \frac{r}{L} \delta A_x^{(1)} + \cdots as\, r \to 0\,.$$

- A short computation yields

$$\sigma(\omega) = \frac{-i}{\omega} \frac{\delta A_x^{(1)}}{L\, \delta A_x^{(0)}}\,.$$

Holographic Electromagnetism (formal)

- The holographic dictionary $\mathcal{F} = F|_{\partial M},\ \mathcal{J} = \imath_n W$
- Identify $\mathcal{W}$ $\mathcal{J} = \star^{-1} d \star (\mathcal{F} - \mathcal{W})$
- Maxwell's equations on the boundary $d\mathcal{F} = 0,\ d \star \mathcal{W} = \star \mathcal{J}_{ext}$
- Standard decomposition

$$\mathcal{F} = \boldsymbol{\mathcal{E}} \wedge dt + \star^{-1}(\boldsymbol{\mathcal{B}} \wedge dt),$$
$$\mathcal{W} = \boldsymbol{\mathcal{D}} \wedge dt + \star^{-1}(\boldsymbol{\mathcal{H}} \wedge dt),$$
$$\mathcal{J} = -\langle \rho \rangle dt + \boldsymbol{j}$$

- Define conductivity and dielectric function

$$\boldsymbol{j} = \sigma \cdot \boldsymbol{\mathcal{E}}$$
$$\boldsymbol{\mathcal{D}} = \epsilon \cdot \boldsymbol{\mathcal{E}}$$

Simplified

- We can read off a potential $\mathcal{A}$ on the boundary.
- We can read off a current $\mathcal{J}$ on the boundary.
- We quite naturally want the boundary theory to obey Maxwell's equations, in particular

$$\partial_\mu F^{\mu\nu} - \mathcal{J}^\nu = 0.$$

Boundary conditions

- For a harmonic perturbation i the x-direction, an absence of additional external fields means that, (in a specific gauge)

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

- This BC is related to an RPA form of the Green's function

Our research: collective excitations

- Imposing natural, but non-trivial, boundary conditions to perturbations to ensure certain types of dynamics in the boundary theory.
- We have (so far) mainly looked at ”plasmons” as they are ubiquitous in metals and only require the inclusion of long-range Coulomb interactions.

$$\omega^2 A_x + p(\omega, k_x) A_x' \Big|_{\partial M} = 0$$

So lets get into some specifics

Bulk plasmons

[1712.05672],[1808.05867]

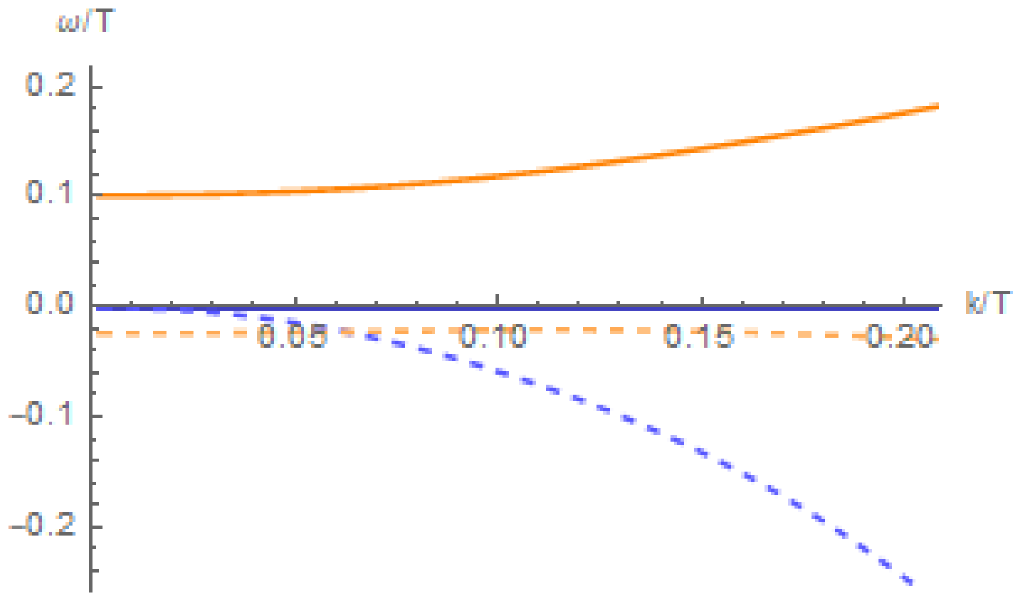
- Simplest possible model: A Reissner Nordström metal

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \Lambda + \frac{1}{2}R$$

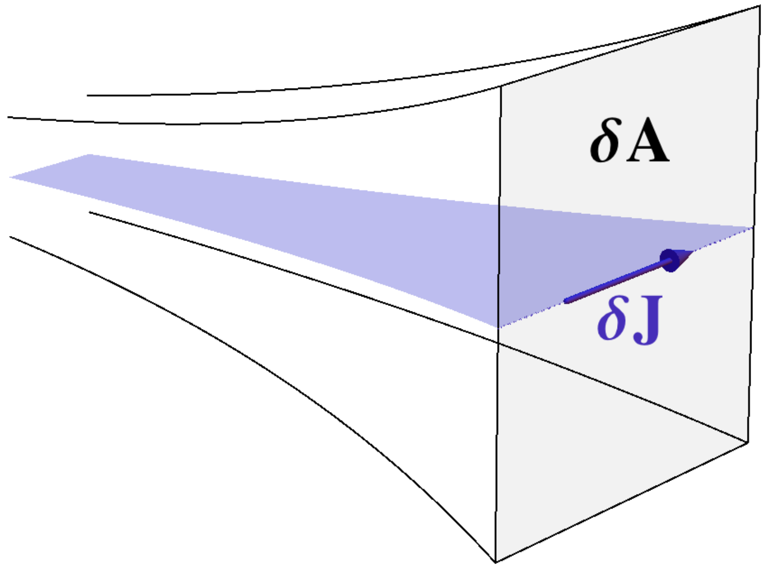
- Einstein-Maxwell gravity in AdS_4
- Perturbations treated in linear response.
- With boundary condition

$$\omega^2 A_x + \lambda\, A'_x|_{\partial M} = 0$$

- Damping is consistent with Mitrano et al. (2018)



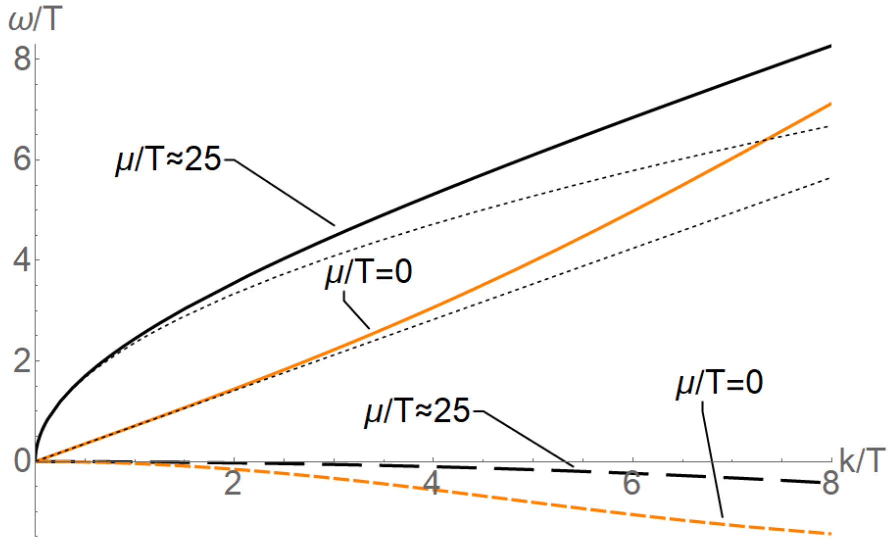
2D plasmons
[1804.02284]



- Co-dimension one. BCs adjusted accordingly.

$$\omega^2 A_x + \frac{|k_x|}{2} A_x' \Big|_{\partial M} = 0$$

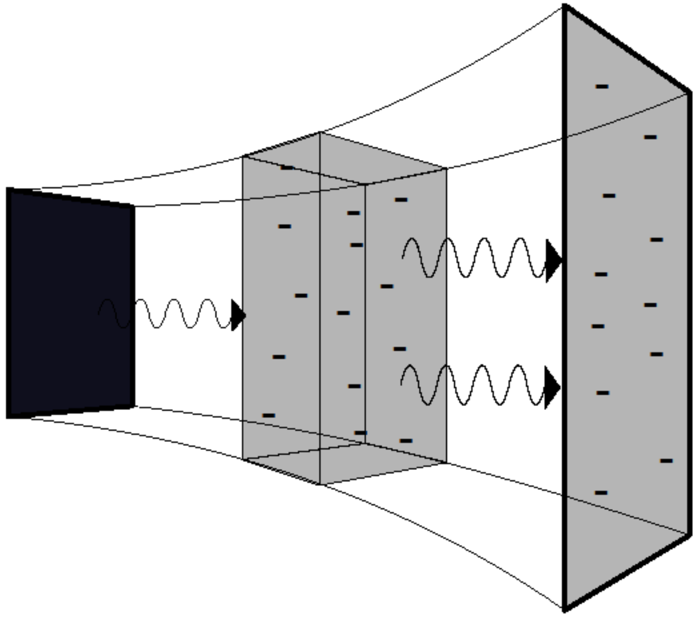
- Real part, $Re[\omega] \sim \sqrt{k}$, as expected. Imaginary part in agreement with Lucas and Das Sarma (2018).



Better bulk models: the electron cloud

[1810.11416]

- The RN black hole unstable at small temperatures.
- The local (bulk) chemical potential could potentially support charged fermions.
- Also allows for additional parameters – more possible boundary theories!
- Significantly more complicated due to the introduction of the charged particles



Better bulk models – momentum dissipation

[1905.00804],[1912.07321]

Introduction of linear axion allows for both explicit and spontaneous breaking of translational invariance.
Unlikely to be as precise as a lattice model, but massively simpler while still including the essentials.

$$\ldots + \frac{1}{4} m^2 V(X), \qquad X = \partial_\mu \phi^I \partial^\mu \phi^I,$$

with $V = X$ and $V = X^3$ for the two specific cases.

$$\phi^I = \alpha x^I + \delta \phi^I$$

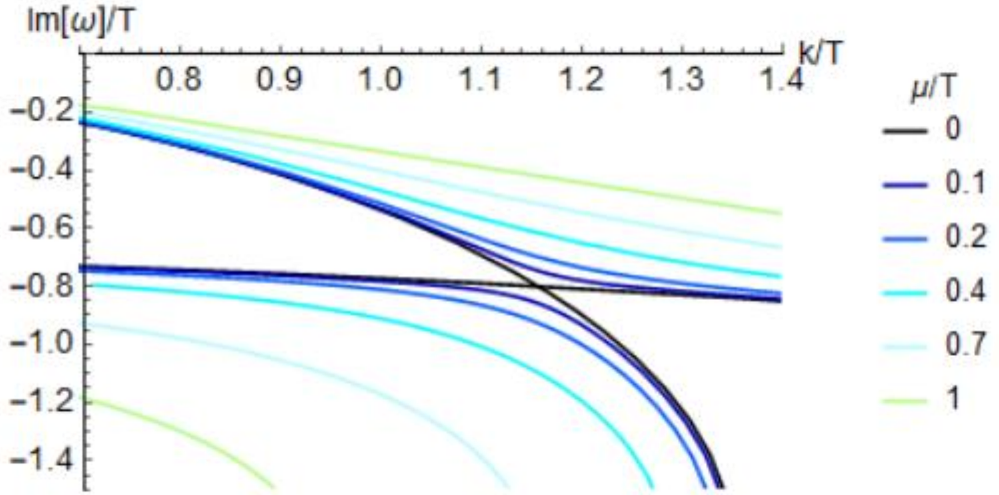
Momentum relaxation – ”dirty” plasma

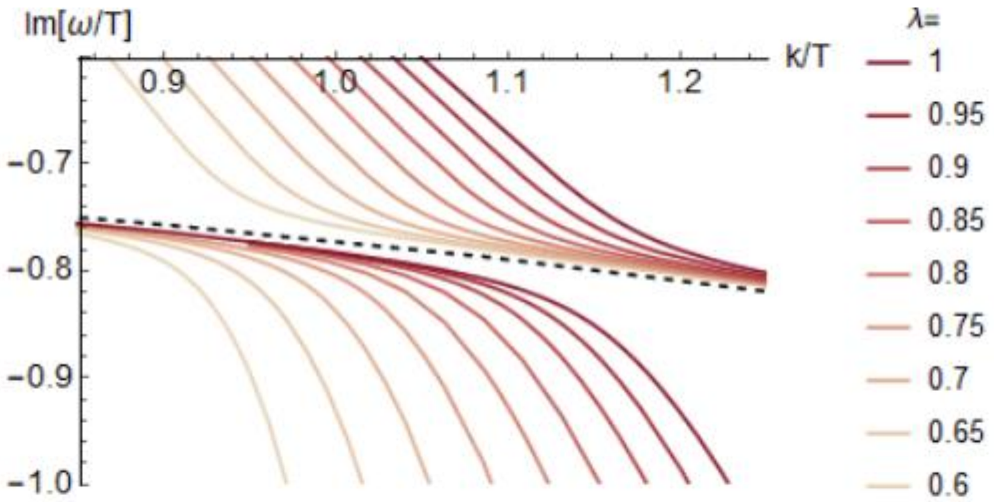
- Mathiessen rule

$$\tau_{tot}^{-1} = \underbrace{\tau^{-1}}_{\text{EM interactions}} + \underbrace{\tau_M^{-1}}_{\text{momentum dissipation}}$$

Momentum relaxation – ”dirty” plasma

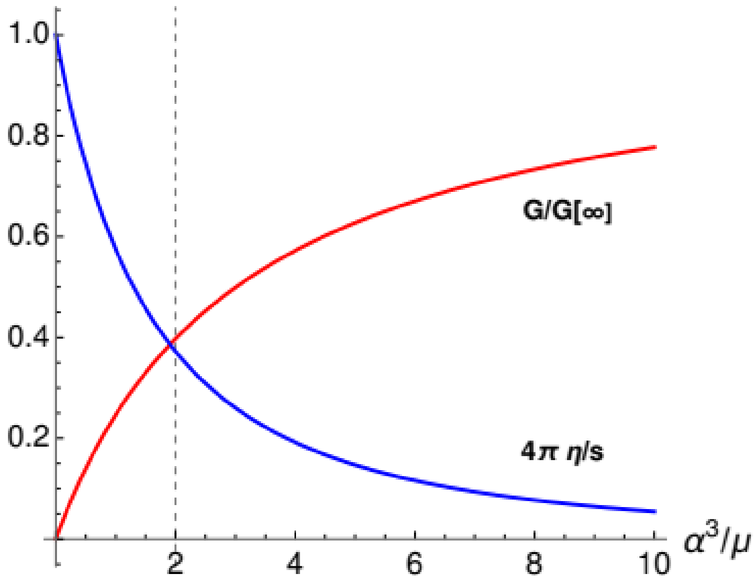
- Mode repulsion in transverse sector

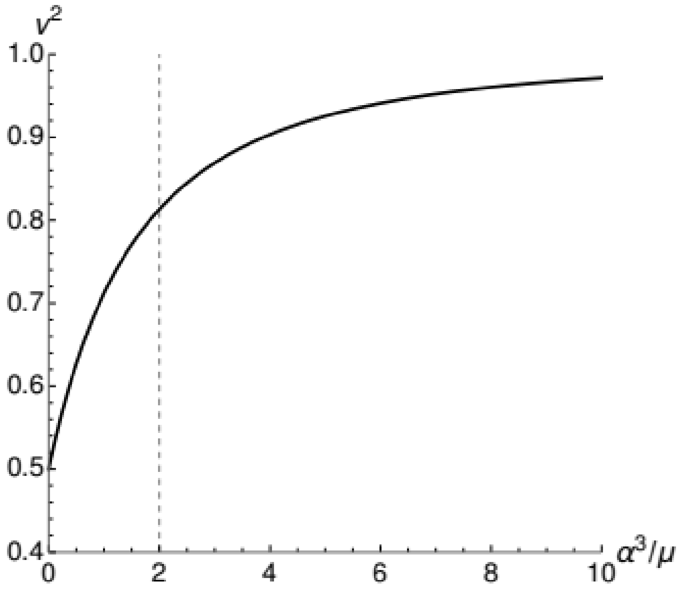


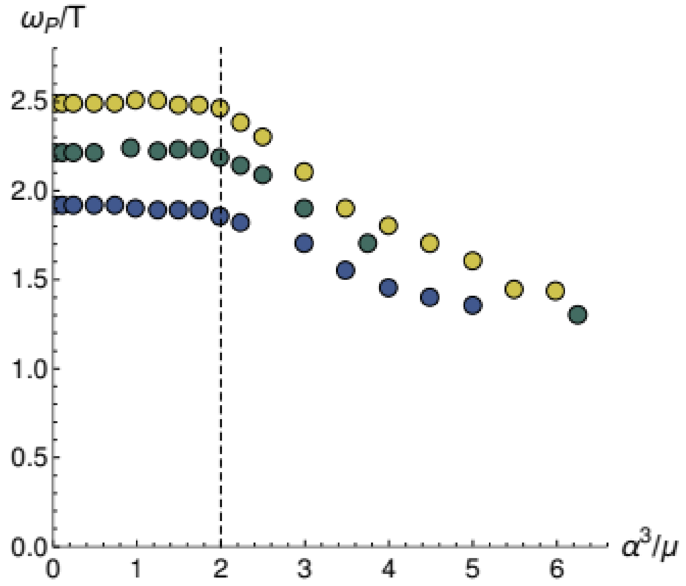


Momentum relaxation – elastic plasma

- Crystal diffusion
- Transition between fluid regime and a crystal regime







Conclusions

- Plasmons are interesting
- Multiple different kinds of plasmons can be studied
- Current experimental results are within grasp of holography
- New things (that can be very difficult to find experimentally) are also obtainable
- Mixed boundary conditions in holography are very important to properly model electromagnetism

Outlook

- Better models!
- Magnetic fields (relevant in experiments) – coming soon ☺
- Interface plasmons
- Top-down models
- Other phenomena where dynamic polarization plays a role, e.g. impurities
- Other explicit phenomena in the boundary theory

Thanks