Probing the medium with heavy quarks using effective field theory

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Motivation

Energy loss of a heavy quark in a strongly coupled $\mathcal{N} = 4\ SU(N_c)$ supersymmetric plasma has been calculated using AdS/CFT correspondence. The primary mechanism is through excitation of hydrodynamic modes.
While there is no dual description of strongly coupled QCD plasma, one should be able to study the interaction of hydrodynamic modes of the plasma with the heavy quark in the strong coupling limit using a two-scale ($\boldsymbol{M}$ and $\boldsymbol{l_{hydro}^{-1}}$) bottom-up EFT.

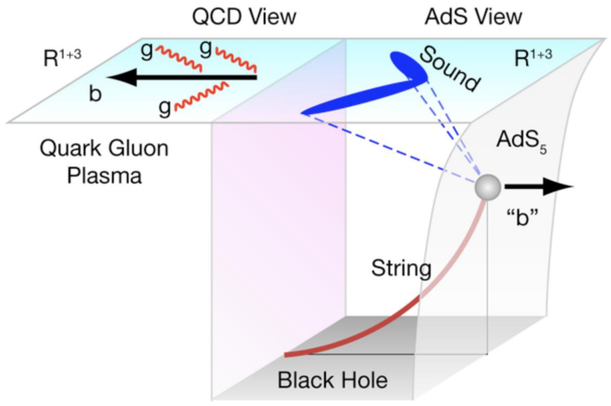


Image source: M. Gyulassy, Physics 2, 107

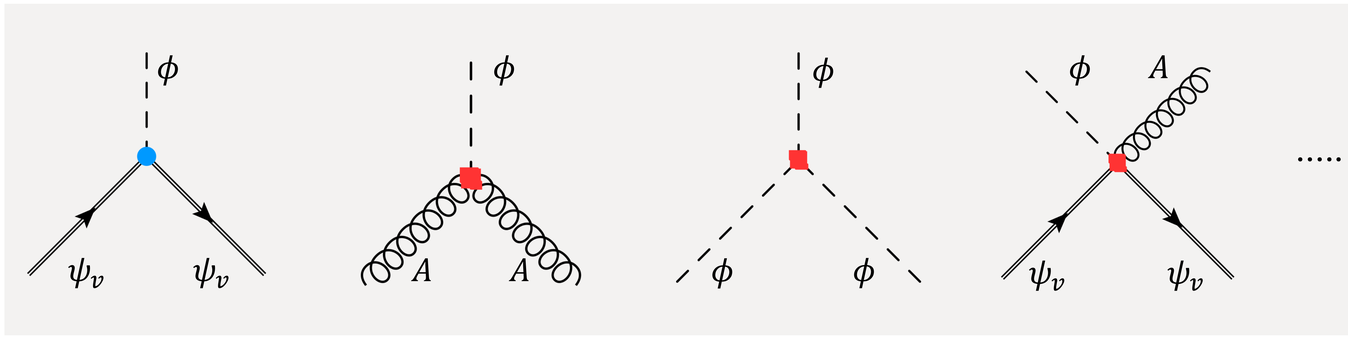
Degrees of freedom & Symmetries

- Hydrodynamic field: $\boldsymbol{\Phi^I(\vec{x}, t)},\ \boldsymbol{I = 1, 2, 3}$
- Heavy Quark field: $\boldsymbol{\psi_v(x)}$
- Gluon field: $\boldsymbol{A_\mu(x)}$

In addition to spacetime symmetries and the $SU(3)$ gauge symmetry of QCD, we have the following internal symmetries for the hydrodynamic field.

- $\boldsymbol{\Phi^I \longrightarrow \Phi^I + \alpha^I,}\quad \boldsymbol{\alpha^I = const.}$
- $\boldsymbol{\Phi^I \longrightarrow R^I{}_J\,\Phi^J,}\quad \boldsymbol{R^I{}_J \in SO(3)}$
- $\boldsymbol{\Phi^I \longrightarrow \xi^I(\Phi),}\quad \boldsymbol{det\left(\frac{\partial \xi^I}{\partial \Phi^J}\right) = 1}$

Feynman rules



● Dim. 5 operator ■ Dim. 6 operator

EFT Lagrangian

➢ To lowest order in derivative expansion and consistent with the symmetries, $\boldsymbol{\Phi^I}$ couples to $\boldsymbol{\psi_v}$ and $\boldsymbol{A_\mu}$ via

$$\boldsymbol{J^\mu = \frac{1}{3!}\varepsilon^{\mu\alpha\beta\gamma}\varepsilon_{IJK}\partial_\alpha\Phi^I\partial_\beta\Phi^J\partial_\gamma\Phi^K}$$

➢ Lagrangian up to $\boldsymbol{1/M}$ and lowest order in derivative expansion ($\boldsymbol{\partial_\mu \ll l_{hydro}^{-1}}$):

$$\boldsymbol{\mathcal{L} = F(X) + Z_A(X)G^a_{\mu\nu}G^{a\mu\nu} + Z_\psi(X)\bar{\psi}_v v\cdot iD\psi_v + \mathrm{M(X)}\bar{\psi}_v\psi_v}$$
$$\boldsymbol{+P(X)\bar{\psi}_v\, v\cdot J\,\psi_v + Q(X)\bar{\psi}_v J\cdot i\vec{D}\psi_v + R(X)\bar{\psi}_v\sigma^{\mu\nu}\psi_v\omega_{\mu\nu}}$$

where $\boldsymbol{X = J^\mu J_\mu}$ and $\boldsymbol{\omega_{\mu\nu} = \partial_\mu J_\nu - \partial_\nu J_\mu}$ and $\boldsymbol{F, Z_A, Z_\psi}$ ... are generic functions of $\boldsymbol{X}$.

➢ Expanding in small perturbations about equilibrium $\boldsymbol{\Phi^I = x^I + \phi^I}$, gives us the dynamics of heavy quark, gluon fields and ANY NUMBER of phonons to lowest order in their momenta.

Outlook

❖ An EFT of heavy quarks in a strongly coupled medium might provide powerful calculational tool to understand energy loss through collective modes.

❖ Future work: Understanding the finite temperature version of the EFT is crucial since higher dimensional operators can be enhanced due to hard thermal loop effects.

References

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3. S. Gupta, arXiv:2307.12250