Massless Mode and Positivity Violation in Hot QCD

A Thermal-Field-Theory Study of Gribov-Zwanziger Quantization

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Heavy ion collisions $\rightarrow g \sim \mathcal{O}(1)$

- RHIC: $T_0 \sim 2T_c$; LHC: $T_0 \sim 4T_c$ ($T_c \simeq 160$ MeV)
- Quark Gluon Plasma: weakly coupled gas vs. strongly coupled liquid
- Running coupling expected: $g \sim \mathcal{O}(1)$
- Neither tiny, nor huge: INTERMEDIATE coupling
  - Conventional perturbation theory: $g \ll 1$
  - Strong-coupling formalisms (e.g. AdS/CFT): $g \gg 1$
- How to tackle it directly (based on thermal field theory)?
  - Characteristics of non-Abelian plasma comparing to Abelian plasma
  - Long-rang correlations: collective excitations
- Impact of CONFINEMENT effects on deconfined phase!
Thermal field theory primer ($\mu = 0$ for simplicity, $g \ll 1$)

- $T$ much bigger than particle’s bare masses: massless particles
- More scales than in the vacuum (screenings etc): non-analytic medium contributions to free energy

\[
\begin{array}{ccccccc}
ad_0 & a_2g^2 & a_4g^4 & a_6g^6 & \ldots \\
& b_3g^3 & b_4g^4 & b_5g^5 & b_6g^6 & \ldots \\
& & c_6g^6 & \ldots \\
\end{array}
\]  

($T$, hard) \hspace{1cm} (gT, soft or electric, HTL) \hspace{1cm} ($g^2T$, ultrasoft or magnetic)

- Thermal mass $m_D \sim gT$: massless particles $\rightarrow$ massive quasiparticles
- Massive quasiparticles $\rightarrow$ short-range(!) correlations ($\sim 1/gT$)
- Linde problem: $c_6 \sim \sum_{n=4}^{\infty} (\text{loops}), \ g^2T$ non-pert./confining
- Where is (how to generate) LONG-RANGE correlations in hot QCD?
Collective excitations of hot QCD - Challenges

- Collective behaviors of quarks/gluons are crucial in studying QGP
  - Debye screening $\rightarrow$ massive quasiparticles $m_D \sim gT$ (electric scale)
  - Confining magnetic scale $g^2 T$ not included due to Linde problem
  - QED and QCD (collective modes) are INDISTINGUISHABLE(!) in conventional thermal-field setups $\rightarrow$ weakly coupled
  - HOW TO DISTINGUISH? (key in generating long-range correlations!)

Fig. 1. Dispersion relation for particles and holes.
Collective excitations of hot plasmas – Hints

- Strongly coupled QGP (sQGP) – massless modes
  - Long-range correlations → strongly coupled
  - Quasinormal modes from AdS/CFT (Kovtun, Starinets, hep-th/0506184)
    - Zero modes from DSE (Gao, Qin, Liu, Roberts, Schmidt, arXiv:1401.2406)
    - Massless modes from IR gluon propagator (Chernodub, Zakharov, hep-ph/0703167)
  - Resummed perturbation theory?

- Confinement effects – positivity violation of spectral functions
  - No Källén-Lehmann representation exists → not part of the physical spectrum, thus confined (Oehme, Zimmermann, 80)
  - Limited knowledge for quarks
  - Resummed perturbation theory?

- Are they interconnected?!
Quark thermal self-energy

- Crucial measure of collective behaviors: screening masses, dispersion relations, spectral functions

\[ \Sigma(P) = (ig)^2 C_F \int \gamma^\mu S(K) \gamma^\nu D^{\mu\nu}(P - K) \]

- At high \( T \) (\( g \ll 1 \)), Gribov-Zwanziger action (Gribov 78; Zwanziger 89) provides a renormalizable framework to study confinement effects at \( g^2 T \)

- \( D^{\mu\nu}(P) = \frac{P^2}{p^4 + \gamma_G^4} \left( \delta_{\mu\nu} - \frac{P_\mu P_\nu}{p^2} \right) \) with \( \gamma_G = \frac{d}{d+1} \frac{N_c}{4\sqrt{2\pi}} g^2 T \) (Zwanziger, hep-ph/0610021; Fukushima, SU, arXiv:1304.8004)

- Hard-thermal-loop (HTL) systematics (\( g \ll 1 \)): contributions from \( P \ll K \) on the same order as tree-level ones, gauge invariant (Braaten, Pisarski, 90)

- Warm-up for gluons
Quark screening mass

- $m_q^2(0) = C_F g^2 T^2 / 8$
- Anti-screening induced by $\gamma_G \sim g^2 T$
- In line with expectations from lattice (Kaczmarek, Zantow, hep-lat/0503017)
- Necessary in restoring confined phase

SU, Tywoniuk, arXiv:1409.3203
Dispersions relations and residues of poles

- Massive modes recovered
- A new massless mode(!)
- Generic for Gribov-like approaches
- Space-like: sound wave at small $p$, $\omega \approx v_s p$ ($v_s = 1/\sqrt{3}$)
- Hydrodynamics-like behaviors
- Long-range correlations incorporated
Collective excitations of hot QCD

Massless mode & positivity violation

Dispersion relations and residues of poles

- Non-positive residue → 1st evidence of positivity violation (IR!) for quarks
- Direct connection b.t. positivity violation & a collective d.o.f.!
- Massless mode grows with $g$ (through $\gamma G$): magnetic scaling (assured by novel branch-cut structures)
- Genuine feature of non-Abelian theories, distinctive from QED(!)
Summary and outlook

- Significance of confinement effects to “deconfined” phase
  - Massless mode & (IR) positivity violation: genuine non-Abelian effects
  - Non-exclusive for finite $T$ systems

CONFINEMENT PHYSICS IS CRUCIAL FOR XQCD!!!

- Gluons on the way: new positivity violation in IR? ($\text{SU}$, Tywoniuk)
- Improved hard-thermal-loop (iHTL) effective action
- Phase transition and bound states:
  - Analytical spectral functions: novel branch cuts
  - In combination with lattice and functional methods
Outlook – Heavy-ion phenomenology

- Roles of **CONFINEMENT** effects in heavy-ion experiments
  - Long-range correlations via massless mode $\rightarrow$ sQGP

- QGP transport coefficients: near-equilibrium dynamics
  - Viscosities: suppressed $\eta$ & enhanced $\zeta$ near $T_c$, onset of sQGP
  - Heavy-quark potential near $T_c$: confining, Coulomb gauge (Greensite, Olejnik, Zwanziger, hep-lat/0401003; Popovici, Watson, Reinhardt, arXiv:1003.3863; Golterman, Greensite, Peris, Szczepaniak, arXiv:1201.4590) $\rightarrow$ enhanced jet quenching parameter $\hat{q}(\sim 1/\eta)$
  - Electrical conductivity, heavy-quark diffusion...

- QGP thermalization: far-from-equilibrium dynamics
  - $g \ll 1$ in the initial stage of QGP evolution
  - $1/g^2 T$ the longest scale $\rightarrow$ QGP evolution in the deep IR, BEC(?)

- QGP in strong $B$ fields: transport coefficients, anomalous transports...