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: $T_0 \sim 2\,T_c$; LHC: $T_0 \sim 4\,T_c$ ($T_c \simeq 160\,\mathrm{MeV}$)
- 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

a_0	$a_2 g^2$		$a_4 g^4$		$a_6 g^6$	...	(T, hard)
		$b_3 g^3$	$b_4 g^4$	$b_5 g^5$	$b_6 g^6$	...	(gT, soft or electric, HTL)
					$c_6 g^6$	...	($g^2 T$, ultrasoft or magnetic)
d_0	$d_2 g^2$	$d_3 g^3$	$d_4 g^4$	$d_5 g^5$	$d_6 g^6$	...	

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

Collective excitations of hot plasmas – Challenges

- Collective behaviors of quarks/gluons are crucial in studying QGP
  - Debye screening → 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 → weakly coupled
  - HOW TO DISTINGUISH? (key in generating long-range correlations!)

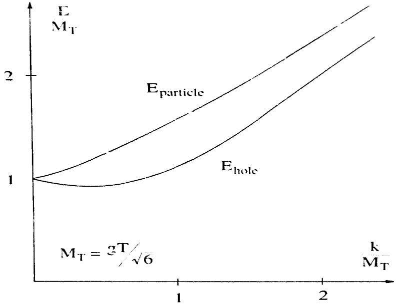


Fig. 1. Dispersion relation for particles and holes.

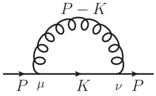
Collective excitations of hot plasmas – Hints

- 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)
    - Well explored for gluons at any T: taking place at UV (Reviews: Alkofer, von Smekal, hep-ph/0007355; Maas, arXiv:1106.3942)
    - 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

$$\Sigma(P) = (ig)^2 C_F \sum\!\!\!\!\!\!\!\int_{\{K\}} \gamma^\mu S(K) \gamma^\nu D^{\mu\nu}(P-K)$$

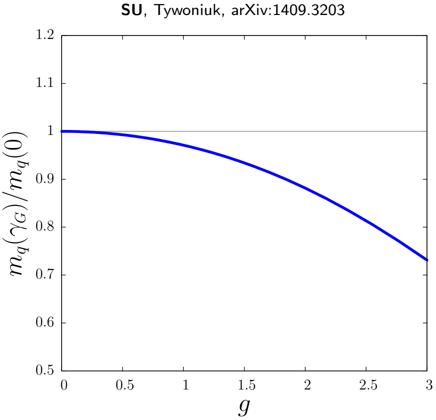


- At high T ($g \ll 1$), Gribov-Zwanziger action (Gribov 78; Zwanziger 89) provides a renormalizable framework to study confinement effects at $g^2 T$
  - $D^{\mu\nu}(P) = \frac{P^2}{P^4+\gamma_G^4}\left(\delta_{\mu\nu} - \frac{P_\mu P_\nu}{P^2}\right)$ with
    $\gamma_G = \frac{d}{d+1}\frac{N_c}{4\sqrt{2}\pi} g^2 T$ (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

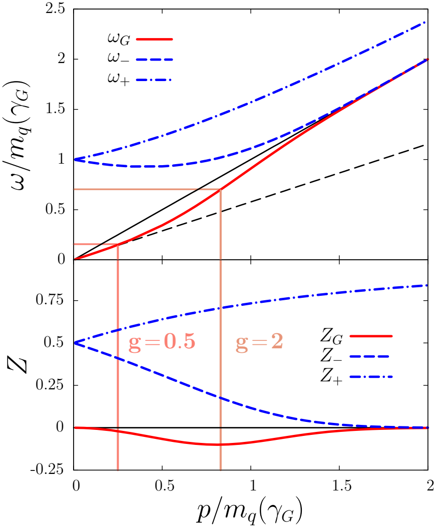
Quark screening mass



- $m_q^2(0) = C_F g^2 T^2/8$
- 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

Dispersion relations and residues of poles

SU, Tywoniuk, arXiv:1409.3203



- 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

Dispersion relations and residues of poles

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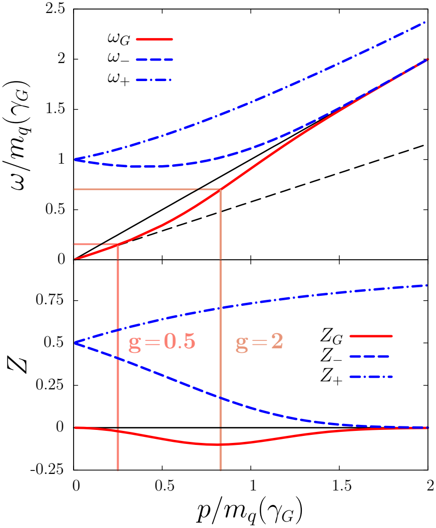

- Non-positive residue → 1st evidence of positivity violation (IR!) for quarks
- Direct connection b.t. positivity violation & a collective d.o.f.!
- Massless mode grows with g (through γ_G): magnetic scaling (assured by novel branch-cut structures)
- Genuine feature of non-Abelian theories, distinctive 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
  - Finite density μ: chiral spirals (Kojo, Hidaka, McLerran, Pisarski, arXiv:0912.3800; Kojo, Hidaka, Fukushima, McLerran, Pisarski, arXiv:1107.2124)
  - Strong magnetic fields B: chiral condensate (Kojo, **SU**, arXiv:1211.7318; Watson, Reinhardt, arXiv:1310.6050; Mueller, Bonnet, Fischer, arXiv:1401.1647), meson spectra (Hattori, Kojo, **SU**, arXiv: 1512.07361)

  CONFINEMENT PHYSICS IS CRUCIAL FOR XQCD!!!

- Gluons on the way: new positivity violation in IR? (**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 η & enhanced ζ near T_c, onset of sQGP (Florkowski, Ryblewski, **SU**, Tywoniuk, arXiv:1504.03176 and arXiv:1509.01242)
  - 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) $\longrightarrow$ 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...