LONG-RANGE CORRELATIONS IN THE QGP AT REALISTIC TEMPERATURES

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(I) motivation

(II) novel excitations of hot QCD

(III) jet quenching parameter

(IV) outlook

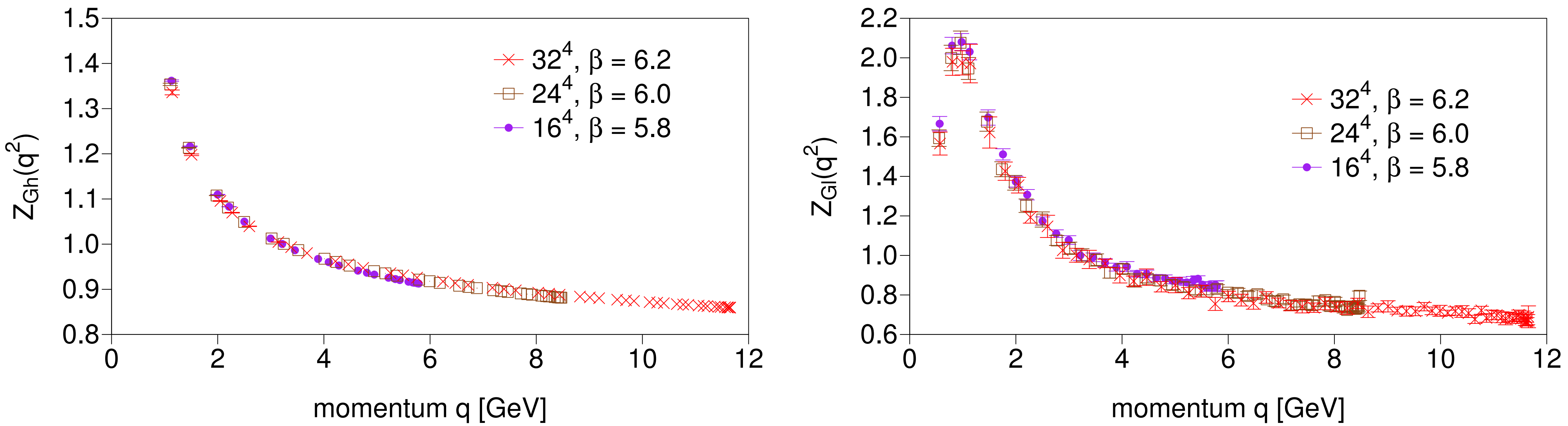
HEAVY-ION COLLISIONS

- Quark-Gluon Plasma vs. Quark-Gluon Liquid?
  - close to universal bound $\eta/s \sim 1/4\pi$ Policastro, Son, Starinets '01
- RHIC: $T_0 \sim 2T_c$; LHC: $T_0 \sim 4T_c$ (T_c=160 MeV)
- Intermediate coupling regime $g \sim O(1)$!
  - Conventional perturbation theory ($g \ll 1$)
  - Strong-coupling techniques ($g \gg 1$)
- Need for novel approaches which contain the hallmarks of genuine QCD: asymptotic freedom & confinement
  - within a renormalizable, resummed framework
  - useful for phenomenological applications in realistic conditions (temperature, coupling,…)

LATTICE PROPAGATOR FEATURES

- general features: propagators deviate from perturbative expectations
  - ghosts: enhancement; gluons: suppression
- two features of confinement!
- both are missing in perturbative (Fadeev-Popov) quantization
- No surprise: (resummed) PT is missing dynamics around T_c!

Landau gauge: Ilgenfritz et al., arXiv:1010.5120



Gribov copies in YM

Gribov '78, Singer'78

- residual gauge transformations in the IR after FP — need non-perturbative gauge fixing in IR!
- Gribov's suggestion: restriction of functional integration
  - reduction of physical states in the IR Gribov '78; Feynman '81; Zwanziger '97
- GZ action: renormalizable framework!
  - ideal for perturbative calculations (incorporating confinement)
- Non-pert. parameter γ_G from self-consistent gap equation — breaks conformal symmetry!
  - high-T limit: $\gamma_G \sim g^2 T$ — magnetic scale! Zwanziger '06; Fukushima, Su '13

Modified gluon propagator
(Landau gauge)

$$D^{\mu\nu}(P) = \left(\delta^{\mu\nu} - \frac{P^\mu P^\nu}{P^2} \right) \frac{P^2}{P^4 + \gamma_G^2}$$

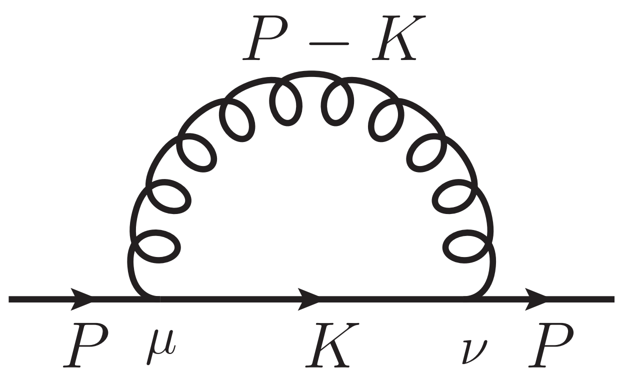
CONFINEMENT AT FINITE T

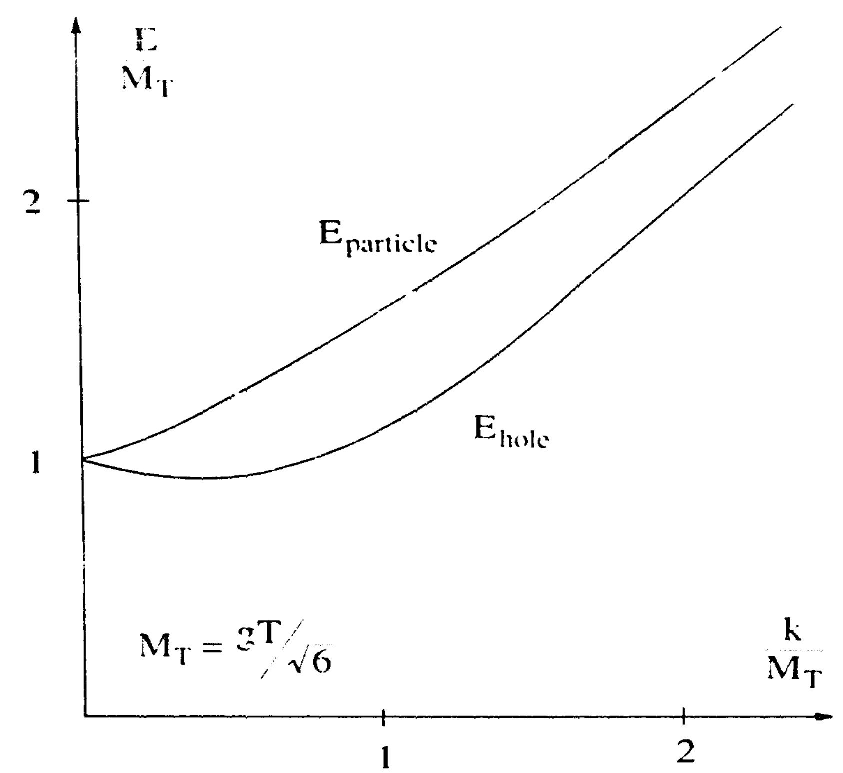
- QCD at high T ($g \ll 1$) is confining Linde '80; Gross, Pisarski, Yaffe '81
  - 3D effective theory with mass gap $\sim g^2 T$: magnetic confinement
  - beyond hard-thermal-loop's (HTL) scope Braaten, Pisarski '92
- as a consequence, positivity violation of spectral functions at any T:
  - absence of free particles at low momentum, therefore "confinement"
  - well-established for pure-glue Maas arXiv:1106.3942
    - confinement effects in functional RGE Haas, Fister, Pawlowski 1308.4960
  - unclear for quarks
- Long-range correlations in strongly-coupled QGP (sQGP) — massless modes
  - Quasi-normal modes in AdS/CFT Kovtun, Starinets hep-th/0506184
  - Zero mode from DSE Gao, Qin, Liu, Roberts, Schmidt arXiv:1401.2406
  - What about resummed perturbation theory?

GZ: HIGH-T QUARK SELF ENERGY

Su, KT 1409.3203

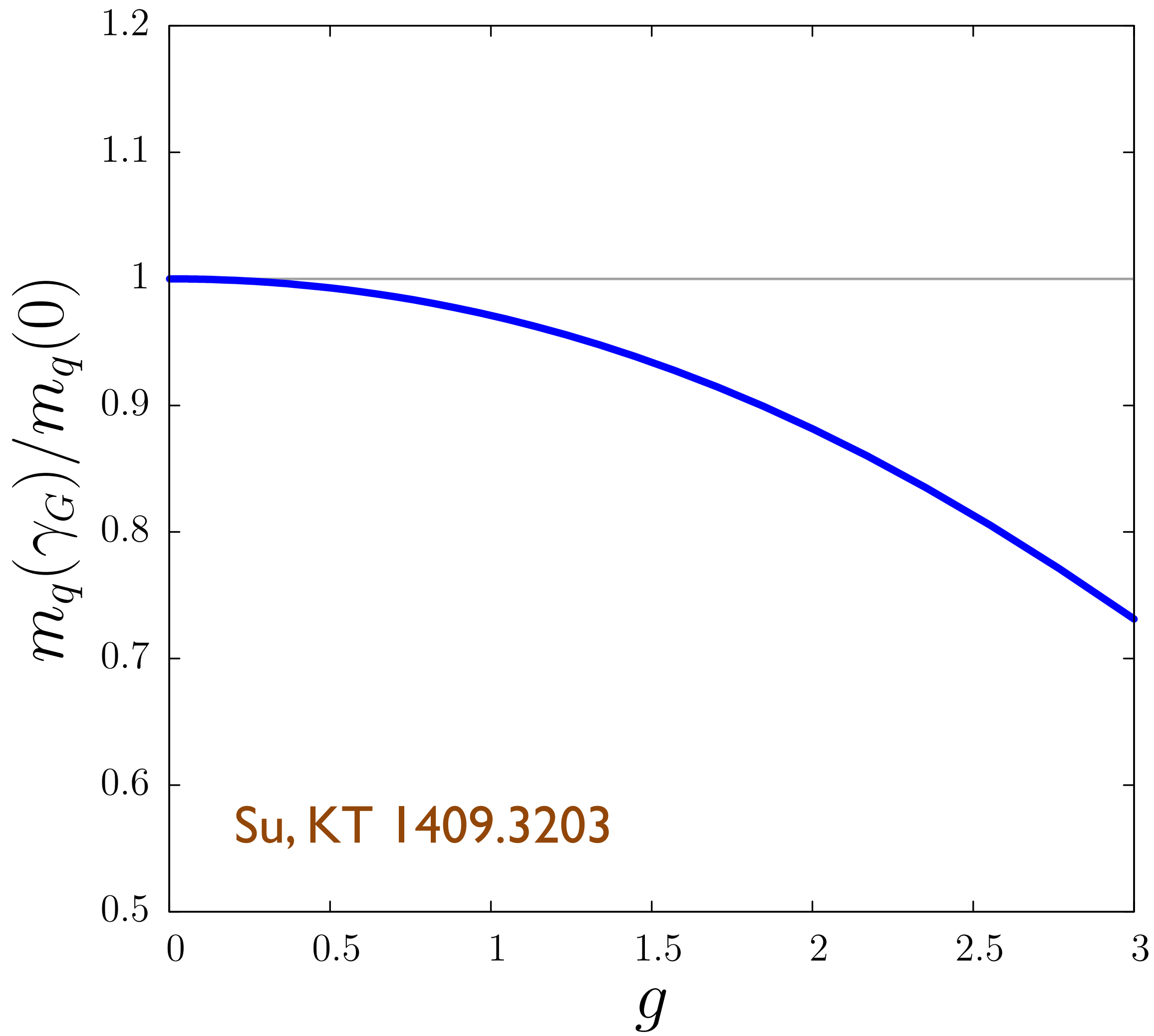
- goal: quark d.o.f. at high-T ($g \ll 1$)
  ($\Sigma(P)$: T^2 contribution is gauge invariant)
- universal behavior: Debye screening
  - collective, quasiparticle excitations
  - QED & QCD indistinguishable?
- Hard Thermal Loop (HTL) systematics: warm-up for gluons
- novel ingredients:
  - including a magnetic scale in the setup leading to a modified pole structure





Weldon Physica A (1989) 169
Klimov (1982), Weldon (1982), Weldon & Pisarski (1989)

QUARK THERMAL SCREENING MASS



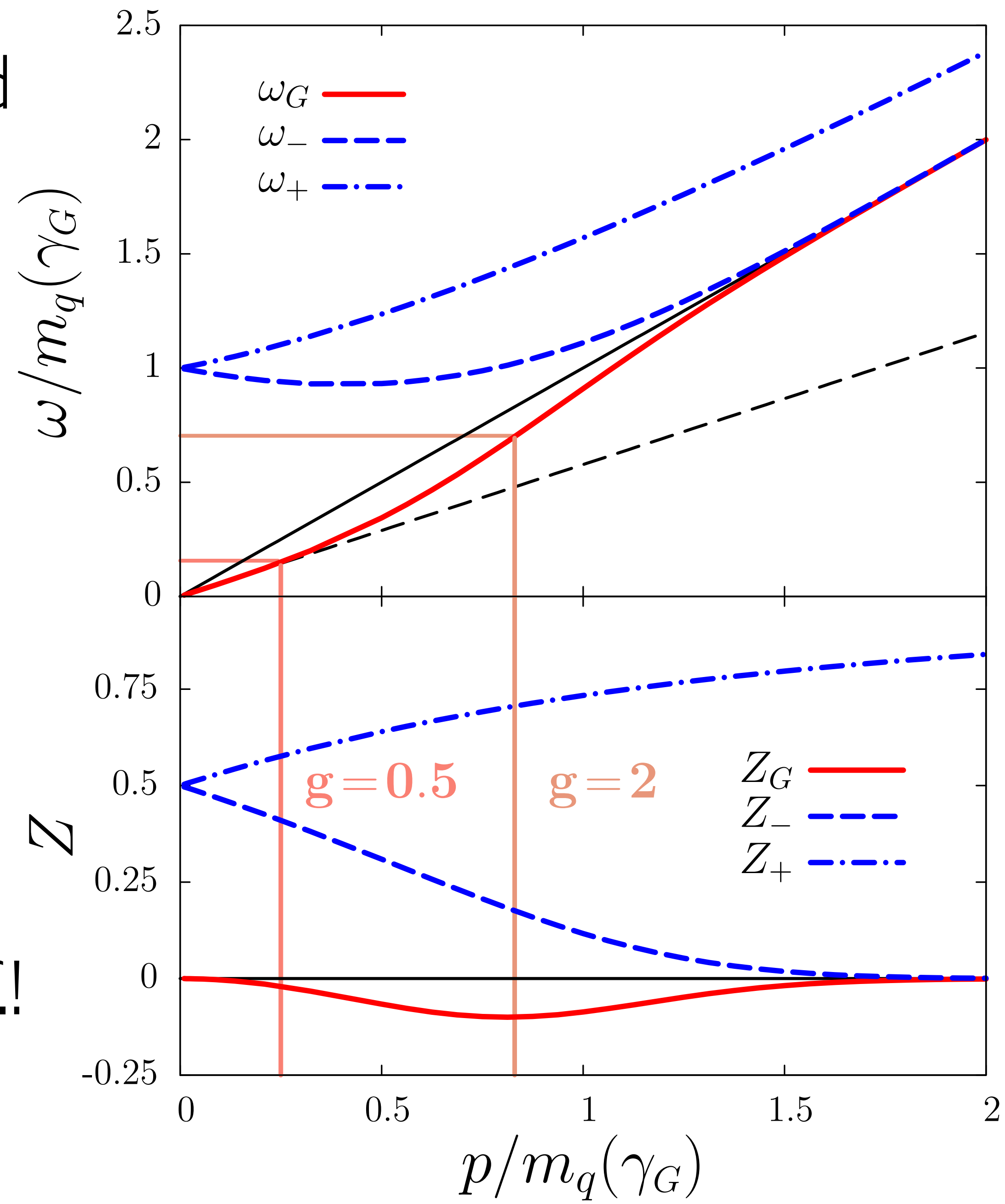
- $m_q(0) = C_F\, g^2T^2/8$
- anti-screening induced by the magnetic scale ($\gamma_G \sim g^2 T$)
- in line with expectations from the lattice

  Kaczmarek, Zantow hep-lat/0503017
- necessary in restoring confined phase

HOT QUARK COLLECTIVE D.O.F.S

- improved HTL analysis for QCD:
  - particle/hole excitations recovered
  - new massless excitation (long-range correlation)
- novel scalings:
  - improved thermal mass (as HTL)
  - massless mode grows with $\sim g^2 T$
- residues: 1st evidence of positivity violation for hot quarks in PT & direct connection to a collective d.o.f.!
- genuine non-Abelian effect

Su, KT 1409.3203



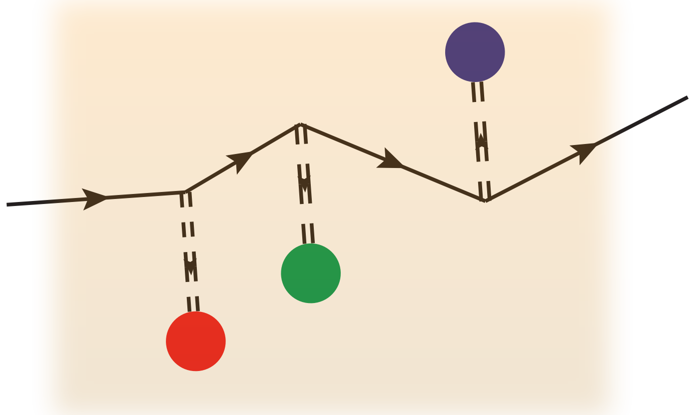
Massless, hydro-like behavior of space-like mode: $\omega_G = v_s\, k$

JET QUENCHING PARAMETER

$$P(k_\perp) = \int d^2x_\perp e^{ik_\perp \cdot x_\perp} \frac{1}{N_c} \langle \mathrm{Tr}\, U^\dagger(x_\perp) U(0) \rangle$$

- propagation of a fast particle in the medium — Wilson line
- **P** = probability of transverse momentum broadening via diffusion (Brownian motion) w/ coefficient $\hat{q}$
- transport theory: $\hat{q} \sim T^3 s/\eta$

  Arnold, Moore, Yaffe '00; Asakawa, Bass, Muller '06; Majumder, Muller, Wang '07
- sQGP expectation: smaller η/s and larger $\hat{q}$ than from pQCD
- same parameter governs radiation & energy loss of leading particle



$$\frac{\partial P(k_\perp, L)}{\partial L} = \hat{q} \frac{\partial^2 P(k_\perp, L)}{\partial^2 k_\perp} + \ldots$$

Baier, Dokshitzer, Mueller, Peigné, Schiff (1997-2000)
Zakharov '96
Arnold, Moore, Yaffe '01
Blaizot, Dominguez, Iancu, Mehtar-Tani '14

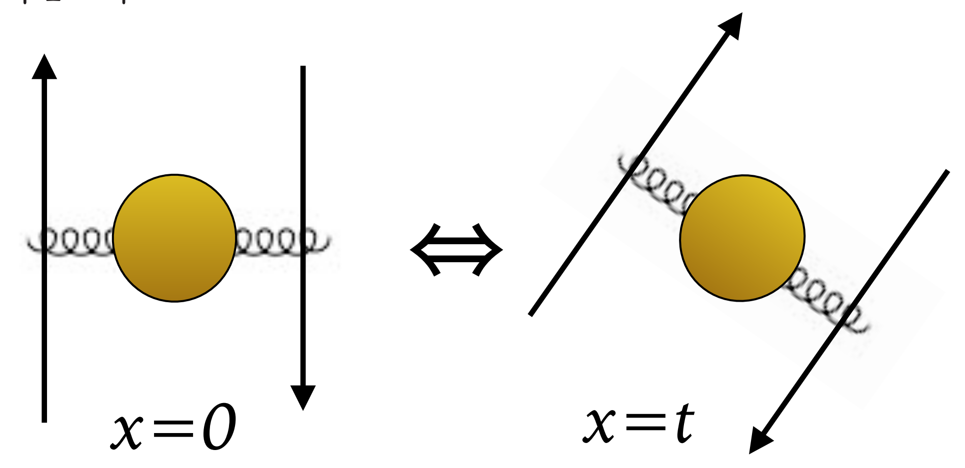
Relation to static quark potential

- two-point space-like correlator $C(x_\perp) = g^2 C_{\mathcal{R}} \int \mathrm{d}x^+ D^{>++}(x^+, x_\perp)$
- boost to rest frame, formally static (heavy) quark potential

$$\hat{q} = \int \frac{\mathrm{d}^2 q_\perp}{(2\pi)^2} q_\perp^2 C(q_\perp)$$

- continuation to Euclidean — direct comparison to lattice (static, electric) QCD
  Caron-Huot '08; Laine '12
- we exploit existing high-T formalism in order to explore non-perturbative effects from magnetic scale!

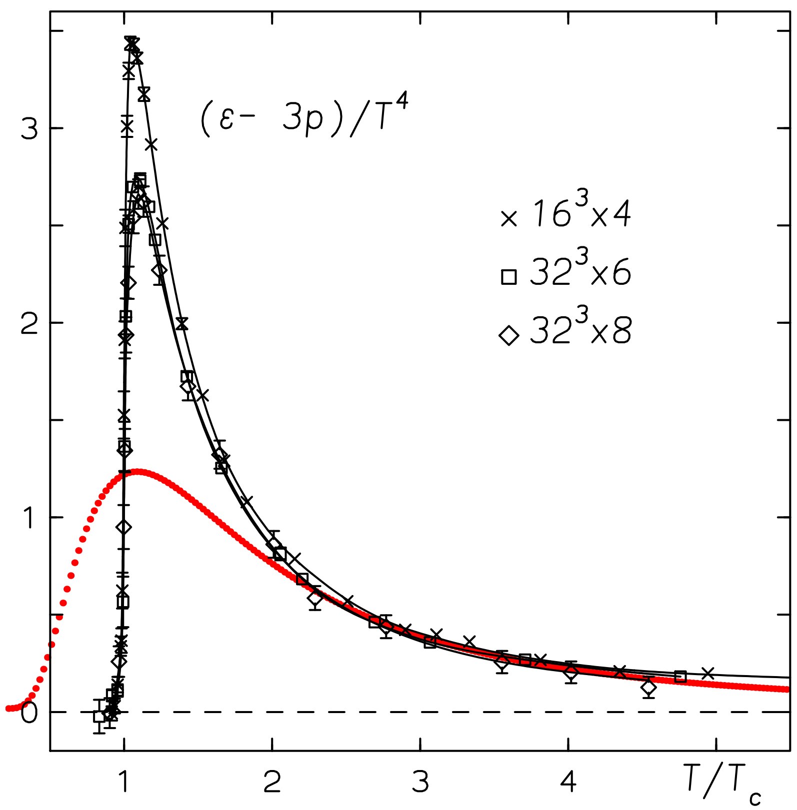
$$\lim_{|q_\perp| \ll m_D} C(q_\perp) = -V_{q\bar{q}}(q_\perp)$$



FINITE-T POTENTIAL

$$E_G(\boldsymbol{p}) = \sqrt{\boldsymbol{p}^2 + \frac{\gamma_G^4}{\boldsymbol{p}^2}}$$

Gribov dispertion relation



Zwanziger PRL 94 (2005)182301

- modified dispersion relation
  - large penalty to excite soft gluon!
  - perturbative sector unchanged
- EOS (= interaction measure) peaks around phase transition
- calculate $V_C(\mathbf{r})$: renormalized color-Coulomb potential
  - "one-gluon exchange" approximation to static quark potential

  Golterman et al. PRD 85 (2012) 08016
  Zwanziger PRD 76 (2006) 125014

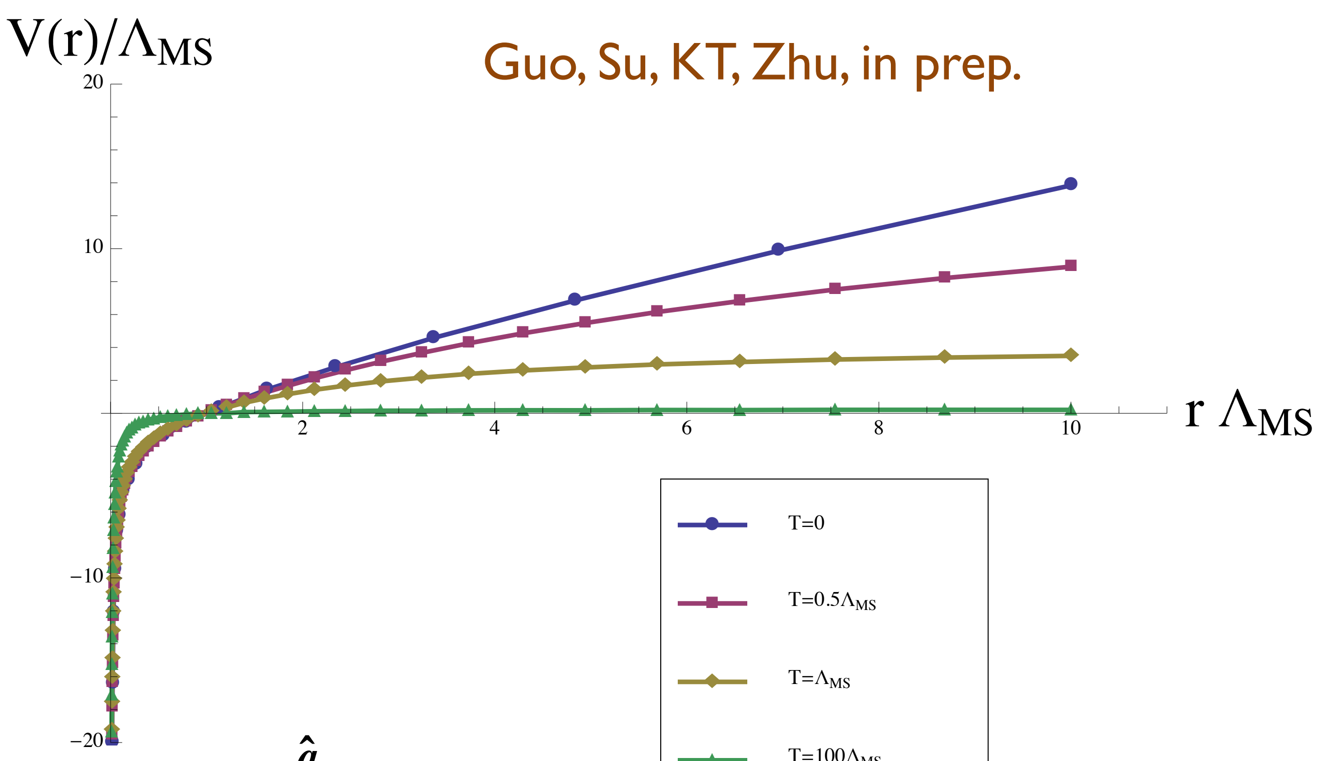
A FIRST LOOK AT q̂

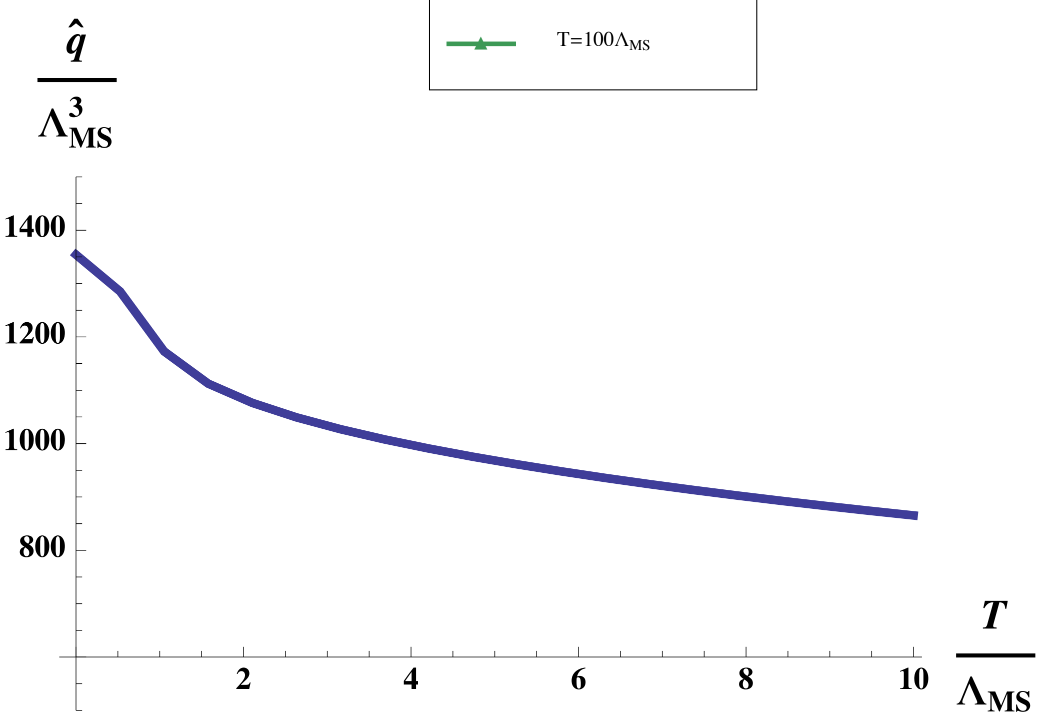
- approx linear potential at T=0
  - confinement!
  - PT @ finite-T: Debye screening, always negative!
- finite-T corrections arise self-consistently through the gap equation
  - anti-screening!
- trend: jet quenching parameter enhanced by the magnetic scale
- (collisional) shear viscosity follows the exact opposite trend, as expected!

$$\eta_C = -\frac{1}{15T}\int \frac{d^3p}{(2\pi)^3}\frac{p^4}{E_p}\bar{\Delta}(p)\,\frac{\partial n_B(\omega)}{\partial \omega}\Big|_{\omega=E_p}$$

deviation from equilibrium

Guo, Su, KT, Zhu, in prep.





SUMMARY

- missing ingredient in hot QGP
  - crucial impact of confinement effects on the deconfined phase
  - presence of massless mode paves the way for transport properties of QGP with long-range correlations
  - goes hand in hand with anti-screening effects, enhances "interactions", affects transport coefficients
    - enhanced jet quenching, suppressed viscosity

⇒ **role of confinement for heavy-ion collisions!**