Consistency of Perfect Fluidity and Jet Quenching in semi-Quark-Gluon-Monopole Plasmas (sQGMP)

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Outline

- Inconsistency between soft bulk & hard jet transport properties
- Nonperturbative medium near $T_c$
- The CUJET3.0 jet energy loss model: pQCD/DGLV + sQGMP (semi-QGP + magnetic monopoles)
- Simultaneous description of high-$p_T$ $R_{AA}$ and $v_2$ at RHIC and LHC; connecting $qhat/T^3(T)$ and $\eta/s(T)$
- Probe deconfinement using jet quenching observables?
- Jet quenching in p+A?
- Summary
Bulk perfect fluidity vs pQCD jet quenching

Bulk: nonperturbative, $\eta/s \sim 0.1-0.2$

Jet quenching: pQCD, $\eta/s \sim 0.5-1.0$

- Bulk perfect fluidity and jet quenching inconsistent?

\[ \frac{\eta}{s} \approx \frac{0.071}{\alpha_s^2 \log(1/\alpha_s)} \]

Jet quenching: 50% underprediction of high $p_T$ $v_2$

Bulk: IP-Glasma + MUSIC, Gale et al. 2013
Jet quenching parameter and $\eta/s$

\[ \hat{q} = \rho \int d^2 q_\perp q_\perp^2 \frac{d\sigma}{d^2 q_\perp} \]

\[ \eta/s = \frac{1}{s} \frac{4}{15} \sum_a \rho_a \langle \rho \rangle_a \lambda_a^{tr} \]
\[ = \frac{4T}{5s} \sum_a \rho_a \left( \sum_b \rho_b \int_0^{(S_{ab})/2} dq_2^2 \frac{4q^2}{S_{ab}} \frac{d\sigma_{ab}}{dq^2} \right)^{-1} \]
\[ = \frac{18T^3}{5s} \sum_a \rho_a \hat{q}_a(T, E = 3T) \]

\[ \hat{q}_N/T_{\text{eff}}^3 (\text{DIS}) \]
\[ \hat{q}_N/T_{\text{eff}}^3 (\text{DIS}) \]

\[ \hat{q}/T^3 \approx \begin{cases} 
4.6 \pm 1.2 & \text{at RHIC}, \\
3.7 \pm 1.4 & \text{at LHC},
\end{cases} \]

\[ \hat{q} \approx \begin{cases} 
1.2 \pm 0.3 \quad \text{GeV}^2/\text{fm} & \text{at } T = 370 \text{ MeV}, \\
1.9 \pm 0.7 & \text{at } T = 470 \text{ MeV},
\end{cases} \]

\[ \eta \approx \begin{cases} 
1.25 & \text{for weak coupling}, \\
\frac{T^3}{\hat{q}} & \text{for strong coupling}.
\end{cases} \]

Danielewicz, Gyulassy, PRD 1985

Hirano, Gyulassy, NPA 2006

Majumder, Muller, Wang, PRL 2007
What can be pumped out of vacuum to account for the “missing” degrees of freedom?

What would be a lattice compatible, microscopic description of the near $T_c$ matter?

Does this help reconciling the “soft” vs “hard” transport inconsistency?
Liao-Shuryak E-M Seesaw Scenario

- $T <\ll \Lambda_{\text{QCD}}$: Vacuum: confined
- $T \sim \Lambda_{\text{QCD}}$: $T_c$, sQGP
- $T >\gg \Lambda_{\text{QCD}}$: wQGP: screening

**Emergent plasma with E & M charges:**
- chromo-magnetic monopoles are the “missing DoF”

**Electric Flux Tube:**
- Magnetic Condensate

- Jet-Medium Coupling

- $\alpha_E \ast \alpha_M = 1.$


- Slide courtesy of Jinfeng Liao
The semi-Quark-Gluon-Monopole Plasmas

- Near Tc: **semi-QGP** (Pisarski, Hidaka, Lin, Satow…)
  - Cf. Pisarski’s Talk on Tue Morning

- **Semi-QGP** suppresses color-electric DOFs as powers of Polyakov loop

\[
L(\vec{x}) \equiv \mathcal{P} \exp \left( ig \int_0^{1/T} d\tau A_0(\tau, \vec{x}) \right) \quad \ell_n(Q) \equiv \langle tr L^n \rangle / N_c = \sum_{a=1}^{N_c} e^{inQ^a/T} / N_c.
\]

\[
n_{ab}(E) = \frac{1}{e^{(E-i(Q^a-Q^b))/T} - 1} \quad \rightarrow \quad \langle \sum_{ab} n_{ab} \rangle_Q \sim N_c^2 T^3 \ell^2
\]

\[
\tilde{n}_a(E) = \frac{1}{e^{(E-iQ^a)/T} + 1} \quad \rightarrow \quad \langle \sum \tilde{n}_a \rangle_Q \sim N_c T^3 \ell
\]

\[
V_{\text{non-pert}}^{glue}(q) = \frac{4\pi^2}{3} T^2 T_{\text{deconf}}^2 \left( -\frac{c_1}{5} q(1-q) - c_2 q^2 (1-q)^2 + \frac{c_3}{15} \right) \text{arXiv:1011.3820, 1205.0137}
\]

- “semi-QGP” + emergent chromo-magnetic monopoles = sQGMP

- Phenomenologically how can we implement such a microscopic sQGMP in a pQCD jet energy loss framework?
  - Does this simultaneously explain data of \( R_{AA} \) and \( v_2 \) at RHIC and LHC?
  - Does this provide a quantitative connexion between the perfect fluidity of QGP and pQCD jet quenching?
CUJET3.0 = pQCD/DGLV + semi-QGP + monopoles

Original DGLV has only quark/ gluon scattering centers

Now include both color-electric and color-magnetic scattering centers

The electric scales as a power law of the Polyakov loop as in the semi-QGP model, the left over “missing” DOFs are the mag. monopoles

Polyakov Loop suppressed color-electric components

=1, by Dirac Quantization

Relativistic flow corrections

Liu et al. 2007; Baier et al. 2007

\( \alpha_c = \frac{2}{3} \)

\( \alpha_c = 1 \)
Lattice Constraints: Polyakov Loop, EOS, E & M Screening Masses

- The CUJET3.0 implementations of the color-electric and magnetic components are well constrained by available lattice data of Polyakov loop, EOS and E & M screening masses.

Bazavov et al., PRD 80 (2009)
Borsanyi et al., JHEP 09 (2010)
arXiv:1411.3673
CUJET3.0 simultaneously describes high pT \((R_{AA}+v_2)\ast(\text{light+heavy})\ast(\text{RHIC+LHC})\)

The combined set of observables \((R_{AA}+v_2)\ast(\text{RHIC+LHC})\ast(pion+D+B)\) are consistently accounted for in CUJET3.0 using lattice data constrained sQGMP near Tc + pQCD jet quenching

JX, J. Liao, M. Gyulassy, arXiv:1411.3673
CUJET3.0’s D/π suppression ratio compared with data

The ratio of D and π, ch’s RAA imposes further constraints on jet energy loss models

Less than one $R_{AA}^{\pi, ch}$ in $10\text{GeV} < p_T < 30\text{GeV}$

Figures from ALICE, arXiv:1509.06888
CUJET3.0: $q_{\text{hat}}(E,T)$ for quark jets in sQGMP

Liu et al. PRL 2006
\[ \hat{q} \approx 26.69 \sqrt{\lambda/4\pi T^3} \]

\[ \hat{q}_F/T^3 \]

\[ \lambda = 16\pi \]

\[ \lambda = 8\pi \]

\[ \lambda = 4\pi \]

\[ 50\text{GeV} \]

\[ 10\text{GeV} \]

\[ 2\text{GeV} \]

\[ \text{SYM} \]

\[ \text{pQCD+HTL} \]

\[ \text{Au+Au at RHIC} \]

\[ \text{Pb+Pb at LHC} \]

JET Collaboration, PRC 2014

JX, Liao, Gyulassy, arXiv:1411.3673

\[
\hat{q}_F = \int_0^{6ET} dq^2 \left( q^2 + f_E^2 \mu^2 \right) \left( q^2 + f_M^2 \mu^2 \right) \rho(T) \times 
\left[ (C_{qq} f_q + C_{qg} f_g) \alpha_s^2 (q^2) + C_{qm} (1 - f_q - f_g) \right] 
\]

\[ f_q = c_q L(T), \quad f_g = c_g L(T)^2 \quad \rho(T) \sim p(T)/T \quad \text{p(T) from s95p-v0-PCE EOS} \]

- CUJET3.0 solution exhibits a “volcano” interpolation of $q_{\text{hat}}/T^3$ between strong “AdS-like” sQGP at $T=200-350\text{MeV}$ to more transparent “HTL-like” wQGP for $T>400\text{MeV}$
**pQCD jet quenching + sQGMP: \( \eta/s(T) \)**

*CUJET3.0 provides a quantitative connection between the jet transport properties controlling the hard jet quenching observables and the bulk viscous transport properties controlling the soft "perfect fluidity" of QGP observed at RHIC and LHC.*

*How to make full use of this connection?*

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Jiechen Xu, 09/29/2015 @ QM15
Deconfinement: Quark number susceptibility vs Polyakov loop

- Quark DOFs are dynamic and almost massless rather than static and massive.
- Use normalized quark number susceptibility instead of Polyakov loop for the deconfinement rate of quarks near $T_c$.

JX, Liao, Gyulassy, arXiv:1508.00552
Light hadron and open heavy flavor $R_{AA}$ with “fast deconfinement”

- The parameter is adjusted to fit to LHC charged hadron $R_{AA}$ at $p_T=12.5\text{GeV}$
- The beauty $R_{AA}$ distinguishes the different liberation schemes
- The combination of light hadron and open heavy flavor $R_{AA}$ may be used as a measure of deconfinement

JX, Liao, Gyulassy, arXiv:1508.00552
The shear viscosity with “fast deconfinement”

- The shear viscosity minimum is sensitive to how rapidly quark DOFs are deconfined.
- The slope of $\eta/s(T)$ is affected mainly by the temperature dependence of $E$ and $M$ screening masses.

Jiechen Xu, 09/29/2015 @ QM15

arXiv:1508.00552
Jet quenching in p+A?

CUJET3.0/DGLV (preliminary)

- Same pA Hydro from McGill group is used, cf. Shen et al. 1504.07989 & Gale’s Talk on Monday
- Min. bias see mild quenching at \( p_T \sim 15 \text{GeV} \); Central collisions see strong jet suppressions

Gale, QM15 Monday Talk

Jiechen Xu, 09/29/2015 @ QM15
Azimuthal anisotropy of charged hadrons in p+A

- Significant $v_2$ up to $p_T \sim 30$ GeV in central pA collisions in CUJET
- Compared with HTL QGP, in sQGMP, the monopoles contribute to a $\sim 0.03$ boost in high $p_T$ $v_2$, this magnitude of enhancement is similar to the one in 20-30% AA

Shen et al. arXiv:1504.07989 & Gale’s Talk on Monday
Combining the \textit{pQCD} jet quenching kernal and the microscopic semi-Quark-Gluon-Monopole Plasma (sQGMP) model, CUJET3.0 describes $(R_{AA}+v_2) \times (\text{pion+D+B}) \times (\text{RHIC+LHC})$ simultaneously

- $qhat$ bridges the AdS/CFT limit near $T_c$ and the HTL pQCD limit at high $T$
- $\eta/s$ approaches the perfect fluid $\sim0.1$ near $T_c$, and rises rapidly as $T$ rises

How rapidly quark DOFs are deconfined near $T_c$ significantly affects the suppression of open heavy flavors and the shear viscosity minimum

Non-negligible suppressions of high-$p_T$ light hadrons in most-central $pA$ collisions; the high-$p_T v_2$ enhancement from monopoles in such system is similar to that in AA
Backup
An alternative qhat measure in sQGMP

\[
\tilde{q}_F'(E, T) = \int_0^{6ET} dq_\perp^2 \frac{2\pi}{(q_\perp^2 + f_E^2 \mu_\perp^2(z))(q_\perp^2 + f_M^2 \mu_\perp^2(z))} \rho(T) \\
\times \left\{ [C_{qq} f_q + C_{qg} f_g] \cdot \left[ \alpha_s^2(q_\perp^2) \right] \cdot \left[ f_E^2 q_\perp^2 + f_E^2 f_M^2 \mu_\perp^2(z) \right] + [C_{qm}(1 - f_q - f_g)] \cdot \left[ 1 \right] \cdot \left[ f_M^2 q_\perp^2 + f_E^2 f_M^2 \mu_\perp^2(z) \right] \right\}.
\]

![Graphs showing the behavior of \( \tilde{q}_F'(E, T) \) with temperature.]

- The alternative qhat as well as the eta/s converges to the HTL limit at high temperature.

JX, Liao, Gyulassy, arXiv:1508.00552

Jiechen Xu, 09/29/2015 @ QM15
Open heavy flavor $R_{AA}$ distinguishes the different liberation schemes
qhat and eta/s in the “fast liberation” scheme

The shear viscosity near $T_c$ is sensitive to how fast quark DOFs are deconfined.

JX, Liao, Gyulassy, arXiv:1508.00552

- The shear viscosity near $T_c$ is sensitive to how fast quark DOFs are deconfined.
Both RAA and v2 are surprisingly insensitive to the form of the relativistic flow corrections in both CUJET2.0 (pQCD+HTL) and CUJET3.0 (semi-QGP + magnetic monopoles)
Pressure Scheme (PS) vs Entropy Scheme (ES)

The graphs illustrate the comparison between the Pressure Scheme and the Entropy Scheme in the context of particle production in high-energy collisions. The schemes are compared for different collision systems and energies, showing the evolution of various physical quantities such as energy density, entropy density, and other relevant parameters as a function of temperature.

The figures depict the following:

- **Pressure Scheme**
  - (a) $s/4T^3$ vs $\rho/T^4$ vs $B/T^4$ for different temperatures.
  - (c) $\chi^2$ Scheme: $\rho/T^4$ vs $p/p_T$ for different temperatures.

- **Entropy Scheme**
  - (b) $\rho/T^4$ vs $E$ for different temperatures.
  - (d) $\chi^2$ Scheme: $\rho/T^4$ vs $p/p_T$ for different temperatures.

The graphs are labeled with various symbols and lines representing different collision systems and energy conditions, such as Au+Au, Pb+Pb, and ALICE, with specific energy and centrality ranges.

Jiechen Xu, 09/29/2015 @ QM15

JX, Liao, Gyulassy, arXiv:1508.00552
Convergence of the DGLV opacity series

Figure 15. Radiated gluon transverse momentum distribution for a heavy quark jet with energy $E = 20$ GeV traversing a brick plasma of size $L = 5$ fm emitting a gluon with energy $\omega = 5$ GeV. The mass of the quark $M = 4.75$ GeV. The DGLV opacity series calculated up to $n=1$ (black), 3 (blue), 5 (green), 7 (orange), 9 (red) are shown in the figure. The opacity expansion computed up to ninth order is shown to converge to the ASW multiple soft scattering limit (maroon, dashed) for small $k_\perp \lesssim \hat{q} L \approx 1$ GeV. At large $k_\perp$, differs from the ASW limit, DGLV has a robust Landau tail. Other parameters used in the simulation are: $\lambda = 1.16$ fm, $\mu = 0.5$ GeV, $m_g = 0.356$ GeV, $T = 0.258$ GeV, $n_f = 0$, $\alpha_s = 0.3$.

JX, Buzzatti, Gyulassy, JHEP 1408, 063 (2014)
CUJET: to solve the heavy quark energy loss puzzle + to explain the surprising transparency of QGP at LHC

- Recouling scattering centers

\[ Q^2 = q^2 \]

\[ Q_2^2 = q^2 - M^2 = \frac{k^2}{x_+(1-x_+)} + \frac{x_+M^2}{1-x_+} + \frac{m_g^2}{x_+} \]

\[ Q^2 = (2T)^2 \]

Zakharov, JETP Lett. 2008

Buzzatti, Gyulassy, 2013; JX, Buzzatti, Gyulassy, 2014

- Multi-scale running strong coupling

- Path length fluctuations:
  \[ T(\tau_{\text{max}}) = T_f \]


Djordjevic and Heinz, PRC (2008)
High-$p_T$ $v_2$ in the pQCD energy loss model

- The 50% underestimation of $v_2$ can be accounted for if the average coupling strength is tuned up by 10% from in- to out-of-reaction plane paths.

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Jiechen Xu, 09/29/2015 @ QM15
Open charm’s and beauty’s high $p_T$ $R_{AA}$ and $v_2$ at RHIC and LHC (20-30% centrality) from CUJET3.0

Jiechen Xu, 09/29/2015 @ QM15
CUJET3.0: HF Decay Electron RAA & v2

To be compared with data
Path length dependence of jet energy loss in sQGMP

Monopoles bring non-perturbative effects into the pQCD energy loss theory

JX, Liao, Gyulassy, arXiv:1508.00552
Path length dependence of heavy quark energy loss in sQGMP

Jiechen Xu, 09/29/2015 @ QM15

JX, Liao, Gyulassy, arXiv:1508.00552
Near-Tc properties of sQGMP are special!

Jet transport coefficient $q/T^3$ computed from CUJET3.0 shows a prominent peak near Tc!

Shear viscosity, $\eta/s$, computed from CUJET3.0 shows a clear minimum near Tc and a rapid rise at high T!

CUJET3.0 = [pQCD] + [semi-QGP] + [magnetic monopoles] bridges the “soft” bulk perfect fluidity and the “hard” jet quenching ($\eta/s \sim T^3/qhat$)

BES@RHIC and LHC are both essential to constrain and map out the strongly non-conformal QCD confinement transition physics