Suppression of energy loss from partially ionized color

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Outline

- Introduction: ionization in QED/QCD plasmas

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- Collisional energy loss in partially ionized plasma

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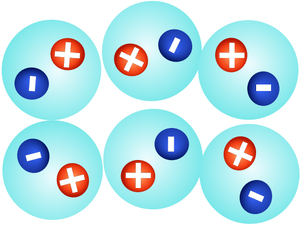
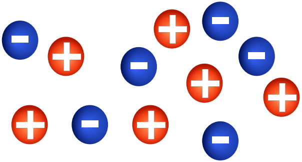
- Collisional energy loss in partially ionized plasma
- Conclusions

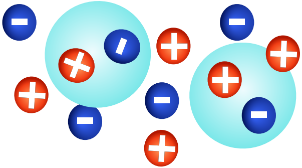
Ionization in QED plasma



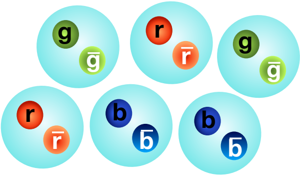
Neutral state $\rightsquigarrow$ atoms,
electric neutrality > atomic scales



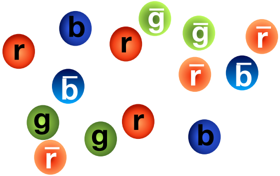
Completely ionized plasma $\rightsquigarrow$ plasma with freely moving electric charges



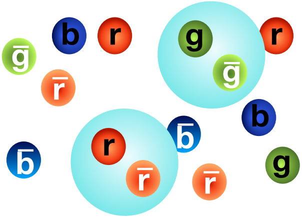
Partially ionized plasma $\rightsquigarrow$ *partially* ionized plasma with atoms and electric charges



Neutral state ⇝ confined phase, color neutrality > hadronic scale



Completely ionized plasma ⇝ perturbative QGP with freely moving charges



Partially ionized plasma ⇝ *partial* ionization of color: hadrons and color charges; semi-QGP, nontrivial holonomy

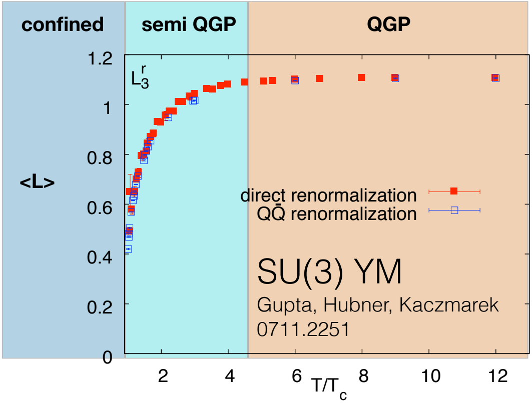
Polyakov loop as a measure of partial ionization: pure glue

Polyakov loop: $\langle L \rangle \sim e^{-F_{\text{test qk}}/T}$

Confined: $F_{\text{test qk}} \to \infty$, $\langle L \rangle \to 0$

Semi QGP: $0 < \langle L \rangle < 1$
$\langle L \rangle$ measures degree of ionization

Perturbative QGP: $F_{\text{test qk}}/T \to 0$, $\langle L \rangle \to 1$

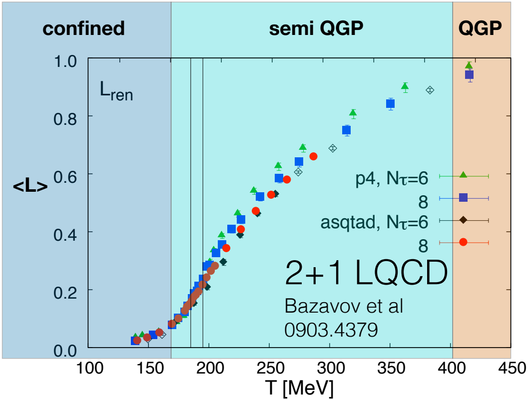


Polyakov loop: $\langle L \rangle \sim e^{-F_{\text{test qk}}/T}$

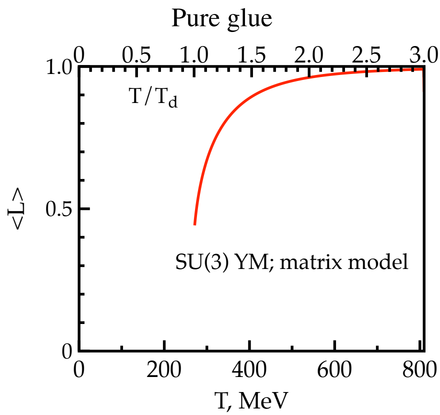
Confined: $F_{\text{test qk}} \to \infty$, $\langle L \rangle \to 0$

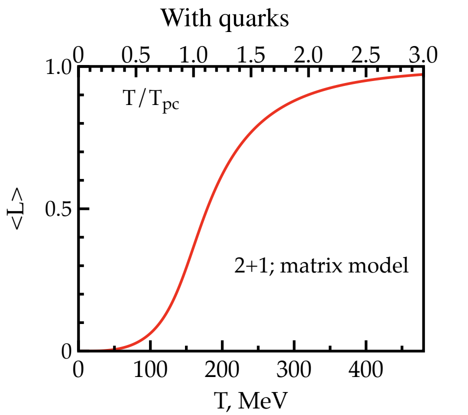
Intermediate regime: $0 < \langle L \rangle < 1$ $\langle L \rangle$ measures degree of ionization

Deconfined: $F_{\text{test qk}}/T \to 0$, $\langle L \rangle \to 1$

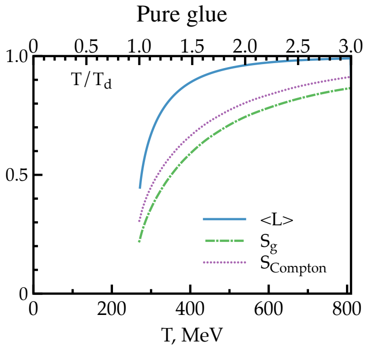


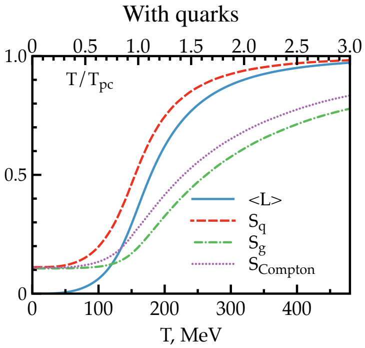
Polyakov loop: matrix model





Punchline: transition region (“semi”-QGP): must exhibit partial ionization of color
shear viscosity, energy loss…must depend upon the degree of ionization





$S_i = \frac{\text{energy loss in semi-QGP}}{\text{energy loss inperturbative QGP}}$

S_i increases as color is ionized

- $i = q$ scattering on light quark (t channel)
- $i = g$ scattering on gluons (t channel)
- $i =$ Compton scattering on gluons, Compton scattering (u channel)

Perturbative vs semi-QGP

Usual argument of kinetic theory

Majumder, Muller and Wang, hep-ph/0703082

Liao and Shuryak, 0810.4116

Asakawa, Bass, and Muller, hep-ph/0603092, 1208.2426

- Viscosity $\eta \sim \rho^2/\sigma$
  - ρ - density of color charges $\rho \sim 1$
  - σ - crossection: $\sigma \sim g^4$, g - coupling
  - large $g \rightsquigarrow$ small η

- Energy loss $\frac{dE}{dx} \sim g^2\rho^2$
  - large $g \rightsquigarrow$ large $\frac{dE}{dx}$

Semi-QGP

Y. Hidaka, R, Pisarski 0912.0940

R. Pisarksi, V. Skokov proceedings of QM2013

- Viscosity $\eta \sim \rho^2/\sigma$
  - ρ - density of color charges, $\rho \sim \langle L \rangle^2$
  - σ - crossection: $\sigma \sim \langle L \rangle^2$
  - $\eta \sim \langle L \rangle^2$, small in semi-QGP

- Energy loss (large N_c)
  - $\frac{dE}{dx} \sim \langle L \rangle \cdot \frac{dE}{dx}$ on light quarks $+\langle L \rangle^2 \cdot \frac{dE}{dx}$ on gluons

Details

- Matrix model
- Collisional energy loss in large N_c limit
- Collisional energy loss due to scattering on light quark, $N_c = 3$
- Collisional energy loss due to scattering on gluons, $N_c = 3$
- Outlook: radiative?!

Non-zero Polyakov loop $\rightsquigarrow$ non-trivial holonomy

- Polyakov loop $L = \mathrm{Tr}\,\mathcal{P}\exp\left(ig\int_0^{1/T} A_0 d\tau\right)$
- Anzatz for $[A_0]_{ab} = \delta_{ab}\frac{Q^a}{g}$, for the sake of simplicity $Q^a = 2\pi T\cdot q^a$
- Tracelessness tr $\mathrm{A}_0 = 0 \rightsquigarrow \sum_a Q^a = \sum_a q^a = 0$
- Classical approximation: zero action for A_0
- One loop about A_0: Gross, Pisraski, Yaffe '81:

$$U_{\text{pert}} = -2\pi^2 T^4\left[\frac{N^2-1}{45} - \frac{1}{3}\sum_{a,b}(q_a - q_b)^2\left(1 - |q_a - q_b|\right)^2\right]$$

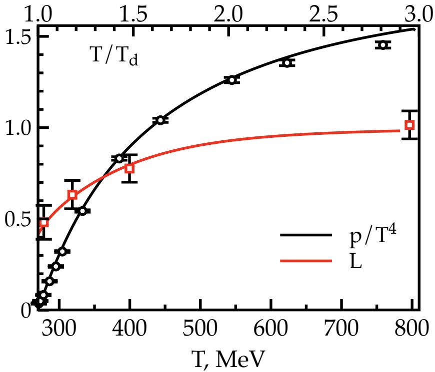
  Gives only trivial A_0
- Non-perturbative contribution are modeled by (R. Pisarski et al)

$$U_{\text{non-pert}} = T^2 T_d^2\left[c_1\sum_{a,b}^{N}|q_a - q_b|\left(1 - |q_a - q_b|\right) + c_2\sum_{a,b}^{N}(q_a - q_b)^2\left(1 - |q_a - q_b|\right)^2 + c_3\right]$$

- c_i are fixed to get transition at $T = T_d$, and describe lattice data
- three colors: $q_1 = -q_2 = q$, $q_3 = 0$. Confining at $q = 1/3$ and perturbative $q = 0$.

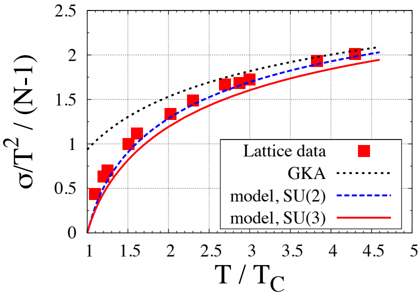
Model vs lattice

Pressure for pure glue



t'Hooft loop
(interface between different $Z(N)$ sectors)

Dumitru et al, 1011.3820



$$V \to V + \frac{1}{g^2} \sum_a^N \left(\frac{\partial Q_a}{\partial z}\right)^2$$

Quark and gluon propagator in a background A_0 field: Hidaka, Pisarski 0906.1751

- Distribution function for gluons

$$n^g_{a,b}(p,Q) = \left[\exp\left(\frac{E - i(Q_a - Q_b)}{T}\right) - 1\right]^{-1}$$

- Distribution function for quarks

$$n^q_a(p,Q) = \left[\exp\left(\frac{E - iQ_a}{T}\right) + 1\right]^{-1}$$

Limits:

- Trivial holonomy or perturbative QGP, $Q = 0$

$$n^g(p, Q=0) = \left[\exp\left(\frac{E}{T}\right) - 1\right]^{-1}$$

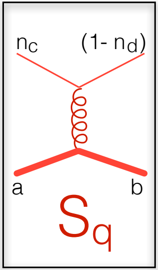
$$n^q(p, Q=0) = \left[\exp\left(\frac{E}{T}\right) + 1\right]^{-1}$$

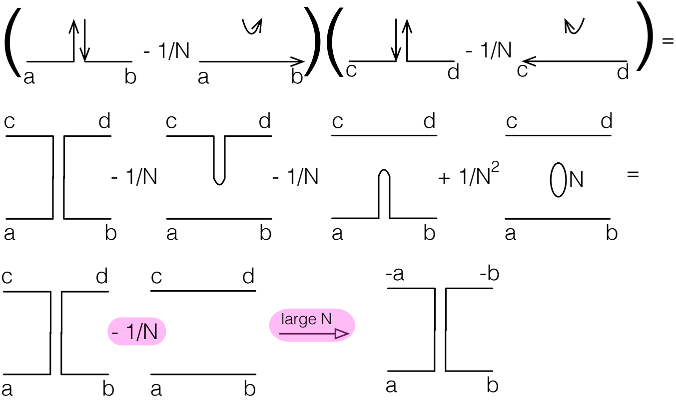
- Confining limit, large N:

$$n^q = 0$$

$$n^g = 0$$

Large N limit for scattering off light quark: birdtracks





$$\sim \sum_{ab} n_a(1 - n_b)$$

Large N limit

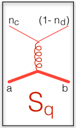
$$\frac{dE}{dx} \propto \sum_{a,b}^{N} \int [dk][dk'][dp'] f(p,k,k',p') n(E_k + iQ_a) \left[1 - n(E_{k'} + iQ_b)\right]$$

$$\sum_a n(E_k + iQ_a) = \sum_a \left[\exp\left(\beta E_k + i\beta Q_a\right) + 1\right]^{-1}$$

$$= \sum_{n=1}^{\infty} (-1)^n \exp\left(-\beta E_k\right) \sum_a \exp(in\beta Q_a) = \sum_{n=1}^{\infty} (-1)^n \exp\left(-\beta E_k\right) \mathrm{tr}\, L^a$$

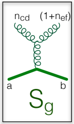
for small tr L scattering off **light quarks**

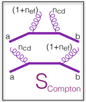
$$\frac{dE}{dx} \propto \mathrm{tr} L \cdot \left(\frac{dE}{dx}\right)_{\mathrm{pert.}}$$



Similar argument for scattering off **gluons** gives

$$\frac{dE}{dx} \propto (\mathrm{tr}\, L)^2 \cdot \left(\frac{dE}{dx}\right)_{\mathrm{pert.}}$$





N=3

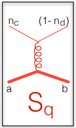
As in pQCD, but taking into account modification of distribution function in final/initial state.

N=3: Scattering off light quarks

$$S_i = \left(\frac{dE}{dx}\right)_i \Big/ \left(\frac{dE}{dx}\right)_{i,\text{pert.}}$$

- Scattering off light quark

$$S_q = \frac{12}{\pi^2(N^2-1)} \sum_{l=1}^{\infty} \sum_{m=0}^{l-1} (-1)^{l+1} \frac{l-2m}{l^3} \left(\text{tr } L^{l-m} \text{tr } L^m - \frac{1}{N} \text{tr } L^l \right)$$



  - Perturbative limit $Q \to 0$, so $\forall i$ $\text{tr } L^i \to 1$:

$$S_q(Q=0) = \frac{12}{\pi^2(N^2-1)} \sum_{l=1}^{\infty} \sum_{m=0}^{l-1} (-1)^{l+1} \frac{l-2m}{l^3} (N^2-1) = 1$$

  - Confining limit $q \to 1/3$, so $\forall i = kN$, where k is integer, $\text{tr } L^i \to N$, otherwise $\text{tr } L^{j \neq kN} \to 0$:

$$S_q(q=1/3) = \frac{12}{\pi^2(N^2-1)} \sum_{k=1}^{\infty} \sum_{m=0}^{Nk-1} (-1)^{kN+1} \delta_{mj N} \frac{kN-2m}{k^3 N^3} (N^2-1)$$

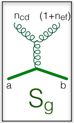
$$= \frac{1}{N^2} \text{for odd } N, \ \frac{2}{N^2} \text{ otherwize}$$

N=3: Scattering off gluons

$$S_i = \left(\frac{dE}{dx}\right)_i \Big/ \left(\frac{dE}{dx}\right)_{i,\text{pert.}}$$

- Scattering off gluons (t channel)

$$S_g = \frac{6}{\pi^2(N^2-1)} \sum_{l=1}^{\infty} \sum_{m=0}^{l-1} \frac{l-2m}{l^3} \left(\text{tr}\, L^{l-m} \cdot \text{tr}\, L^{l} \cdot \text{tr}\, L^{m} - \text{tr}\, L^{2l}\right)$$



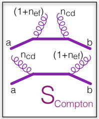
- Compton scattering off gluons (u channel), only Polyakov loop terms

$$S_{\text{Compton}} = \cdots (\text{tr}\, L^{l} \text{tr}\, L^{l-m} \text{tr}\, L^{m}$$

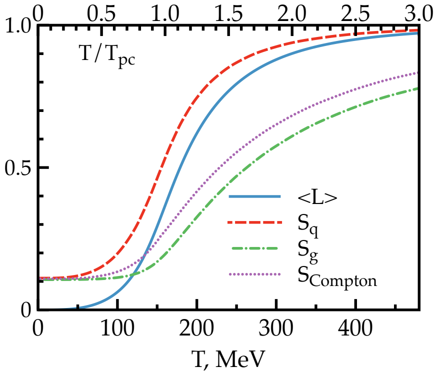
$$-\frac{2}{N}\text{tr}\, L^{m}\text{tr}\, L^{2l-m} - \frac{2}{N}\text{tr}\, L^{l-m}\text{tr}\, L^{l+m} + \frac{4}{N}\text{tr}\, L^{2l}$$

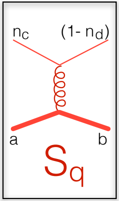
$$+\frac{1}{N^2}(\text{tr}\, L^{m})^2\, \text{tr}\, L^{2(l-m)} + \frac{1}{N^2}\left(\text{tr}\, L^{l-m}\right)^2 \text{tr}\, L^{2m} - \frac{4}{N^2}\text{tr}\, L^{2(l-m)}\text{tr}\, L^{2m}$$

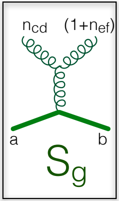
$$+\frac{1}{N^3}\left(\text{tr}\, L^{2m}\right)^2 \text{tr}\, L^{2(l-m)})$$

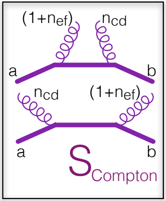


Numerical results



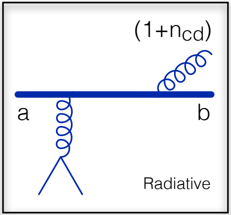


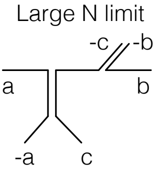




$$S_i = \left(\frac{dE}{dx}\right)_i \Big/ \left(\frac{dE}{dx}\right)_{i,\text{pert.}}$$

- Different processes are supressed dufferently
- Processes with gluons are supressed stronger then thouse with quarks
- $\forall i; S_i \to 1/N^2$ at low temperatures





Suppressed by

$$n_{-a}(1 - n_c)(1 + n_{-c,-b}) \sim \mathrm{tr}\, L$$

Conclusions

- LQCD: shallow dependence of $\langle L \rangle$ on T
- This suggest that **semi-QGP** region (region with partial ionization of color) is broad and has to be taken into account when computing energy loss viscosity and etc
- Collisional energy loss is supressed in semi-QGP either linearly (for scattering off light quarks) or quadratically (for scattering off gluons) by Polyakov loop
- Radiative energy loss is harder to cumpute, but, at least, in large N limit it also gets supressed at least quadratically by Polyakov loop

Thank you!