Strongly Coupled QGP from in-Medium T-matrix Approach?

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Outline

1) Background and Motivation

2) Define Heavy-Quark Potential Based on Lattice Data

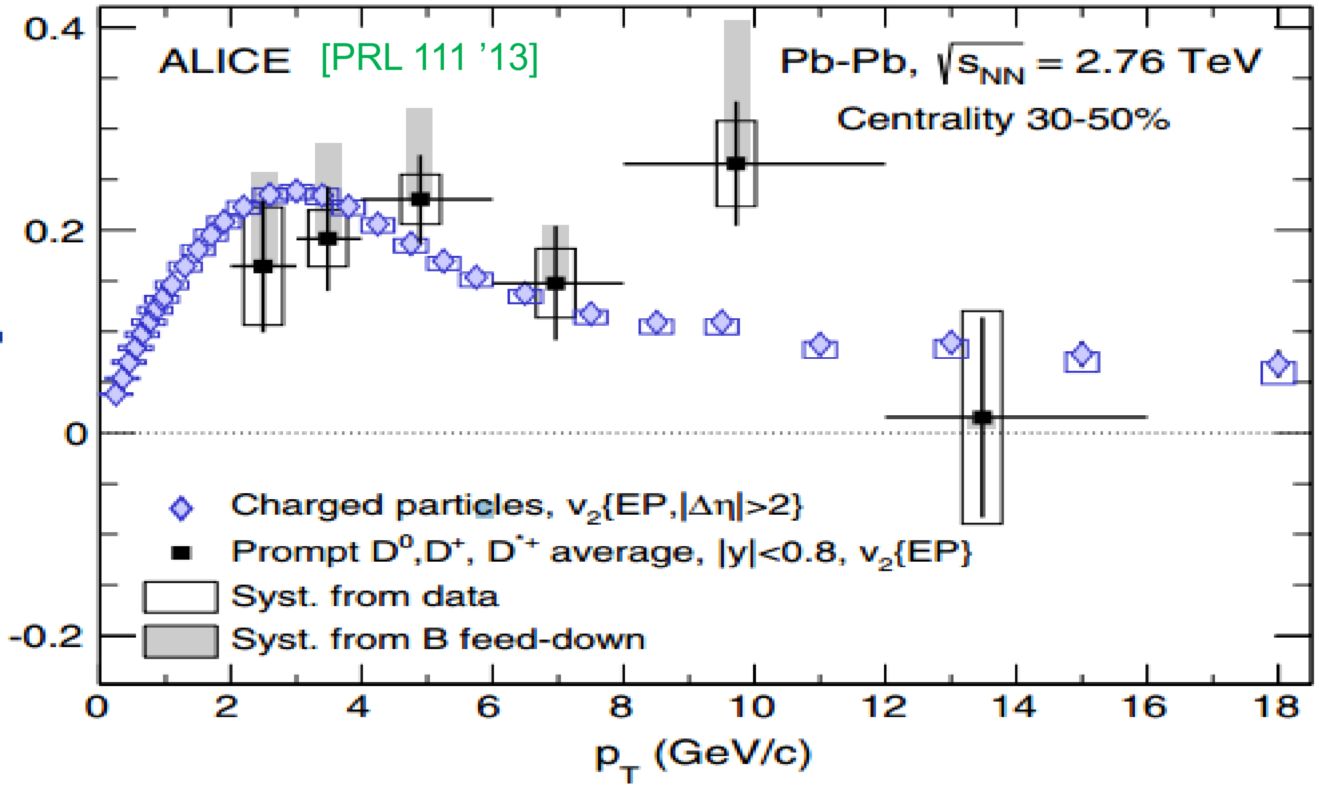
- Calculation of heavy-quark free energy from in-medium T-matrix
- Fit to lattice data and extract the potential

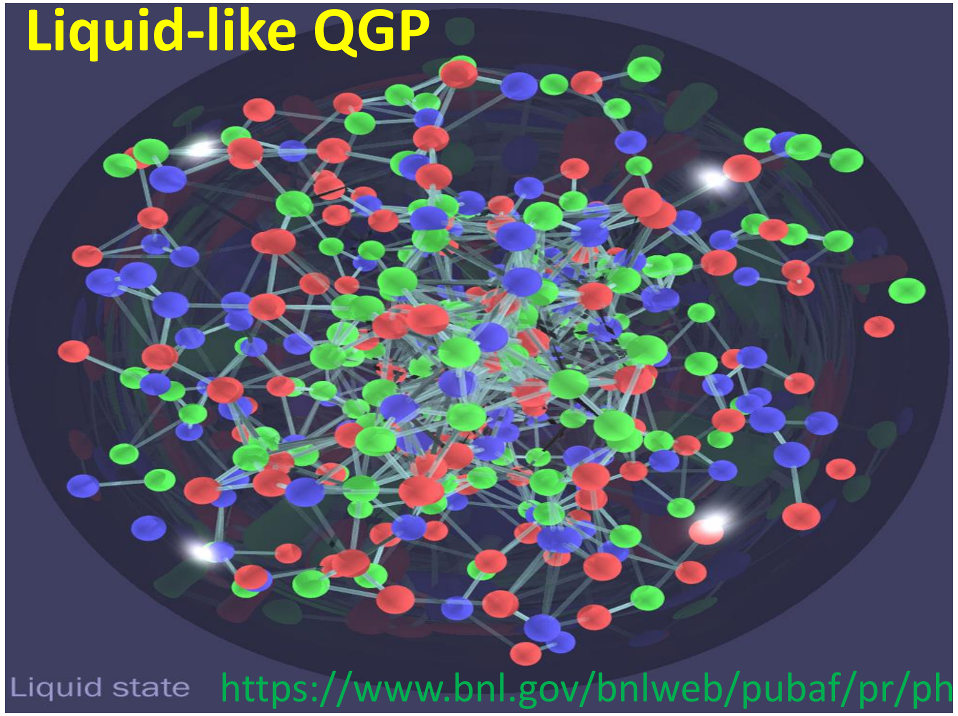
3) Insights for QGP from the New Potential

- Calculation of the heavy quark transport coefficients
- QGP equation of state and in-medium partons' spectral functions

4) Conclusions

Heavy-Quark Elliptic Flow and Strongly Coupled QGP





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Strongly Coupled System

Non-Perturbative →

In-Medium T-matrix with Lattice-based Potential

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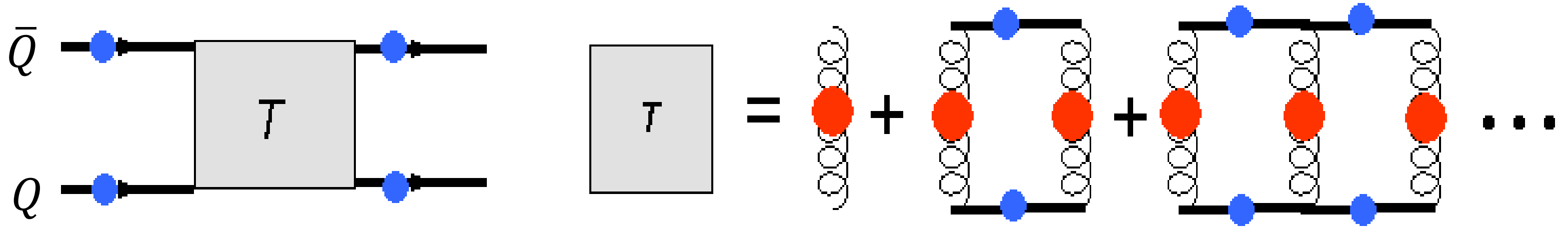
Heavy-Quark Free Energy from in-Medium T-matrix

- Lattice QCD can generate free energy data:

$$F_{Q\bar{Q}}(T,r) = -T\ln\left(\tilde{G}^{>}(-i\tau,r)\right)|_{\tau=\beta}$$

- Infinite-mass limit: T-matrix can calculate $\tilde{G}^{>}(-i\tau,r)$ as:



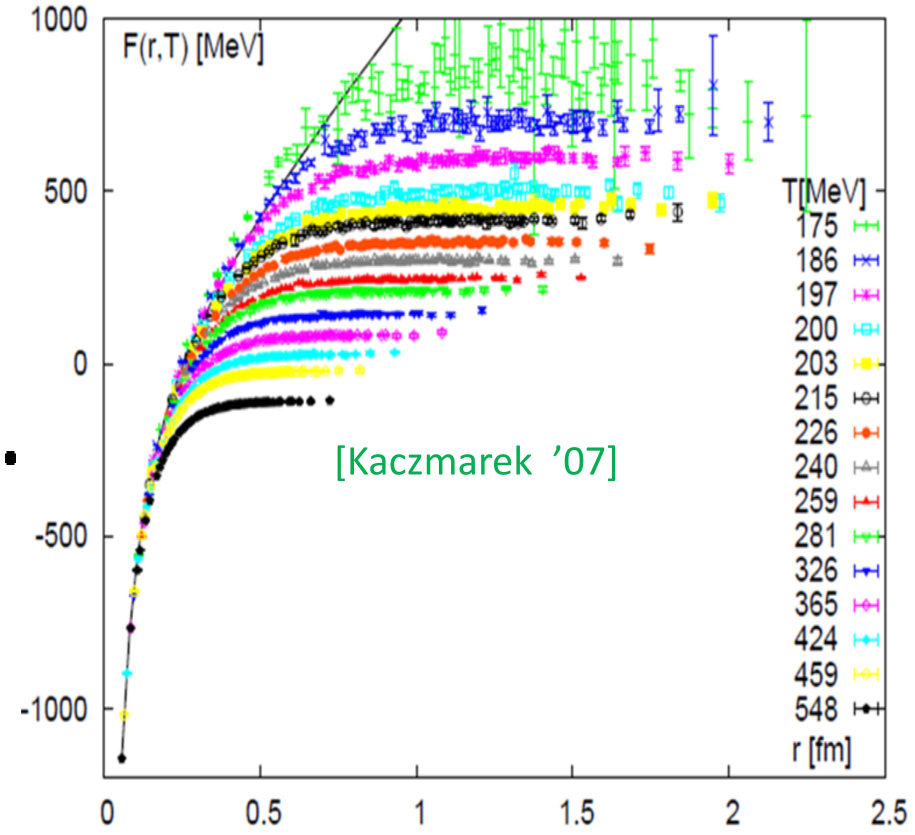
$$G(z,r) = \frac{1}{[\hat{G}(z)]^{-1} - V(z,r)}$$

$\hat{G}$: *two body propogator*

$$-\frac{1}{\pi}\mathrm{Im}\,[G(E+i\epsilon,r)]$$

$$F_{Q\bar{Q}}(T,r) = -T\ln\left(\int_{-\infty}^{\infty} dE\ \frac{-1}{\pi}\frac{(V+\hat{\Sigma})_I(E)}{\left(E-(V+\hat{\Sigma})_R\right)^2+(V+\hat{\Sigma})_I^2(E)}e^{-\beta E}\right)$$

[SYF Liu + Rapp, '15]



➢ Compare T-matrix $F_{Q\bar{Q}}(T,r)$ with lattice $F_{Q\bar{Q}}(T,r)$ to extract in-medium $V(r)$ and $\hat{\Sigma}$

Fit to Lattice Data:

❖Screened Cornell $V(r)$ with imaginary part

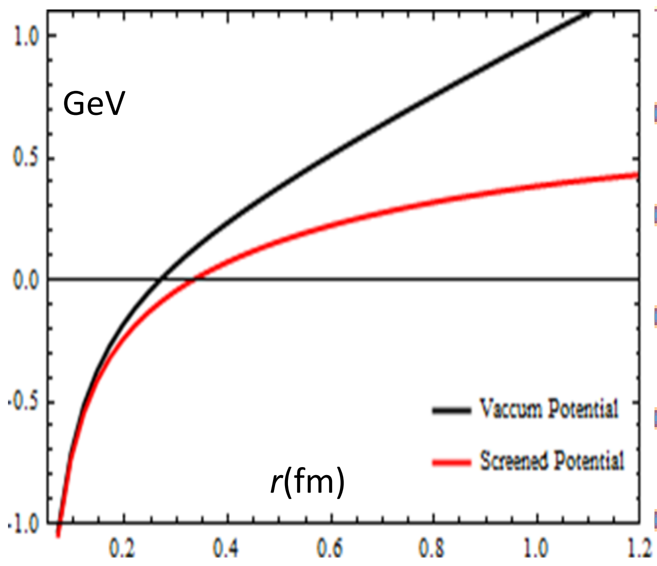
- Real part of the potential + self energy:

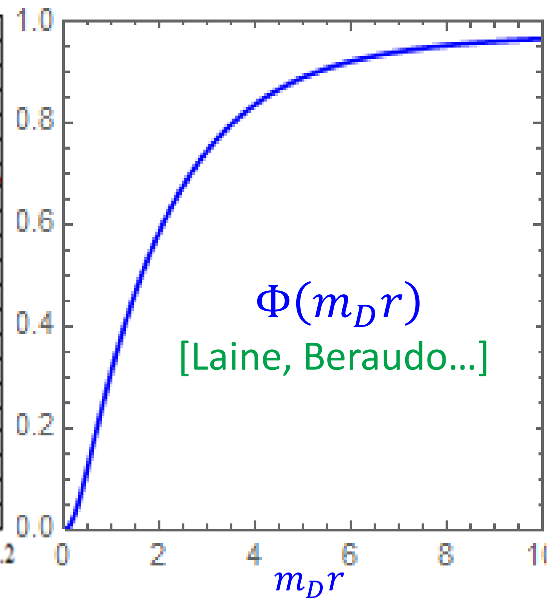
$$(V+\Sigma)_R = -\frac{4}{3}\alpha_s\frac{e^{-m_D r}}{r} - \frac{4}{3}\alpha_s m_D - \sigma\left(\frac{e^{-m_s r}}{m_s} - \frac{1}{m_s}\right)$$

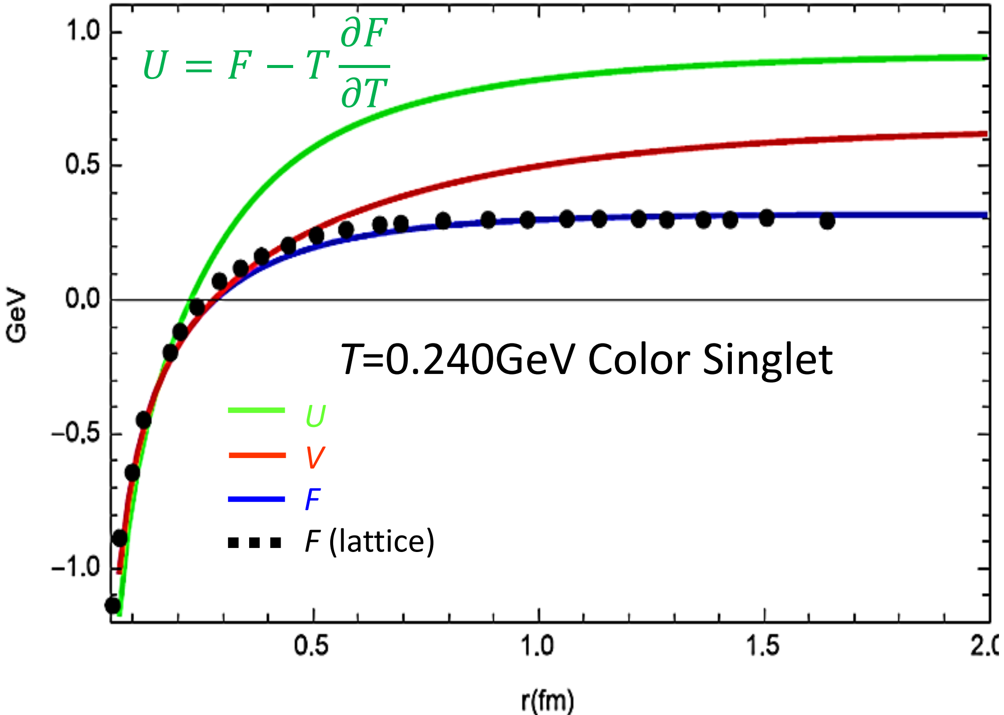
- Imaginary part of the potential + self energy:

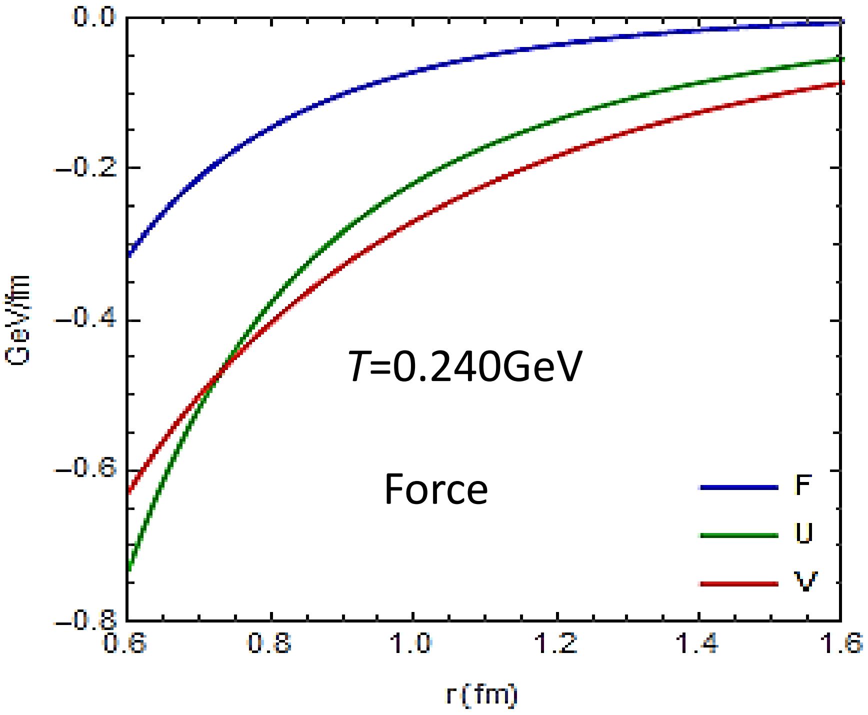
$$\left(V+\hat{\Sigma}\right)_I(E) = \hat{\Sigma}_I(E)\Phi(m_D r)$$

[Riek+Rapp '11]









➢ ***V* has the largest force at long range**

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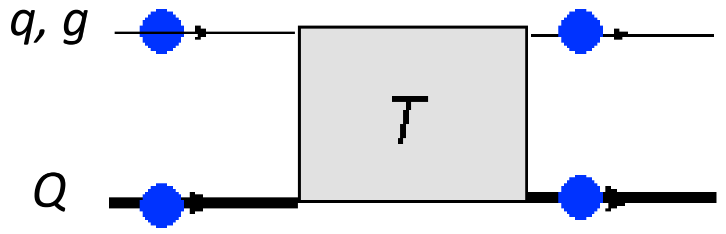
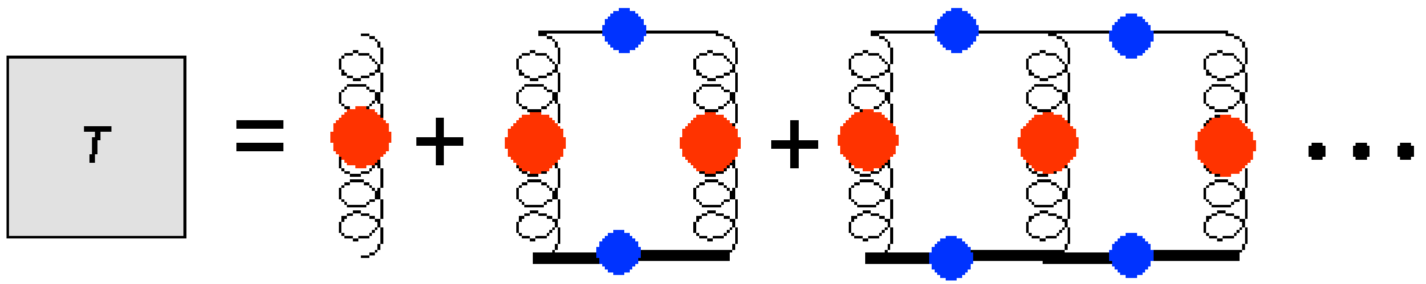
Heavy-Light T-matrix and Heavy-Quark Transport in QGP

- Heavy-light T-matrix





$$T(E|\mathbf{p},\mathbf{p}') = R(\mathbf{p},\mathbf{p}')K(\mathbf{p}-\mathbf{p}') + \int d^3\tilde{\boldsymbol{k}}\, R(\mathbf{p},\mathbf{k})K(\mathbf{p}-\mathbf{k})\hat{G}(E|\mathbf{k})T(E|\mathbf{k},\mathbf{p}')$$

$R(\mathbf{p},\mathbf{p}')$ ➢ Relativistic correction for heavy-heavy potential for heavy-light scattering

[Riek+ Rapp, ’10]

$K(\mathbf{p}-\mathbf{p}')$ ➢ Kernel includes Non-perturbative string interaction

- Relaxation rate (drag coefficient)

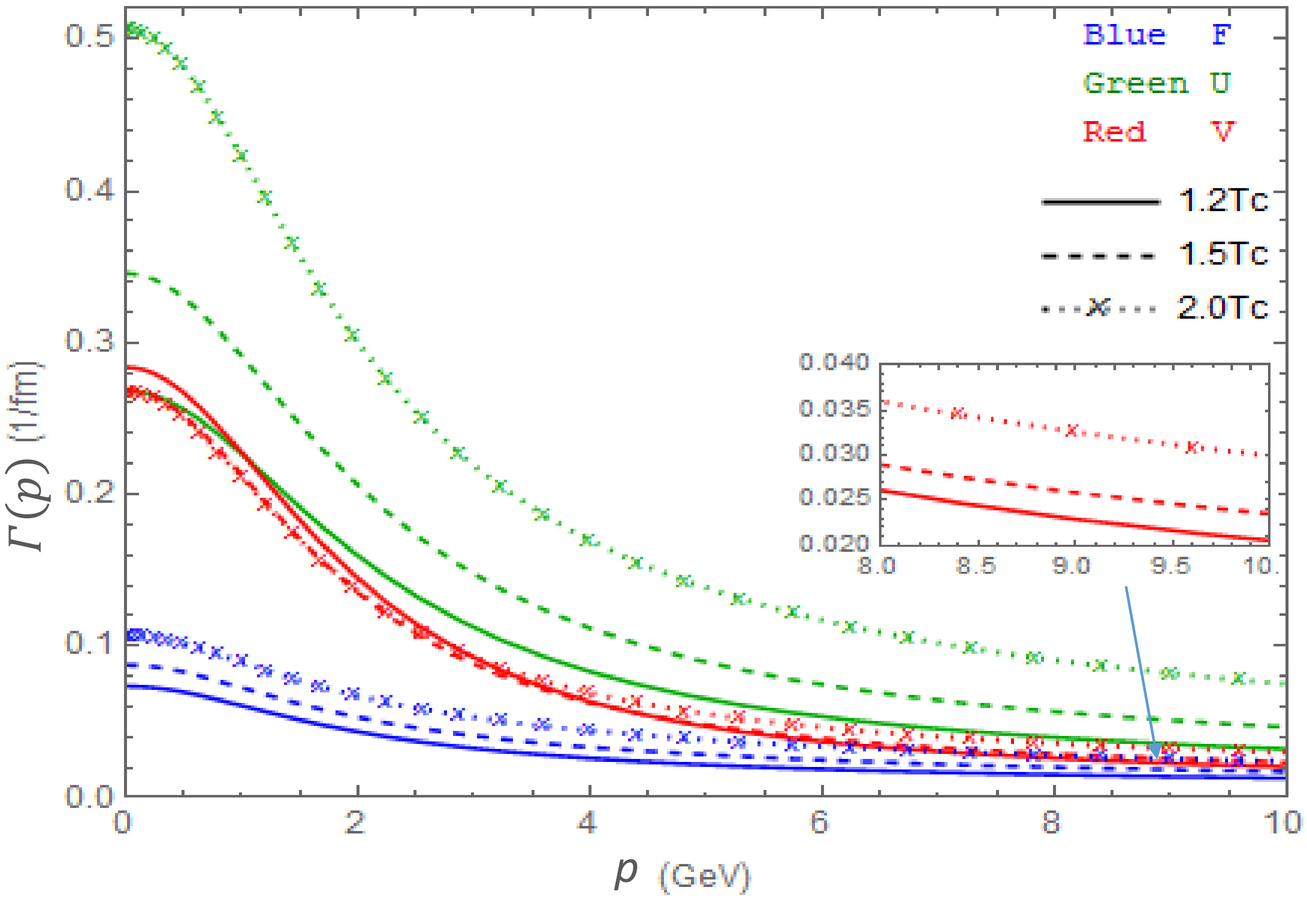
$$\Gamma(p) = \frac{1}{2\omega_Q(p)}\sum\int d^3\tilde{q}\, d^3\tilde{q}'\, d^3\tilde{p}'\, n_i(\omega_q)\cdot\frac{(2\pi)^4}{d_c}C_f|T(E_{cm}|\mathbf{p}_{cm},\mathbf{p}'_{cm})|^2\delta^4(p+q-p'-q')\left(1-\frac{p\,p'}{p^2}\right)$$

[Svetitsky, ‘88]

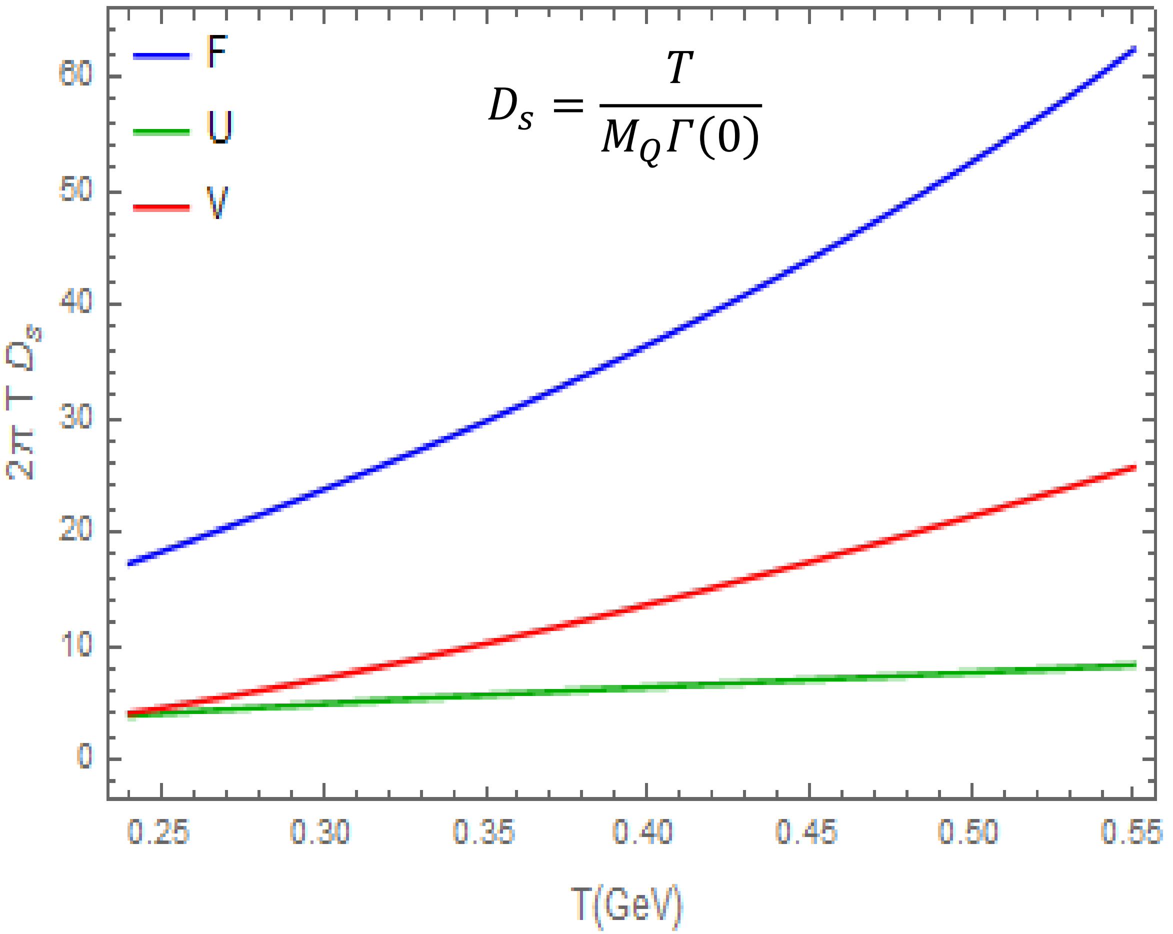
***F* (Free energy), *U* (Internal energy), or *V* (Potential extracted from *F*) ?**

Heavy-Quark Transport Coefficients

Relaxation rate for *F* *U* *V*



Spatial Diffusion Coefficient



- **For *V***
  - **Infrared enhancement due to long range force**
  - **Different (slightly reversed) *T* dependence at low *p***
  - **Recover usual *T* dependence at high *p***

T-matrix Approach to QGP Equation of State (EoS)

❖Luttinger-Ward-Baym formalism For many-body system:

$$\Omega(T) = \sum_{s,c,f} \int \widetilde{d^4p} \pm \left[[\ln(-G^{-1}) + \Sigma\, G] - \sum_{\nu} \frac{1}{2\nu} \Sigma_\nu\, G \right]$$

$\hat{G}$: two body propagator

❖Self-energy from T-matrix:

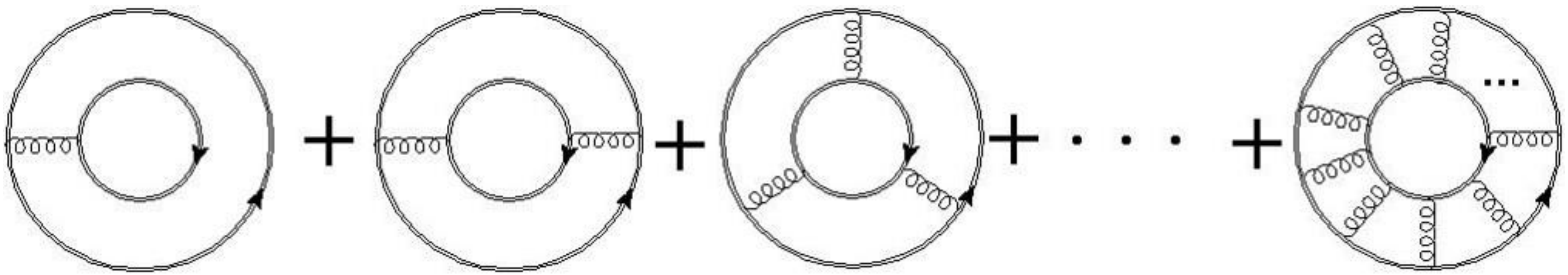
$$\Sigma(\omega_n, p) = \sum_{s,c,f} \int \widetilde{d^4p}\, T\, G = \sum_{s,c,f} \int \widetilde{d^4p} \{V + V\hat{G}V + \cdots + V\hat{G}V\hat{G} \ldots . V\}\, G \quad = \sum_{s,c,f,n} \int \widetilde{d^4p}\, V\left(1 - \hat{G}V\right)^{-1} G$$

Matrix Inverse

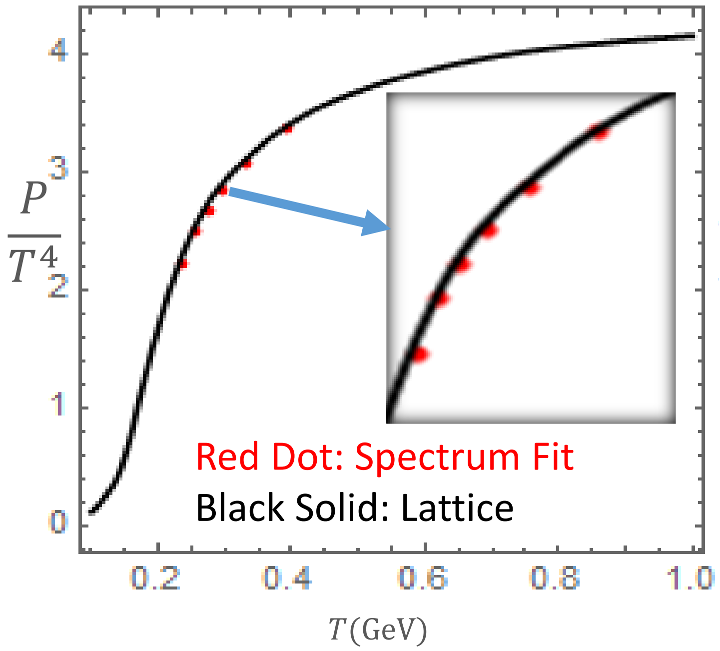
❖Matrix Log to sum up the skeleton expansion

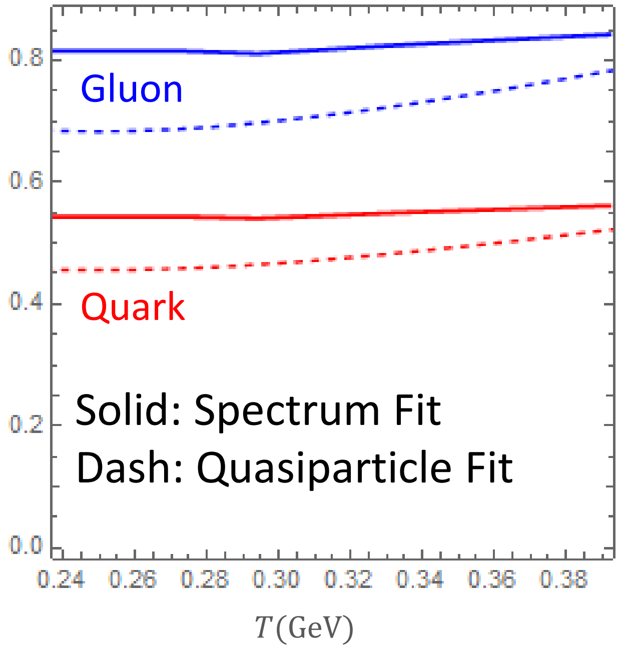
$$\sum_{\nu} \frac{1}{2\nu} \Sigma_\nu = \frac{1}{2} \sum_{s,c,f} \int \widetilde{d^4p} \left\{V + \frac{1}{2} V\hat{G}V + \cdots + \frac{1}{\nu} V\hat{G}V\hat{G} \ldots . V\right\} \mathrm{G} = \boxed{\frac{1}{2} \sum_{s,c,f} \int \widetilde{d^4p} \{-\hat{G}^{-1} \ln\left(1 - \hat{G}V\right)\} G}$$

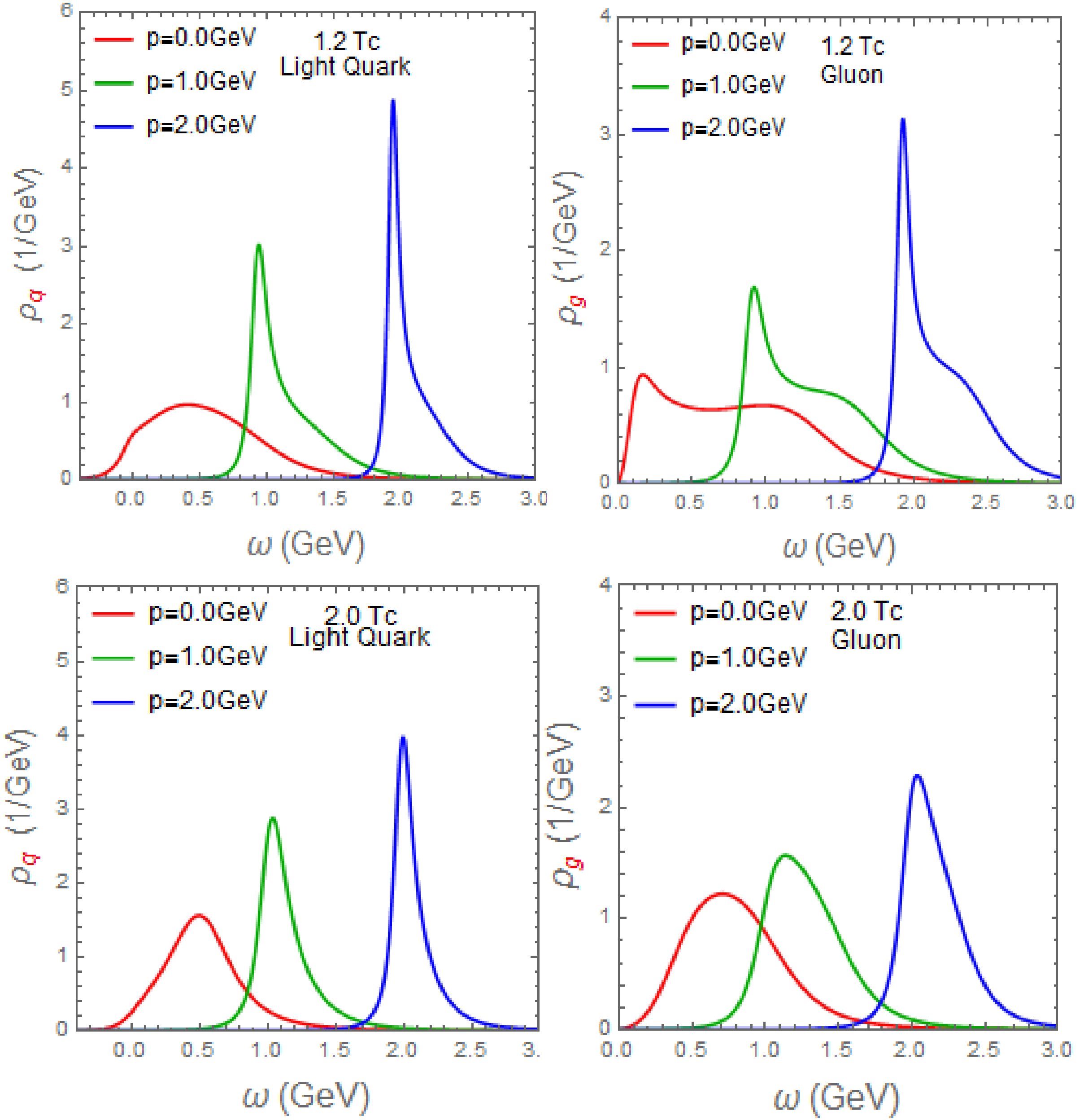
Matrix Log



Fits to Lattice EoS and Light Partons' Spectral Functions







- Based on same V as before
- Light parton mass as fit parameter
- No quasi-particles at low *p* and low *T*
- More quasi-particle like at high *p* or high *T*

Conclusions and Perspectives

- Present findings
  - Developed approach to define in-medium V
  - Extracted potential from lattice $F_{Q\bar{Q}}(T,r)$
  - V generates large relaxation rates for heavy quarks (strongly coupled)
  - V leads to broad light-parton spectral functions at soft momentum (liquid?)
- Future work
  - Apply self-consistent formalism to calculate $F_{Q\bar{Q}}$ and EoS simultaneously
  - Implement off-shell light parton spectra for heavy-quark transport coefficients

Thanks!