Complex potential at T>0 in 2+1 flavor QCD

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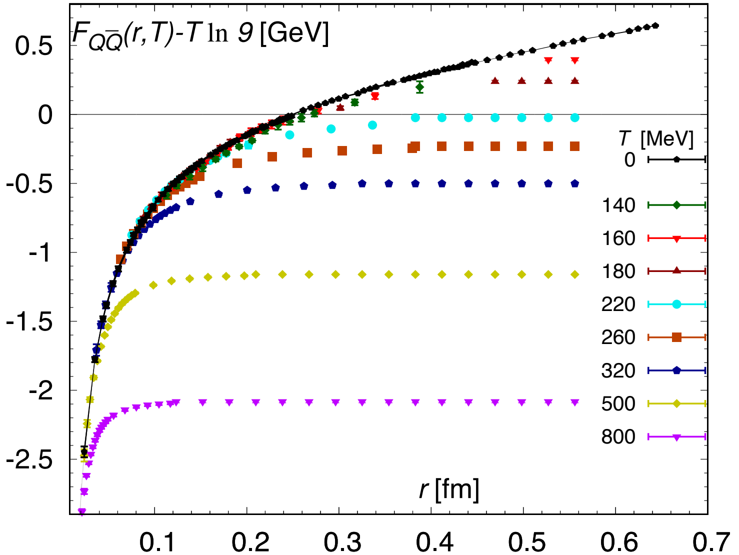
Work with A. Bazavov, O. Kaczmarek, R. Larsen, S. Mukherjee, A. Rothkopf, J. Weber (HotQCD Collaboration)

$Q\bar{Q}$ free energy shows screening

J. Weber et al (TUMQCD)

Does color screening in high temperature QCD leads to quarkonium melting ?



HEFTY COLLABORATION

Lattice 2023, FNAL, July 31-August 4, 2023

Quark anti-quark potential at *T>0*

Conjecture, Matsui and Satz, PLB 178 (86) 416 $-\frac{4}{3}\frac{\alpha_s}{r}+\sigma r \to -\frac{4}{3}\frac{\alpha_s}{r}e^{-m_D r}, T>T_c$

Extending pNRQCD to *T>0*: the potential is complex, the real part can have thermal correction but is not necessarily screened, except when $r \sim 1/m_D$

Based on weak coupling

Laine, Philipsen, Romatschke, Tassler, JHEP 03 (06) 054
Brambilla, Ghiglieri, PP, Vairo, PRD 78 (08) 014017

Calculate the potential non-perturbatively on the lattice by considering Wislon loops of size r x τ at *T>0*

$$W(r,\tau,T)=\int_{-\infty}^{\infty}\rho_r(\omega,T)e^{-\omega\tau}$$

If potential at $T>0$ exists the $\rho_r(\omega,T)$ should have a well defined peak at $\omega \simeq \mathrm{Re}V(r,T)$, and the width of the peak is $\mathrm{Im}V(r,T)$

Rothkopf, Hatsuda, Sasaki, PRL 108 (2012) 162001

Challenge: reconstruct $\rho_r(\omega,T)$

$$\rho_r(\omega,T=0)=\delta(\omega-V(r))+\sum_n \delta(\omega-E_n(r))$$

Hybrid potentials, pairs of static-light mesons ...

Details of the lattice calculations

HISQ action, $T = 153 - 352$ MeV

$a = 0.028$ fm, $m_l = m_s/5$, ($m_\pi = 320$ MeV), $96^3 \times N_\tau$, $N_\tau = 56,\ 36,\ 32,\ 28,\ 24,\ 20$

$a = 0.040$ fm, $m_l = m_s/20$, ($m_\pi = 160$ MeV), $64^3 \times N_\tau$, $N_\tau = 64,\ 32,\ 30,\ 28,\ 26,\ 24,\ 22,\ 20,\ 18,\ 16$

$a = 0.049$ fm, $m_l = m_s/20$, ($m_\pi = 160$ MeV), $64^3 \times N_\tau$, $N_\tau = 64,\ 26,\ 24,\ 22,\ 20,\ 18,\ 16$

Calculate correlation functions of temporal Wilson line instead of Wilson loops (better signal)

Gradient (Zeuthen) flow for noise reduction:

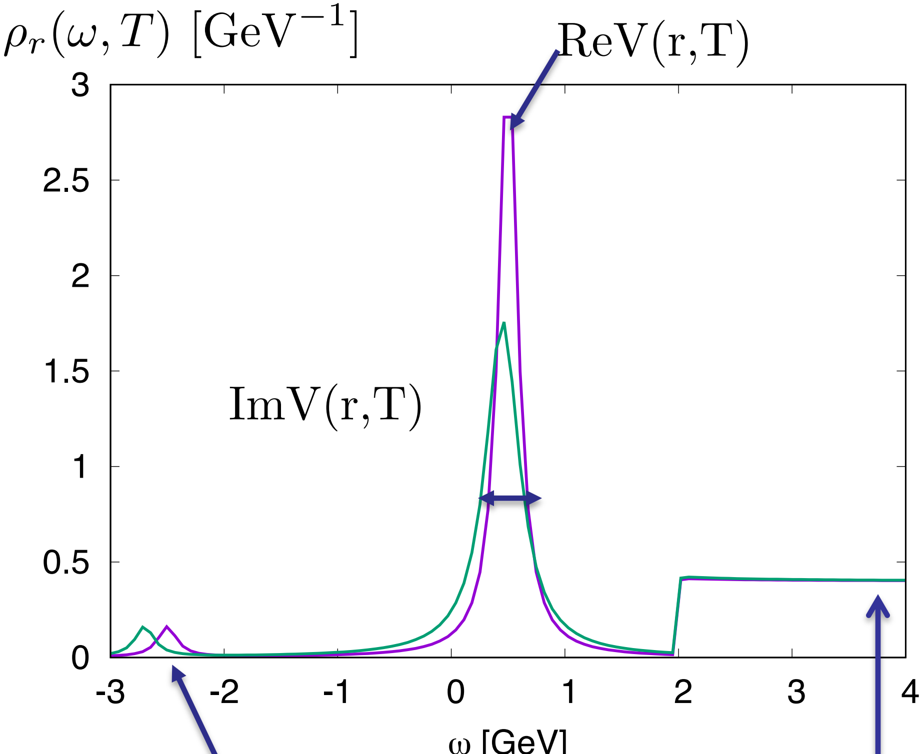
$$A_\mu(x) \to B_\mu(\tau_F, x) \qquad B_\mu(0, x) = A_\mu(x) \qquad \partial_{\tau_F} B_\mu(\tau_F, x) = -g_0^2 \frac{\delta S_{\rm YM}[B]}{\delta B_\mu(\tau_F, x)}$$

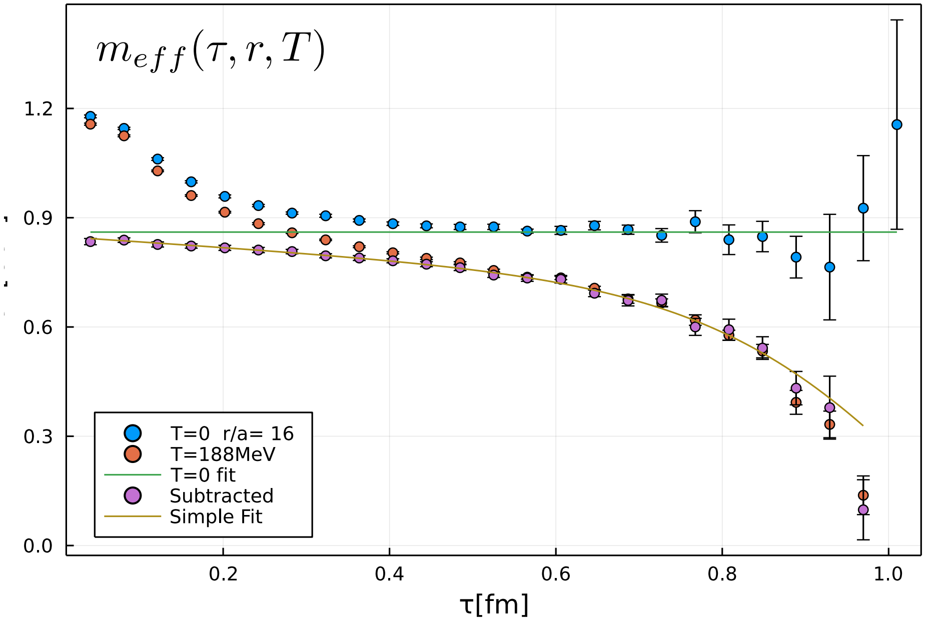
Gauge fields are smeared in the radius $\sqrt{8\tau_F}$

$$\sqrt{8\tau_F}\,T = 0.04 - 0.05$$

$$m_{eff}(r, \tau, T) = -\partial_\tau \log(W(\tau, r, T)) \simeq \frac{1}{a} \ln \frac{W(r, \tau, T)}{W(r, \tau + a, T)}$$

Spectral function and effective masses





$$\rho_r(\omega,T) = \rho_r^{tail}(\omega,T) + \rho_r^{peak}(\omega,T) + \rho_r^{high}(\omega)$$

See, Bala et al (HotQCD), PRD 105 (2022) 054513

$$W^{high}(r,\tau) = \int_{-\infty}^{\infty} d\omega \rho_r^{high}(\omega) e^{-\omega\tau}$$

On the lattice: $W^{high}(r,\tau) =$
$W(r,\tau,T=0) - A_0 \exp(-V(r)\tau)$

No plateau at $T > 0$ in m_{eff} at $T > 0$

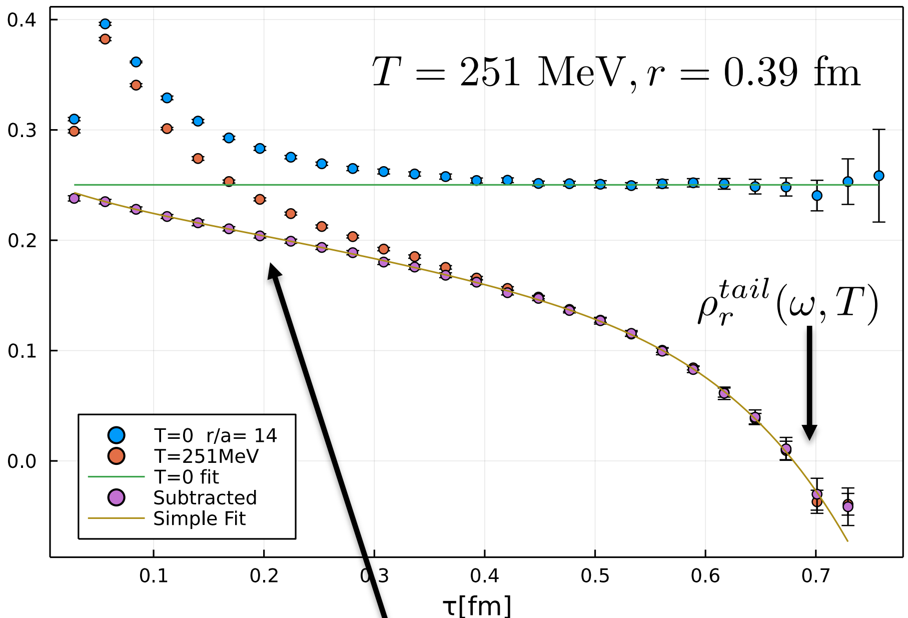
Only tiny T-dependence for small τ

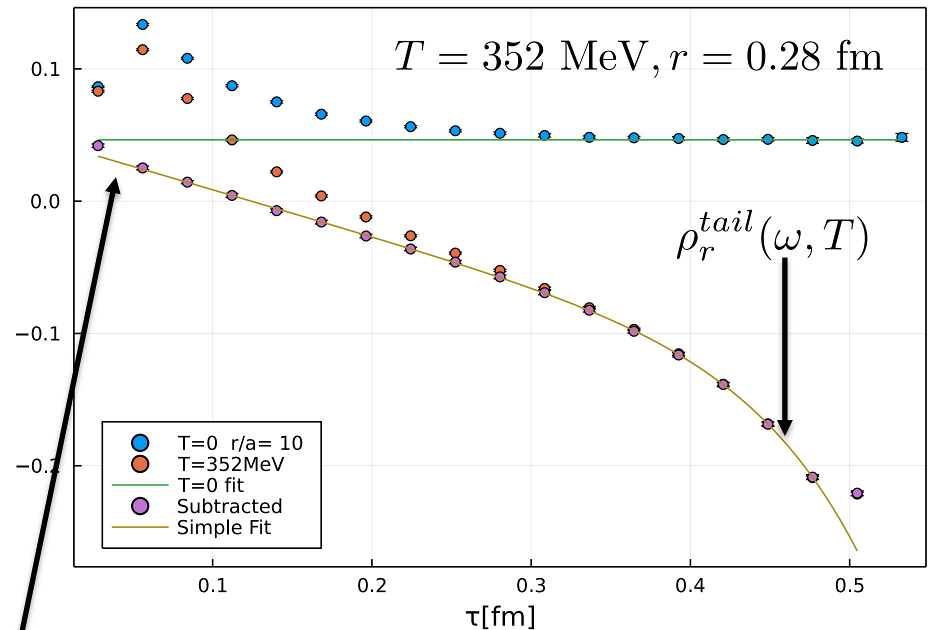
Distortions at small τ due to flow

$$W^{sub}(r,\tau,T) = W(r,\tau,T) - W^{high}(r,\tau)$$

Spectral function and effective masses

- No plateau in m_{eff} at $T > 0$ and only small T-dependence for small τ
- Distortions for small τ are largely removed by subtraction





m_{eff} for the subtracted correlator has milder τ-dependence, which is approximately linear

Thermal width

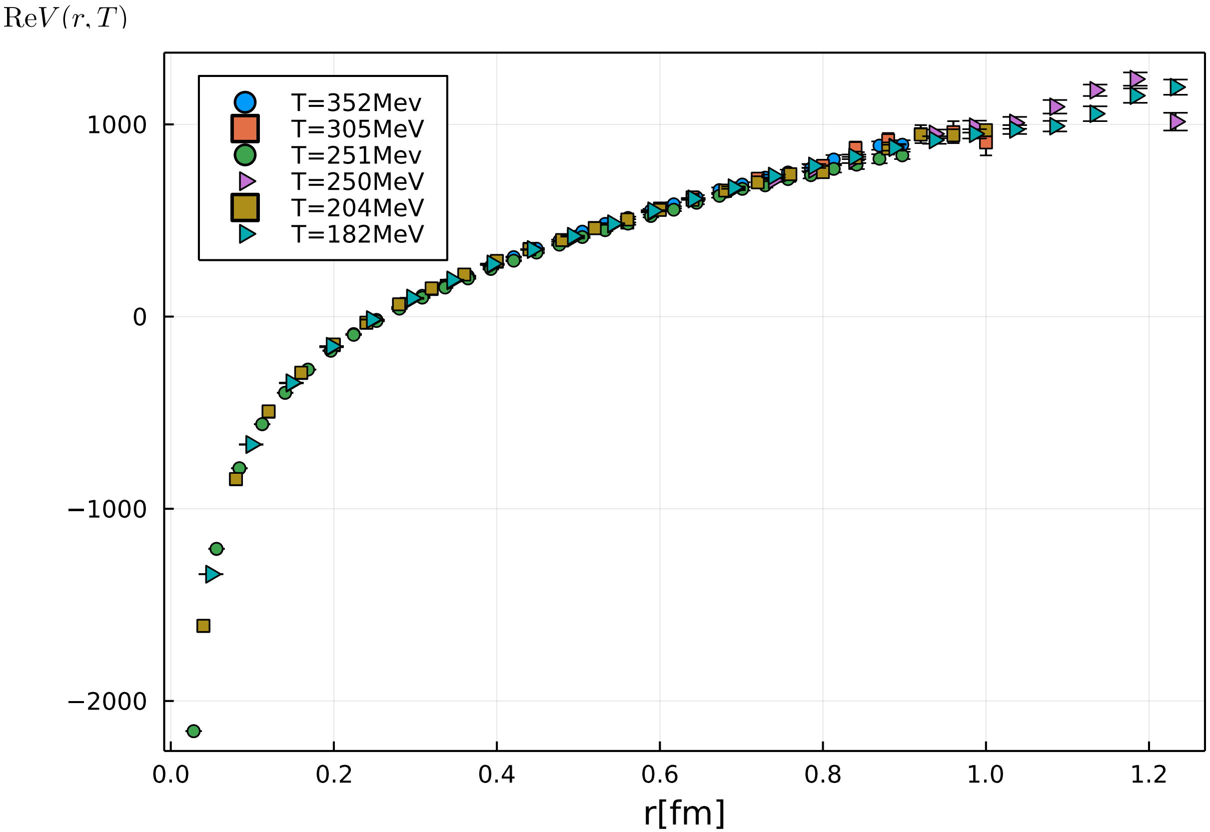
If $\rho_r(\omega, T)$ is Gaussian m_{eff} is linear in τ

$$m_{eff}(\tau \simeq 0, r, T) \simeq V(r, T = 0)$$

Model spectral function and the complex potential

$$\rho_r^{peak}(\omega,T)=\frac{A}{\pi}\frac{\Gamma(\omega,r,T)}{(\omega-\mathrm{Re}V(r,T))^2+\Gamma^2(\omega,r,T)}.\qquad \rho_r^{tail}(\omega,T)=A^{tail}\delta(\omega-E^{tail})$$

$$\Gamma(\omega,r,T)=\begin{cases}\Gamma_0(r,T) & -2\Gamma_0<\omega<2\Gamma_0\\ 0 & n \text{ otherwise}\end{cases}$$

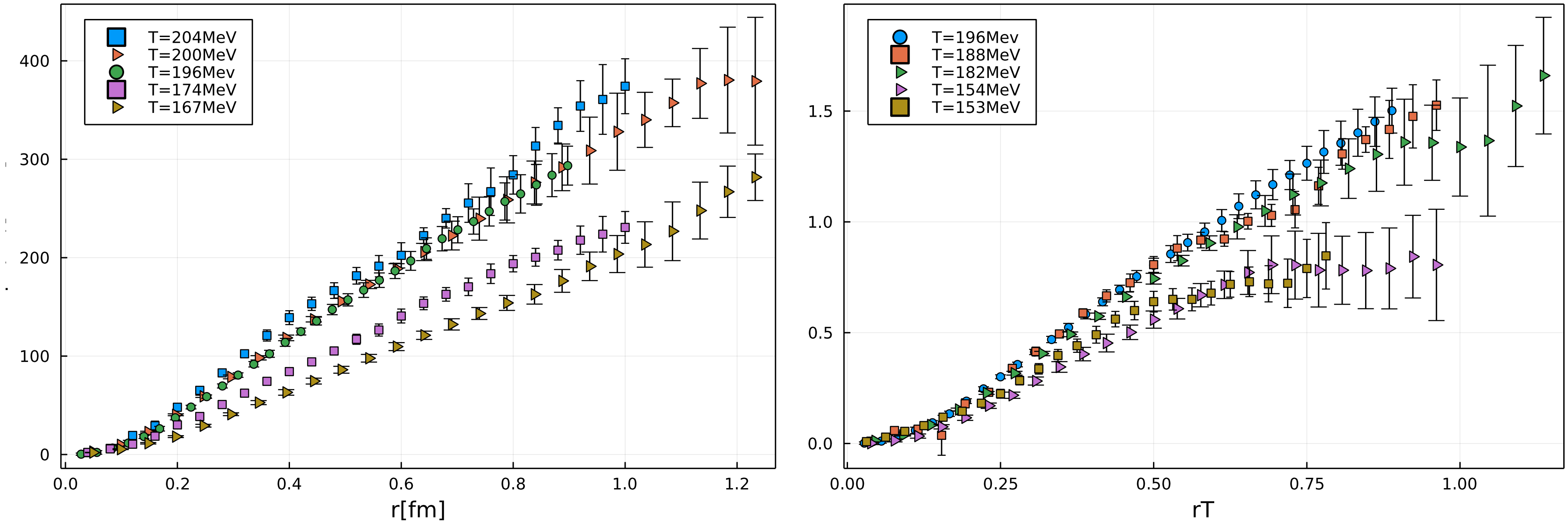


$\mathrm{Re}V(r,T)$ shows only tiny temperature dependence and no hint of screening !

The same result if $\rho_r^{peak}(\omega,T)\sim\exp(-(\omega-\mathrm{Re}V(r,T))^2/(\mathrm{Im}V(r,T))^2)$

Imaginary part of the potential

$\mathrm{Im}V(r,T)$ [GeV] $\qquad$ $\mathrm{Im}V(r,T)/T$



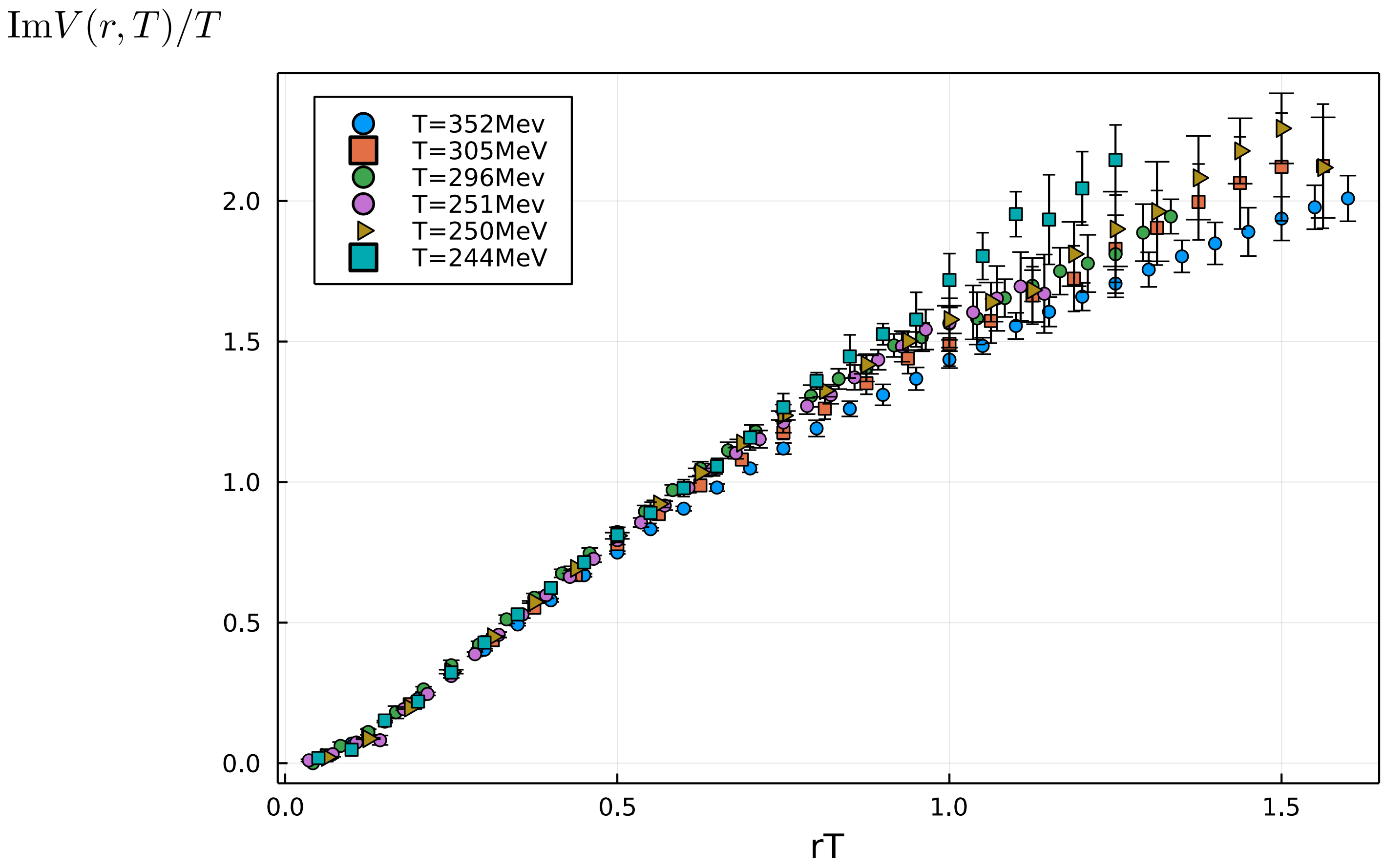
circles: $a = 0.028$ fm, squares: $a = 0.040$ fm, triangles: $a = 0.049$ fm

$\mathrm{Im}V(r,T)$ increases with increasing temperature and distance

No apparent quark mass effects for $T > 196$ MeV

No apparent cutoff effects

Imaginary part of the potential (cont'd)



For 244 MeV $< T <$ 352 MeV $\mathrm{Im}V(r,T)/T$ approximately scales with rT as one would expect based on weak coupling calculations

Summary

- The complex $Q\bar{Q}$ potential has been estimated in 2+1 flavor QCD using HISQ action with $a = 0.028$ fm, $a = 0.040$ fm and $a = 0.049$ fm
- The real part of the potential is not screened contrary to common expectations
- The imaginary part of the potential increases with the temperature and distance for 244 MeV $< T < 352$ MeV scales with the temperature