格子QCDシミュレーションによる QGP媒質中の重いクォーク間ポテンシャルの研究

WHOT-QCD Collaboration

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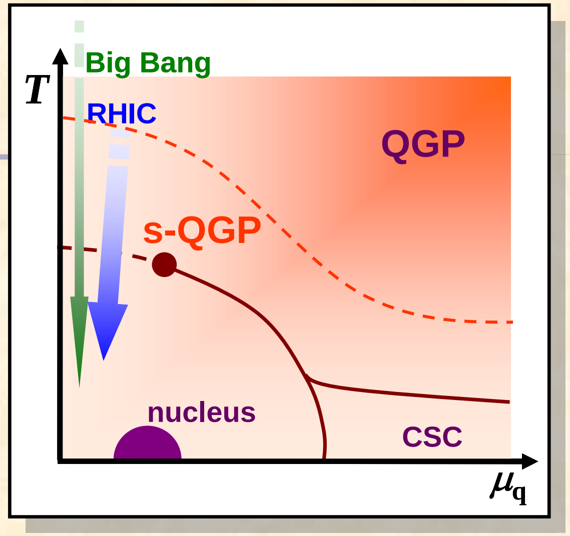
Introduction



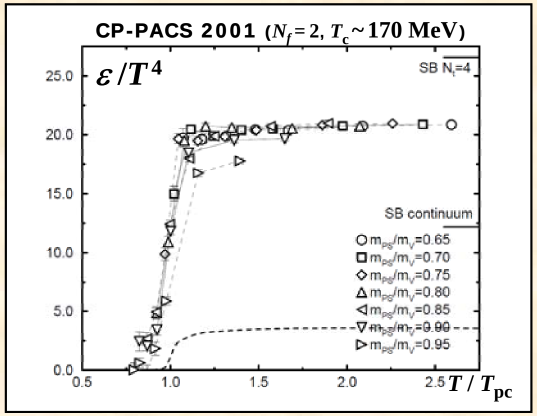
Study of Quark-Gluon Plasma (QGP)

- Early universe after Big Bang
- Relativistic heavy-ion collision

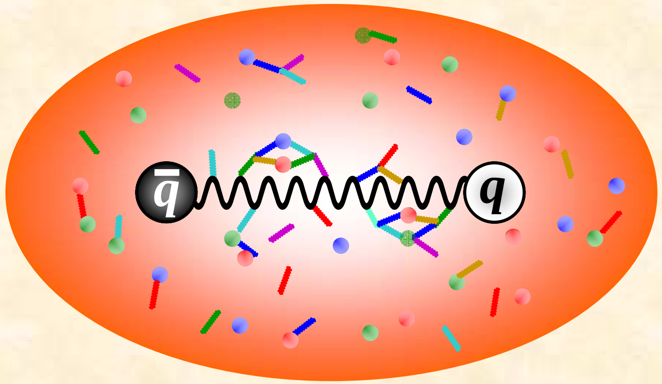
Theoretical study based on first principle (QCD)

⇒ Lattice QCD simulation at finite (T, μ_q)

Bulk properties of QGP (p, ε, T_c,…) are well investigated.



Internal properties of QGP are still uncertain.



Properties of quarks and gluons in QGP

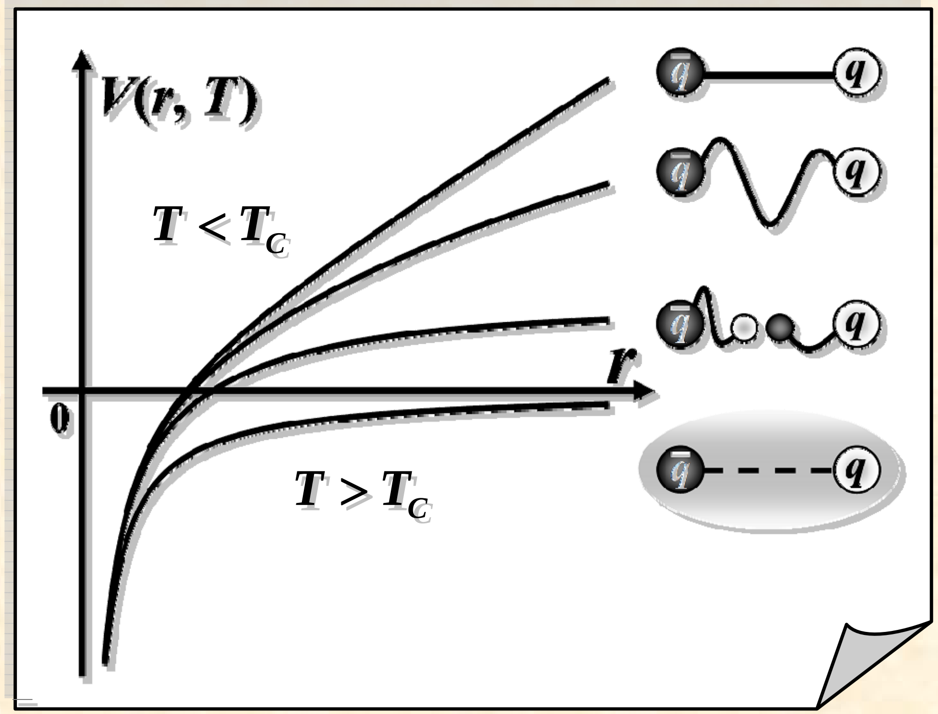
- **Heavy-quark potential:** free energy btw. static charged quarks in QGP

1. Relation of inter-quark interaction between zero and finite T
2. Temperature dependence of Debye screening length

Heavy-quark potential at finite *T*

Heavy-quark potential

⟹ **interaction btw. static quark (Q) and antiquark ($\bar{Q}$) in QCD matter**



- $T = 0,\ V(r) = -\frac{\alpha}{r} + \sigma r$
- $T > 0$, **string tension (σ) decreases, string breaking at r_c**
- **At $T > T_c$, screening effect in QGP**

$$V(r,T) = -\frac{\alpha_{\text{eff}}(T)}{r} e^{-m_D(T) r}$$

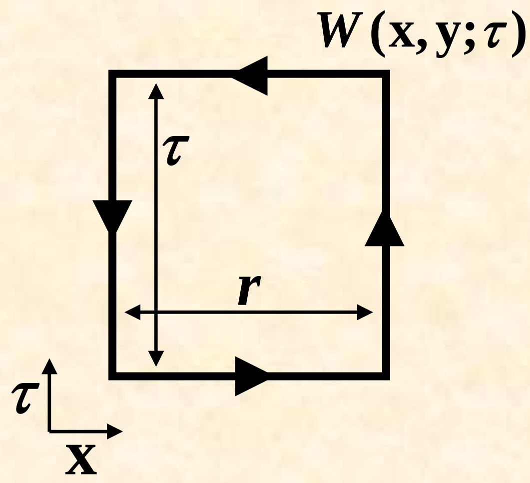
<u>Properties of heavy-quark potential in quark-gluon plasma</u>

- **Heavy-quark bound state (J/ψ, ϒ) in QGP**
- **Screening effect in QGP**
- **Inter-quark interaction btw. $\bar{Q}$Q and QQ**

⟹ **Lattice QCD simulations**

Heavy-quark free energy

<u>To characterize an interaction b/w static quarks,</u>



$T = 0$

<u>Heavy-quark potential</u>   Brown and Weisberger (1979)

⇐ Wilson-loop operator

$$V(r) = -\lim_{\tau\to\infty}\left[\tau^{-1}\ln\langle W(\mathrm{x},\mathrm{y};\tau)\rangle\right]$$

$$= -\frac{\alpha}{r} + \sigma r$$

$T > 0$

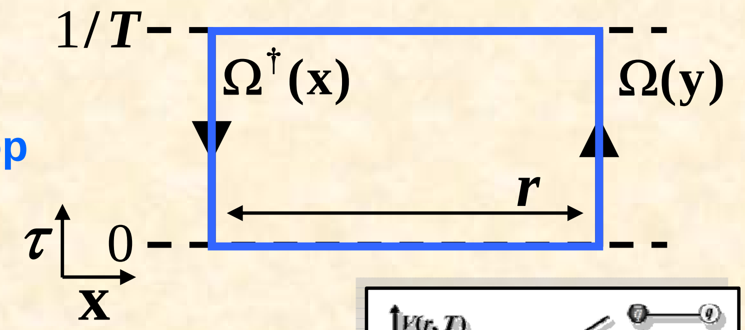
<u>Heavy-quark free energy</u>   Nadkarni (1986)

Polyakov-line $\Omega(\mathrm{x}) = \prod_{\tau=1}^{N_t} U_4(\mathrm{x},\tau)$:   static quark at x

Correlation b/w Polyakov-lines projected to a color singlet channel in the Coulomb gauge

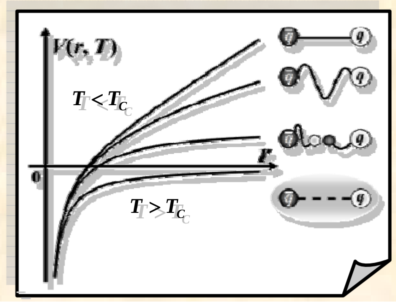
$$\Rightarrow \quad F^1(r,T) = -T\ln\langle \mathrm{Tr}\Omega^\dagger(\mathrm{x})\Omega(\mathrm{y})\rangle$$

Operator similar to the Wilson-loop
at finite T



Heavy-quark free energy may behave in QGP as:

- short r: $F^1(r,T) \sim V(r)$ (no effect from thermal medium)
- mid r : screened by plasma
- long r : two single-quark free energies w/o interactions

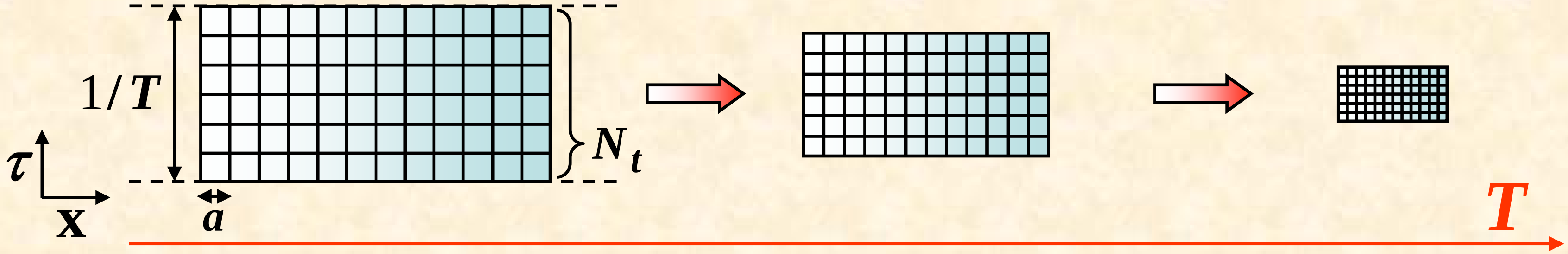


Approaches of lattice simulations at finite T

To vary temperature on the lattice,

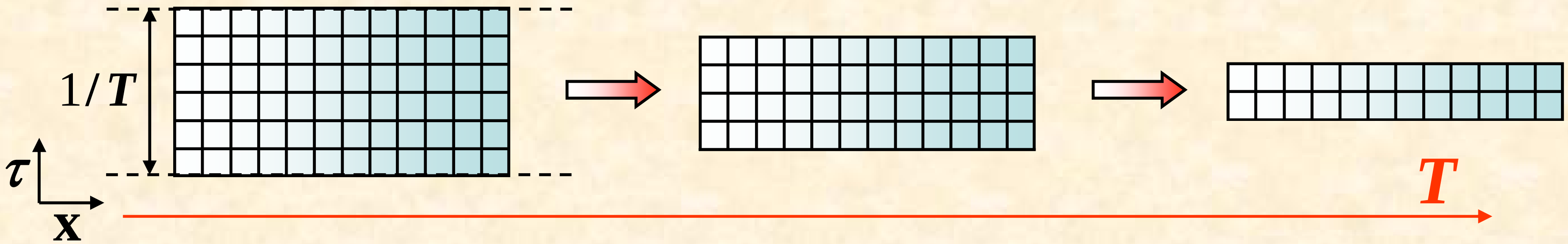
$T = 1/(aN_t)$ — a: lattice spacing; N_t: lattice size in E-time direction

- **Fixed N_t approach**
  - Changing a (controlled by the gauge coupling ($\beta = 6/g^2$)), fixing N_t



Advantages: T can be varied arbitrarily, because β is an input parameter.

- **Fixed scale approach** WHOT-QCD, PRD 79 (2009) 051501.
  - Changing N_t , fixing a



Advantages: investigation of T dependence w/o changing spatial volume possible.

renormalization factor dose not change when T changes.

Results of numerical simulations

1. **Heavy-quark potential at $T = 0$ and $T > 0$**
2. **Heavy-quark potential for various color-channels**
3. **Heavy-quark potential at finite density (μ_q)**

Simulation details

N_f = 2+1 full QCD simulations

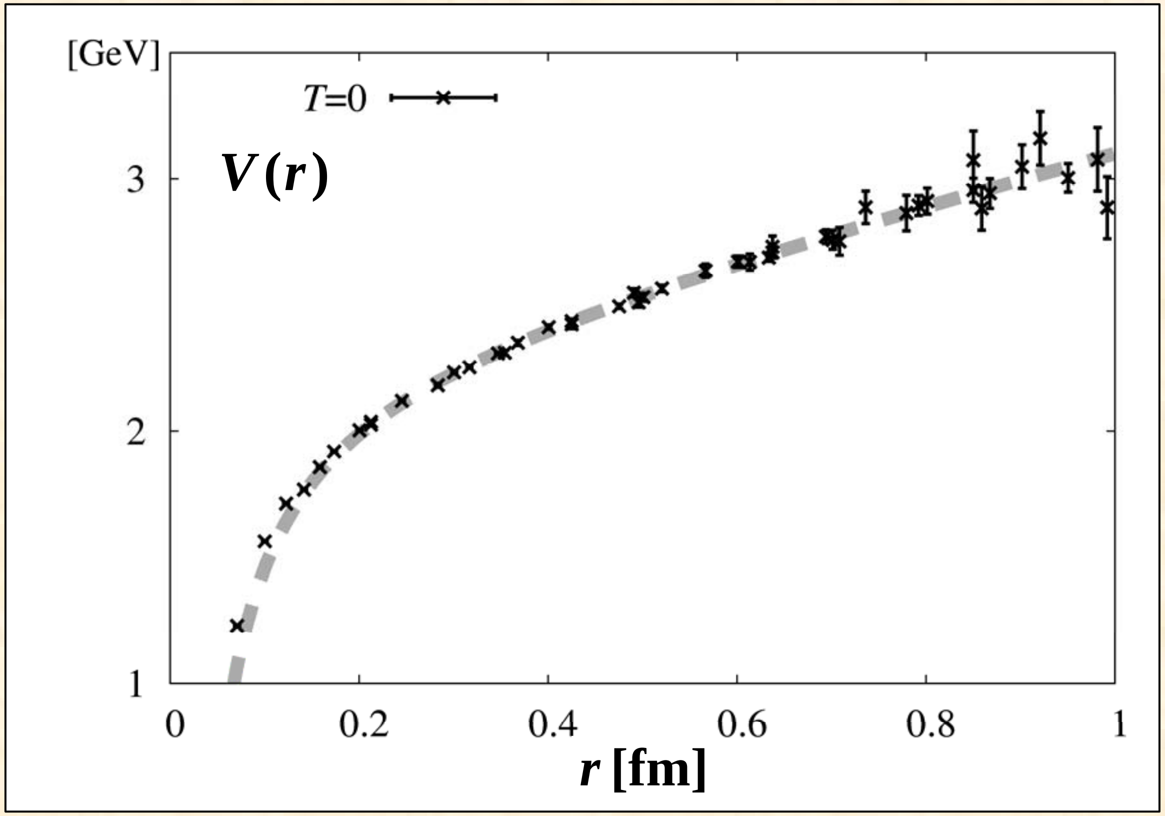
- Lattice size: N_s^3 x N_t = 32^3 x 12, 10, 8, 6, 4

  ⟹ Temperature: T ~ 200-700 MeV (5 points)

- Lattice spacing: a = 0.07 fm
- Light quark mass*: m_{s}/m_{ρ} = 0.6337(38)
- Strange quark mass*: $m_{\mathrm{N}}/m_{\mathrm{K}^*}$ = 0.7377(28)
- Scale setting: Sommer scale, r_0 = 0.5 fm

*CP-PACS & JLQCD Coll., PRD78 (2008) 011502.

Heavy-quark potential at $T = 0$



Data calculated by CP-PACS & JLQCD Coll. on a $28^3 \times 58$ lattice

Phenomenological potential

$$V(r) = -\frac{\alpha_0}{r} + \sigma r + V_0$$

= Coulomb term at short *r*

+ Linear term at long *r*

+ const. term

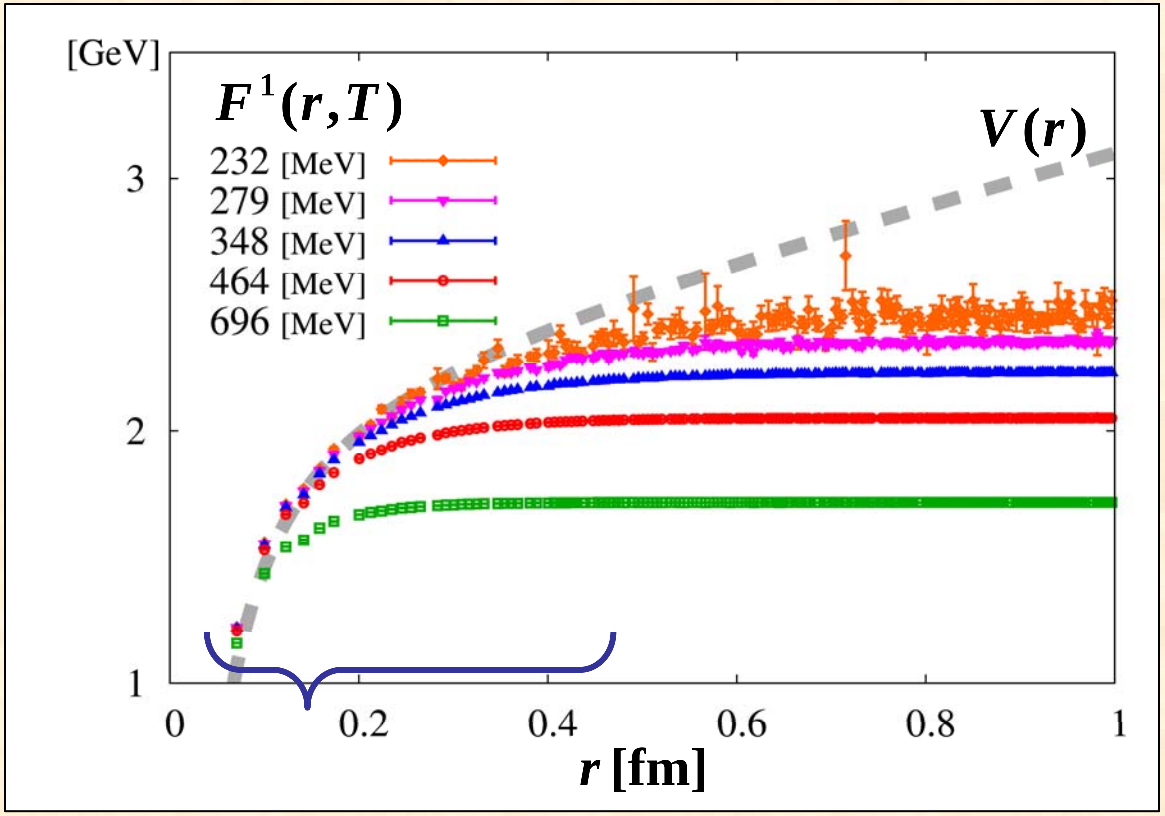
Our fit results

$$\alpha_0 = 0.441$$

$$\sqrt{\sigma} = 0.434\,\mathbf{GeV}$$

$$V_0 = 2.23\,\mathbf{GeV}$$

Heavy-quark free energy at $T > 0$



At short distance

$F^1(r,T)$ at any T

converges to

$V(r) = F^1(r,T=0)$.

⇕

Short distance physics is insensitive to T.

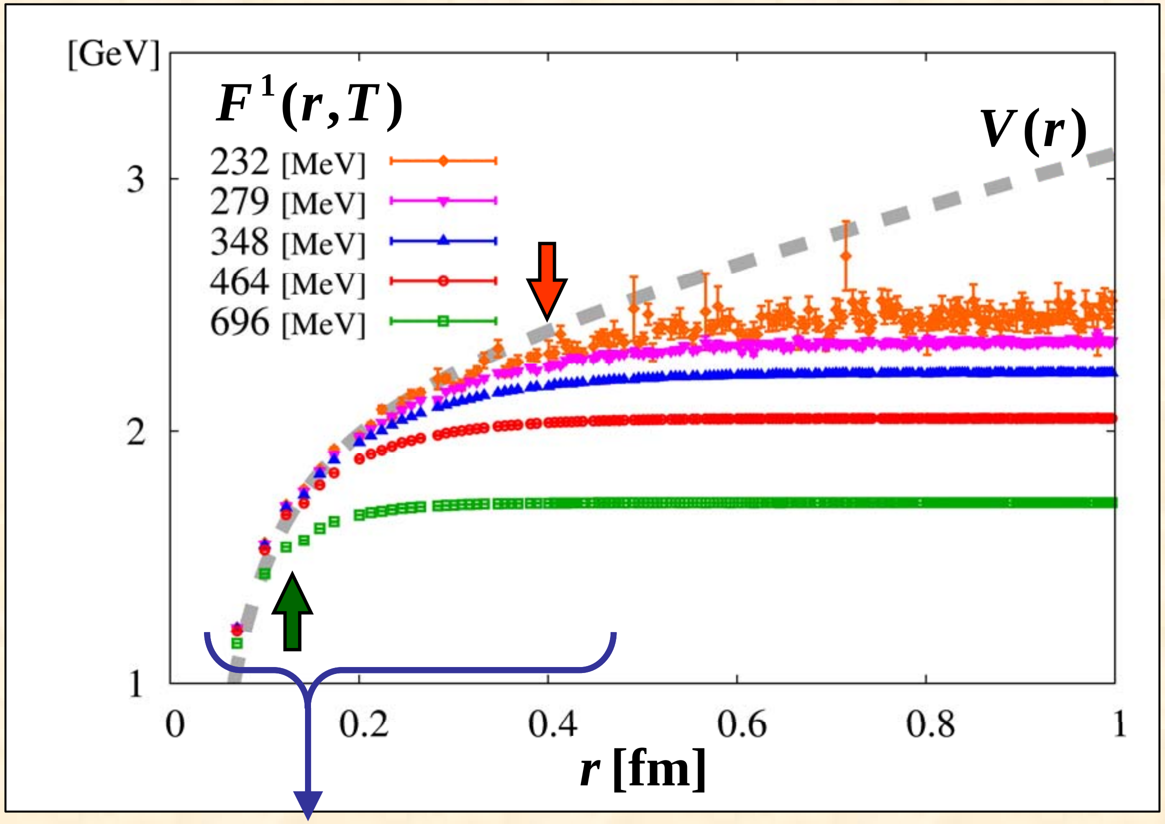
Note:

In the fixed N_t approach, this property is used to adjust the constant term of $F^1(r,T)$.

In our fixed scale approach, because the renormalization is common to all T.
no further adjustment of the constant term is necessary.

⇨ **We can confirm the expected insensitivity!**

Heavy-quark free energy at $T > 0$



At short distance

$F^1(r,T)$ at any T converges to $V(r) = F^1(r,T=0)$.

⇕

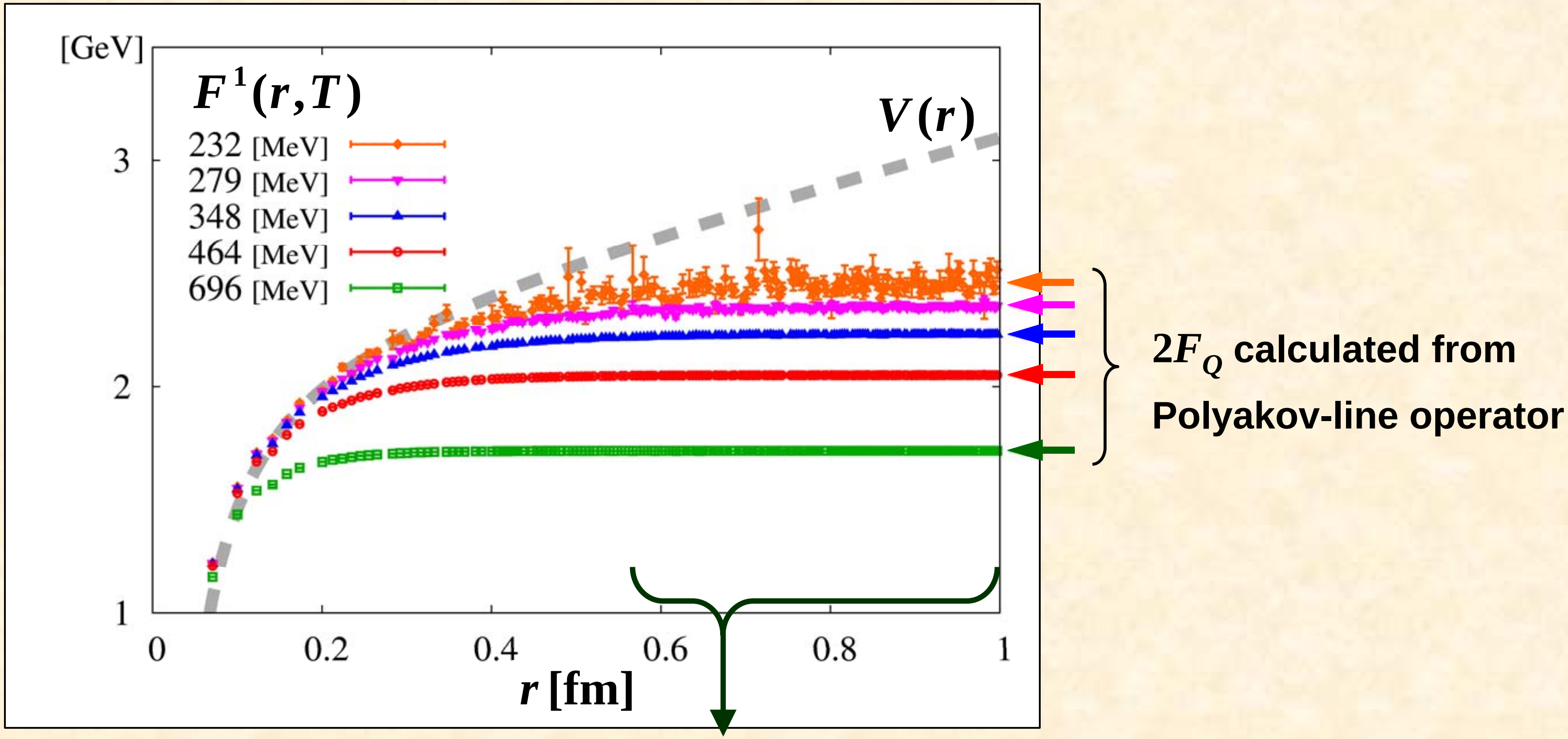
Short distance physics is insensitive to T.

$T \sim 200$ MeV: $F^1 \sim V$ up to 0.3--0.4 fm
$T \sim 700$ MeV: $F^1 \fallingdotseq V$ even at 0.1 fm

} Range of thermal effect is T-dependent

⟹ Debye screening effect

Heavy-quark free energy at $T > 0$



<u>Long distance</u>

$F^1(r,T)$ becomes flat and has no increase lineally.

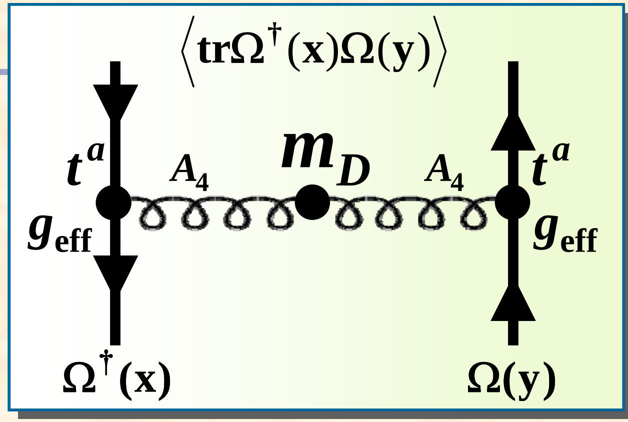
⇒ **Confinement is destroyed due to a thermal medium effect.**

At large r, correlation b/w Polyakov-lines will disappear,

$$F^1(r,T) = -T\ln\langle \mathrm{Tr}\Omega^\dagger(\mathrm{x})\Omega(\mathrm{y})\rangle \xrightarrow{r\to\infty} -T\ln\langle \mathrm{Tr}\Omega\rangle^2 = 2F_Q$$

⇒ F^1 **converges to 2x(single-quark free energy) at long distance**

Debye screening effect in QGP



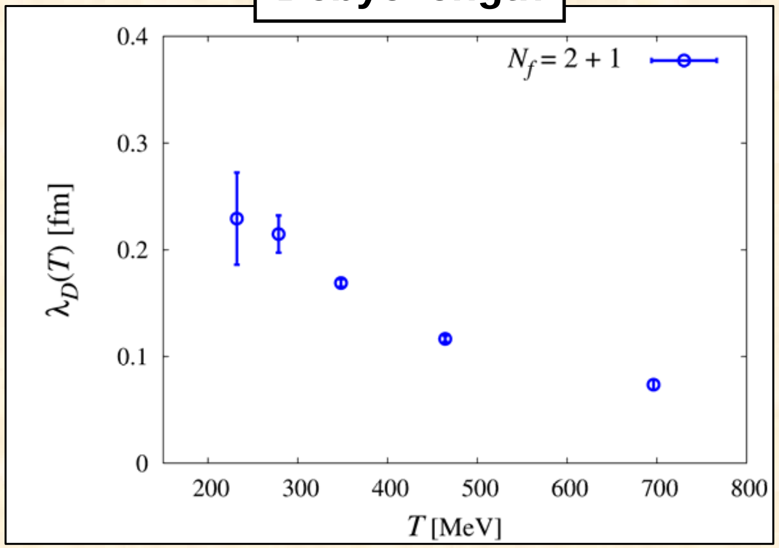
Single gluon exchange ansatz

$$F^1(r,T) = -T\ln\langle \mathrm{Tr}\Omega^\dagger(x)\Omega(y)\rangle \rightarrow -\frac{4}{3}\frac{\alpha_{eff}(T)}{r}e^{-m_D(T)r} + 2F_Q$$

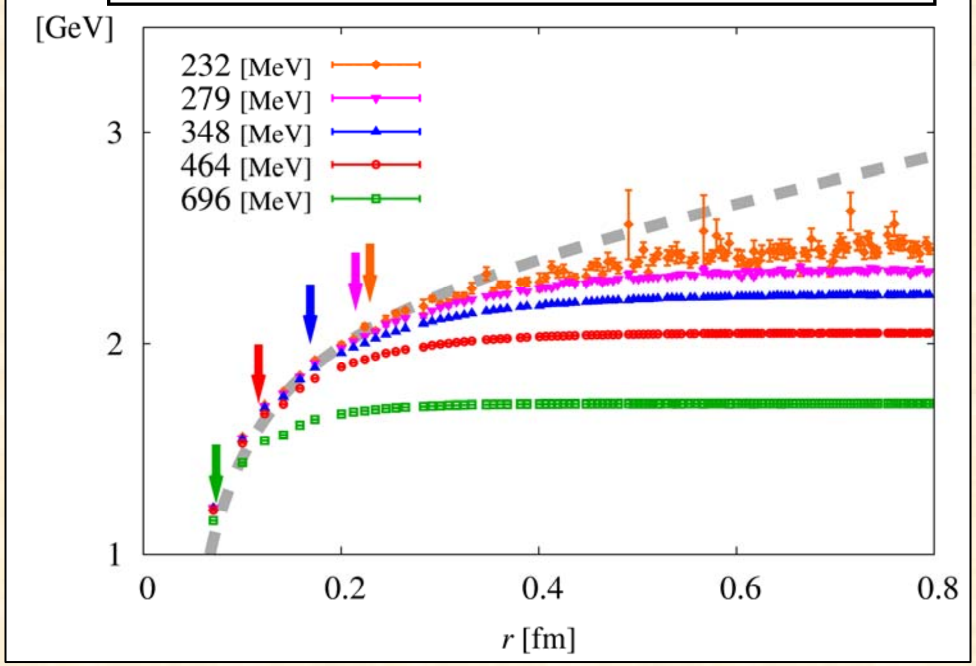
$g_{eff} \equiv \sqrt{4\pi\alpha_{eff}}$: effective running coupling

$m_D (= 1/\lambda_D)$: Debye screening mass (length)

Debye length



Debye length on heavy-quark potential

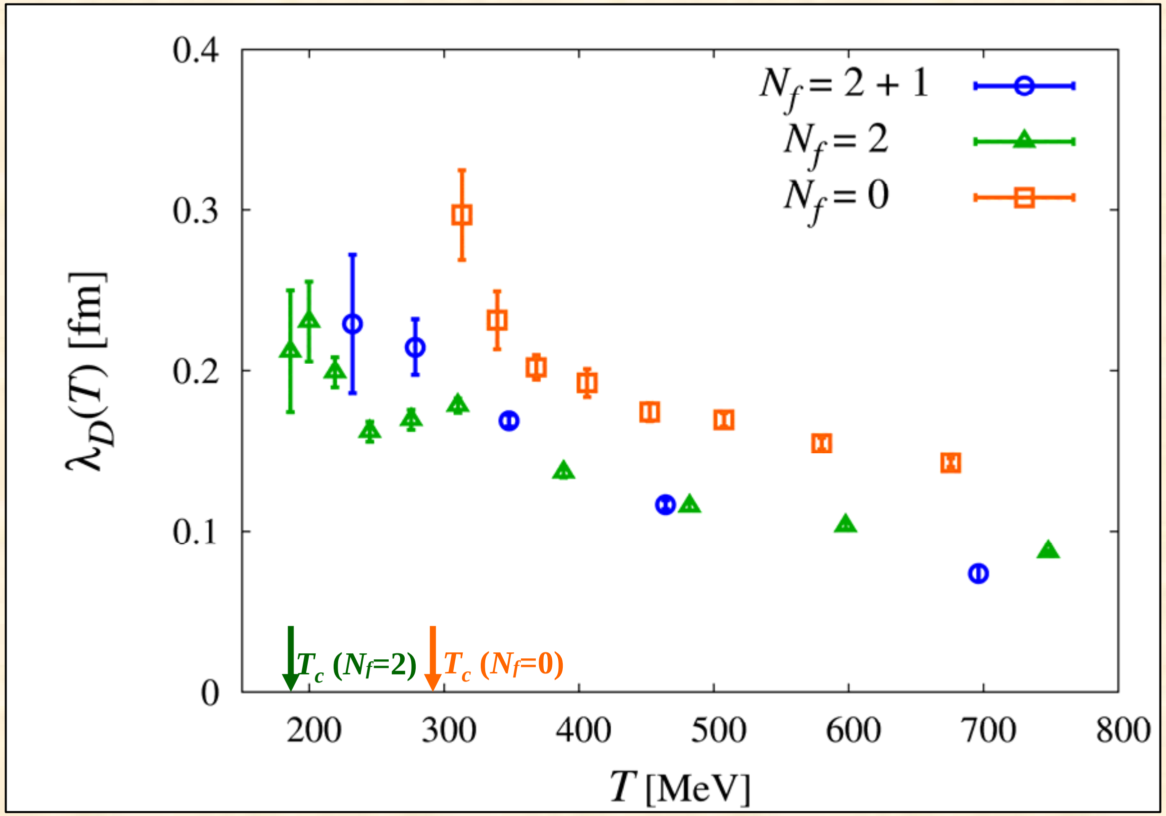


- λ_D small when T increases
- λ_D: distance where $F^1(r,T)$ departs from $V(r)$

$$\Rightarrow \quad r < \lambda_D : \; F^1(r,T) \sim -\frac{\alpha_0}{r}, \qquad r > \lambda_D : \; F^1(r,T) \sim -\frac{\alpha(T)}{r}\exp(-r/\lambda_D)$$

Debye screening effect in QGP

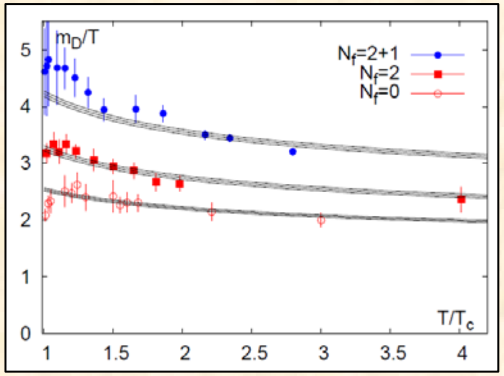
Flavor dependence of Debye length



$N_f = 2$: **fixed Nt ap.**
16^3x4, $m_s/m_\rho = 0.65$
WHOT, PRD75 (2007) 074501

$N_f = 0$: **fixed scale ap.**
20^3x(26-8)
WHOT, in preparation

c.f.) Staggered-type quark action



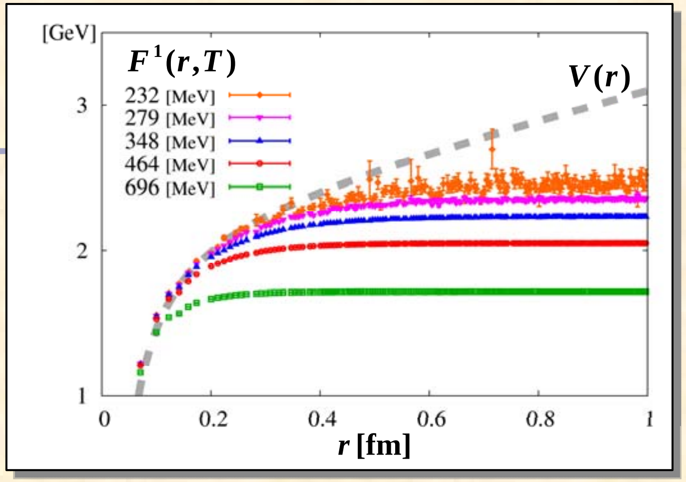
RBC-Bielefeld collaboration
Fixed Nt ap., m_s ~ 220 MeV

Magnitude of Debye length

$$\lambda_D^{N_f=2+1} \sim \lambda_D^{N_f=2} < \lambda_D^{N_f=0}$$

Dynamical quark effects are important for Debye effect.

Summary



Properties of quark-gluon plasma

⟹ Heavy-quark potential ($F^1(r,T)$) defined by free energy btw. static charged quarks

1. Heavy-quark potential at $T = 0$ and $T > 0$

- At short r: F^1 at any T converges to heavy-quark potential at $T = 0$

  ⟹ Short distance physics is insensitive to T.

- At mid r : screening effect appears
- At long r: F^1 becomes flat and has no linear behavior.

  ⟹ Correlation b/w Polyakov-lines disappears and F^1 converges to $2F_Q$

2. Debye screening effect in QGP

- Debye length by single gluon exchange ansatz: $F^1(r,T) = -\frac{\alpha(T)}{r}\exp(-r/\lambda_D) + 2F_Q$

  ⟹ λ_D small when T increases

  $r < \lambda_D$: Coulomb attraction, $r > \lambda_D$: screening by plasma

$$F^1(r,T) \sim -\frac{\alpha_0}{r}, \qquad F^1(r,T) \sim -\frac{\alpha(T)}{r}\exp(-r/\lambda_D)$$

Dynamical quark effects are important for Debye effect.