

Three regimes of hot QCD.

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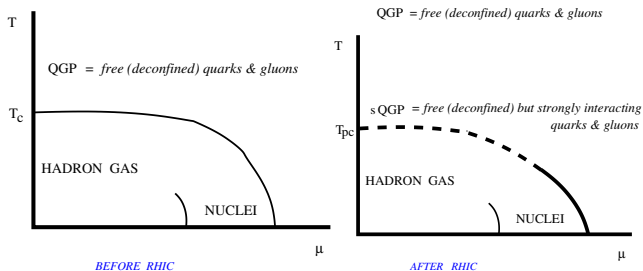
23rd October 2021



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- 3 QCD above T_{pc}



Before and after RHIC



The chiral restoration crossover is observed at $T = 100 - 200$ MeV with the pseudocritical temperature at $T_{pc} \sim 155$ MeV (BW collaboration, 2006).

Confirmed by HotQCD collaboration.

Why "free (deconfined)" ? - There are no experimental evidences.

Because the **nonrenormalized** Polyakov loop suggested an inflection point only slightly above $T_{pc} \sim 155$ MeV.

Is it true?



Polyakov loop today

Is there a deconfinement crossover at the temperatures of the chiral restoration crossover?

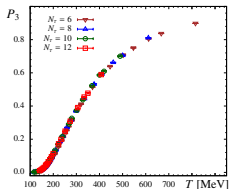


Figure : P. Petreczky and H.-P. Schadler, Phys. Rev. D **92** (2015) 094517.

A steady increase of the **renormalized** Polyakov loop beginning from $T = 0$ to $T \sim 1$ GeV. No hint of a deconfinement crossover in the $T = 100 - 200$ MeV region!

The inflection point is around $T_d \sim 300$ MeV. It is precisely the temperature of the center symmetry ("deconfinement") first order phase transition in the pure glue theory!

Two independent pseudocritical temperatures: $T_{pc} \sim 155$ MeV and $T_d \sim 300$ MeV.



Polyakov loop today

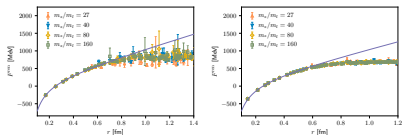


Figure : Left: $T = 141$ MeV; right: $T = 166$ MeV.
 D. A. Clarke, O. Kaczmarek, F. Karsch, A. Lahiri, arXiv:1911.07668 .

The same flattening above and below T_{PC} . No hint of deconfinement at T_{PC} .

A widespread interpretation: a flattening means a Debye screening of the color charge (i.e. deconfinement).

The Debye screening by definition: A negative electric potential gets weaker than the Coulombic potential:

$$-1/r \longrightarrow -1/r \exp(-\mu r)$$

A flattening of the positive linear potential means a string breaking and not the Debye screening. There is still confinement.

What physics do we have above $T_{PC} \sim 155$ MeV ?



Chiral spin symmetry

The **electric interaction is defined via color charge** (Lorentz-invariant)

$$Q^a = \int d^3x \Psi^\dagger(x) \frac{t^a}{2} \Psi(x).$$

It has both $U(1)_A$ and $SU(N_F)_L \times SU(N_F)_R$ symmetries.
 On top of it it has a **$SU(2)_{CS}$** chiral spin symmetry:

$$\Psi \rightarrow \Psi' = \exp\left(i \frac{\varepsilon^n \Sigma^n}{2}\right) \Psi$$

$$\Sigma = \{\gamma_k, -i\gamma_5\gamma_k, \gamma_5\}.$$

$$SU(2)_{CS} \times SU(N_F) \subset SU(2N_F)$$

$SU(2N_F)$ is also a symmetry of the color charge.

$$U(1)_A \times SU(N_F)_L \times SU(N_F)_R \subset SU(2N_F)$$

The color charge (and electric interaction) have a larger symmetry than symmetry of the QCD Lagrangian as the whole.

Symmetries of the QCD action

Interaction of quarks with the gluon field in Minkowski space-time:

$$\bar{\Psi}\gamma^\mu D_\mu\Psi = \bar{\Psi}\gamma^0 D_0\Psi + \bar{\Psi}\gamma^i D_i\Psi.$$

The temporal term includes an interaction of the color-octet charge density

$$\bar{\Psi}(x)\gamma^0 \frac{t^c}{2}\Psi(x) = \Psi(x)^\dagger \frac{t^c}{2}\Psi(x)$$

with the chromo-electric part of the gluonic field. **It is invariant under $SU(2)_{CS}$ and $SU(2N_F)$.** The spatial part contains a quark kinetic term and interaction with the chromo-magnetic field. **It breaks $SU(2)_{CS}$ and $SU(2N_F)$.**

The quark chemical potential term $\mu\Psi(x)^\dagger\Psi(x)$

$$S = \int_0^\beta d\tau \int d^3x \bar{\Psi}[\gamma_\mu D_\mu + \mu\gamma_4 + m]\Psi,$$

is **$SU(2)_{CS}$ and $SU(2N_F)$ invariant.**



Observation of the chiral spin symmetry at $T=0$

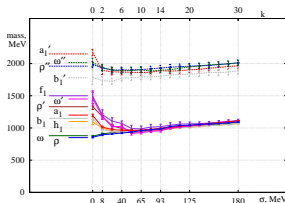
Banks-Casher:

$$\langle \bar{q}q \rangle = -\pi\rho(0).$$

Low mode truncation:

$$S = S_{Full} - \sum_{i=1}^k \frac{1}{\lambda_i} |\lambda_i\rangle\langle\lambda_i|.$$

M.Denissenya, L.Ya.G., C.B.Lang, PRD 89(2014)077502; 91(2015)034505 with JLQCD overlap ensembles:



$SU(2)_{CS}$ and $SU(4)$ symmetries.

The magnetic interaction is located predominantly in the near zero modes while the confining electric interaction is distributed among all modes.

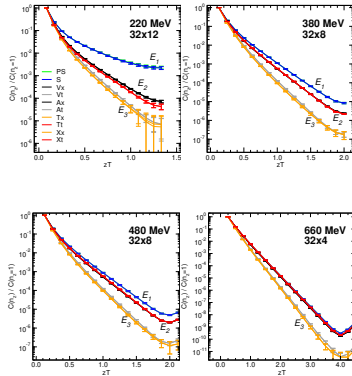
Confinement and chiral symmetry breaking are not correlated.

Should be observed above T_{PC} without truncation. L.Ya.G., at CPOD 2016



Symmetries of spatial correlators above T_{pc}

C. Rohrhofer, Y. Aoki, G. Cossu, H. Fukaya, C. Gattringer, L.Ya.G., S. Hashimoto, C.B. Lang, S. Prelovsek, PRD 96 (2017) 09450; PRD 100 (2019) 014502.
 $N_f = 2$ QCD with the chirally symmetric Domain Wall Dirac operator (JLQCD ensembles).



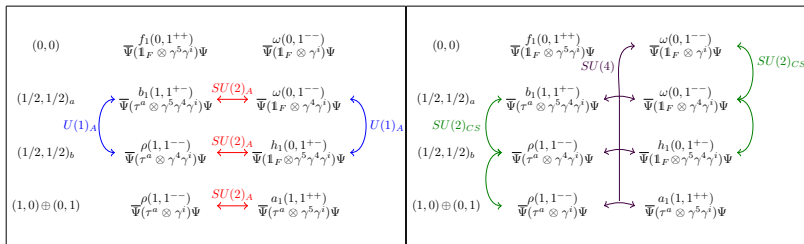
E_1 - $U(1)_A$ symmetry; E_2 & E_3 - $SU(2)_{CS}$ and $SU(4)$ symmetries.
 $SU(2)_{CS}$ and $SU(4)$ symmetries persist up to $T \sim 500$ MeV.

Temporal correlators above T_{pc}

t-direction Euclidean correlator in the hadron rest frame:

$$C_{\Gamma}(t) = \sum_{x,y,z} \langle \mathcal{O}_{\Gamma}(x, y, z, t) \mathcal{O}_{\Gamma}(\mathbf{0}, 0)^{\dagger} \rangle.$$

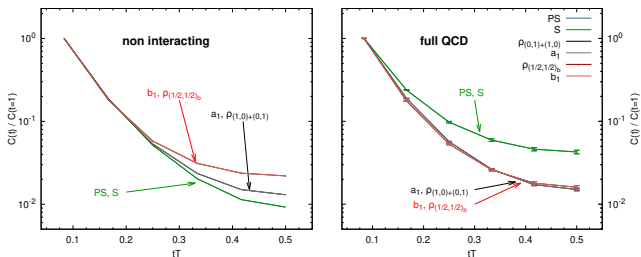
where $\mathcal{O}_{\Gamma} = \bar{q} \Gamma \frac{\boldsymbol{\tau}}{2} q$ are all possible $J = 0$ and $J = 1$ local operators.



Temporal correlators above T_{pc}

C. Rohrhofer, Y. Aoki, L.Ya.G., S. Hashimoto, PLB 802(2020) 135245

$N_F = 2$ Domain wall Dirac operator at physical quark masses, 12×48^3 lattice at $T = 220$ MeV (JLQCD ensembles)



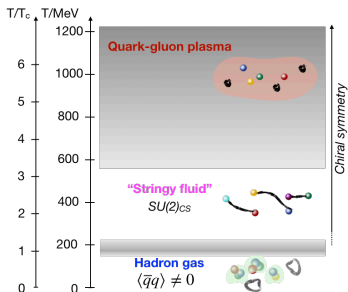
Free quarks: $SU(2)_L \times SU(2)_R$ and $U(1)_A$ multiplets.

Full QCD at $T = 220$ MeV: $U(1)_A$, $SU(2)_L \times SU(2)_R$, $SU(2)_{CS}$ and $SU(2N_F)$ multiplets.

Above T_{pc} QCD is approximately $SU(2)_{CS}$ and $SU(2N_F)$ symmetric.



Three regimes of QCD



We can distinguish three different regimes according to symmetries and properties (degrees of freedom).

$0 - T_{pc}$ - Hadron Gas;

$T_{pc} - 3T_{pc}$ - Stringy Fluid (chiral, $SU(2)_{CS}$ and $SU(4)$ symmetries; **electric confinement**)

$T > 3T_{pc}$ - a smooth approach to QGP (chiral symmetry; **magnetic confinement**)



Fluctuations of conserved charges as a probe of deconfinement

- S. Jeon and V. Koch, PRL 85 (2000) 2076
 M. Asakawa, U. W. Heinz and B. Muller, PRL 85 (2000) 2072
 F. Karsch, S. Ejiri and K. Redlich, NPA 774 (2006) 619

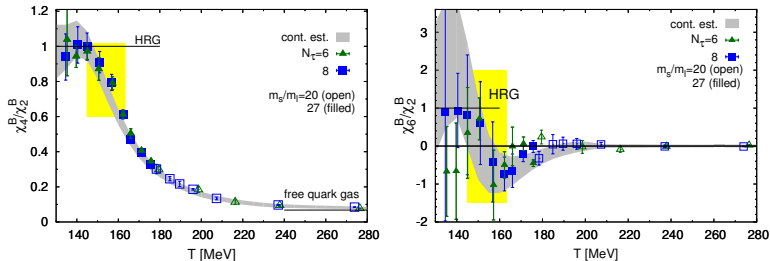


Figure : A. Bazavov et al, PRD 95 (2017) 054504

Traditional interpretation: evidence of deconfinement (free quarks)

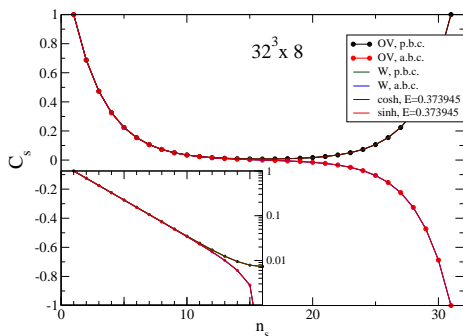


Free quarks on a finite lattice. L.Y.G and C.B. Lang, EPJA, 57 (2021) 182

A single quark propagator:

$$p.b.c. \sim \exp(-Ez) + \exp(-E(N_s - z)) \equiv f + \bar{b} \quad (1)$$

$$a.b.c. \sim \exp(-Ez) - \exp(-E(N_s - z)) \equiv f - \bar{b} \quad (2)$$

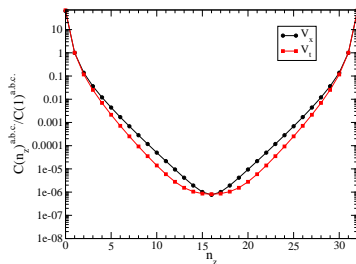
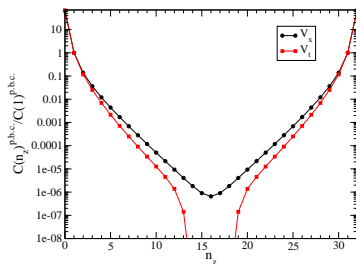


Free quarks on a finite lattice. L.Y.G and C.B. Lang, EPJA, 57 (2021) 182

A $\bar{q}q$ propagator:

$$p.b.c. : (f + \bar{b})(\bar{f} + b) = f\bar{f} + b\bar{b} + fb + \bar{b}\bar{f} \quad (3)$$

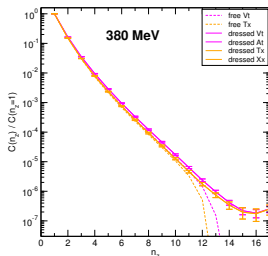
$$a.b.c. : (f - \bar{b})(\bar{f} - b) = f\bar{f} + b\bar{b} - fb - \bar{b}\bar{f} \quad (4)$$



V_t – conserved charge (red); V_x – transverse current (black).



An independent evidence for confinement in conserved charge channels



Dashed - correlator of the charge operator V_t calculated with free quarks, solid - full QCD.

Confining interaction kills contributions from large distances (in the infrared) between quarks. That is why the diffractive pattern disappears.

The fluctuations of conserved charges are given by integrals of the correlator. The integrals are insensitive to the infrared region (large distance) where confinement is manifest.