Symmetries of temporal correlators and the nature of hot QCD.

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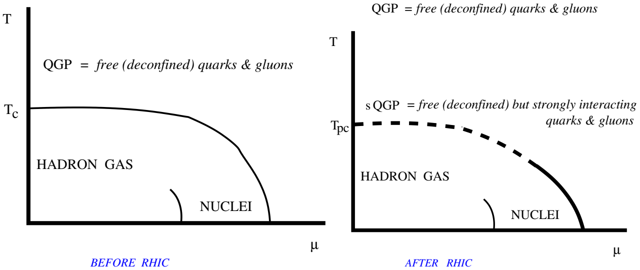
Before and after RHIC



Why "free (deconfined)" ? - There are no experimental evidences.
Because the Polyakov loop suggested a deconfinement transition at the (or near) chiral restoration temperature.
Is it true?

Polyakov loop today

The chiral restoration phase transition in the chiral limit is at $T_c \sim 130$ MeV (Bielefeld - BNL, 2019)

At physical quark masses a smooth chiral restoration crossover is observed at $T = 100 - 200$ MeV with a pseudocritical temperature at $T_{pc} \sim 155$ MeV (Budapest-Wuppertal, 2006).

Is there a deconfinement crossover at the same temperatures?

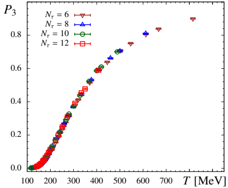


Figure : P. Petreczky and H.-P. Schadler, Phys. Rev. D **92** (2015) 094517.

No hint of a deconfinement crossover in the $T = 100 - 200$ MeV region.
In a pure glue theory ($m_q = \infty$) a first order center symmetry ("deconfinement") phase transition is observed at $T_d \sim 300$ MeV.
An inflection point of the renormalized Polyakov loop at the physical point is at ~ 300 MeV.

Polyakov loop today

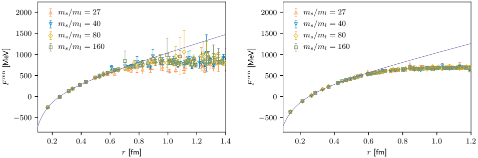


Figure : Left: $T = 141$ MeV; right: $T = 166$ MeV.
D. A. Clarke, O. Kaczmarek, F. Karsch, A. Lahiri, arXiv:1911.07668 .

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). Wrong! 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.

The real world should be influenced by two critical temperatures $T_c \sim 130$ MeV and $T_d \sim 300$ MeV.

Crucial questions

Below $T_{pc} \sim 155$ MeV we have a hadron gas.

At very high temperatures we have a QGP with quasiquarks and quasigluons as degrees of freedom. It is also a gas.

At RHIC and LHC temperatures $T \sim 150 - 400$ MeV experimentalists observe a liquid.

It is highly nontrivial and suggests that a transition from a hadron gas to QGP is not a simple crossover. There must be an intermediate regime with its own properties.

What degrees of freedom are there and how do they explain that it is a liquid?

We need observables that would clarify this issue!

Chiral spin symmetry

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

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

Symmetry groups of the color charge and of the electric interaction.
The $SU(2)_{CS}$ chiral spin transformations:

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

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

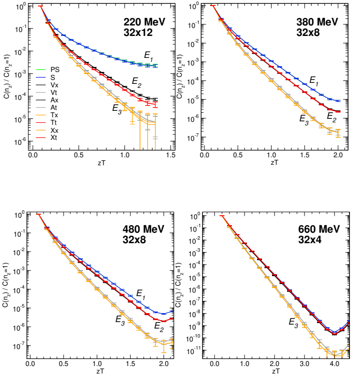
The $SU(2)_{CS}$ transformations: $L \longleftrightarrow R$. Can be extended to $SU(2N_F)$.
The magnetic interaction is defined via spatial current. No $SU(2)_{CS}$ symmetry.

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

L.Ya.G., EPJA 51 (2015) 27; L.Ya.G., M. Pak,PRD, 92 (2015) 016001

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.



$E1$ - $U(1)_A$ symmetry; $E2$ & $E3$ - $SU(2)_{CS}$ and $SU(4)$ symmetries.
$SU(2)_{CS}$ and $SU(4)$ symmetries persist up to $T \sim 500$ MeV.
The same symmetries should be seen in temporal correlators.

Temporal correlators and spectral density above T_{pc}

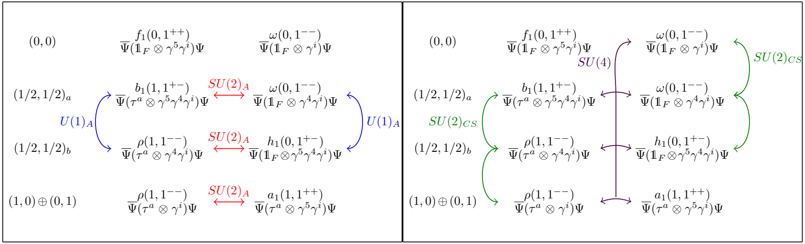
The spectral density $\rho(\omega)$ is an integral transform

$$C_\Gamma(t) = \int d\omega \frac{\cosh(\omega(t - \frac{1}{2T}))}{\sinh(\omega \frac{1}{2T})} \rho_\Gamma(\omega) \qquad (1)$$

of the t-direction Euclidean correlator:

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

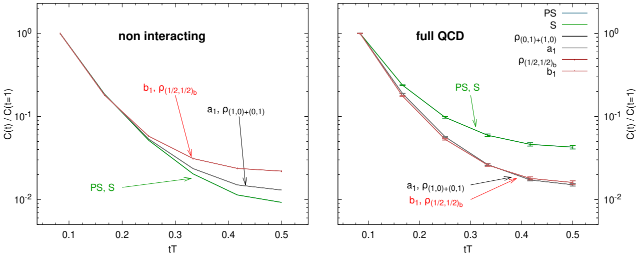
where $\mathcal{O}_\Gamma = \bar{q}\Gamma \frac{\boldsymbol{\tau}}{2} q$ are all possible $J = 0$ and $J = 1$ local operators.



Temporal correlators and spectral density 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.



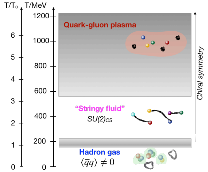
Free quarks: $SU(2)_L \times SU(2)_R$ and $U(1)_A$ multiplets.

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

$N_F=2$



We can distinguish three different regimes according to symmetries and properties. $0 - T_{pc}$ - 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)

$N_F=2+1$