Chiral spin symmetry and the QCD phase diagram.

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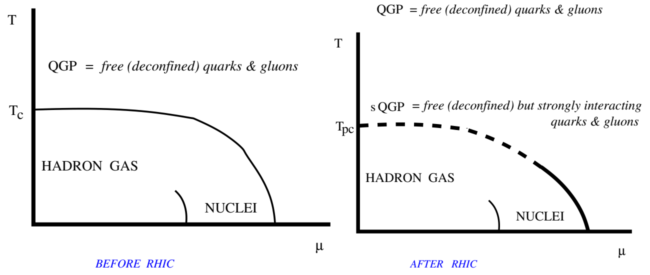
Before and after RHIC



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?

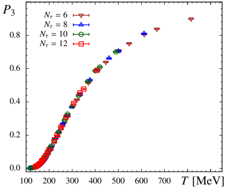


Figure : P. Petreczky and H.-P. Schadler, Phys. Rev. D **92** (2015) 094517.

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.

Polyakov loop today

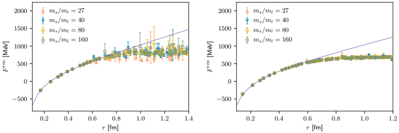


Figure : Left: $T = 141$ MeV; right: $T = 166$ MeV.
D. A. Clarke, O. Kaczmarek, F. Karsch, A. Lahiri, arXiv:1911.07668 .

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. L.Ya.G.,EPJA,2015; L.Ya.G., M.Pak,PRD, 2015

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:

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

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

$$\begin{pmatrix} R \\ L \end{pmatrix} \to \begin{pmatrix} R' \\ L' \end{pmatrix} = \exp\left(i \frac{\varepsilon^n \sigma^n}{2}\right) \begin{pmatrix} R \\ L \end{pmatrix}$$

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

$SU(2N_F)$ 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:

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

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 $\mu\Psi(x)^{\dagger}\Psi(x)$

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

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

Observation of the chiral spin symmetry at T=0

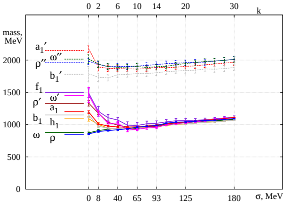
Banks-Casher:

$$<\bar{q}q>= -\pi\rho(0).$$

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

Chiral spin symmetry above T_{pc}

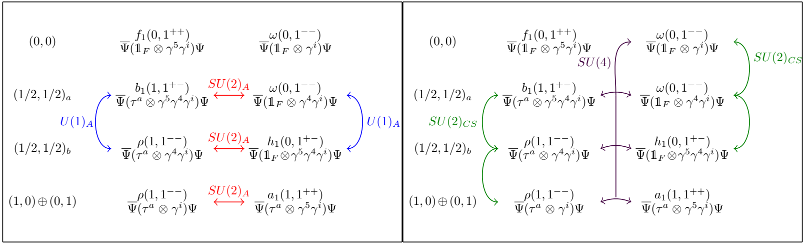
$$C_\Gamma(t,x,y,z) = \langle \mathcal{O}_\Gamma(t,x,y,z)\mathcal{O}_\Gamma(\mathbf{0},0)^\dagger \rangle \,.$$

$$C_\Gamma^s(z) = \sum_{x,y,t} C_\Gamma(t,x,y,z) \,,$$
$$C_\Gamma^t(t) = \sum_{x,y,z} C_\Gamma(t,x,y,z) \,,$$

collect the spectral information projected on the $(p_x = p_y = \omega = 0)$ and $(p_x = p_y = p_z = 0)$ axes, respectively.

$$C_\Gamma(t,\mathbf{p}) = \int_0^\infty \frac{d\omega}{2\pi} K(t,\omega)\rho_\Gamma(\omega,\mathbf{p}) \,,$$
$$K(t,\omega) = \frac{\cosh(\omega(t-1/2T))}{\sinh(\omega/2T)} \,.$$

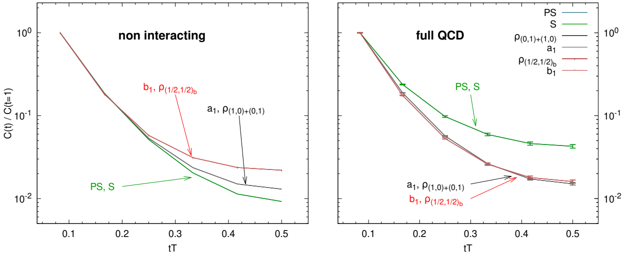
Temporal correlators above T_{pc}



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)



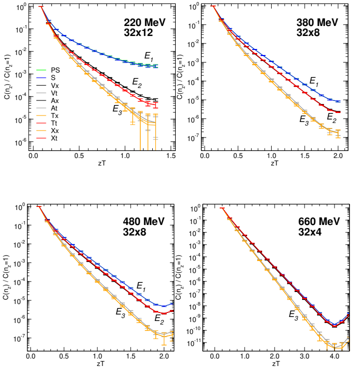
Free quarks: $SU(2)_L \times SU(2)_R$ and $U(1)_A$ multiplets.

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.

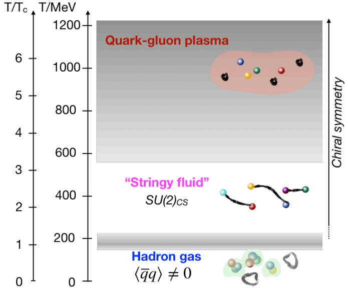
Spatial correlators above T_{pc}

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).



$E1$ - $U(1)_A$ symmetry; $E2$ & $E3$ - $SU(2)_{CS}$ and $SU(4)$ symmetries.
$SU(2)_{CS}$ and $SU(4)$ symmetries persist up to $T \sim 500$ MeV.

Three regimes of QCD



$0 - T_{pc}$ - Hadron Gas (broken chiral symmetry);

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

Stringy fluid is mostly populated with scalar and pseudoscala hadron-like states with some admixture of $J = 1$ states.

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

Screening masses and stringy fluid, L.G., O. Philipsen, R. Pisarski, 2204.05083

$$
\begin{aligned}
e^{pV/T} = Z &= \mathrm{Tr}(e^{-aHN_\tau}) \\
&= \mathrm{Tr}(e^{-aH_zN_z}) = \sum_{n_z} e^{-E_{n_z}N_z} \; ,
\end{aligned}
$$

QGP - parton dynamics drives observables.

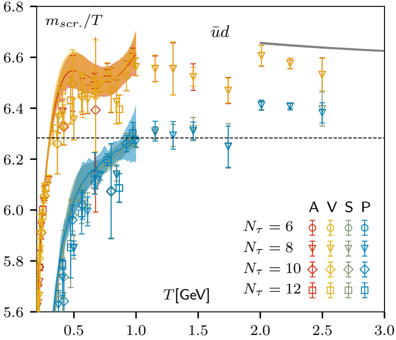
Screening masses are accessible by perturbative and nonperturbative (lattice) calculations.

Lattice at $T \sim 1$ - 160 GeV (M.D. Brida et al, 2112.05427) :

$$
\begin{aligned}
\frac{m_{PS}}{2\pi T} &= 1 + p_2\,\hat{g}^2(T) + p_3\,\hat{g}^3(T) + p_4\,\hat{g}^4(T) \; , \\
\frac{m_V}{2\pi T} &= \frac{m_{PS}}{2\pi T} + s_4\,\hat{g}^4(T) \; ,
\end{aligned}
$$

Screening masses and stringy fluid, L.G., O. Philipsen, R. Pisarski, 2204.05083

From A. Bazavov et al, PRD 100, 094510 (2019)

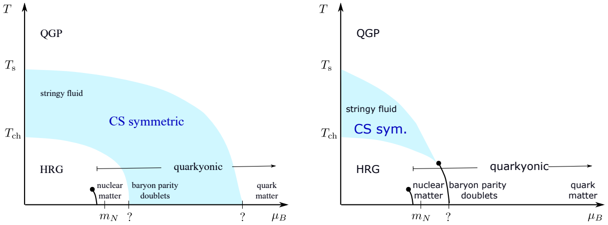


An independent demonstration of the existence of a temperature window $T_{pc} < T < 3T_{pc}$, in which chiral symmetry is restored but the dynamics is inconsistent with a partonic description.

Chiral spin symmetric band, L.G., O. Philipsen, R. Pisarski, 2204.05083

$$\frac{T_{\rm ch}(\mu_B)}{T_{\rm ch}(0)} = 1 - 0.016(5)\left(\frac{\mu_B}{T_{\rm ch}(0)}\right)^2 + \ldots\,,$$

$$\frac{dT_{\rm s}}{d\mu_B} = -\frac{2C_2}{C_0}\frac{\mu_B}{T} - \frac{2C_2^2}{C_0^2}\left(\frac{\mu_B}{T}\right)^3 + \ldots\,.$$



Parity doublets

B.W. Lee, Chiral Dynamics, 1972
C. E. Detar, T. Kunihiro, PRD 39, 2805 (1989)
D. Jido, M. Oka, A. Hosaka, Progr. Th. Phys. 106, 873 (2001)

$$\Psi = \begin{pmatrix} \Psi_+ \\ \Psi_- \end{pmatrix}$$

$$\begin{aligned} \Psi &\rightarrow \exp\left(\imath \frac{\theta_V^a \tau^a}{2} \otimes \mathbb{1}\right) \Psi \\ \Psi &\rightarrow \exp\left(\imath \frac{\theta_A^a \tau^a}{2} \otimes \sigma_1\right) \Psi \end{aligned}$$

$$\begin{aligned} \mathcal{L} &= i\bar{\Psi}_+\gamma^\mu\partial_\mu\Psi_+ + i\bar{\Psi}_-\gamma^\mu\partial_\mu\Psi_- \\ &\quad -m\bar{\Psi}_+\Psi_+ - m\bar{\Psi}_-\Psi_- \end{aligned}$$

$$\Psi_R = \frac{1}{\sqrt{2}}(\Psi_+ + \Psi_-); \quad \Psi_L = \frac{1}{\sqrt{2}}(\Psi_+ - \Psi_-)$$

$$\begin{aligned} \mathcal{L} &= i\bar{\Psi}_L\gamma^\mu\partial_\mu\Psi_L + i\bar{\Psi}_R\gamma^\mu\partial_\mu\Psi_R \\ &\quad -m\bar{\Psi}_L\Psi_L - m\bar{\Psi}_R\Psi_R \end{aligned}$$

Parity doublets

Free parity doublet has a $SU(4)$ symmetry - M. Catillo, L.G., PRD 98 (2018) 014030

$$\tilde{\Psi} = \begin{pmatrix} \Psi_R \\ \Psi_L \end{pmatrix}$$

$$\begin{aligned} \mathcal{L} &= i\bar{\Psi}_L \gamma^\mu \partial_\mu \Psi_L + i\bar{\Psi}_R \gamma^\mu \partial_\mu \Psi_R \\ &\quad - m\bar{\Psi}_L \Psi_L - m\bar{\Psi}_R \Psi_R \end{aligned}$$

$$\begin{pmatrix} \Psi_R \\ \Psi_L \end{pmatrix} \rightarrow \exp\left(i\frac{\varepsilon^n \sigma^n}{2}\right) \begin{pmatrix} \Psi_R \\ \Psi_L \end{pmatrix}$$

$$\{(\tau^a \otimes \mathbb{1}), (\mathbb{1} \otimes \sigma^n), (\tau^a \otimes \sigma^n)\}$$

The QCD phase diagram