

# Implications of the chiral spin symmetry for QCD at high temperatures and densities.

L. Ya. Glozman

Institut für Physik, FB Theoretische Physik, Universität Graz

5th September 2018



- 1 Chiralspin symmetry
- 2 Observation of the chiralspin symmetry
- 3 Conclusions to part I
- 4 Approximate  $SU(2)_{CS}$  and  $SU(4)$  symmetries at high T.
- 5 Conclusions to part II

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

The Dirac Lagrangian in the chiral limit

$$\mathcal{L} = i\bar{\Psi}\gamma_\mu\partial^\mu\Psi = i\bar{\Psi}_L\gamma_\mu\partial^\mu\Psi_L + i\bar{\Psi}_R\gamma_\mu\partial^\mu\Psi_R,$$

where

$$\psi_R = \frac{1}{2}(1 + \gamma_5)\psi, \quad \psi_L = \frac{1}{2}(1 - \gamma_5)\psi,$$

is chirally symmetric

$$SU(N_F)_L \times SU(N_F)_R \times U(1)_A \times U(1)_V.$$

Fermion charge (Lorentz-invariant)

$$Q = \int d^3x \bar{\Psi}(x)\gamma_0\Psi(x) = \int d^3x \Psi^\dagger(x)\Psi(x)$$

is invariant with respect to any unitary transformation. So far known unitary transformations are those which leave the Dirac Lagrangian invariant:

$$SU(N_c), SU(N_F), U(N_F)_L \times U(N_F)_R$$



# Chiral spin symmetry, L.Ya.G., EPJA (2015); L.Ya.G., M. Pak, PRD, (2015)

The  $SU(2)_{CS}$  chiral spin transformations and generators:

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

$$\Sigma^n = \{\gamma_k, -i\gamma_5\gamma_k, \gamma_5\},$$

$n = 1, 2, 3$ .  $\gamma_k$  is any Hermitian Euclidean gamma-matrix:

$$\gamma_i\gamma_j + \gamma_j\gamma_i = 2\delta^{ij}; \quad \gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4.$$

The  $\mathfrak{su}(2)$  algebra  $[\Sigma^a, \Sigma^b] = 2i\epsilon^{abc}\Sigma^c$  is satisfied with any  $k = 1, 2, 3, 4$ .

The free massless Dirac Lagrangian does not have this symmetry. However, it is a symmetry of the fermion charge

The fermion charge has a larger symmetry than the Dirac eq.



## Chiralspin symmetry, L.Ya.G., EPJA (2015); L.Ya.G., M. Pak, PRD, (2015)

The chiralspin transformation and generators can be presented in an equivalent form. With  $k = 4$  they are

$$\Sigma^n = \{\mathbb{1} \otimes \sigma^1, \mathbb{1} \otimes \sigma^2, \mathbb{1} \otimes \sigma^3\}.$$

Here the Pauli matrices  $\sigma^i$  act in the space of spinors

$$\Psi = \begin{pmatrix} R \\ L \end{pmatrix}, \quad (1)$$

where  $R$  and  $L$  represent the upper and lower components of the right- and left-handed Dirac bispinors

The  $SU(2)_{CS}$ ,  $k = 4$  transformation can then be rewritten as

$$\Psi \rightarrow \Psi' = \exp\left(i\frac{\varepsilon^n \Sigma^n}{2}\right) \Psi = \exp\left(i\frac{\varepsilon^n \sigma^n}{2}\right) \begin{pmatrix} R \\ L \end{pmatrix}. \quad (2)$$

A fundamental irreducible representation of  $SU(2)_{CS}$  is two-dimensional and the  $SU(2)_{CS}$  transformations mix the  $R$  and  $L$  components of fermions.



## Chiral spin symmetry, L.Ya.G., EPJA (2015); L.Ya.G., M. Pak, PRD, (2015)

An extension of the direct  $SU(2)_{CS} \times SU(N_F)$  product leads to a  $SU(2N_F)$  group. This group contains the chiral symmetry of QCD  $SU(N_F)_L \times SU(N_F)_R \times U(1)_A$  as a subgroup.

Its transformations are given by

$$\Psi \rightarrow \Psi' = \exp\left(i \frac{\epsilon^m T^m}{2}\right) \Psi,$$

where  $m = 1, 2, \dots, (2N_F)^2 - 1$  and the set of  $(2N_F)^2 - 1$  generators is

$$\{(\tau^a \otimes \mathbb{1}_D), (\mathbb{1}_F \otimes \Sigma^n), (\tau^a \otimes \Sigma^n)\} \quad (3)$$

with  $\tau$  being the flavour generators with the flavour index  $a$  and  $n = 1, 2, 3$  is the  $SU(2)_{CS}$  index.

$SU(2N_F)$  is also a symmetry of the fermion charge, while not a symmetry of the Dirac eq.



## 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.**



## Low mode truncation

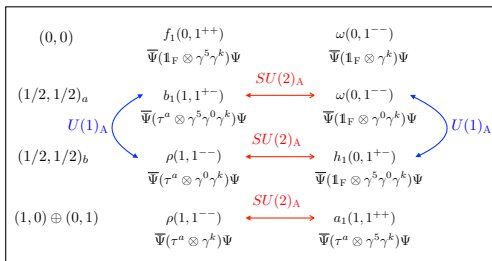
Banks-Casher:

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

What we do (initiated by C.B. Lang, M. Schroeck, 2011):

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

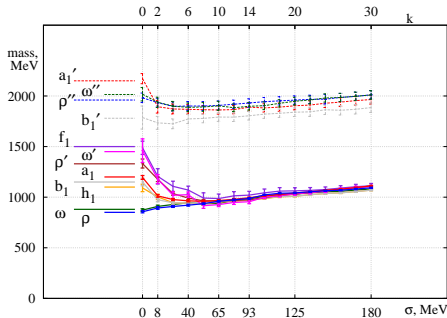
Chiral symmetry expectations for  $J = 1$  mesons:





$$J = 1$$

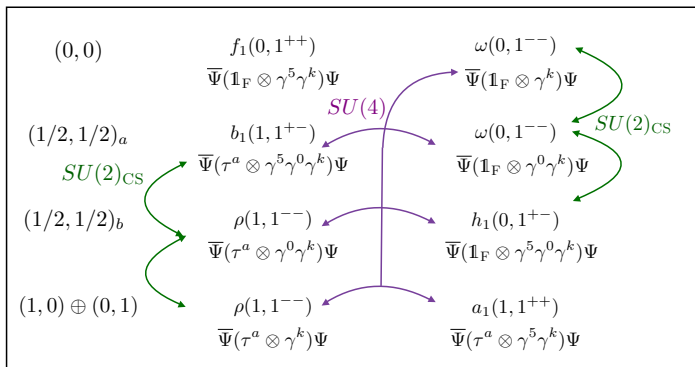
We use  $N_f = 2$  JLQCD overlap gauge configurations.



We clearly see a larger degeneracy than the  $SU(2)_L \times SU(2)_R \times U(1)_A$  symmetry of the QCD Lagrangian.



## L.Ya.G., M. Pak, PRD 92(2015)016001



## Conclusions to part I and prediction for high T

Observed on the lattice  $SU(2)_{CS}$  and  $SU(2N_F)$  symmetries of hadrons upon elimination of the near-zero modes are **symmetries of confinement in QCD** that is due to chromo-electric charge-charge interaction.

The **chromo-magnetic** interaction in QCD contributes only to the near-zero modes. It breaks explicitly both  $SU(2)_{CS}$  and  $SU(2N_F)$  symmetries of confinement.

The hadron spectra observed in a real world can be viewed as a result of splitting of the primary energy levels with the  $SU(4)$  symmetry by means of dynamics associated with the near-zero modes.

Above  $T_c$   $SU(2)_L \times SU(2)_R$  gets restored and the near-zero modes of the Dirac operator are suppressed. **Then we expect emergence of  $SU(2)_{CS}$  and  $SU(4)$  - no deconfinement.** L.Ya.G. 1610.00275



## Spatial correlators at high T. Full QCD, no truncation.

C. Rohrhofer, Y. Aoki, G. Cossu, H. Fukaya, L.Ya.G., S. Hashimoto,  
 C. B. Lang, S. Prelovsek, PRD 96 (2017) 094501

$N_f = 2$  QCD with the chirally symmetric Dirac operator.

$$C_\Gamma(n_z) = \sum_{n_x, n_y, n_t} \langle \mathcal{O}_\Gamma(n_x, n_y, n_z, n_t) \mathcal{O}_\Gamma(\mathbf{0}, 0)^\dagger \rangle.$$

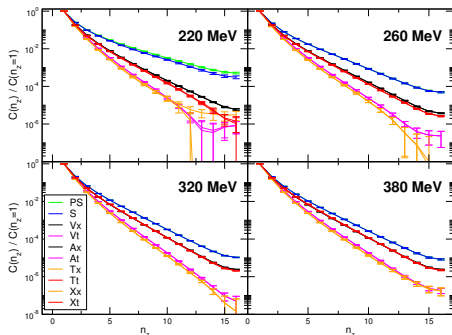
where  $\mathcal{O}_\Gamma(x) = \bar{q}(x) \Gamma \frac{\mathcal{T}}{2} q(x)$  are all possible  $J = 0$  and  $J = 1$  local operators:

Name	Dirac structure	Abbreviation	
<i>Pseudoscalar</i>	$\gamma_5$	<b>PS</b>	] $U(1)_A$
<i>Scalar</i>	$\mathbb{1}$	<b>S</b>	
<i>Axial-vector</i>	$\gamma_k \gamma_5$	<b>A</b>	] $SU(2)_A$
<i>Vector</i>	$\gamma_k$	<b>V</b>	
<i>Tensor-vector</i>	$\gamma_k \gamma_3$	<b>T</b>	] $U(1)_A$
<i>Axial-tensor-vector</i>	$\gamma_k \gamma_3 \gamma_5$	<b>X</b>	

**Table** : Operators considered in this work and their transformation properties. The open vector index  $k$  denotes the components 1, 2, 4, *i.e.*  $x, y, t$ .



## Spatial correlators at high T. Full QCD, no truncation.



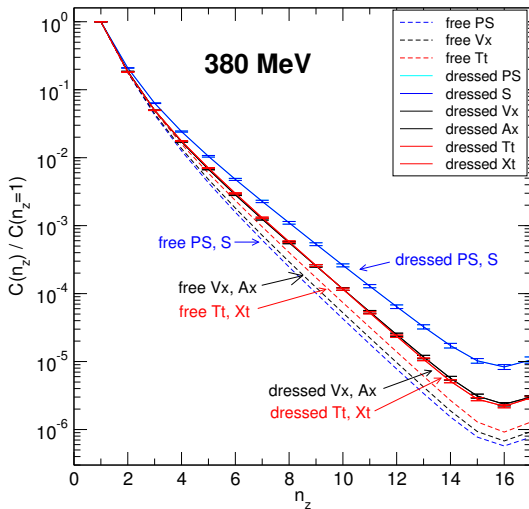
In total we observe three different multiplets:

$$E_1(U(1)_A) : \quad PS \leftrightarrow S$$

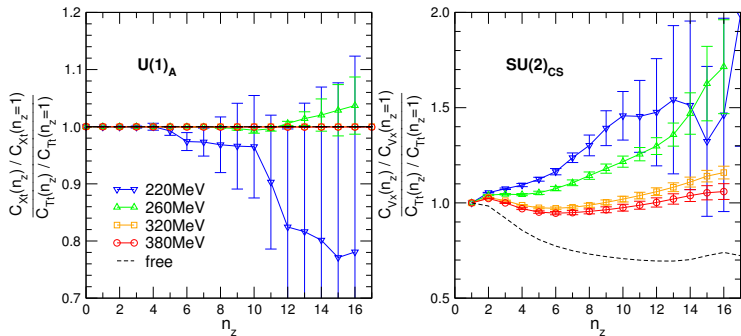
$$E_2(SU(4)) : \quad V_x \leftrightarrow T_t \leftrightarrow X_t \leftrightarrow A_x$$

$$E_3(SU(4)) : \quad V_t \leftrightarrow T_x \leftrightarrow X_x \leftrightarrow A_t$$

## Spatial correlators at high T. Full QCD, no truncation.



# Spatial correlators at high T. Full QCD, no truncation.

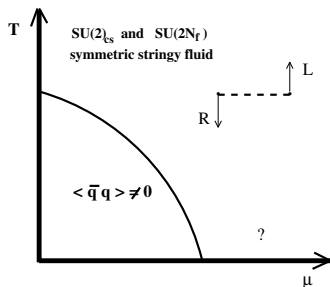


At  $T=380$  MeV we observe approximate  $SU(2)_{CS}$  and  $SU(4)$  symmetries at the level of 5%.

Will a non-zero chemical potential break this symmetry?

$$S = \int_0^\beta d\tau \int d^3x \bar{\Psi} [\gamma_\mu D_\mu + \mu \gamma_4 + m] \Psi, \quad (4)$$

The quark chemical potential term  $\mu \bar{\Psi} \gamma_4 \Psi$  is invariant under  $SU(2)_{CS}$  and  $SU(2N_F)$ .





## Conclusions to part II

We observe emergence of approximate  $SU(2)_{CS}$  and  $SU(4)$  symmetries at  $2T_c$ .

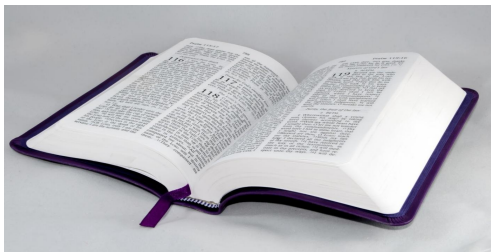
Emergence of  $SU(2)_{CS}$  and  $SU(4)$  symmetries indicates that the chromo-magnetic interaction is suppressed while confining chromo-electric interaction is still active.

These symmetries are incompatible with the scenario of a plasma of asymptotically free, deconfined quarks and gluons.

Elementary objects: chiral quarks connected by chromo-electric field: Strings.



## Conclusions to part II



**The holy QGP**

And then came the Age of Enlightenment...

