

# Dynamical chiral symmetry breaking and restoration

## Degeneracies of meson spectra from analytic structure

Reinhard Alkofer

Institute of Physics, University of Graz

BTSLXX Symposium, Budapest, June 11 - 12, 2026  
on the occasion of the 70th birthday of Prof. Tamás Sándor Bir'o



# Hot & Cold Baryonic Matter (HCBM) 2010 in Budapest



- 1 A new state of matter directly above  $T_\chi$ ?
- 2 Degeneracies and analytic structure
- 3 Quark propagators' poles and quark-gluon vertex
- 4 Cordial congratulations and a big "Thank You" ...

# A new state of matter directly above $T_\chi$ ?

- Yesterday's talk by Tamás Csörgö:  
A second transition in QCD?
- Adelaide lattice group:  
Evidence for a second finite- $T$  transition in QCD  
from center vortex (de-)percolation,  
see, e.g., 2411.19446.
- Fujimoto, Fukushima, Hidaka, McLerran:  
A new state of matter between the hadronic phase and the QGP?  
*Spaghetti of quarks with glueballs?*, *Quarkyonic Matter?*, see,  
e.g., 2506.00237
- Lowdon, Philipsen:  
Changed but identifiable spectral properties of pseudoscalar  
mesons through the QCD chiral crossover,  
2412.08371.



# A new state of matter directly above $T_\chi$ ?

What is going on in QCD in temperature range  
 $T_\chi \approx 150 \text{ MeV} < T < T_2 \approx 290 \text{ MeV}$ ?



Suggestion by L. Glozman: *Stringy Fluid*

- Observation by the Graz lattice group (2018):  
**All** spatial meson correlators PS-S-V- AV degenerate above  $T_\chi$ .
- Deduced symmetry from multiplet structure:

## Chiral Spin Symmetry

see, e.g., L.Y. Glozman, O. Philipsen, R.D. Pisarski, 2204.05083  
& L.Y. Glozman, 2209.10235.

- Applies to temperature range from  $T_\chi$  to 2 -3  $T_\chi$  (?).
- Symmetry of the purely chromoelectric part of QCD
- Basis for the picture of a stringy fluid as a state of matter.

Chiral Spin Symmetry is larger than symmetry of free fermions!?!



# Degeneracies and analytic structure

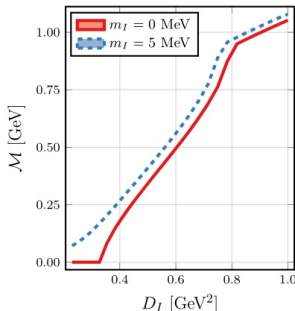
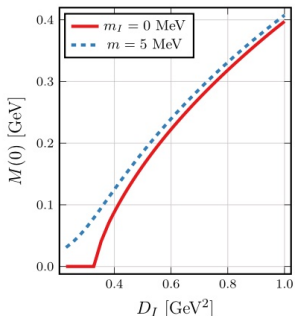
A complementary and/or additional view on such degeneracies:

[R.A., C.S. Fischer, F. Zierler, 2602.17456]

Solution of the quark propagator's Dyson-Schwinger and the mesons' Bethe-Salpeter equations in three models with an adjustable strength:

- Poles (at least three) of the quark propagator identified:  
Lowest-lying pole reflects quark constituent mass

Strength of chiral symmetry breaking



# Degeneracies and analytic structure

- Solutions of the mesons' Bethe-Salpeter equations:  
As function of coupling strength regions of  
**degenerate meson spectra!**

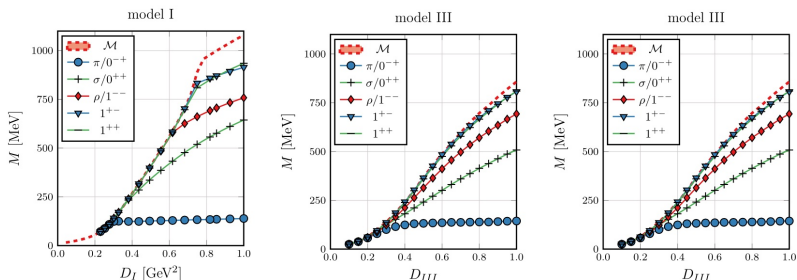


FIG. 4. Masses of mesons with quantum numbers  $J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}$  as functions of the strength parameters  $D_{I,III,III}$  of models I–III. In all cases we obtain the same pattern of degeneracy at small interaction strengths. Shown is furthermore the parameter  $\mathcal{M}$  characterizing the largest parabolic region symmetric to real  $p^2$  with apex  $-\mathcal{M}/4$ .

Generic observed pattern when going from weak to strong coupling:

Pseudoscalar mesons (= Goldstone bosons) non-degenerate, i.e., lighter, above chiral transition / crossover. 😊

Then:

**Whenever a quark propagator pole enters the domain of integration in the Bethe-Salpeter equation a degeneracy is lifted!**

- Suggests a direct link between the quark spectral function and its analytic properties to the observable meson spectra.
- Observed degeneracies in lattice data when going above  $T_\chi$ :  
Interaction strength weakens  
⇒ larger domain of analyticity for quark correlation functions  
⇒ degenerate spectra & an emergent symmetry?

Obvious task:

Perform a realistic calculation for  $T$  in range up to 2-3  $T_\chi$ .

Functional methods have been successfully applied to QCD at non-vanishing temperatures and densities,

see, e.g., C.S. Fischer, J.M. Pawłowski, contribution to the Encyclopedia of Nuclear Physics, 2606.03703.

However:

Time-like properties and analytic structure depend crucially on a precisely determined quark-gluon vertex ☹

# Quark propagators' poles and quark-gluon vertex

Most recent calculations of the quark-gluon vertex suggest:  
[see, e.g., G. Wieland, R.A., 2604.20235]

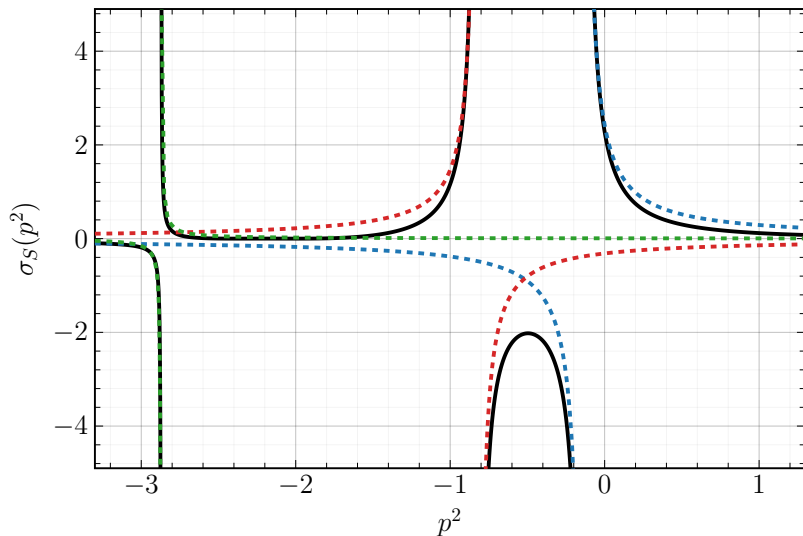
Two tensorial couplings,  
the anomalous **chromomagnetic** (cf. QED Pauli term) and  
the **spin-momentum curvature** ones  
are much more important for non-perturbative physics  
than the gluons' vector coupling (tree-level term)!

One of the many consequences:

Quark propagator poles at  $\approx 360$  and  $930$  MeV. (3rd pole at  $1.7$  GeV?)

# Quark propagators' poles and quark-gluon vertex

Scalar part of quark propagator (quenched calculation in chiral limit):



## 2nd pole possesses a negative residue!

Robust feature! Implies positivity violation!

Relation to quark confinement!?!?

[R.A., M.N. Ferreira, A.S. Miramontes, J.M. Morgado, J. Papavassiliou,  
in preparation]

Implications for physics at non-vanishing temperatures?

What is going on in QCD in temperature range  
 $T_\chi \approx 150 \text{ MeV} < T < T_2 \approx 290 \text{ MeV}$ ?

A mere speculation:

1st transition:

At  $T_\chi = 150 \dots 160 \text{ MeV}$  chiral crossover.

Above  $T_\chi$ : Degenerate hadron spectra but still confinement,  
a novel state of matter?

2nd transition:


At  $T_{YM} \approx 285 \text{ MeV}$  transition from strong / charge confinement to  
some Higgs-type confinement (maybe accompanied by an FMS  
mechanism) and  $U_A(1)$  restoration???

# Cordial congratulations & a big “Thank You” to Tamás!

Dear Tamás!

On behalf of the Graz Particle Physics Group I cordially congratulate you to your birthday! We wish you health, happiness and a lot of success in the years to come.

And a big “Thank You” for all your support of the Austrian-Croatian-Hungarian Triangle (ACHT) meetings from 2008 until now! We, the Graz group, enjoyed the 14 meetings a lot, and we appreciate all the efforts you took to make these meetings so successful.

Looking forward to the next one 

[Home](#) [Participants](#) [Speakers](#) [Programme](#) [Schedule](#)

## Non-Perturbative Functional Methods in Quantum Field Theory

A Triangle  
Workshop in  
Theoretical  
Particle Physics

Jan. 23 - 25, 2008  
Hévíz, Hungary



organized by  
Eötvös Loránd  
University Budapest

in cooperation with

Karl-Franzens  
Universität Graz,  
Rudjer Boskovic  
Institute Zagreb  
University of Zagreb

**The main goal** of the workshop is to bring together researchers actively investigating collective features of strong matter using variants of Dyson-Schwinger equations. We offer opportunity to participants to present in some detail their research subjects including the latest results. Plenty of time will be left for discussions with the hope that such personal encounters might efficiently initiate cooperation among groups geographically located within a circle of 200 km radius from Hévíz. In particular, delocalisation of young doctoral students and post-docs is strongly envisaged.

The workshop is open also to interested researchers from other institutions of the former Triangle Collaboration.

**Scientific program:** The subjects of the talks announced cover phenomenological and theoretical aspects of the Dyson-Schwinger approach to QCD, effective scalar theories of strong matter in vacuum and also in different environments. Special emphasis will be devoted to technical procedures of truncating the SD-hierarchy, treatment of symmetry breaking, explicit construction of renormalised (finite, cut-off independent) equations and their numerical solutions.