Dualities of the ($N_c = 2, 3, \infty$) QCD phase diagram: chiral imbalance, baryon density

Roman N. Zhokhov
IZMIRAN, IHEP

Russian Science Foundation
БАЗИС
Фонд развития теоретической физики и математики

K.G. Klimenko, IHEP

T.G. Khunjua, University of Georgia

details can be found in

JHEP 06 (2020) 148 arXiv:2003.10562 [hep-ph]
Phys.Rev. D100 (2019) no.3, 034009 arXiv: 1904.07151 [hep-ph]
JHEP 1906 (2019) 006 arXiv:1901.02855 [hep-ph]
Eur.Phys.J. C79 (2019) no.2, 151, arXiv:1812.00772 [hep-ph],
Phys.Rev. D98 (2018) no.5, 054030 arXiv:1804.01014 [hep-ph],
Phys.Rev. D97 (2018) no.5, 054036 arXiv:1710.09706 [hep-ph]
Phys.Rev. D95 (2017) no.10, 105010 arXiv:1704.01477 [hep-ph]

The work is supported by

- Russian Science Foundation (RSF)

  under grant number 19-72-00077

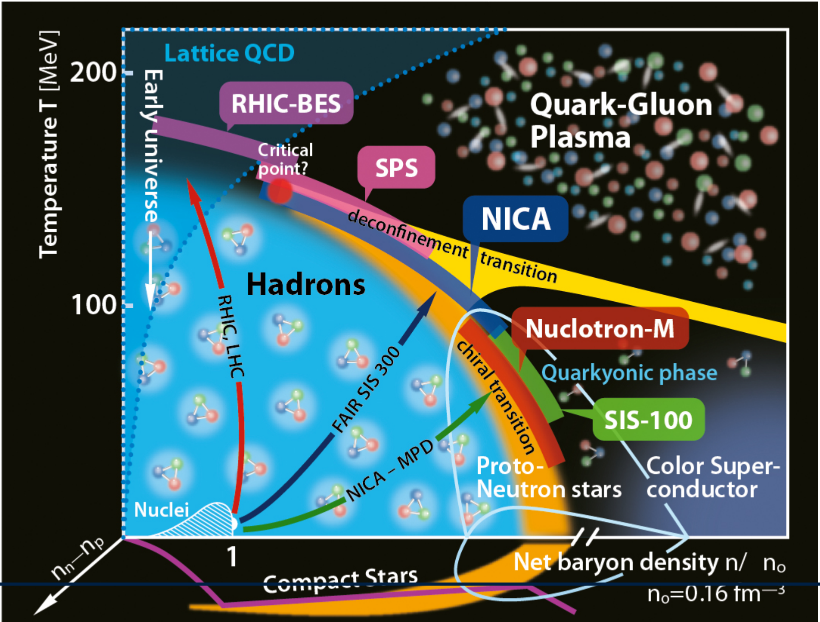
  RSF | Russian Science Foundation

- Foundation for the Advancement of Theoretical Physics and Mathematics

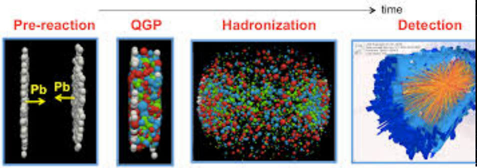
  БАЗИС

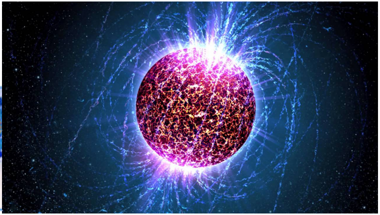
  Фонд развития теоретической физики и математики

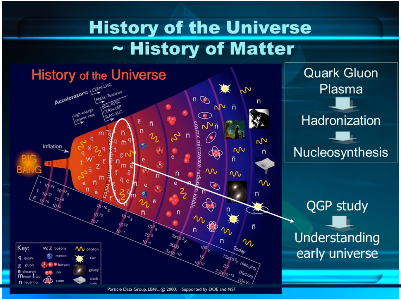
QCD at extreme conditions: QCD Dhase Diagram

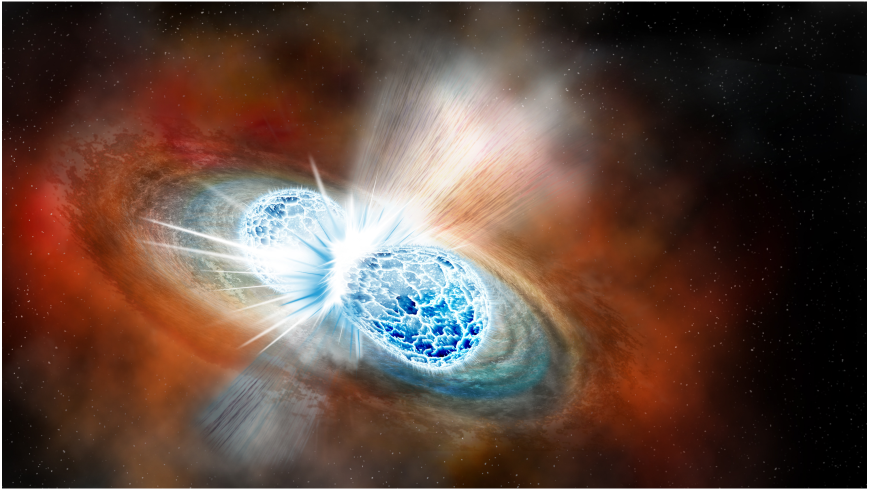


QCD at extreme conditions





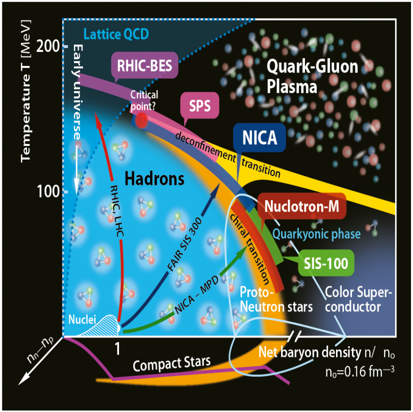




QCD Dhase Diagram and Methods

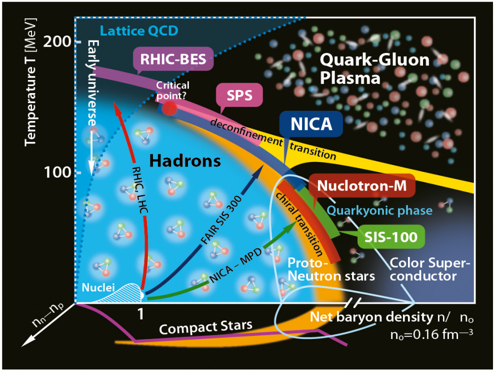
QCD at T and μ
(QCD at extreme conditions)

- heavy ion collisions
- neutron stars
- Early Universe
- Neutron star mergers



- Chiral symmetry breaking
- Confinement

QCD Phase Diagram

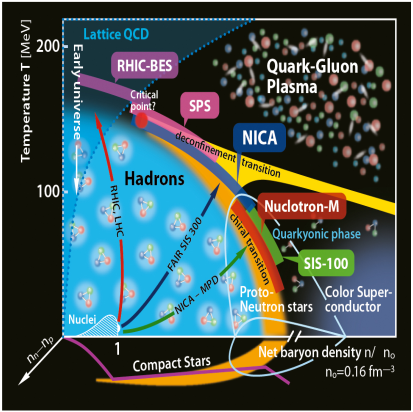


Two main phase transitions

- confinement-deconfinement
- chiral symmetry breaking phase—chriral symmetric phase

QCD at T and μ
(QCD at extreme conditions)

- neutron stars
- heavy ion collisions
- Early Universe
- Neutron star mergers

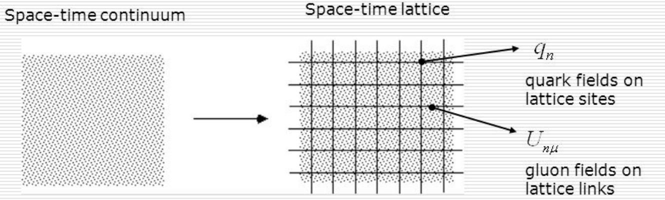


Methods of dealing with QCD

- First principle calcultion – lattice QCD
- Effective models
- DSE, FRG
- .....

QCD on a space-time lattice

K. G. Wilson 1974



- Feynman path integral
  - Action $S_{QCD} = \frac{1}{g_s^2} \sum_P tr(UUUU) + \sum_f \bar{q}_f (\gamma \cdot U + m_f) q_f$
  - Physical quantities as integral averages

Monte Carlo Evaluation of the path integral

$$\langle O(U,\bar{q},q) \rangle = \frac{1}{Z} \int \prod_{n\mu} dU_{n\mu} \prod_n d\bar{q}_n dq_n \, O(U,(U,\bar{q},q)) e^{-S_{QCD}}$$

lattice QCD at non-zero baryon chemical potential μ_B

It is well known that **at non-zero baryon chemical potential** μ_B **lattice simulation** is quite challenging due to the **sign problem**
complex determinant

$$(Det(D(\mu)))^{\dagger} = Det(D(-\mu^{\dagger}))$$

Methods of dealing with QCD

- perturbative QCD, pQCD, high energy
- First principle calcaltion – lattice Monte Carlo simulations, LQCD
- **Effective models**

Chiral pertubation theory χPT

Nambu–Jona-Lasinio model, NJL

Polyakov-loop extended Nambu–Jona-Lasinio model PNJL

Quark meson model

NJL model can be considered as **effective model for QCD**.

the model is **nonrenormalizable**
Valid up to $E < \Lambda \approx 1$ GeV $\mu, T < 600\,\mathrm{MeV}$

Parameters G, Λ, m_0 chiral limit $m_0 = 0$

dof– **quarks**, no gluons only **four-fermion interaction**

attractive feature — dynamical CSB

the main drawback – lack of confinement (PNJL)

Nambu–Jona-Lasinio model

$$\mathcal{L} = \bar{q}\gamma^{\nu}\mathrm{i}\partial_{\nu}q + \frac{G}{N_c}\Big[(\bar{q}q)^2 + (\bar{q}\mathrm{i}\gamma^5 q)^2\Big]$$

$$q \to e^{i\gamma_5\alpha}q$$

continuous symmetry

$$\widetilde{\mathcal{L}} = \bar{q}\Big[\gamma^{\rho}\mathrm{i}\partial_{\rho} - \sigma - \mathrm{i}\gamma^5\pi\Big]q - \frac{N_c}{4G}\Big[\sigma^2 + \pi^2\Big].$$

Chiral symmetry breaking

$1/N_c$ expansion, leading order

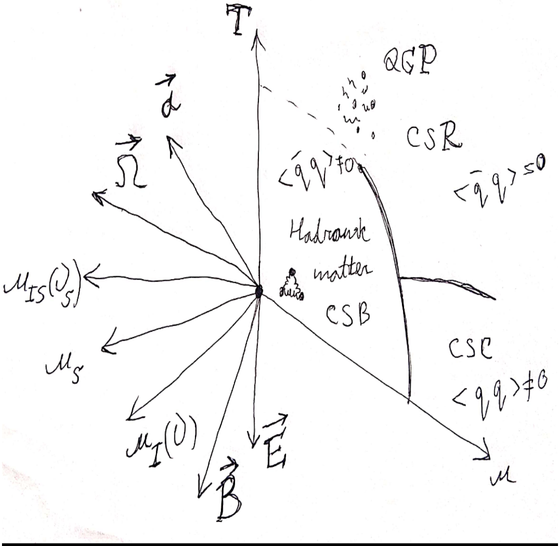
$$\langle\bar{q}q\rangle \neq 0$$

$$\langle\sigma\rangle \neq 0 \quad \longrightarrow \quad \widetilde{\mathcal{L}} = \bar{q}\Big[\gamma^{\rho}\mathrm{i}\partial_{\rho} - \langle\sigma\rangle\Big]q$$

More external conditions to QCD

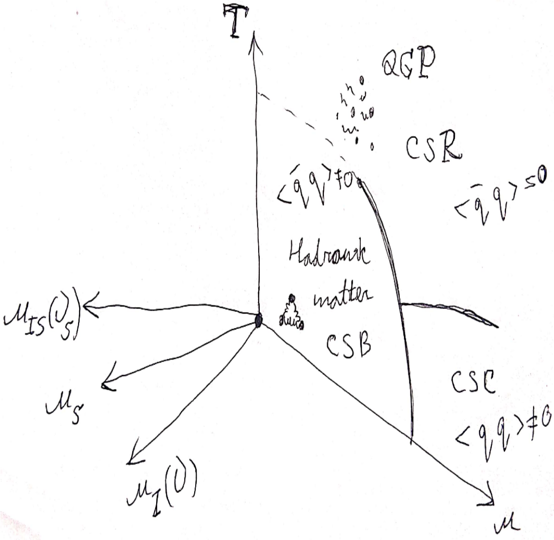
More than just QCD at (μ, T)

- more chemical potentials μ_i
- magnetic fields
- rotation of the system $\vec{\Omega}$
- acceleration $\vec{a}$
- finite size effects (finite volume and boundary conditions)



More than just QCD at (μ, T)

- **more chemical potentials** μ_i
- magnetic fields
- rotation of the system
- acceleration
- finite size effects (finite volume and boundary conditions)



Baryon chemical potential μ_B

Allow to consider systems with non-zero baryon densities.

$$\frac{\mu_B}{3}\bar{q}\gamma^0 q = \mu\bar{q}\gamma^0 q,$$

Baryon chemical potential μ_B

Allow to consider systems with non-zero baryon densities.

$$\frac{\mu_B}{3}\bar{q}\gamma^0 q = \mu\bar{q}\gamma^0 q,$$

Isotopic chemical potential μ_I

Allow to consider systems with isospin imbalance ($n_n \neq n_p$).

$$\frac{\mu_I}{2}\bar{q}\gamma^0\tau_3 q = \nu\left(\bar{q}\gamma^0\tau_3 q\right)$$

$$n_I = n_u - n_d \quad \longleftrightarrow \quad \mu_I = \mu_u - \mu_d$$

chiral (axial) chemical potential

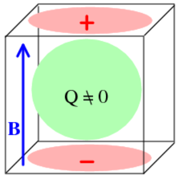
Allow to consider systems with chiral imbalance (difference between densities of left-handed and right-handed quarks).

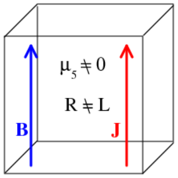
$$n_5 = n_R - n_L \quad \longleftrightarrow \quad \mu_5 = \mu_R - \mu_L$$

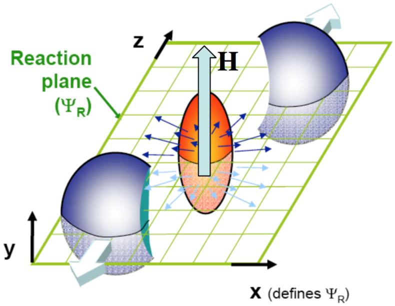
The corresponding term in the Lagrangian is

$$\mu_5 \bar{q} \gamma^0 \gamma^5 q$$

Chiral magnetic effect



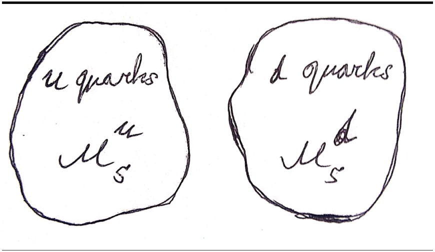




$$\vec{J} \sim \mu_5 \vec{B},$$

A. Vilenkin, PhysRevD.22.3080,
K. Fukushima, D. E. Kharzeev and H. J. Warringa, Phys. Rev. D **78** (2008) 074033

Chiral isospin imbalance



$$\mu_5^u \neq \mu_5^d \qquad \text{and} \qquad \mu_{I5} = \mu_5^u - \mu_5^d$$

Term in the Lagrangian — $\frac{\mu_{I5}}{2}\bar{q}\tau_3\gamma^0\gamma^5 q = \nu_5(\bar{q}\tau_3\gamma^0\gamma^5 q)$

$$n_{I5} = n_{u5} - n_{d5}, \qquad n_{I5} \quad \longleftrightarrow \quad \nu_5$$

Chiral isospin imbalance n_{I5} and μ_{I5} generation

- Chiral isospin imbalance n_{I5} and hence μ_{I5} can be **generated by** $\vec{E} \,||\, \vec{B}$

  (*for* n_5 *and* μ_5 *M. Ruggieri, M. Chernodub, H. Warringa et al*)

- in **dense quark matter**
  - Chiral separation effect
    (Thanks for the idea to Igor Shovkovy)
  - Chiral vortical effect

Different chemical potentials and matter content

$$\mu = \frac{\mu_B}{3}, \qquad \nu = \frac{\mu_I}{2}, \qquad \mu_5, \qquad \nu_5 = \frac{\mu_{I5}}{2}$$

Different chemical potentials and matter content

$$\mu = \frac{\mu_B}{3}, \qquad \nu = \frac{\mu_I}{2}, \qquad \mu_5, \qquad \nu_5 = \frac{\mu_{I5}}{2}$$

Two colour QCD case

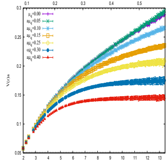
QC_2D

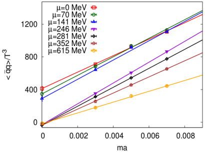
There are similar transitions:

- confinement/deconfinement
- chiral symmetry breaking/restoration

At large μ

- deconfinement
- chiral symmetry is restored





At large T

- deconfinement
- chiral symmetry is restored

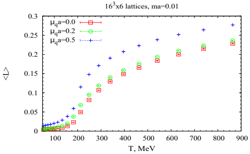


Figure 1 Polyakov loop as a function of T for three values of the baryon chemical potential.

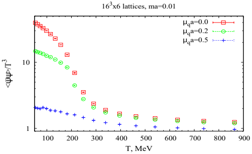


Figure 2: Chiral condensate as a function of T for three values of the baryon chemical potential. The ordinate axis is given on a logarithmic scale.

A lot of quantities coincide up to few dozens percent

SU(2)	**SU(3)**

Critical temperature

Phys. Lett. B712 (2012) 279-283, JHEP 02 (2005) 033

$T_c/\sqrt{\sigma}$=0.7092(36) $T_c/\sqrt{\sigma}$=0.6462(30)

Topological susceptibility

Nucl.Phys.B 715 (2005) 461-482

$\chi^{\frac{1}{4}}/\sqrt{\sigma}$=0.3928(40) $\chi^{\frac{1}{4}}/\sqrt{\sigma}$=0.4001(35)

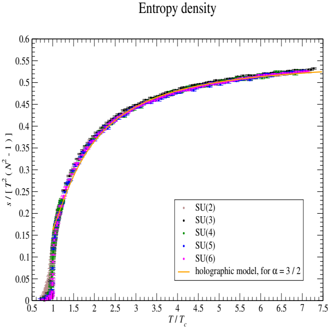
Shear viscosity

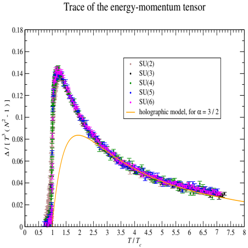
JHEP 1509 (2015) 082, Phys.Rev. D 76 (2007) 101701

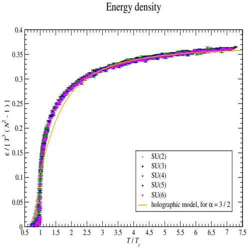
η/s=0.134(57) η/s= 0.102(56)

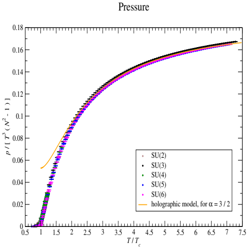
Thermodynamic properties are similar

The **entropy density** per gluon degree of freedom (N^2-1), in units of T^3, **as a function of the temperature** (in units of T_c), for the **gauge group SU(N$_c$)**. These are the results obtained from lattice simulations.

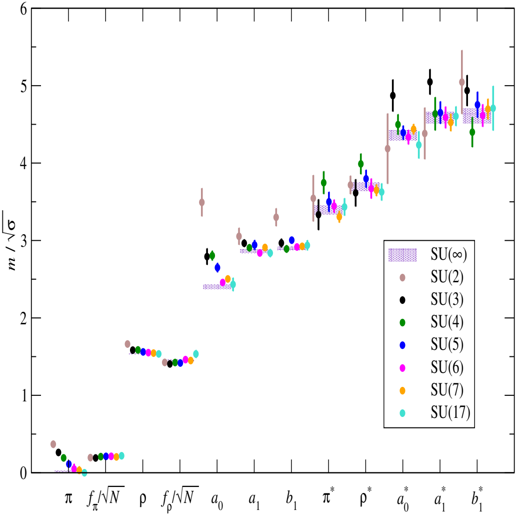








JHEP 1205 (2012) 135, arXiv:1111.0580 [hep-th]



Mesonic spectrum at different N_c are similar

Physics Reports 526 (2013) 93-163,

Masses (in units of the square root of the string tension σ) of various meson states, and the decay constants of the pion and the rho meson, obtained from from a quenched computation in the chiral limit.

Some properties of dense medium are similar

diquark condensate Δ at asymptotically large baryon chemical potential

$$\Delta = b\mu_B g^{-5} \exp\left(-\frac{c}{g}\right)$$

b and c are constants, g is the small gauge coupling

D. T. Son, Phys. Rev. D 59 (1999) 094019

T. Schaefer, F. Wilczek, Phys. Rev. D 60, 114033 (1999), arXiv:hep-ph/9906512

D.T. Son, M.A. Stephanov, arXiv:hep-ph/0011365

Quarks have baryon number one-half $B = 1/2$

Baryons consist of two quarks (diquarks) instead of three.

In effective NJL type models

Mesons (quark-antiquark)

Baryons (diquarks)

are

dynamic hadronic degrees of freedom

This can teach us important lessons about phase transitions of quark-hadron matter at non-zero baryon density

After bosonisation in NJL type models diquarks starts to be dynamical and investigations of $N_c = 2$ NJL type models, where both mesons (quark-antiquark composite fields) and baryons (diquarks) acts as dynamic hadronic degrees of freedom, can teach us important lessons about phase transitions of quark-hadron matter at non-zero baryon density.

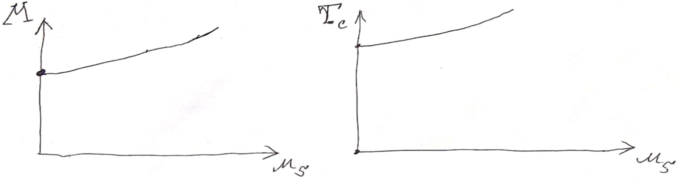
A number of papers predicted **anticatalysis** (T_c decrease with μ_5) of dynamical chiral symmetry breaking

A number of papers predicted **catalysis** (T_c increase with μ_5) of dynamical chiral symmetry breaking

lattice results show the **catalysis**

(ITEP lattice group, V. Braguta, A. Kotov, et al)

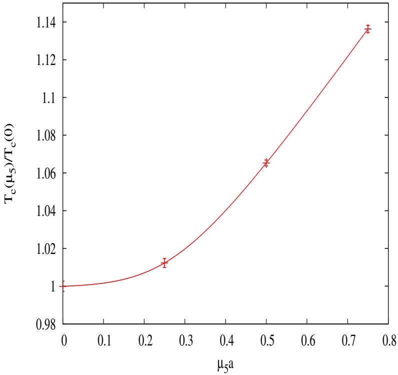
QCD at non-zero μ_5



catalysis of CSB by chiral imbalance:

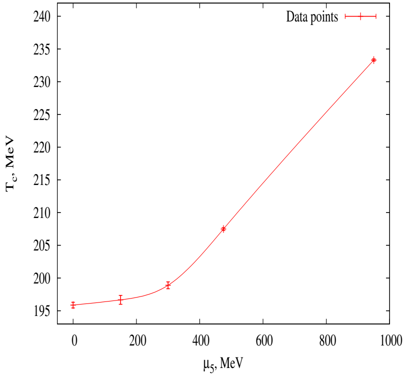
- increase of $\langle \bar{q} q \rangle$ as μ_5 increases
- increase of critical temperature T_c of chiral phase transition (crossover) as μ_5 increases

SU(2)



V. Braguta, A. Kotov et al, JHEP 1506, 094 (2015),PoS LATTICE 2014, 235 (2015)

SU(3)



V. Braguta, A. Kotov et al, Phys. Rev. D 93, 034509 (2016), arXiv:1512.05873 [hep-lat]

We consider a NJL model, which describes dense quark matter with two massless quark flavors (u and d quarks).

$$\mathcal{L} = \mathrm{i}\bar{q}\gamma^{\nu}\partial_{\nu}q + \bar{q}\mathcal{M}\gamma^{0}q +$$

$$+G\Big[(\bar{q}q)^2 + (\bar{q}i\gamma^5\vec{\tau}q)^2 + \left(\bar{q}i\gamma^5\sigma_2\tau_2 q^c\right)\left(\overline{q^c}i\gamma^5\sigma_2\tau_2 q\right)\Big]$$

q is the flavor doublet, $q = (q_u, q_d)^T$,

q_u and q_d are four-component Dirac spinors.

$q^c = C\bar{q}^T$, $\overline{q^c} = q^T C$ are charge-conjugated spinors.

$$\mathcal{L} = \mathrm{i}\bar{q}\gamma^\nu \partial_\nu q + \bar{q}\mathcal{M}\gamma^0 q +$$

$$+\mathrm{G}\Big[(\mathrm{q})^2 + (\bar{q}i\gamma^5\vec{\tau}q)^2 + \big(\bar{q}i\gamma^5\sigma_2\tau_2 q^c\big)\big(\overline{q^c}i\gamma^5\sigma_2\tau_2 q\big)\Big]$$

quark matter with nonzero

baryon density $n_B = (n_u + n_d)/3 \equiv n_q/3$ (conjugated to μ_B)

isospin density $n_I = (n_u - n_d)/2$ (conjugated to μ_I)

chiral isospin density $n_{I5} = (n_{u5} - n_{d5})/2$ (conjugated to μ_{I5})

$$\bar{q}\mathcal{M}\gamma^0 q \equiv \bar{q}\left[\frac{\mu_B}{2} + \frac{\mu_I}{2}\tau_3 + \frac{\mu_{I5}}{2}\gamma^5\tau_3 + \mu_5\gamma^5\right]\gamma^0 q$$

To find the thermodynamic potential we use a semi-bosonized version of the Lagrangian

$$\tilde{L} = \bar{q}\Big[i\hat{\partial} + \mathcal{M}\gamma^0 - \sigma - i\gamma^5\vec{\tau}\vec{\pi}\Big]q - \frac{\sigma^2 + \vec{\pi}^2}{4G} - \frac{\Delta^*\Delta}{4H}$$
$$-\frac{\Delta}{2}\left[\bar{q}i\gamma^5\sigma_2\tau_2 q^c\right] - \frac{\Delta^*}{2}\left[\overline{q^c}i\gamma^5\sigma_2\tau_2 q\right]$$

Equations of motion for bosonic fields

$$\sigma(x) = -2G(\bar{q}q); \quad \pi_a(x) = -2G(\bar{q}\mathrm{i}\gamma^5\tau_a q)$$
$$\Delta(x) = -2H\left[\overline{q^c}i\gamma^5\sigma_2\tau_2 q\right] = -2H\left[q^T C i\gamma^5\sigma_2\tau_2 q\right]$$
$$\Delta^*(x) = -2H\left[\bar{q}i\gamma^5\sigma_2\tau_2 q^c\right] = -2H\left[\bar{q}i\gamma^5\sigma_2\tau_2 C\bar{q}^T\right]$$

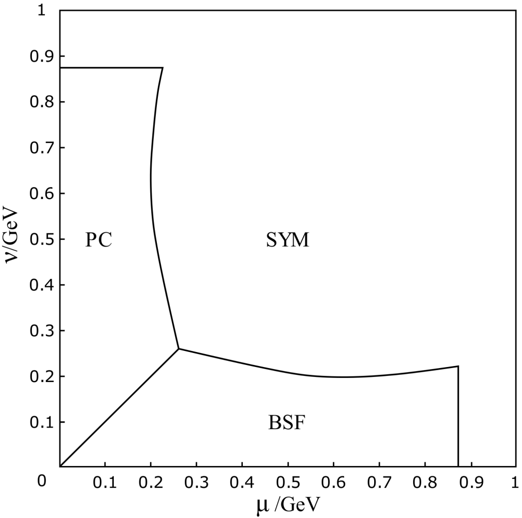
Condansates ansatz $\langle\sigma(x)\rangle$, $\langle\pi_a(x)\rangle$ and $\langle\Delta(x)\rangle$ do not depend on spacetime coordinates

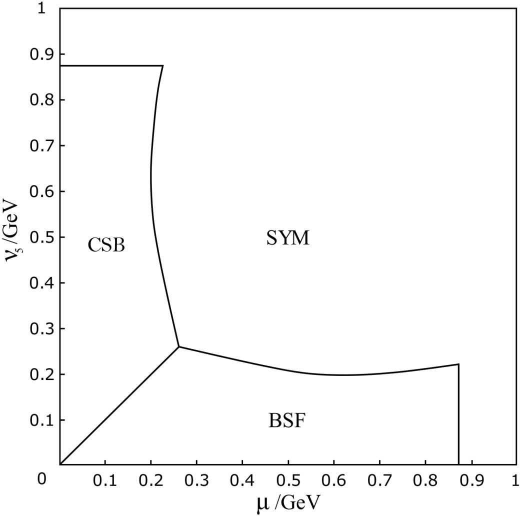
$$\langle\sigma(x)\rangle = M, \quad \langle\pi_1(x)\rangle = \pi, \quad \langle\pi_2(x)\rangle = 0, \quad \langle\pi_3(x)\rangle = 0,$$

$$\langle\Delta(x)\rangle = \langle\Delta^*(x)\rangle = \Delta$$

where M, π and Δ are already constant quantities.

Phase structure of QC_2D: $(\mu,\ \nu)$-phase diagram




CSB
SYM
BSF
ν_5 /GeV
μ /GeV
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Phase structure of QC_2D: $(\nu,\ \nu_5)$-phase diagram

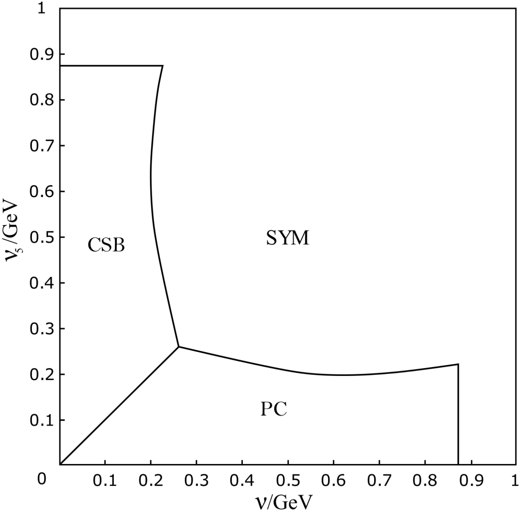


fig1_1-eps-converted-to.pdf

Dualities

It is not related to holography or gauge/gravity duality

it is the dualities of the phase structures of different systems

The TDP

$\Omega(T, \mu, \mu_i, ..., \langle \bar{q}q \rangle, ...)$

The TDP

$$\Omega(T, \mu, \mu_i, ..., \langle \bar{q} q \rangle, ...) \qquad \Omega(T, \mu, \nu, \nu_5, ..., M, \pi, ...)$$

The TDP

$$\Omega(T, \mu, \mu_i, ..., \langle \bar{q} q \rangle, ...) \qquad \Omega(T, \mu, \nu, \nu_5, ..., M, \pi, ...)$$

The TDP (phase daigram) is invariant under

Interchange of - condensates - matter content

$$\Omega(M, \pi, \nu, \nu_5)$$

$$M \longleftrightarrow \pi, \qquad \nu \longleftrightarrow \nu_5$$

$$\Omega(M, \pi, \nu, \nu_5) = \Omega(\pi, M, \nu_5, \nu)$$

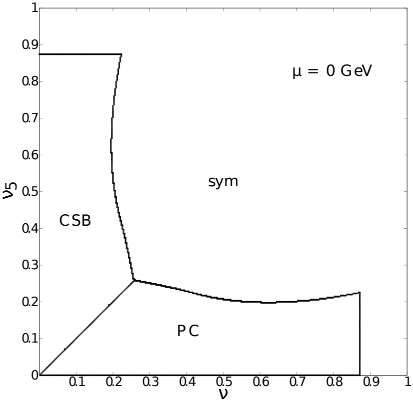


Figure: NJL model results

$$\Omega(M, \pi, \nu, \nu_5) = \Omega(\pi, M, \nu_5, \nu)$$

$$\mathcal{D}: \; M \longleftrightarrow \pi, \quad \nu \longleftrightarrow \nu_5$$

Duality between chiral symmetry breaking and pion condensation

$$\text{PC} \longleftrightarrow \text{CSB} \quad \nu \longleftrightarrow \nu_5$$

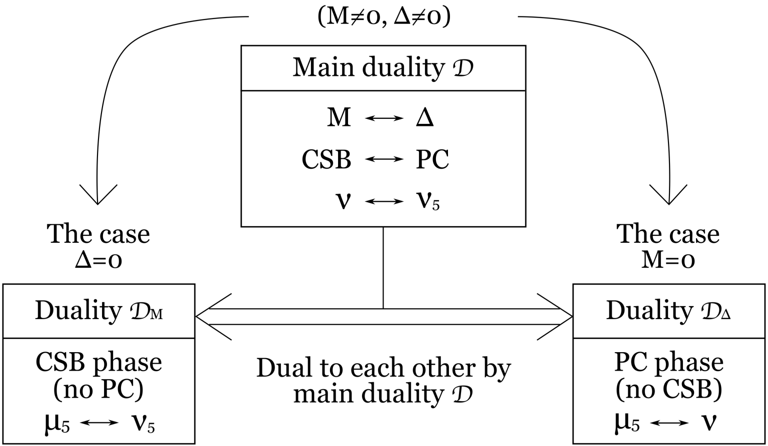
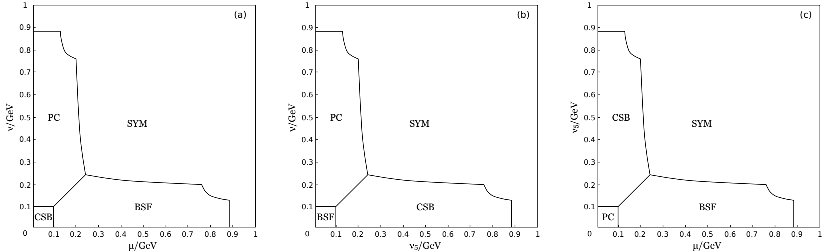


Figure: Dualities

Dualities in QC_2D



$$(a) \qquad \mathcal{D}_1: \quad \mu \longleftrightarrow \nu, \quad \pi_1 \longleftrightarrow |\Delta|$$

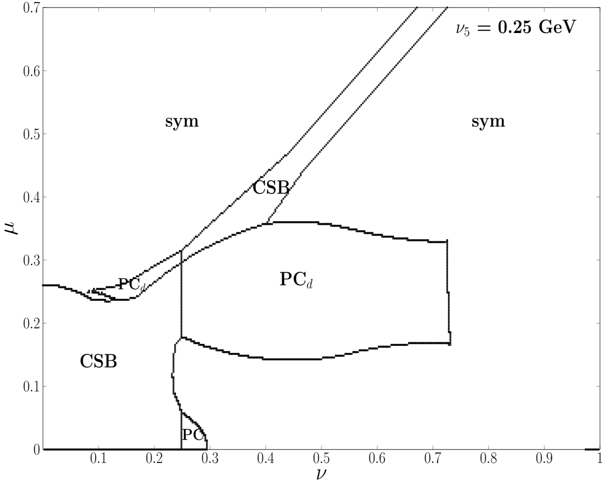
$$(b) \qquad \mathcal{D}_3: \quad \nu \longleftrightarrow \nu_5, \quad M \longleftrightarrow \pi_1$$

$$(c) \qquad \mathcal{D}_2: \quad \mu \longleftrightarrow \nu_5, \quad M \longleftrightarrow |\Delta|$$

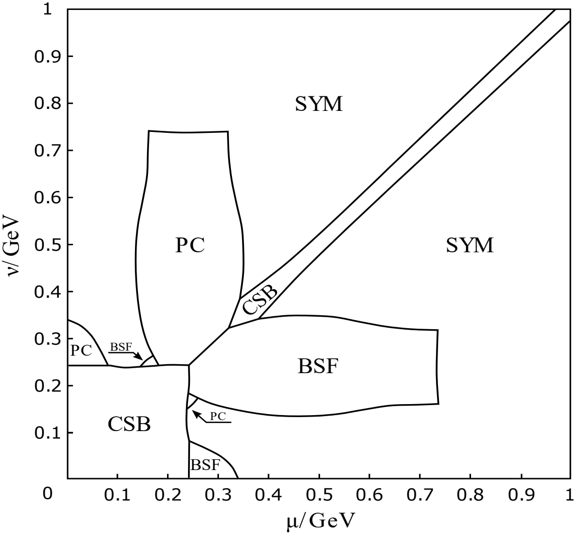
Uses of Dualities

How (if at all) it can be used

in three color case discussed in Particles 2020, 3(1), 62-79


ν_5 = 0.25 GeV
sym
sym
CSB
PC$_d$
PC$_d$
CSB
PC
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
μ
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
ν

Phase structure of QC_2D



- Based on the **duality** one can show that there is **no mixed phase**, i.e. two non-zero condensates simultaneously.

  This greatly simplifies the numeric calculations.

- Phase diagram is **highly symmetric** due to **dualities**

  The **whole phase diagram**, including diquark condensation, **in two color case** can be obtained from the results of **three color case** without any diquark condensation.

In the early 1970s Migdal (Sawyer, Scalapino, Kogut, Manassah) suggested the possibility of **pion condensation in a nuclear matter**

A.B. Migdal, Zh. Eksp. Teor. Fiz. 61, 2210 (1971) [Sov. Phys. JETP 36, 1052 (1973)]; A. B. Migdal, E. E. Saperstein, M. A. Troitsky and D. N. Voskresensky, Phys. Rept. 192, 179 (1990). R.F. Sawyer, Phys. Rev. Lett. 29, 382 (1972); J. Kogut, J.T. Manassah, Physics Letters A, 41, 2, 1972, Pages 129-131

(In medium pion mass properties and the RMF models.) **pion condensation** with zero momentum (s-wave condensation) is **highly unlikely to be realized** in nature in **matter of neutron star.**

A. Ohnishi D. Jido T. Sekihara, and K. Tsubakihara, Phys. Rev. C80, 038202 (2009) . .

Pion condensation in NJL model, chiral limit

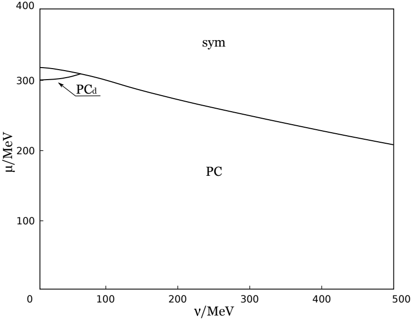


Figure: (ν, μ) phase diagram in NJL model in the chiral limit.

PC phenomenon maybe could be realized in **dense baryonic matter (non-zero baryon density**

K. G. Klimenko, D. Ebert
J.Phys. G32 (2006) 599-608;
Eur.Phys.J.C46:771-776,(2006)

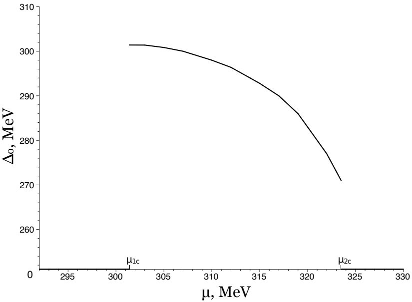
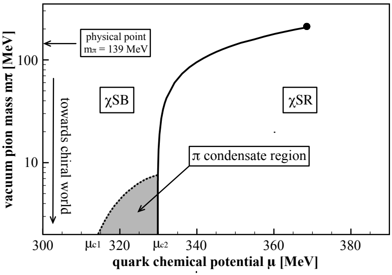


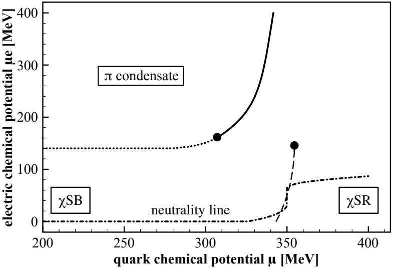
Figure: Pion condensate in dense quark matter in NJL model.

PC phenomenon is realized in **dense baryonic matter**

even in **charge neutral and β-equilibrated case**

K. G. Klimenko, D. Ebert
J.Phys. G32 (2006) 599-608;
Eur.Phys.J.C46:771-776,(2006)





(μ,m_0) phase portrait. (μ,μ_e) phase portrait.

No PC condensation in the neutral case at the physical point

(H. Abuki, R. Anglani, M. Ruggieri etc.
Phys. Rev. D **79** (2009) 034032.

Pion condensation in NJL model, physical point

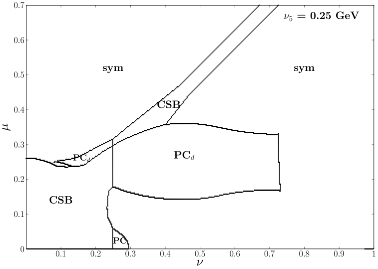
There are a number of **external parameters** such as **chiral imbalance** that can generate **PC in dense quark matter**.

See small review

Symmetry 2019, 11(6), 778
arXiv:1912.08635 [hep-ph]

Special Issue "Nambu-Jona-Lasinio model and its applications" of symmetry

(Thanks to Tomohiro Inagaki)



Charge neutrality and β-equilibrium can destroy the generation of PC

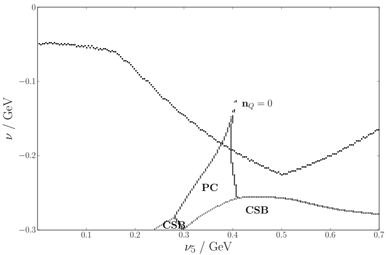
So it is interesting to see if chiral imbalance can generate PC in dense quark matter even in this case

- Charge neutrality and β-equilibrium in neutron stars
- There are constraints in HIC ($n_Q = 0.4 n_B$)

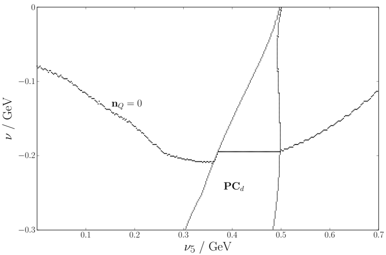
  Hot QCD Collaboration arXiv:1812.08235 [hep-lat]
- Or β-equilibrium in neutron star mergers

  Mark Alford Phys. Rev. C 98, 065806 (2018); arXiv:1803.00662 [nucl-th]

Chiral imbalance and electric neutrality



$(\nu_5,\, \nu)$ phase portrait at $\mu =$ 450 MeV and $\mu_5 = 0$.



$(\nu_5,\, \nu)$ phase portrait at $\mu =$ 500 MeV and $\mu_5 = 150$ MeV.

Chiral imbalance generates the charged pion condensation in dense electric neutral matter.

There have been discussed several **mechanism of generation of chiral imbalance in neutron stars**.

It is interesting in light of new and expected data on masses and radii to extend the studies and

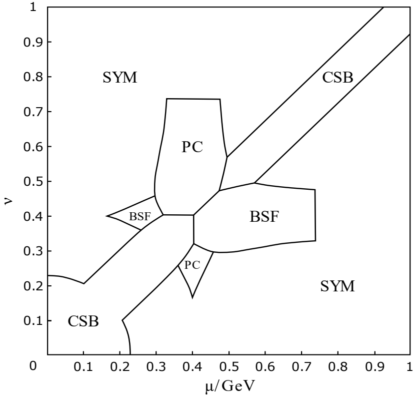
- find the **EOS** in the presence of **chiral imbalance**

- and explore **the M-R relation** for **neutron star with chiral imbalance**

(Consideration of phase structure of dense electric neutral baryonic matter with β-equilibrium is a first step in that direction.)

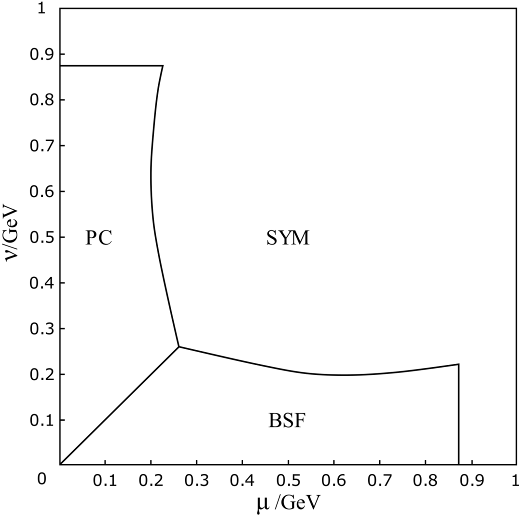
PC_d phase and diquark condensation

- PC_d phase has been predicted without possibility of diquark condensation
- Diquark condensation can take over the PC_d phase
- In two colour case diquark condensation is in a sense even stronger than in three colour case and starts from $\mu > 0$



PC_d phase is unaffected by BSF phase in two color case. Maybe one can infer that it is the case also for 3 color QCD

Diquark phase at non-zero μ_B



Duality, Chiral limit

$$\mathcal{L}_{\rm QCD} = \sum_{f=u,d} \bar{q}_f (i\not{D} - m_f) q_f - \frac{1}{4}\mathcal{G}_{\mu\nu,a}\mathcal{G}^{\mu\nu}_a .$$

$$\mathcal{L}_{\rm NJL} = \sum_{f=u,d} \bar{q}_f \Big[\mathrm{i}\gamma^\nu \partial_\nu - m_f \Big] q_f + \frac{G}{N_c}\Big[(\bar{q}q)^2 + (\bar{q}\mathrm{i}\gamma^5 \vec{\tau} q)^2 \Big]$$

m_f is current quark masses

In the chiral limit $m_f = 0$ the Duality $\mathcal{D}$ is exact

m_f : $\frac{m_u + m_d}{2} \approx 3.5$MeV
In our case typical values of $\mu, \nu, ..., T, .. \sim 10 - 100s$ MeV, for example, 200-400 MeV
One can work in the chiral limit $m_f \to 0$
$m_f = 0 \quad \to \quad m_\pi = 0$
physical m_f a few MeV $\quad \to \quad$ physical $m_\pi \sim 140$ MeV

Duality between CSB and PC is **approximate** in **physical point**

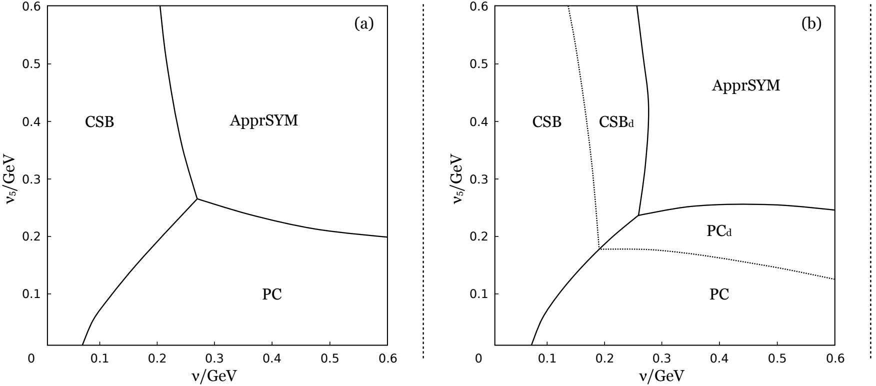


Figure: (ν, ν_5) phase diagram

Dualities on the lattice

$(\mu_B, \mu_I, \mu_{I5}, \mu_5)$

$\mu_B \neq 0$ impossible on lattice but if $\mu_B = 0$

$\mu_B \neq 0$ impossible on lattice but if

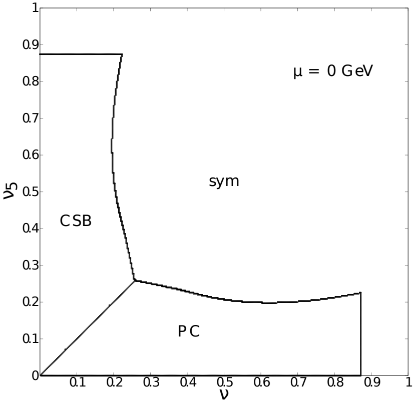
$$\mu_B = 0$$

- **QCD at** μ_5 —- (μ_5, T)

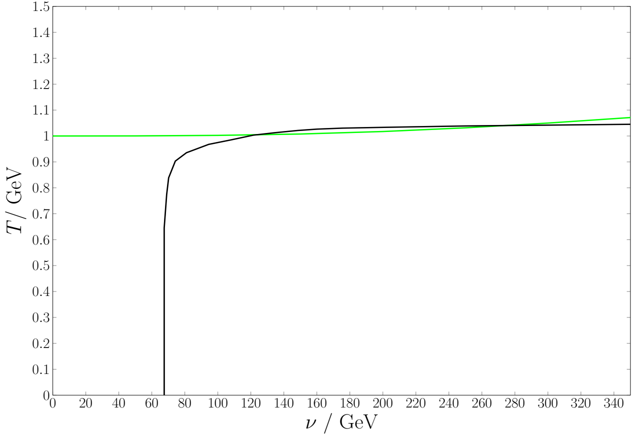
  V. Braguta, A. Kotov et al, ITEP lattice group

- **QCD at** μ_I —- (μ_I, T)

  G. Endrodi, B. Brandt et al, Emmy Noether junior research group, Goethe-University Frankfurt, Institute for Theoretical Physics ()



Dualities on the lattice



T_c^M as a function of μ_5 (green line) and $T_c^{\Delta}(\nu)$ (black)

- (μ_B, μ_I, ν_5)-phase diagram of two color QCD was studied
  PC *in dense matter with chiral imbalance*
  in *in dense electic neutral matter in β-equilibrium*
- It was shown that there exist dualities
- Richer structure of Dualities in the two colour case
- There have been shown how dualities can be used
- the generation of PC *in dense matter by chiral imbalance* is not obstructed by diquark condensation