# Study of quark-gluon matter within lattice simulation of QCD

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ITEP

15 February, 2016

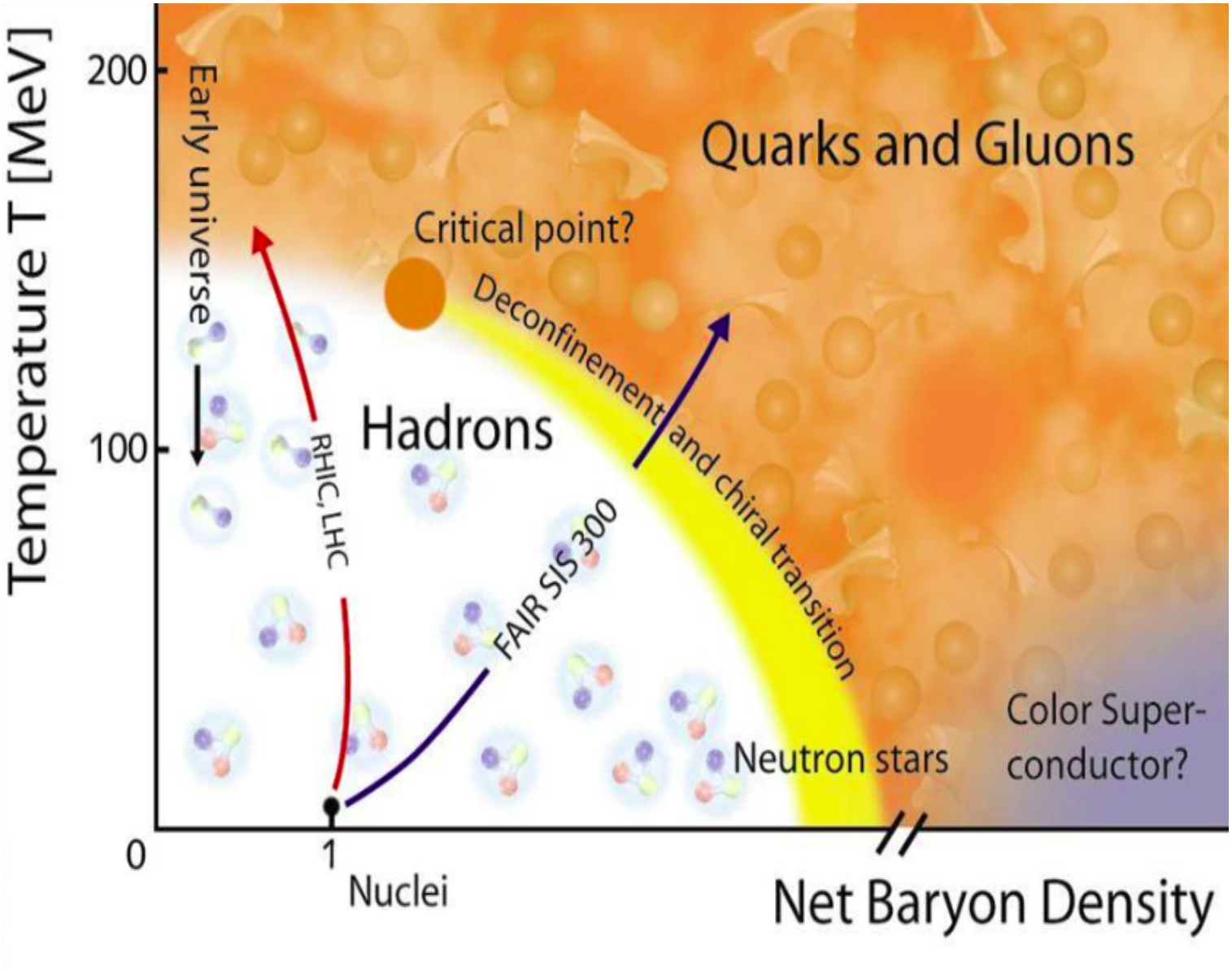
- Title of the project:
  **Study of quark-gluon matter within lattice simulation of QCD**
- Leader:
  **V.V. Braguta**
- Team:
  - **A.Yu. Kotov**
  - **A.A. Nikolaev**
  - **N.Yu. Astrakhantsev**
- Numerical simulations were performed at
  - ITEP supercomputer
  - Federal center for collective usage at NRC Kurchatov Institute

## GOALS OF THE PROJECT

- Dense two-color QCD
- Anomalous transport phenomena
- Transport coefficients of QCD

# PROPERTIES DENSE SU(3) QCD FROM STUDY OF DENSE SU(2) QCD

# QCD phase diagram



## SU(3) QCD

- $Z = \int DUD\bar{\psi}D\psi \ \exp\left(-S_G - \int d^4x\bar{\psi}(\hat{D}+m)\psi\right) =$
  $= \int DU \exp\left(-S_G\right) \times \det\left(\hat{D}+m\right)$
- Eigenvalues go in pairs $\hat{D}$ : $\pm i\lambda \Rightarrow$
  $\det\left(\hat{D}+m\right) = \prod_\lambda(\lambda^2+m^2) > 0$
  i.e. one can use lattice simulation
- Introduce chemical potential: $\det\left(\hat{D}+m\right) \rightarrow \det\left(\hat{D}-\mu\gamma_4+m\right) \Rightarrow$
  the determinant becomes complex (sign problem)

## SU(2) QCD

- $(\gamma_5 C\tau_2)\cdot D^* = D\cdot(\gamma_5 C\tau_2)$
- Eigenvalues go in pairs $\hat{D}-\mu\gamma_4$: $\lambda, \lambda^*$
- For even $N_f$ $\det\left(\hat{D}-\mu\gamma_4+m\right) > 0 \ \Rightarrow$ free from sign problem

## Similarities:

- There are transitions: confinement/deconfinement, chiral symmetry breaking/restoration
- A lot of observables are equal up to few dozens percent:

**Topological susceptibility** (Nucl.Phys.B715(2005)461):

$\chi^{1/4}/\sqrt{\sigma} = 0.3928(40)$ $(SU(2))$, $\chi^{1/4}/\sqrt{\sigma} = 0.4001(35)$ $(SU(3))$

**Critical temperature** (Phys.Lett.B712(2012)279):

$T_c/\sqrt{\sigma} = 0.7092(36)$ $(SU(2))$, $T_c/\sqrt{\sigma} = 0.6462(30)$ $(SU(3))$

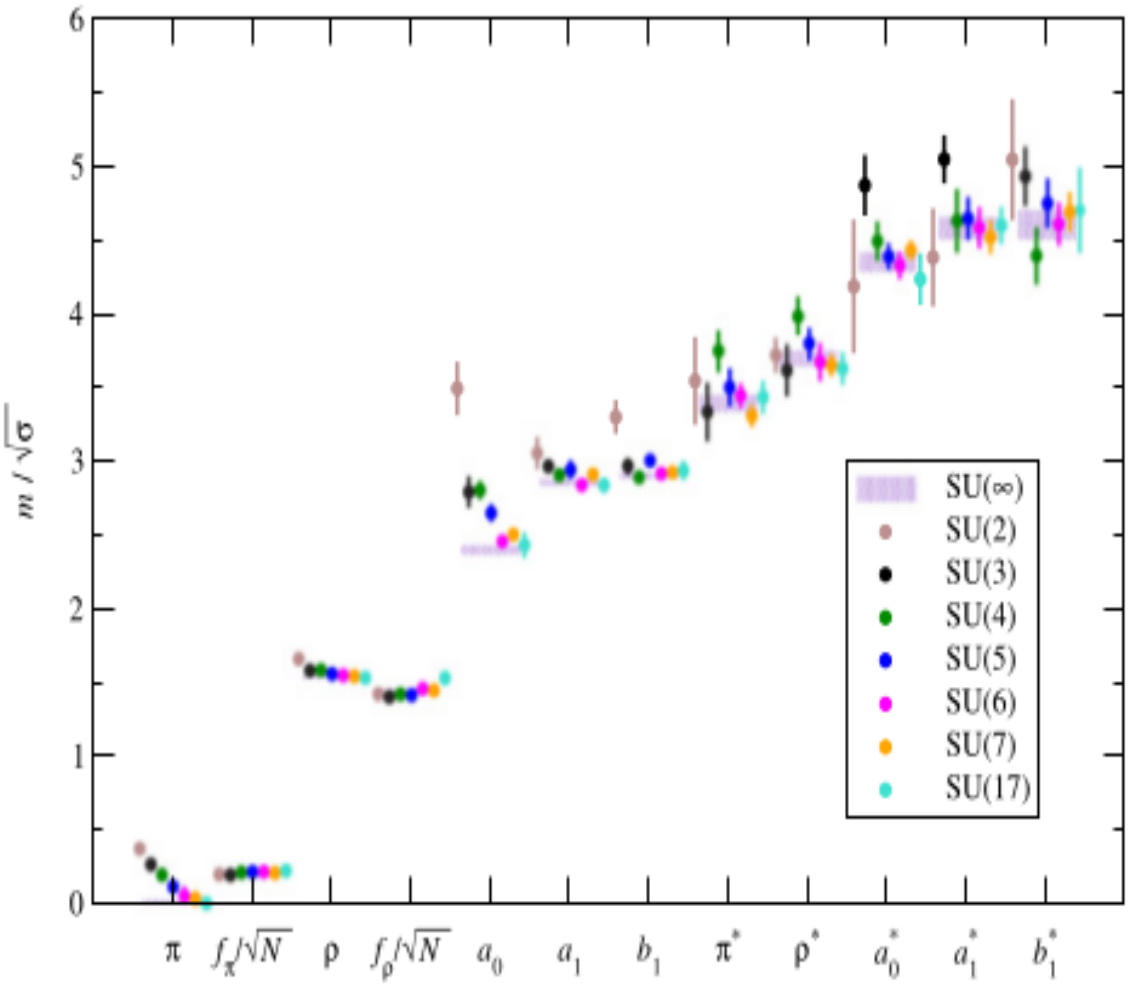
**Shear viscosity** :

$\eta/s = 0.134(57)$ $(SU(2))$, $\eta/s = 0.102(56)$ $(SU(3))$

JHEP 1509(2015)082 Phys.Rev. D76(2007)101701

## Similarities:

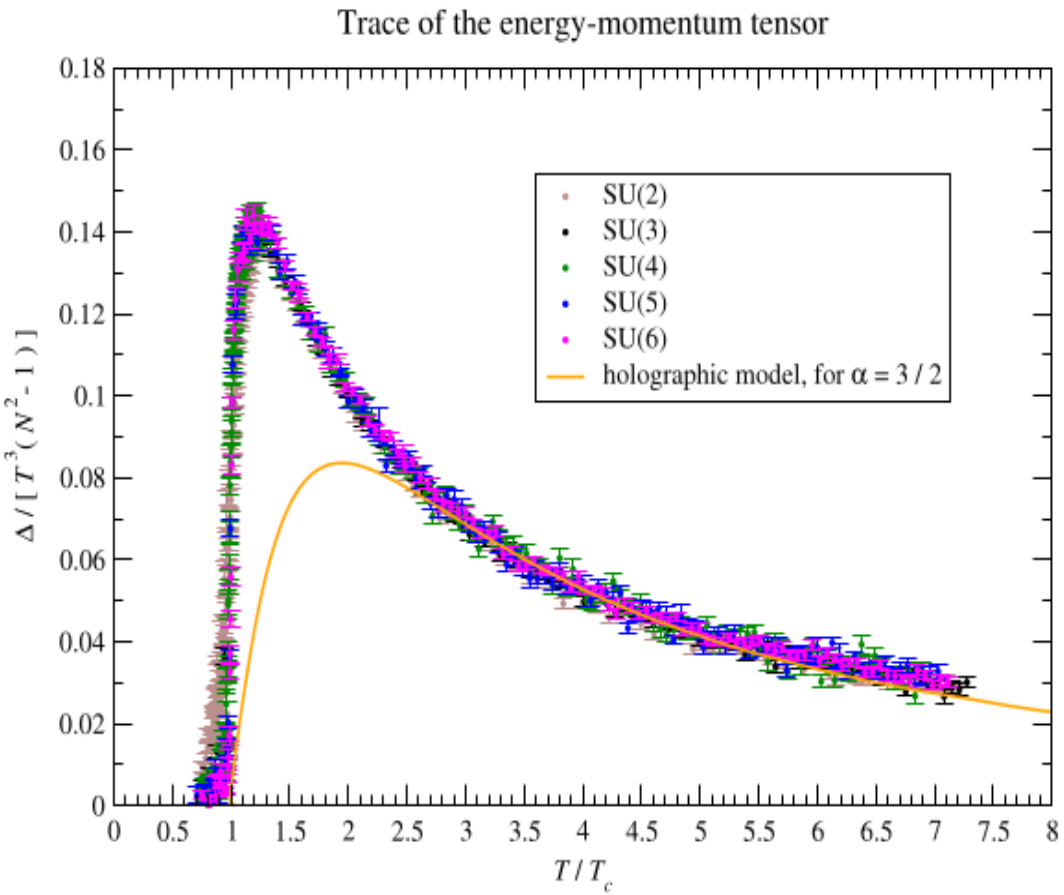
- **Spectroscopy** (Phys.Rep.529(2013)93)



## Similarities:

- Thermodynamic properties (JHEP 1205(2012)135)
- Properties of dense medium (Phys.Rev.D59(1999)094019):

$$\Delta \sim \mu g^{-5} \exp\left(-\frac{3\pi^2}{\sqrt{2}g}\right)$$



## To summarize:

- Dense SU(2) QCD can be used to study dense SU(3) QCD
  - Calculation of different observables
  - Study of different physical phenomena
- Lattice study of SU(2) QCD contains full dynamics of real system (contrary to phenomenological models)

## Current status:

- We have accomplished the code for lattice simulation of dense SU(2) QCD
  - Staggered dynamical fermions
  - Rooting (in continuum $N_f = 2$ quarks)
  - Improved action (rapid convergence to continuum)
- We have studied the phase diagram of dense two-color QCD up to the chemical potential $\mu \sim 1000$ MeV
  ( baryon density $\sim 10\times$(nuclear density) )
- We are conducting simulations at extremely large baryon density

## Results:

- We observe $\mu < m_\pi/2$ hadronic phase
- Transition to superfluid phase $\mu \simeq m_\pi/2$ (BEC)
- $\mu > m_\pi/2, \mu < m_\pi/2 + 150$ MeV dilute baryon gas
- Hadronic phase and BEC phase are well described by CHPT
- Deviation from CHPT from $\mu > 350$ MeV (dense matter)
- BCS phase $\mu \sim 500$ MeV, transition BEC$\rightarrow$BCS is smooth
- BCS phase is similar to quarkyonic phase

**FIRST PAPER WHERE ALL PHASES ARE OBSERVED!**

**BEST PAPER IN THIS DOMAIN!**

## Quarkyonic phase:

- Baryons (on the surface) ✓
- Quarks (inside the Fermi sphere $|p| < \mu$) ✓
- No chiral symmetry breaking ✓
- The system is in confinement phase ✓

**We observe quarkyonic phase**

**One can expect that there is quarkyonic phase in SU(3) theory**

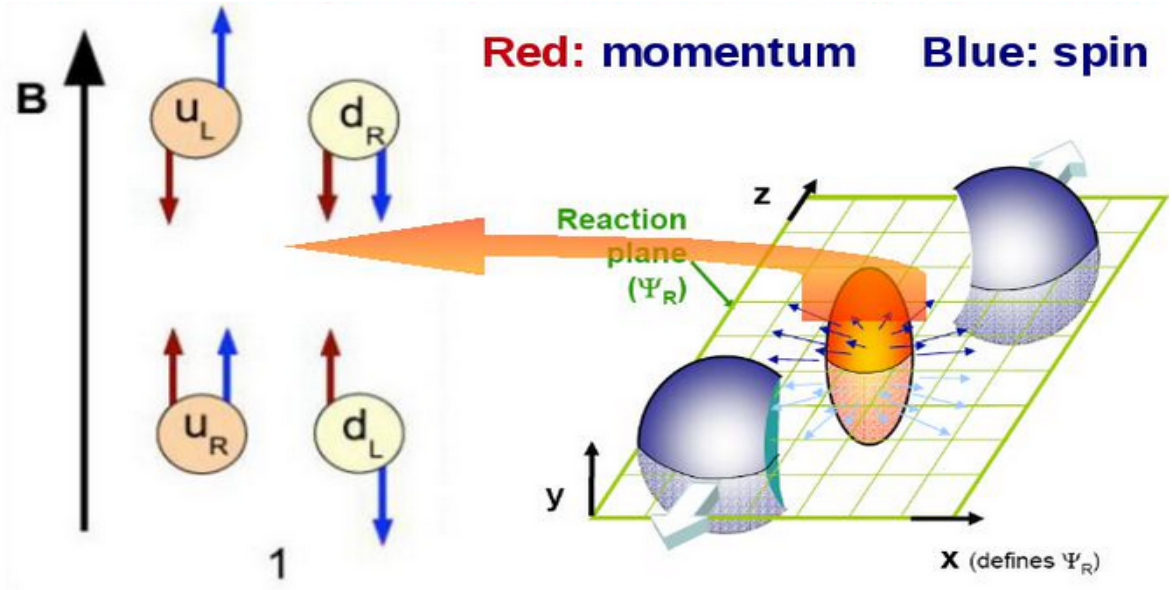
## Predictions for SU(3) (estimation!):

- Quarkyonic phase starts from $n \sim (5-10)\times$nuclear density
- Restoration of chiral symmetry ($(5-10)\times$nuclear density) $\Rightarrow$ can be seen in experiment

## Experimental signature:

- Chiral symmetry is restored (pions become heavy)
- Baryons on the surface of Fermi sphere ($p/\pi$ is increased)

# ANOMALOUS TRANSPORT PHENOMENA



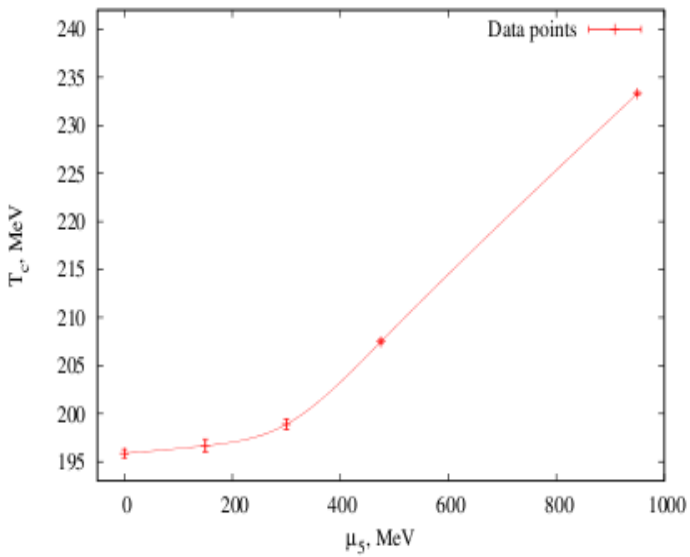

## Chiral magnetic effect

$$\vec{J}_V = \frac{\mu_5}{2\pi^2}\vec{H}$$

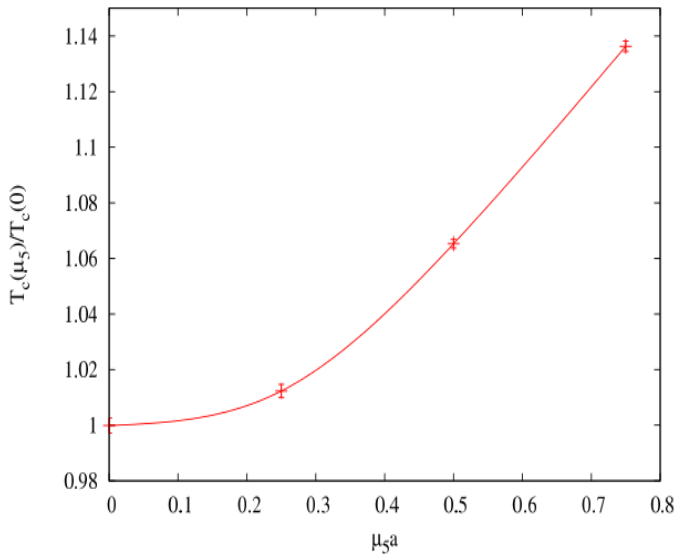
Can be studied in experiment ( observed at RHIC and LHC)

## The first lattice study of QCD like theories with nonzero $\mu_5$

- We studied the phase diagram of SU(2) QCD with dynamical staggered fermions and nonzero $\mu_5$
- We studied the phase diagram of SU(3) QCD with dynamical Wilson fermions and nonzero $\mu_5$



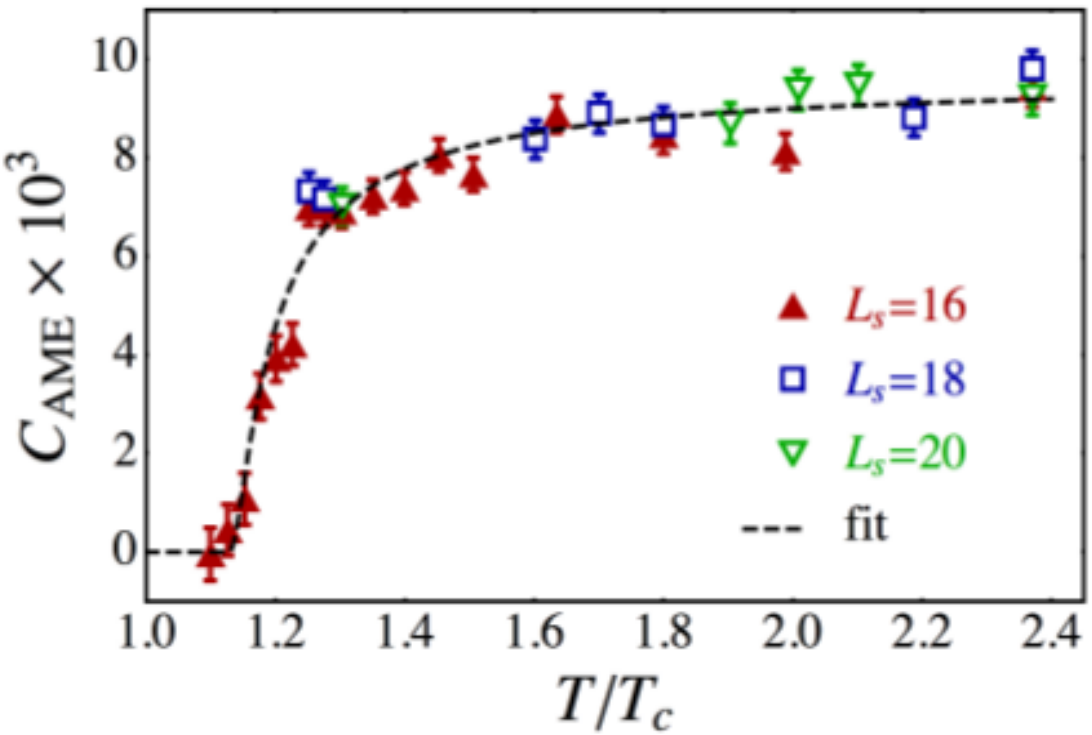

SU(2)




SU(3)

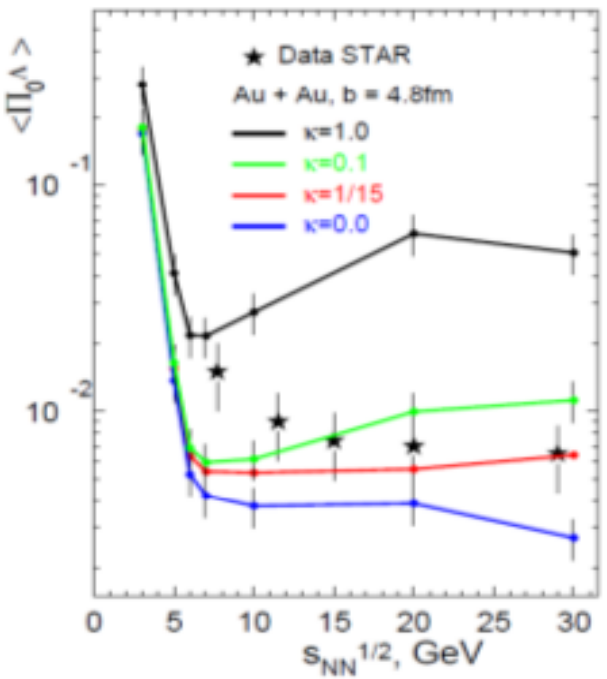
## Anomalous transport phenomena

- Axial magnetic effect: $T^{0i} = \sigma_A^{\epsilon} B_5$
- Axial chiral vortical effect: $J_A = \sigma_A \omega$
- $\sigma_A^{\epsilon} = \sigma_A$
- We have studied temperature dependence of the ACVE: $C_{AME} = \frac{\sigma_A}{T^2}$



# Gravitational anomaly "measurement"

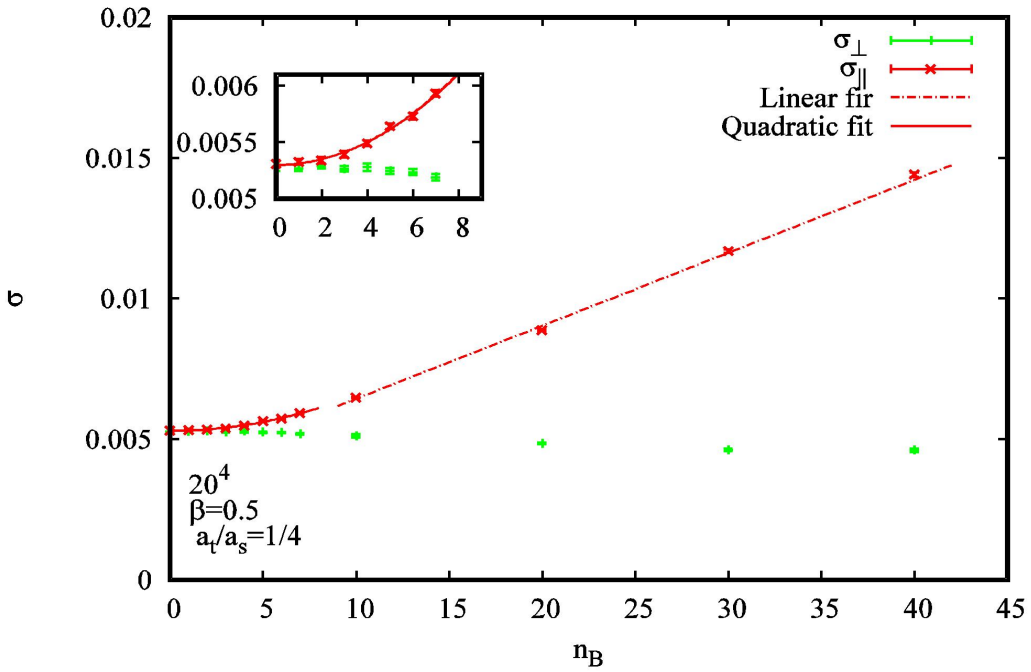
- Change anomaly coefficient – from free gas to lattice data
- k – suppression wrt free quarks result
- Lattice ~ 0.07




Slide of O.Teryaev at XIIIth DIAS-TH Winter School

## Anomalous transport phenomena in condensed matter

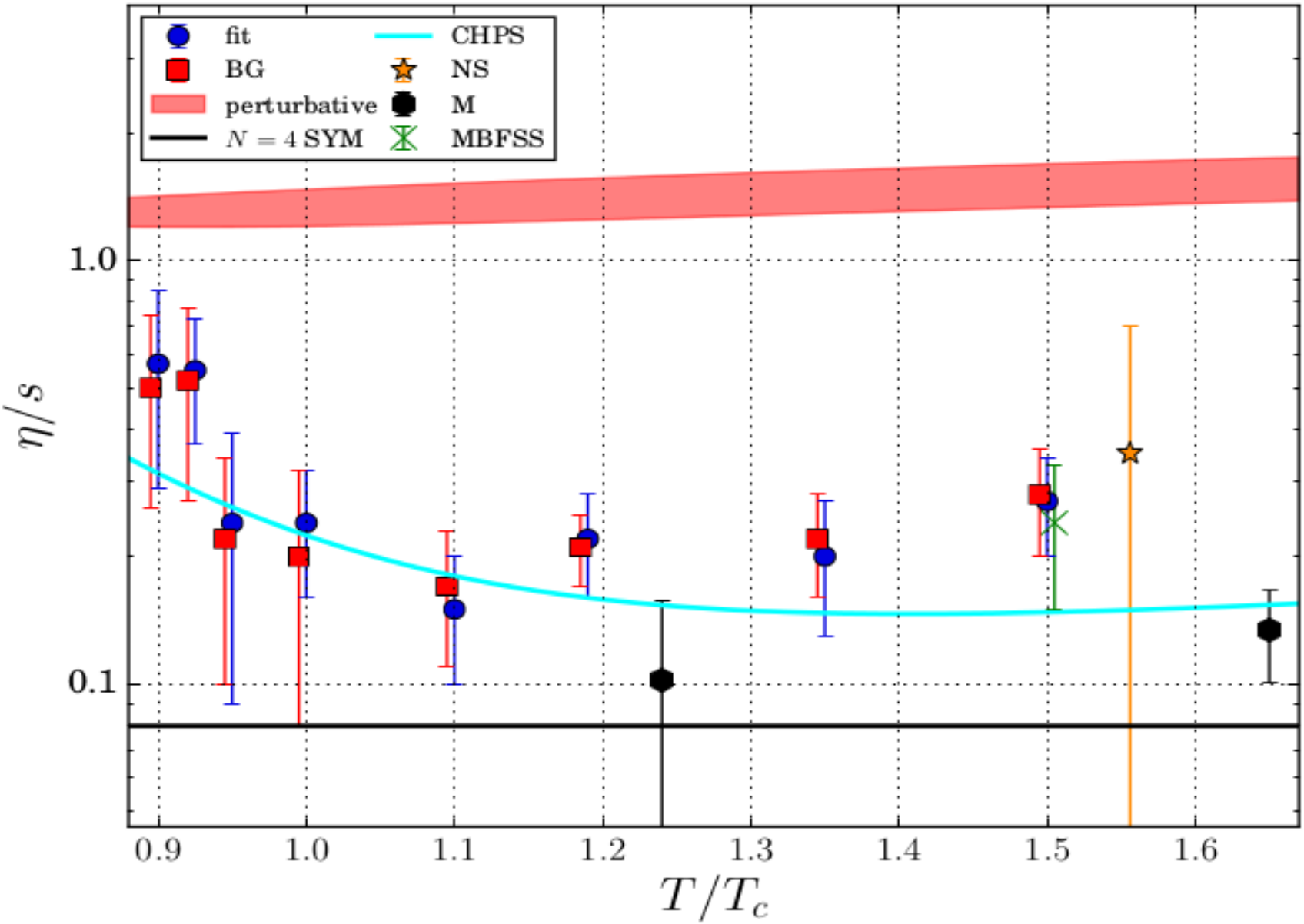
- It was observed CME in nonequilibrium systems (Weyl and Dirac semimetals)
- We have carried out lattice measurement of the conductivities along and perpendicular to magnetic field: $\sigma_{\parallel}, \sigma_{\perp}$ (the first lattice study!)
- Observation of CME and we are going to measure it in QCD



# TRANSPORT COEFFICIENTS IN QCD

## Numerical study of transport coefficients of QCD

- We developed the program for high accuracy calculation of correlation function of energy-momentum tensor
- We measured shear viscosity in SU(2) QCD: $\frac{\eta}{s} = (0.134 \pm 0.057)$
- We have studied temperature dependence of shear viscosity in SU(3) QCD


fit
BG
perturbative
$N = 4$ SYM
CHPS
NS
M
MBFSS
1.0
0.1
$\eta/s$
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
$T/T_c$