Study of the confinement-deconfinement transition in dense medium by means of lattice two-color QCD

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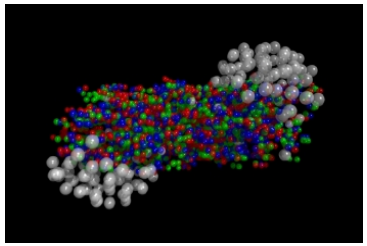
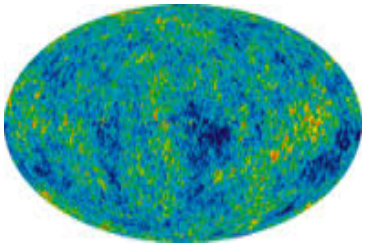
What happens if we compress matter as much as possible?

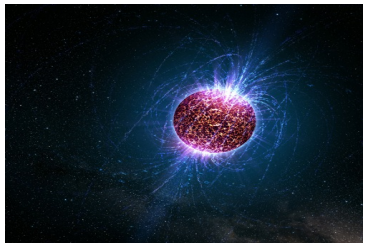
Introduction

- Baryon density $n_B - n_{\bar{B}}$
- Excess of baryons over antibaryons
- Excess of quarks over antiquarks



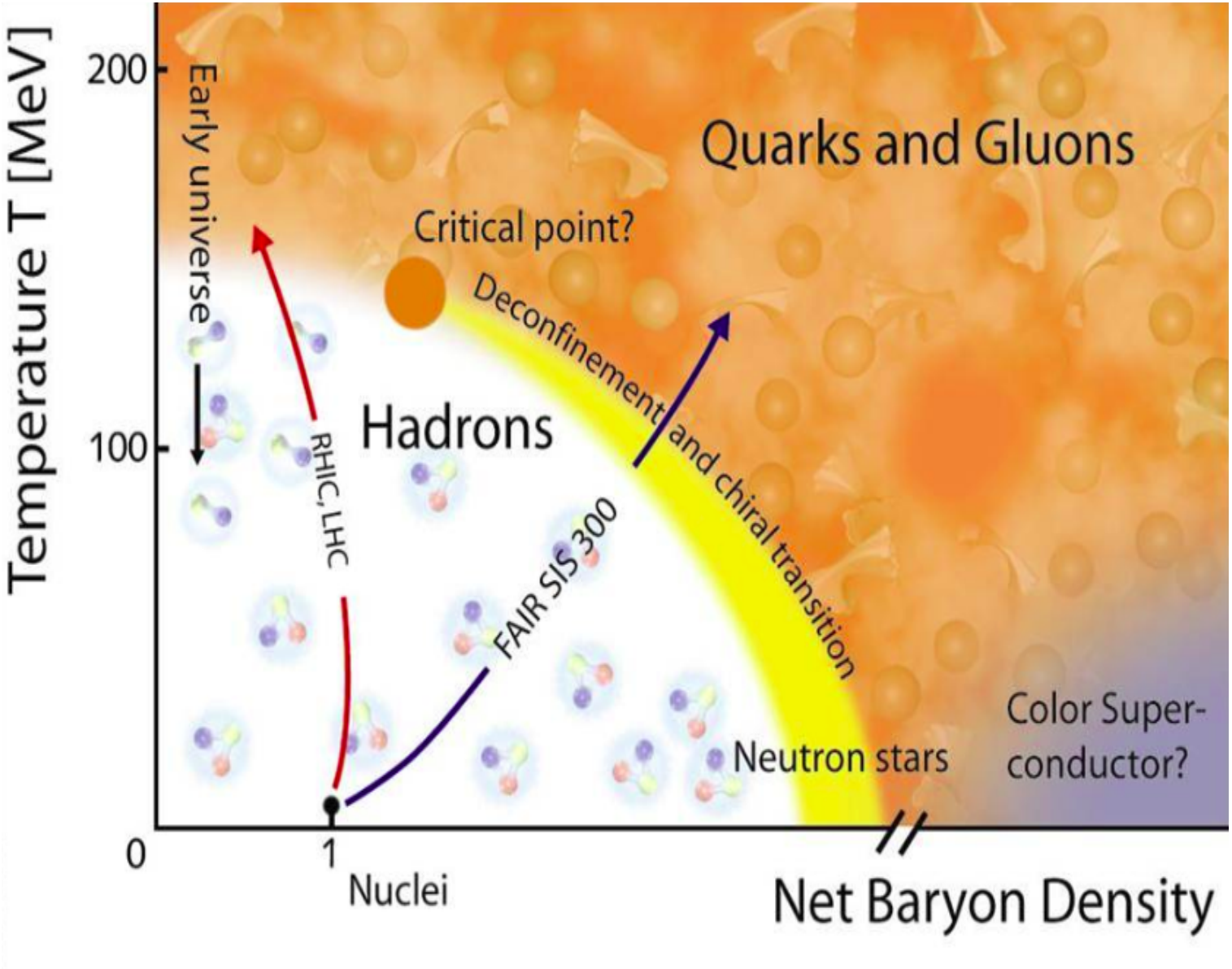
- Applications
  - Heavy ion collisions
  - Neutron stars
  - Early Universe



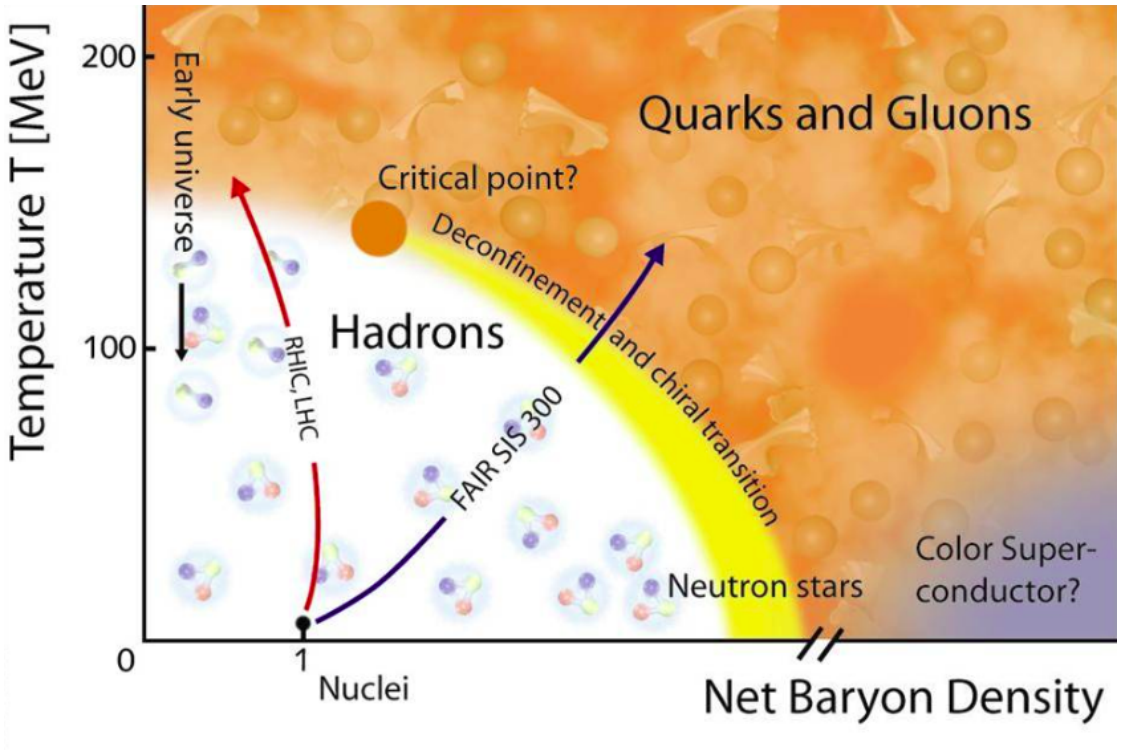


- Baryon chemical potential $\mu_B = N_c \mu_q$

QCD phase diagram



Phenomena at large baryon density



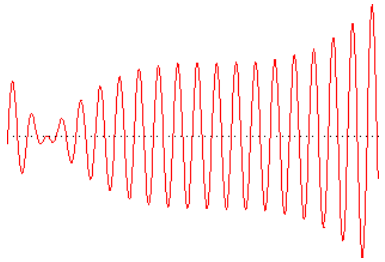
Predicted by phenomenological models, e.g.

- Color-Flavour Locking
- Nonuniform phases
- Chiral symmetry restoration
- Deconfinement

μ and Lattice QCD

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: $\det\left(\hat{D}+m\right) \to \det\left(\hat{D}-\mu\gamma_4+m\right) \Rightarrow$
  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 $\hat{D}-\mu\gamma_4$: λ, λ^*
- For even N_f $\ \det\left(\hat{D}-\mu\gamma_4+m\right) > 0 \ \Rightarrow$ **free from sign problem**

Differences between SU(3) and SU(2) QCD

- The Lagrangian of the SU(2) QCD has the symmetry: $SU(2N_f)$ as compared to $SU_R(N_f) \times SU_L(N_f)$ for $SU(3)$ QCD
- Goldstone bosons ($N_f = 2$) $\pi^+, \pi^-, \pi^0, d, \bar{d}$

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However, in dense medium:

- **Chiral symmetry is restored**
  symmetry breaking pattern is not important
- **Relevant degrees of freedom are quarks and gluons**
  rather than goldstone bosons

$SU(2)$ & $SU(3)$ QCD have many common properties

- There are transitions: confinement/deconfinement, chiral symmetry breaking/restoration
- A lot of observables are very close:

Topological susceptibility (Nucl.Phys.B715(2005)461):
$\chi^{1/4}/\sqrt{\sigma} = 0.3928(40)\ (SU(2)), \quad \chi^{1/4}/\sqrt{\sigma} = 0.4001(35)\ (SU(3))$

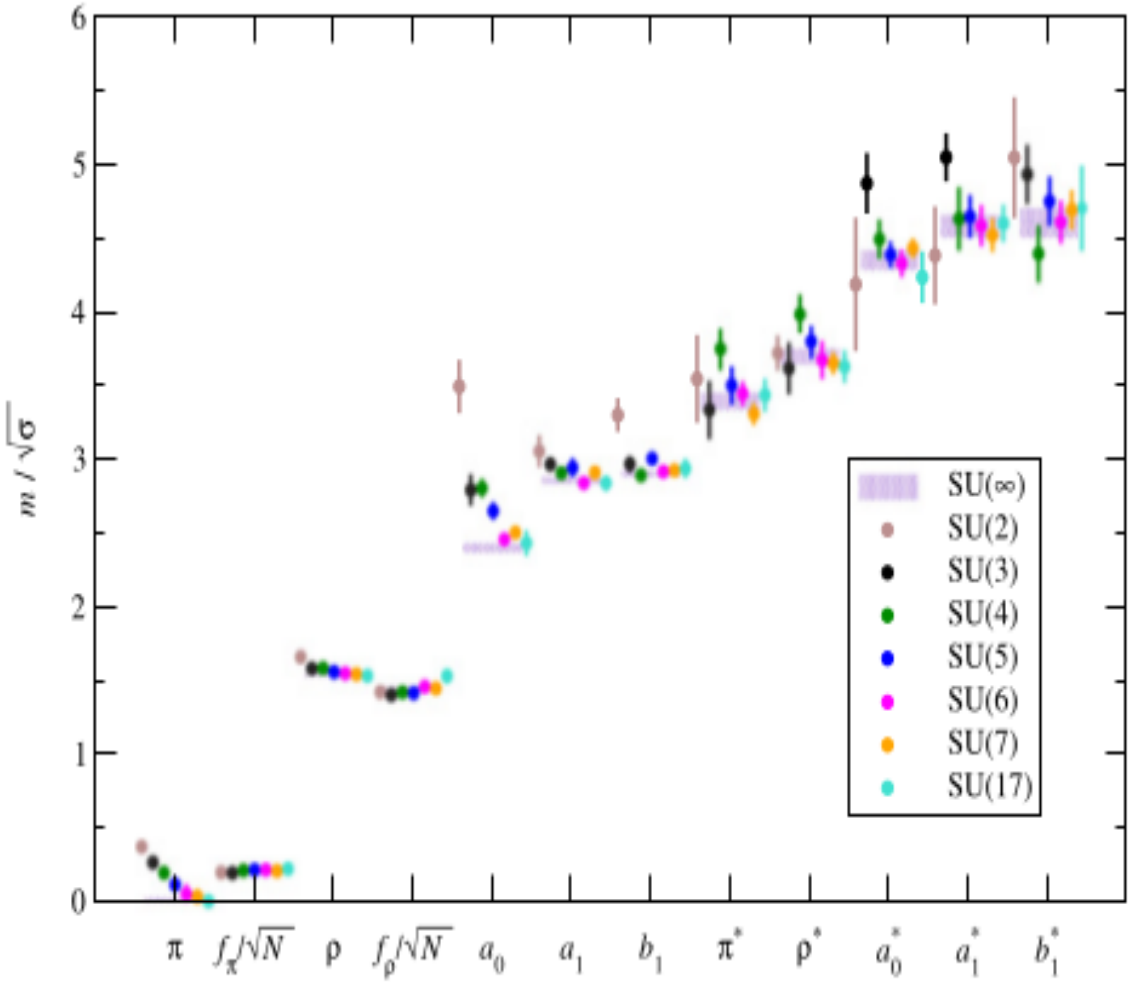
Critical temperature (Phys.Lett.B712(2012)279):
$T_c/\sqrt{\sigma} = 0.7092(36)\ (SU(2)), \quad T_c/\sqrt{\sigma} = 0.6462(30)\ (SU(3))$

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

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

$SU(2)$ & $SU(3)$ QCD have many common properties

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



$SU(2)$ & $SU(3)$ QCD have many common properties

- Thermodynamic properties (JHEP 1205(2012)135)
- Some properties of dense medium (Phys.Rev.D59(1999)094019):
  $\Delta \sim \mu g^{-5} \exp\left(-\frac{3\pi^2}{\sqrt{2}g}\right)$

$SU(2)$ & $SU(3)$ QCD

- 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)

The aim: **numerical study of (cold) dense SU(2) QCD within lattice simulation**

Phase structure of the system

What did we observe earlier?
Braguta et al. Phys.Rev. D94 (2016) no.11, 114510

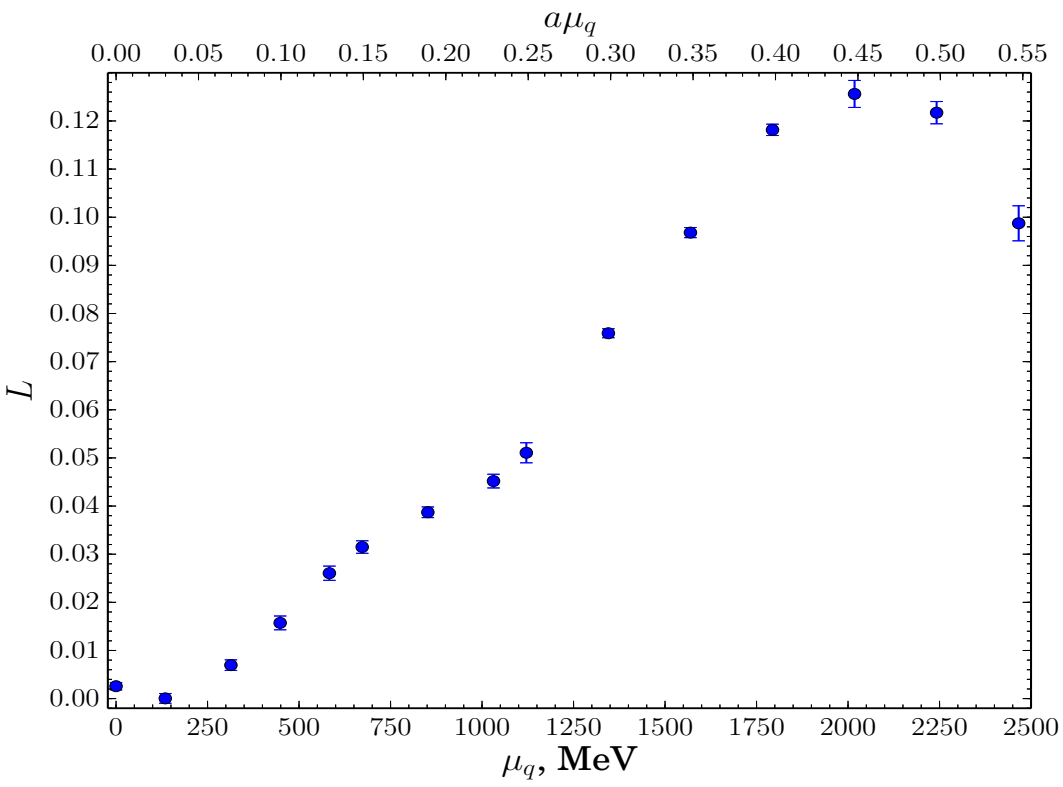
- Hadronic phase
- BEC phase at $\mu_q \sim m_\pi/2$
- BCS phase
- Always confining ???

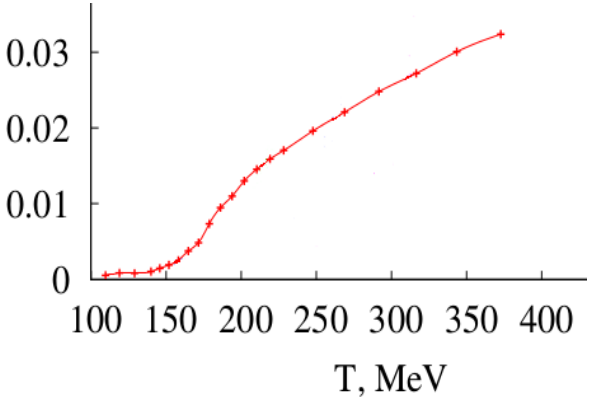
Parameters

Details of the simulation:

- Staggered fermions
- Tree-level improved gauge action
- $a = 0.044$ fm
  $\Rightarrow$ **close to continuum limit**
  one can reach larger density without lattice artifacts
  $\mu > 2000$ **MeV**
- $m_\pi = 740(40)$ MeV
- $m_\pi / m_\rho \sim 0.55$
- Lattice: 32^4

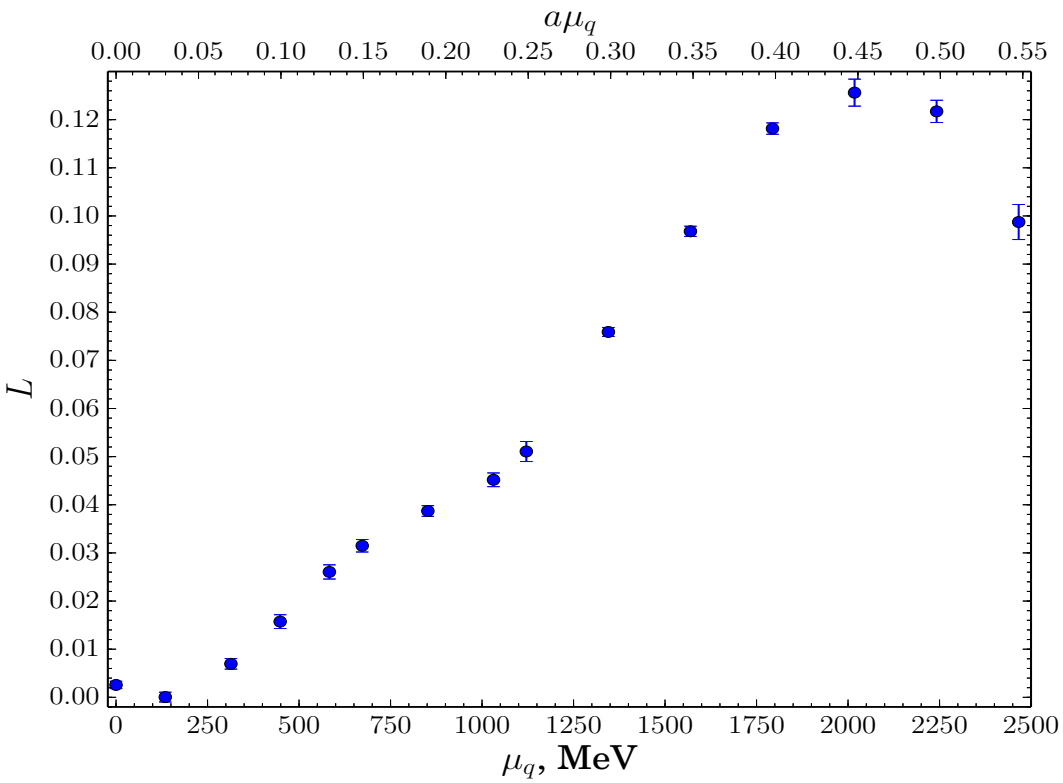
Polyakov loop





Compare with L at $\mu = 0$ vs T

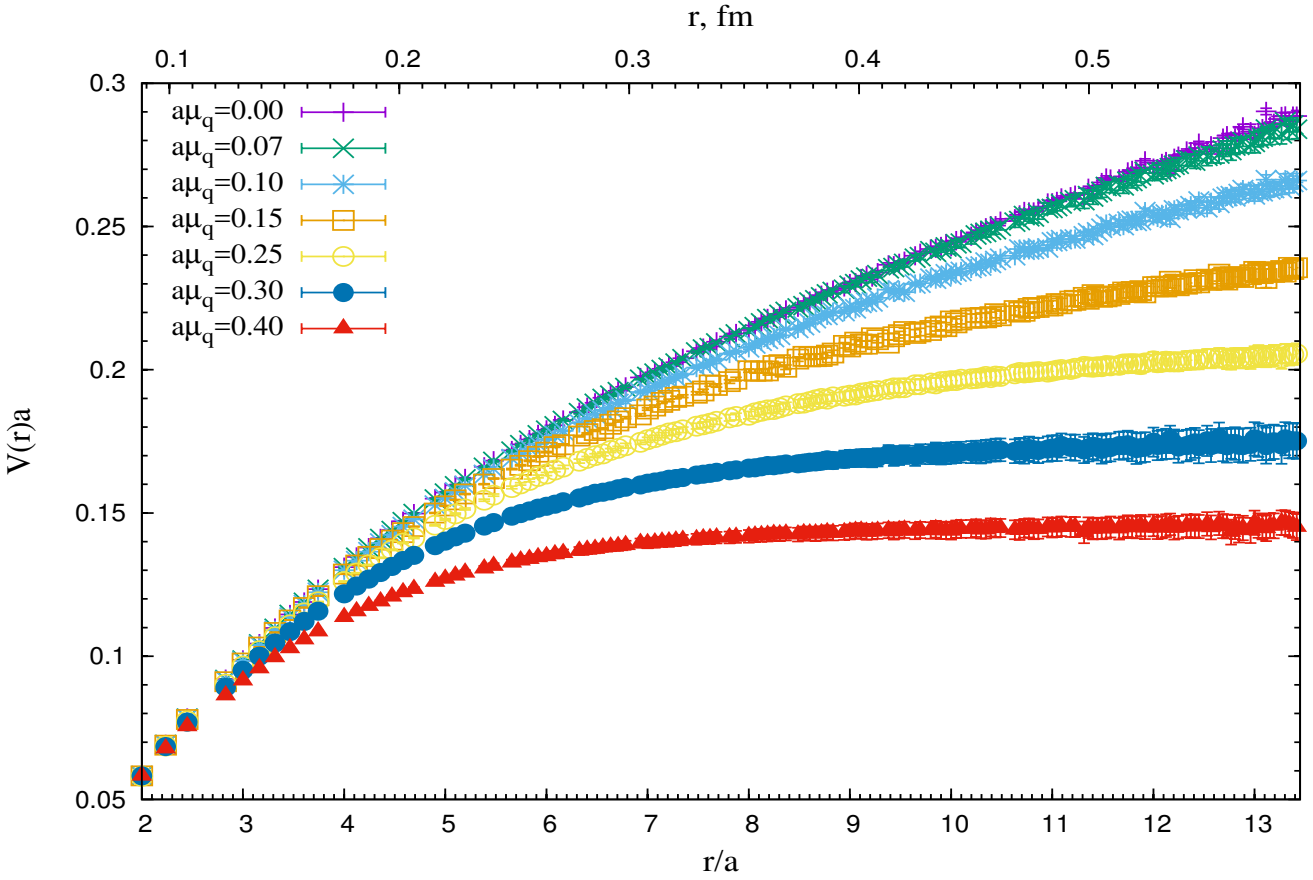
Polyakov loop



Rich physics?

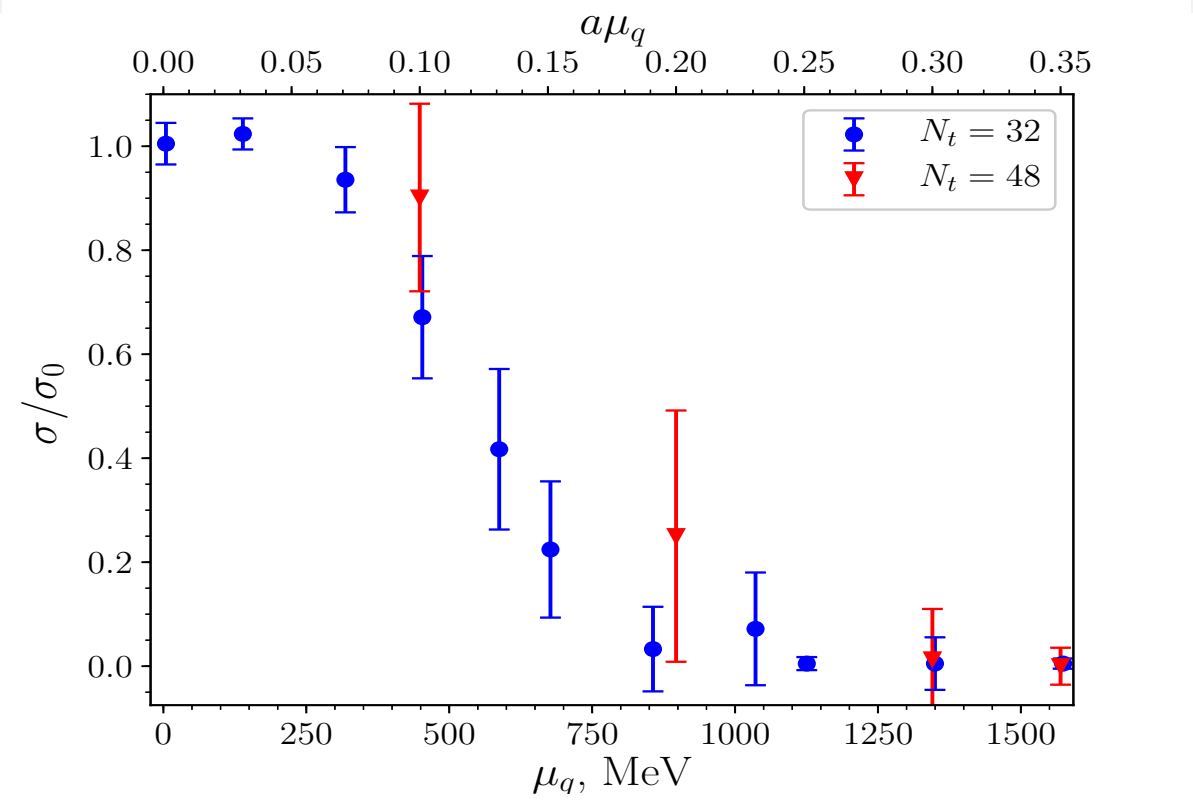
- Critical chemical potential $\mu \simeq$900-1100 MeV ($a\mu \sim 0.2 - 0.25$)

Potential between static quark-antiquark pair



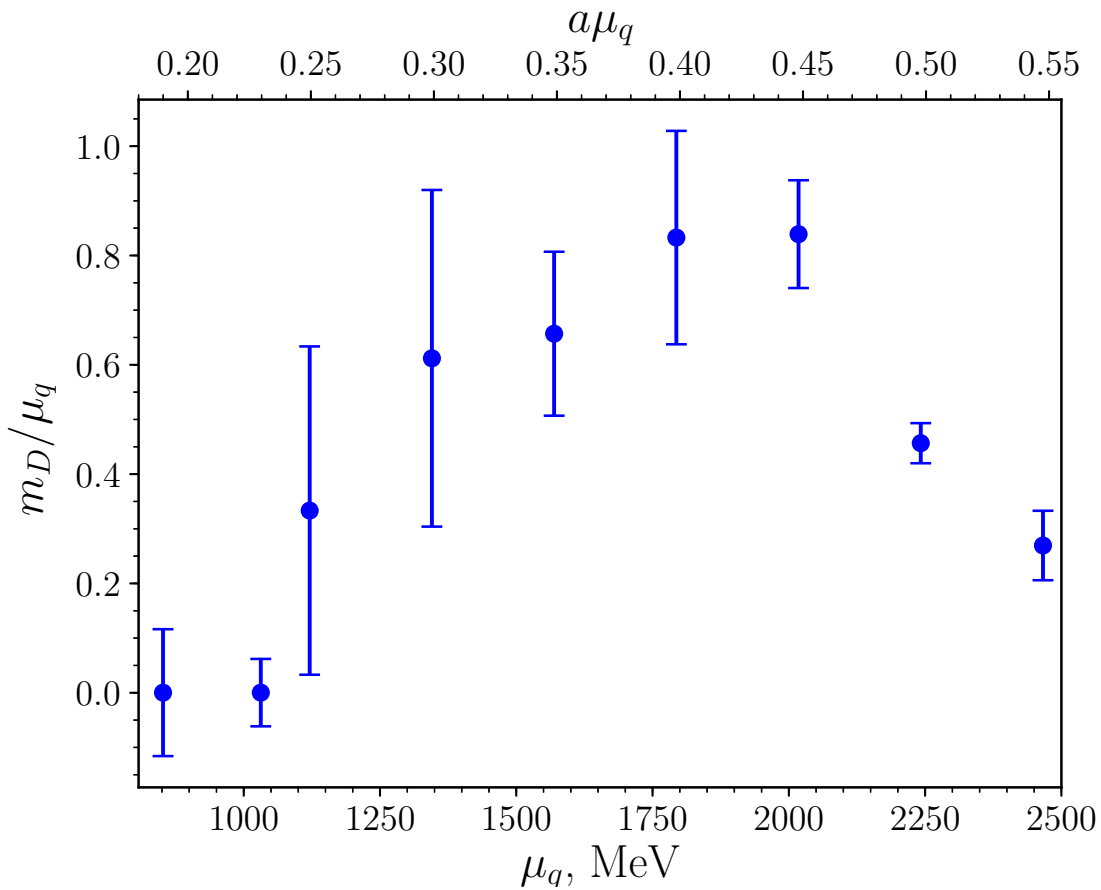
We observe deconfinement in dense medium!

String tension



- Good fit by the Cornell potential: $V(r) = A + \frac{B}{r} + \sigma r$
  $\mu \leq 1100$ MeV
- Good fit by the Debye potential: $V(r) = A + \frac{B}{r} e^{-m_D r}$
  $\mu \geq 1300$ MeV

Debye mass

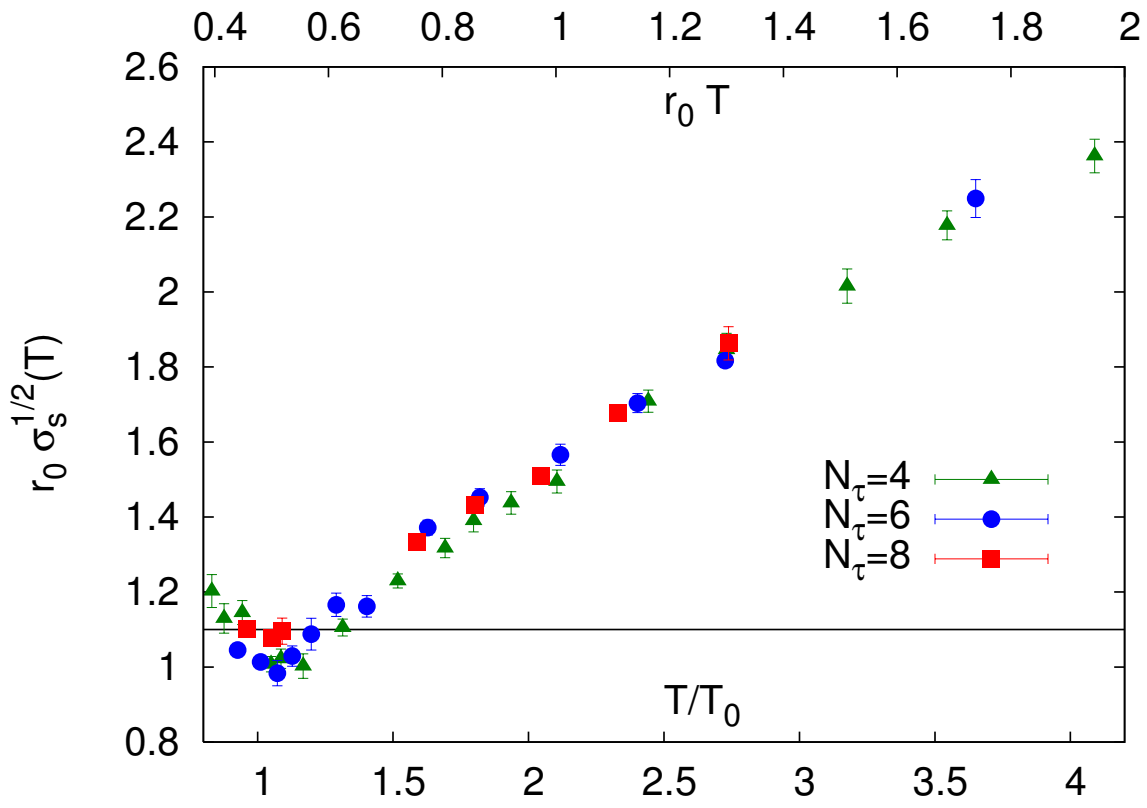


$$V(r) = \frac{\alpha}{r} e^{-m_D r} + c$$

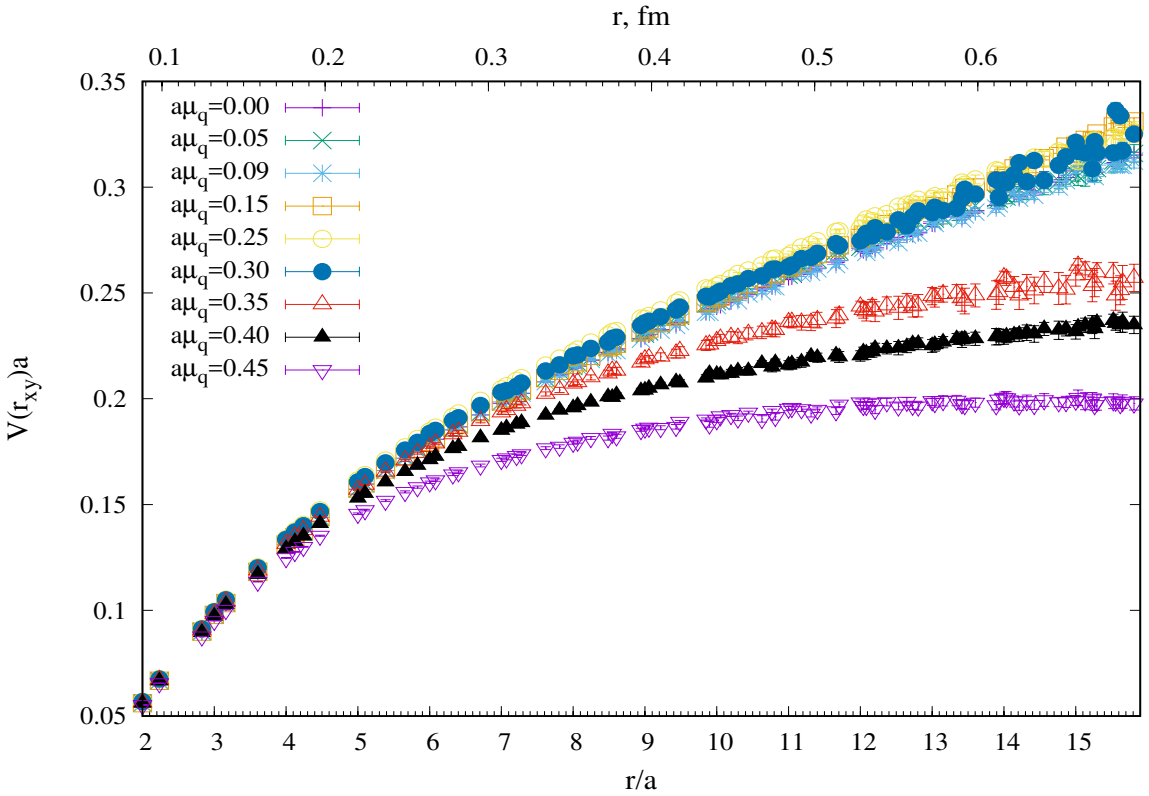
$$\mu_q^c \sim 850 - 1100 \text{ MeV}$$

Spatial string tension

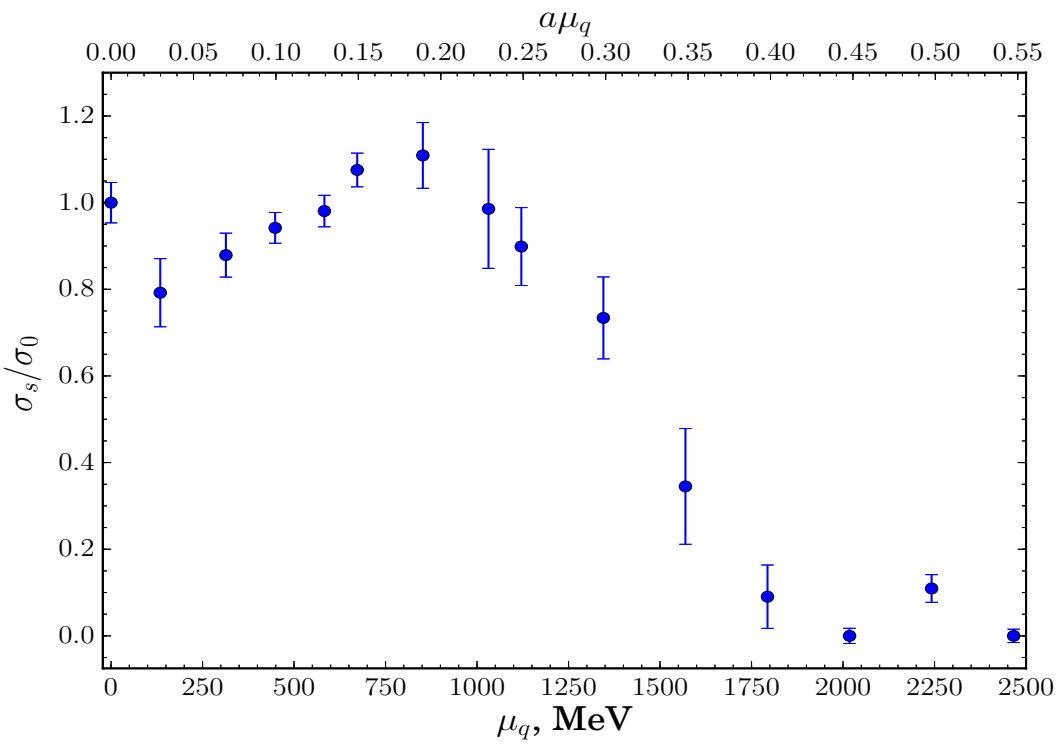
Given by Wilson loop in spatial directions.
The Spatial String Tension and Dimensional Reduction in QCD
M. Cheng et al. Phys.Rev. D78 (2008) 034506



Spatial potential $V(r)$

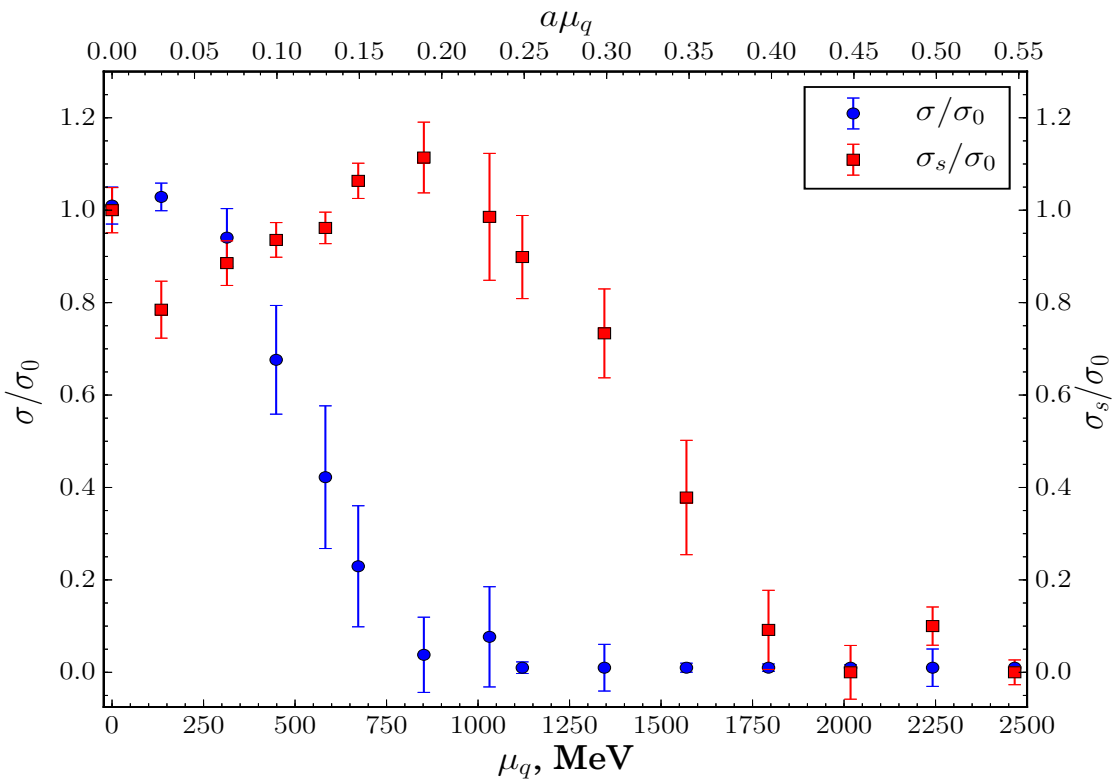


Spatial string tension

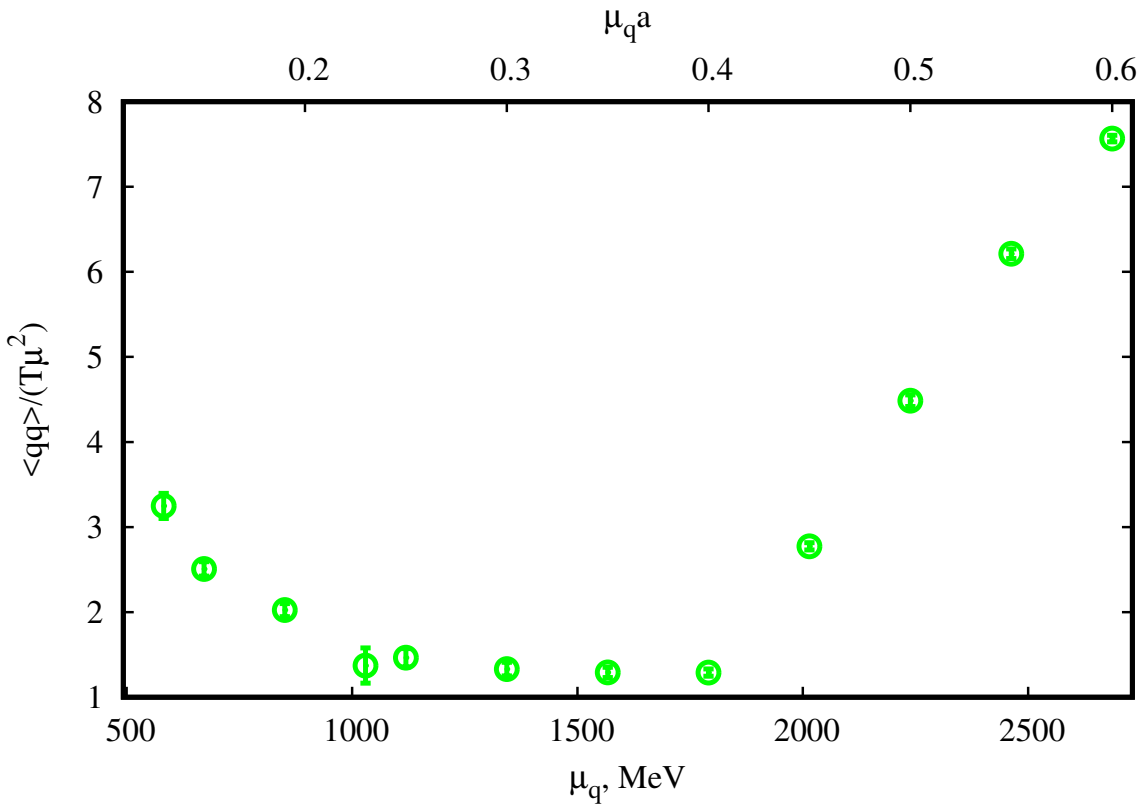


- Deconfinement at $\mu > 1000$ MeV ($a\mu > 0.2 - 0.25$)
- Spatial string tension disappears at $\mu \geq 2000$ MeV ($a\mu > 0.45$)
- Different from finite T transition

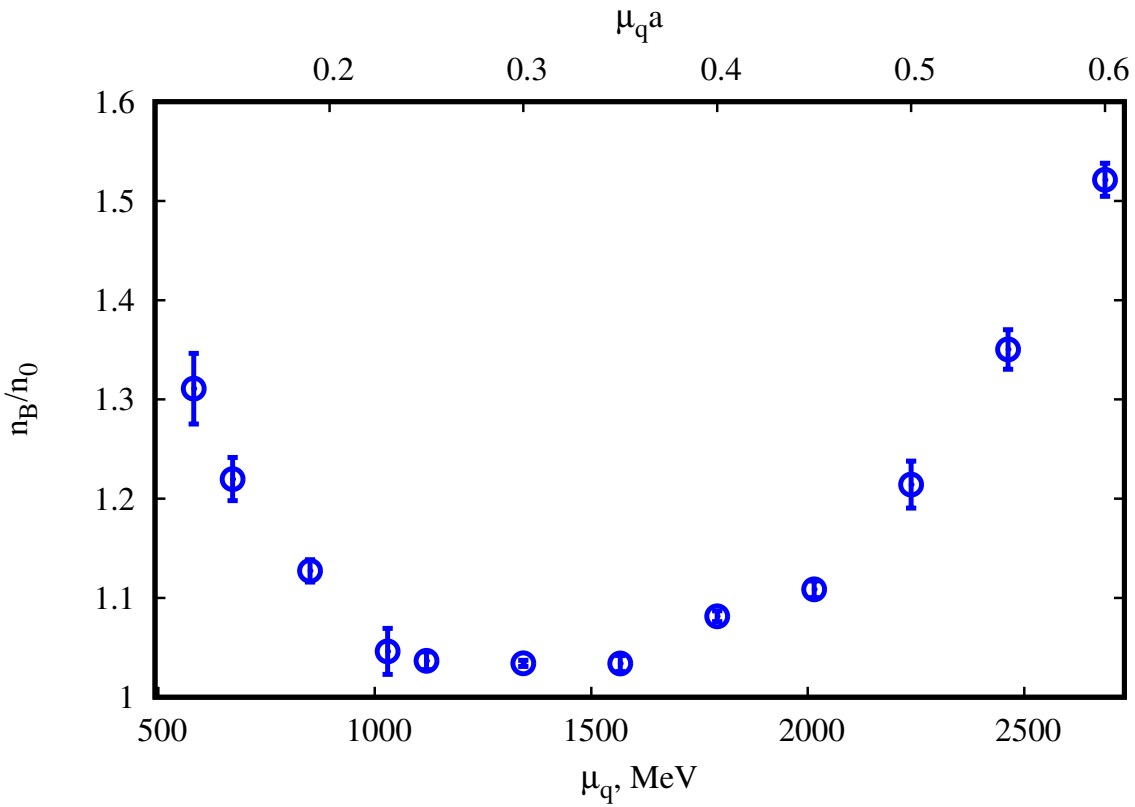
Comparison of both string tensions



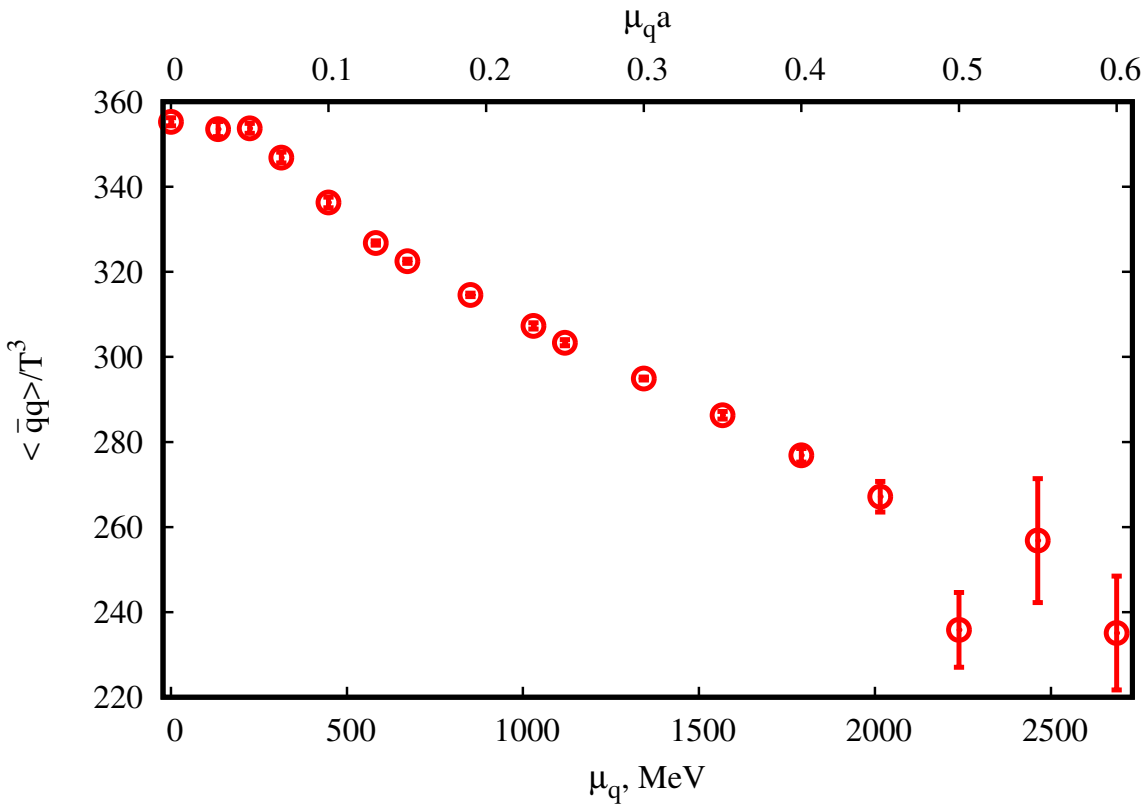
Diquark condensate



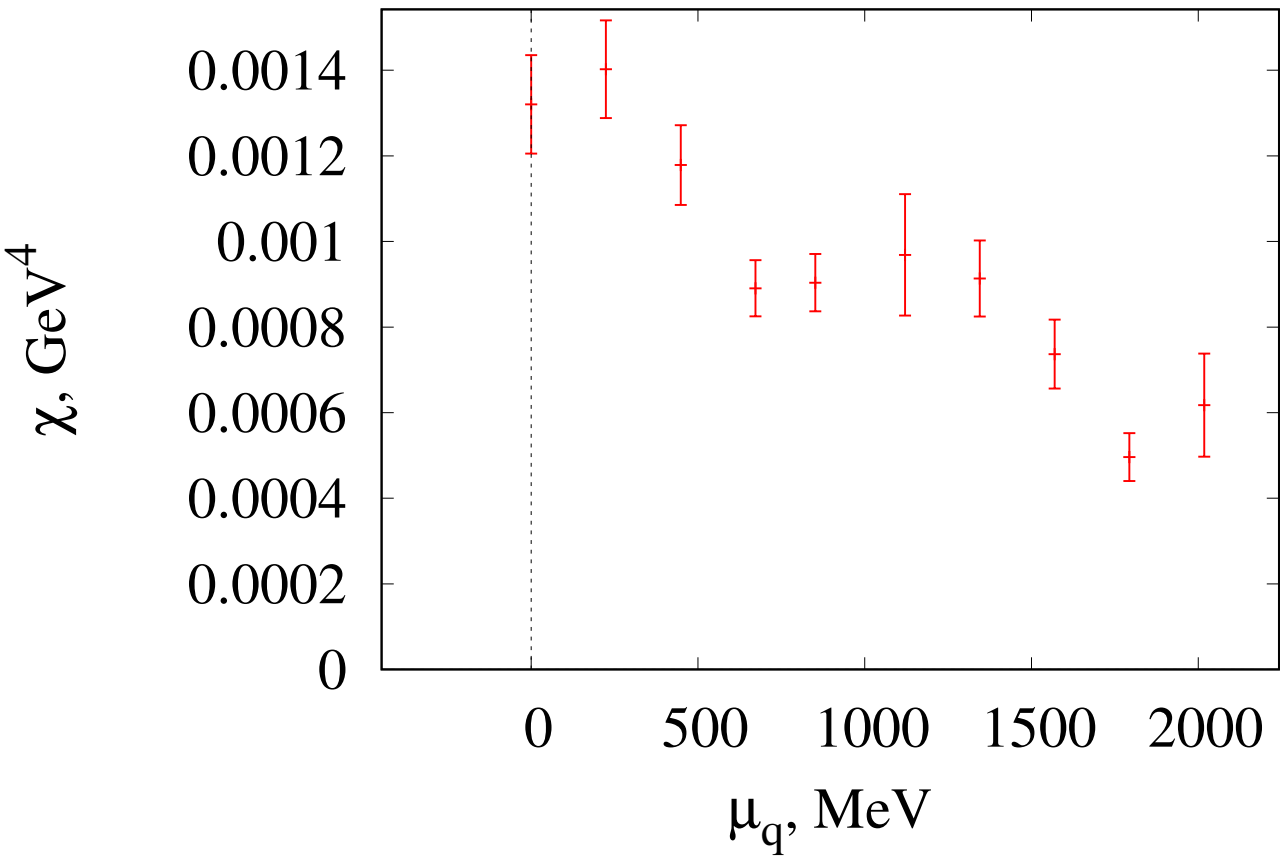
Baryon density



Chiral condensate



Topological susceptibility (preliminary!)



- Signatures of $U_A(1)$ restoration
- Further investigation is required (meson masses)

Conclusion

- **Deconfinement in dense medium**
- Difficult to determine critical chemical potential $\mu \sim 850 - 1100$ MeV
- Spatial string tension disappears $\mu \geq 2000$ MeV
- Deconfinement at large density is different from the finite temperature deconfinement
- Quark-gluon plasma at large density is perturbative (gas of quarks and gluons)