Observation of Deconfinement in Cold Dense Quark Matter

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Outline:

1. Introduction
2. Confinement/deconfinement transition at finite density
3. Polyakov lines correlation functions in dense quark matter
4. Conclusion and discussion

Based on papers: Phys.Rev.D94 (2016) no.11, 114510, JHEP 1803 (2018) 161, arXiv:1808.06466

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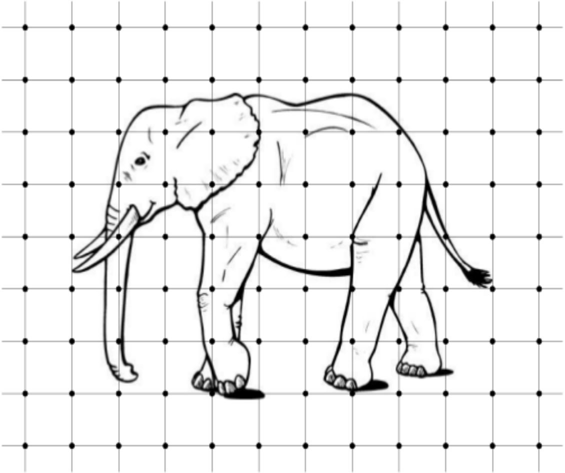
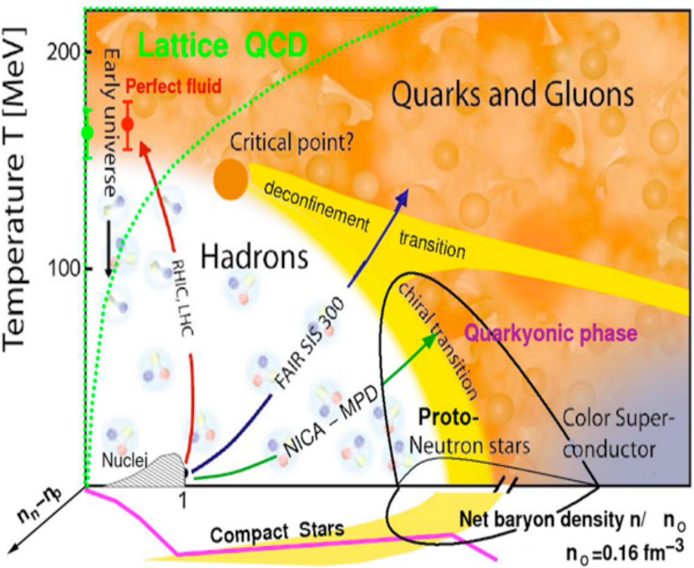


Lattice simulation of strongly correlated system

- Allows to study strongly interacting systems
- Based on the first principles of quantum field theory
- Uncertainties can be systematically reduced
- Very powerful due to the development of computer systems and algorithms

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 $\hat{D}-\mu\gamma_4$: 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

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):

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

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

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

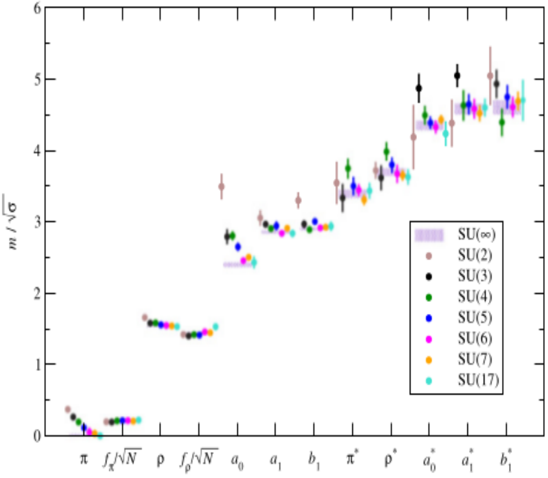
Shear viscosity :

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

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

Similarities:

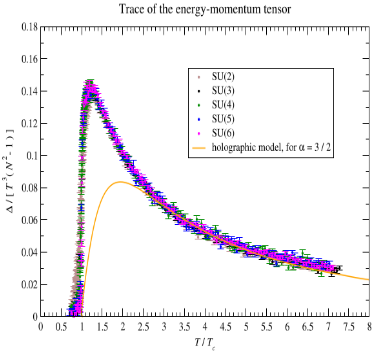
- Spectroscopy (Phys.Rep.529(2013)93)



Similarities:

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

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



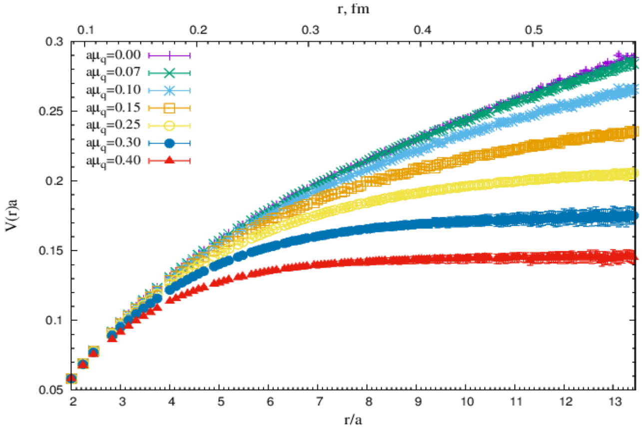
To summarize:

- 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)

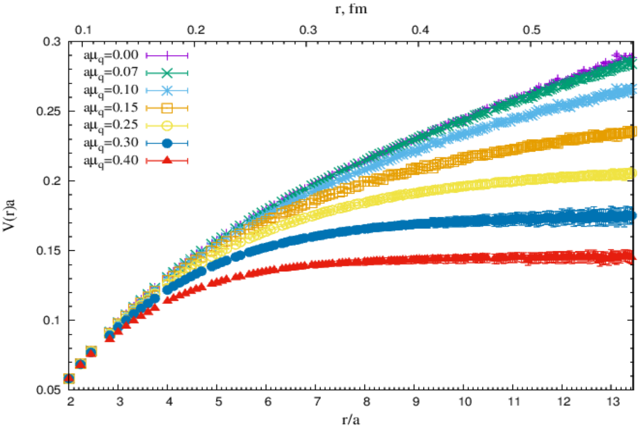
Study of QCD at high densities

- Staggered fermions
  $S_l = \sum_x (ma)\bar{\psi}_x\psi_x + \frac{1}{2}\sum_{x,\mu}\eta_\mu(x)\left(\bar{\psi}_{x+\mu}U_{x,\mu}\psi_x - \bar{\psi}_x U^+_{x,\mu}\psi_{x+\mu}\right)$
  $\lim_{a\to 0} S_l \to \int d^4x\bar{\psi}(\hat{D}+m)\psi$
- Rooting $N_f = 2$
- Diquark source in the action $\delta S \sim \lambda\psi^T(C\gamma_5)\times\sigma_2\times\tau_2\psi$
- 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
- Lattice: $32^3 \times 32$
- Measure Wilson loop of size $T \times R$: $W(R,T)$
- Calculate static potential: $V(r) = -\lim_{T\to\infty}\frac{1}{T}\log W(R,T)$

Potential between static quark-antiquark pair

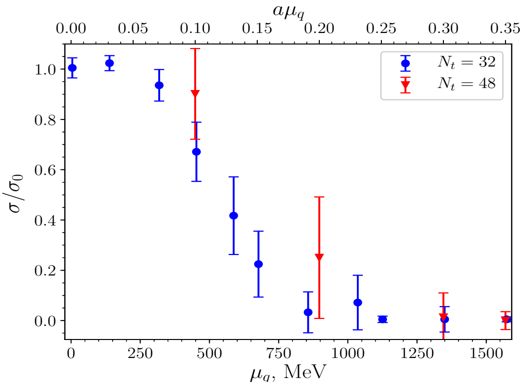


Potential between static quark-antiquark pair



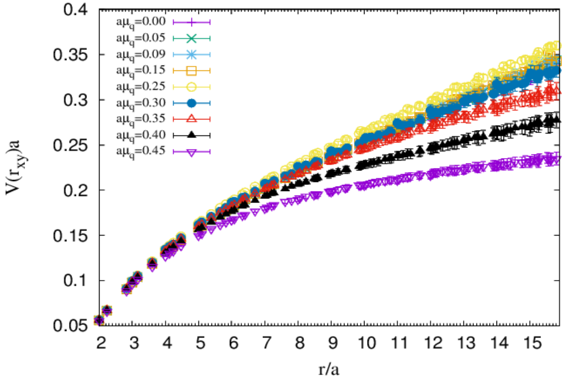
We observe deconfinement in dense medium!

String tension

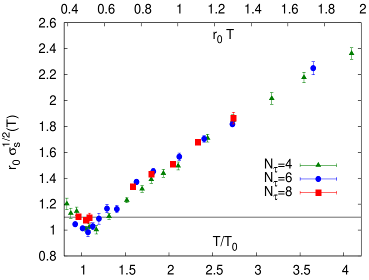


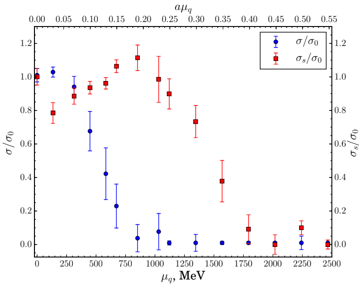
- Good fit by the Cornell potential: $V(r) = A + \frac{B}{r} + \sigma r \quad \mu \leq 1100$ MeV
- Good fit by the Debye potential: $V(r) = A + \frac{B}{r} e^{-m_D r} \quad \mu \geq 850$ MeV
- Confinement/deconfiniment transition in $\mu \in (850, 1100)$ MeV

Spatial potential $V(r)$

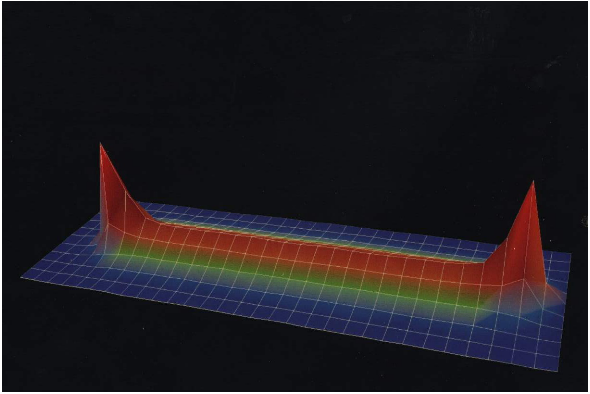


Spatial string tension





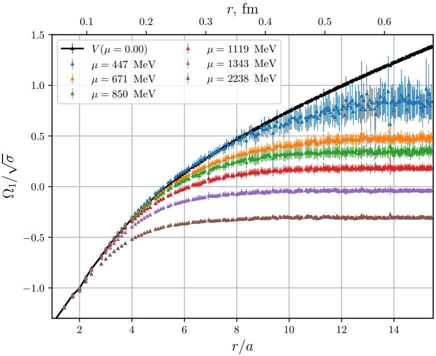
- Deconfinement at $\mu > 900 - 1100$ MeV?
- Spatial string tension disappears at $\mu \geq 1800$ MeV ($a\mu > 0.4$)
- Different behaviour of spatial string tension at finite temperature and finite density
- No magnetic screening at sufficiently large density
- Cold dense quark matter is asymptotically a gas of quarks and gluons



Polyakov lines correlation function

- $\frac{\Omega(\boldsymbol{r},\boldsymbol{T},\mu)}{\boldsymbol{T}} = -\log\left[\langle TrL(0)\cdot TrL^{+}(\vec{r})\rangle\right]$
- Ω is grand potential – fundamental object in QCD
- Describes interaction of quark-antiquark pair
- Sensitive to phase transitions and properties of QCD medium

String breaking in cold dense quark matter

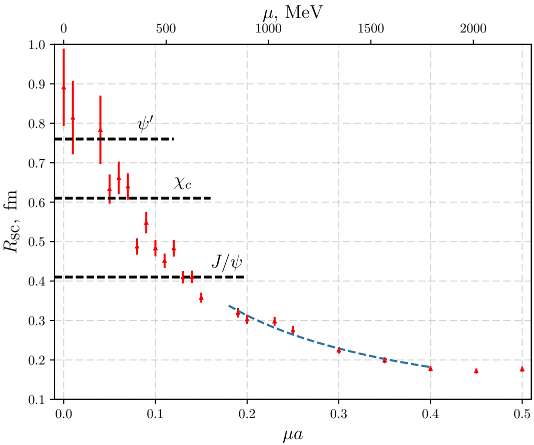


The grand potential and string breaking

- The plateau in the grand potential is the manifestation of the string breaking
- The large the baryon density the smaller the string breaking distance
- Quantitative study of the string breaking phenomenon: the screening length

$$\Omega(\infty, \mu) = V_{\mu=0}(R_{sc})$$

Screening length and quarkonia dissociation

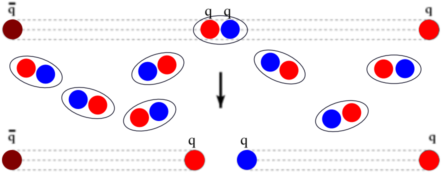


The screening length

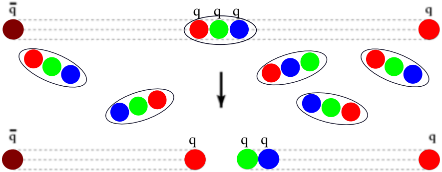
- In confinement phase the R_{sc} is described by string breaking
- In deconfinement phase the R_{sc} is described by Debye screening(Blue curve)
- Onset of quarkonia dissociation (in confinement!)
- The larger baryon density the smaller the R_{sc}

String breaking in dense medium

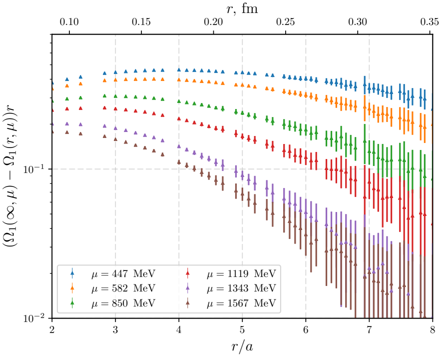
In SU(2) QCD:



Analogous mechanism may be proposed in SU(3) QCD:



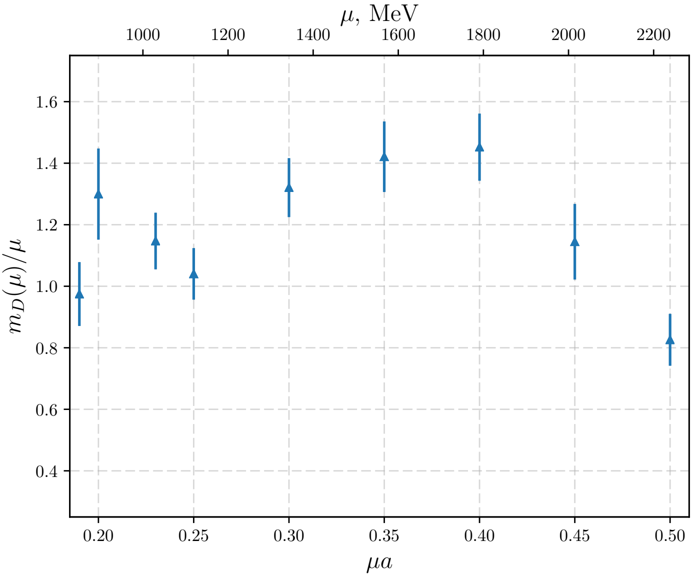
Debye screening in dense medium



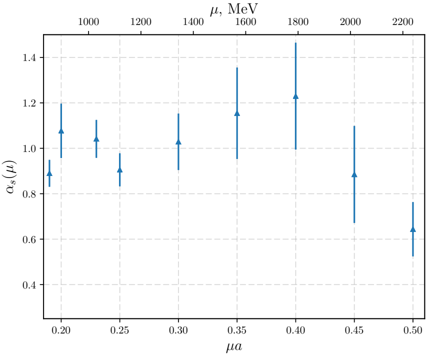
Debye screening in dense cold quark matter

- $\Omega_1(r,\mu) = \Omega_1(\infty,\mu) - \frac{3}{4}\frac{\alpha_s(\mu)}{r} exp(-m_D r)$
- We observe exponential Debye screening
- From fit we determine the $m_D(\mu)$ and $\alpha_s(\mu)$

Debye mass in cold dense matter

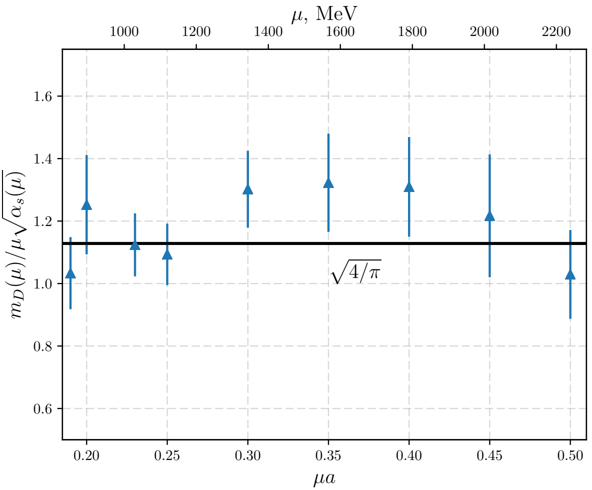


Effective coupling constant in cold dense matter



$\alpha_s \sim 1$ i.e. even at high density QCD is strongly correlated

One-loop formula for the Debye mass



- The one-loop formula: $m_D^2(\mu) = \frac{4}{\pi}\alpha_s(\mu)\mu^2 \;\Rightarrow\; \frac{m_D(\mu)}{\mu\sqrt{\alpha_s(\mu)}} = \sqrt{\frac{4}{\pi}}$
- The one-loop formula works well even for the $\alpha_s \sim 1$

Conclusion:

- **First observation of deconfinement in dense medium**
- Difficult to determine critical chemical potential $\mu_c \in (850, 1100)$ MeV
- Spatial string tension disappears $\mu \geq 1800$ MeV
- Deconfinement at finite density is different to deconfinement at finite temperature
- String breaking distance decreases with density
- Heavy quarkonia dissociate at moderate denisties due to string breaking
- We observe Debye screening phenomenon in deconfinement phase
- Even at high density QCD is strongly correlated