Baryonic matter under Extreme Conditions

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Outline:

- Introduction
- Baryonic matter at finite temperature
  - Theoretical perspective to phase diagram
  - Lattice study of dense QCD
- QCD under extreme conditions
- The phase diagram from astrophysics
- Baryonic matter at low temperature
  - Theoretical perspective
  - QCD-like theories
- Conclusion

Baryon density and chemical potential

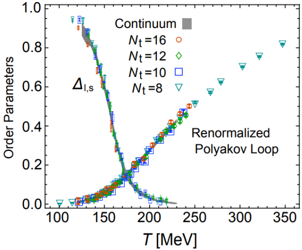
- For Helmholtz free energy the number of particles is fixed
  $F = F_N(T,V) = -T \log Z_N,\ Z_N = Tr \exp\left(-\frac{\hat{H}}{T}\right)$
- Grand canonical ensemble
  $Z = Tr \exp\left(-\frac{\hat{H}}{T}\right) \to Tr \exp\left(-\frac{\hat{H}-\mu\hat{N}}{T}\right)$
  $Z = \sum_N \sum_i e^{-\frac{E_{i,N}}{T}} \times e^{-\frac{\mu N}{T}} = \sum_N e^{-\frac{F_N}{T}} \times e^{-\frac{\mu N}{T}}$
- Gibbs free energy: $\Omega(\mu) = -T \log Z(\mu)$

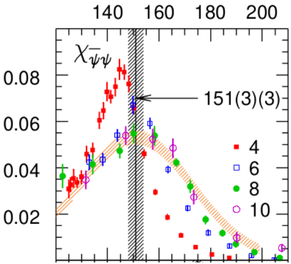
$$n = -\frac{1}{V}\frac{\partial\Omega(\mu)}{\partial\mu}$$

- For u, d, s-quarks one can introduce μ_u, μ_d, μ_s:
  $Z = Tr \exp\left(-\frac{\hat{H}-\mu_u\hat{N}_u-\mu_d\hat{N}_d-\mu_s\hat{N}_s}{T}\right)$
  $n_u = -\frac{1}{V}\frac{\partial\Omega}{\partial\mu_u}, n_d = -\frac{1}{V}\frac{\partial\Omega}{\partial\mu_d}, n_s = -\frac{1}{V}\frac{\partial\Omega}{\partial\mu_s}$
- Instead of the μ_u, μ_d, μ_s one uses μ_B, μ_I, μ_S
  $n_B = \frac{1}{3}(n_u + n_d + n_s), n_I = n_u - n_d,$
  $n_B = -\frac{1}{V}\frac{\partial\Omega}{\partial\mu_B}, n_I = -\frac{1}{V}\frac{\partial\Omega}{\partial\mu_I}$

Chiral symmetry breaking in QCD

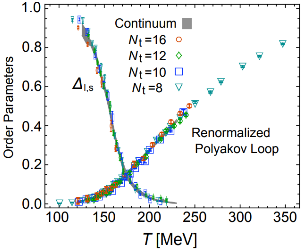
- Massless QCD Lagrangian
  $\mathcal{L} = \bar{\Psi} i\hat{D}\Psi = \bar{\Psi}_R i\hat{D}\Psi_R + \bar{\Psi}_L i\hat{D}\Psi_L$
- For N_f quarks chiral symmetry is
  $SU_L(N_f) \times SU_R(N_f) \times U_V(1) \times U_A(1)$
- Order parameter: chiral condensate
  $\langle\bar{\Psi}\Psi\rangle = \langle\bar{\Psi}_L\Psi_R\rangle + \langle\bar{\Psi}_R\Psi_L\rangle$
  - CS is broken: $\langle\bar{\Psi}\Psi\rangle \neq 0,\ M_q \neq 0$
  - CS is restored: $\langle\bar{\Psi}\Psi\rangle = 0,\ M_q = 0$
- Dynamical chiral symmetry breaking
  $SU_L(N_f) \times SU_R(N_f) \to SU_V(N_f)$
- In massless QCD the first or the second order phase transition
- But for $m_q \neq 0$ CS symmetry is explicitly broken. $M_q \sim 10 \to 300$ MeV
- CS breaking/restoration is crossover
  $T_c = (151 \pm 4)$ MeV
  Z. Fodor, Phys.Lett.B 643 (2006)

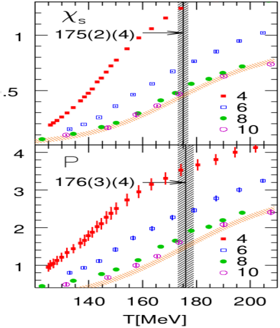




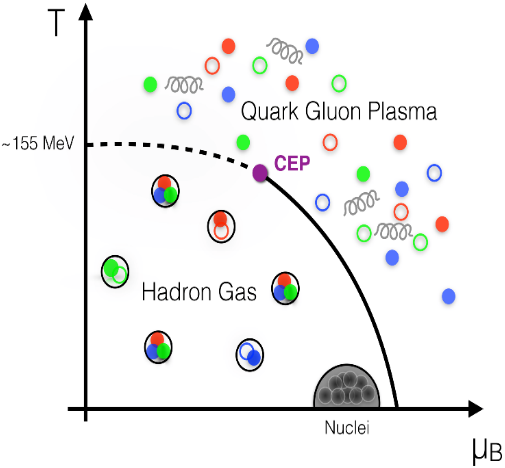
Confinement/deconfinement transition in QCD

- Order parameter Polyakov line:
  $P(\vec{x}) = \langle Tr P \exp \left(ig \int_0^T dx^4 \hat{A}_4(\vec{x}, x^4) \right) \rangle$
  $P = e^{-F_Q/T}$
  - Confinement: $F_Q = \infty \Rightarrow P = 0$
  - Deconfinement: $F_Q < \infty \Rightarrow P \neq 0$
- Z_3 symmetry of gluodynamics
  but $P \to e^{2\pi k/3i} P$, $k = 0, 1, 2$
- P is similar to magnetization in ferromagnetic
- First order phase transition in SU(3) gluodynamics
- Quarks violate Z_3 symmetry
- Confinement/deconfinement is crossover
  $T_c = (176 \pm 5)$ MeV
  Z. Fodor, Phys.Lett.B 643 (2006)





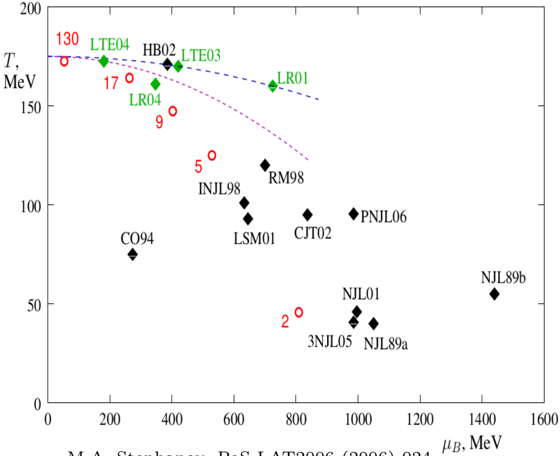
QCD phase diagram



- The other point of view: transition at finite n_B is crossover

K. Fukushima, e-Print: 2501.01907

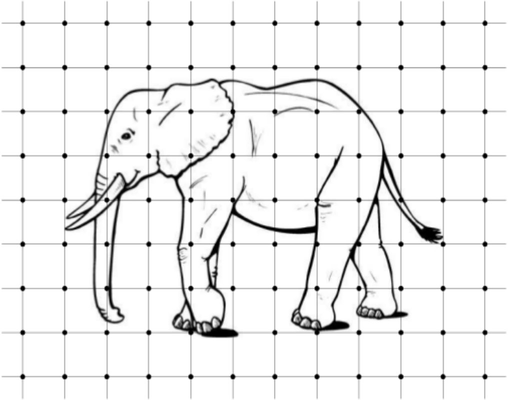
Critical point: theory



M.A. Stephanov, PoS LAT2006 (2006) 024

- Large systematic uncertainty of theoretical models
- QCD is nonlinear theory with large coupling constant
- Too complicated for first-principles theoretical study

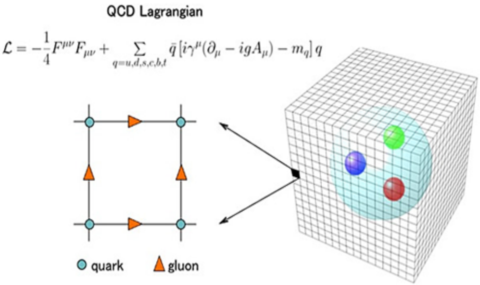
Lattice QCD



Lattice simulation

- Allows to study strongly interacting systems
- Based on the first principles of quantum field theory
- Powerful due to modern supercomputers and algorithms

Lattice QCD



- Introduce regular cubic four dimensional lattice $N_s \times N_s \times N_s \times N_t = N_s^3 \times N_t$
- Lattice spacing–a
- Degrees of freedom
  - **Gluon fields:** 3x3 matrices $U \in SU(3)$, live on links
  - **Quarks fields:** column $q, \bar{q}$, live on sites

Lattice QCD

- We study QCD in thermodynamic equilibrium
- QCD partition function
  $Z = \int DU \exp\left(-S_G(U)\right) \times \prod_{i=u,d,s\dots} \det\left(\hat{D}_i(U) + m_i\right)$
- In continuum lattice partition function exactly reproduces QCD partition function
  - Gluon contribution: $S_G(U)\Big|_{a\to 0} = -\frac{1}{4}\sum_{a=1}^{8} F_a^{\mu\nu} F_{\mu\nu}^a$
  - Quark contribution:
    $\bar{q}(\hat{D}(U) + m)q\Big|_{a\to 0} = \bar{q}(\gamma^\mu \partial_\mu + ig\gamma^\mu A_\mu + m)q$
- Carry out continuum extrapolation $a \to 0$
- Uncertainties (discretization and finite volume effects) can be systematically reduced
- The first principles based approach. No assumptions!
- Parameters: coupling constant $g(a)$ and masses of quarks $m_q(a)$

Lattice QCD

- We calculate partition function

  $$Z \sim \int DU e^{-S_G(U)} \prod_{i=u,d,s...} \det\left(\hat{D}_i(U) + m_i\right) = \int DU e^{-S_{eff}(U)}$$

  - 96×48^3
  - Variables: $96 \cdot 48^3 \cdot 4 \cdot 8 \sim 300 \cdot 10^6$
  - Matrices: $100 \cdot 10^6 \times 100 \cdot 10^6$
- Simulations at physical quark masses and $a \sim 0.05$ fm
- Stochastic process: Hybrid Monte Carlo(HMC) generates $\{U_1\} \to \{U_2\} \to \{U_3\} \to ....$
- For sufficiently large n: $p(U) \sim e^{-S_{eff}(U)}$
- Calculation of observable $O(U)$
  $\langle O \rangle = \frac{1}{N} \sum_{i=1}^{N} O(U_i)$

Lattice simulations at finite baryon density

Zero baryon density

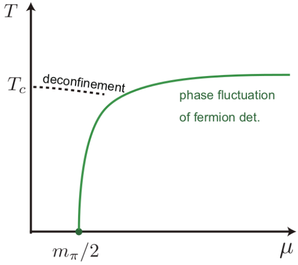
- For MC the probability distribution should be positive
  $p(U) \sim e^{-S_G(U)} \times \det(\hat{D}+m), \quad \hat{D} = \gamma^\mu(\partial_\mu + ig\hat{A}_\mu)$
- Eigenvalues of the $\hat{D}$ are imaginary and form pairs $(i\lambda, -i\lambda)$
  $\gamma_5 \hat{D}^+ \gamma_5 = \hat{D} \Rightarrow \quad \gamma_5 \hat{D} \gamma_5 = -\hat{D}$
  $\hat{D}\psi_\lambda = i\lambda\psi_\lambda \Rightarrow \hat{D}\gamma_5\psi_\lambda = -i\lambda\gamma_5\psi_\lambda$
- $\det(\hat{D}(U)+m) = \prod_n (i\lambda_n + m)(-i\lambda_n + m) = \prod_n (\lambda_n^2 + m^2) \geq 0$

Nonzero baryon density

- $\hat{D} = \gamma^\mu(\partial_\mu + ig\hat{A}_\mu) + \mu\gamma_4$
- Complex eigenvalues and complex determinant
- Strongly oscillating at large volume V

$\det(\hat{D}(U)+m) = |\det(\hat{D}(U)+m)| \times e^{i\theta(U)},$
$e^{i\theta(U)} = e^{i\mu V f(U)}$

- Monte Carlo methods are not applicable - Sign problem

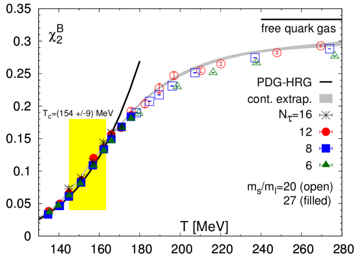


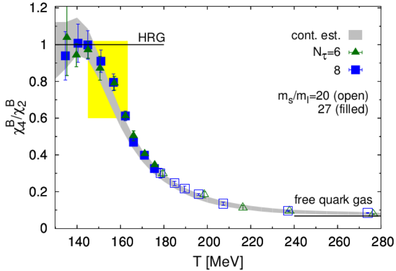
Possible solutions to the sign problem

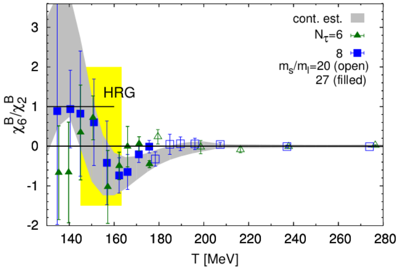
- Taylor expansion
- Reweighting method
- Analytic continuation from imaginary chemical potential
- Canonical method
- Complex Langevin method
- Dual formulations
- Lefschetz thimbles

Taylor expansion

- $O(T,\mu) = \sum_n c_n(T) \left(\frac{\mu}{T}\right)^n$,
  $c_n = \frac{1}{n!} \left(\frac{\partial^n O}{\partial \mu^n}\right)_{\mu=0}$
- c_n can be calculated on lattice
- Larger uncertainty at larger n
  manifestation of the sign problem
- Small baryon densities can be studied
- Example: equation of state
  $$\frac{p(T,\mu_B)-p(T,0))}{T^4} = \sum_k \frac{\chi_{2k}(T)}{(2k!)} \left(\frac{\mu_B}{T}\right)^{2k}$$



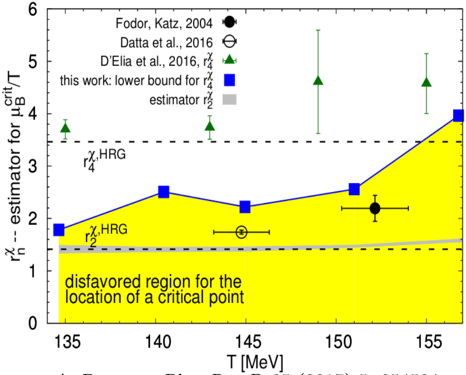




A. Bazavov, Phys.Rev.D 95 (2017) 5, 054504

Convergence of Taylor expansion

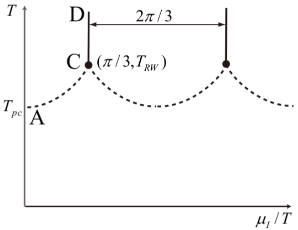
- $O(T,\mu) = \sum_n c_n(T) \left(\frac{\mu}{T}\right)^n$
- Slow convergence in hadronic phase
- Few terms are enough in QGP phase
- Radius of convergence $r = \lim_{n\to\infty} \left|\frac{c_n}{c_{n+1}}\right|$

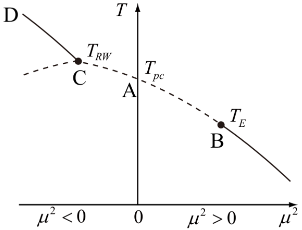


A. Bazavov, Phys.Rev.D 95 (2017) 5, 054504

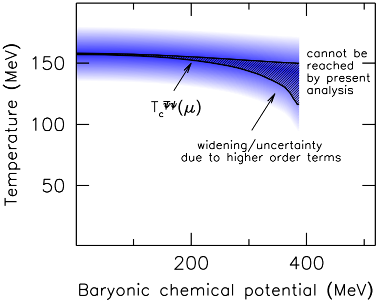
Simulations at imaginary chemical potential

- At $\mu = i\mu_i$ HMC can be applied
  $\hat{D}(i\mu_I) = \gamma^\mu(\partial_\mu + ig\hat{A}_\mu) + i\mu_i\gamma_4$
  $\det(\hat{D}(U) + m) = \prod_n(\lambda_n^2 + m^2) \geq 0$
- Roberge-Weiss transition
  At $\mu_i = \pi T$ Polyakov loop changes phase $P \to e^{-2\pi/3i}P$
- II order transition at C
  $T_{RW} = 208(5)$ MeV, $\mu_i = \pi T$
  Phys.Rev.D 93 (2016) 7, 074504
- One can study QCD in the region $\mu_i < \pi T$





Critical temperature at finite baryon density

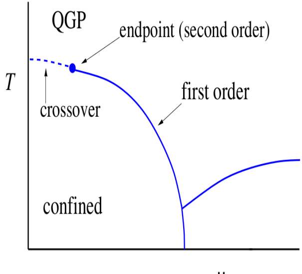


- $\frac{T_c(\mu_B)}{T_c(0)} = 1 - \kappa \left(\frac{\mu_B}{T_c(0)} \right)^2$
- $\kappa = 0.0180(40)$

  Phys. Rev. D89 no. 7, (2014) 074512
- $\kappa = 0.0149(21)$

  Phys. Lett. B751 (2015) 559–564
- $\kappa = 0.0135(20)$

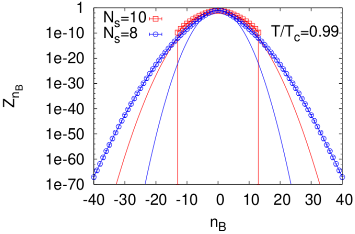
  Phys. Rev. D90 no. 11, (2014) 114025

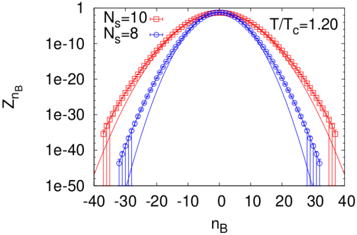


Canonical method

- Gibbs free energy Ω
  $\Omega = -T \log Z(\mu)$,
  $Z(\mu) = Tr \exp\left(-\frac{\hat{H}-\mu\hat{N}}{T}\right)$
- Helmholtz free energy F_n
  $F_n = -T \log Z_n$,
  $Z_n = Tr \exp\left(-\frac{\hat{H}}{T}\right)$
- Fugacity expansion
  $Z(\mu) = \sum_n Z_n e^{n\mu/T}$
- Z_n can be calculated on lattice

$Z_n = \int_{-\pi}^{\pi} \frac{d\varphi}{2\pi} Z(i\mu_i) e^{-in\varphi}$, $\varphi = \frac{\mu_i}{T}$

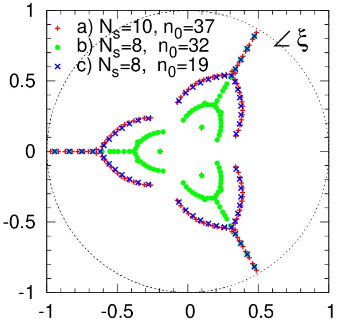




K. Nagata e-Print: 2108.12423

Canonical method

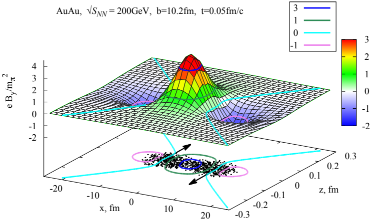
- $Z(\xi) = \sum_{n=-N}^{N} Z_n \xi^n, \xi = e^{\mu/T}$
- Lee-Yang zeros $Z(\xi) = 0$
- The distribution of Lee-Yang zeros approaches the real axis in the thermodynamic limit and causes the singularity in thermodynamic quantities.
- Perspective approach: $N_B \sim 10$, $L_s \sim 2$ fm, $n_B \sim 1$ fm$^{-3} >$ 0.17 fm^{-3}
- But very complicated: small volumes, large lattice spacing, heavy pion, beyond double precision
- Recent studies: V. G. Bornyakov, Phys. Rev. D 95 (2017), Phys. Rev. D 107 (2023); HotQCD, Phys.Rev.D105 (2022); S. Borsányi e-Print: 2502.03211,

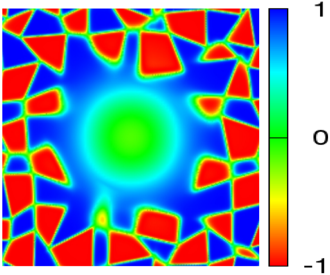


K. Nagata e-Print: 2108.12423

Strong magnetic field in heavy ion collisions

- Heavy ion collision creates huge magnetic field $eB < 1\ \mathrm{GeV}^2$
  D.Kharzeev, L.McLerran, H.Warringa, Nucl.Phys.A803 (2008);
  V.Skokov, A.Illarionov, V.Toneev, Int. J. Mod. Phys. A 24 (2009)
  V.Voronyuk, V.Toneev, W.Cassing, E.Bratkovskaya, V.Konchakovski, S.Voloshin, Phys. Rev C 84 (2011)
- Strong eB modifies vacuum properties
  Magnetic catalysis
  V.Gusynin, P.Miransky, V.Shovkovy, Phys.Rev.Lett. 73 (26)
- Catalyzing role of electromagnetic field on deconfinement
  B.Galilo, S.Nedelko , Phys. Rev. D 84 (2011)
  S.Nedelko, V.Voronin, Eur. Phys. J A (2015)
- Inverse magnetic catalysis
  F.Bruckmann, G.Endrodi, T.Kovacs, JHEP 04 (2013)

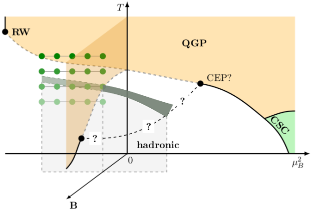




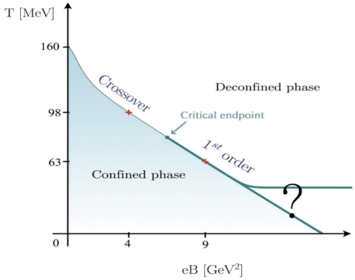
$F\tilde{F}/F^2$

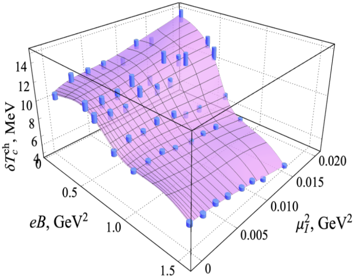
Dense QCD at nonzero magnetic field

- Idea: consider
  the phase diagram in space (T, μ_B, eB)
- Crossover at $eB = 4$ GeV^2 and first order at $eB = 9$ GeV^2
  M. D'Elia, Phys.Rev.D 105 (2022) 3, 034511
- Phase diagram at $\mu_B \neq 0$, $eB < 1.5$ GeV^2
  Inverse magnetic catalysis at finite μ_B
  V. Braguta Phys.Rev.D 100 (2019) 11, 114503
- $\delta T_c(eB, \mu_B) = \delta T_c(eB, \mu_B) - A_2(eB)\mu_B^2$
  $(T^{CEP}, \mu_B^{CEP}) = (100(25), 800(140))$ MeV
  V.Braguta, Phys.Rev.D 100 (2019) 11



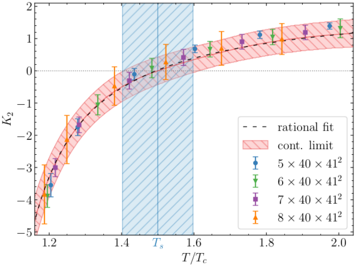
S. Borsanyi, PoS LATTICE2023 (2024) 164

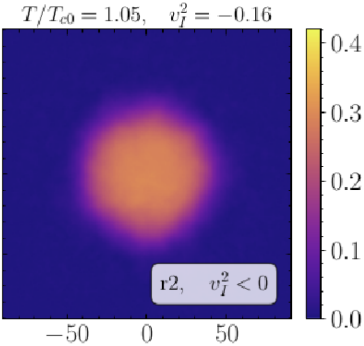




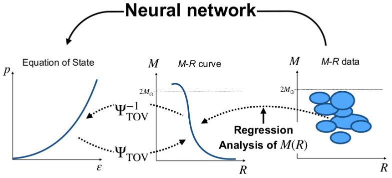
Relativistic rotation in heavy ion collisions

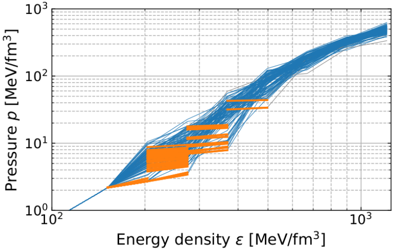
- Characteristic $\Omega \sim 10$ MeV
  STAR, Nature 548, 62 (2017)
- $v \sim c$ at $r \sim 10 - 20$ fm ($\sim 10^{22}$ s^{-1})
- Relativistic rotation of baryon matter
  General relativity effects must be accounted
- Rotation influences both quark and gluon degrees of freedom
- Suprising results from lattice simulations at $\mu_B = 0$
  V.Braguta, Phys.Rev.D 103 (2021) 9, 094515; PoS LATTICE2022 (2023) 190; Phys.Lett.B 855 (2024); Phys.Rev.D 110 (2024); Phys.Lett.B 852 (2024); Phys.Lett.B 852 (2024)
- Competition between quark and gluon sectors
- Negative moment of inertia
- Inhomogenious phase transitions
  talk of Artem Roenko, on 19 February at 16:15





QCD phase diagram from astrophysics





- Machine-learning analysis
  Fujimoto, Y., Fukushima, K., Murase, K., JHEP03(2021)
- Neutron star data on the radius-mass $R - M$
- Data $R - M \Rightarrow$ EoS (maximum likelihood method)
- Likely crossover but the first-order phase transitions is not excluded

Dense QCD at low temperature

- No good solution. The sign problem is manifested in all approaches
- One can conduct lattice studies for $\mu \leq \text{few} \times T$
- At low or zero temperature these approaches do not work
- The only possibility: QCD-like theories
  Without sign problem and common properties to real QCD

QCD-like theories

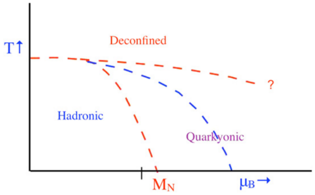
- Two-color QCD
  Symmetry $(\gamma_5 C \tau_2) \cdot D^* = D \cdot (\gamma_5 C \tau_2) \Rightarrow$ pairs (λ, λ^*)
- QCD at finite isospin density: $\mu_u = -\mu_d = \mu_I \Rightarrow \mu_B = 0$
  $\det(\hat{D}(\mu_I) + m) \times \det(\hat{D}(-\mu_I) + m) = |\det(\hat{D}(\mu_I) + m)|^2$
- ...

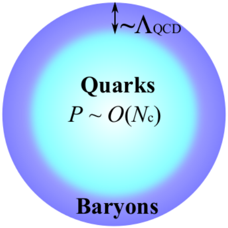
Sketch of dense QCD phase diagram

Phases of dense quarks at large Nc

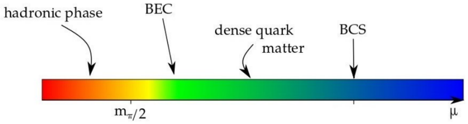
L.McLerran, R.D. Pisarski, Nuclear Physics A796 (2007)

- Hadronic phase $\mu_B < M_N$
- Dilute baryonic matter $\mu_B > M_N$
- Liquid–gas transition
  $\mu_B - M_N \sim \frac{\Lambda_{QCD}}{N_c^2} \sim \frac{\Lambda_{QCD}}{N_c^2} \sim 30$ MeV
- Quarkyonic phase $(\mu \sim \Lambda_{QCD})$
  - Quarks form Fermi sphere
  - Baryon on Fermi surface
  - Chiral symmetry is restored
  - Confinement
- Deconfinement: $\mu_B \gg \Lambda_{QCD}$





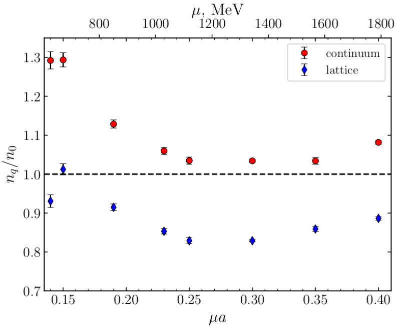
Phases in two-color QCD



Similar to Quarkyonic phase

- Fermi sphere is formed: $n_q \simeq n_{SB}$
- Baryons on the surface $\Sigma \sim \mu^2$
- Chiral symmetry is restored
- The system is in confinement

  V.Braguta, Phys.Rev.D 94 (2016), Phys.Rev.D 102 (2020); Etsuko Itou, JHEP 10 (2024); S. Hands, PoS LATTICE2024 (2025)



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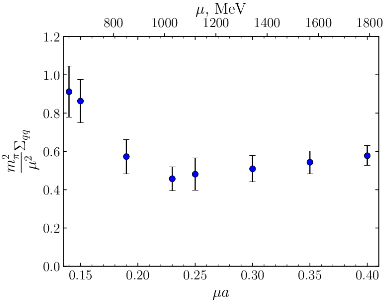
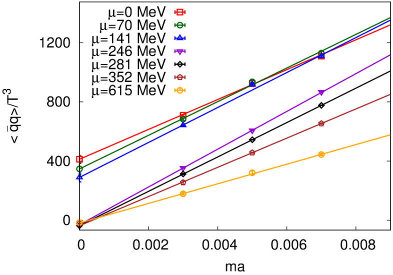


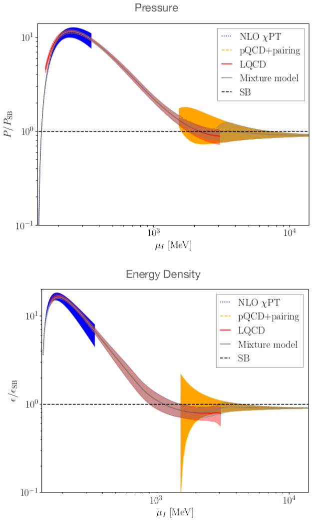


Phases of QCD at finite isospin density

Similar to Quarkyonic phase

- Fermi sphere is formed: $n_I \simeq n_{SB}$
- π^+ mesons on the surface $\Sigma \sim \mu_I^2$
- Chiral symmetry is restored
- The system is in confinement

  NPLQCD, Phys.Rev.D 108 (2023), Phys.Rev.Lett. 134 (2025), G. Endrodi JHEP 07 (2023)



Quark matter at high baryon density

- The Fermi sphere is formed and $\alpha_s(\mu) \ll 1$
- One gluon exchange potential is attractive in the colour anti-triplet state
- Instability towards the formation of Cooper pairs
- Colour-superconductivity (CSC) with diquark condensate
  M. Iwasaki and T. Iwado, Phys. Lett. B350 (1995)
  M. G. Alford, K. Rajagopal, and F. Wilczek, Phys. Lett. B422 (1998)

  R. Rapp, T. Schafer, E. V. Shuryak, and M. Velkovsky, Phys. Rev. Lett. 81 (1998)
- Scalar diaquark condensate: $d_{\alpha i} \sim \epsilon_{\alpha\beta\gamma}\epsilon_{ijk}\langle\psi^T_{\beta j}C\gamma_5\psi_{\gamma k}\rangle$
  - Colour-flavour locked phase: $\epsilon_{l\beta\gamma}\epsilon_{ljk}\langle\psi^T_{\beta j}C\gamma_5\psi_{\gamma k}\rangle$

    F. Wilczek, Nucl.Phys. B 537 (1999)
  - Two-flavour superconducting phase: $\epsilon_{3\beta\gamma}\epsilon_{jk}\langle\psi^T_{\beta j}C\gamma_5\psi_{\gamma k}\rangle \neq 0$

    F. Wilczek, Phys. Lett. B 422 (1998)
- Diquark condensates $d_{\alpha i}$: $[ud], [us], [ds]$-diquarks

  Nucl. Phys. A743 (2004) 127, Phys. Rev. Lett. 93 (2004) 132001, Phys. Rev. D71 (2005) 034002, Nucl. Phys. B558 (1999) 219–242, arXiv:hep-ph/0407257

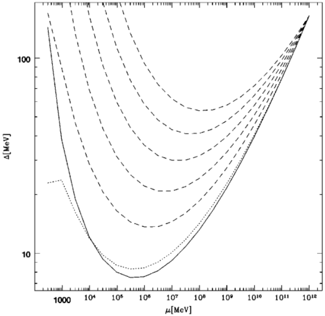
Quark matter at high baryon density

- Spin-one diquarks
  Phys. Rev. D66 (2002) 114010, Phys. Rev. Lett. 91 (2003) 242301, arXiv:hep-ph/0407257, Phys. Lett. B350 (1995) 163, hys. Rev. D71 (2005) 054016
- CSC at finite temperature
  Melting pattern: CFL $\to$ $([du],[ds])$ $\to$ $[ud]$ $\to$ NQM
  Phys. Rept. 107 (1984) 325, Phys. Rev. D63 (2001) 074018, Phys. Rev. Lett. 93 (2004) 132001, Phys. Rev. D71 (2005) 034002
- $U_A(1)$-anomaly and chiral symmetry breaking
  Phys. Rev. Lett. 97 (2006) 122001, Phys. Rev. D76 (2007) 074001, JHEP 12 (2008) 060, Phys. Rev. D81 (2010) 125010
- Meson masses: $M_{\pi^\pm} > M_{K^\pm} \simeq M_{K^\pm}$: $\pi^+([\bar{d}\bar{s}][su])$, $\pi^+([\bar{d}\bar{s}][ud])$
  Phys. Lett. B464 (1999) 111–116, Phys. Rev. D61 (2000) 074012, Phys. Rev. D62 (2000) 059902
- Kaon condensation in QM
  Nucl. Phys. A697 (2002) 802–822, Phys. Rev. D65 (2002) 054042, Phys. Rev. D71 (2005) 034004, Phys. Rev. D81 (2010) 054033, Phys. Rev. D72 (2005) 094032
- Spatially modulated chiral condensate: $\langle\bar{\psi}(x)\psi(x)\rangle = \sigma\cos 2\vec{q}\vec{x}$, $|\vec{q}| = \mu_q$
  D. Deryagin, D. Grigoriev, V. A. Rubakov, Int. J. Mod. Phys. A7 (1992)
- ...

Quark matter at $\mu_B \gg \Lambda_{QCD}$

Dense QCD

- Typical mass gap in BCS:
  $\Delta \sim \exp\left(-\frac{C}{\mu^2 g^2}\right)$
- Mass gap in CSC: $\Delta \sim g^{-5}\mu \exp\left(-\frac{3\pi^2}{\sqrt{2}g}\right)$
  D. T. Son Phys. Rev. D59
  T. Schäfer, F. Wilczek, Phys. Rev. D60
- Debye screening of chromoelectric field
- Landau damping of chromomagnetic field
- Typical scale is $\Delta \sim 100$ MeV
- $T_c \sim \Delta$



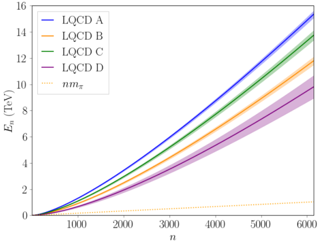
QCD-like theories

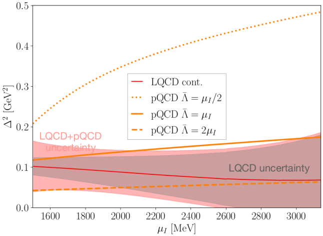
- Two-color QCD: $\Delta \sim g^{-5}\mu \exp\left(-\frac{2\pi^2}{g}\right)$
  T. Schäfer Nucl. Phys. B 2000, 575, 269–284
- QCD with isospin density:
  $\Delta \sim g^{-5}\mu \exp\left(-\frac{3\pi^2}{2g}\right)$

D. T. Son, M. A. Stephanov, Phys.Rev.Lett. 86 (2001) 592

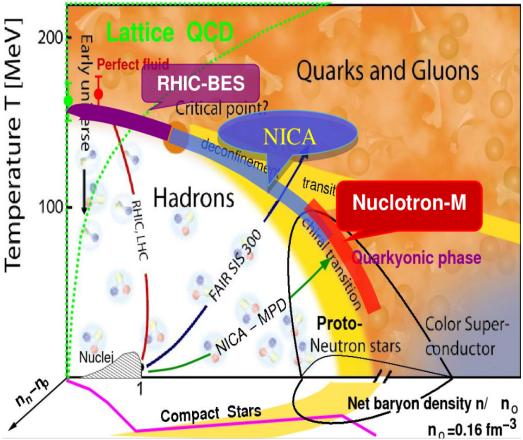
Quark matter at high isospin density

- Correlation function of many pions $C(t) = \langle (\pi^+(\vec{x},0))^n (\pi^-(\vec{y},t))^n \rangle$
- Late time behaviour $C_n(t) \to e^{-E_n t}$
- $N_f = 2+1$ and physical quark masses
- $n = 6144$
- C_{6144} varies by 10^5 orders of magnitude 2-double and 3-double precision NPLQCD, Phys.Rev.D 108 (2023), Phys.Rev.Lett. 134 (2025)
- Mass gap $\Delta \sim 100$ MeV
- Similar magnitude of Δ in two-color QCD





Conclusion



- Poor understanding of QCD at finite baryon density
- Rich physics due to extreme conditions

  Large baryon density, strong electromagnetic fields, relativistic rotation...
- NICA creates unique conditions for studying completely new physics