The Phase Diagram of Nuclear Matter

PHY599: Graduate Seminar II

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Outline

Phases of matter

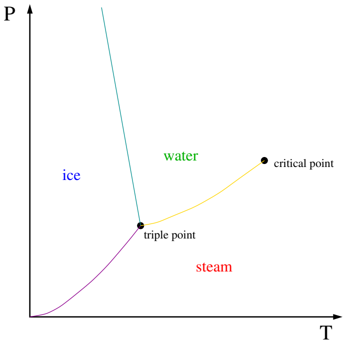
"[...] A phase is a region of space (a thermodynamic system), throughout which all physical properties of a material are essentially uniform. Examples of physical properties include density, index of refraction, magnetization and chemical composition." (wikipedia.org)

Phases of Matter

- Characterized by **order parameters** such as magnetization, pairing amplitude etc..
- Two phases may differ by their **symmetry**

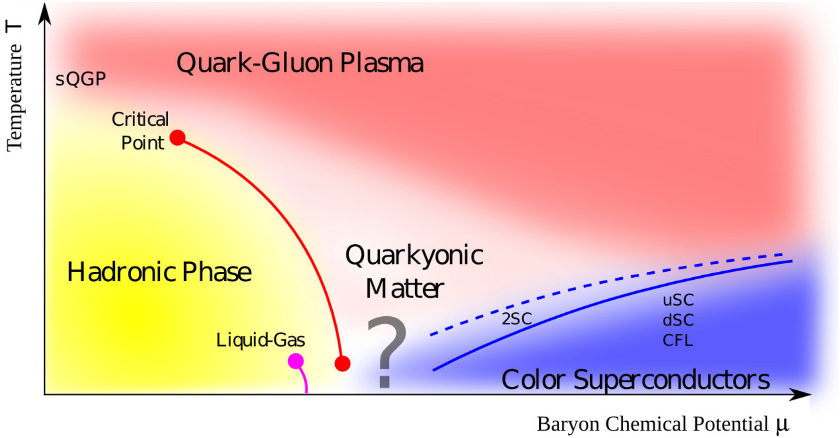
- liquid/gas $\rightarrow$ crystal : translational symmetry
- paramagnet $\rightarrow$ ferromagnet : SO(3) spin-rotation symmetry

  $\vdots$



Ref. [1]

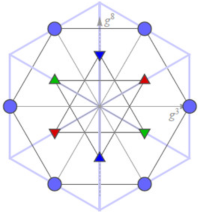
Vacuum and hadronic matter



Ref. [2] (mod.)

QCD and the strong force

- QCD is a gauge theory with gauge group SU(3)
- defining (and its conjugate) representation of SU(3) is $\mathbf{3}/\mathbf{3}^*$
  $\rightarrow$ 3 (anti-) quarks: red, green, blue
- adjoint representation is $\mathbf{8}$
  $\rightarrow$ 8 gluons (force carriers)
- Two different types of stable hadrons:
  - $q_r q_g q_b$ baryon
  - $\bar{q}q$ meson



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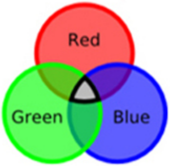

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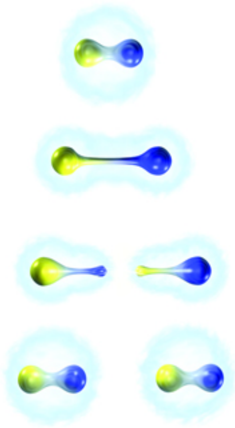
QCD and the strong force

- heuristic potential for the strong force between $\overline{q}q$ pair:

  $$V(r) = -\frac{A(r)}{r} + Kr$$

  however $A(r) \propto 1/\ln(r^{-1})$
  $\rightarrow$ **asymptotic freedom**
- for large seperations r the potential rises linearly : high energy density enables creation of $\overline{q}q$ pairs
  $\rightarrow$ **Color confinement**



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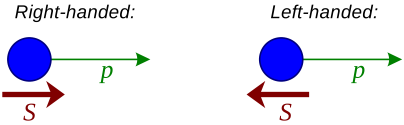
Chiral symmetry breaking

- **Helicity**: projection of the spin onto the direction of the momentum

$$\vec{h} = \frac{\vec{S} \cdot \vec{p}}{|\vec{p}|}$$

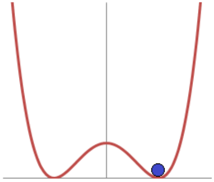


en.wikipedia.org

- Particles with mass: Lorentz-boost can invert helicity
- Mass term (Higgs-mech.) $\mathcal{L}_m = m\overline{\psi}\psi = m(\psi_L^\dagger \psi_R + \psi_R^\dagger \psi_L)$ **breaks the chiral symmetry**
- Mass discrepancy: Nucleon mass $m_n \sim 1$ GeV **BUT:** (current) quark mass $m_d \sim 7$ MeV, $m_u \sim 3$ MeV

Chiral symmetry breaking

- QCD vacuum unstable to formation of $q\bar{q}$ pairs: $\langle(\psi_L^\dagger\psi_R + \psi_R^\dagger\psi_L)\rangle \neq 0$
- By interacting with this "vacuum" a propagating quark can change its helicity as if it had mass
  $\rightarrow$ **constituent mass** Σ
- Chiral symmetry **spontaneously** broken
- Approximate Goldstone modes: $\pi^\pm$,π^0



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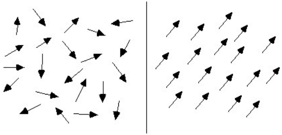

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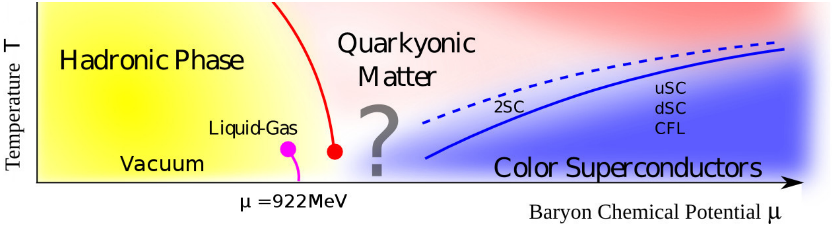
Vacuum and hadronic matter

- **Vacuum** is characterized by
  - broken chiral symmetry
  - pion fluctuations
  - dilute baryons
- Liquid-gas transition at $\mu_0 \simeq 922\text{MeV}$
- **Nuclear matter** formed by condensed baryons



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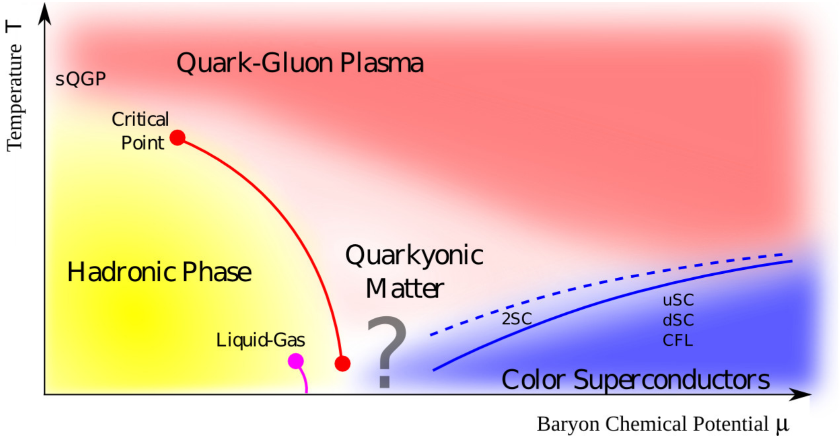
Quark-Gluon Plasma



Ref. [2] (mod.)

Quark-Gluon Plasma

- For $\mu = 0$ (no baryons) light pions $\pi^{\pm}, \pi^0$ are the main degrees of freedom (DoF)
- Raising the temperature can "break up" the mesons
  $\rightarrow$ Quarks and gluons become fundamental DoFs:
  Quark-Gluon Plasma (QGP)
- Naked color charges lead to screened potential

$$V(r) = -\frac{A(r)}{r} + Kr$$

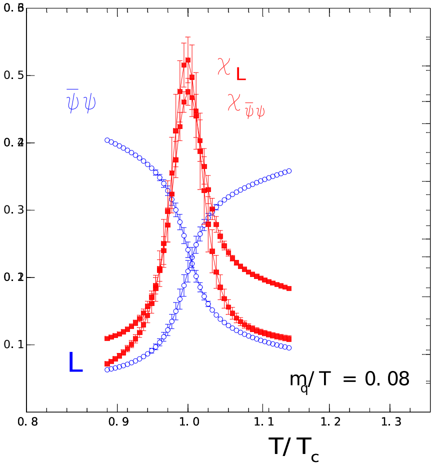
$$\downarrow$$

$$V_{QGP}(r) = -\frac{A(r)}{r} \exp -r/\lambda_D$$

- Simple thermodynamic calculations predict $T_c \simeq 144$MeV

Lattice QCD

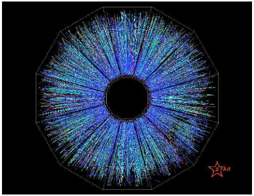
- Lattice QCD predicts $T_c \simeq 170\text{MeV}$
- Chiral symmetry is restored: $\langle\overline{\psi}\psi\rangle \simeq 0$
- Quark free energy function $L \propto exp(-f_q/T)$ increases: **No color confinement**
- Susceptibilities χ_L and $\chi_{\overline{\psi}\psi}$ peak: indicates crossover



Ref. [1]

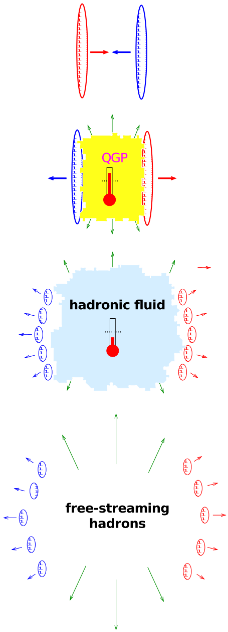
Experimental methods

- Question: How can a QGP be detected?
- May have existed between 10^{-5} and 10^{-4} seconds after the Big Bang
- No direct observation possible BUT: if transition from QGP to hadronic phase was first order, footprints in the form of hadronic "bubbles" might exist
- Other possibilty: **relativistic heavy-ion collisions** e.g. at **ALICE** at the LHC and **RHIC** in Brookhaven



Ref. [1]

- Colliding particles have CM energy of up to 3.5TeV
- Lorentz-contracted: “pancake” shape
- Different phases of collision:
  - QGP formation in the mid-rapidity region $y = \frac{1}{2}\ln(\frac{E+k_z}{E-k_z}) \simeq 0$
  - QGP expands and cools down : for $T < T_c$, hardrons start to form
  - **Chemical freezeout**: composition of formed hadrons stays fixed
  - **Thermal freezeout**: hadron gas expands, cools down until reactions are to rare to maintain thermal equilibrium



Ref. [1]

Observables

- J/ψ- suppression: Screening effects diminish the formation of $\bar{c}c$ mesons
- Strangeness enhancement
  - Strange baryons are likelier to form because chiral symmetry is restored
  - High gluon density enables new formation processes such as gluon-fusion $gg \to s\bar{s}$
- Elliptical flow
- Jet quenching
- ...

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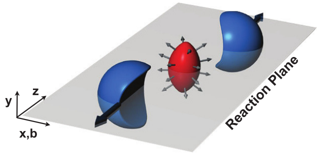
- **Elliptical flow**
- **Jet quenching**
- ...

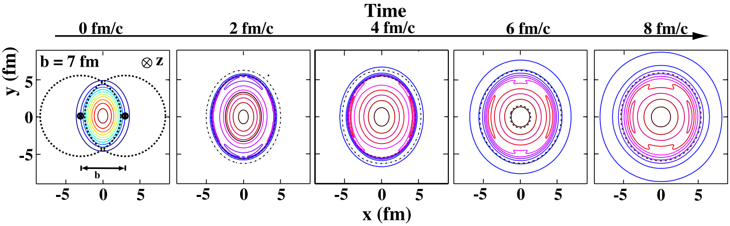
Elliptical flow

- Non-central heavy-ion collisions: nuclear overlap is spatially anisosotropic
- Anisotropy in the momentum-distribution of outgoing particles

$$\frac{dn}{d\phi} \sim 1 + 2v_2(p_T)\cos 2\phi$$



Ref. [3]



Ref. [3]

Jet quenching

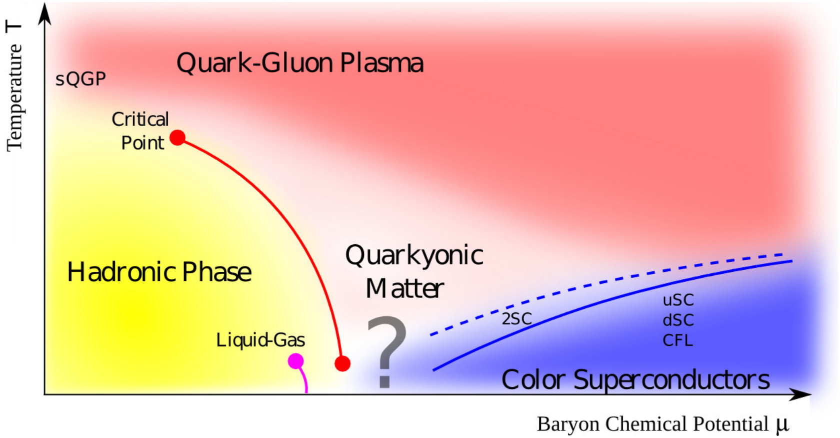
Jet-quenching:

- Jets, produced during collision, interact with QGP
- Far less high-p_T particles observed if QGP present
- Can be used as a "tomographic tool" to probe the parton density inside of QGP

By probing hydrodynamics of system: QGP found at RHIC is **perfect liquid**

$\rightarrow$ strongly interacting QGP : sQGP

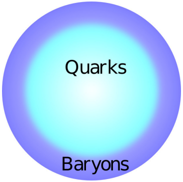
Quarkyonic matter



Ref. [2] (mod.)

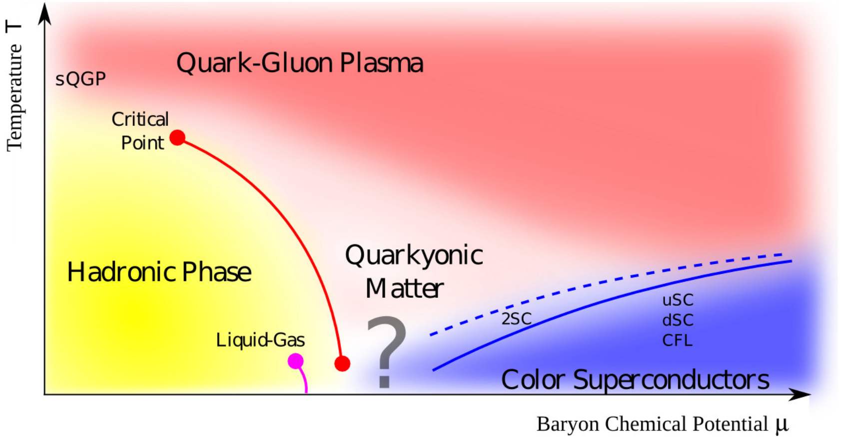
Quarkyonic matter

- Deep inside the Fermi sphere: weakly interacting quarks
- Surface: Strongly interacting quarks $\rightarrow$ meson/baryon excitations
- Theoretical model derived for $N_c \rightarrow \infty$
- Many unanswered questions



Ref. [2] (mod.)

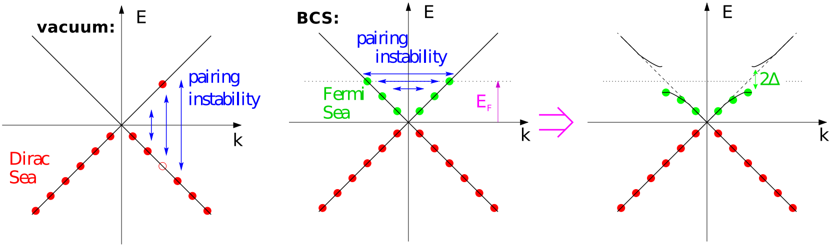
Color superconductivity



Ref. [2] (mod.)

Color superconductivity

- Weak attractive qq interactions can lead to a **BCS pairing instability**
- Force between two quarks due to single gluon exchange is attractive
- Analogous to the electrons in a metal, quarks can condense in pairs



Ref. [1]

Possible evidence

- Neutron stars are comparably cool with $T \lesssim 10 MeV$
- Core might be in QM/SC phase but bulk is normal nuclear matter $\rightarrow$ hard to detected
- SC core might stabilize neutron star magnetic fields
- Neutrino detection in formation of neutron stars

Conclusion / Open questions

- Phase diagram of QCD has exciting properties
- Far from complete understanding
  (especially for intermediate μ/T)

- Connection between confinement and chiral SB?
- Weakly interacting QGP for high enough T?

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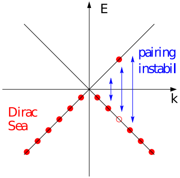
Explicit vs. spontaneous symmetry breaking

QCD: Chiral symmetry

- Chiral symmetry of vaccum spontaneously broken $\rightarrow$ **constituent mass** $\Sigma \sim \langle\overline{\psi}\psi\rangle$
- Quark mass m explicitly breaks chiral symmetry
- Approximate Goldstone modes: $\pi^{\pm}$,π^{0}

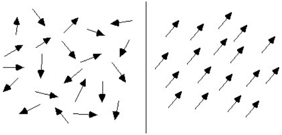
Ferromagnet: SO(3) symmetry

- Below critical temperature spins align spontaneously $\rightarrow$ **spontaneous magnetisation** M
- External magnetic field h explicitly breaks SO(3)
- Goldstone modes: spin-waves



$$\langle\overline{\psi}\psi\rangle \longleftrightarrow M$$

$$m \longleftrightarrow h$$



Derivation of T_c

- Consider non-interacting particles
- Blackbody radiation pressure of pion gas

$$P_\pi = -\frac{\partial \Omega_\pi}{\partial V}|_{T,\mu} = 3 \times (\frac{\pi^2}{90})T^4$$

- Pressure for the QGP

$$P_{\bar{q}q} = 2 \times 2 \times 3 \times \frac{7}{4} \times (\frac{\pi^2}{90})T^4$$
$$P_g = 2 \times 8 \times (\frac{\pi^2}{90})T^4$$

- Setting the pressures equal and taking confinement into account we arrive at $T_c \simeq 144$MeV
- Lattice QCD predicts $T_c \simeq 170$MeV