QCD phase diagram and quark matter at high densities

Micaela Oertel

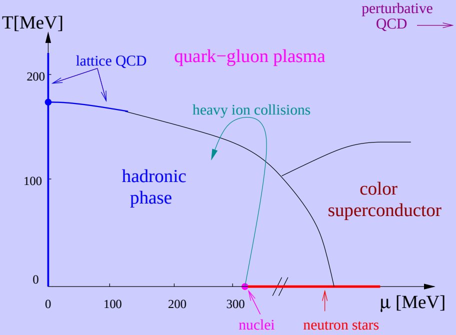
LUTH, Meudon

MICRA 2009, Copenhagen, august 23-29

Punchline

If the nuclear part of the EOS is uncertain, this is even more true for the quark part . . .

What do we know about the QCD phase diagram?



- Nuclear Part: constraints from measurements of nuclear parameters, mainly for symmetric matter
- Zero chemical potential: lattice QCD calculations $\longrightarrow$ phase transition to QGP at $T \approx 150$ MeV

(for example: A. Bazavov et al., PRD '09)

- Very high densities $n \gg n_0$ (or temperatures): perturbative QCD calculations
- High density quark matter: color superconducting phases in analogy with electronic superconductors but with attractive QCD interaction
- Intermediate densities (n several times n_0)?

Intermediate densities of several times n_0

Theoretical questions:

- Can we trust usual nuclear forces for densities $n \gtrsim (2-3)n_0$?
- Is there a transition to exotic (hyperons, quarks,...) matter?

Experimental or observational constraints?

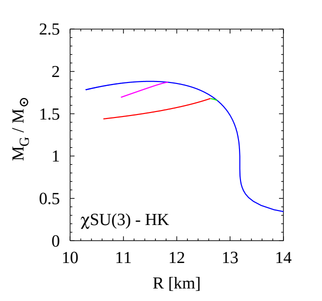
- No direct experimental constraint!
- Constraints from heavy ion collisions? Perhaps not:
  - Much higher energy densities (temperatures)
  - Is there an equilibrium reached?

  $\longrightarrow$ not easy to interpret correctly
- We can have a look at neutron star properties

Constraints from neutron star properties?

- Stars with “exotica” have in general smaller maximum masses than pure hadronic stars due to the softening of the EOS
- But: EOS of the quark phase is still less known than hadronic one, an additional repulsive (vector) interaction easily brings hybrid (hadronic+quark matter) star maximum masses in agreement with recent observations of high mass neutron stars (Alford et al., Nature ’07)
- Quark stars (if they exist): different mass-radius relation because they are self-bound
- Phase transitions observable (back-bending phenomenon, energy release)?

Example: static configurations with hadronic, hadronic/normal quark, and hadronic/ color superconducting quark matter



(M. Buballa et al. PLB ’04)

Description of quark matter at high densities

For the quark phase mainly two models are used:

Bag models:

- Confinement schematically introduced via a constant external "bag" pressure, B
- Inside the bag: perturbative interaction for quarks
- Stable hybrid stars, even pure quark stars possible

NJL-type models (chiral symmetry breaking!):

- Very high (constituent) strange quark masses ($\approx$ 500 MeV) at the relevant densities $\longrightarrow$ difficult to get stable hybrid stars containing strange quarks
- Mimic density dependent bag constant, $B = B(\rho)$

Color superconductivity can be included in both models

- Many possible pairing channels $\longrightarrow$ many different possible phases depending on parameter choice (m_s, coupling strength), external constraints (neutrality)
- Energetically favored over normal phases for $T < T_c$
- For the main phases, critical temperatures $T \approx 50$ MeV
- Effect on EOS small ($\approx$ 5 %)
- Electromagnetic properties, neutrino/heat transport, viscosities can be very different from one phase to another

Summary

The physics of high density quark matter is very interesting, in particular since we know that there will be color superconducting phases. But for densities relevant for neutron stars and gravitational collapse of massive stars, many unknowns remain. Even the pure existence of quark matter at these densities is uncertain. In addition, this density region is not accessible from first principles: perturbative QCD is not applicable and lattice QCD (computer simulations of QCD) cannot reach these densities. We therefore rely on more or less realistic models trying to incorporate all the important qualitative features. Observational (experimental?) constraints are thus very important!