Color superconductivity

Analogies to ultracold gases
and
Experimental signatures

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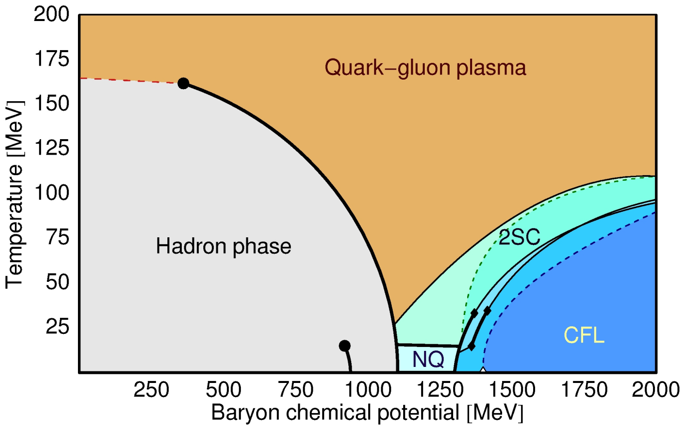
Outline

Overview

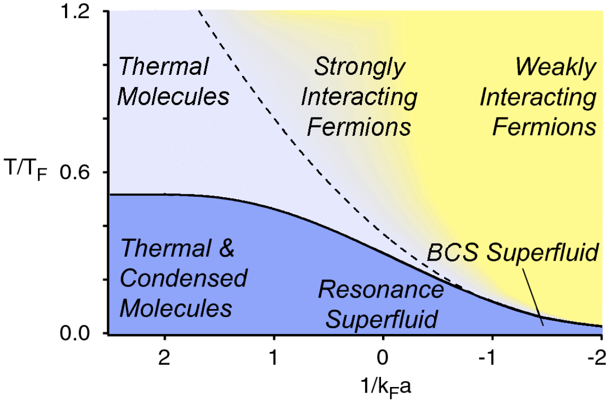
QCD phase diagram



[Ruester et al.]

- Which region is theoretically described by what?
- Which region is probed by what?
- Experimental control of the probed region

Atomic phase diagram



[W. Ketterle and M. W. Zwierlein]

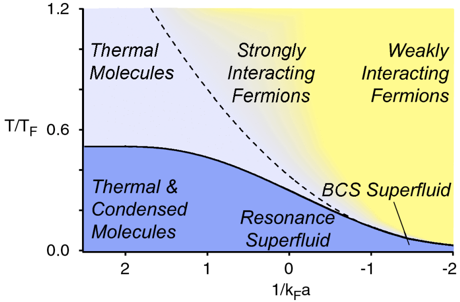
- comparison to QCD
- different axis: $\mu \rightarrow a$
- easy control of temperature and interaction (Feshbach resonances)

Where to look for Superconductivity?

- Superconductivity requires:
  - in a fermionic system:
  - attractive interaction (to form pairs)
  - low temperature
  - high density $\Rightarrow$ high μ (for QCD)
- QCD (asymptotically) features an attractive interaction (one gluon exchange)
- Possible abundances:
  - Heavy ion collisions
  - Compact stars (neutron stars)
  - ...

Overview

Phases in BEC/BCS



- trapped atoms (fermions/bosons)
  $\Rightarrow \mu(T)$ given by normalization
- Adjustable coupling (by Feshbach resonance)
- observation of **condensation**
- observation of **vortices**

Comparison of relevant variables

QCD	Atoms
μ is $\sqrt{s}$-dependent measured from composition	μ given by N
T from collision	T adjusted by cooling
coupling strength from μ	coupling (scattering length) adjustable
additionally color & flavor dof	
dense matter (to free quarks)	dilute gas (to avoid losses)

Equation of State (EoS)

- Free Fermi gas (no interaction):

$$\bar{E}_0 = \frac{3}{5}\frac{k_{\mathrm{F}}^2}{2m}$$

- for strong coupling:

$$\xi = \frac{E}{\bar{E}_0}$$

QCD

$$\xi = \frac{3}{4}$$

Ultracold gas

$$\xi = 0.09 - 0.5$$

in QCD case:
strongly interacting phase hardly distinguishable by EoS

Pairing

Consider weak coupling limit

QCD

asymptotically free
one-gluon exchange:

$$\Delta \propto \Lambda_{\mathrm{BCS}} \exp\left(-\frac{3\pi^2}{\sqrt{2}g}\right)$$

$$T_c = \frac{e^\gamma}{\pi}\Delta$$

exponentially suppressed

Ultracold gas

weak coupling
BCS regime

$$\Delta \propto \exp\left(-\frac{\pi}{2k_{\mathrm{F}}|a|}\right)$$

$$T_c = \frac{e^\gamma}{\pi}\Delta$$

Stressed pairing

QCD	**Atoms**
effect of different m_q	spin-polarization

leads to difference in Fermi-surface

partial pairing possible in 2SC phase	only one pairing pattern no pairing

but: pairs with $\mathbf{q} \neq 0$

$$\Delta(\vec{x}) = \Delta e^{2i\vec{q}\cdot\vec{x}}$$

FFLO/LOFF phase

order parameter has spatial dependence

What can we learn?

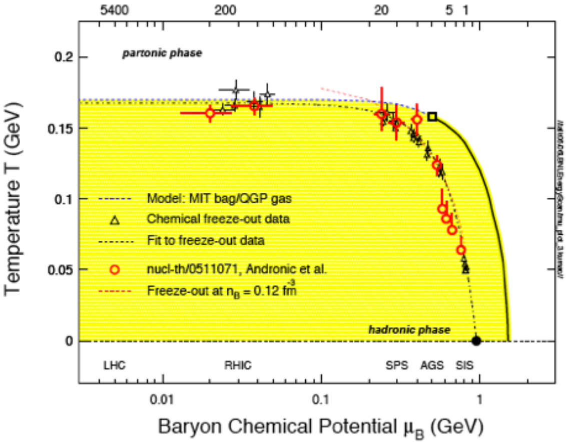
- Similar behaviours
- nomenclature, formulation
- Universal features
  (not depending on the details of the interaction)
- separation of interaction-dependent phenomena

Overview

Prerequisites to observe CSC

- high $\mu \Rightarrow$ high net baryon density
- sufficiently low temperature
- **but:** no cooling mechanism in HIC
- lower limit in T probably above T_c

Feasibility



[N. Xu]

- HIC can only probe high-temperature region

Overview

Compact Stars

- Star evolution determined by its mass
- Stabilization by Fermi pressure
  - white dwarfs (e^--pressure) (typ. $M \approx M_\odot$, $R \approx 10^{-2} R_\odot$)
  - neutron stars (n-pressure) (typ. $M \approx M_\odot$, $R \approx 10^{-5} R_\odot$)
- Structure of a neutron star
- Charge neutrality

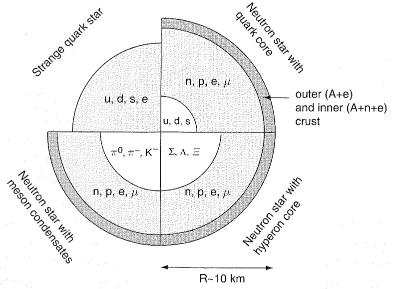
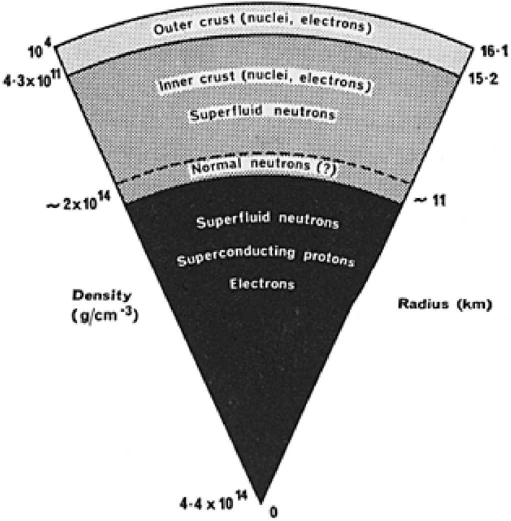


Fig. 9.1. Possible internal structures and compositions of four different types of compact stars.

[Yagi, Hatsuda, Miake]

Neutron star



- $T_{\mathrm{core}} \approx 1\mathrm{MeV}$
- $\rho_{\mathrm{core}} \approx 5 - 10 \cdot \rho_0$
- core:
  quark or hadronic matter
- quark matter (if any)
  in SC phase
- nn-pairing $\rightarrow$
  superfluidity
- pp-pairing $\rightarrow$
  electromagnetic
  superconductor

Equation of State (EoS)

- $P = P(\rho)$?
- from radial equilibrium:

$$\frac{dP}{dr} = -\frac{Gm(r)\rho(r)}{r^2}$$

- EoS $\Rightarrow R(M) \propto \frac{1}{M^{\frac{1}{3}}}$

Equation of State (EoS)

- $P = P(\rho)$?
- from radial equilibrium:

$$\frac{dP}{dr} = -\frac{Gm(r)\rho(r)}{r^2}$$

- EoS $\Rightarrow R(M) \propto \frac{1}{M^{\frac{1}{3}}}$
- CSC is a Fermi-surface effect
  $\Rightarrow$ small influence on EoS ($\propto \left(\frac{\Delta}{\mu}\right)^2$)
- not sensitive enough to detect CSC

Low Mass X-ray Binary (LMXB)

- LMXBs consist of a ns/bh and a donor
- accretion from companion
- gaining angular momentum **and** moment of inertia
- decreasing core density, decreasing quark matter part
- in model: effectively no change in frequency
- observation: cumulation of LMXBs around 250-350 Hz

only probes the EoS
(existence of a quark core)

Cooling history

- cooling governed by heat capacity and neutrino emission:
  e. g. $d \rightarrow u\ e^{-}\ \bar{\nu}_e$
- C_V and L_ν dominated by Fermi-surface effects
- if $\Delta \gg T$ for all quarks
  $\Rightarrow$ contribution suppressed by $e^{-\frac{\Delta}{T}}$
- C_V and L_ν much smaller than in nuclear matter outside the core
- $\Rightarrow$ Probing for small gaps
  which would lead to high cooling rate

Supernova neutrinos

- shortly after SN too hot ($30 - 50\mathrm{MeV}$) for SC
  $\Rightarrow$ rapid cooling below T_c
- mean free path for νs increases
- sudden release of neutrinos
- looking for bump in neutrino signal

R-mode instabilities

- ns with sufficiently high angular rotation frequency Ω
  $\Rightarrow$ unstable to r-mode oscillations
- damping by viscosity
- damping is exponentially suppressed for gapped SC
- SC quark star instable for $\Omega \gtrsim 10 - 100\mathrm{Hz}$
  many stars faster $\Rightarrow$ no SC pure quark stars
- if only core SC
  friction to mantle leads to damping

Magnetic field evolution

- in conventional electric SC: Meissner effect
  magnetic field penetration only in flux tubes
- anchor for the magnetic field
- magnetic flux within the core cannot decay !
- measurement: dipole moment
- but: magnetic flux lines can move
- $\Rightarrow$ no clear signature

Glitches

- Glitch: sudden jump in the rotational frequency
- pairing between species of different μ:
  possibility of pairs with non-zero momentum (LOFF)
- Assume LOFF phase $\rightsquigarrow$ spatially varying gap
- Assume superfluid $\rightsquigarrow$ vortices
- pinning of vortices to structured superfluid
- rotation frequency $\propto$ vortex density
- abrupt change of overall rotation frequency

Overview

Summary

- Universal (interaction independent) features
- Color superconductivity observation difficult
- Atomic case easier to control

References

D. Rischke
The Quark-Gluon Plasma in Equilibrium
[nucl-th/0305030v2]

M. Shifman
At the frontiers of Particle Physics: Handbook of QCD
[hep-ph/0011333v2]

Th. Schaefer
From Trapped Atoms to Liberated Quarks
International Journal of Modern Physics E

S. R. Beane and M. J. Savage
The Quark-Mass Dependence of Two-Nucleon Systems
[nucl-th/0208021]

A. Sedrakian, J. W. Clark, M. Alford
Pairing in Fermionic Systems
World Scientific

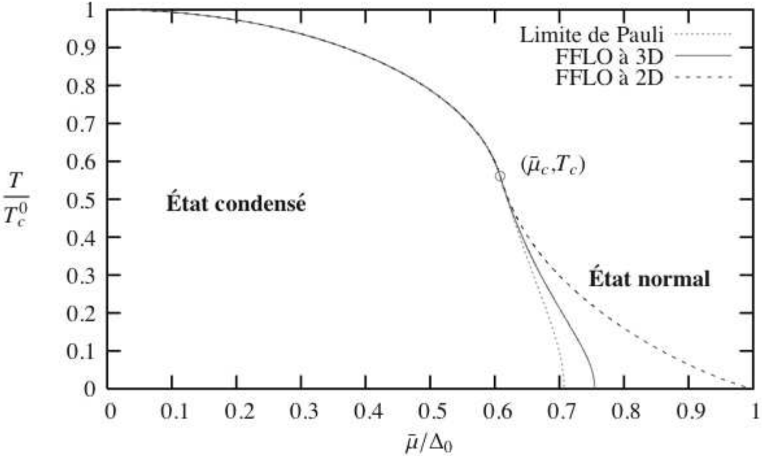
References (cont.)

- K. Yagi, T. Hatsuda and Y. Miake
  Quark-Gluon Plasma
  Cambridge University Press
- L. Pitaevskii and S. Stringari
  Bose-Einstein Condensation
  Oxford Science Publications
- W. Ketterle and M. W. Zwierlein
  Making, probing and understanding ultracold Fermi gases
  [arXiv:0801.2500]
- N. Xu
- Ruester et al.
  The phase diagram of neutral quark matter: Self-consistent treatment of quark masses
  [hep-ph/0503184]

References (cont.)

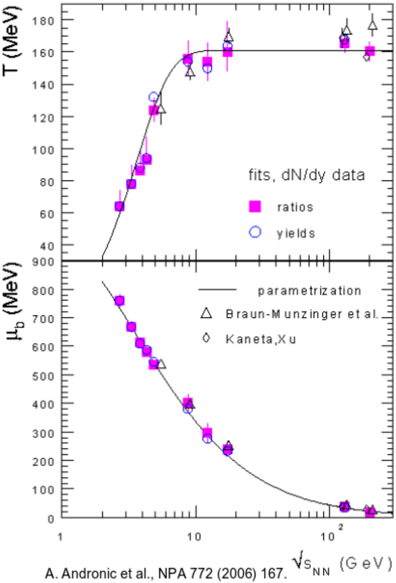
R. Combescot
Introduction to FFLO phases and collective mode in the BEC-BCS crossover
[cond-mat/0702399]

FFLO/LOFF



[R. Combescot]

$\mu(\sqrt{s})$, $T(\sqrt{s})$

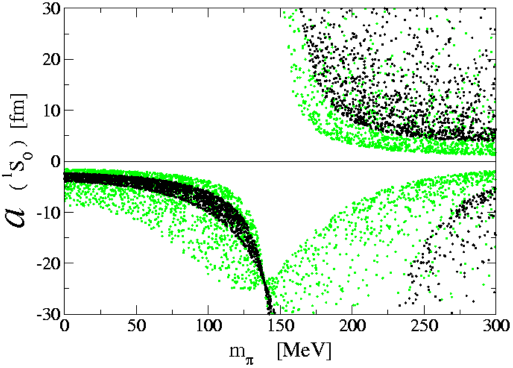


A. Andronic et al., NPA 772 (2006) 167.

[Andronic et al.]

Feshbach resonance: **B** $\leftrightarrow m_\pi$

Dependence of scattering length in QCD on m_π
similar to Feshbach resonance



[Beane, Savage]

Plausibility, Explanation ???
m_π determined by what ??? chiral symmetry ???