Quark Matter in Neutron Stars

David Blaschke
Univ. Wrocław & JINR Dubna

PRex @ ECT*, August 4, 2009

PSR J0205+64 in 3C58
Quark Matter in Neutron Stars

David Blaschke
Univ. Wrocław & JINR Dubna

- Introduction: Hadronic Cooling and EoS Problem
- Quark Substructure and Phases
- Hybrid Star Structure & Cooling
- Quarkyonic Matter?

PRex @ ECT*, August 4, 2009
DU threshold for most hadronic EoS active in neutron stars with typical masses!

Klähn, et al., PRC 74, 035802 (2006); [nucl-th/0602038]
Universal behavior of $(1-2x(n))^2 E_S(n)$?

Exclude $NL_\rho$, $NL_\rho\delta$, DBHF for violation of DU constraint → “universal” high-density behavior of $\beta^2(n)E_S(n)$

**Mass and flow constraint**

1. Mass and flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusions

![Mass-Radius constraint and Flow constraint](image)

- Large Mass ($\sim 2 \, M_\odot$) and radius ($R \geq 12 \, \text{km}$) $\Rightarrow$ stiff EoS;
- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS!

DU threshold and ‘hadronic’ neutron stars (II)

- DU threshold ⇒ sensitivity to tiny mass variations;
- Description of Vela not possible with typical masses!

S. Popov et al., PRC 74 (2006); D.B. and H. Grigorian, Prog. Part. Nucl. Phys. 59 (2007) 139
• DU threshold: overpopulation of a small mass window;
• Hadronic cooling not fast enough to describe Vela with $M < 1.5 \ M_\odot$!

EoS constraint from double pulsar J0737-3039?

1. Mass and flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusions

Double core scenario:

Baryon mass vs. gravitational mass - constraint or consistency check?

Podsiadlowski et al., MNRAS 361 (2005) 1243
1. Mass and flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusion
Phase diagram of QCD: Chiral quark models

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusion
Quantum Field Theory for chiral Quark Matter

• Partition function for chiral Quark Field theory

\[ Z[T, V, \mu] = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi \exp \left\{ - \int^\beta d\tau \int_V d^3x [\bar{\psi}(i\gamma^\mu \partial_\mu - m - \gamma^0 \mu)\psi - \mathcal{L}_{\text{int}}] \right\} \]

• Current-current coupling (4-fermion interaction)

\[ \mathcal{L}_{\text{int}} = \sum_{M=\pi,\sigma,...} G_M (\bar{\psi} \Gamma_M \psi)^2 + \sum_D G_D (\bar{\psi}^C \Gamma_D \psi)^2 \]

• Bosonisation (Hubbard-Stratonovich Transformation)

\[ Z[T, V, \mu] = \int \mathcal{D}\phi_M \mathcal{D}\Delta_D^\dagger \mathcal{D}\Delta_D \exp \left\{ - \sum_M \phi_M^2 \frac{1}{G_M} - \sum_D \frac{|\Delta_D|^2}{4G_D} + \frac{1}{2} \text{Tr} \ln S^{-1}[\{M_M\}, \{\Delta_D\}] \right\} \]

• Collective (stochastic) Fields: Mesons (\(\phi_M\)) and Diquarks (\(\Delta_D\))

• Systematic Evaluation: Mean field + Fluctuations

  – Mean-field Approximation: Order parameter for Phase transitions (Gap equations)
  – Fluctuations (2. Order): Hadronic Correlations (Bound- & Scattering states)
  – Fluctuations of higher Order: Hadron-Hadron Interaction
Dynamical quark masses and diquark gaps at $T = 0$ for intermediate diquark coupling $G_D = 0.75 \, G_S$

Dispersion relations for $G_D = 0.75 \, G_S$, $T = 0$, $\mu = 465$ MeV (left), $G_D = 1.0 \, G_S$, $T = 59$ MeV, $\mu = 500$ MeV (right)

The phases are:

- NQ: $\Delta_{ud} = \Delta_{us} = \Delta_{ds} = 0$;
- NQ-2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$, $0 \leq \chi_{2SC} \leq 1$;
- 2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$;
- uSC: $\Delta_{ud} \neq 0$, $\Delta_{us} \neq 0$, $\Delta_{ds} = 0$;
- CFL: $\Delta_{ud} \neq 0$, $\Delta_{ds} \neq 0$, $\Delta_{us} \neq 0$;

Result:

- Gapless phases only at high T,
- CFL only at high chemical potential,
- At $T \leq 25$-30 MeV: mixed NQ-2SC phase,
- Critical point $(T_c, \mu_c) = (48 \text{ MeV}, 353 \text{ MeV})$,
- Strong coupling, $G_D = G_S$, similar, no NQ-2SC mixed phase.

Rüster et al, PRD 72 (2005) 034004;
Blaschke et al, PRD 72 (2005) 065020;
Abuki, Kunihiro, NPA768 (2006) 118;
Warringa et al, PRD 72 (2005) 014015
1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

- Large Mass ($\sim 2 \, M_\odot$) and radius ($R \geq 12 \, \text{km}$) $\Rightarrow$ stiff quark matter EoS;
  Note: DU problem of DBHF removed by deconfinement! and: CFL core Hybrids unstable!

- Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS!
  Note: Quark matter removes violation by DBHF at high densities

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

– Shen et al. EoS from supernova studies in contradiction with low-density flow constraint!
– Density-dependent RMF (DD-2F) tuned to fit Shen at very low densities

Typel, Röpke, Klähn, D.B., Wolter, work in progress
Large Mass ($\sim 2 \, M_\odot$) and radius ($R \geq 12 \, \text{km}$) $\Rightarrow$ stiff quark matter EoS;
Note: DU problem of DBHF removed by deconfinement! and: CFL core Hybrids unstable!

Flow in Heavy-Ion Collisions $\Rightarrow$ not too stiff EoS!
Note: Quark matter removes violation by DBHF at high densities

Hybrid Stars that masquerade as Neutron Stars

- Moment of Inertia $\Rightarrow$ objects with large masses necessary
- Surface redshift $\Rightarrow$ large values ($> 0.5$) troublesome for quark matter

Phase diagram for the CBM  NICA experiments

Phase diagram for isospin-symmetric matter, for hybrid star maximum masses $M_{max} = 1.9 \, M_\odot$ ($\eta_V = 0.25$) and $M_{max} = 1.7 \, M_\odot$ ($\eta_V = 0.25$) and accessibility in HIC experiments at different energies.

Wide variety of supernovas - progenitor mass dependence
Supernova Collapse in the Phase Diagram

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

Supernova evolution in the phase diagram

Nuclear matter

2SC
Supernova Collapse in the Phase Diagram (II)

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

Supernova evolution in the phase diagram

Nuclear matter

15 M\textsubscript{sun}

(Harald Dimmelmeier)

2SC

\[ T \text{ [MeV]} \]

\[ \rho \text{ [g cm}^{-3}\text{]} \]
Supernova Collapse in the Phase Diagram

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

Supernova evolution in the phase diagram

Nuclear matter

Temperature $T$ [MeV]

Density $\rho$ [g cm$^{-3}$]

$15 \, M_{\text{sun}}$ (Harald Dimmelmeier)

$40 \, M_{\text{sun}}$ (Tobias Fischer)
Supernova 1987A - 20 years later:

- Big mystery of rings!
- Double degenerate core in common envelope?
- 2.14 ms periodic signal
- Explanation for 99% of GRB?

Middleditch, 0705.3846 [astro-ph]
What has happened here ??

Supernova 1987A - 20 years later:

- Explosion powered by QCD transition?
- Antineutrino burst signal?

Talk by M. Liebendörfer
Phase diagram: effect of neutrino trapping

Phase diagrams of charge neutral quark matter in $\beta$-equilibrium at strong coupling, $\eta = 1.0$, for fixed values of the electron neutrino chemical potential, $\mu_\nu = 0$ (left-hand side) and $\mu_\nu = 200$ MeV (right-hand side).

The effect of neutrino untrapping \((Y_{le} = 0.4 \rightarrow 0)\) on hybrid star configurations. The release of gravitational binding energy amounts to \(\approx 0.04 \, M_\odot\). Blue rectangle in lower right is the constraint by Podsiadlowski et al., MNRAS (2005)

The energy flux per unit time \( l(r) \) through a spherical slice at distance \( r \) from the center is:

\[
l(r) = -4\pi r^2 k(r) \frac{\partial(T e^\Phi)}{\partial r} e^{-\Phi} \sqrt{1 - \frac{2M}{r}}.
\]

The factor \( e^{-\Phi} \sqrt{1 - \frac{2M}{r}} \) corresponds to relativistic corrections of time and distance scales.

The equations for energy balance and thermal energy transport are:

\[
\frac{\partial}{\partial N_B} (l e^{2\Phi}) = -\frac{1}{n} (\epsilon_{\nu} e^{2\Phi} + c_V \frac{\partial}{\partial t} (Te^\Phi))
\]

\[
\frac{\partial}{\partial N_B} (Te^\Phi) = -\frac{1}{k 16\pi^2 r^4 n} le^\Phi
\]

where \( n = n(r) \) is the baryon number density, \( N_B = N_B(r) \) is the total baryon number in the sphere with radius \( r \) and

\[
\frac{\partial N_B}{\partial r} = 4\pi r^2 n (1 - \frac{2M}{r})^{-1/2}
\]

Neutrino processes in quark matter: Emissivities

- **Quark direct Urca (QDU)** the most efficient processes
  \[ d \rightarrow u + e + \bar{\nu} \text{ and } u + e \rightarrow d + \nu \]
  \[ \epsilon_{\nu}^{\text{QDU}} \approx 9.4 \times 10^{26} \alpha_s u Y_e^{1/3} \zeta_{\text{QDU}} T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1} , \]
  Compression \( u = n/n_0 \approx 2 \), strong coupling \( \alpha_s \approx 1 \)

- **Quark Modified Urca (QMU) and Quark Bremsstrahlung (QB)**
  \[ d + q \rightarrow u + q + e + \bar{\nu} \text{ and } q_1 + q_2 \rightarrow q_1 + q_2 + \nu + \bar{\nu} \]
  \[ \epsilon_{\nu}^{\text{QMU}} \sim \epsilon_{\nu}^{\text{QB}} \approx 9.0 \times 10^{19} \zeta_{\text{QMU}} T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1} . \]

- **Suppression due to the pairing**
  \( \text{QDU}: \zeta_{\text{QDU}} \sim \exp(-\Delta_q/T) \)
  \( \text{QMU} \text{ and } \text{QB}: \zeta_{\text{QMU}} \sim \exp(-2\Delta_q/T) \) for \( T < T_{\text{crit},q} \approx 0.57 \Delta_q \)

- **\( e+e \rightarrow e+e+\nu+\bar{\nu} \)**
  \[ \epsilon_{\nu}^{ee} = 2.8 \times 10^{12} Y_e^{1/3} u^{1/3} T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1} , \]
  becomes important for \( \Delta_q/T >> 1 \)

**References**

2SC phase: 1 color (blue) is unpaired (mixed superconductivity)

**Ansatz 2SC + X phase:**

\[ \Delta_X(\mu) = \Delta_0 \exp[\alpha(1 - \mu/\mu_c)] \]


<table>
<thead>
<tr>
<th>Model</th>
<th>( \Delta_0 ) [MeV]</th>
<th>( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>II</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>III</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>IV</td>
<td>5</td>
<td>25</td>
</tr>
</tbody>
</table>


Pairing gaps for hadronic phase
**AV18 - Takatsuka et al. (2004)**
and 2SC + X phase
2SC + X phase, $\Delta_0 = 1$ MeV, $\alpha = 10$
Too large mass for Vela required

Log N - Log S test fails

2SC + X phase, $\Delta_0 = 5$ MeV, $\alpha = 25$

Temperature-age and Vela mass OK

Log N - Log S test passed

Hybrid star cooling passes all modern tests:

- Temperature - age
- Log N - Log S
- Brightness constraint
- Vela mass (Population synthesis)

D.B., H. Grigorian, PPNP (2007)
Sequential ’deconfinement’ of quark flavors

D.B., F. Sandin, T. Klähn, J. Berdermann,
Sequential deconfinement in asymmetric NS matter

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

Single-flavor (d-CSL) phase in competition

Ansatz: isotropic Color-spin-locking (CSL)
\[ \hat{\Delta} = \Delta(\gamma^3 \lambda_2 + \gamma^1 \lambda_7 + \gamma^2 \lambda_5) \]

See also:
Global charge neutrality: quark-nuclear hybrid

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

- \( \mu_q = 350 \text{ MeV} \)
- \( \mu_q = 400 \text{ MeV} \)
- \( \mu_q = 450 \text{ MeV} \)
- \( \mu_q = 500 \text{ MeV} \)

Charge Neutrality

Charge density [fm \( ^3 \)]

Charge chemical potential \( \mu_Q \) [MeV]
Dash-dotted lines: border between oppositely charged phases

\[ \implies \text{single-flavor phase only in isospin-asymmetric matter!} \]

d-CSL: single-flavor phase in neutron stars

Equation of state

Configuration Sequences

d-CSL: single-flavor phase in neutron stars (II)

d-quark drip at crust-core boundary: Candidate for “deep crustal heating” (DCH) process?


Cooling: processes in single-flavor quark matter are blocked!

**Quark Urca**

\[ \bar{\nu} \rightarrow e^{-} + d \]

**Momentum conservation triangle**

\[ p_{F,d} \]
\[ p_{F,u} \]
\[ p_{F,e} \]

\[ \theta_{da} \]
\[ \theta_{ue} \]
\[ \theta_{de} \]

not operative since u-quark Fermi sea not populated \((p_{F,u} = 0)\)

**d-CSL phase:**
Quark processes are excluded

Crust: Tsuruta law; Gaps: AV18

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL hybrid
5. Conclusion

Cooling of X-ray transient KS 1731: too fast without “deep crustal heating” (DCH) process!


K. Levenfish, P. Haensel (2007)
Extreme States of Matter - The Phase Diagram

Simulations
Lattice QCD

\[ n_o - 3 = 0.16 \text{ fm} \]

Net baryon density \( n/n_0 \)

Nuclei
NICA − MPD
Deconfinement and chiral transition
Color Superconductor?

Early universe
RHIC, LHC

FARSIS 300
NICA − MPD
Neutron stars

Temperature \( T \) [MeV]

Net baryon density \( n/n_0 \)

\[ n_0 = 0.16 \text{ fm}^{-3} \]
Extreme States of Matter - The Phase Diagram

- Lattice QCD
- Perfect fluid
- Early universe
- Critical point?
- Hadrons
- deconfinement
- transition
- deconfinement transition
- Color Superconductor?
- Net baryon density $n/ n_0$
  $n_0 = 0.16 \text{ fm}^{-3}$

- Nuclei
- RHIC, LHC
- FAIR SIS 300
- NICA - MPD
- Neutron stars
- Compact Stars
Extreme States of Matter - The Phase Diagram

Lattice QCD

Perfect fluid

Early universe

Critical point?

Quarks and Gluons

Quarkyonic phase

Hadrons

deconfinement

transition

chiral transition

Net baryon density $n/ n_0$

$n_0 = 0.16 \text{ fm}^{-3}$

L. McLerran and R. Pisarski, NPA 796 (2007) 83
Constraints on the high-density EoS

- Compact star masses $\sim 2 M_\odot$ require stiff EoS
- Flow data provide upper limits on the stiffness

Local charge neutrality: 2SC + DBHF hybrid

- diquark coupling lowers phase transition density
- vector meanfield stiffens quark matter EoS

Global charge neutrality: d-CSL + DBHF hybrid

- single flavor phase (d-CSL) as consequence of dynamical $\chi$SR
- no d-CSL in symmetric matter: $x_{p,\text{crit}} < 0.2$
- no Urca cooling processes $\rightarrow$ no neutrino trapping?

Next steps

- apply to superbursts, X-ray transients, high-mass supernovae
- extend to inhomogeneous phases: surface tension and Coulomb effects
New ways to understand Dense Matter

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF hybrid
4. d-CSL + DBHF hybrid
5. Conclusion

http://www.esf.org/compstar
Dense QCD Phases in Heavy Ion Collisions and Supernovae

October 11-13, 2009  Prerow, Germany
www.mpg.uni-rostock.de/~hic4fair

Organizers
C. Greiner
J. Wambach
D. Blaschke

Local Organizers
G. Röpke
A. Wierling
D. Zablocki

✧ Nonequilibrium and Transport Phenomena in Dense Matter
✧ Equation of State and QCD Phase Transitions
✧ Hadron Production in Heavy Ion Collisions
✧ QCD in Compact Stellar Objects, Supernovae and Mergers

International Round-Table Workshop
“Physics at NICA”,
Dubna, Russia, September 8-13, 2009

HIC for FAIR Workshop
“Dense Matter in HIC and Supernovae”
Prerow, Germany, October 11-13, 2009
http://www.mpg.uni-rostock.de/~hic4fair

ESF Research Networking Programme
“CompStar” (2008-2013)
http://www.esf.org/compstar
THANKS FOR YOUR ATTENTION!

1. Mass and Flow constraint
2. Chiral Quark model
3. 2SC + DBHF Hybrid
4. d-CSL + DBHF hybrid
5. Conclusions