Quark matter in neutron stars: where do we stand?

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Alford, Han, Schwenzer, arXiv:1904.05471
Outline

I What is quark matter?
   Phase diagram of dense matter
   Does quark matter have distinguishing characteristics?

II Quark matter in neutron stars
   Astrophysics and microphysics:
   ▶ Equation of state
   ▶ Spindown
   ▶ Cooling
   ▶ Merger dynamics

III Summary
   Manifestations of quark matter in neutron stars
   Looking to the future
I. What is quark matter?

*Conjectured* QCD phase diagram

Heavy ion collisions: deconfinement crossover and chiral critical point

Neutron stars: color superconducting quark matter core?

Neutron star mergers: dynamics of warm matter, heavy remnant
Phases of (cool) quark matter

- Quark matter is "Unconfined"
  Spatially localized baryonic "bags"
  are not the relevant degrees of freedom,
  But confinement is not an observable.
  E.g., excited states are still created by
  gauge-invariant baryonic operators

- Color superconductivity
  In the ultra-high density limit, we expect the ground state to be a
  condensate of Cooper pairs of quarks. Many pairing patterns
  - Color-Flavor-Locked (CFL): all 3 colors and flavors pair
  - 2SC: only $u,d,u,d$ undergo pairing
  - LOFF: spatially modulated condensate, forming a "crystal"
  - Color-Spin-Locked (CSL): pairing of all 3 colors of a single flavor
  - ...
Phases of quark matter

Prediction of an NJL model, uniform phases only

Warringa, hep-ph/0606063
Summary

- There are observables that would point to quark matter in neutron stars
- There is no hard evidence for quark matter in neutron stars
- There is no hard evidence ruling out quark matter in neutron stars
- There is evidence against matter made of quasi-free quarks
- There is one mystery that quark matter could solve.
How do we distinguish forms of matter?

- **Landau classification**: qualitative observables (order parameters) signalling **spontaneous breaking of exact symmetries**.
  - Baryon number $\rightarrow$ superfluidity
  - Electromagnetic gauge sym $\rightarrow$ superconductivity
  - Spacetime translation and rotation $\rightarrow$ crystallization

- **Large quantitative differences**
  - Spontaneous breaking of approximate symmetries
    - e.g. chiral symmetry breaking $\rightarrow$ light pions
  - Quantitative transitions (gas/plasma, metal/insulator);
    properties of Fermi surface
Is quark matter distinguishable?

Landau classification:

<table>
<thead>
<tr>
<th>Matter type</th>
<th>superfluid</th>
<th>supercond</th>
<th>crystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td>nucleons (unpaired)</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>nucleons (paired)</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>hyperon-nucleon</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>neutrons (inner crust)</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>unpaired quarks</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>2SC</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>CFL</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>LOFF</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
</tr>
</tbody>
</table>

No exact symmetry breaking pattern distinguishes quark matter.
Beyond the Landau classification

Quantitative transitions

**hadronic matter**: low energy fermionic degrees of freedom are **non-relativistic** (low Fermi velocity)

**quark matter**: low energy fermionic degrees of freedom are **relativistic** (high Fermi velocity)

Manifestation: affects transport properties, e.g.

- beta equilibration $\rightarrow$ bulk viscosity
- $\nu$ emission $\rightarrow$ cooling

Approximate symmetry breaking

e.g., **hadronic matter**: chiral sym breaking, light pions.

**quark matter** (unpaired or 2SC): chiral sym restored

Manifestation: not clear. Bosons play subleading role.
II. Quark matter in neutron stars

Conventional scenario

Neutron/hybrid star

Strange Matter Hypothesis

Bodmer 1971; Witten 1984; Farhi, Jaffe 1984

Strange star
Signatures of quark matter in compact stars

Observable ← Microphysical properties (and neutron star structure) ← Phases of dense matter

<table>
<thead>
<tr>
<th>Property</th>
<th>Nuclear phase</th>
<th>Quark phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass distribution (mass, radius, Λ)</td>
<td>eqn of state ε(p)</td>
<td>known up to ∼ n_{sat}</td>
</tr>
</tbody>
</table>
# Signatures of quark matter in compact stars

Observable $\leftarrow$ Microphysical properties (and neutron star structure) $\leftarrow$ Phases of dense matter

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<tbody>
<tr>
<td>mass distribution (mass, radius, $\Lambda$)</td>
<td>eqn of state $\varepsilon(p)$</td>
<td>known up to $\sim n_{\text{sat}}$</td>
</tr>
<tr>
<td>spindown (spin freq, age)</td>
<td>bulk viscosity</td>
<td>Depends on phase:</td>
</tr>
<tr>
<td></td>
<td>shear viscosity</td>
<td>$n,p,e$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$n,p,e, \mu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$n,p,e, \Lambda, \Sigma^-$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$n$ superfluid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p$ supercond</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\pi$ condensate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$K$ condensate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cooling (temp, age)</td>
<td>heat capacity</td>
<td>Depends on phase:</td>
</tr>
<tr>
<td></td>
<td>neutrino emissivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>thermal cond.</td>
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<tr>
<td></td>
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<tr>
<td>glitches (superfluid, crystal)</td>
<td>shear modulus</td>
<td>unpaired</td>
</tr>
<tr>
<td></td>
<td>vortex pinning</td>
<td>CFL</td>
</tr>
<tr>
<td></td>
<td>energy</td>
<td>CFL-$K^0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2SC</td>
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<td>CSL</td>
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<td>LOFF</td>
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<td></td>
<td>1SC</td>
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<td>...</td>
</tr>
<tr>
<td>merger dynamics (grav waves)</td>
<td>eqn of state</td>
<td></td>
</tr>
<tr>
<td></td>
<td>bulk viscosity</td>
<td></td>
</tr>
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</table>
Quark Matter and the Equation of State

“Masquerade effect”

EoS may be very similar in different phases (e.g. in metals: superconducting vs. “normal”).

Uncertainty about quark matter EoS allows tuning its parameters to match hadronic EoS.

Sharp 1st-order phase transition

This could indicate nuclear to quark matter transition

How would a strong first-order transition in the EoS be manifest in observations?

Conformal speed of sound

Quark matter: massless weakly-interacting fermions have \( c_s^2 \approx 1/3 \)

Hadronic matter: relativistic mean field models can give \( c_s^2 \approx 1 \)
Manifestation of 1st OPT: twin stars

equation of state

\[ c_s^2 \lesssim \frac{1}{2} \]
no twin

\[ c_s^2 \gtrsim \frac{1}{2} \]
Twin Branch

weakly first-order transition

Constraints on $1^{\text{st}}$ OPT from $M_{\text{max}}$

DBHF (stiff) NM, $c_{\text{QM}}^2 = 1/3$

$\frac{n_{\text{trans}}}{n_0}$

$\Delta \varepsilon/\varepsilon_{\text{trans}}$

$2 \, M_\odot$ observation allows two scenarios:

- **high** $p_{\text{trans}}$: very small connected branch
- **low** $p_{\text{trans}}$: no twin stars!

Alford, Han, arXiv:1508.01261; see also Tews et al, arXiv:1801.01923, etc.

With $c_{\text{QM}}^2 \lesssim \frac{1}{3}$ you can just barely get a $2M_\odot$ star.
Most et. al., arXiv:1807.03684

solid lines: gravitational wave strain
translucent lines: instantaneous frequency

For EoS with a 1st-order transition to quark matter, the GW signal develops a phase difference of order $\pi$. 
For EoS with a sharp 1st-order phase transition, GW spectrum shows a shifted $f_2$ peak.
An **r-mode** is a quadrupole flow that emits gravitational radiation. It becomes unstable (i.e. arises spontaneously) when a star spins fast enough, and if the shear and bulk viscosity are low enough.

The unstable $r$-mode can spin the star down very quickly, in a few days if the amplitude is large enough.

(Andersson gr-qc/9706075; Friedman and Morsink gr-qc/9706073; Lindblom astro-ph/0101136)

If neutron star spins quickly $\Rightarrow$ some interior physics damps the $r$-modes
Typical $r$-mode instability region

- Instability region depends on viscosity of star’s interior.
- Behavior of stars inside instability region depends on saturation amplitude of $r$-mode.

Shear viscosity grows at low temperature (long mean free paths).

Bulk viscosity has a resonant peak when beta equilibration rate matches $r$-mode frequency.
r-modes and pulsars

There are stars in the “forbidden zone” for nuclear matter

Data for accreting pulsars in binary systems (LMXBs) vs instability curves for:
- **nuclear** stars
- **hybrid** stars with *unpaired* quark matter (possible tension with cooling data)

Another Possibility:
- “tiny r-mode” (small $\alpha_{\text{sat}}$)
r-mode spindown very slow

R-modes Summary

- r-modes are sensitive to viscosity and other damping characteristics of interior of star

- **Mystery:** There are stars *inside* the instability region for standard “nuclear matter with viscous damping” model.

- Possible explanations:
  - Microphysical extra damping (e.g. unpaired quark matter)
  - Astrophysical extra damping (some currently unknown mechanism in a nuclear matter star)
  - “tiny r-mode”: very low saturation amplitude

Need $\alpha_{\text{sat}} \lesssim 10^{-8}$: what mechanism can do this?

Hybrid star: nuclear $\leftrightarrow$ quark phase conversion dissipation

Alford, Han, Schwenzer, arXiv:1404.5279
Quark Matter and Cooling

We can understand cooling in terms of hadronic models with slow (modified Urca) or intermediate (pair breaking) cooling.

For isolated neutron stars, we do not know their mass. If we knew the masses, the cooling data would provide a more demanding constraint.

See also, e.g., Wei, Burgio, Schulze, arXiv:1812.07306, Beloin et al, arXiv:1812.00494, etc
Cooling of a star with quark matter core

Unpaired quark matter would cool very fast: is it ruled out?

CFL quark matter: little impact on cooling.

This model has quark matter with 2-flavor “2SC” quark pairing and weak pairing of the blue quarks.

It can accommodate data with masses ranging from $1.1 \ M_\odot$ to $1.7 \ M_\odot$. 

(Grigorian, Blaschke, Voskresensky, astro-ph/0411619)
III. Manifestations of quark matter in neutron stars

- **Fast pulsar mystery**: suppression of r-modes
  - r-modes stabilized by bulk viscosity in quark matter
  - r-mode amplitude kept low by quark-hadron conversion
- **Sharp first-order transition to denser phase**
  - separate branch of twin stars (different radii)
  - effect on grav waves from mergers
  - effect on tidal deformability
- **Phase with** $c_s^2 \approx 1/3$ (weakly-interacting light quarks)
  - close to being ruled out by max mass measurement
- **Phase with more/lighter fermions**
  - fast cooling of unpaired quark matter
  - shifted bulk viscosity peak in unpaired quark matter
- **Superfluid insulating phase** (probably CFL quark matter)
  - very low specific heat affects cooling after bursts
- **Very rigid crystalline phase at high density** (LOFF phase)
  - high ellipticity $\Rightarrow$ grav waves from pulsar
Looking to the Future

What do we need to detect quark matter in neutron star cores??

- More data on observable properties of neutron stars
  - mass and radius
  - spindown (spin and age)
  - cooling (temperature, age, mass)
  - grav waves from “mountains” and mergers

- Better modelling of neutron stars and mergers:
  - astrophysical damping and saturation mechanisms for r-modes
  - mechanism of glitches
  - effects of magnetic fields
  - mergers: finer resolution; turbulence? magnetic fields; dissipation;

- Understand high-density matter
  - understand nuclear matter better: EoS, paired phases
  - better models of quark matter: Functional RG, Schwinger-Dyson
    quark matter EoS and phases (crystalline (LOFF) or...?)
  - solve the sign problem and do lattice QCD at high density.