Quark matter in neutron stars: where do we stand?

Mark Alford
Washington University in St. Louis

Alford, Han, Schwenzer, `arXiv:1904.05471`

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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

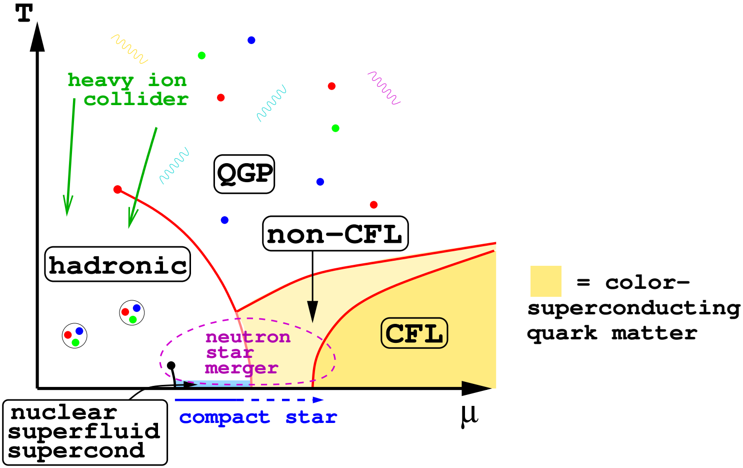
III Summary

Manifestations of quark matter in neutron stars

Looking to the future

I. What is quark matter?

Conjectured QCD phase diagram



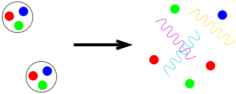
heavy ion collisions: deconfinement crossover and chiral critical point

neutron stars: color superconducting quark matter core?

neutron star mergers: dynamics of warm matter, heavy remnant

Phases of (cool) quark matter

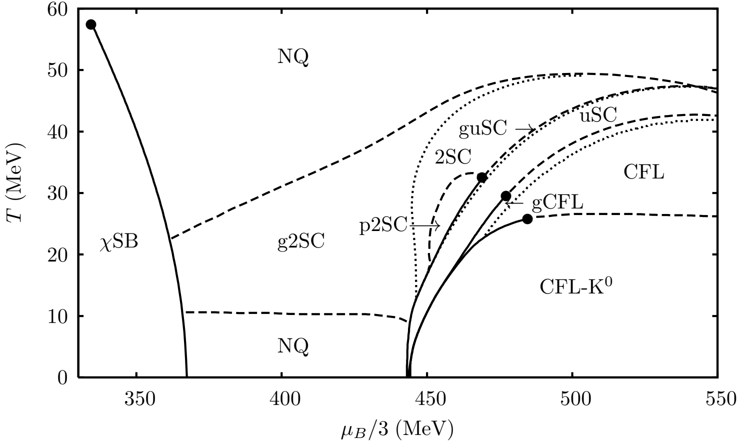
- Quark matter is "Unconfined"
  Spatially localized baryonic "bags"
  are not the relevant degrees of freedom,
  But confinement is not an observable.
  E.g., excited states are still created by
  gauge-invariant *baryonic* operators



- 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 → superfluidity
  - Electromagnetic gauge sym → superconductivity
  - Spacetime translation and rotation → crystallization
- Large quantitative differences
  - spontaneous breaking of approximate symmetries e.g. chiral symmetry breaking → light pions
  - Quantitative transitions (gas/plasma, metal/insulator); properties of Fermi surface

Is quark matter distinguishable?

Landau classification:

Matter type	superfluid	supercond	crystalline
nucleons (unpaired)	✗	✗	✗
nucleons (paired)	✓	✓	✗
hyperon-nucleon	✓	✗	✗
neutrons (inner crust)	✓	✗	✓
unpaired quarks	✗	✗	✗
2SC	✗	✗	✗
CFL	✓	✗	✗
LOFF	✓	✗	✓

No exact symmetry breaking pattern distinguishes quark matter

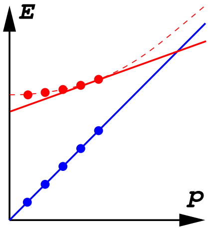
Beyond the Landau classification

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 → bulk viscosity
ν emission → 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.

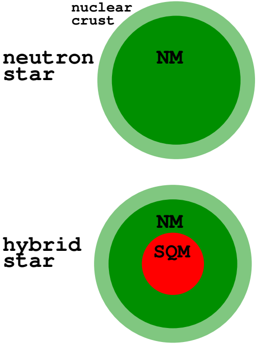
II. Quark matter in neutron stars

Conventional scenario

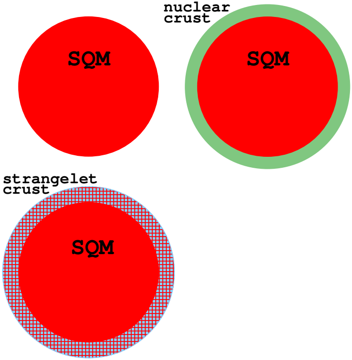
Strange Matter Hypothesis

Bodmer 1971; Witten 1984; Farhi, Jaffe 1984

Neutron/hybrid star



Strange star



Signatures of quark matter in compact stars

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

	Property	Nuclear phase	Quark phase
mass distribution (mass, radius, Λ)	eqn of state $\varepsilon(p)$	known up to $\sim n_{\mathrm{sat}}$	unknown; many models

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spindown (spin freq, age)	bulk viscosity shear viscosity	Depends on phase: $n\,p\,e$ $n\,p\,e,\mu$ $n\,p\,e,\Lambda,\ \Sigma^-$ n superfluid p supercond π condensate K condensate	Depends on phase: unpaired CFL CFL-K^0 2SC CSL LOFF 1SC ...
cooling (temp, age)	heat capacity neutrino emissivity thermal cond.		
glitches (superfluid, crystal)	shear modulus vortex pinning energy		
merger dynamics (grav waves)	eqn of state bulk viscosity		

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

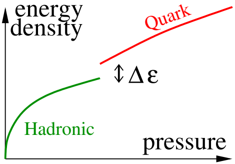
Quark matter: massless weakly-interacting fermions have $c_s^2 \approx 1/3$
Hadronic matter: relativistic mean field models can give $c_s^2 \approx 1$

Manifestation of 1^{st}OPT: twin stars

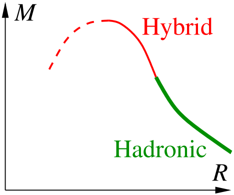
equation of state

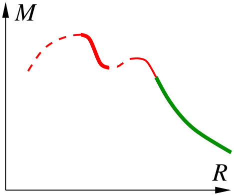
$c_s^2 \lesssim 1/2$
no twin

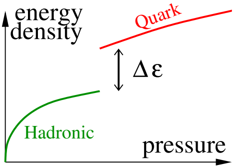
$c_s^2 \gtrsim 1/2$
Twin Branch



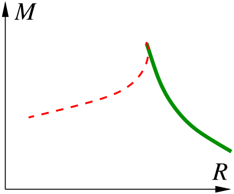
weakly
first-order
transition

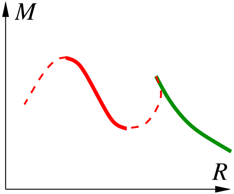






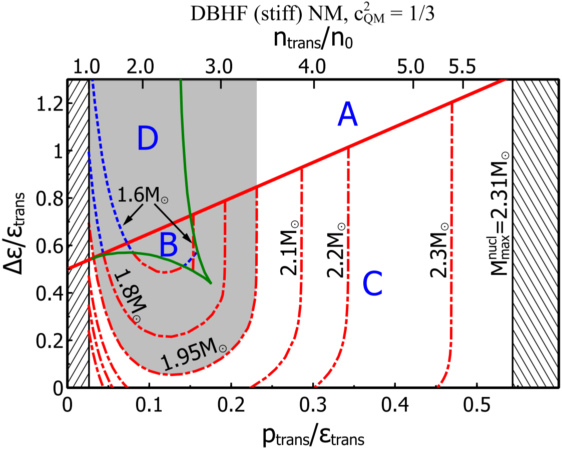
strongly
first-order
transition





Alford, Han, Prakash, `arXiv:1302.4732`; Montana, Tolos, Hanauske, Rezzolla, `arXiv:1811.10929`

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



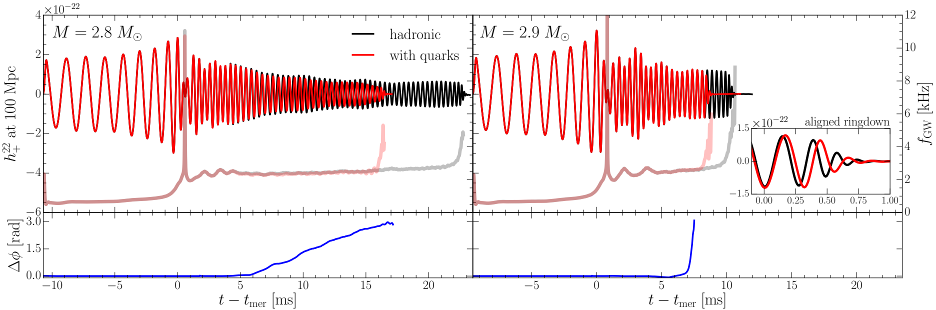
$2\,M_\odot$ observation allows two scenarios:

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

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

With $c^2_{\rm QM} \lesssim \frac{1}{3}$ you can just barely get a $2M_\odot$ star.

$1^{\rm st}$OPT: grav waves from mergers

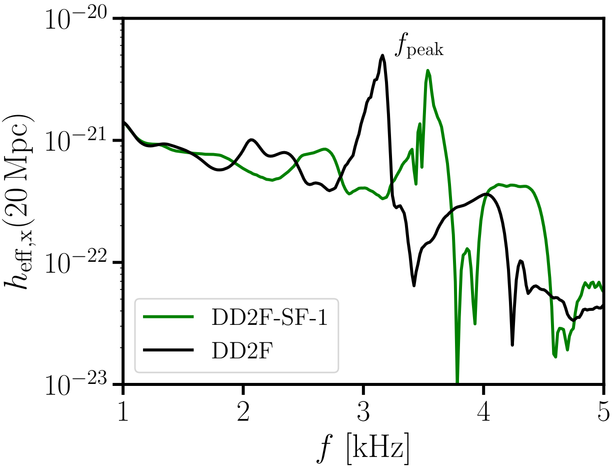


Most et. al., `arXiv:1807.03684`

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 π.

1^{st}OPT: grav waves from mergers



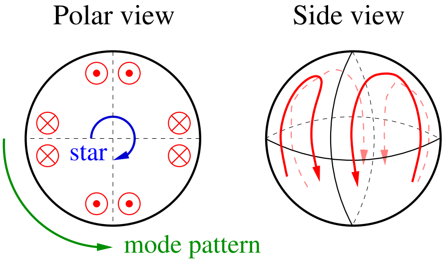
Bauswein et. al.,
`arXiv:1809.01116`

For EoS with a sharp 1st-order phase transition, GW spectrum shows a shifted f_2 peak.

Quark matter and spin-down

Spindown via grav. waves depends on properties of the star's interior.

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.

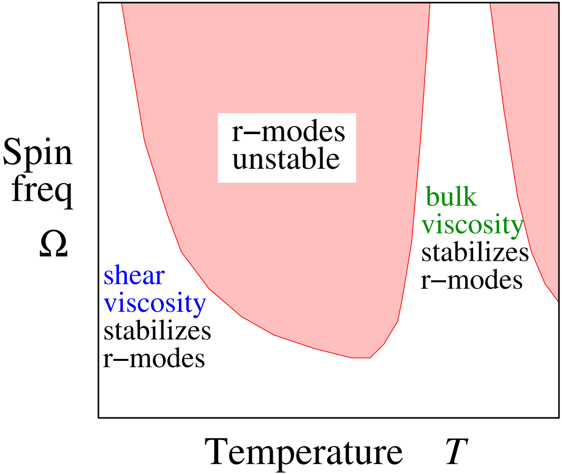


The unstable r-mode can spin the star down very quickly, in a few days if the amplitude is large enough

(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



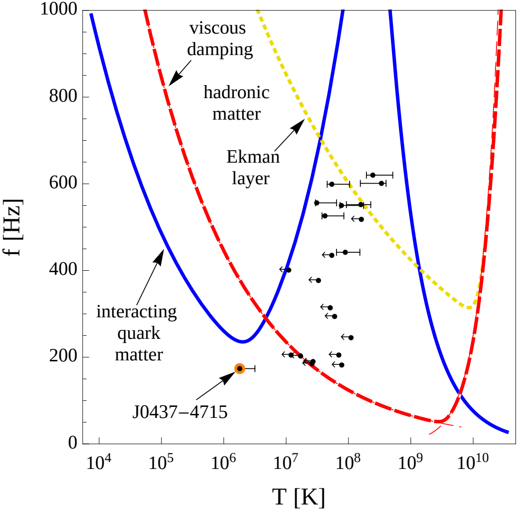
Shear viscosity grows at low temperature (long mean free paths).

Bulk viscosity has a resonant peak when beta equilibration rate matches r-mode frequency

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

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 $\alpha_{\rm sat}$) r-mode spindown very slow

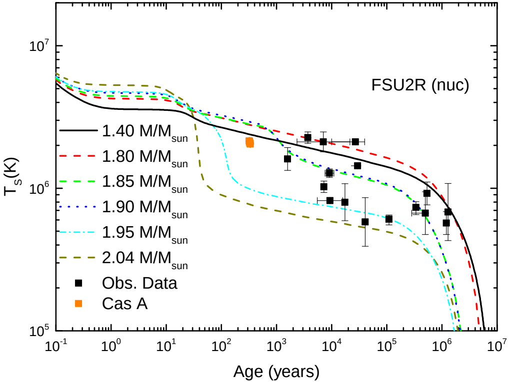
(Alford, Schwenzer, `arXiv:1310.3524`; Haskell, Degenaar, Ho, `arXiv:1201.2101`)

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 $\alpha_{\rm sat} \lesssim 10^{-8}$: what mechanism can do this?
    Hybrid star: nuclear $\rightleftharpoons$ 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.

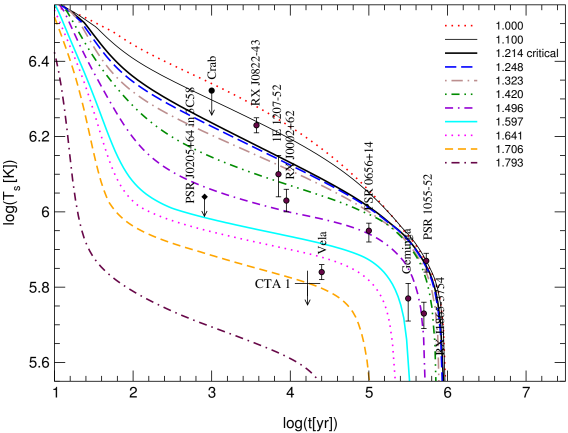


For isolated neutron stars, we do not know their mass.

If we knew the masses, the cooling data would provide a more demanding constraint.

(Negreiros, Tolos, et al, `arXiv:1804.00334`)
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



(Grigorian, Blaschke, Voskresensky, `astro-ph/0411619`)

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 accomodate data with masses ranging from 1.1 $M_\odot$ to 1.7 $M_\odot$.

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 ⇒ 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.