Quark matter in neutron stars

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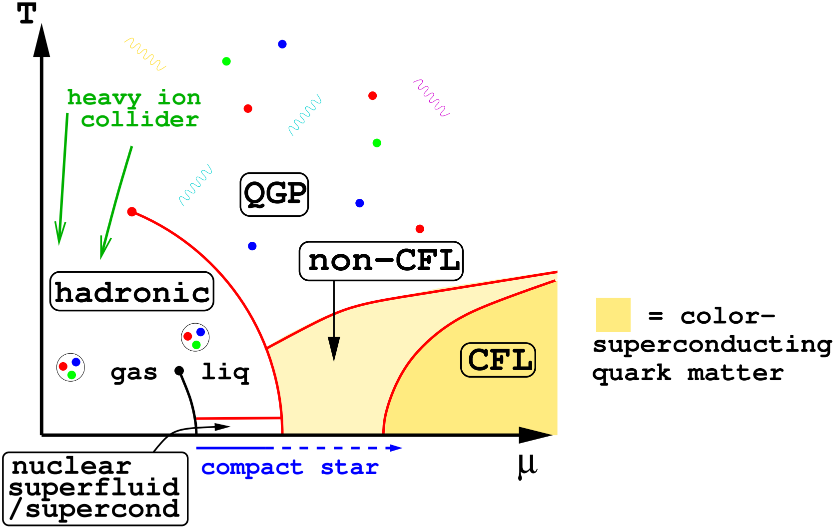
Schematic QCD phase diagram



M. Alford, K. Rajagopal, T. Schäfer, A. Schmitt, arXiv:0709.4635 (RMP review)
A. Schmitt, arXiv:1001.3294 (Springer Lecture Notes)

Signatures of quark matter in compact stars

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

	Property	Nuclear phase	Quark phase
mass, radius	eqn of state	known up to n_{sat}	unknown, can be parameterized

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

Color superconducting phases

Attractive QCD interaction $\Rightarrow$ Cooper pairing of quarks.

We expect pairing between *different flavors*.

Quark Cooper pair: $\langle q^{\alpha}_{ia} q^{\beta}_{jb} \rangle$

color $\alpha, \beta = r, g, b$
flavor $i, j = u, d, s$
spin $a, b = \uparrow, \downarrow$

Each possible BCS pairing pattern P is an 18×18 color-flavor-spin matrix

$$\langle q^{\alpha}_{ia} q^{\beta}_{jb} \rangle_{1PI} = \Delta_P \, P^{\alpha\beta}_{ij\,ab}$$

The attractive channel is:

	color antisymmetric	[most attractive]
	space symmetric	[s-wave pairing]
	spin antisymmetric	[isotropic]
$\Rightarrow$	flavor antisymmetric	

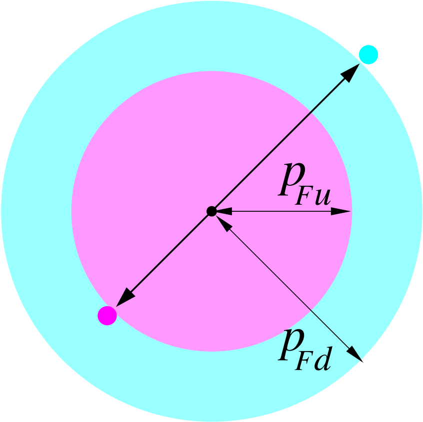
Quark matter in the real world

In the real world there are three factors that combine to oppose pairing between different flavors.

1. Strange quark mass is not infinite nor zero, but intermediate. It depends on density, and ranges between about 500 MeV in the vacuum and about 100 MeV at high density.
2. Neutrality requirement. Bulk quark matter must be neutral with respect to all gauge charges: color and electromagnetism.
3. Weak interaction equilibration. In a compact star there is time for weak interactions to proceed: neutrinos escape and flavor is not conserved.

These factors favor *different Fermi momenta* for different flavors which *opposes* pairing between different flavors

Mismatched Fermi surfaces oppose Cooper pairing



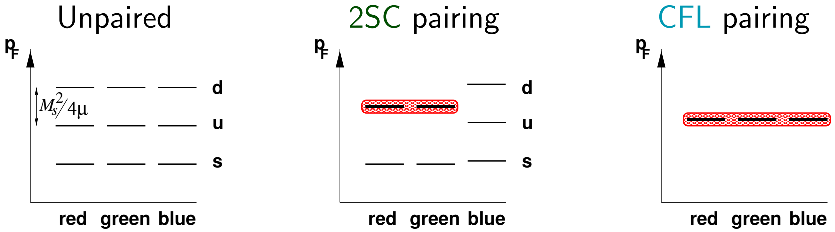
u and d quarks near their Fermi surfaces cannot have equal and opposite momenta.

$\langle u(k)d(-k)\rangle$ condensate is energetically penalized.

The strange quark mass is the cause of the mismatch:

$$p_{Fd} - p_{Fu} \approx p_{Fu} - p_{Fs} \approx \frac{M_s^2}{4\mu}$$

Cooper pairing vs. the strange quark mass



CFL: Color-flavor-locked phase, favored at the highest densities:

$$\langle q_i^\alpha q_j^\beta \rangle \sim \delta_i^\alpha \delta_j^\beta - \delta_j^\alpha \delta_i^\beta = \epsilon^{\alpha\beta N} \epsilon_{ijN}$$

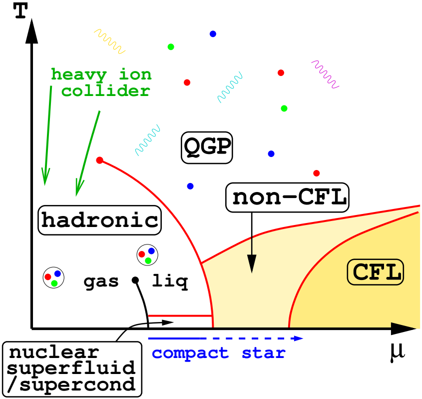
breaks chiral symmetry by a new mechanism: $\langle qq \rangle$ instead of $\langle \bar{q} q \rangle$.

2SC: Two-flavor pairing phase. May occur at intermediate densities:

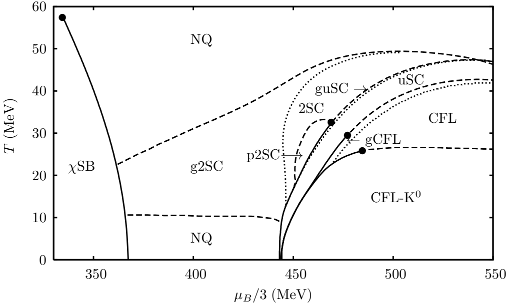
$$\langle q_i^\alpha q_j^\beta \rangle \sim \epsilon^{\alpha\beta 3} \epsilon_{ij3} \sim (rg - gr)(ud - du)$$

or: CFL with kaon condensation (CFL-K^0),
crystalline phase (LOFF), p-wave “meson” condensates,
single-flavor pairing (color-spin locking, ∼liq ^{3}He-B).

Phases of quark matter, again



NJL model, uniform phases only



Warringa, hep-ph/0606063

But there are also non-uniform phases, such as the crystalline ("LOFF" / "FFLO") phase. (Alford, Bowers, Rajagopal, hep-ph/0008208)

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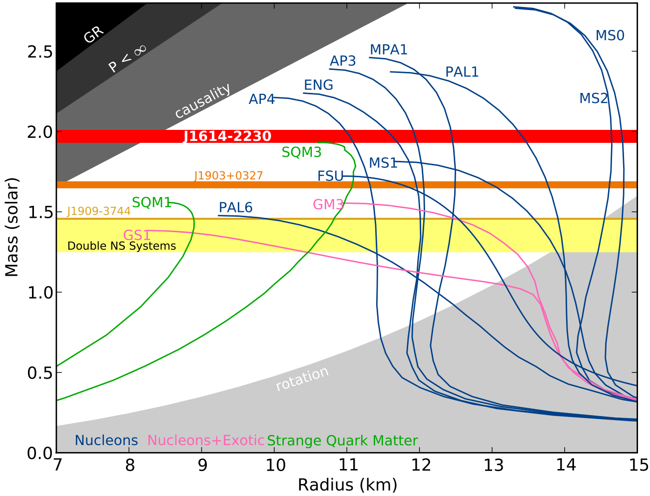
Discovery of a $2M_\odot$ mass neutron star



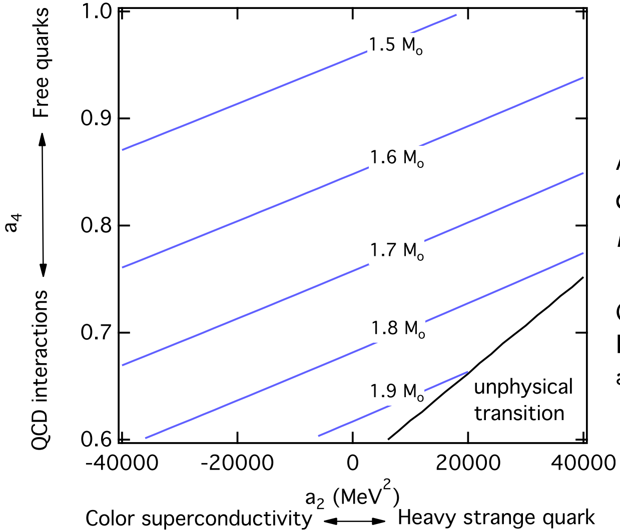
$$M = 1.97 \pm 0.04\, M_\odot$$

Demorest et al, Nature 467, 1081 (2010).

Can quark matter be the favored phase at high density?

Constraints on the quark matter EoS (1)

Polynomial ansatz: $p \sim a_4\mu^4 + a_2\mu^2 + B$

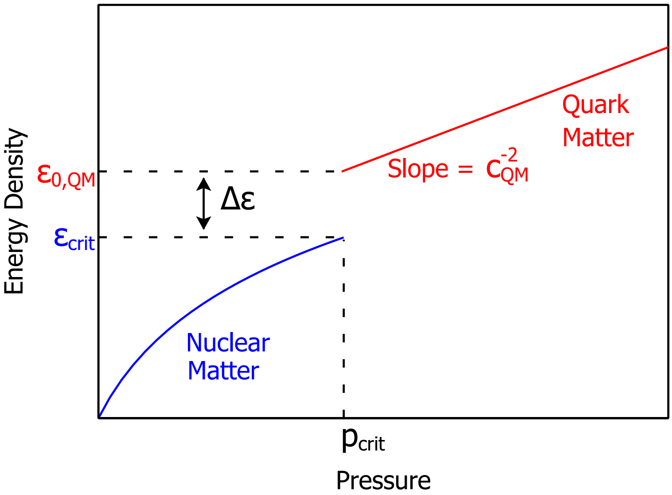


Assumes transition to quark matter at $n_{\rm crit} = 1.5 n_{\rm sat}$

Özel, Psaltis, Ransom, Demorest, Alford, `arXiv:1010.5790`

Generic quark matter EoS

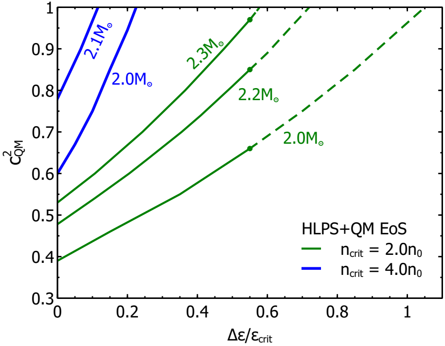
Generic ansatz: $\varepsilon(p) = \varepsilon_{\rm crit} + \Delta\varepsilon + c_{\rm QM}^{-2}(p - p_{\rm crit})$



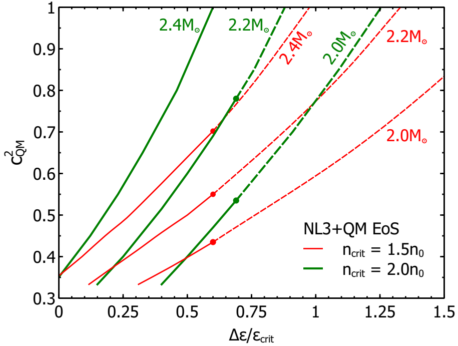
Constraints on the quark matter EoS (2)

Generic ansatz: $\varepsilon(p) = \varepsilon_{\rm crit} + \Delta\varepsilon + c_{\rm QM}^{-2}(p - p_{\rm crit})$

QM + Soft Nuclear Matter



QM + Hard Nuclear Matter



Alford, Han, Prakash, `unpublished`

1. Observations can constrain QM EoS but not rule out generic QM
2. Constraints depend on NM EoS up to transition density

Transport properties and low-energy excitations

Transport properties are determined by *low-energy excitations*. These are very different for different phases.

For 2 light and 1 massive flavor, approx symmetry group is

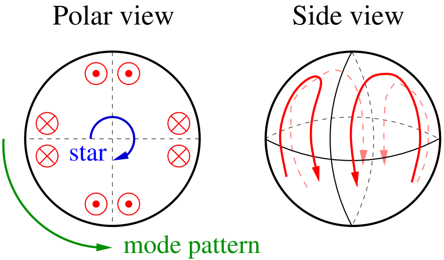
$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_B \times U(1)_S{}^*$$

Phase	unbroken sym	gapless modes	light modes
unpaired	no breaking	9 quarks	
2SC	$SU(2)_c\times$ global	5 quarks	
CFL	$SU(2)_V \times U(1)_S{}^*$	sf phonon "H"	K^0, K^+
...			

* weak interactions break strangeness slightly.

r-modes and gravitational spin-down

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.

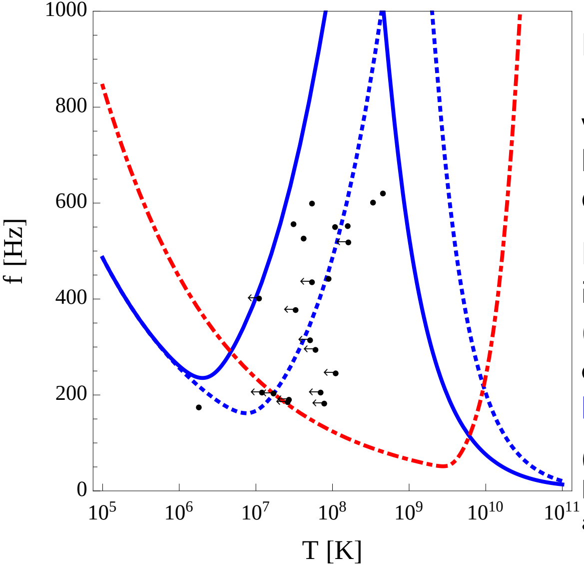


The unstable *r*-mode can spin the star down very quickly, in a few days if the amplitude is large enough

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

neutron star spins quickly	$\Rightarrow$	interior viscosity must be high enough to damp the *r*-modes

Constraints from r-modes: old stars (1)



Regions above curves are "forbidden" because viscosity is too low to hold back the *r*-modes.

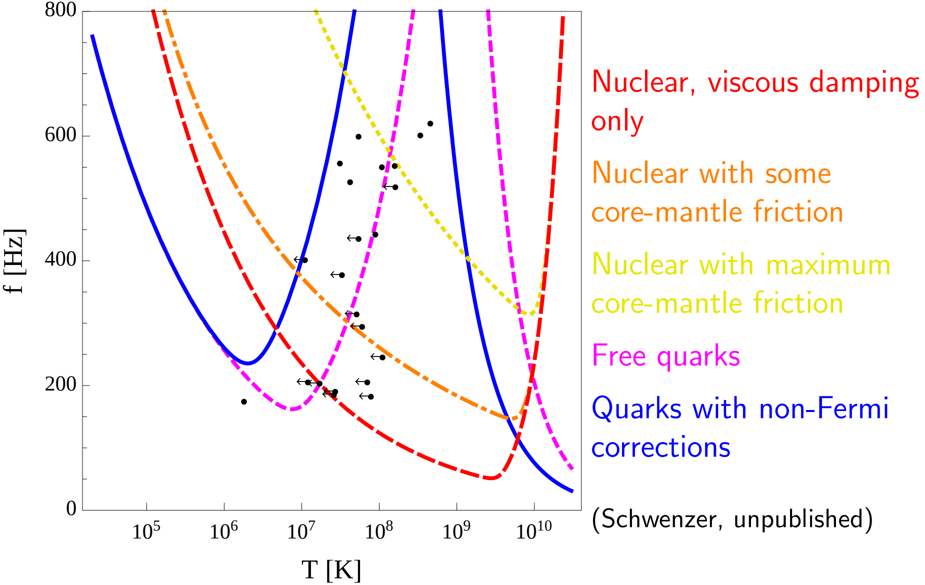
Only viscous damping included.

Data for accreting pulsars in binary systems (LMXBs) vs instability curves for nuclear and hybrid stars.

(Schwenzer, `arXiv:1212.5242`; Haskell, Degenaar, Ho, `arXiv:1201.2101`)

Need more than nuclear matter viscous damping

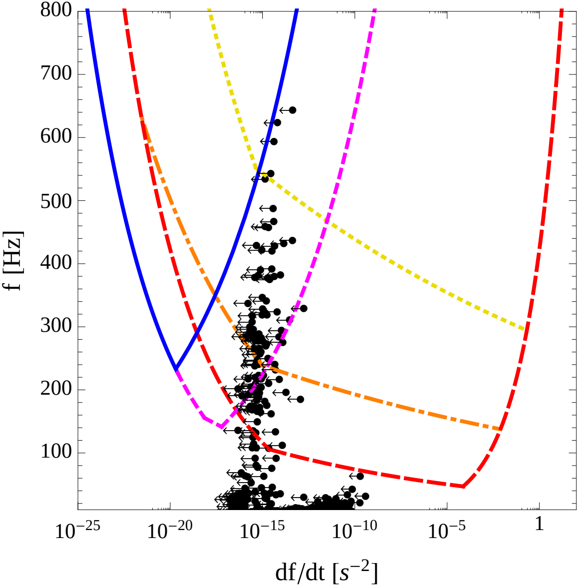
Constraints from r-modes: old stars (2)



Need something beyond the simple nuclear matter model

Constraints from r-modes: spindown rate

f vs $\dot{f}_R$ (df/dt from r-mode spindown)



Either
Measured $\dot{f}$ is close to $\dot{f}_R$
$\Rightarrow$ many of these stars are doing r-mode spindown, and amplitude must be inexplicably small

Or
$\dot{f}_R \ll$ measured $\dot{f}$, but we don't know how stars could end up in that region of $f, T, \dot{f}$.

(Schwenzer, unpublished)

Future directions

- Neutron-star phenomenology of color superconducting quark matter:
  - Are there any other r-mode damping mechanisms?
  - neutrino emissivity and cooling
  - structure: nuclear-quark interface (gravitational waves?)
  - color supercond. crystalline phase (glitches) (gravitational waves?)
  - CFL: vortices but no flux tubes; stability of vortices...
- More general questions:
  - instability of gapless phases; better treatment of LOFF
  - role of large magnetic fields
  - better weak-coupling calculations
  - better models of quark matter: Functional RG, Schwinger-Dyson
  - solve the sign problem and do lattice QCD at high density.

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