Hybrid Stars: how can we identify them?

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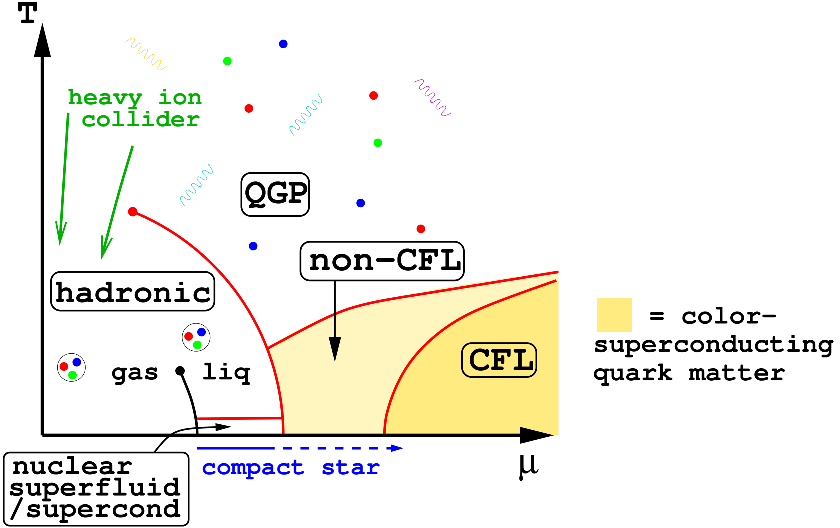
Alford, Han, Prakash, arXiv:1302.4732
Alford, Schwenzer, arXiv:1310.3524

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 $\varepsilon(p)$	known up to $\sim n_{\rm sat}$	unknown; many models

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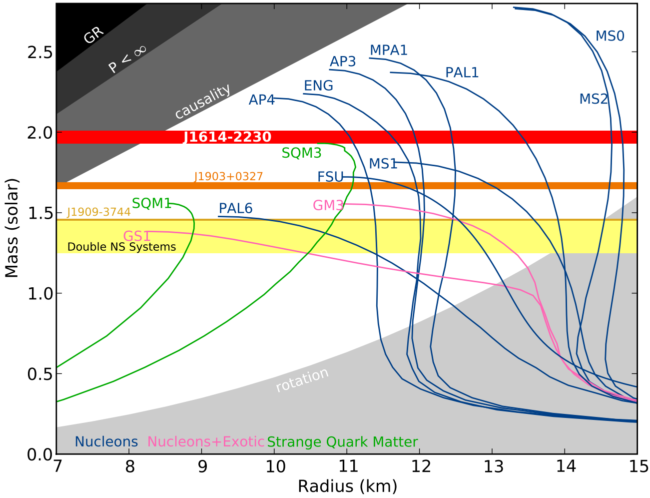
	Property	Nuclear phase	Quark phase
mass, radius	eqn of state $\varepsilon(p)$	known up to $\sim n_{\rm sat}$	unknown; many models
spindown (spin freq, age)	bulk viscosity shear viscosity	Depends on phase: $n\,p\,e$ $n\,p\,e,\mu$ $n\,p\,e,\Lambda,\,\Sigma^-$ n superfluid p supercond π condensate K condensate	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		

Nucl/Quark EoS $\varepsilon(p) \Rightarrow$ Neutron star $M(R)$



Recent measurement:

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

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

Can quark matter be the favored phase at high density?

Constraining QM EoS by observing $M(R)$

Does a $2\,M_\odot$ star rule out quark matter?

Lots of literature on this question, with various models of quark matter

- MIT Bag Model; (Alford, Braby, Paris, Reddy nucl-th/0411016)
- NJL models; (Paoli, Menezes, arXiv:1009.2906)
- PNJL models (Blaschke et. al; arXiv:1302.6275)
- 2-loop perturbation theory (Kurkela et. al., arXiv:1006.4062)
- MIT bag, NJL, CDM, FCM, DSM (Burgio et. al., arXiv:1301.4060)
- Talks by Rischke, Schramm, Dexheimer, Zappalà, Yasutake

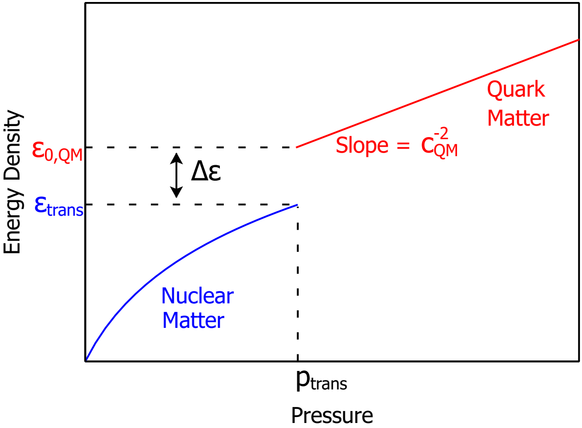
We need a model-independent parameterization of the quark matter EoS:

- framework for relating different models to each other
- observational constraints can be expressed in universal terms

A fairly generic QM EoS

Model-independent parameterization with Constant Speed of Sound (CSS)

$$\varepsilon(p) = \varepsilon_{\mathrm{trans}} + \Delta\varepsilon + c_{\mathrm{QM}}^{-2}(p - p_{\mathrm{trans}})$$



QM EoS params:

$p_{\mathrm{trans}}/\varepsilon_{\mathrm{trans}}$

$\Delta\varepsilon/\varepsilon_{\mathrm{trans}}$ $(\lambda - 1)$

c_{QM}^2

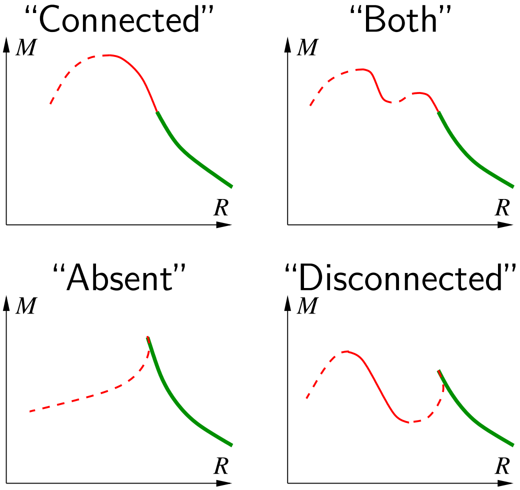
Zdunik, Haensel, arXiv:1211.1231; Alford, Han, Prakash, arXiv:1302.4732

Hybrid star $M(R)$

Hybrid star branch in $M(R)$ relation has 4 typical forms

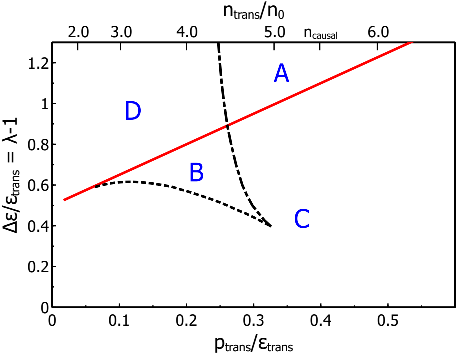
$\Delta\varepsilon < \Delta\varepsilon_{\rm crit}$
small energy density jump at phase transition

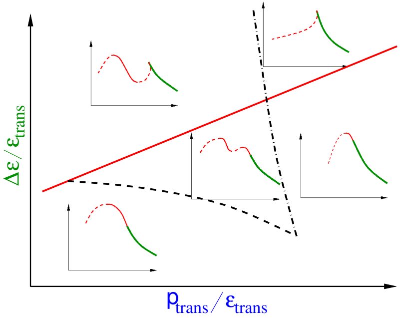
$\Delta\varepsilon > \Delta\varepsilon_{\rm crit}$
large energy density jump at phase transition



"Phase diagram" of hybrid star $M(R)$

Soft NM + CSS($c^2_{\mathrm{QM}} = 1$)





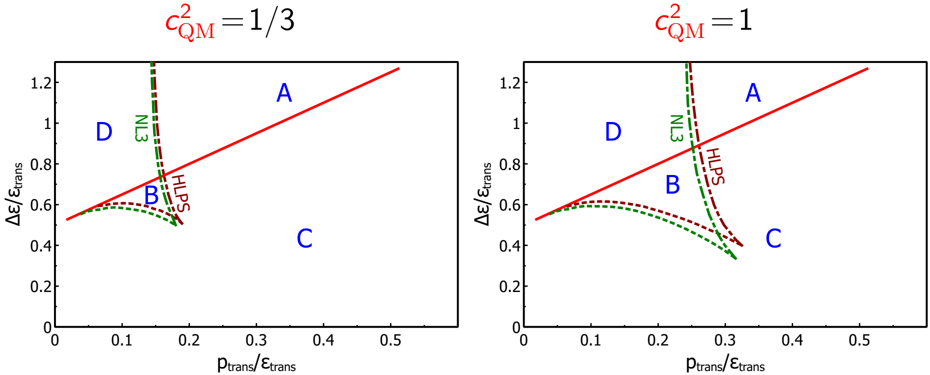
Above the red line ($\Delta\varepsilon > \Delta\varepsilon_{\mathrm{crit}}$), connected branch disappears

$$\frac{\Delta\varepsilon_{\mathrm{crit}}}{\varepsilon_{\mathrm{trans}}} = \frac{1}{2} + \frac{3}{2}\frac{p_{\mathrm{trans}}}{\varepsilon_{\mathrm{trans}}}$$

(Seidov, 1971; Schaeffer, Zdunik, Haensel, 1983; Lindblom, gr-qc/9802072)

Disconnected branch exists in regions D and B.

Sensitivity to NM EoS and $c^2_{\rm QM}$

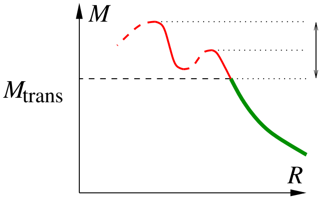


- NM EoS (HLPS=soft, NL3=hard) does not make much difference.
- Higher $c^2_{\rm QM}$ favors disconnected branch.

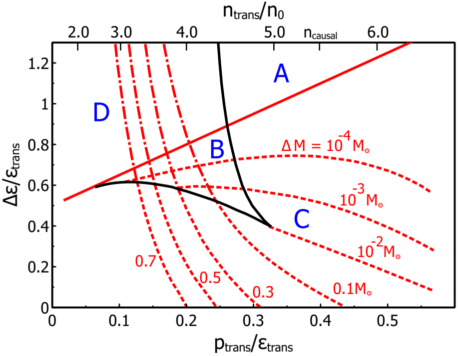
Observability of hybrid star branches

Measure length of hybrid branch by

$$\Delta M \equiv \begin{pmatrix}\text{mass of heaviest}\\ \text{hybrid star}\end{pmatrix} - M_{\text{trans}}$$



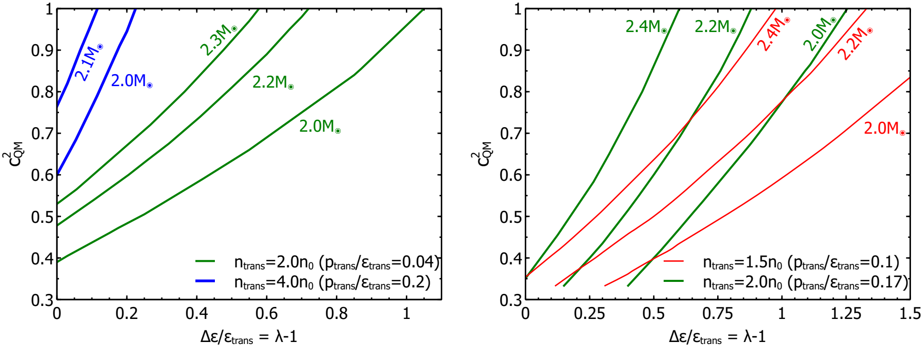
Soft NM + CSS($c^2_{\text{QM}} = 1$)



- Connected branch is observable if p_{trans} is not too high and there is no disconnected branch
- Disconnected branch is always observable

Constraints on QM EoS from max mass

QM + Soft Nuclear Matter   QM + Hard Nuclear Matter



Alford, Han, Prakash, arXiv:1302.4732; Zdunik, Haensel, arXiv:1211.1231

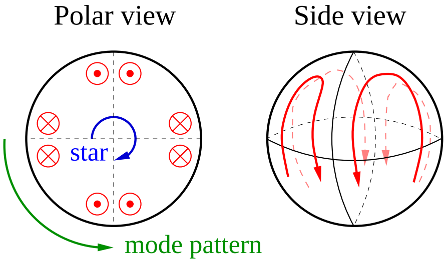
- Max mass can constrain QM EoS but not rule out generic QM
- For soft NM EoS, need $c^2_{\rm QM} \gtrsim 0.4$

Quark matter EoS Summary

- CSS (Constant Speed of Sound) is a generic parameterization of quark matter EoS at densities just above the transition.
- Any specific model of quark matter corresponds to particular values of the CSS parameters ($p_{\rm trans}/\varepsilon_{\rm trans}$, $\Delta\varepsilon/\varepsilon_{\rm trans}$, $c^2_{\rm QM}$). Its predictions for hybrid star branches then follow from the generic CSS phase diagram.
- Existence of $2M_\odot$ neutron star $\rightarrow$ constraint on CSS parameters. For soft NM we need $c^2_{\rm QM} \gtrsim 0.4$ ($c^2_{\rm QM} = 1/3$ for free quarks).
- More measurements of $M(R)$ would tell us more about the EoS of nuclear/quark matter. If necessary we could enlarge CSS to allow for density-dependent speed of sound.

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.



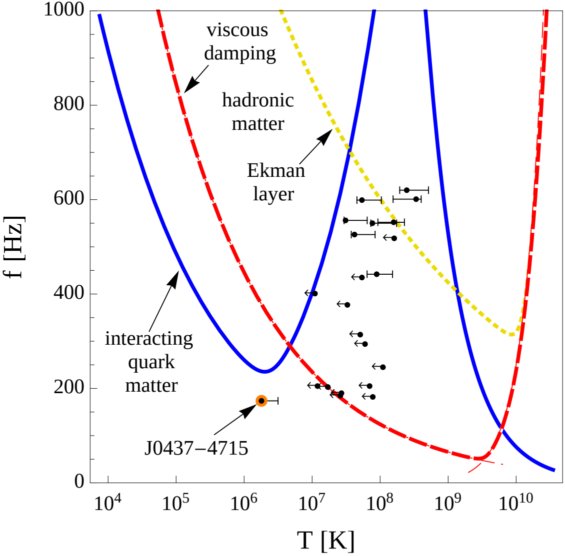
The unstable *r*-mode can spin the star down very quickly, in a few days if the amplitude is large enough

(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

r-modes and old pulsars

Above curves, r-modes go unstable and spin down the star



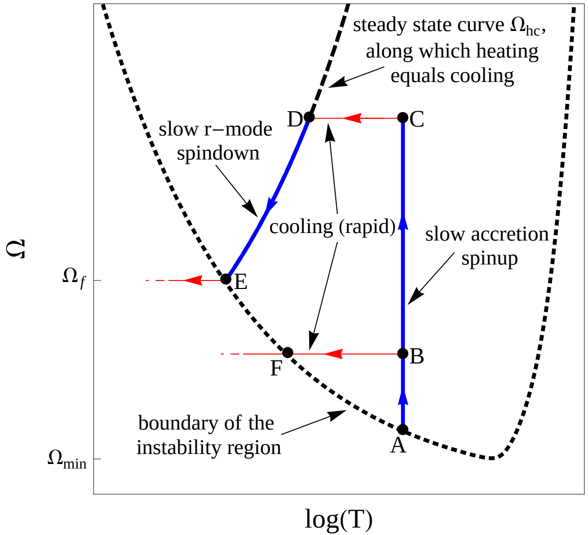
Data for accreting pulsars in binary systems (LMXBs) vs instability curves for nuclear and hybrid stars.

Possibilities:

- additional damping (e.g. quark matter)
- r-mode spindown is very slow

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

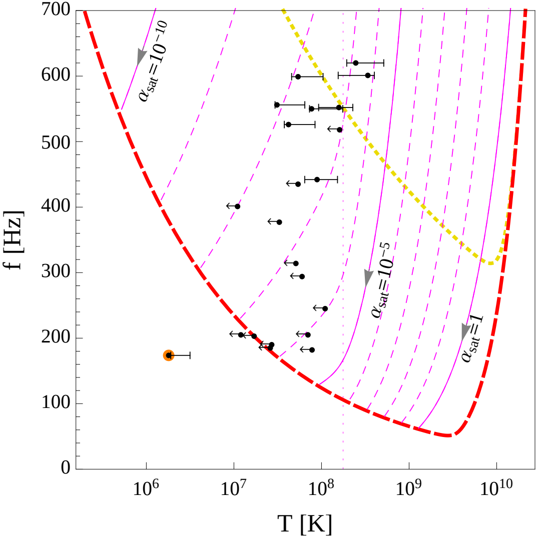
Spindown via r-modes of an old neutron star



Steady-state spindown curve is determined by amplitude $\alpha_{\rm sat}$ at which r-mode saturates.

This determines final spin frequency Ω_f. Stars with $\Omega < \Omega_f$ are *not undergoing r-mode spindown*.

r-mode spindown trajectories



(Alford, Schwenzer, `arXiv:1310.3524`)

Explanations:

1) Instability boundary is wrong (additional damping).

2) Many neutron stars (ms pulsars and LMXBs) are in the instability region, undergoing r-mode spindown with *low* saturation amplitude

- $\alpha_{\rm sat} \sim 10^{-7}$
- $T \gtrsim 10^7$ K (r-mode heating)
- they are emitting grav waves

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. quark matter)
  - Astrophysical extra damping (some currently unknown mechanism in a nuclear matter star)
  - "tiny r-mode" = very low saturation amplitude
- Need:
  - Better temperature measurements
  - Detect grav waves from ms pulsars (beyond advanced LIGO)
  - Better theoretical understanding of r-mode damping and saturation mechanisms

How will we identify hybrid stars?

EoS: density discontinuity at nuclear/quark transition leads to connected and/or disconnected branches in $M(R)$.

We need:

- better measurements of M and R
- theoretical constraints on basic properties of QM EoS ($p_{\rm trans}/\varepsilon_{\rm trans}$, $\Delta\varepsilon/\varepsilon_{\rm trans}$, $c^2_{\rm QM}$)
- knowledge of nuclear matter EoS

Spindown: extra damping in some forms of quark matter can explain current observations, but other scenarios (astrophysical extra damping; r-modes with tiny amplitude) have not been ruled out.

We need:

- Better theoretical understanding of r-mode damping and saturation mechanisms
- Better temperature measurements (ideally, of ms pulsars too)
- Detect grav waves from old pulsars (beyond advanced LIGO) or very young neutron stars (advanced LIGO)