Quark hybrid Stars: how can we identify them?

Prof. Mark Alford
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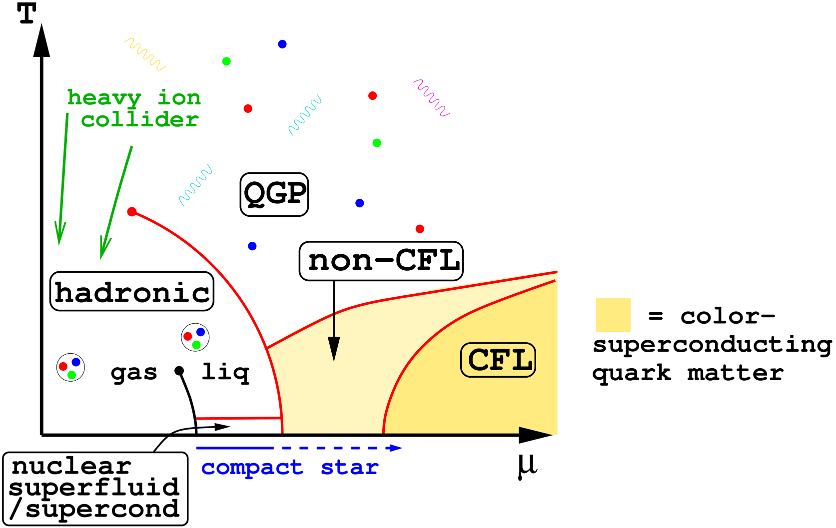
Alford, Han, Prakash, arXiv:1302.4732
Alford, Schwenzer, arXiv:1310.3524

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 $\sim n_{\mathrm{sat}}$	unknown; many models

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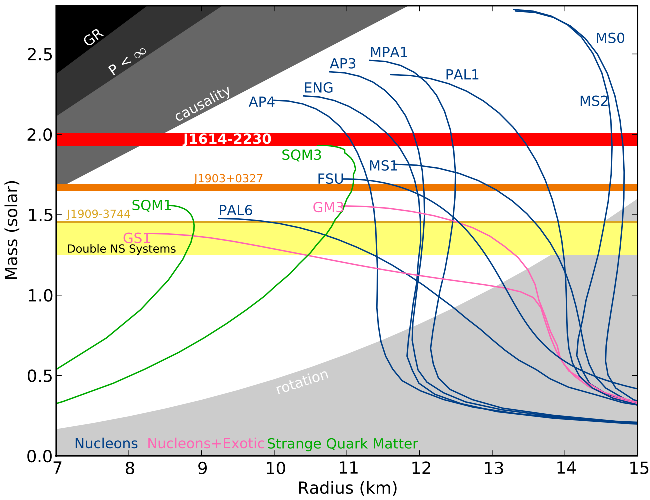
Observable ← Microphysical properties (and neutron star structure) ← Phases of dense matter

	Property	Nuclear phase	Quark phase
mass, radius	eqn of state $\varepsilon(p)$	known up to $\sim n_{\mathrm{sat}}$	unknown; many models
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.	$n\,p\,e,\mu$ $n\,p\,e,\Lambda,\Sigma^-$ n superfluid	CFL CFL-K^0 2SC
glitches (superfluid, crystal)	shear modulus vortex pinning energy	p supercond π condensate K condensate	CSL LOFF 1SC ...

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



Recent measurement:

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

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

Can neutron stars contain quark matter cores?

Constraining QM EoS by observing $M(R)$

Does a $2\,M_\odot$ star rule out quark matter cores (hybrid stars)?

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`; Orsaria et. al.; `arXiv:1212.4213`)
- hadron-quark NLσ model (Negreiros et. al., `arXiv:1006.0380`)
- 2-loop perturbation theory (Kurkela et. al., `arXiv:1006.4062`)
- MIT bag, NJL, CDM, FCM, DSM (Burgio et. al., `arXiv:1301.4060`)

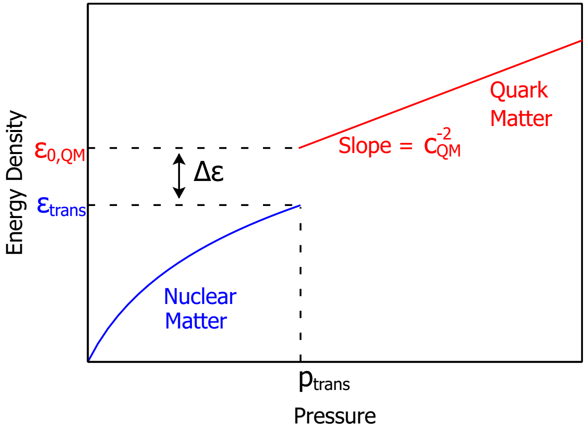
We need a model-independent parameterization of the quark matter EoS:

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

CSS: 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:

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

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

c_{QM}^2

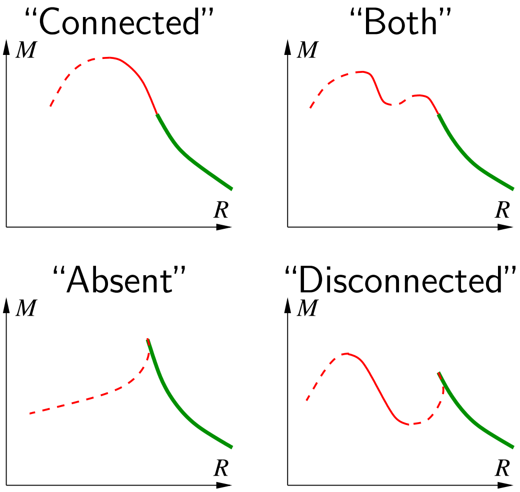
Zdunik, Haensel, arXiv:1211.1231; Alford, Han, Prakash, arXiv:1302.4732

Hybrid star $M(R)$

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

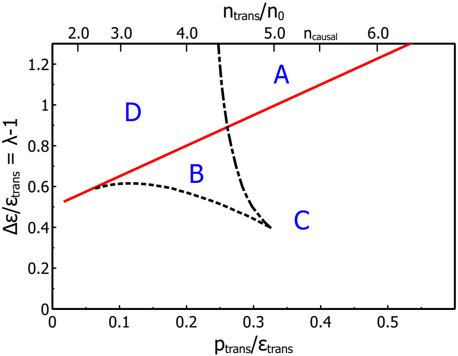
$\Delta\varepsilon < \Delta\varepsilon_{\mathrm{crit}}$
small energy density jump at phase transition

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

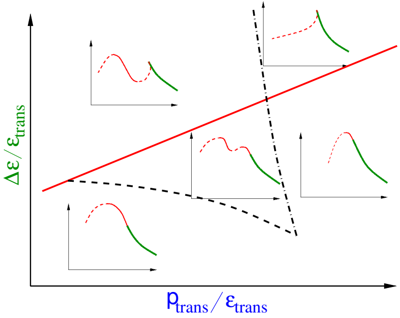


"Phase diagram" of hybrid star $M(R)$

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



Schematic



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

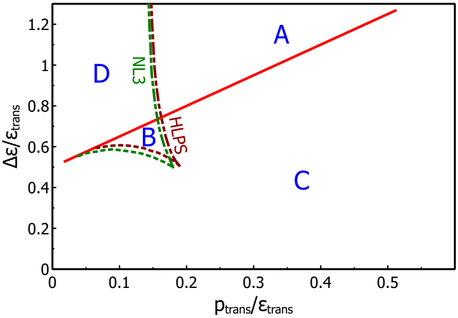
$$\frac{\Delta\varepsilon_{\mathrm{crit}}}{\varepsilon_{\mathrm{trans}}} = \frac{1}{2} + \frac{3}{2}\frac{p_{\mathrm{trans}}}{\varepsilon_{\mathrm{trans}}}$$

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

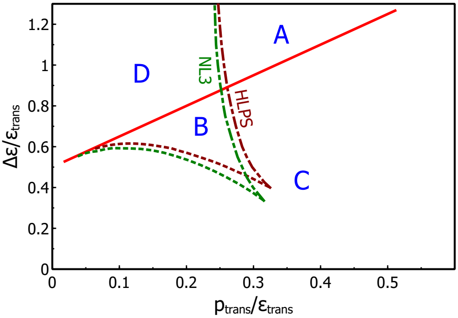
Disconnected branch exists in regions D and B.

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

$c^2_{\mathrm{QM}} = 1/3$



$c^2_{\mathrm{QM}} = 1$

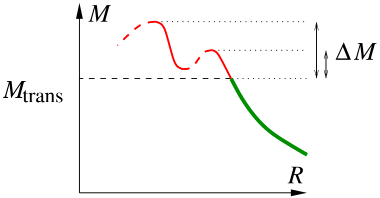


- NM EoS (HLPS=soft, NL3=hard) does not make much difference.
- Higher c^2_{QM} favors disconnected branch.

Observability of hybrid star branches

Measure length of hybrid branch by

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



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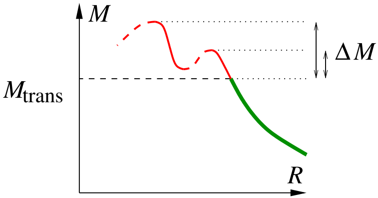
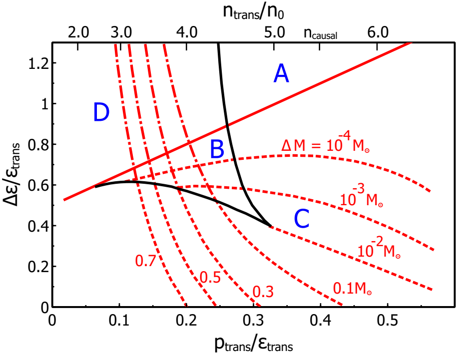
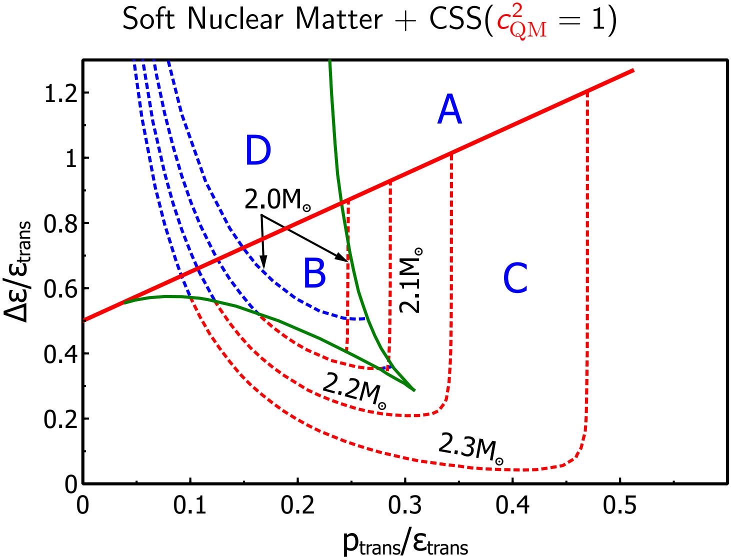


Soft NM + CSS($c^2_{\rm QM} = 1$)



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

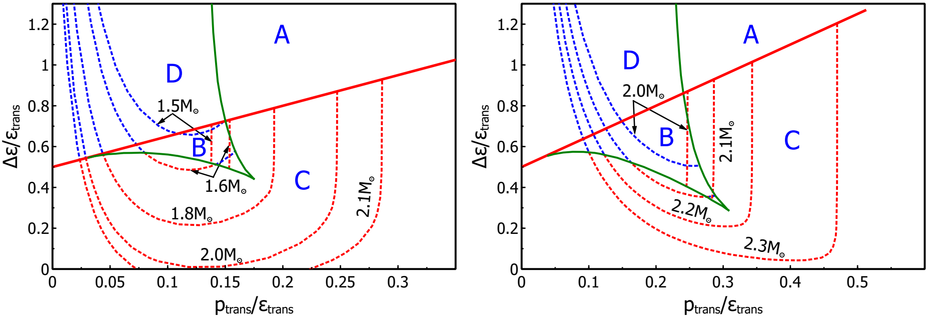
Constraints on QM EoS from max mass



- Max mass data constrains QM EoS but does not rule out generic QM

Dependence of max mass on $c^2_{\rm QM}$

Soft NM + CSS($c^2_{\rm QM} = 1/3$) Soft NM + CSS($c^2_{\rm QM} = 1$)



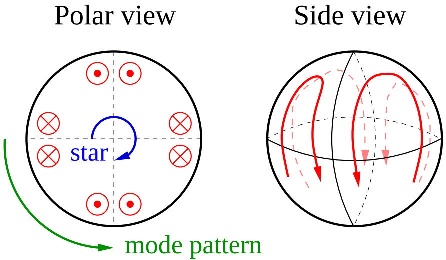
- For soft NM EoS, need $c^2_{\rm QM} \gtrsim 0.4$ to get $2\,M_\odot$ stars

Quark matter EoS Summary

- CSS (Constant Speed of Sound) is a generic parameterization of the EoS close to a sharp first-order transition to quark matter.
- Any specific model of quark matter with such a transition corresponds to particular values of the CSS parameters
  $(p_{\rm trans}/\varepsilon_{\rm trans}, \quad \Delta\varepsilon/\varepsilon_{\rm trans}, \quad c^2_{\rm QM})$.
  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 $c^2_{\rm QM} \gtrsim 0.4 \quad (c^2_{\rm QM} = 1/3$ 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.

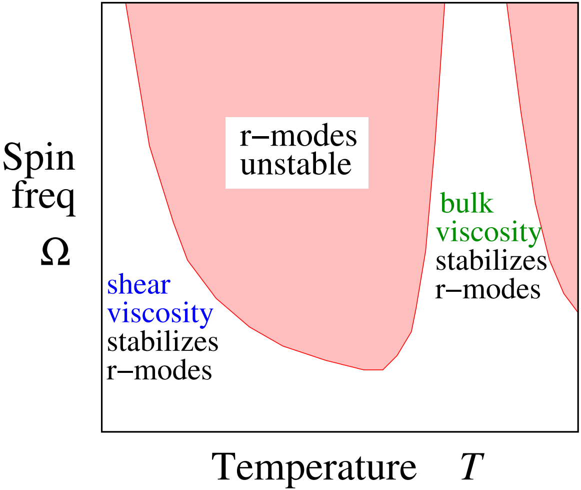


The unstable *r*-mode can spin the star down very quickly, in a few days if the amplitude is large enough

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

neutron star spins quickly	$\Rightarrow$	some interior physics damps the *r*-modes

r-mode instability region for nuclear matter



Shear viscosity grows at low T (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.

Evolution of r-mode amplitude α

$$\frac{d\alpha}{dt} = \alpha(|\gamma_G| - \gamma_V) \qquad \gamma_G = \frac{1}{\tau_G} = \text{grav radiation rate } (< 0)$$

$$\gamma_V = \frac{1}{\tau_V} = \text{r-mode dissipation rate}$$

$$\frac{d\Omega}{dt} = -2Q\,\gamma_V\,\alpha^2\,\Omega \qquad Q \approx 0.1 \quad \text{for typical star}$$

$$\frac{dT}{dt} = -\frac{1}{C_V}(L_\nu - P_V) \qquad L_\nu = \text{neutrino emission}$$

$$P_V = \text{power from dissipation}$$

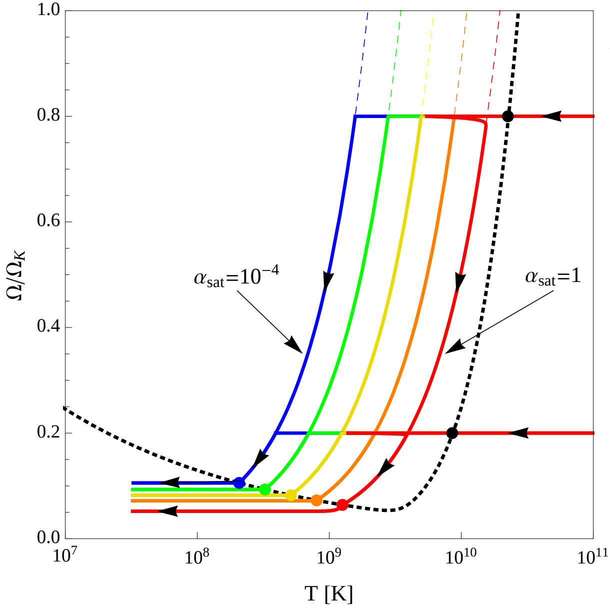
R-mode is unstable when $|\gamma_G(\Omega)| > \gamma_V(T)$ at infinitesimal α.

R-mode saturates when $\gamma_V(\alpha)$ rises with α until

$$\gamma_V(T, \alpha_{\rm sat}) = \gamma_G \qquad (\Rightarrow P_V = P_G)$$

In general, $\alpha_{\rm sat}(T, \Omega)$ is an unknown function determined by microscopic and astrophysical damping mechanisms.

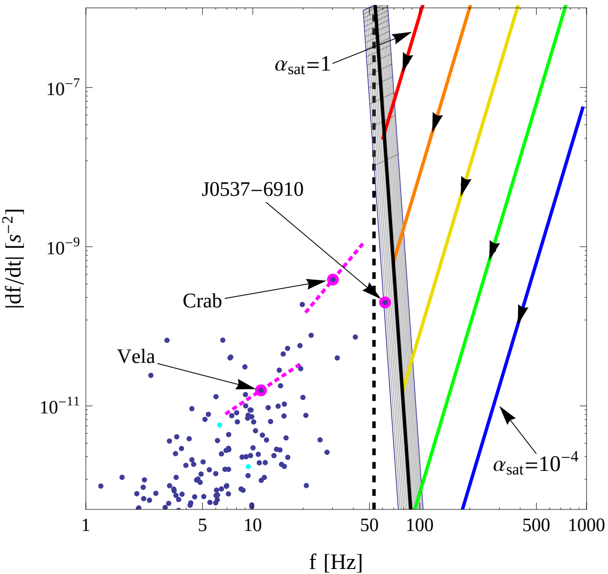
R-modes and young neutron stars



- Young pulsar cools into instability region
- R-mode quickly saturates
- Star spins down along "heating=cooling" line
- Star exits instability region at $\Omega \sim 50\,\mathrm{Hz}$, indp of cooling model

(Alford, Schwenzer arXiv:1210.6091)

Could r-modes explain young pulsar's slow spin?

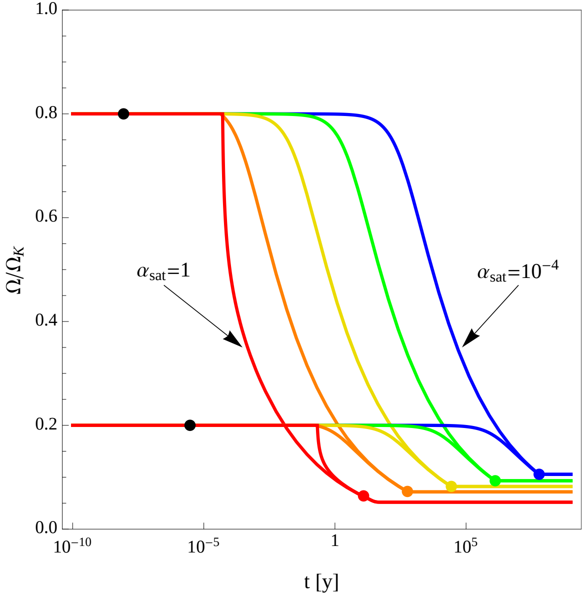


r-modes with $\alpha_{sat} \sim 10^{-2}$ to 10^{-1} could explain slow rotation of young pulsars ($\lesssim$ a few thousand years old)

J0537-6910 is 4000 years old

(Alford, Schwenzer `arXiv:1210.6091`)

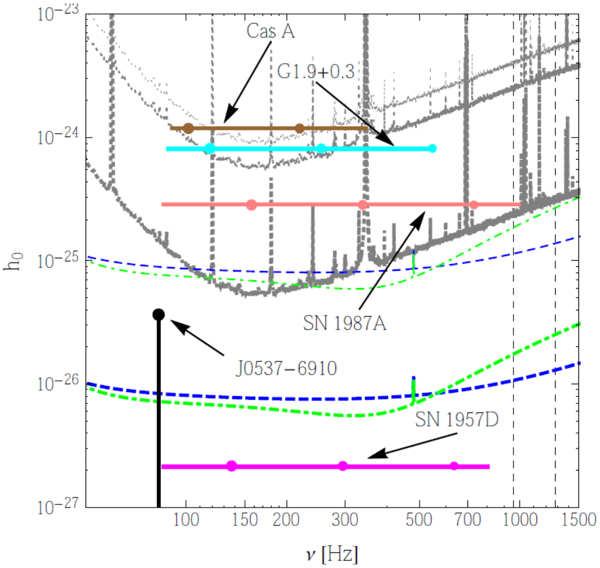
How quickly r-modes spin down pulsars



For $\alpha_{\rm sat}$ in the range 0.01 to 0.1, spindown is complete in 20,000 to 500 years.

(Alford, Schwenzer `arXiv:1210.6091`)

GW from r-mode spindown of young pulsars



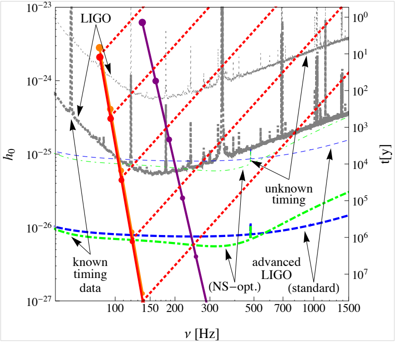
Known young pulsars.

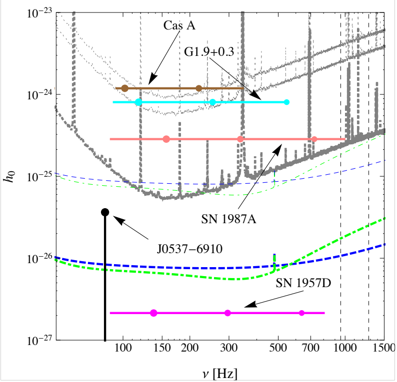
For given age t, h_0 is indp of current freq ν, since if $\Omega = 2\pi\nu$ is higher, spindown would be faster, so $\alpha_{\rm sat}$ must be smaller to ensure we get to freq Ω in time t.

Several known sources would be detected by advanced LIGO if they are mainly spinning down via r-modes.

Gravitational wave emission of young sources

- Advanced LIGO will become operational soon …
- Since r-mode emission can *quantitively* explain the low rotation frequencies of observed pulsars (which spin by now too slow to emit GWs), very young sources are promising targets

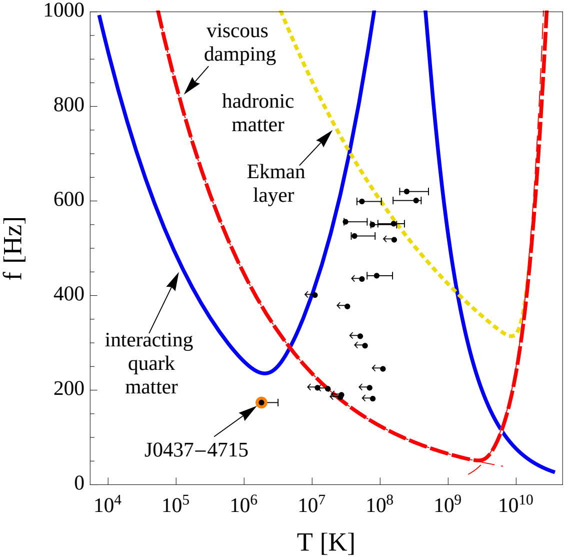




Several potential sources in reach of aLigo

r-modes and old pulsars

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



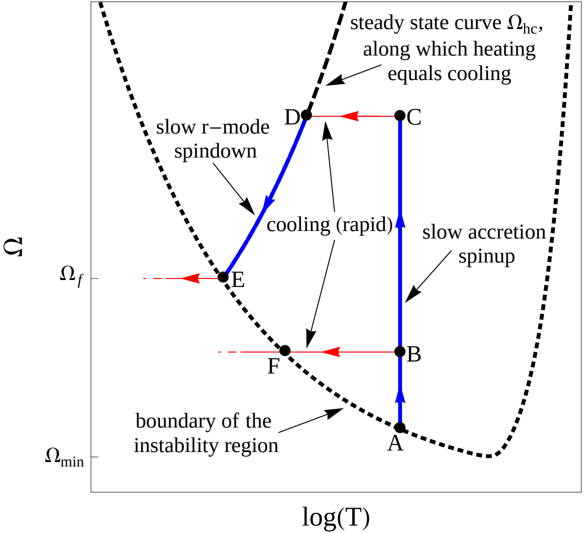
Data for accreting pulsars in binary systems (LMXBs) vs instability curves for nuclear and hybrid stars.

Possibilities:

- additional damping (e.g. quark matter)
- r-mode spindown is very slow (small $\alpha_{\rm sat}$)

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

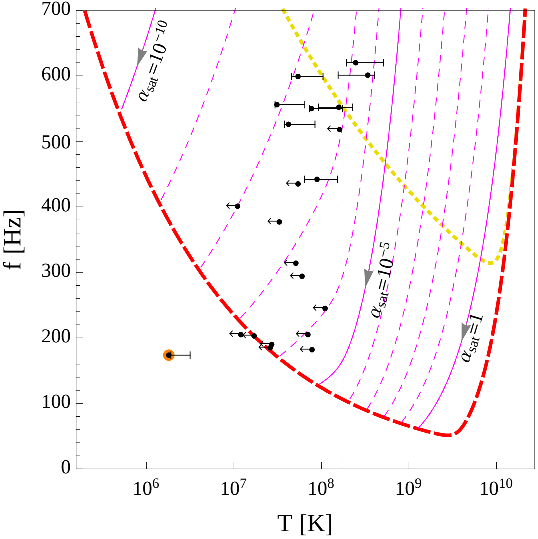
Spindown via r-modes of an old neutron star



Steady-state spindown curve is determined by amplitude α_{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 stuck 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

Gravitational waves from old ms-pulsars

- In addition to the standard case of deformations r-modes are a promising continuous GW-source

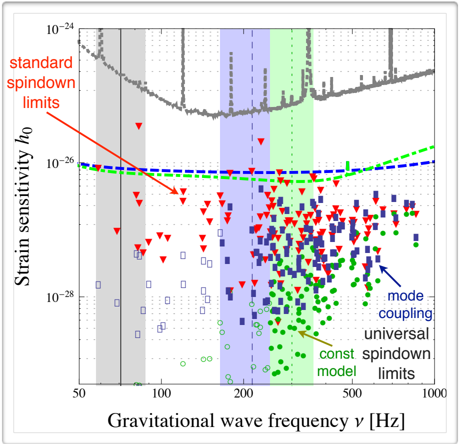
Aasi, *et. al.*, arXiv:1309.4027

- But, the r-mode saturation mechanism depends weakly on source properties …

  ★ novel universal spindown limit for the GW signal

➡ Millisecond pulsars are below the aLigo sensitivity

✓ However they should be detectable with further improvements or 3. generation detectors



$$h_0^{(\mathrm{usl})} = \sqrt{\frac{15}{4}\frac{GI\left|\dot{f}_0\right|}{D^2 f_0}} \left(\frac{\hat{\alpha}_{\mathrm{sat}}^{(\mathrm{mac})}}{\hat{\alpha}_{\mathrm{sat},0}^{(\mathrm{mac})}}\right)^{\frac{1}{1-2\beta/\theta}} \left(\frac{f}{f_0}\right)^{\frac{3+\gamma+2\beta/\theta}{1-2\beta/\theta}}$$

(universal spindown limit)

Alford & Schwenzer, arXiv:1403.7500

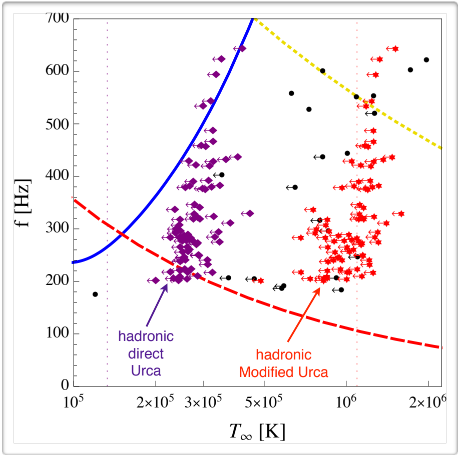
"R-mode temperatures"

- The connection between the spindown curves allows to determine the R-mode temperature of a star with saturated r-mode oscillations (tiny r-mode scenario) for given timing data

$$T_{rm} = \left(I\Omega\dot{\Omega}/\left(3\hat{L}\right)\right)^{1/\theta}$$

- Independent of the saturation mechanism ... but depends on the cooling
- These are only upper bounds since the observed spindown rate can also stem from electromagnetic radiation

★ Measurements of temperatures of fast pulsars would allow us to test if saturated tiny r-modes can be present!



Alford & Schwenzer, arXiv:1310.3524

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

R-modes prospects

- a-LIGO will tell us whether some young neutron stars are spinning down via r-modes
- Better temperature measurements of ms pulsars will tell us whether they are inside the simple nuclear-viscous instability region.
  - If they are inside, this tells us what value of $\alpha_{\rm sat}$ is required for compatibility with the simple nuclear-viscous model.
  - If we also know their $\dot{\Omega}$, we can see if they being heated by r-modes ($T_\infty \sim 10^5$ to 10^6 K).
  - If pulsars with $f \gtrsim 300$ Hz are outside (too cool) this would require amazingly low $\alpha_{\rm sat} \lesssim 10^{-8}$ to be compatible with the simple nuclear-viscous model
- Now that we have calculations of r-mode spindown as a function of general (generic power law) microphysical properties, let's start surveying all known phases of dense matter for their spindown predictions
- Additional astrophysical damping could save simple nuclear-viscous model; what other mechanisms could there be?

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 ($p_{\mathrm{trans}}/\varepsilon_{\mathrm{trans}}$, $\Delta\varepsilon/\varepsilon_{\mathrm{trans}}$, c^2_{QM})
- knowledge of nuclear matter EoS

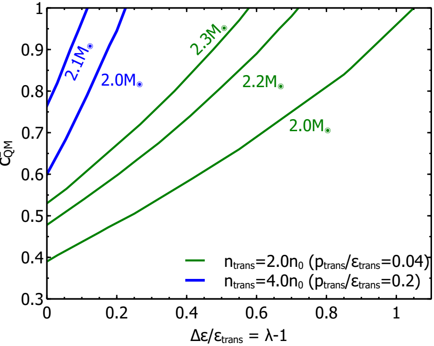
Spindown: extra damping in some forms of quark matter can explain current observations, but other scenarios (astrophysical extra damping; r-modes with tiny amplitude) have not been ruled out.

We need:

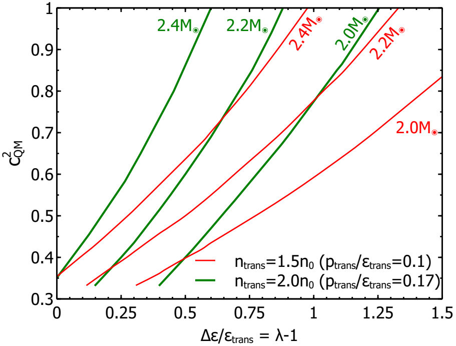
- Better theoretical understanding of r-mode damping and saturation mechanisms
- Better temperature measurements (ideally, of ms pulsars too)
- Detect grav waves from old pulsars (beyond advanced LIGO) or very young neutron stars (advanced LIGO)

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`