Quark matter in neutron stars

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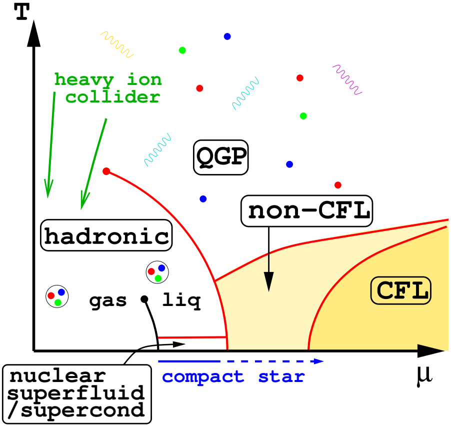
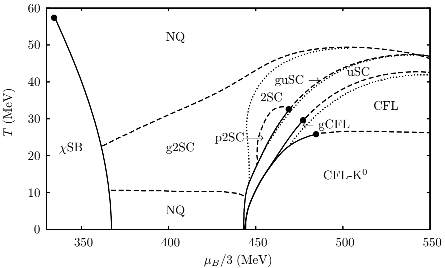
Phases of quark matter



NJL model, uniform phases only



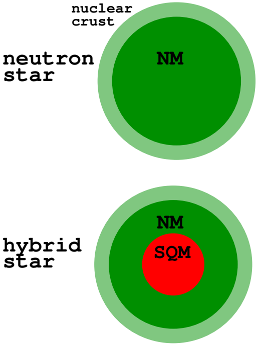
Warringa, hep-ph/0606063

But there are also non-uniform phases, such as the crystalline ("LOFF"/"FFLO") phase.

Quark matter in compact stars

Conventional scenario

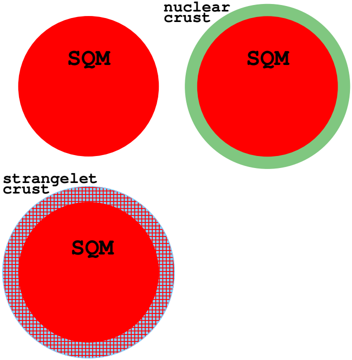
Neutron/hybrid star



Strange Matter Hypothesis

Bodmer 1971; Witten 1984; Farhi, Jaffe 1984

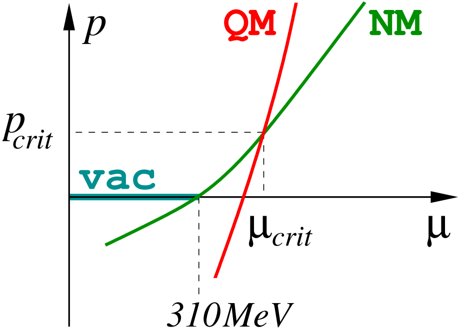
Strange star



Two scenarios for quark matter

Conventional scenario

Vac→NM→QM

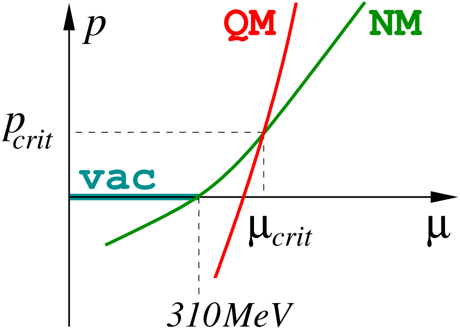


Nuclear→quark matter transition at high pressure, $(\mu_{\rm crit}, p_{\rm crit})$

Two scenarios for quark matter

Conventional scenario

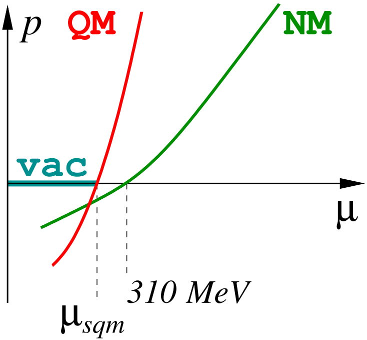
Vac→NM→QM



Nuclear→quark matter transition at high pressure, $(\mu_{\rm crit},\ p_{\rm crit})$

Strange Matter Hypothesis

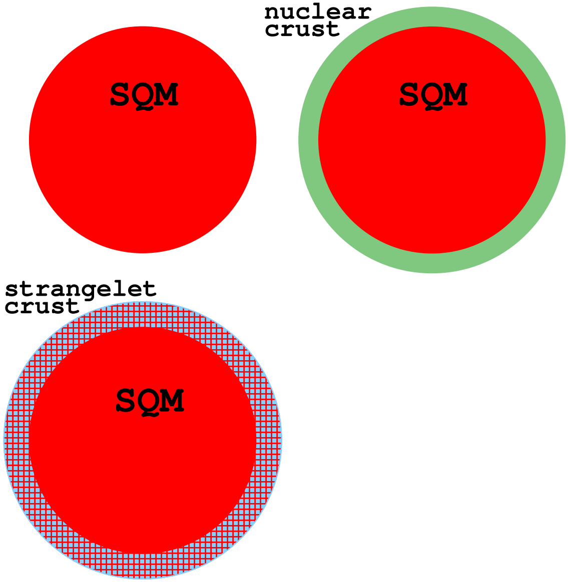
Vac→QM



Vacuum→quark matter transition at $\mu = \mu_{\rm sqm}$, $p = 0$.

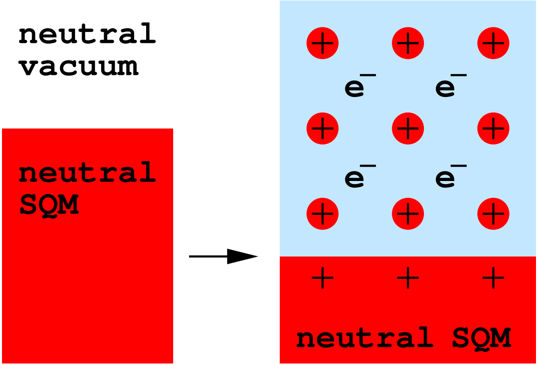
Strange quark matter (SQM) is the favored phase down to $p = 0$.

Stars under the Strange Matter Hypothesis



Strangelet crust

At zero pressure, if its surface tension is low enough, strange matter, like nuclear matter, will undergo charge separation and evaporation in to charged droplets.



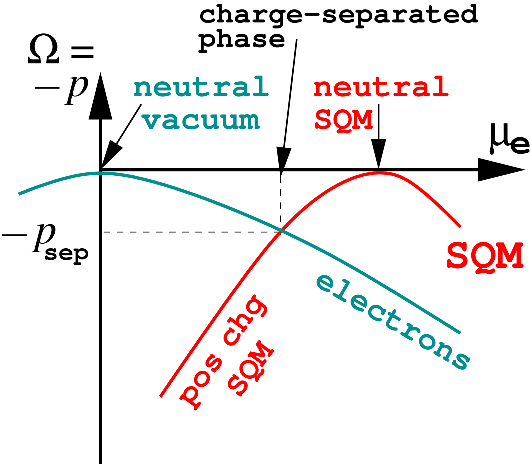
$\sigma_{\rm crit} \lesssim 10\,\mathrm{MeV\,fm^{-2}}$

Crust thickness
$\Delta R \lesssim 1\,\mathrm{km}$

Alford, Eby, `arXiv:0808.0671`

Jaikumar, Reddy, Steiner, `nucl-th/0507055`

Charge separation: a generic feature



charge density $\rho = \dfrac{d\Omega}{d\mu_e}$

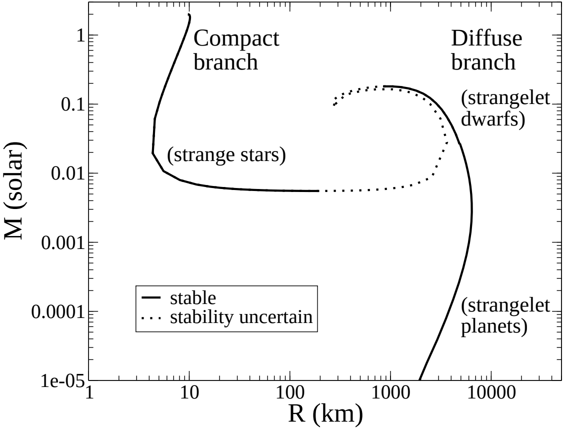
Neutral quark matter and *neutral* vacuum can coexist at zero pressure.

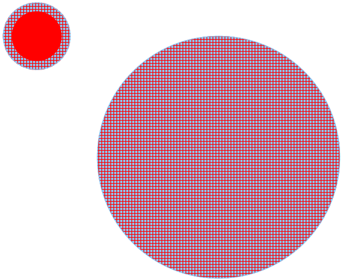
But if they have different electrostatic potentials μ_e then $p_{\rm sep} > 0$ and it is preferable* to form a charge-separated phase with intermediate μ_e.

$*$ unless surface costs are too high, e.g. surface tension, electrostatic energy from $\mathbf{E} = \nabla\mu_e$.

Strange quark matter objects

Similar to nuclear matter objects, if surface tension is low enough.





Alford, Han `arXiv:1111.3937`

Strange Matter Hypothesis summary

- Strange matter is the true ground state at zero pressure.
- For a compact star, ground state is strange matter, perhaps with a strangelet or nuclear matter crust.
- Neutron stars will convert to strange stars if hit by a strangelet.
- Regular matter is immune since strangelets are positively charged.
- If surface tension of strange matter is low enough, it will form atoms, planets, dwarfs, compact stars, roughly like nuclear matter.

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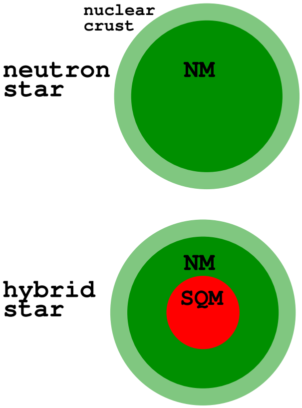
Is SMH ruled out by observations of neutron stars?

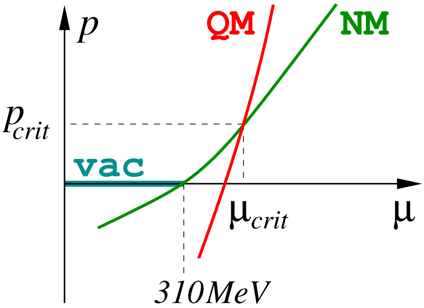
- X-ray burst oscillations indicate ordinary nuclear crust (Watts, Reddy `astro-ph/0609364`). But...
  — Maybe nuclear crust can show similar behavior?
  — Maybe strangelet crust can show similar behavior?
- Would cosmic strangelet flux be large enough to convert all neutron stars? (Friedman, Caldwell, 1991)?
  Depends on SQM params (Bauswein et. al. `arXiv:0812.4248`).

Conventional hypothesis

Transition from nuclear matter to quark matter occurs at high pressure.
Compact stars have nuclear crust/mantle, possible quark matter core.



Vac→NM→QM



Nuclear→quark matter
at high pressure, ($\mu_{\rm crit}$, $p_{\rm crit}$)

Signatures of quark matter in compact stars

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

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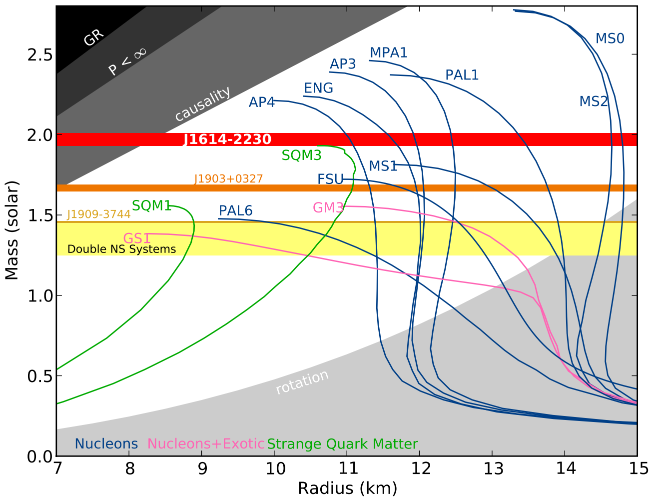
	Property	Nuclear phase	Quark phase
mass, radius	eqn of state $\varepsilon(p)$	known up to $\sim n_{\rm sat}$	unknown; many models
spindown (spin freq, age)	bulk viscosity shear viscosity	Depends on phase:	Depends on phase:
		$n\ p\ e$	unpaired
cooling (temp, age)	heat capacity neutrino emissivity thermal 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:

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

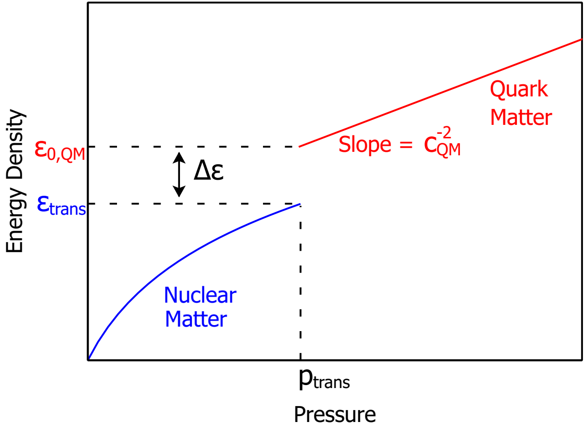
Demorest et al, Nature 467, 1081 (2010).

Can quark matter be the favored phase at high density?

A fairly generic QM EoS

Model-independent parameterization:

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



Zdunik, Haensel, `arXiv:1211.1231`

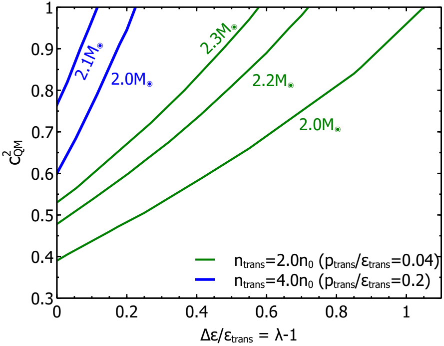
Alford, Han, Prakash, `arXiv:1302.4732`

QM EoS params: $p_{\rm trans}/\varepsilon_{\rm trans}$, $\Delta\varepsilon/\varepsilon_{\rm trans}$, $c_{\rm QM}^2$

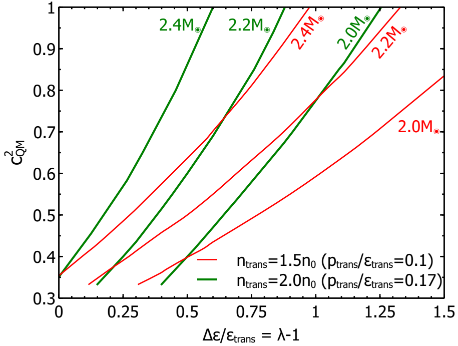
Constraints on QM EoS from max mass

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

QM + Soft Nuclear Matter



QM + Hard Nuclear Matter



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

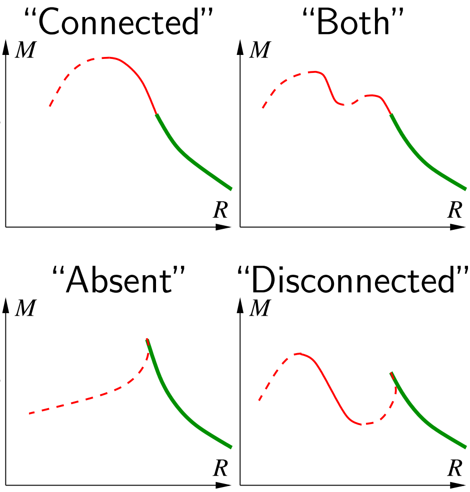
- Max mass can constrain QM EoS but not rule out generic QM
- For soft NM EoS, need $c^2_{\rm QM} \gtrsim 0.4$

Hybrid star $M(R)$

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

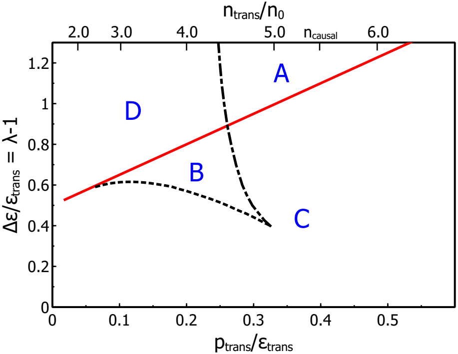
$\Delta\varepsilon < \Delta\varepsilon_{\rm crit}$
small energy density jump at phase transition

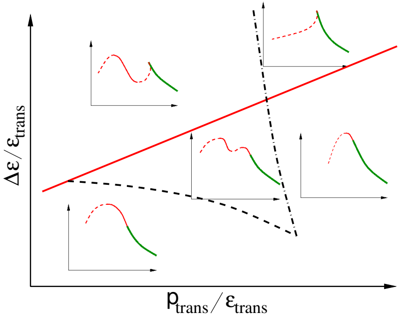
$\Delta\varepsilon > \Delta\varepsilon_{\rm crit}$
large energy density jump at phase transition



“Phase diagram” of hybrid star $M(R)$

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





Above the red line,
connected branch disappears

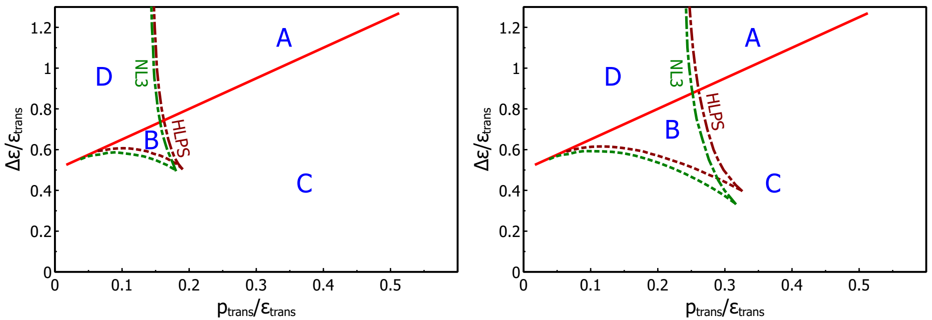
$$\frac{\Delta\varepsilon_{\rm crit}}{\varepsilon_{\rm trans}} = \frac{1}{2} + \frac{3}{2}\frac{p_{\rm trans}}{\varepsilon_{\rm trans}}$$

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

Disconnected branch exists in regions D and B.

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

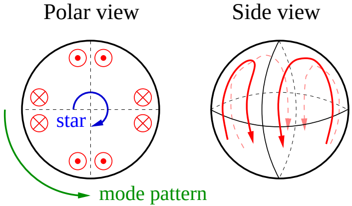
$c^2_{\rm QM} = 1/3$ $\qquad$ $c^2_{\rm QM} = 1$



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

r-modes: gravitational spin-down of compact stars

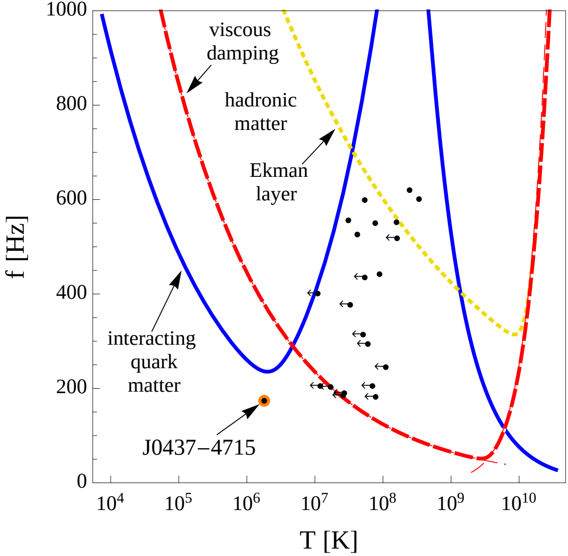
An r-mode is a quadrupole flow that emits gravitational radiation. It becomes unstable (i.e. arises spontaneously) when a star spins fast enough, and if the shear and bulk viscosity are low enough.



Andersson `gr-qc/9706075`

Friedman and Morsink `gr-qc/9706073`

Constraints from r-modes



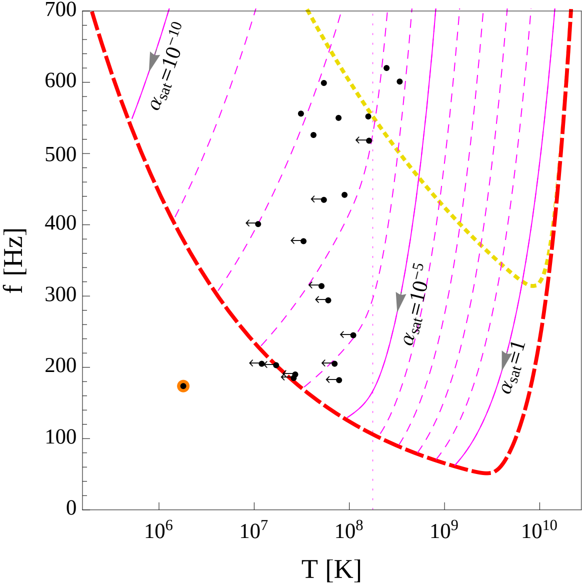
Regions above curves are "forbidden" because viscosity is too low to hold back the *r*-modes.

Data for accreting pulsars in binary systems (LMXBs)

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

Could neutron stars be spinning down via r-modes?

Constraints on r-mode amplitude



steady-state lines (r-mode heating = mod. Urca cooling) for given r-mode amplitude $\alpha_{\rm sat}$.

LMXBs have accretion heating too ⇒ hotter than r-mode steady state.

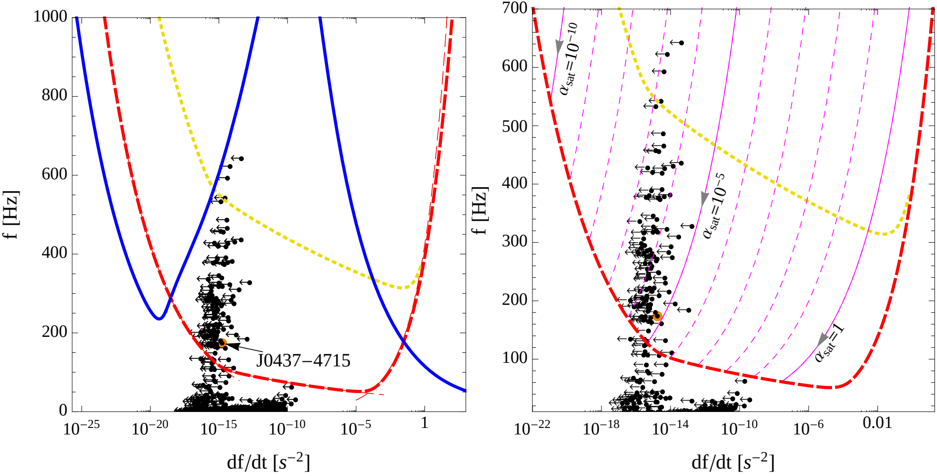
$$\alpha_{\rm sat} \lesssim 10^{-8}$$

No known saturation mechanism can achieve this.

(Alford, Schwenzer, unpublished)

r-modes and timing data

Use df/dt rather than T. Lots of radio pulsar data.



Again, nuclear matter needs additional damping or $\alpha_{\rm sat} \lesssim 10^{-7}$ to be a viable model. (Alford, Schwenzer `unpublished`)

Conventional Scenario summary

- Critical density for nuclear→quark transition is unknown. Neutron stars may have quark matter cores.
- We need signatures that are sensitive to properties of the core
  - Mass-radius curve
  - Cooling (e.g. Cas. A)
  - Spindown (r-mode exclusion regions)
  - Glitches
  - Grav waves? (Spindown, mergers, "mountains")
- We need to understand quark matter phases and how their properties are manifested in these signature behaviors.

The future

- Neutron stars:
  - More data on neutron star mass, radius, age, temperature, etc.
  - Spindown: r-mode damping and saturation mechanisms
  - Cooling: neutrino emissivity of quark matter phases
  - Glitches & grav waves: Color supercond. crystalline phase
  - Other signatures?
- Quark matter properties:
  - Intermediate density phases
  - Role of large magnetic fields
  - Better models of quark matter: PNJL, Schwinger-Dyson
  - Better weak-coupling calculations
  - Solve the sign problem and do lattice QCD at high density