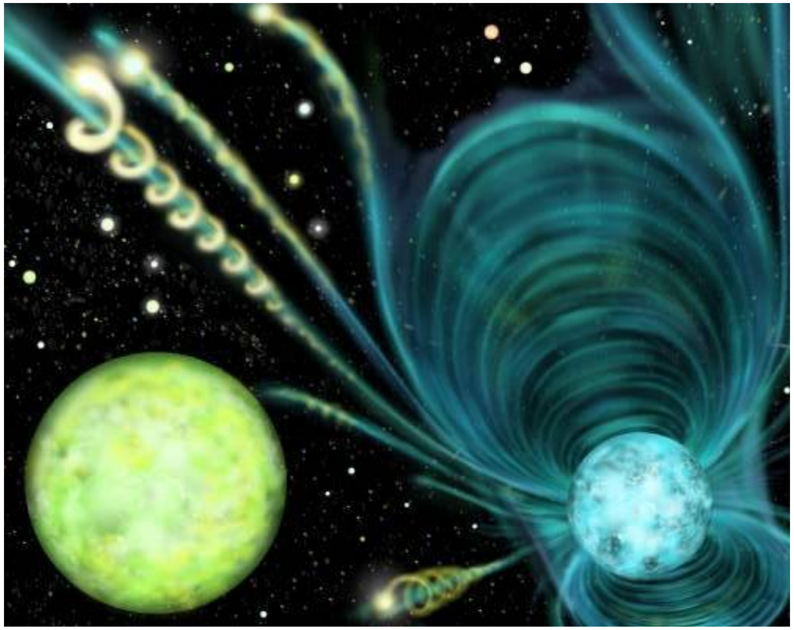
Neutron stars as cosmic laboratories



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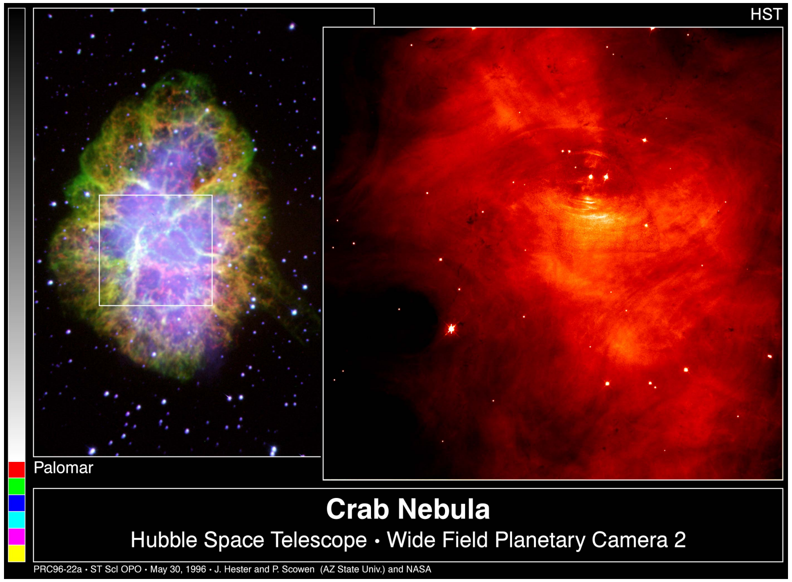
neutron stars

A neutron star is born when a medium-weight star runs out of nuclear fuel and collapses under its own weight.



Once the dust from the supernova explosion has settled the remnant can usually be seen as a radio pulsar.

In addition, there are accreting neutron stars in LMXBs, strongly magnetized magnetars, isolated neutron stars…

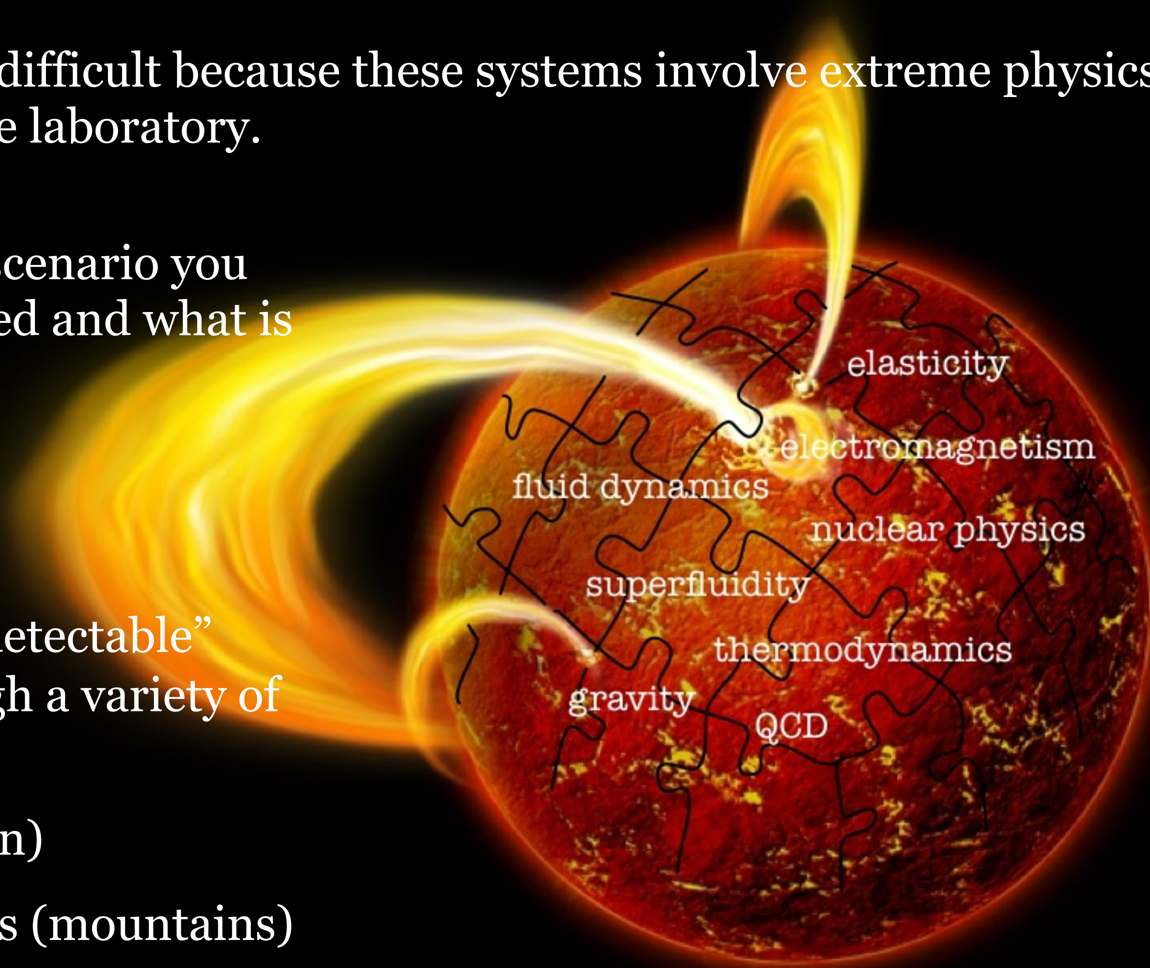
With a solar mass compressed inside a radius of about 10 km, a neutron star represents much extreme physics that cannot be tested in the laboratory.

In this talk I will discuss (some of) the different ways that neutron star observations constrain our understanding of fundamental physics.

theory challenge

Neutron star modelling is difficult because these systems involve extreme physics that cannot be tested in the laboratory.

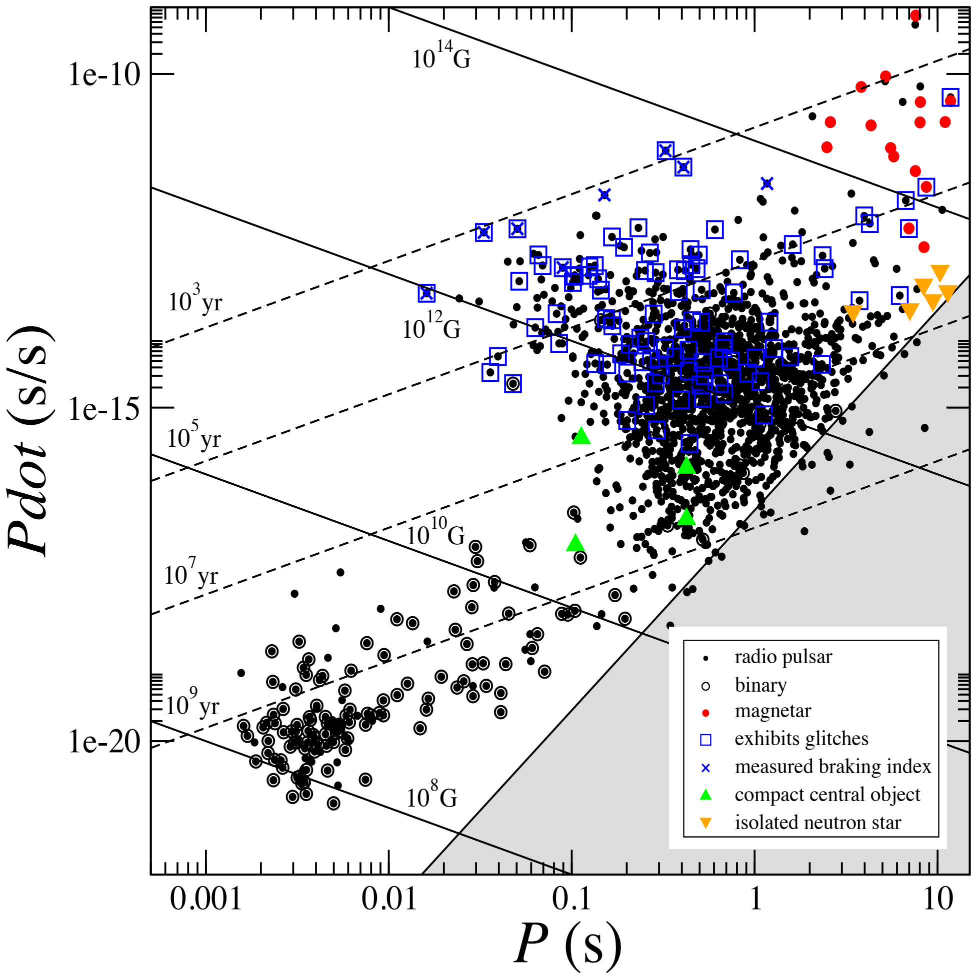
For any proposed model/scenario you need to ask what is included and what is not!



Neutron stars may emit “detectable” gravitational waves through a variety of scenarios;

- merger (tidal interaction)
- crust/core deformations (mountains)
- oscillations/instabilities

pulsar primer



The most precisely determined parameters are the spin and the accompanying spin-down rate.

Different classes of neutron stars populate different parts of the P-P-dot diagram.

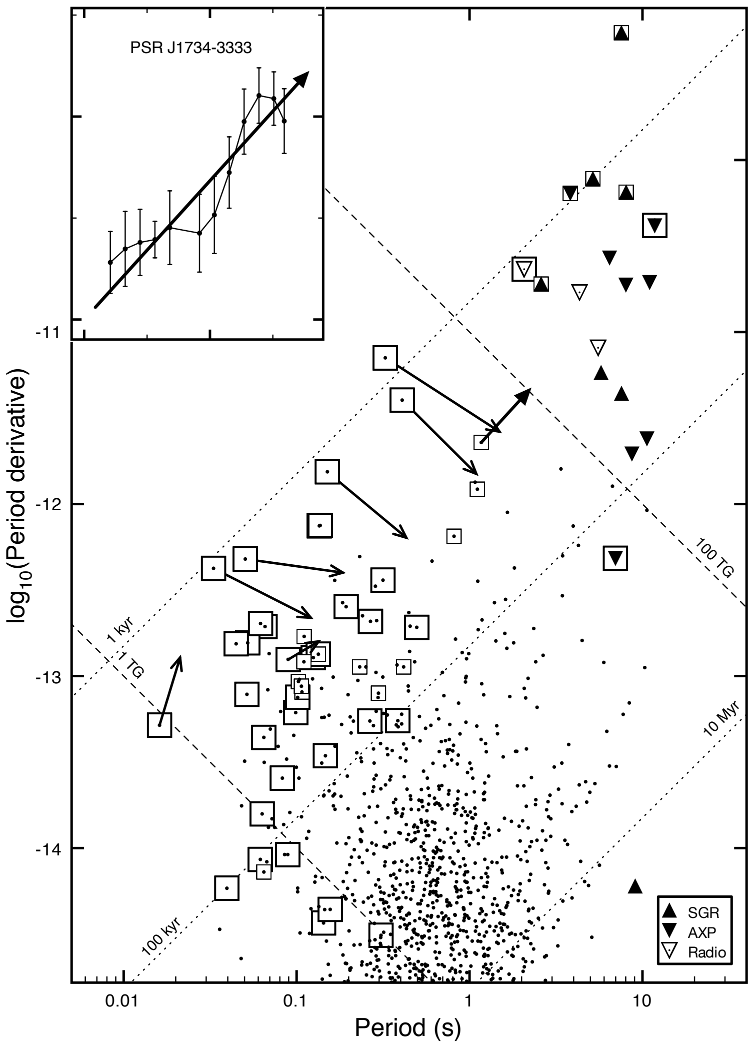
Infer the star's magnetic field (or the star's "age")

$$B^2 \sim P\dot{P}$$

Sanity check is provided by the second derivative, leading to the "braking index".

Many young systems exhibit spin variability and glitches.

braking index



[Espinoza et al 2011]

For canonical magnetic dipole radiation, the braking index should be 3. Observed systems tend to deviate significantly from this.

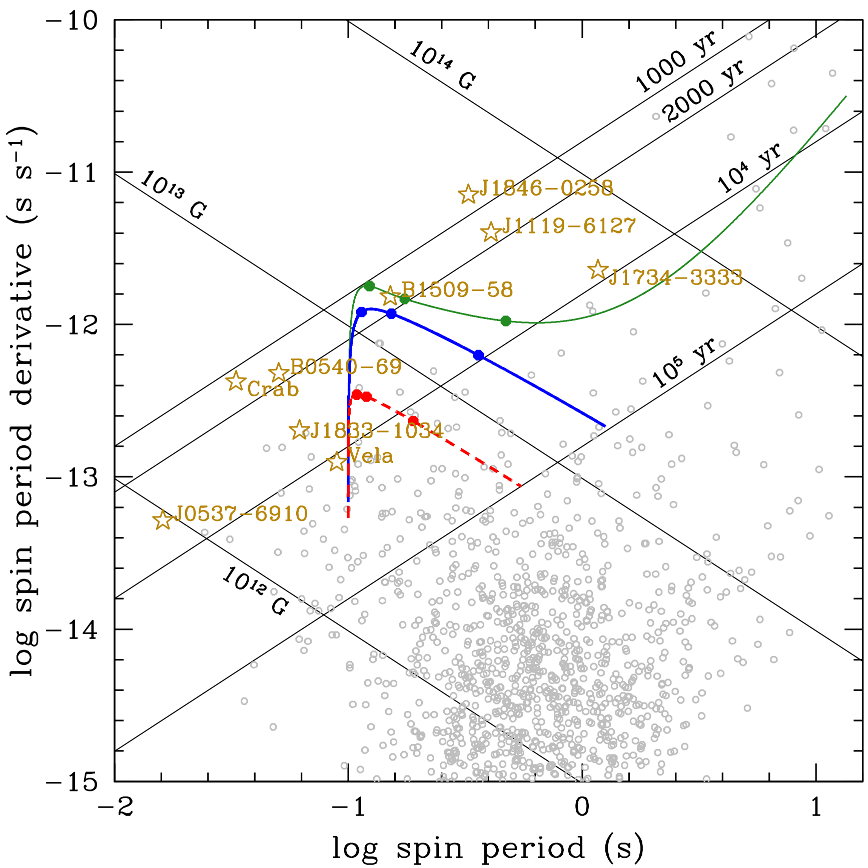
n<3 could be an indication of an increasing magnetic field (pulsars become magnetars as buried field emerges?)

Alternative recent explanation:

Young neutron stars have "evolving" regions of **core** superfluidity.

If the superfluid "decouples" as the star evolves, then the observed component might be associated with less moment of inertia than commonly assumed.

braking index



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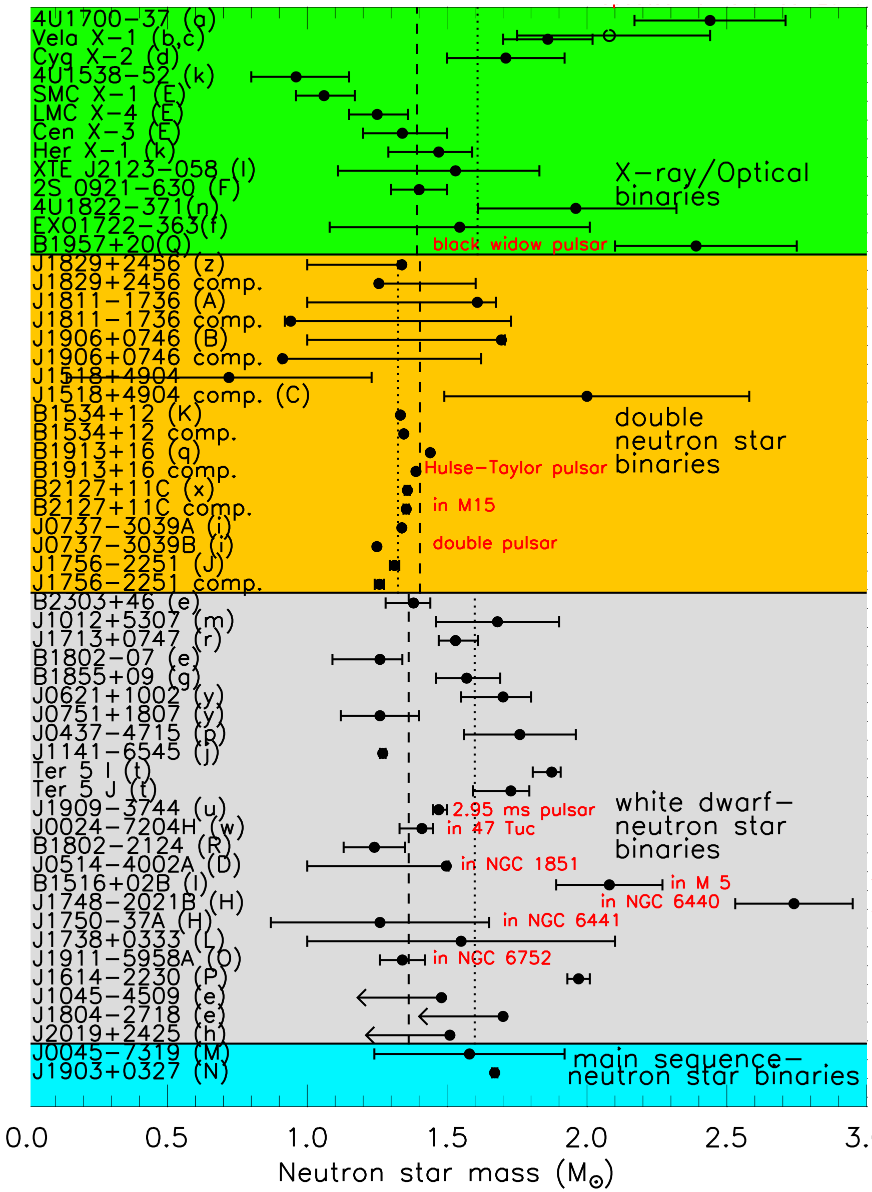
the mass



[courtesy Jim Lattimer]

Neutron star masses can be inferred from binary dynamics.

The relevant “mass function” involves the mass ratio and the inclination so… need to understand the nature of the companion.

Eclipsing systems are ideal…

The inferred masses tend to lie in a relatively narrow range, around 1.4 solar masses.

Most of these systems do not constrain nuclear physics severely.

There are, however, exceptions…

PSR J1614-2230

A 3.15 ms pulsar in an 8.69d orbit with an 0.5 solar mass white dwarf companion.

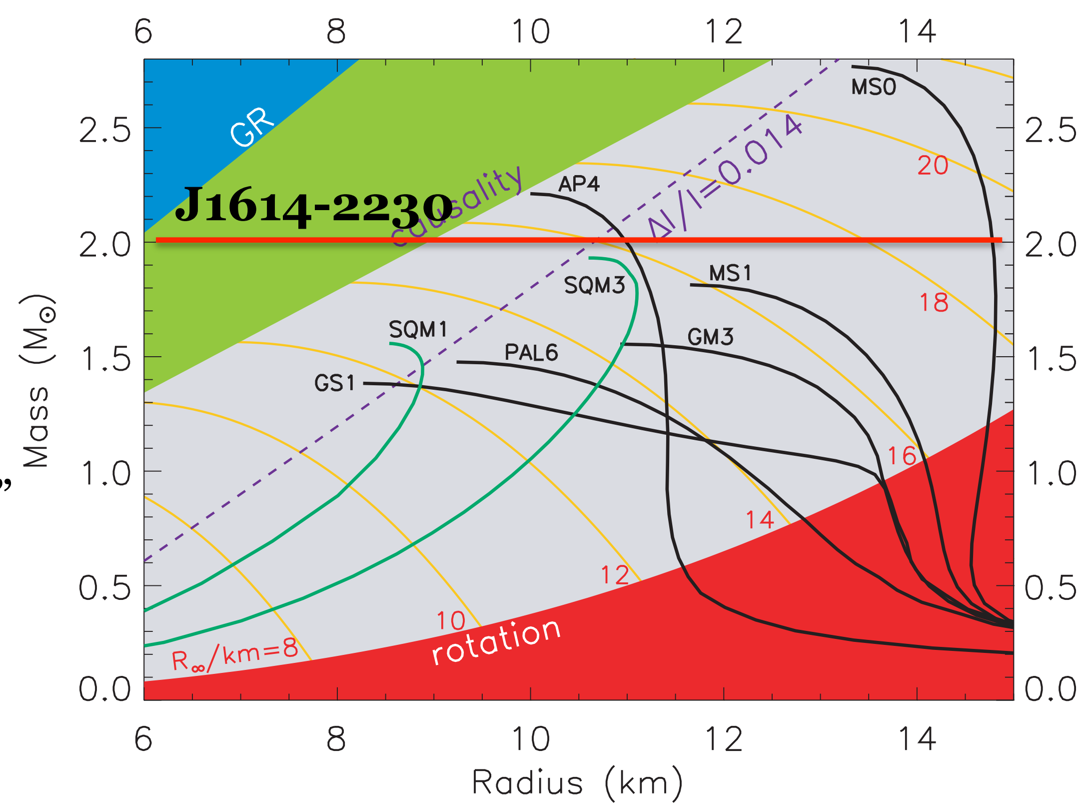
Observed Shapiro time delay yields edge-on inclination, sin i = 0.99984.

The inferred pulsar mass is **1.97 ± 0.04 $M_\odot$**.

A maximum mass near 2 solar masses “rules out” several proposed equations of state.

The presence of softening components like hyperons or deconfined quarks becomes “problematic”.

However, the “next generation” of nuclear physics models may resolve this issue, so it is too early to draw definite conclusions.

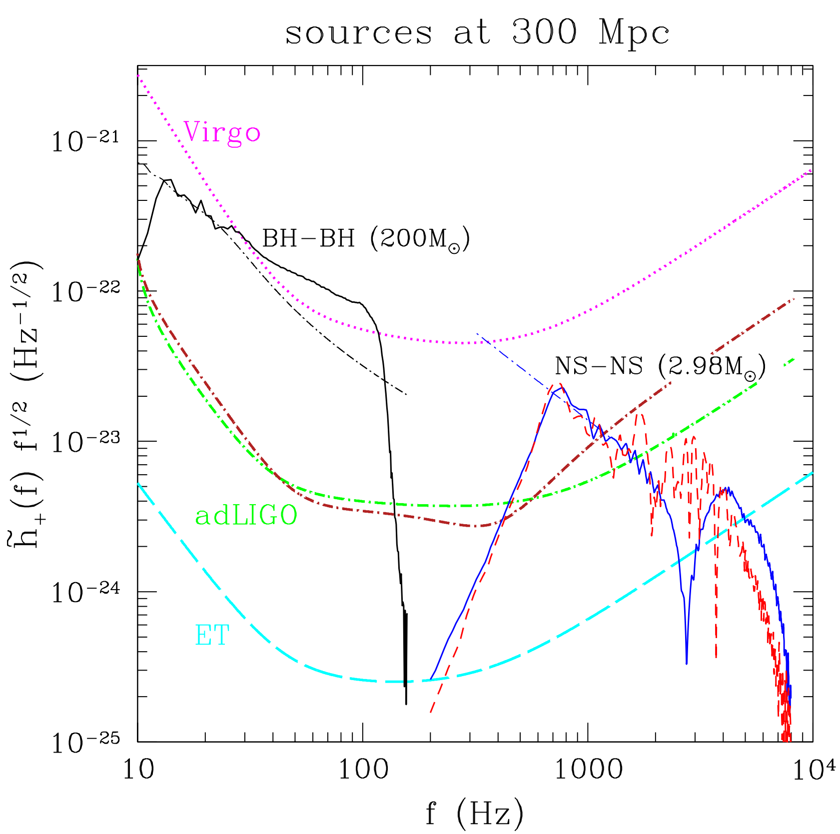


[courtesy Lattimer & Prakash]

mergers

Binary systems are (obviously) important for gravitational wave astronomy.

Can we expect to learn anything beyond individual masses and perhaps spins?



The deviation from point-mass dynamics becomes important at the late stages of binary inspiral.

The star's deformability, encoded in the so-called Love number, may lead to a distinguishable secular effect;

$$\lambda = \frac{2}{3} k_2 R^5 = \frac{Q}{E} = \frac{\text{quadrupole deformation}}{\text{strength of tidal field}}$$

However, this effect and the final "ringdown" signal are likely to require detectors like the Einstein Telescope...

the crust yields

Are fundamental physics aspects detectable or hidden in the fineprint?

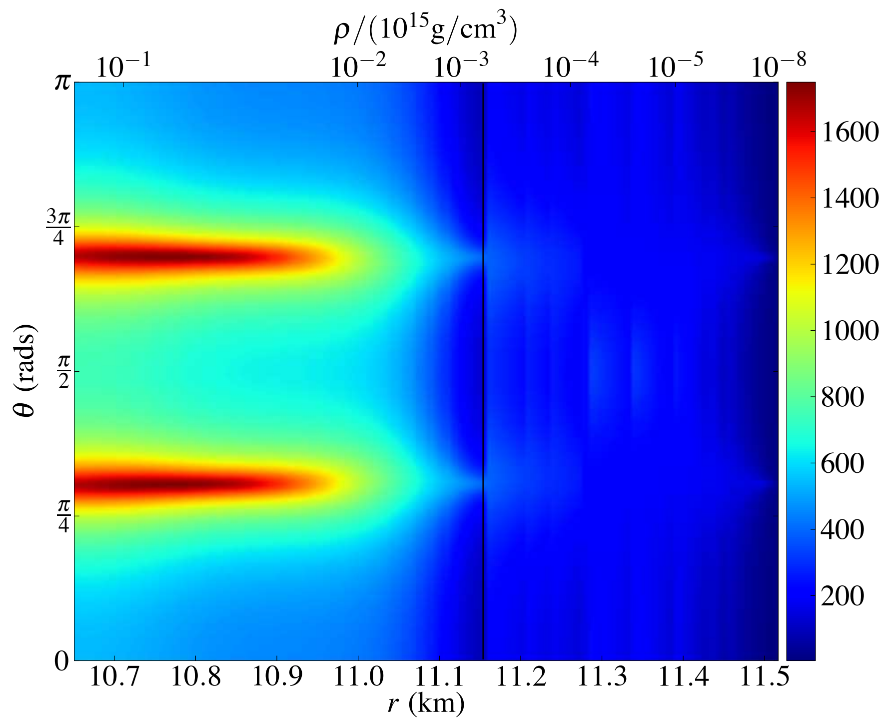
At what point during inspiral does it matter that a neutron star is not a "perfect fluid"?

Final merger provides "standard model" for short gamma-ray bursts…

During inspiral strains builds in neutron star's crust.

Crust yielding, leading to the release of built-up strain, may trigger an observable electromagnetic counterpart to the merger.

This could release as much as 10^{46} erg, so a signal might be visible out to/ beyond 100 Mpc) with current instruments.

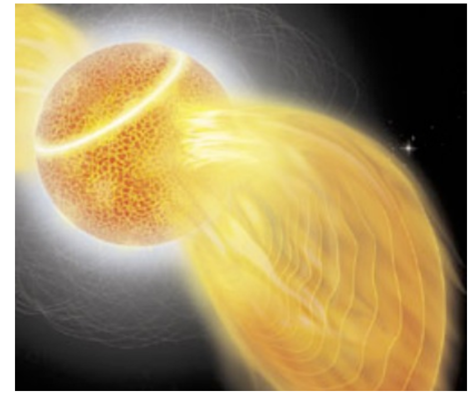


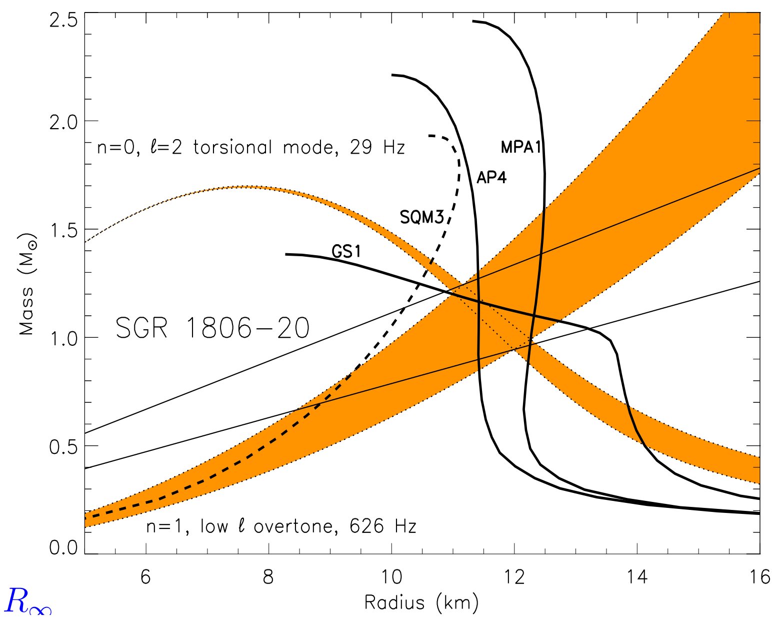
magnetars

Magnetars (SGR/AXP) are neutron stars with superstrong magnetic fields: $B \sim 10^{15}$ G, $P \sim$ 1-10 s

Field decay powers regular gamma-ray flares.

On rare occasions magnetars emit <u>giant</u> flares. Thought to result from crust fractures leading to a rearrangement of the magnetic field.





Three events to date;

— March 5, 1979: SGR 0526-66

— August 27, 1998: SGR 1900+14

— December 27, 2004: SGR 1806-20

Observed quasi-periodic oscillations provide first evidence of neutron star oscillations and opportunity for asteroseismology.

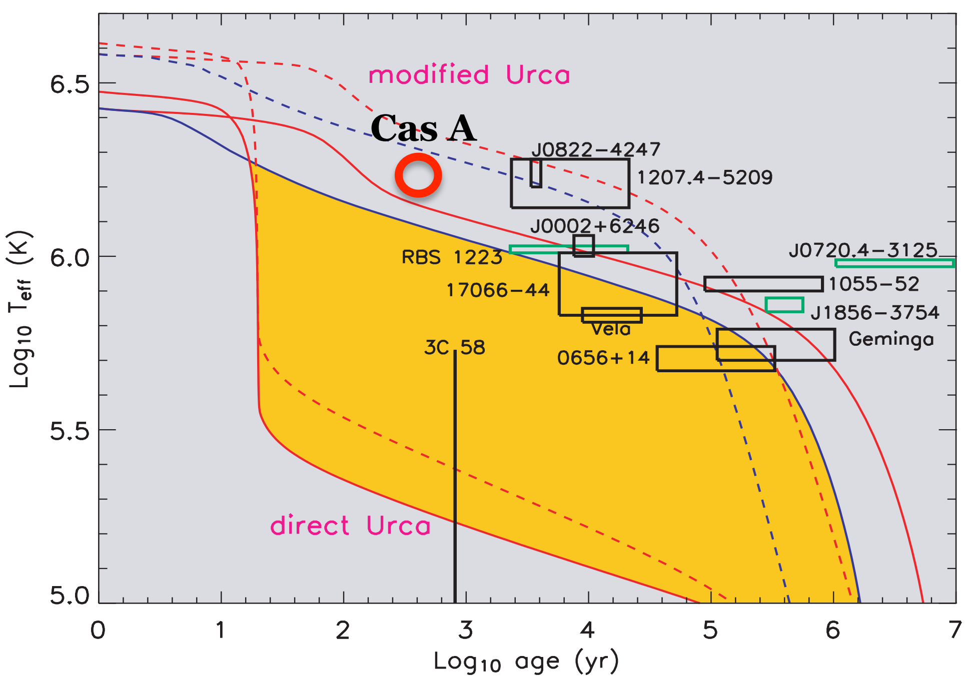
Note: The crust oscillations hardly emits gravitational waves!

Cassiopeia A

Observe 10 compact central objects; X-ray point sources in supernova remnants. Thermal spectra suggest these are young neutron stars with weak magnetic fields (no pulsations are seen).

The Cassiopeia A remnant is the youngest in the galaxy (300 yrs). Best fit of spectrum, consistent with radius 11-12 km, suggests a Carbon atmosphere.

Recent cooling data (temperature drops 4% in 10 yrs) constrains models.



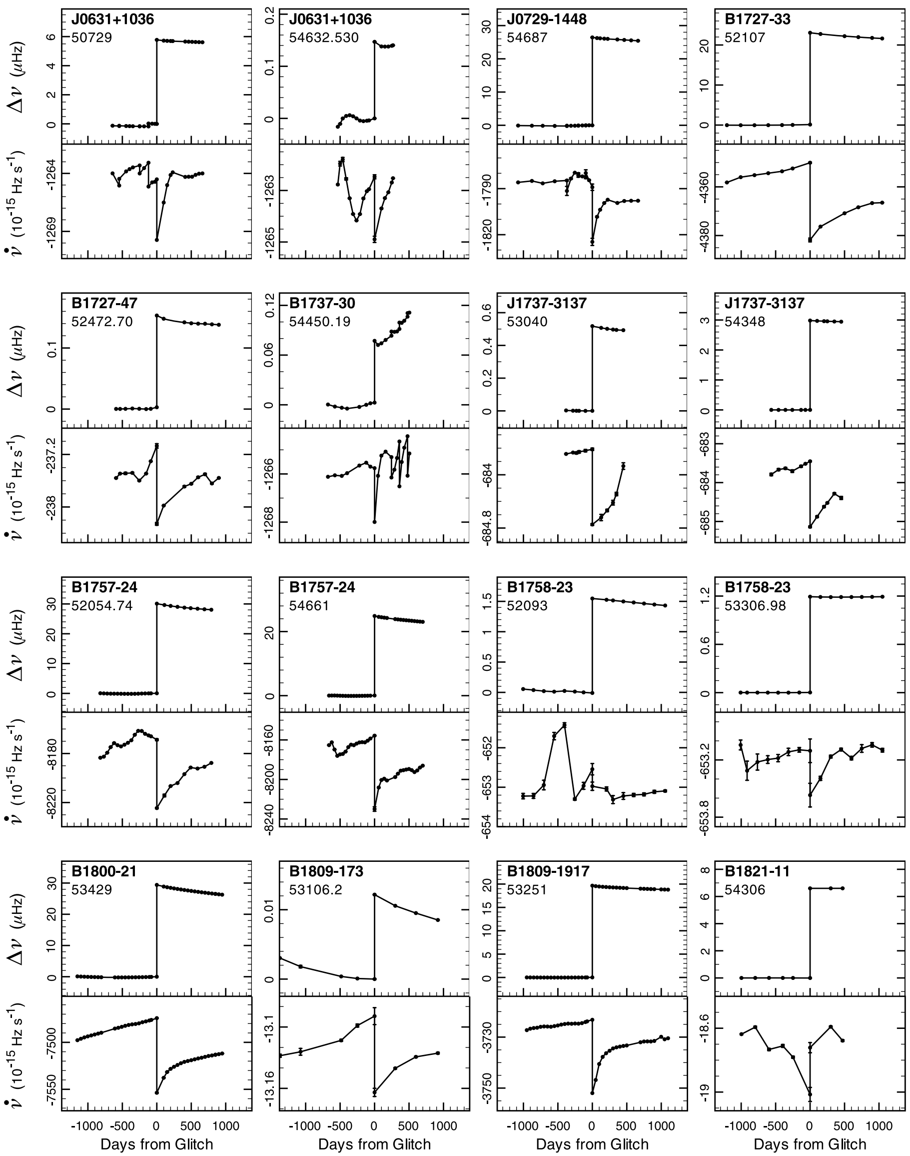
[adapted from Lattimer and Prakash]

Need core proton pairing to keep the star hot initially (T_c well above 10^9 K).

Onset of core neutron superfluidity leads to rapid cooling due to Cooper pair breaking/formation. Infer critical temperature of 5-9x10^8 K.

Best current evidence for neutron star superfluidity!

glitches



[courtesy Espinoza et al]

Many neutron stars are perfect “clocks”, but in some cases the spin is not quite so regular.

“Glitches” have been observed in more than 100 systems (with the first Vela glitch seen already in 1969).

Rich phenomenology!

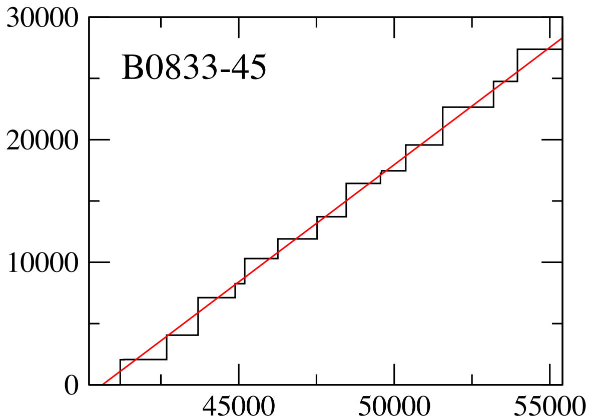
The underlying mechanism is not at all well understood.

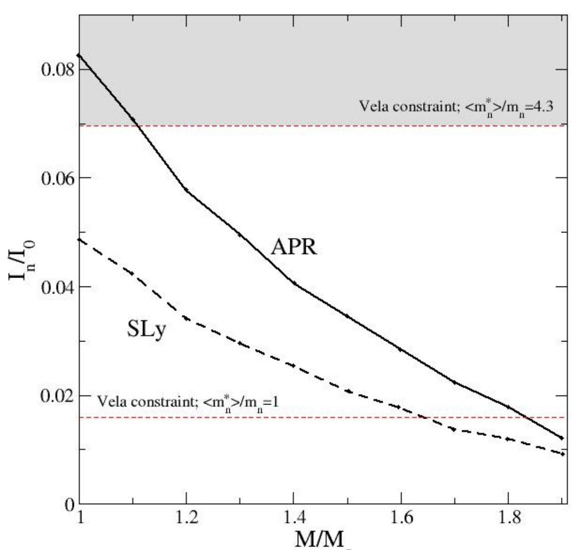
The standard model for large glitch events is based on transfer of angular momentum from a superfluid component to the star’s crust.

Smaller events due to crust “quakes”?

the crust is not enough

The standard view is that glitches are a manifestation of the (singlet) superfluid that permeates the star's crust. This is motivated by the fact that the interaction with the crust nuclei may provide the require vortex pinning.





For systems that glitch regularly, one can estimate the moment of inertia associated with the superfluid component.

Observations suggest that up to 2% of the total moment of inertia must be involved.

The **crust superfluid** model accords with the observations as long as we do not worry about the entrainment.

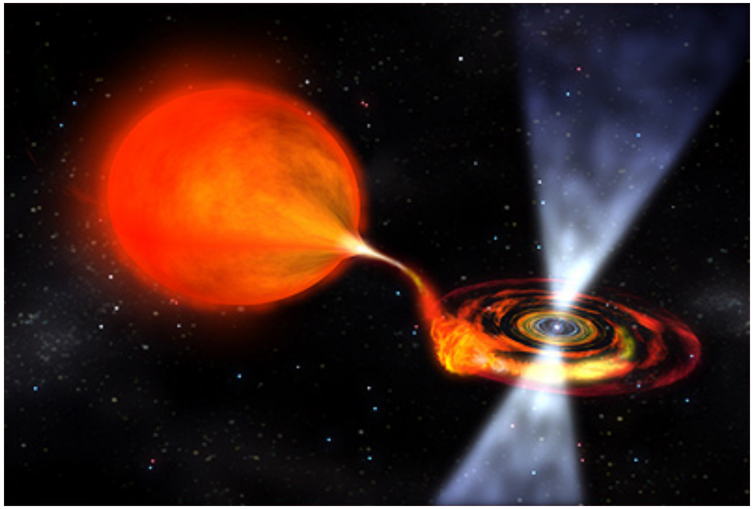
When the large effective neutron mass in the crust lattice is accounted for, we find that the **core superfluid** must also be involved.

Constrains the (singlet) pairing gap…

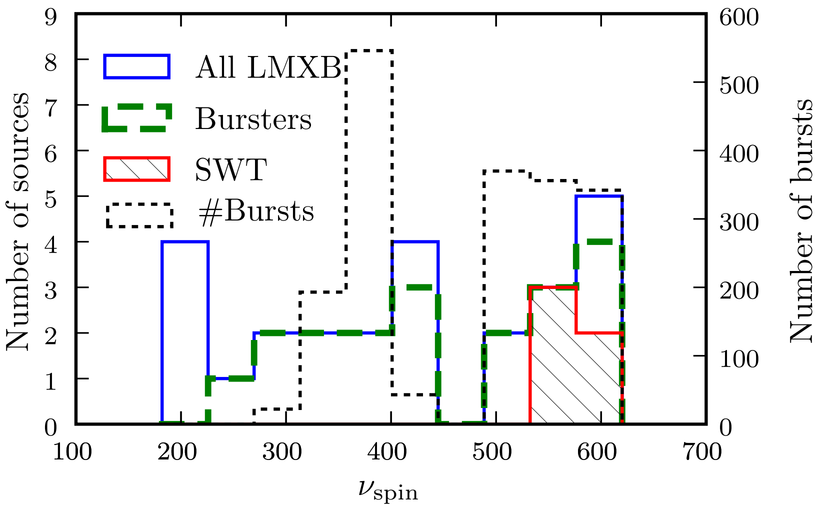
… and raises a number of issues.

X-ray bursts

Millisecond pulsars, like the record holder J1748-2446ad which spins at 716 Hz, are thought to form by accreting matter (and angular momentum) from a binary companion.



Only a few systems are seen as pulsars (in X-ray), like SAX J1808.4-3658 which has a spin period of 2.5 ms. In several other systems the spin is inferred from oscillations associated with X-ray bursts.



The fastest such system, 4U 1608, spins at 640Hz.

Is some kind of speed-limit is enforced?

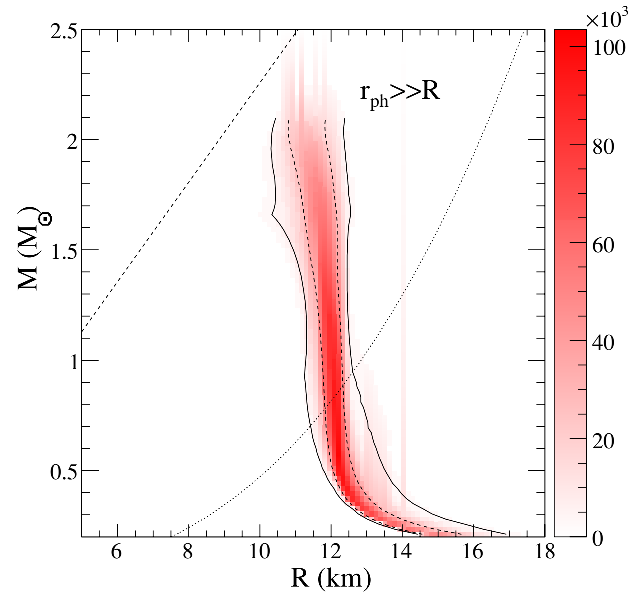
– non-standard accretion torque?

– additional spin-down agent? (mountains, r-modes, B-field deformation)

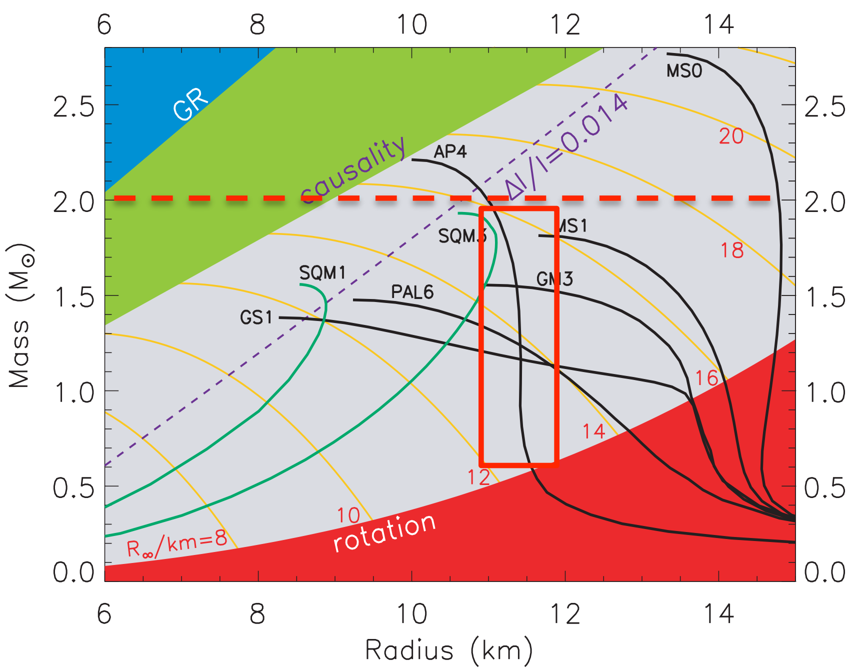
radius constraints

The observed X-ray bursts do not only tell us what the spin-rate is, they can also help us infer the star's radius.

Construct "empirical" equation of state (from a Bayesian analysis to be consistent with the data) based on a combination of systems exhibiting Type-I X-ray bursts with photospheric radius expansion and transient low-mass X-ray binaries.



[courtesy Steiner et al]



The radius of a canonical neutron star should be in the range 11-12 km.

The maximum mass is relatively large, 1.9-2.2 M_o

The data is clearly beginning to constrain the nuclear physics!

... but there are caveats.

r-mode instability

The rotation of accreting neutron stars may be limited by gravitational emission from unstable r-modes.

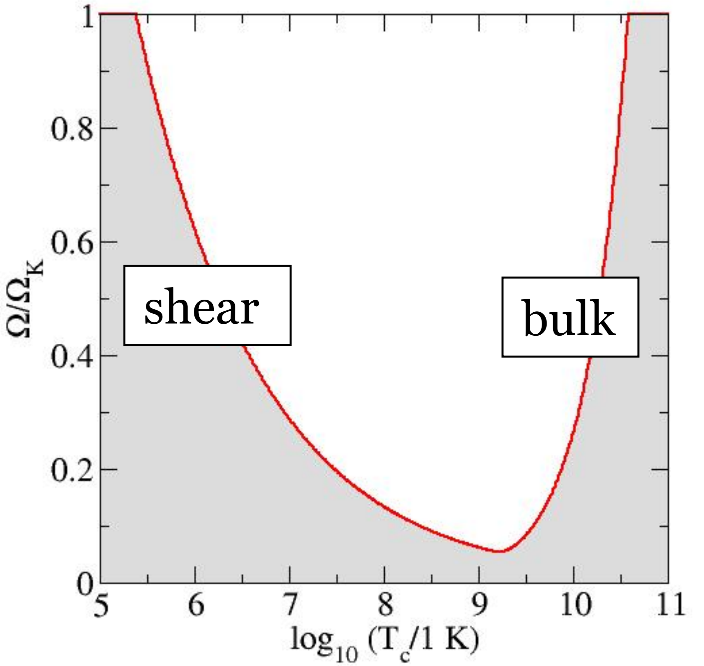
"Instability window" depends on uncertain core physics. Simplest models account for damping due to shear- and bulk viscosity.

Interesting problem since "exotica" could play a crucial role.

Young radio pulsars: Original r-mode window consistent with the inferred birth spin of the Crab PSR (19 ms), but not with the 16 ms X-ray PSR J0537-6910.

Recycled pulsars: Need to allow the formation of a cold 716 Hz PSR (presumably after recycling). This constrains the instability window at low temperatures.

LMXBs: Fastest systems (around 640 Hz) require smaller instability region.



r-mode puzzle

Revisit r-mode scenario for accreting systems in light of recent evidence for neutron superfluidity in Cassiopeia A remnant (affects cooling evolution).

Demonstrates that our understanding of the r-modes is incomplete. Given the "best estimate" for the main damping mechanisms, many observed LMXBs should be unstable.

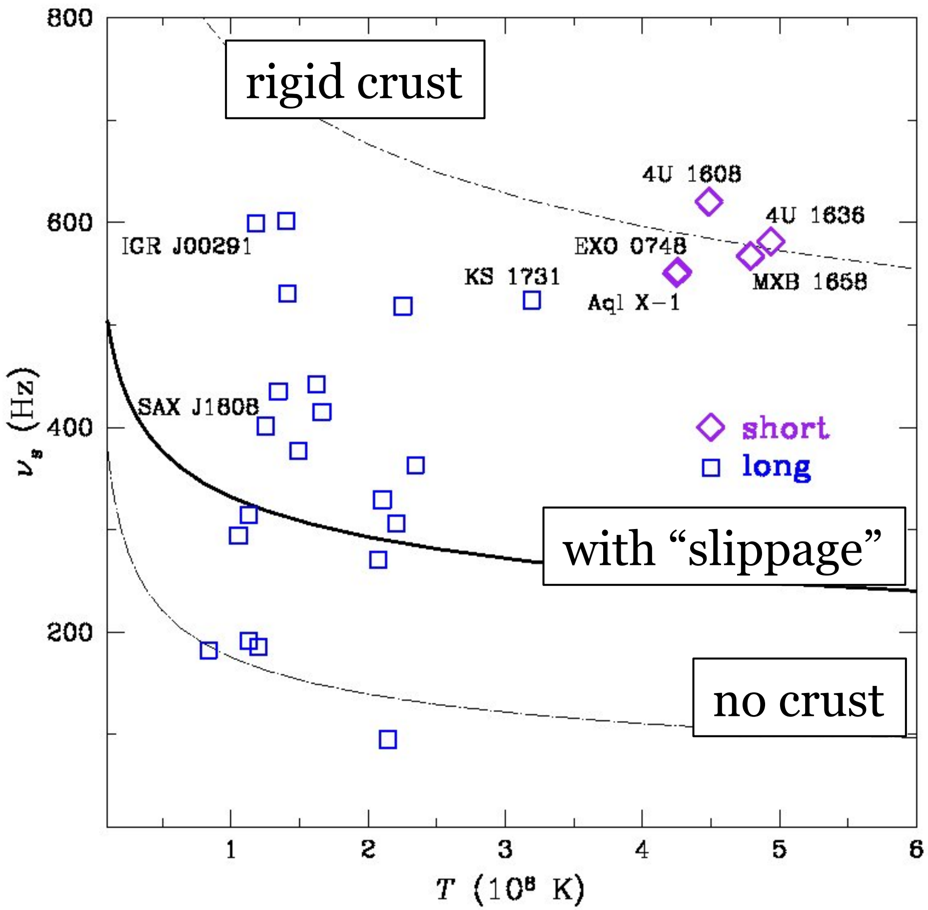
Rigid crust with viscous (Ekman) boundary layer would lead to sufficient damping...

...but the crust is more like jelly, so the effect is reduced ("slippage").

Magnetic field is too weak to alter the nature of the boundary layer.

Superfluid "mutual friction" (due to electrons scattered off vortices) has no effect.

Saturation amplitude due to mode-coupling is too large to allow evolution far into instability region.



“outstanding” questions

What is the state of matter at extreme densities?

Current maximum mass constraint seems to rule out hyperon/quark cores, in “conflict” with expectations. How do we resolve this?

Why do pulsars pulse?

Somewhat remarkably, the pulsar emission mechanism is not well understood despite more than four decades of observations.

What distinguishes the different classes of neutron stars?

Expect the answer to be “the magnetic field”, which then leads on to questions of how the magnetic field forms, and what the interior configuration is.

How do glitches work?

Can we make the superfluid unpinning explanation quantitative, and if so does this model explain all aspects of the observed phenomenology?

What enforces the neutron star speed limit?

Is there a mechanism that prevents neutron stars from reaching the break-up limit? Observations suggest so, but what is it?