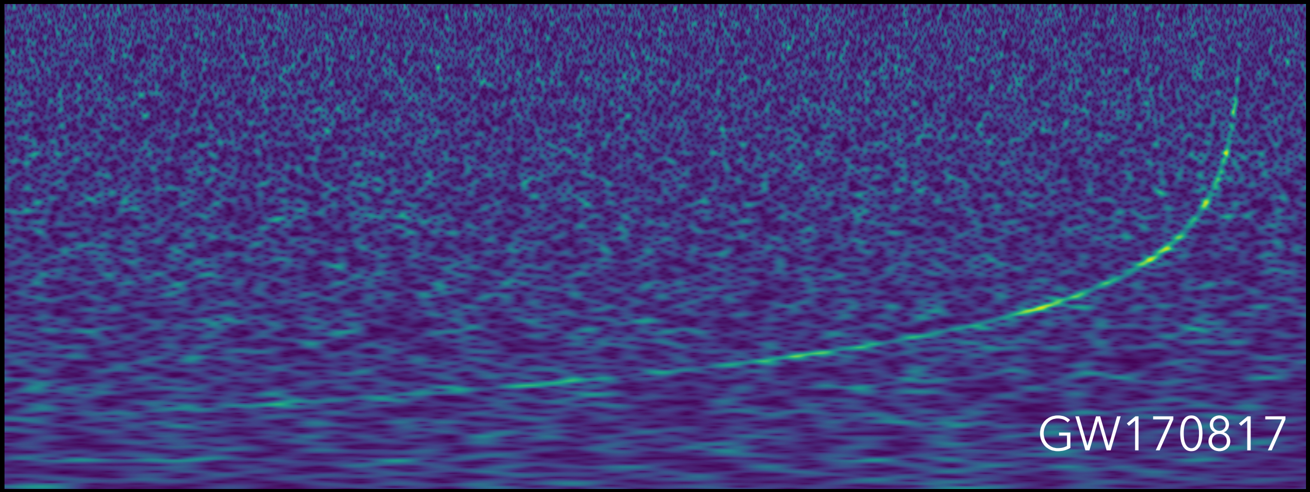
Exploring matter at the extremes

confronting theory with observations

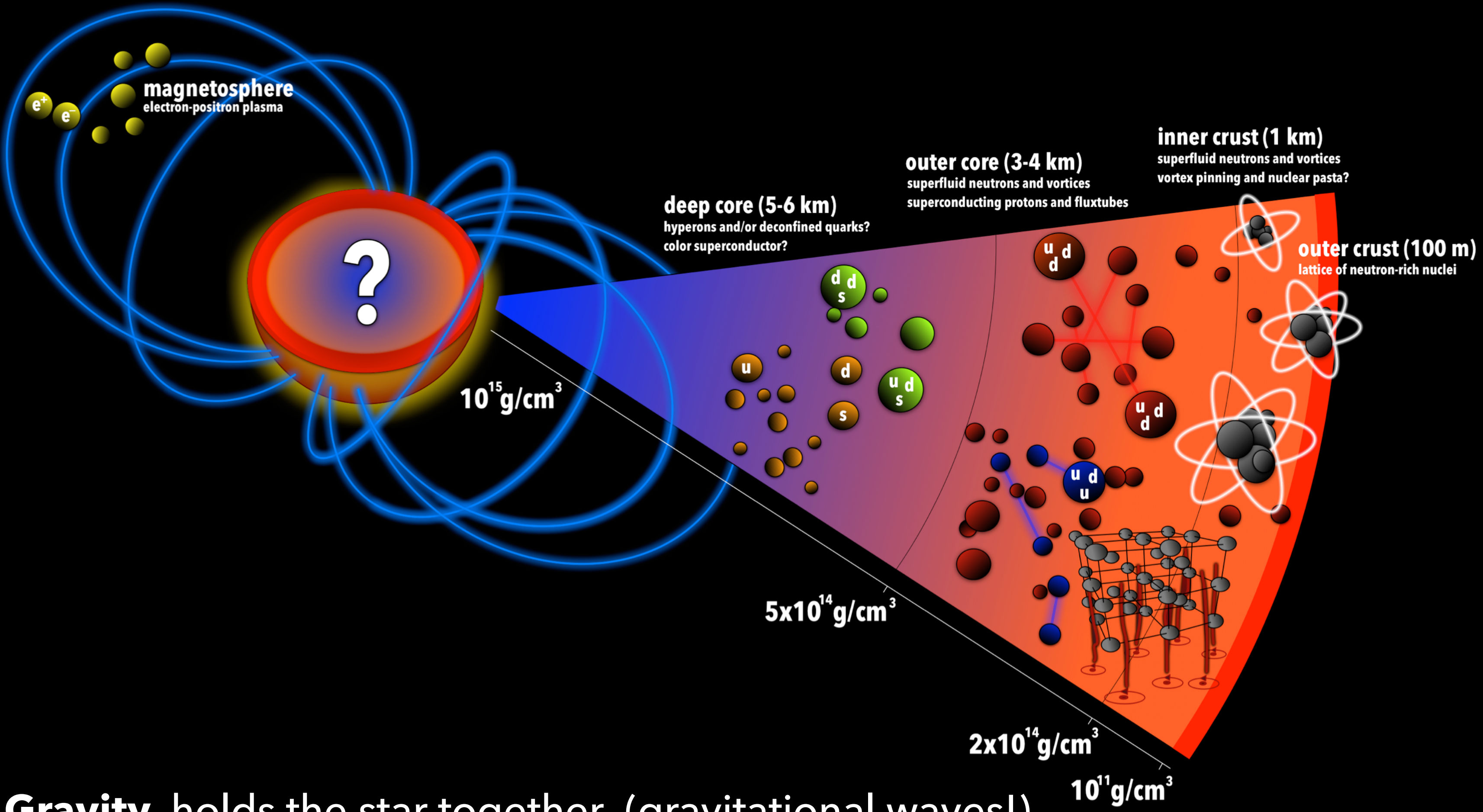


Nils Andersson

STAG RESEARCH CENTRE

UNIVERSITY OF Southampton

Neutron stars are "hands-off" laboratories for extreme physics.



Gravity, holds the star together (gravitational waves!)

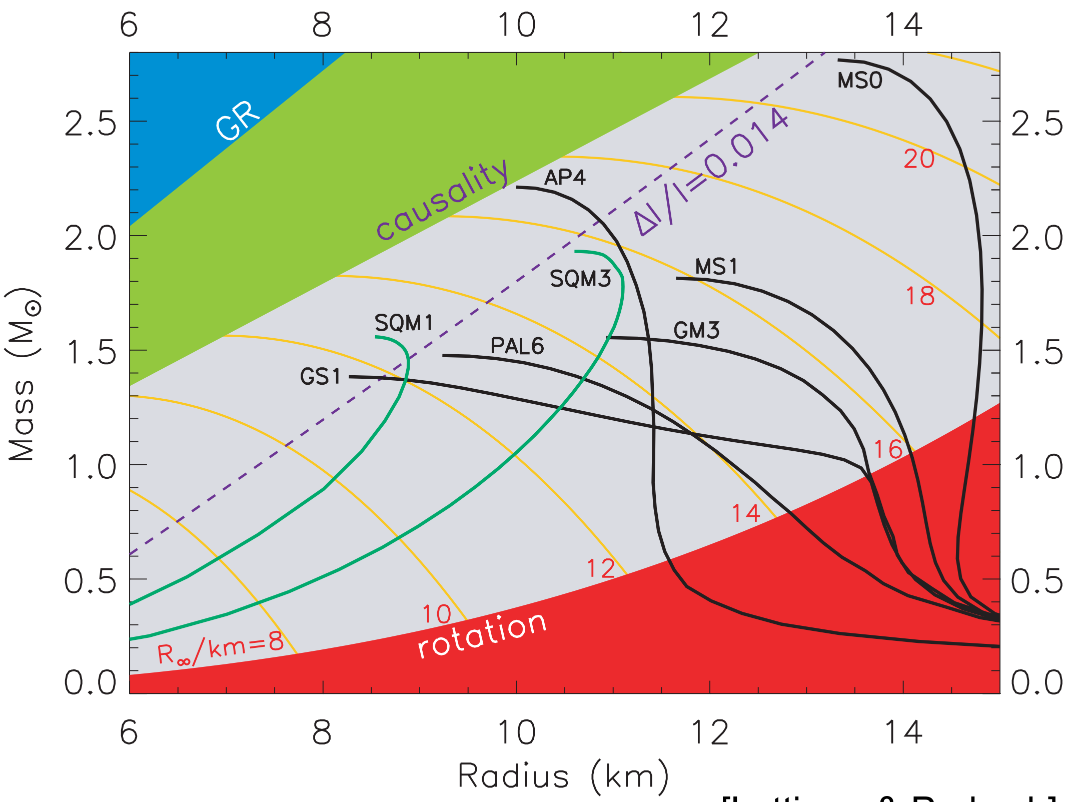
Electromagnetism, makes pulsars pulse and magnetars flare

Strong interaction, determines the internal composition

Weak interaction, affects reaction rates - cooling and internal viscosity

The macroscopic diagnostic of microscopic many-body interactions is a pressure-density-temperature relation: **the equation of state**.

First principle calculations for many-body QCD systems are problematic at high densities (sign problem).

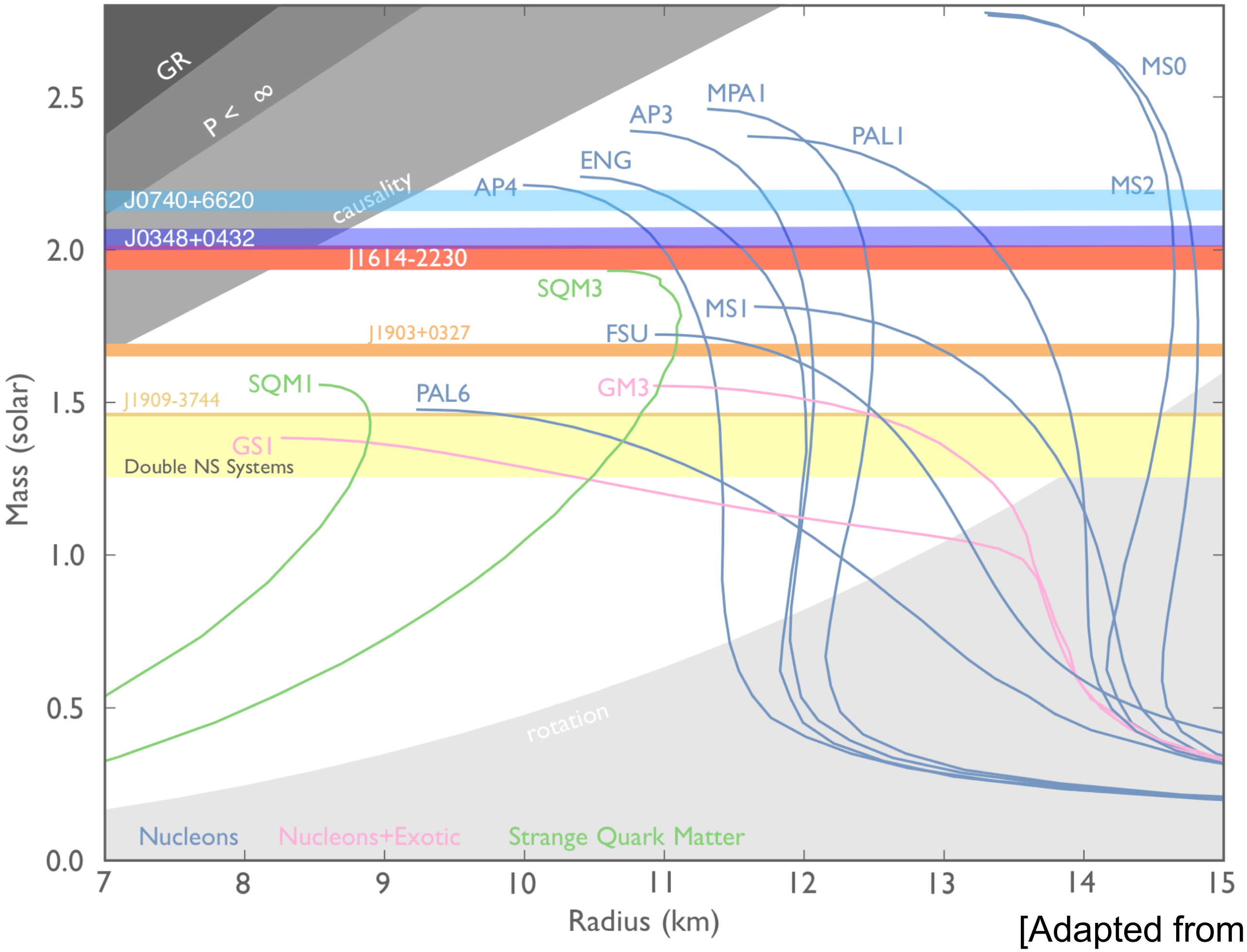


[Lattimer & Prakash]

Basically, three approaches:

- non-relativistic quantum calculations (e.g. APR)
- "phenomenology" (e.g. Skyrme interaction matched to measured nuclear masses)
- relativistic mean-field theory (typically used for hyperons/quarks)

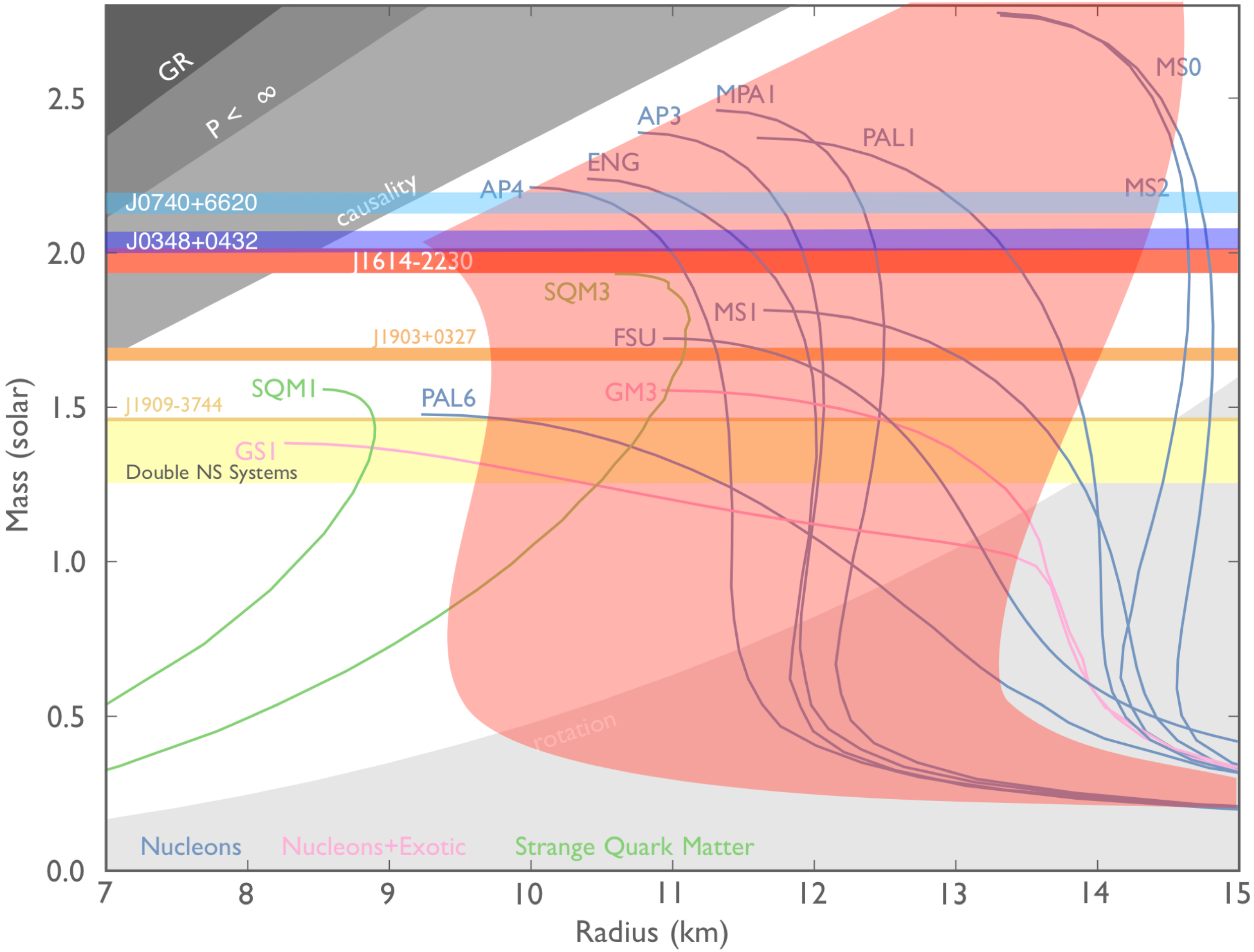
Need experiments and observations to test theory and drive progress.



[Adapted from Antoniadis et al]

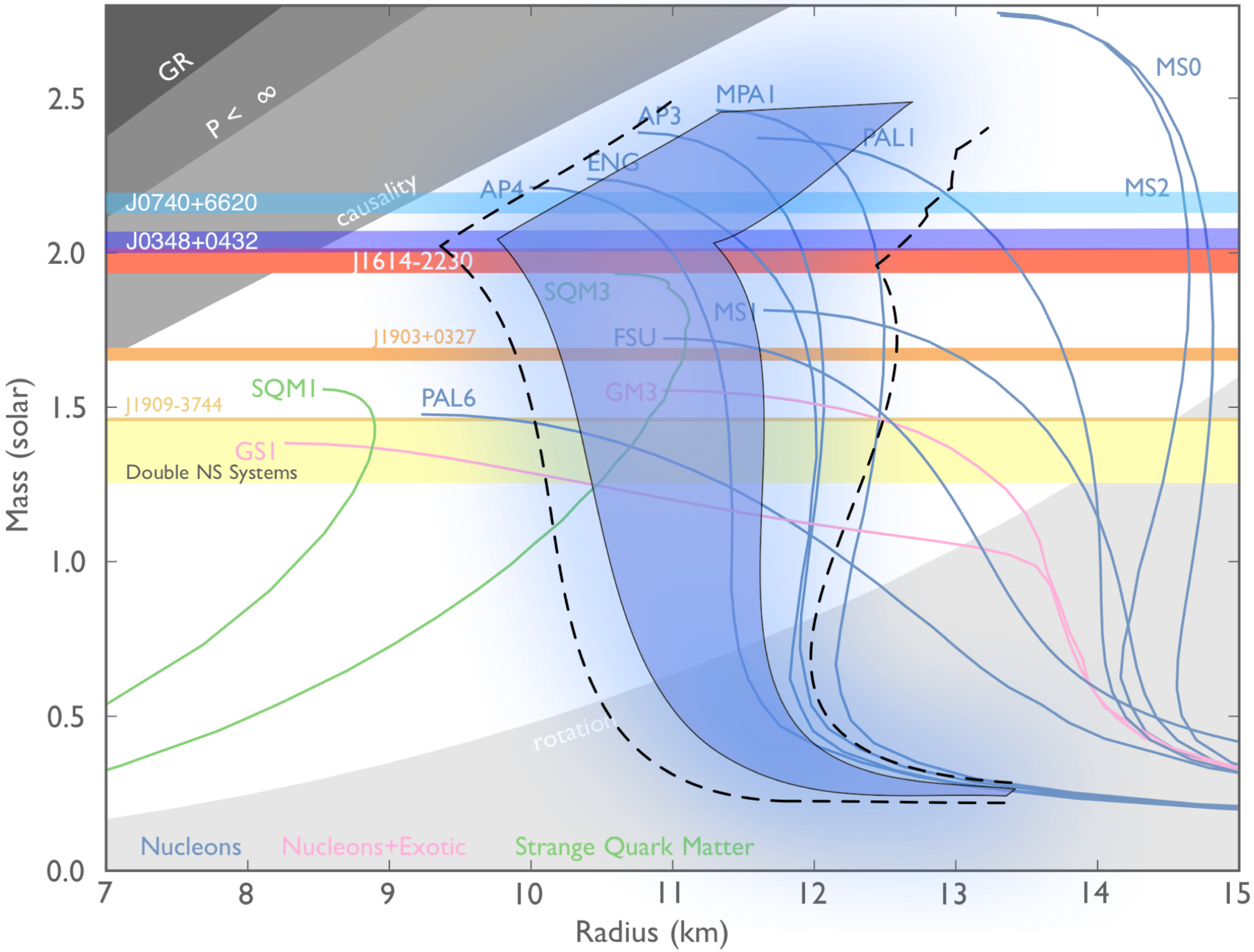
Masses deduced from binary dynamics tend to lie in a relatively narrow range, about 1.1-1.6$M_\odot$. These systems do not constrain nuclear physics (much).

The current record holder is J0348-0432 with (a WD companion and) a mass just over 2$M_\odot$. (Note also the recent evidence for J0740+6620 being 2.17$M_\odot$.)



State-of-the-art chiral effective field theory calculations (Schwenk, Tews and others) provide “reliable” low-density constraints, which can be extrapolated to higher densities (=more massive stars).

Suggests a $1.4M_\odot$ neutron star should have radius in the range 10-14 km.



The radius is "difficult" to infer from radio data (although… the moment of inertia for the Double Pulsar), but may use accreting systems emitting in x-rays.

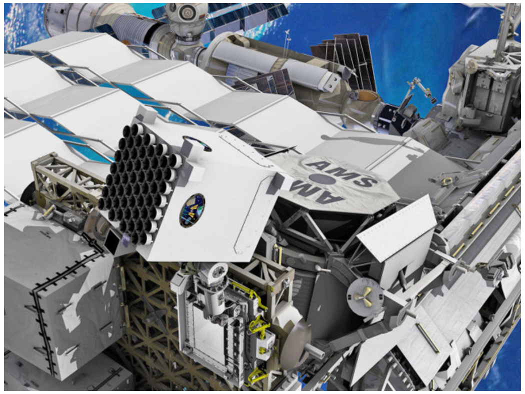
Strategy: Construct "empirical" equation of state (from a Bayesian analysis) based on combining data for a set of systems (work by Steiner et al).

Again, constrains the radius to (conservatively) the range 10-14 km.

NICER has been taking data since 13 June 2017.

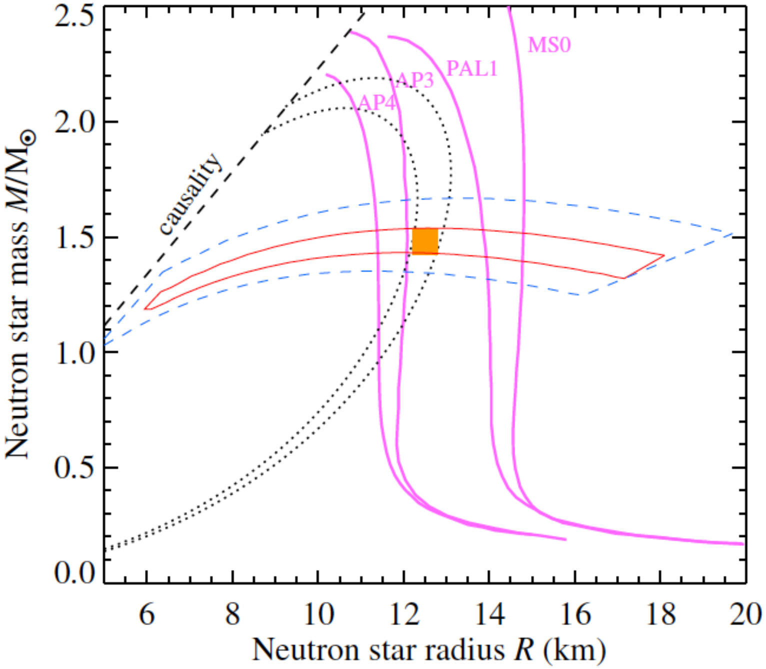
The main aim is to measure pulse profiles associated with non-uniform thermal surface emission of rotation-powered pulsars.

Comparison to theory models leads to estimates of the star's mass and radius.



Preliminary results for PSR J0030+0451 favours two emitting polar caps (=tricky systematics) and a radius in the range 12-15 km.

Expect stronger constraints "soon" (e.g. systems with known mass).



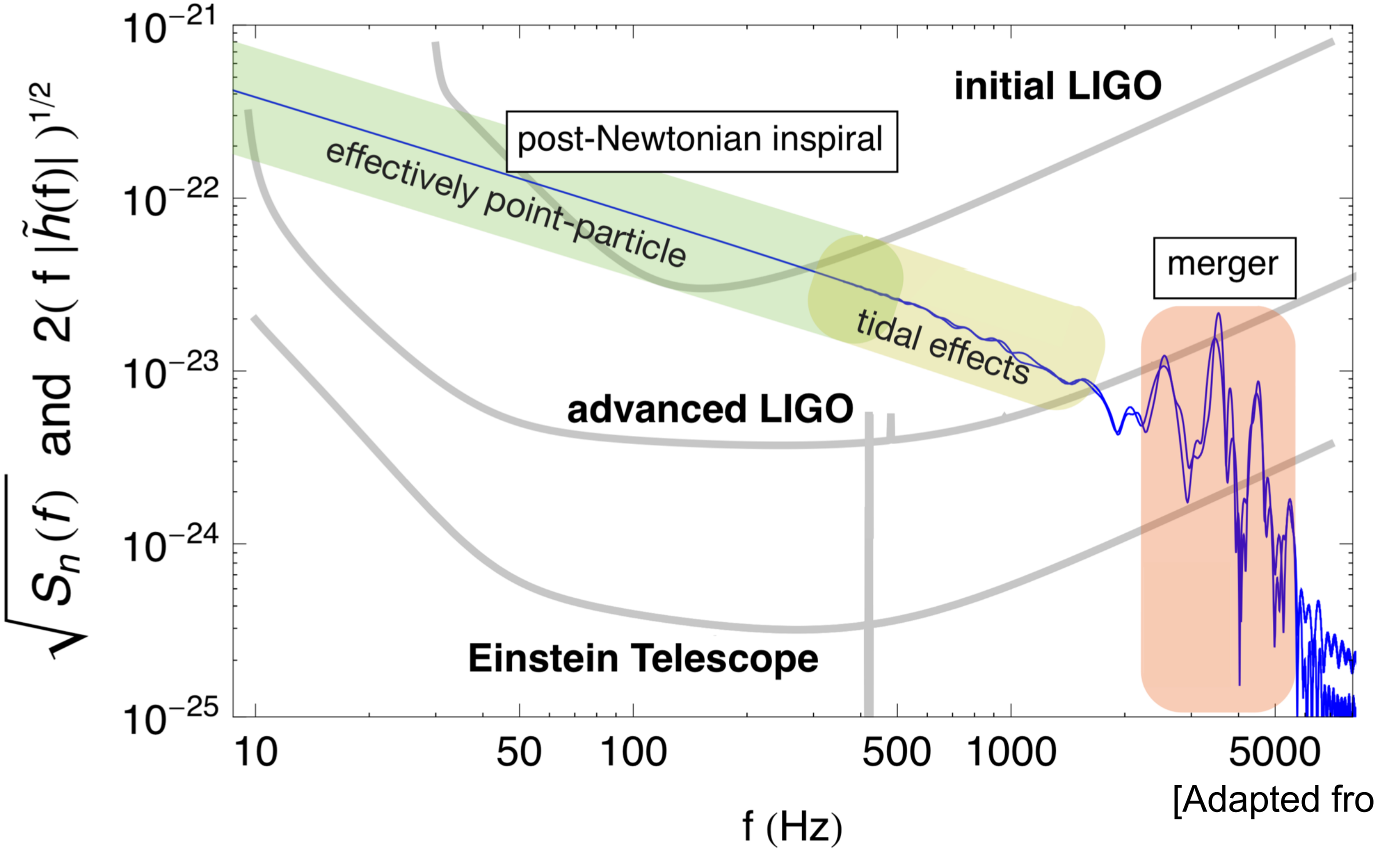
Longer term, we need a high-resolution x-ray timing mission (with a large collection area).

The Chinese-European eXTP and the US led STROBE-X missions are designed to explore the state of matter under extreme conditions.

Significant upgrades from previous instruments (e.g. RXTE) and should (finally!) provide mass-radius constraints at the few % level.

That’s as far as we can see with our eyes…

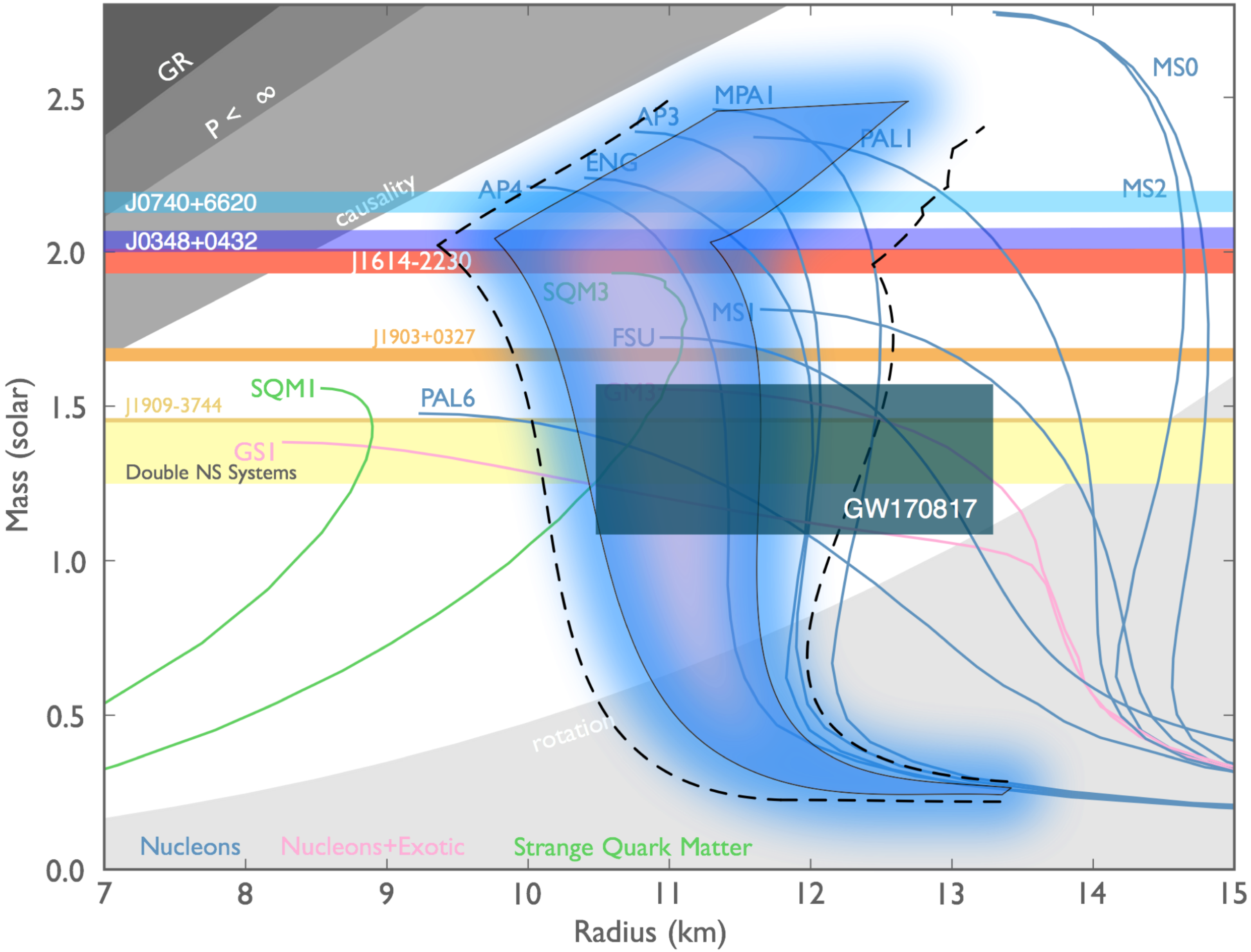
Gravitational-wave astronomy provides new opportunities.



[Adapted from Read]

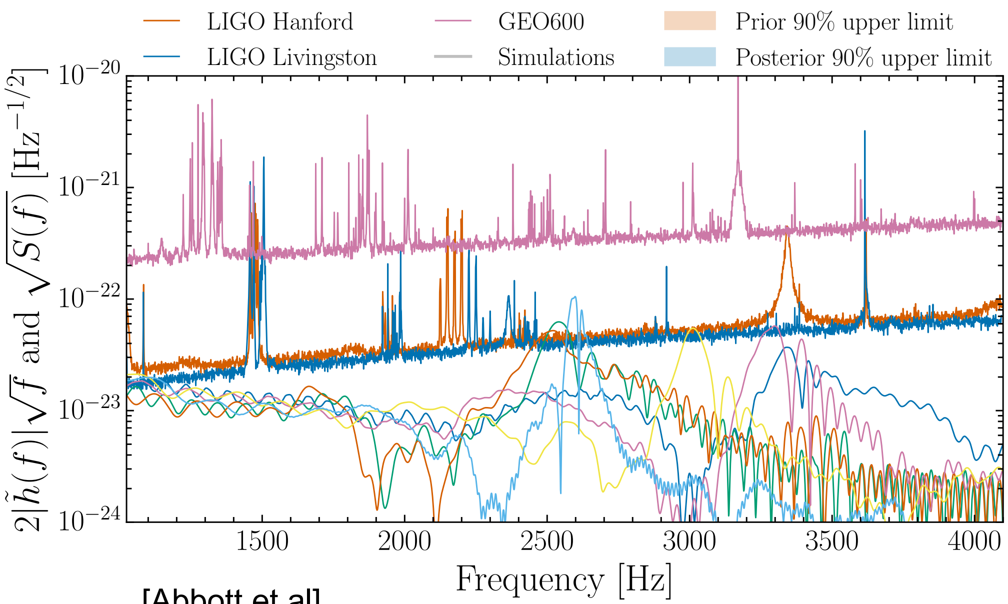
Deviations from point-mass dynamics become important during the late stages of binary inspiral – we should be able to probe matter properties.

The effect is encoded in the tidal deformability (via the Love numbers).



Demonstrated by the spectacular GW170817 signal!

Best constraints on the tidal deformability (assuming the same equation of state, slow spins and maximum mass indicated by pulsar data) suggests a radius in the range R=10.5-13.3 km (similar to the x-ray results…).



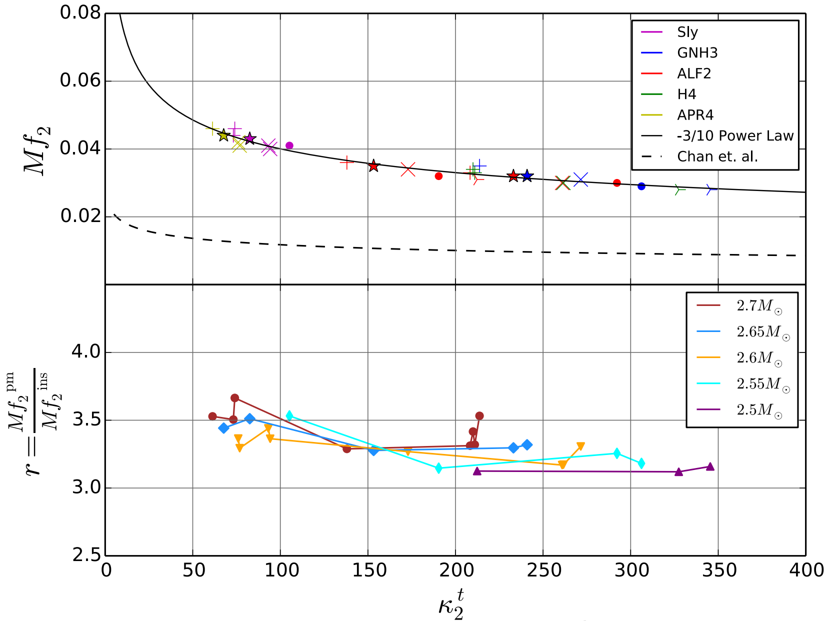
[Abbott et al]

The final merger was not seen in GW170817 – need better sensitivity at high frequencies!

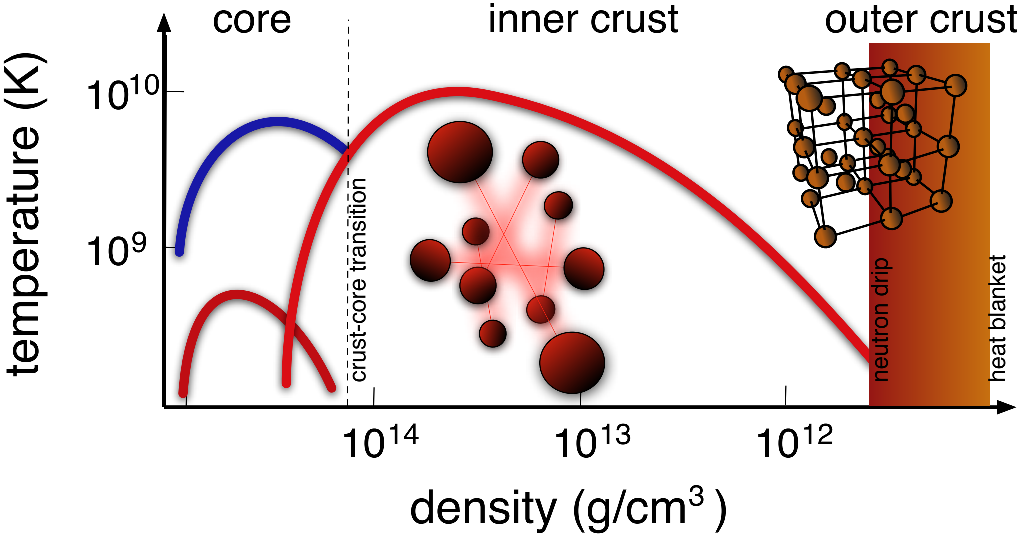
(Part of the case for 3G detectors…)

Eventually… we should be able to detect the oscillations of the merger remnant – enable hot neutron star seismology.

Note: Simulations suggest a correlation between the tidal deformability and the main peak in the spectrum of the oscillating remnant (the f-mode?).



[Chakravarti+NA]



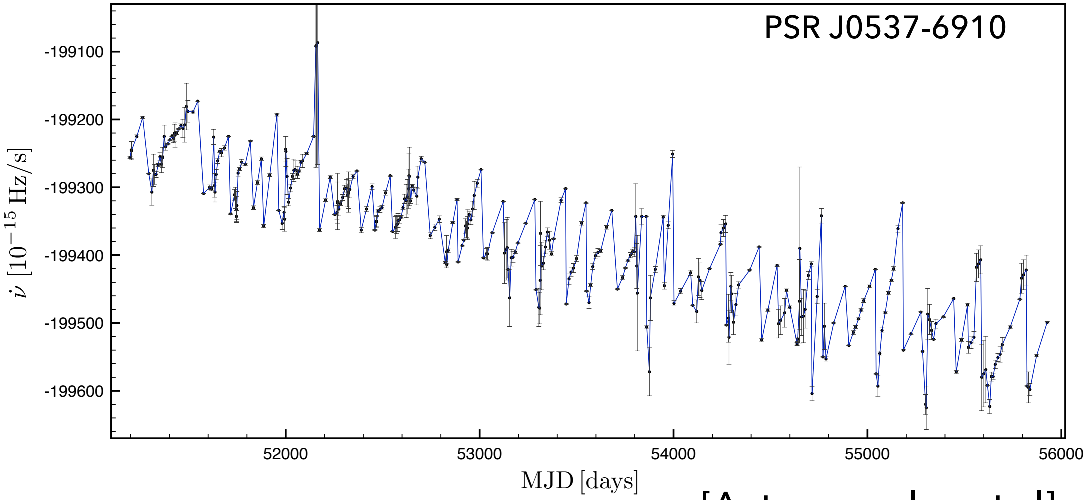
What about other aspects, like the temperature?

A neutron star cools rapidly (mainly due to the Urca reactions) after birth.

Mature systems are "cold" (10^8K<< T_{Fermi}=10^{12}K) so they **should be** either solid or superfluid.

Nuclear physics calculations indicate "BCS-like" pairing gaps for neutrons and protons.

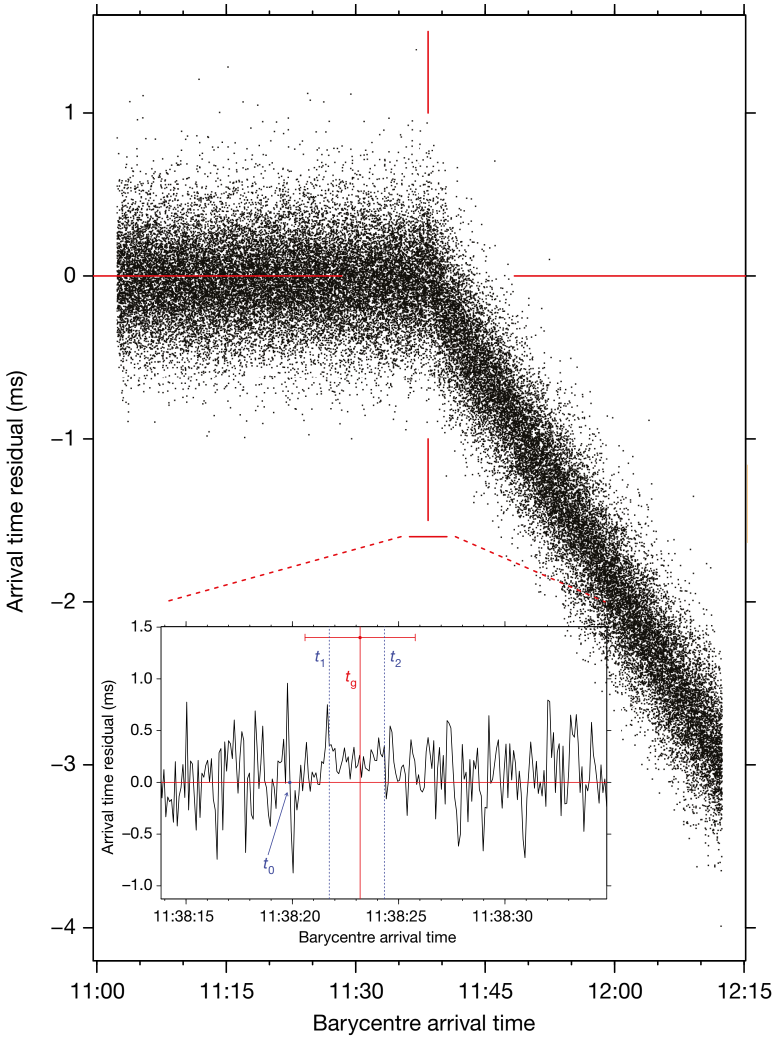
Observational "evidence" from cooling (e.g. the Cas A remnant and thermal relaxation in transients) and timing variability (glitches).



[Antonopoulou et al]

Allow us (at least in principle) to probe physics beyond mass and radius.

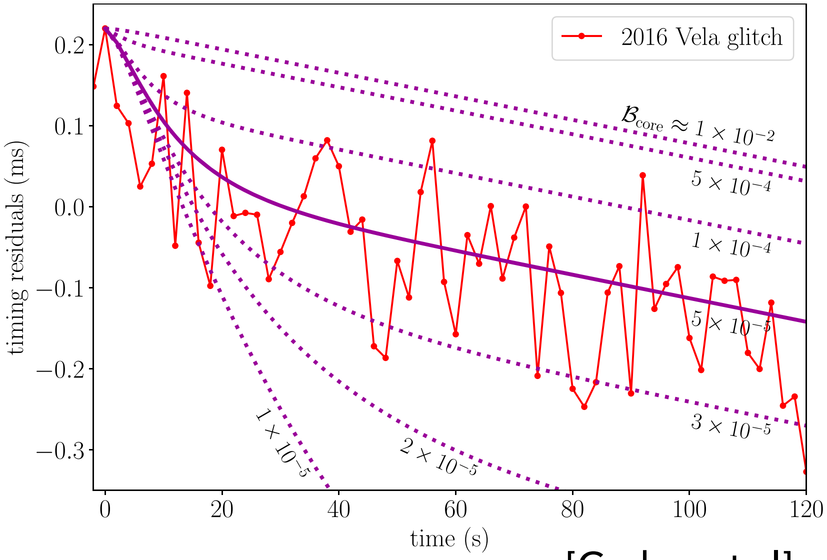
For example, the vortex-mediated mutual friction is key to modelling glitch dynamics as it dictates the timescales involved.



[Palfreyman et al]

Example: The "resolved" Vela glitch from 2016.

The fast glitch rise (< 40s) and subsequent relaxation, provide an opportunity to contrast different models for the mutual friction.



[Graber et al]

take home message

Keep in mind…

After 50 years we still don’t (exactly) know why pulsars pulse and we don’t (quite) understand why magnetars flare.

But… observations are (at least) beginning to constrain the theory.

In order to make progress – and match the precision of the next generation of instruments – we need better models (e.g. state and composition of matter).

Need to involve as much of the physics as we can manage.

Effects may not be “leading order” (as in the case of pulsar glitches) but could still introduce systematics that need to be accounted for (e.g. the tidal deformability).

We also have to (at least, in my opinion…) improve our understanding of evolutionary scenarios.