Gravitational waves from deformed neutron stars

IOP Gravitational Physics Thesis Prize 2021 talk
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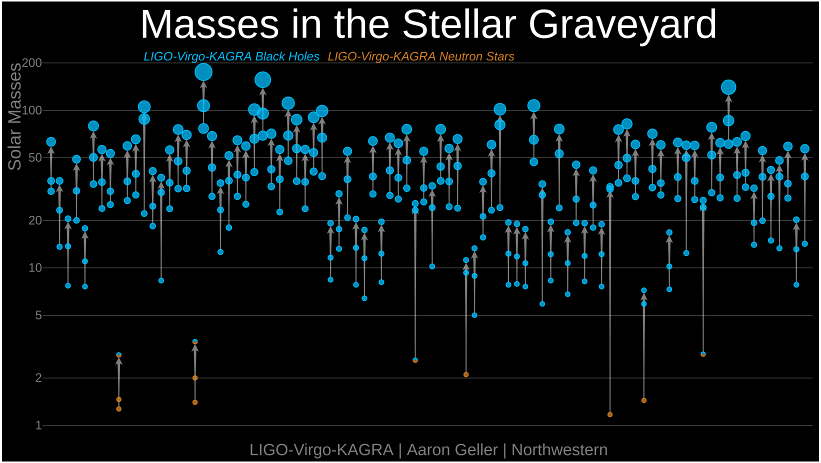
The story so far

- Since 2015, gravitational-wave detectors have witnessed 90 compact-binary coalescences – 2 neutron-star binaries and 3 neutron star-black hole binaries.



Neutron stars as gravitational-wave sources

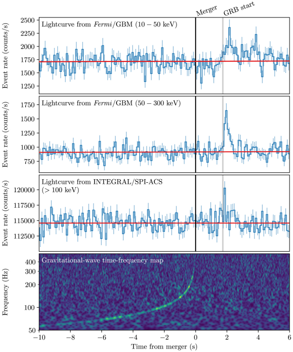
Configurations that radiate gravitational waves

(i) neutron stars in compact binaries experiencing tidal effects

(ii) neutron stars that host deformations known as *mountains*

(iii) modes of oscillation (and associated instabilities)

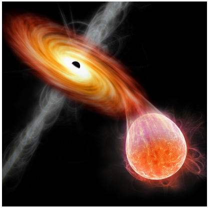
- The first gravitational-wave detection of a neutron star came from the remarkable *multimessenger event* GW170817.
- Gravitational radiation presents an opportunity to constrain the elusive nuclear-matter *equation of state*.
- Although there have been no confirmed detections of rotating neutron stars, searches in the data have provided upper limits on the size of the deformations.

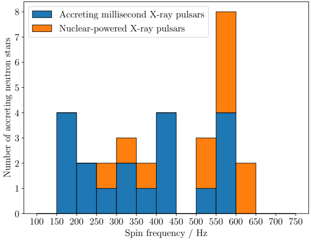


(Abbott *et al.*, 2017)

Low-mass X-ray binaries

- *Low-mass X-ray binaries* have long been considered potential incubators for gravitational-wave emitters (Wagoner, 1984).

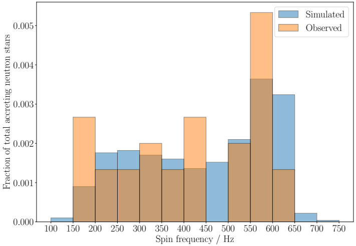




- In fact, no neutron star has been observed that spins (even remotely) close to the centrifugal break-up limit ($\sim 1\,\mathrm{kHz}$ for most equations of state).
- This implies that there is a mechanism that extracts angular momentum from the star; gravitational radiation is a natural candidate.

Spinning up accreting neutron stars

- We conducted a population-synthesis study evolving the spin rates of accreting neutron stars, accounting for the coupling of the accreted matter to the magnetic field and modelling both persistent and transient accretion (Gittins and Andersson, 2019).
- When there was no gravitational-wave emission, our results did not recreate the observed spin distribution.
- However, when the systems emitted gravitational waves – through either permanent crustal mountains, thermal mountains or unstable r-modes – we obtained similar distributions to the observations.



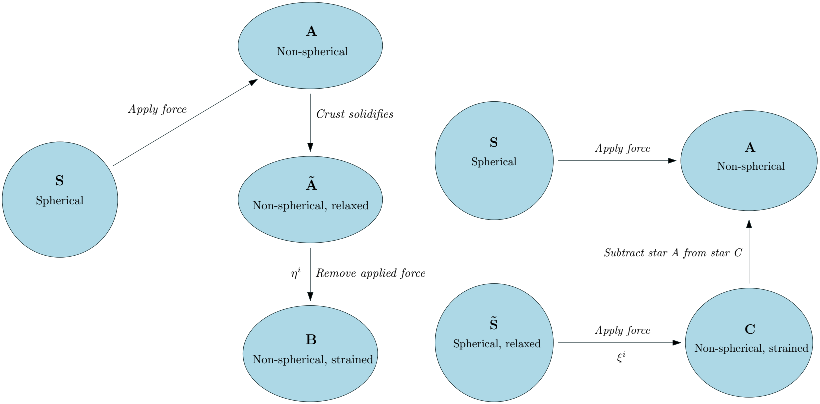
Future directions*

Connect accreting population with rapidly rotating pulsars, incorporating gravitational-wave emission.

The question of the maximum mountain

- There have been theoretical attempts to estimate the *maximum* mountain that a neutron-star crust can support (Ushomirsky, Cutler, and Bildsten, 2000; Haskell, Jones, and Andersson, 2006; Johnson-McDaniel and Owen, 2013). Such an estimate provides a natural limit on the magnitude of the gravitational radiation from a rotating star.
- Previous calculations have generally followed the approach laid out by Ushomirsky *et al.* (2000): ensure the crust is maximally strained at *every point*. But, such a technique does not respect the boundary conditions on the star.

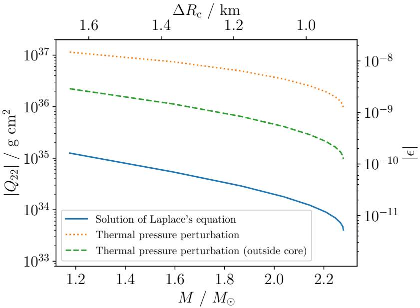
Building a mountain



- We returned to this problem in order to resolve these issues (Gittins, Andersson, and Jones, 2021; Gittins and Andersson, 2021). We developed a new scheme for calculating mountains that requires a description of the deforming force.

Examples of the deforming force

- We generated a set of fully relativistic neutron-star models (with a realistic equation of state) that were subjected to a few specific deforming forces.
- The amplitude of the force on each star was increased until the crust began to fracture. This produced the maximum mountain that each star could support for a given force.
- This illustrates the dependence of the mountain on the formation history of the star.



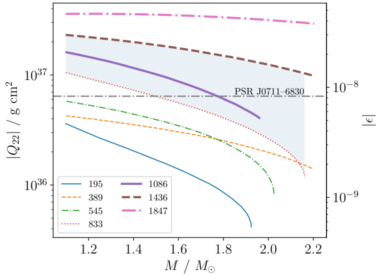
Cf., for a $1.4\,M_\odot$, 10 km Newtonian star, Ushomirsky *et al.* (2000) found

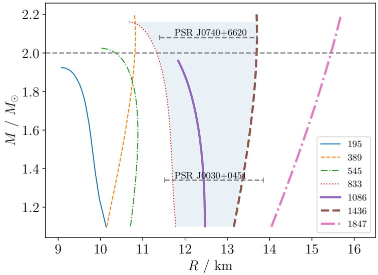
$$Q_{22}^{\max} \approx 1.2 \times 10^{39}\ \mathrm{g\,cm^2},$$

$$\epsilon^{\max} \approx 1.6 \times 10^{-6}.$$

The equation of state

- We also considered the role of the equation of state in supporting the mountains, by implementing a subset of equations of state obtained from chiral effective field theory with a speed-of-sound parametrisation (Tews *et al.*, 2018).

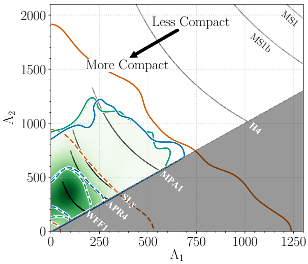




Future directions*

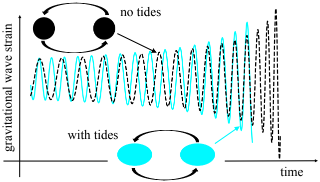
Conduct evolutionary calculations and study the effect of *plasticity*.

Tidal deformations



(Abbott *et al.*, 2018)

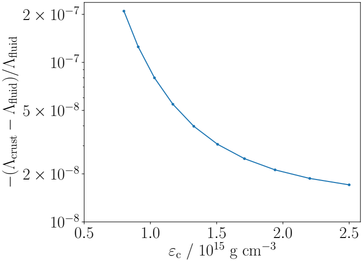
- The signal from binaries with neutron stars are distinguished from that of binary black holes due to *finite-size effects*.
- The susceptibility of the stellar material is characterised by the *tidal deformability*, which depends on the interior composition (Hinderer, 2008).



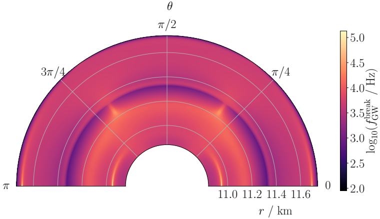
(Carson, 2020)

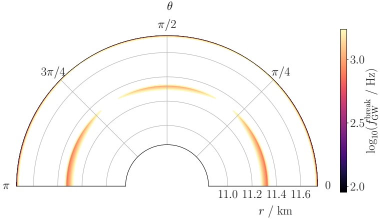
Impact of the crust

- We studied the impact of the crust in *static* tidal deformations of neutron stars (Gittins, Andersson, and Pereira, 2020).
- For realistic stellar models, we found the influence of the crust to be beyond the expected sensitivity of third-generation gravitational-wave instruments.



Crustal fracture during inspiral





- We assumed an equal-mass binary with component masses $M = M_{\mathrm{comp}} = 1.4\,M_\odot$ and calculated the crustal strain during the inspiral.
- The majority of the crust remained intact up until merger, $f_{\mathrm{GW}}^{\mathrm{merger}} \approx 1700\,\mathrm{Hz}$.

Future directions*

Consider whether magnetic fields are relevant in tidal interactions.

Summary

- There are good reasons to expect gravitational radiation to play an important role in the dynamics of neutron stars; the spin distribution of accreting neutron stars can be explained by gravitational-wave torques.
- The question of how large a deformation the crust can sustain will depend on the (possibly quite complex) formation history of the star. For this reason, evolutionary calculations will be necessary to make progress on this problem (see, *e.g.*, Bildsten, 1998; Singh *et al.*, 2020; Osborne and Jones, 2020).
- Compact binaries with neutron stars are proven gravitational-wave sources. The crust is (perhaps surprisingly) robust during inspiral. However, it leaves an imperceptibly small trace on the waveform.
- Plenty of interesting science questions remain!

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