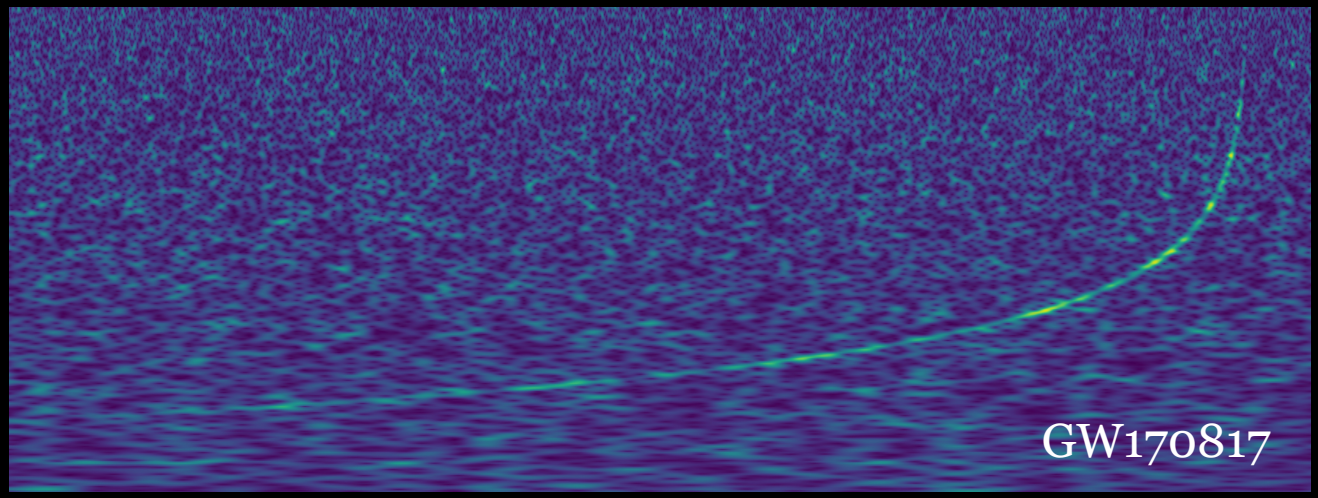
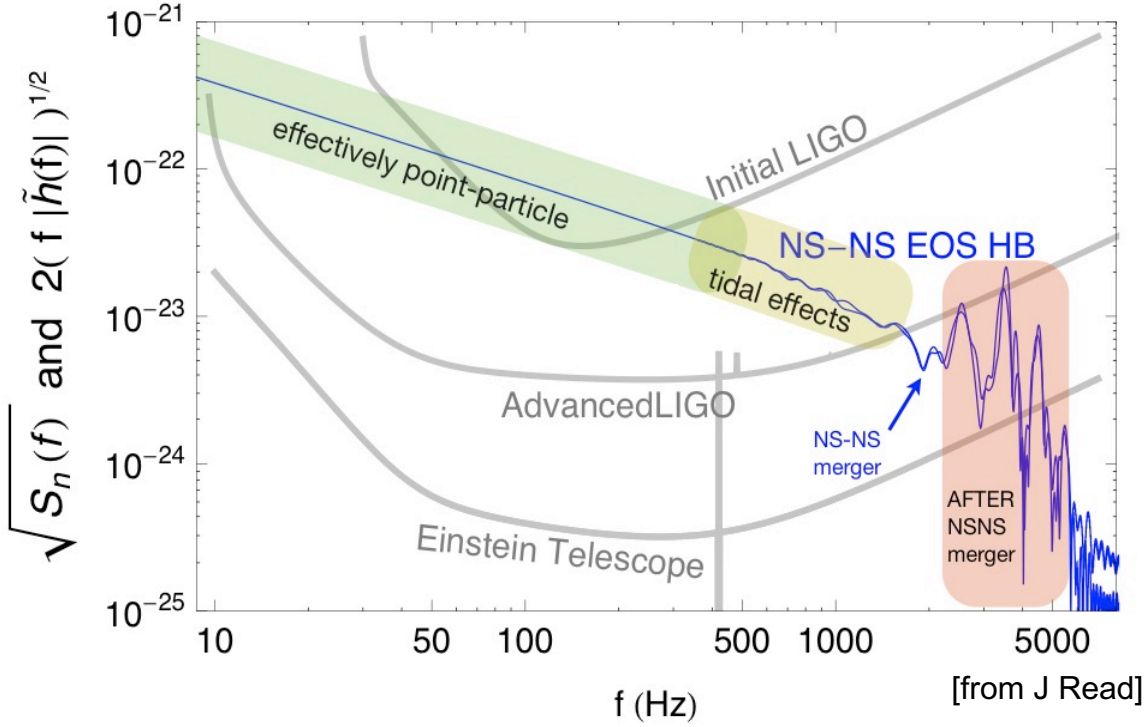
Using gravitational-wave data for neutron star binaries to constrain supranuclear physics



Nils Andersson

STAG RESEARCH CENTRE

UNIVERSITY OF Southampton



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

The tidal interaction affects the number of gravitational-wave cycles

$$\mathcal{N} = \frac{2}{3}\int_{f_a}^{f_b} \frac{E_{\rm orb}}{\dot{E}_{\rm orb}} df \approx \int_{f_a}^{f_b} t_D \left(1 + \frac{E_{\rm r}}{E_{\rm N}} - \frac{\dot{E}_{\rm tide}}{\dot{E}_{\rm gw}}\right) df$$

(a template mismatch by say half a cycle leads to a significant loss of signal to noise)

Difficult to alter GW phasing (e.g. 10^{46} erg at 100 Hz leads to shift of 10^{-3} radians), but the star's deformability, encoded in the so-called Love number, may lead to a distinguishable secular effect;

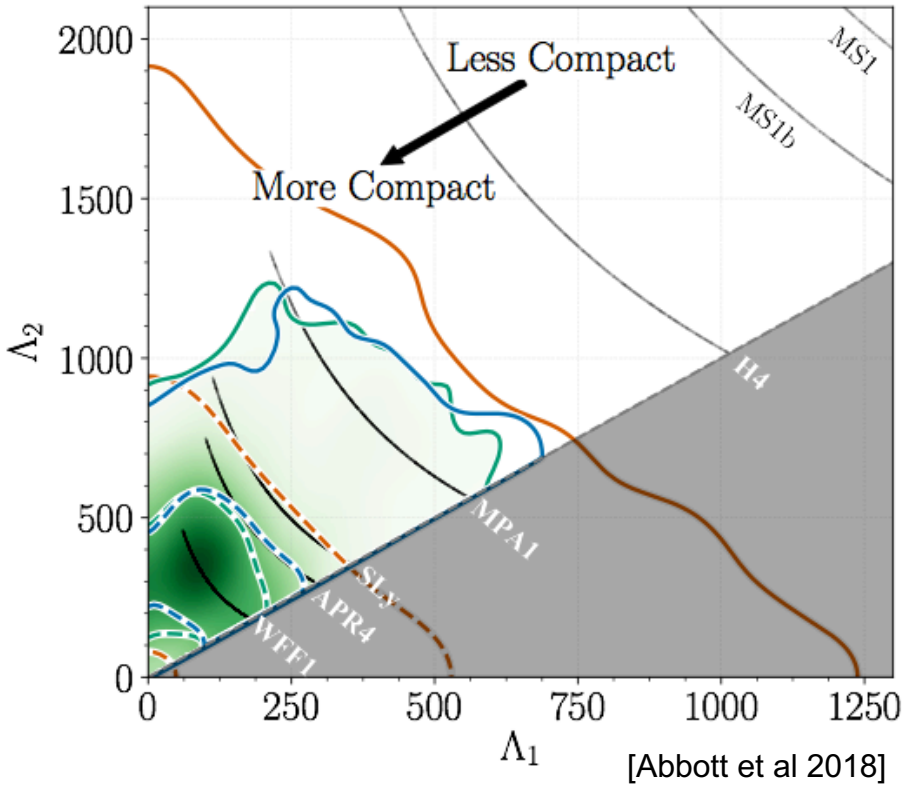
$$\lambda = \frac{2}{3} k_2 R^5 = \frac{Q}{E} = \frac{\text{quadrupole deformation}}{\text{strength of tidal field}}$$

Demonstrated by the spectacular **GW170817** signal:

This single event constrains the neutron star radius to the range

R=10-14 km

Similar to current constraints from x-ray data, but expect NICER to (significantly) improve in this (hopefully soon!).

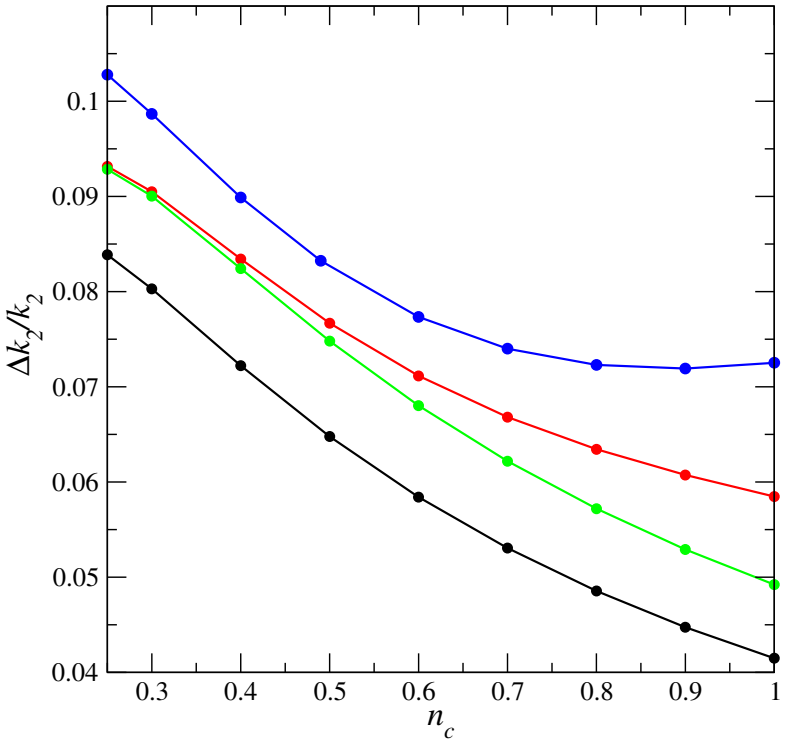


[Abbott et al 2018]

The tidal analysis assumes matter in equilibrium – which may not be realistic.

The inspiral is much faster than the relevant equilibration rates:

$$\tau_M \sim \frac{2 \text{ months}}{T_9^6} , \quad \tau_D \sim \frac{20 \text{ s}}{T_9^4} , \quad \tau_H \sim \frac{1 \text{ ms}}{T_9^2}$$



Rough estimates for "frozen" composition (note conceptual issues with limits) suggest this may lead to a systematic "error" of up to 10%.

Need to quantify to what extent we can use observations to constrain the internal composition.

After all, once we "know" the mass-radius relation we will want to probe the composition and state of matter.

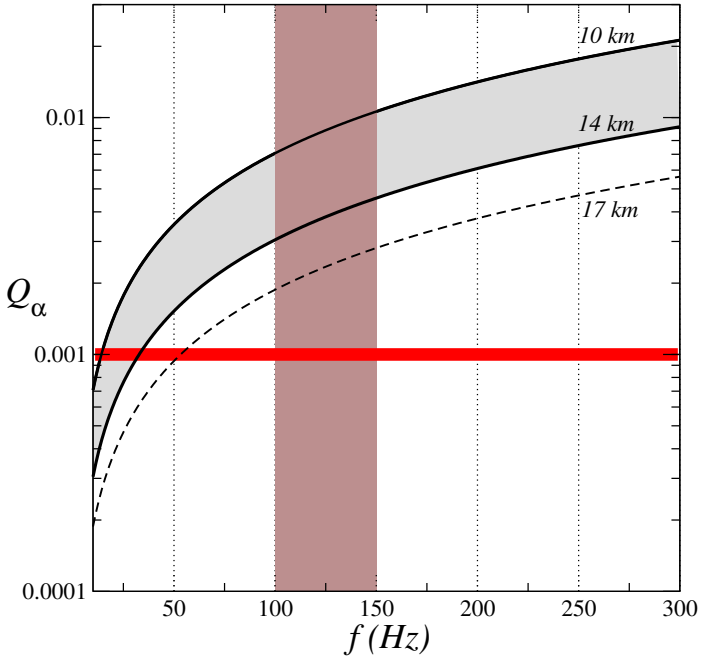
Q. What do we learn from a single data point?

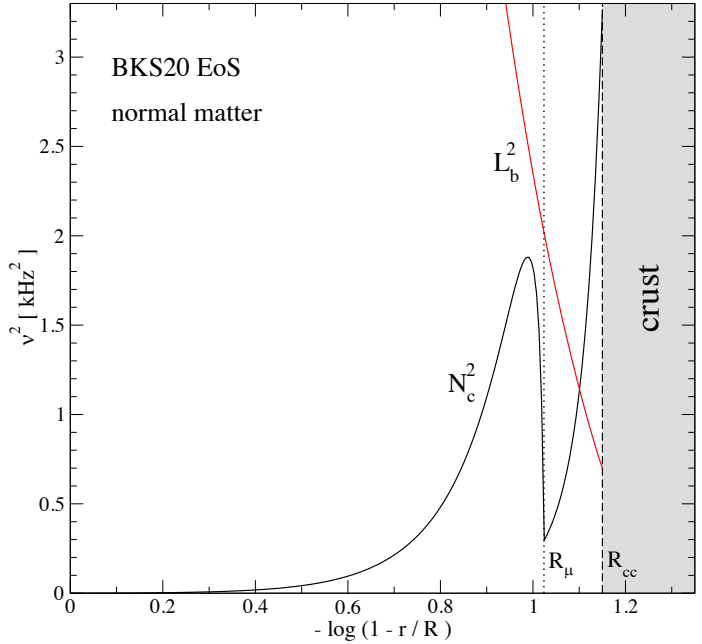
The composition/state of matter affect the star's oscillation modes (e.g. g-modes). These may be excited by the tidal interaction (the dynamical tide).

Observations constrain the "overlap" between the tide and a mode's eigenfunction;

$$\Delta\mathcal{N} \approx -4 \times 10^{-4} \hat{f}_\alpha^{-2} Q_\alpha^2 \left(\frac{c^2 R_1}{G M_1}\right)^5 \frac{1}{q(1+q)}$$

Unlikely to be a major effect, although interesting to note that superfluidity plays a role.





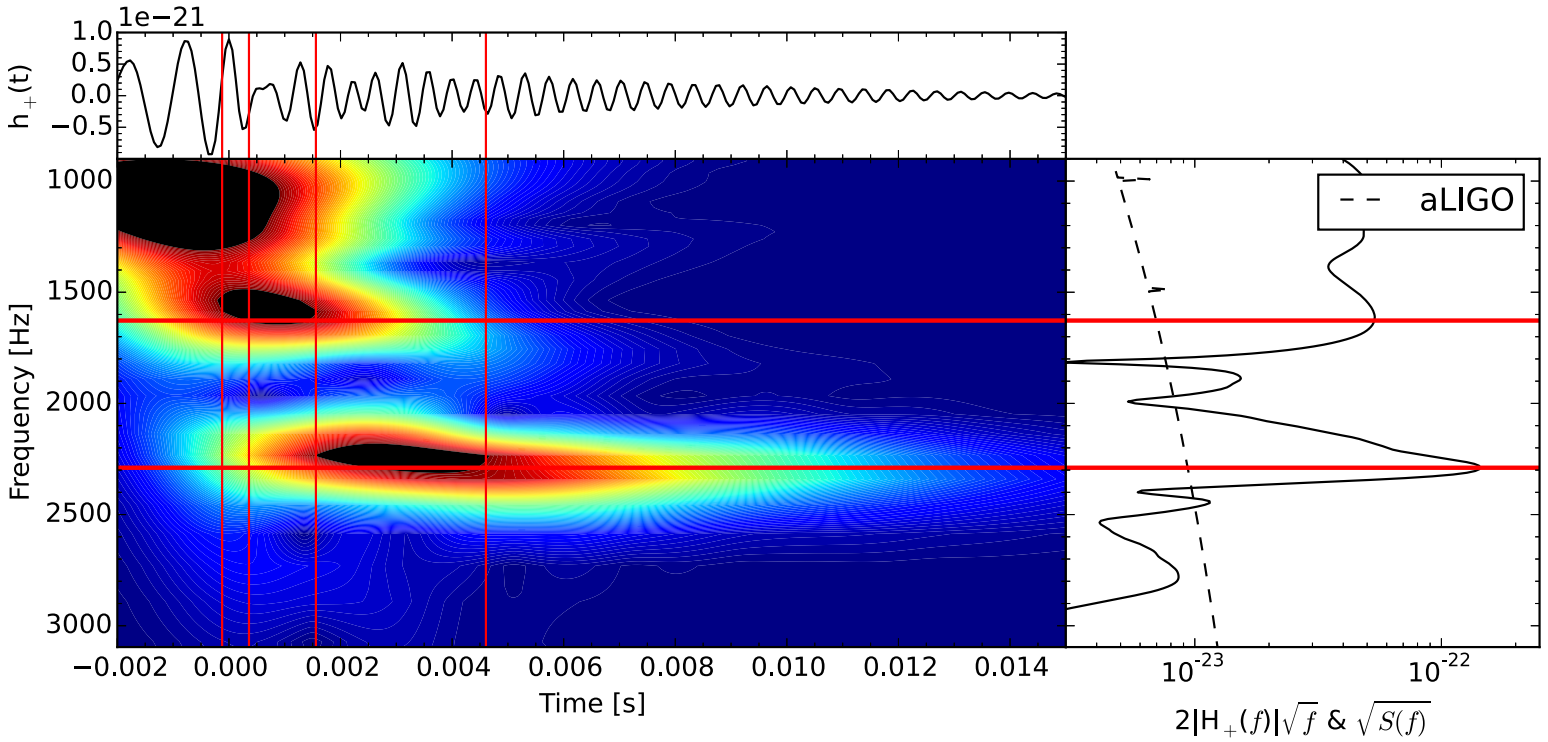
Dynamical excitation of the star's f-mode is important close to merger.

Instability due to p-g mode coupling?

The merger itself was not seen in the GW170817 signal, although the launch of the GRB may require a fairly prompt collapse to a black hole.

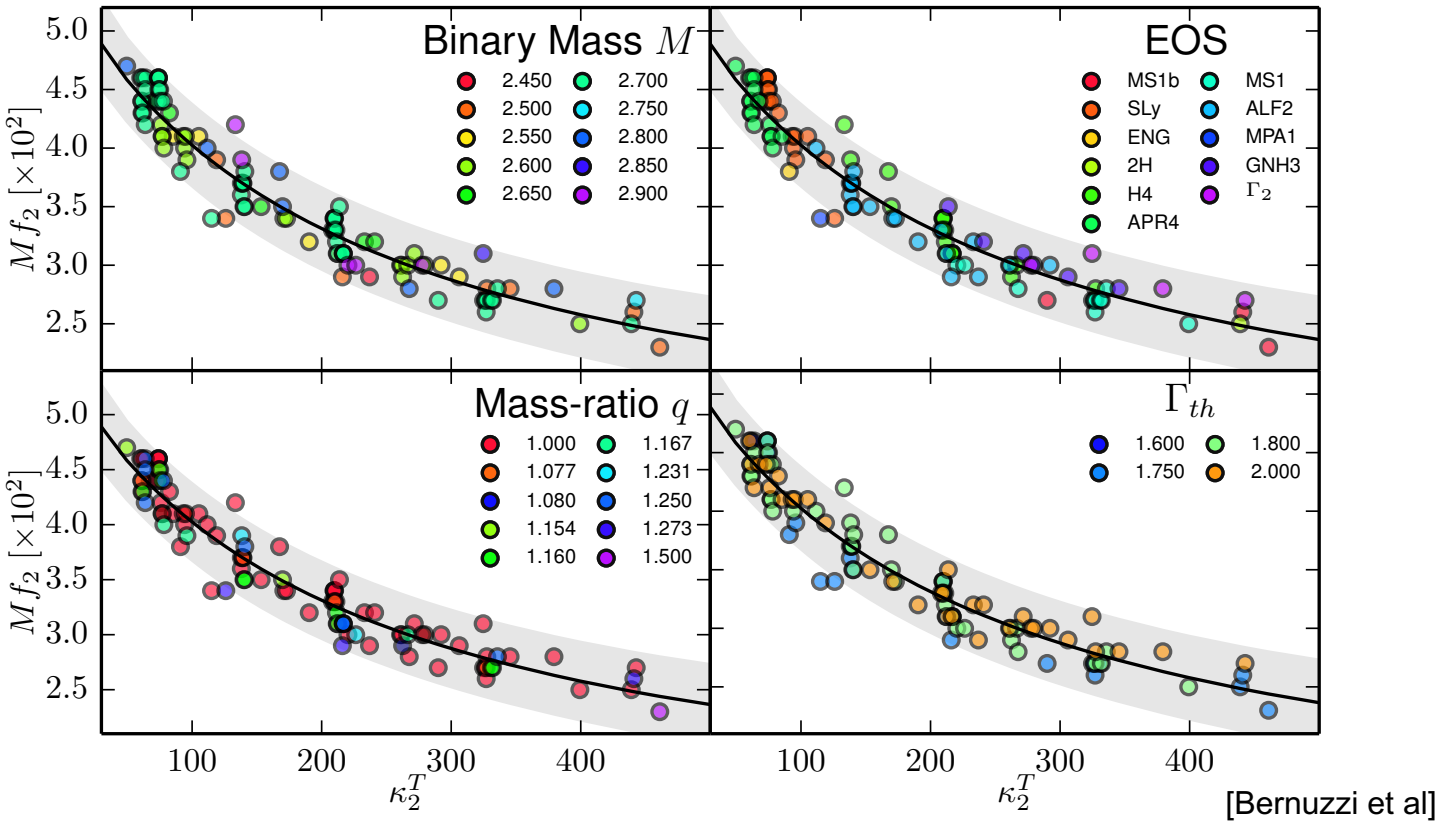
This may be turned into a constraint on the maximum neutron star mass.

Eventually… we should be able to detect the oscillations of the merger remnant.



[Clark et al]

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



[Bernuzzi et al]

This is “useful” as it would help parameter extraction, but at the same time “intriguing” as it suggests thermal effects and differential rotation do not significantly affect the oscillations of the remnant.

What are the “systematic” errors? (Role of magnetic field?)

State of play:

Have seen how gravitational-wave data can be used to constrain uncertain matter properties.

Expect to do better in the future. There will be more detections – although should keep in mind that GW170817 was “special”.

In order to ”dig deeper”, we need to improve the models:

- account for composition variation (reactions?) during late inspiral,
- check role of state of matter (crust/superfluidity),
- build simulations based on actual thermodynamics,
- account for dynamical role of neutrinos (dissipation),
- implement electromagnetism ”beyond ideal MHD”.