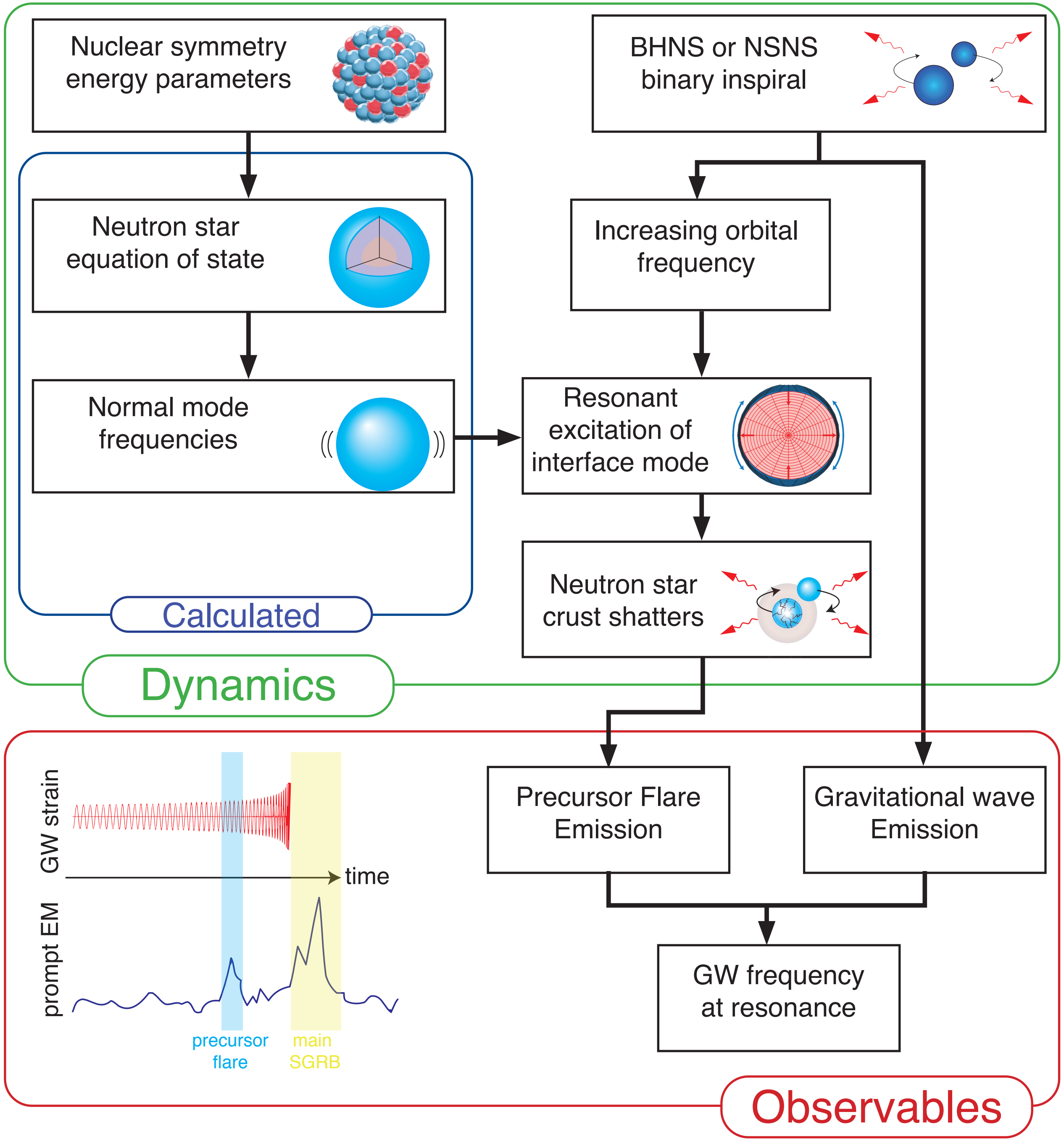
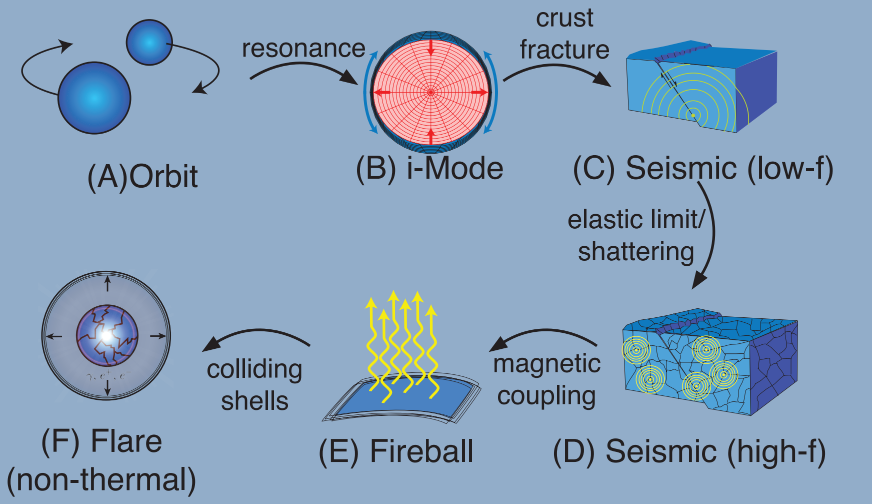
Resonant Shattering Flares:
Probing Nuclear Physics with BHNS and NSNS Mergers

UNIVERSITY OF BATH
Duncan Neill, dn431@bath.ac.uk



Resonant Shattering Flares (RSFs)

- NS perturbations are a superposition of orthogonal modes.
- The time-varying tidal field created by the binary orbit excites these modes.
- As the binary in-spirals, the orbital frequency increases.
- When the orbital frequency matches a mode's natural frequency, that mode is resonantly excited.
- Resonantly excited modes that cause large deformations of the elastic crust may cause it to shatter.
- When the crust shatters, energy is transferred from the resonant mode to seismic waves.
- Seismic waves can couple with a strong surface magnetic field to release a pair-photon fireballs.
- A resonant mode can shatter the crust multiple times, creating multiple fireball shells.
- Multiple fireball shells can collide and emit non-thermal synchrotron radiation: a resonant shattering flare (RSF).
- The GW frequency at the time of the RSF is (approximately) equal to the resonant mode's frequency.
- The mode frequency is dependent on the composition of the NS's crust, which is related to the nuclear symmetry energy.



RSFs may be the dominant EM counterpart to BHNS mergers

RSFs as counterparts to BHNS mergers

- SGRBs and Kilonovae require the NS to be tidally disrupted before the merger, but RSFs do not.
- Tidal disruption only occurs for BHNS systems with a low mass, high spin BH and low compactness NS.
- RSFs require that resonant excitation of the i-mode occurs before the inner-most stable circular orbit (ISCO) of the binary.
- The orbital frequency at the ISCO is dependant on the BH mass and spin, but the i-mode frequency is low and therefore only weak requirements are put on the BH's mass and spin.
- An extra condition for RSFs is that, in order to be observable, they require that the NS has a sufficiently strong magnetic field at its surface. The magnetic field evolution in NSs is highly uncertain, and therefore the distribution of NS fields at the time of BHNS mergers is uncertain.

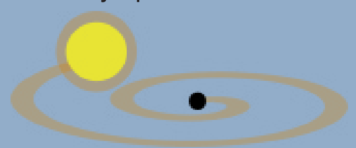
Population Synthesis for BHNS binaries

- The BPASS binary population synthesis code (Eldridge, Stanway et al. (2017) and Stanway & Eldridge et al. (2018)) is used to obtain mass distributions for objects in BHNS binaries, as well as the mass accreted onto the BH.
- For BH spin, we use upper and lower bounds for the spin-up due to accretion.

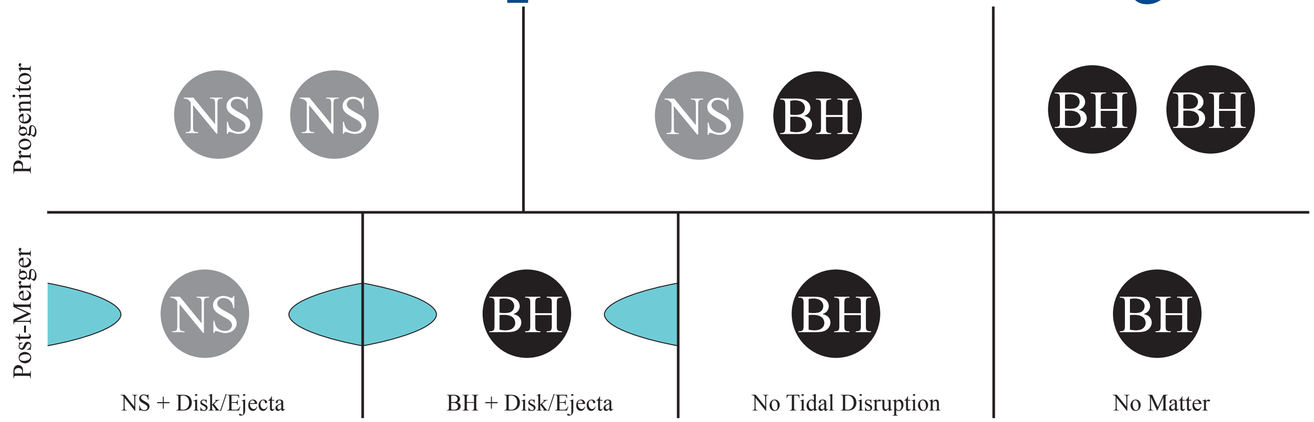
The lower bound assumes that all BHs have zero spin. This is likely closer to reality than the upper bound, as many systems undergo a common envelope phase.

Low BH spin

The upper bound assumes that all accretion is done via a thin equatorial disk (the most efficient way to accrete angular momentum). This is extremely optimistic.



High BH spin



- As the BHNS binary in-spirals, tidal forces acting on the NS grow stronger.
- Tidal disruption occurs when these forces are strong enough to tear the NS apart.
- The dynamics of matter ejected from the NS leads to the emission of SGRBs and Kilonovae.
- Massive or low spin BHs can swallow their NS before tidal disruption occurs. In these cases, no SGRB or Kilonova is produced.
- The lack of EM counterparts to the recently detected GW200105_162426 and GW200115_042309 BHNS mergers is consistent with the assumption that tidal disruption is not common.

We predict that most BHNS systems do not tidally disrupt, but could produce RSFs!

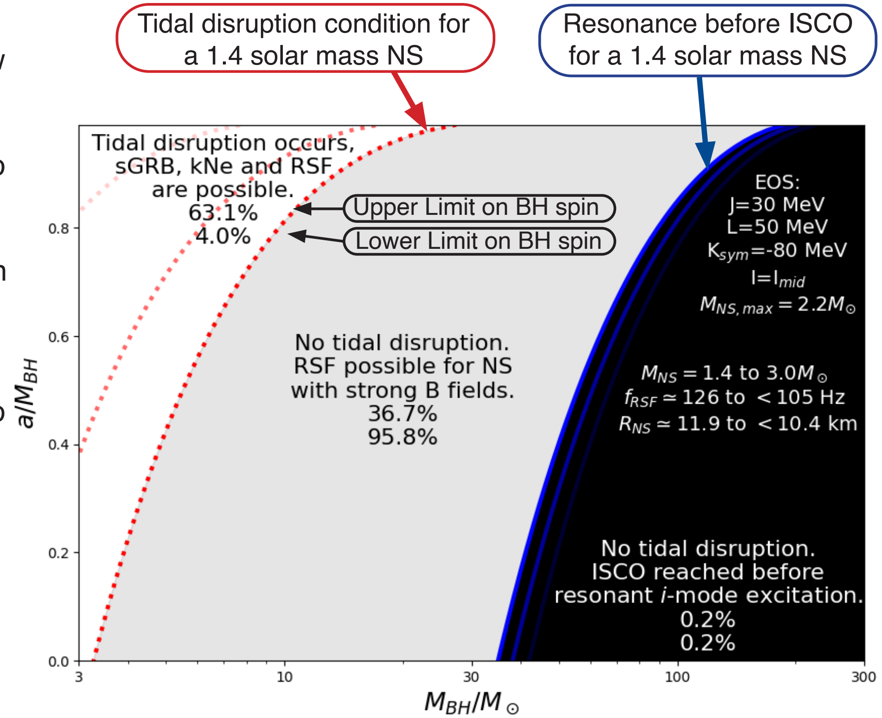


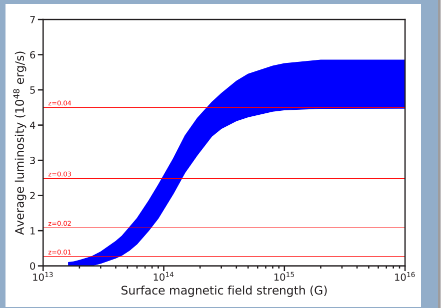
Figure: The requirements for tidal disruption (Foucart (2012)) and resonant i-mode excitation on a plot of BH mass and spin. We show the percentages of BHNS systems in each region of the plot. The lower limit on BH spin is more reasonable than the upper limit.

For more information, watch for Neill, Tsang, Van Eerten, and Ryan (in prep)

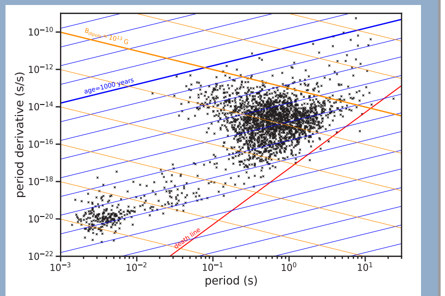
Predicting the rate of detectable RSFs from BHNS mergers

NS magnetic field distribution

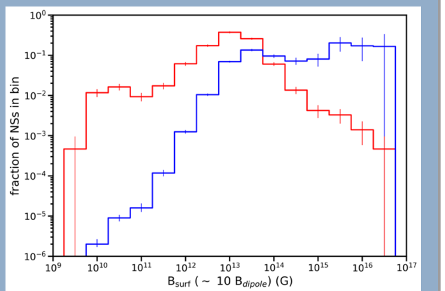
- The magnetic field strength at the surface of a NS is very important for RSFs. It determines the rate at which the energy of seismic waves in the crust is released in pair-photon fireball shells, and thus the total energy of the flare.
- We calculate the luminosity of non-thermal emission from the shocks between colliding shells by following Kobayashi et al. (1997).
- The mass loading of the shells is unknown, and therefore we take a range of possible values. This results in a range of average luminosity at any given surface field strength.



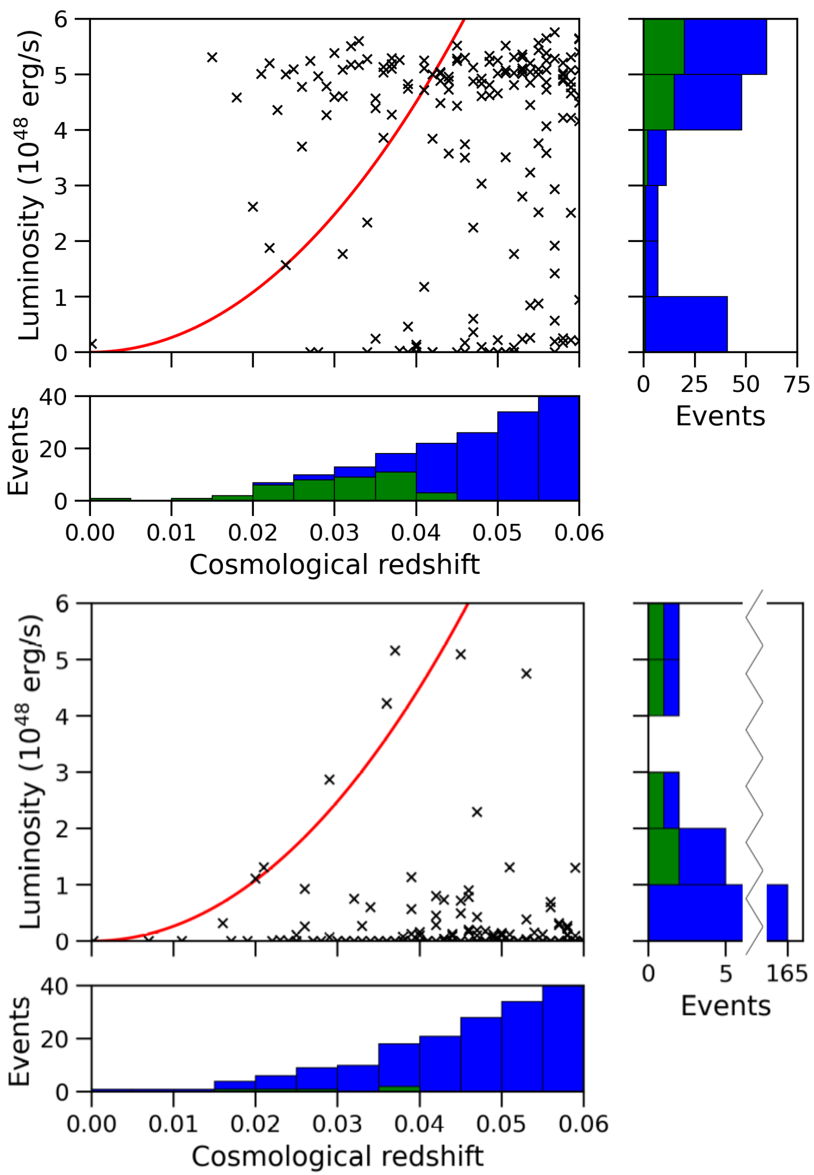
- Using the P-Pdot diagram for known pulsars, we obtain a distribution of NS dipole magnetic field strengths
- For the upper bound on field strength, we assume that NS magnetic fields do not decay, and therefore the same distribution exists beyond the pulsar death line as we see before it.



- For the lower bound, we simply take the distribution on the P-Pdot diagram, without considering the time to cross the death line.



- NS magnetic field evolution is an area of active research. If the magnetic field is contained in the crust, it is likely to decay over ~ 10^8 years, making the distribution at time of BHNS merger closer to the lower bound. If, however, the magnetic field threads the core then it could be frozen in, resulting in little-to-no decay.
- We ignore MSPs (period < 10-2 s), as they are part of a different population of recycled pulsars.



Figures: Luminosities of 10 years of RSFs from BHNS mergers, assuming the upper (top) or lower (bottom) bound on the NS magnetic field distribution. The red line is the requirement for RSFs to be detectable by Fermi/GBM. For the bar charts, green represents detectable RSFs, and blue the total number of BHNS mergers.

- RSFs may be common products of BHNS mergers, but are they luminous enough to be observed?
- Using the star formation rate history of Madau & Dickinson (2014), the metallicity evolution of Langer & Norman (2006), and BPASS's end products of stellar evolution, we obtained the rate of BHNS mergers as a function of redshift.
- We randomly sampled the NS magnetic field distribution to calculate the luminosities of 10 years of RSFs from BHNS mergers, and compared them to the required source luminosity for detection by Fermi/GBM.
- The upper magnetic field distribution results in many detectable RSFs at z<0.04, while the lower limit has only a few.
- The rate of detectable RSFs is high enough that they may be more commonly produced by BHNS mergers than SGRBs or Kilonovae.

~ 0.5 to 4.1 detectable RSFs per year from BHNS mergers!

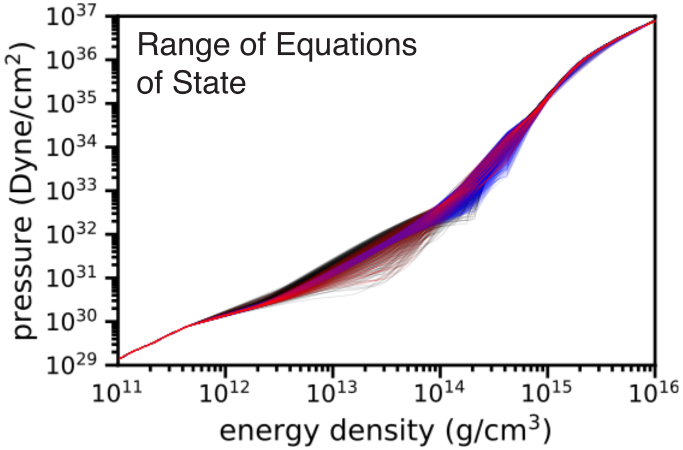
RSFs are effective probes of nuclear symmetry energy

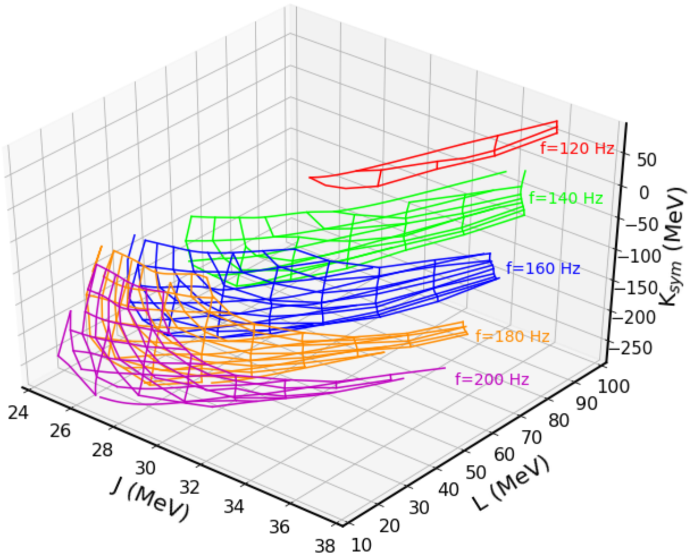
- The i-mode frequency is strongly dependent on the crust composition and the EOS.
- The crust composition is strongly dependent on the nuclear symmetry energy.
- We construct a set of EOSs parametrised by a grid of the first three nuclear symmetry energy parameters: J, L and K_{sym} (the symmetry energy and its first two density derivatives at nuclear saturation density).

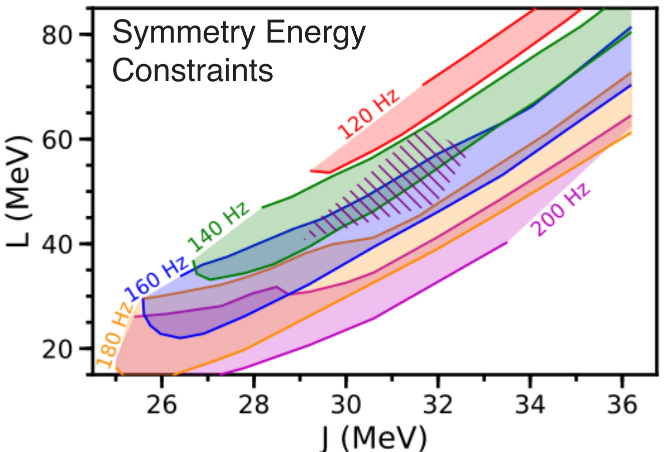
$$E_{\text{sym}}(n_b) = J + L\chi + \frac{K_{\text{sym}}}{2!}\chi^2 + \mathscr{O}(\chi^3),$$

- We calculate the i-mode frequency for these EOSs, and interpolate between them to obtain surfaces of constant i-mode frequency in the J-L-K_{sym} parameter space .
- The i-mode and GWs are both quadrupolar, so their frequencies should be approximately equal at the time of the RSF.
- Therefore, the GW frequency at the time of an RSF constrains J, L and K_{sym} to lie on a particular surface.
- By projecting these surfaces on the J-L axes, we compare potential RSF constraints to those from nuclear experiment.
- RSF constraints are of comparable strength to the combined constraints from terrestrial experiments.

For more information, see Neill, Newton, and Tsang, 'Resonant shattering flares as multimessenger probes of the nuclear symmetry energy', (2021), MNRAS, 504(1), pp.1129-1143

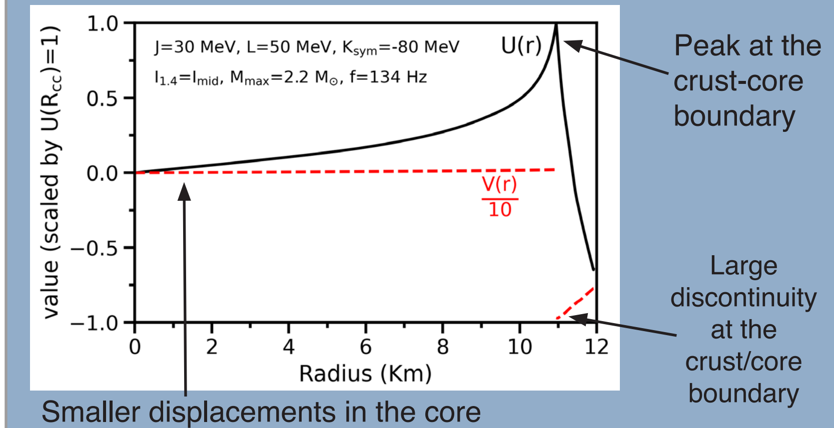






Properties of the i-mode that support the study of nuclear parameters via RSFs

- The crust-core interface mode is strongly dependent on the crust's composition (particularly the denser parts), which is in turn strongly dependent on the nuclear symmetry energy.
- Certain properties of the i-mode make it ideal for triggering RSFs, such as its displacement peaking in the crust which leads to efficient transfer of energy from the mode to seismic waves.
- The i-mode frequency is ~100 Hz, and so GWs emitted during an RSF should be detectable.



Uncertainties

- Resonant excitation occurs within a resonance window which determines the duration of the flare, and the precision to which the i-mode frequency can be measured.
- Mode frequencies are affected by the mass of the NS, and therefore uncertainty in mass measurements weakens our constraints.
- We have not considered uncertainty in the EOS of the NS core. The core only has a minor impact on the i-mode frequency (~ 10%).

Caveats

- The shear modulus calculation that we have used is a fit for the typical ionic lattice found in the outer crust. This may not be accurate for the inner crust, where more exotic forms of matter appear.
- We have calculated mode frequencies using non-relativistic equations. The frequencies obtained using general relativity are expected to differ by around 10%.