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Unlocking neutron-star interiors with tidal resonances

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Tidal imprint on the gravitational wave

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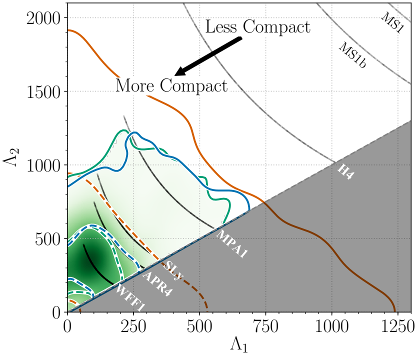
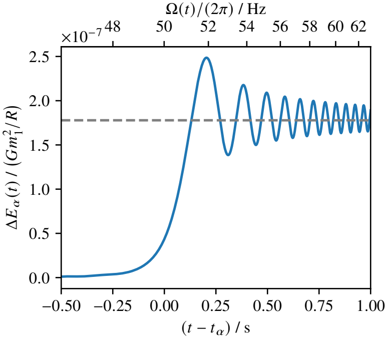
- Tide has two regimes:
  - **Static**—represented by Λ, constrained with GW170817 [1];
  - **Dynamical**—orbital motion excites neutron-star oscillation modes.
- Dynamical tidal waveform models of the f-mode now exist [2–4].
- Modelling the f-mode is necessary for accurate parameter estimation [5–7].



Credit: Abbott et al. [1].

Tidal resonances

- Second aspect of the dynamical tide: resonant excitation of modes.



Energy ΔE_α deposited into the mode during resonance.

- Sources a sudden gravitational-wave phase shift [8]

$$\Delta\Phi_\alpha \approx 0.08 \left(\frac{1.4M_\odot}{m_1}\right)^4 \left(\frac{R}{12\,\mathrm{km}}\right)^2 \frac{2q}{1+q} \times \left[\frac{\mathcal{I}_{\alpha 2,\pm 2}/(m_1 R^2)}{10^{-3}}\right]^2 \left[\frac{100\,\mathrm{Hz}}{\omega_\alpha/(2\pi)}\right]^2,$$

where $\mathcal{I}_{\alpha l m}$, ω_α are properties of the mode.

- **Detectability** remains an open question [9–11].

Modelling the resonances

- We model the resonance as *instantaneous*:

$$\epsilon := \frac{\tau_{\mathrm{res}}}{\tau_{\mathrm{rr}}} \approx 0.07 \left(\frac{\mathcal{M}}{1.2 M_\odot} \right)^{5/6} \left[\frac{\Omega/(2\pi)}{100\,\mathrm{Hz}} \right]^{5/6} \ll 1.$$

- The abrupt change in the orbital phase leads to

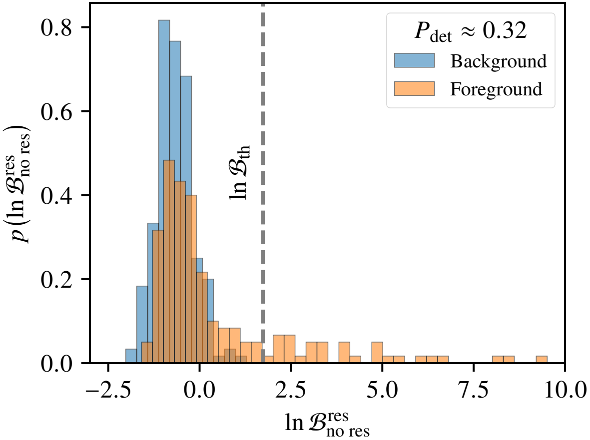
$$\Psi(f) = \Psi_0(f) + \Theta(f - f_\alpha) \left(1 - \frac{f}{f_\alpha} \right) \Delta\Phi_\alpha,$$

  where $\Psi_0(f)$ is a baseline waveform model, which we choose to be `IMRPhenomXAS_NRTidalv3` [4].
- We focus on the simplest case of *one tidal resonance per star*.

Simulating an Einstein Telescope population

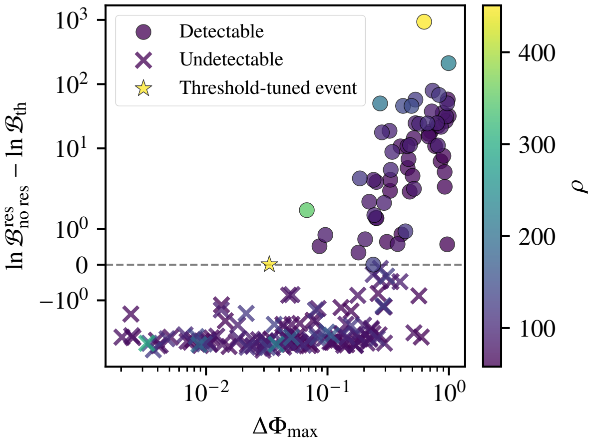
- We simulate an astrophysical population of binary neutron stars observed by the Einstein Telescope over one year.
- The dense matter satisfies an equation of state that is consistent with current constraints [12].
- For the mode parameters,
  - the frequencies f_1, f_2 are drawn uniformly on $[5, 300]\,\mathrm{Hz}$,
  - the phase shifts $\Delta\Phi_1, \Delta\Phi_2$ are drawn log-uniformly on $[10^{-3}, 1]$.
- We inject the 200 loudest signals into the ET-D design sensitivity and analyse the data from $5\,\mathrm{Hz}$.

Gravitational-wave population analysis



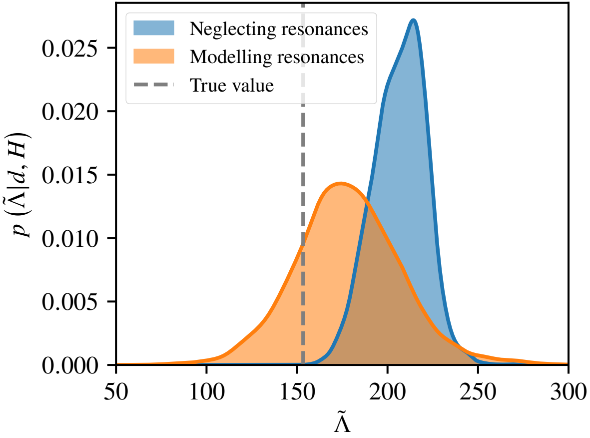
Distributions of the Bayes factor $\mathcal{B}^{\mathrm{res}}_{\mathrm{no\ res}}$ comparing the hypothesis that resonances are present to the hypothesis that they are absent.

Dependence on phase shift



Loudest event produces detectable resonances of $\Delta\Phi_{\rm max} \approx 0.03$.

Neglecting resonances in parameter estimation



Representative event with $\Delta\Phi_{\rm max} \approx 0.24$ and $\rho \approx 83$.

Conclusions

- Tidal resonances may be detectable with the Einstein Telescope.
- Minimum detectable phase shift found to be $\Delta\Phi_\alpha \approx 0.03$.
- Implications for oscillation modes:

Mode	Physics	$\Delta\Phi_\alpha$	Detectability
g-modes	composition	~ 0.08 [13]	✓
inertial modes	rotation	$\sim 0.02 – 0.20$ [14]	✓
core-crust interface mode	core-crust transition	≈ 0.002 [15]	✗

Asteroseismology with the Einstein Telescope may be possible.

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