arXiv:2504.06181 [gr-qc]

Interface modes in inspiralling neutron stars:

A smoking-gun gravitational-wave signature of first-order phase transitions

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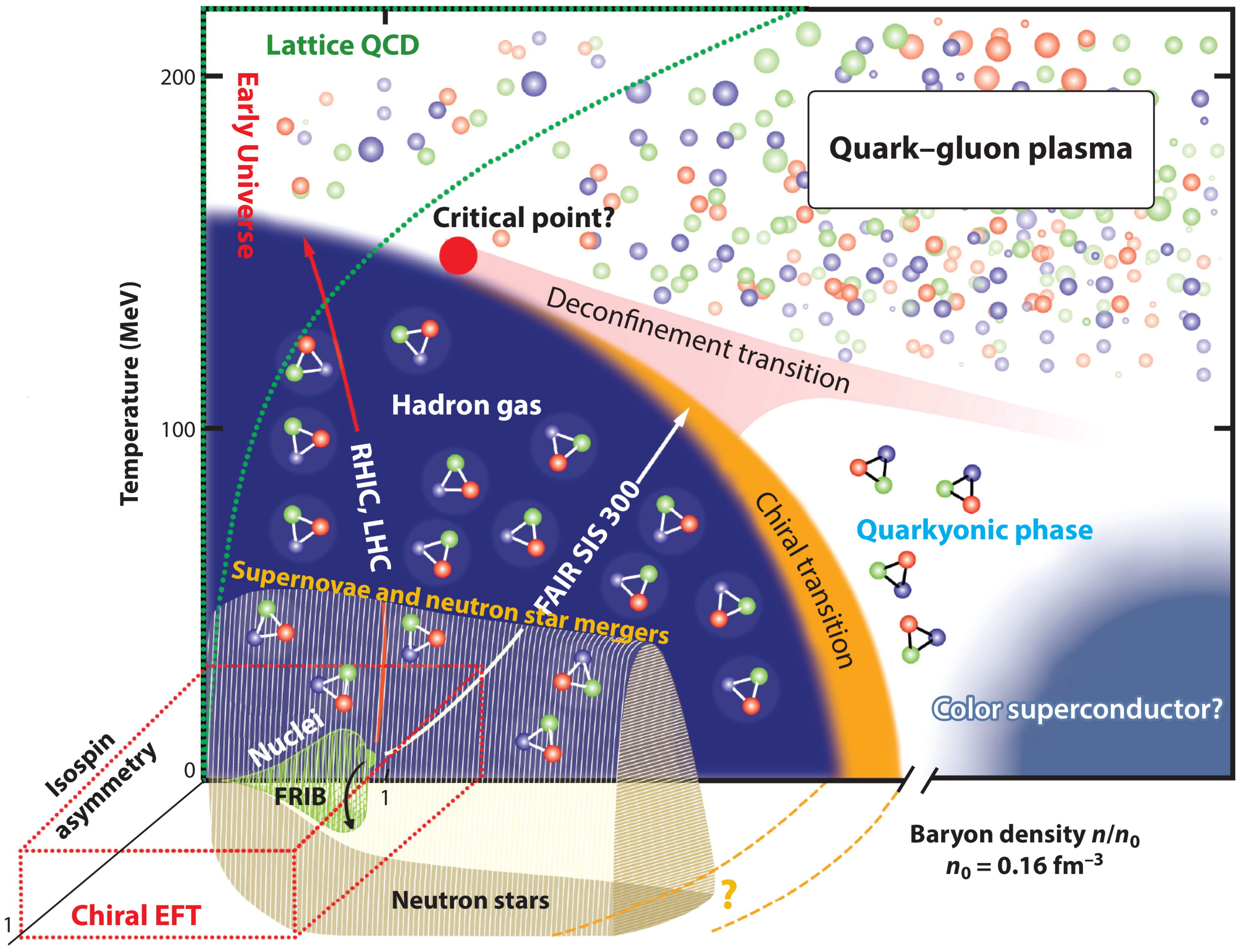
Theoretical background

Dense nuclear matter

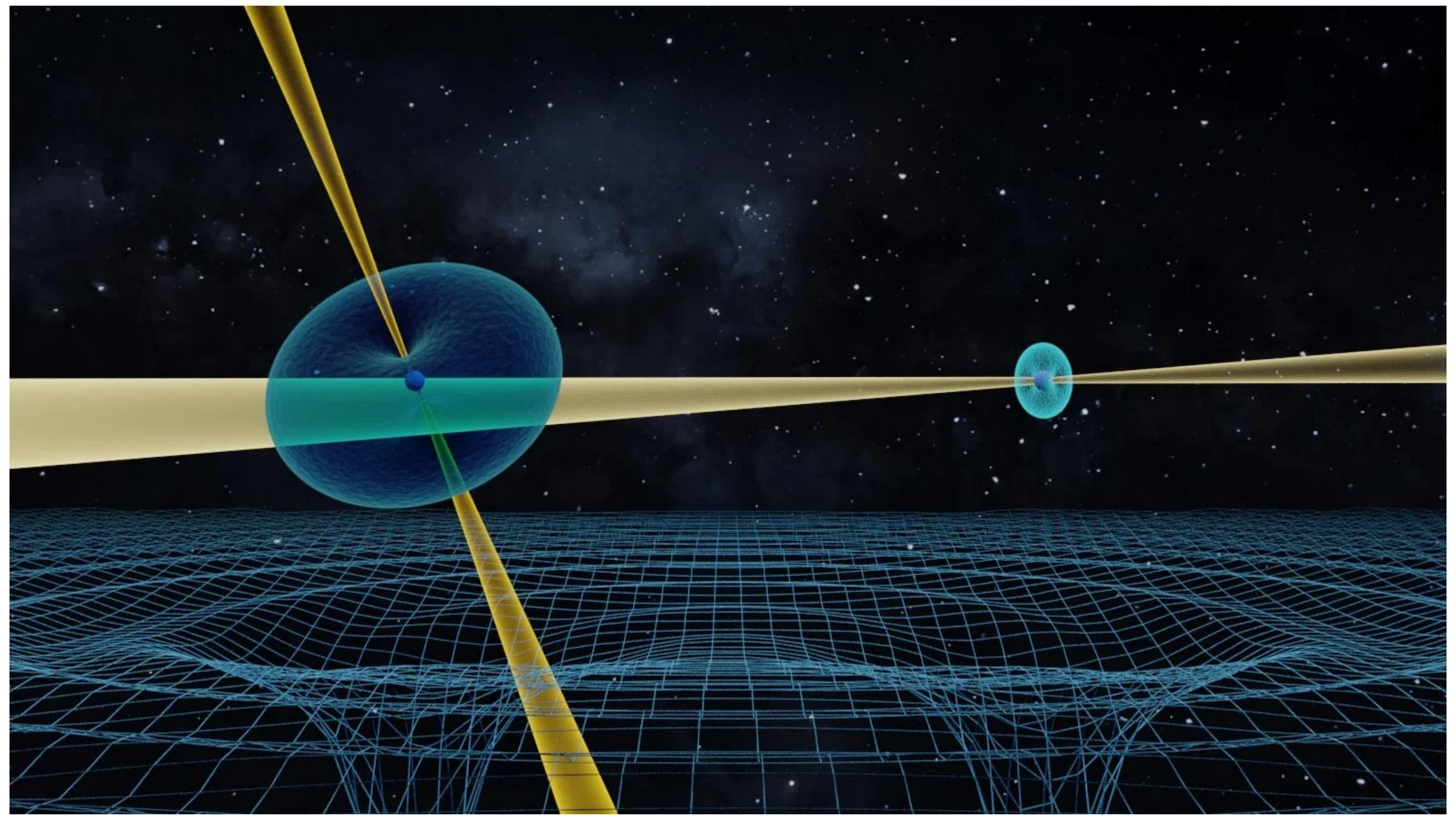


Drischler C, et al. 2021
Annu. Rev. Nucl. Part. Sci. 71:403–32

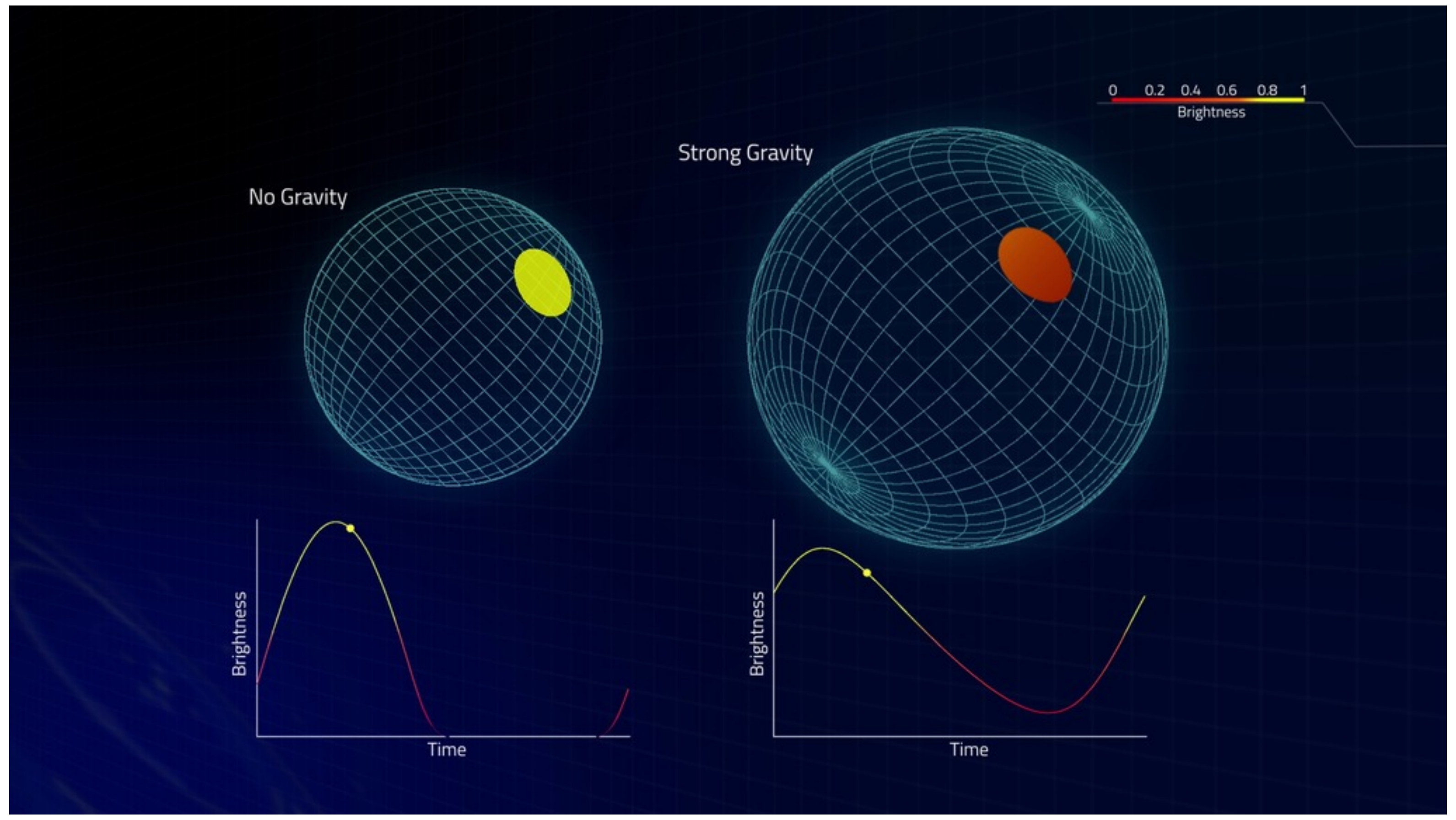
Neutron-star observables

- A natural question is: Do neutron stars harbour this phase transition? And which astrophysical observations may shed light on this?

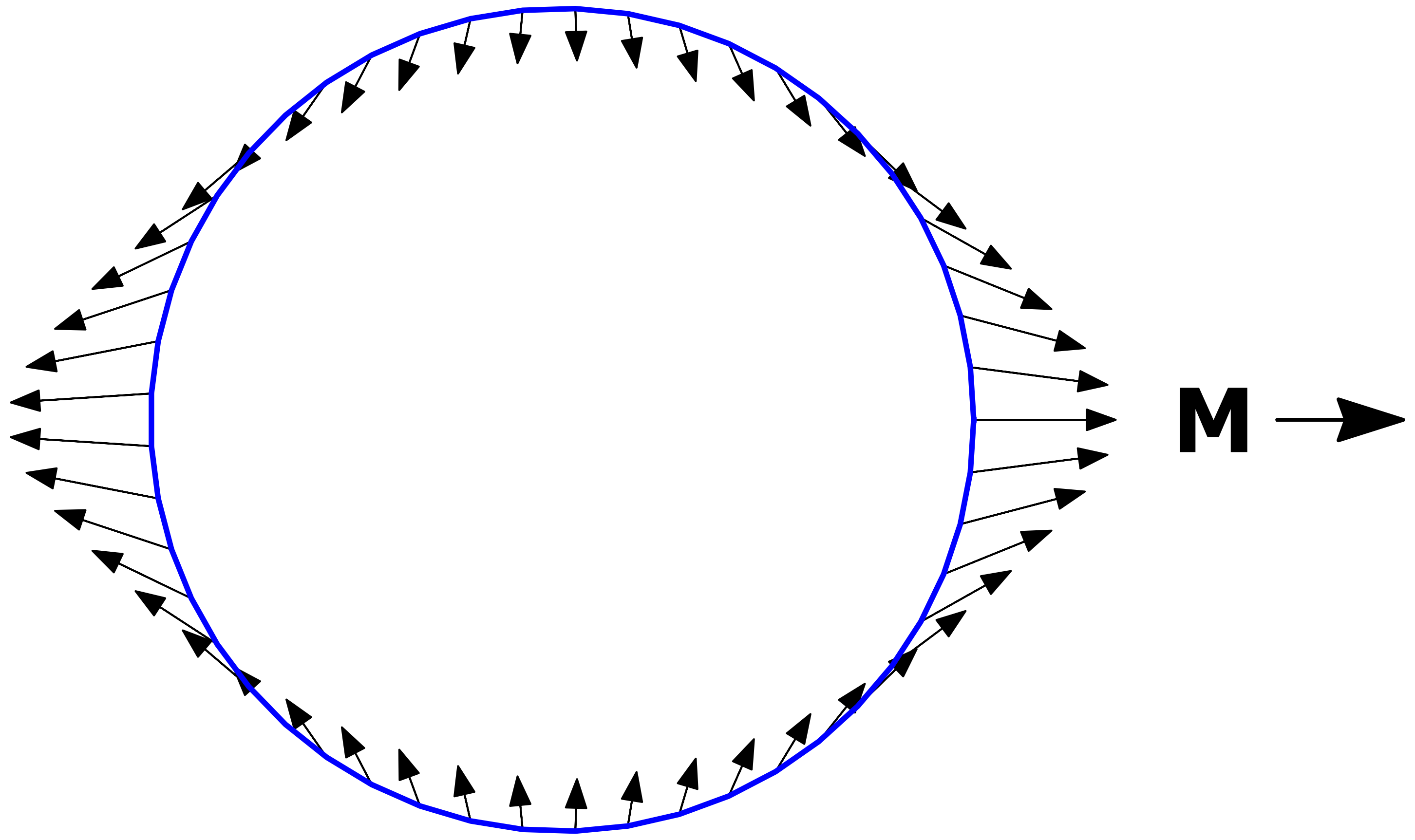
- So far, we examine the neutron-star structure with measurements of mass M, radius R and tidal deformability Λ.



M



R



Λ

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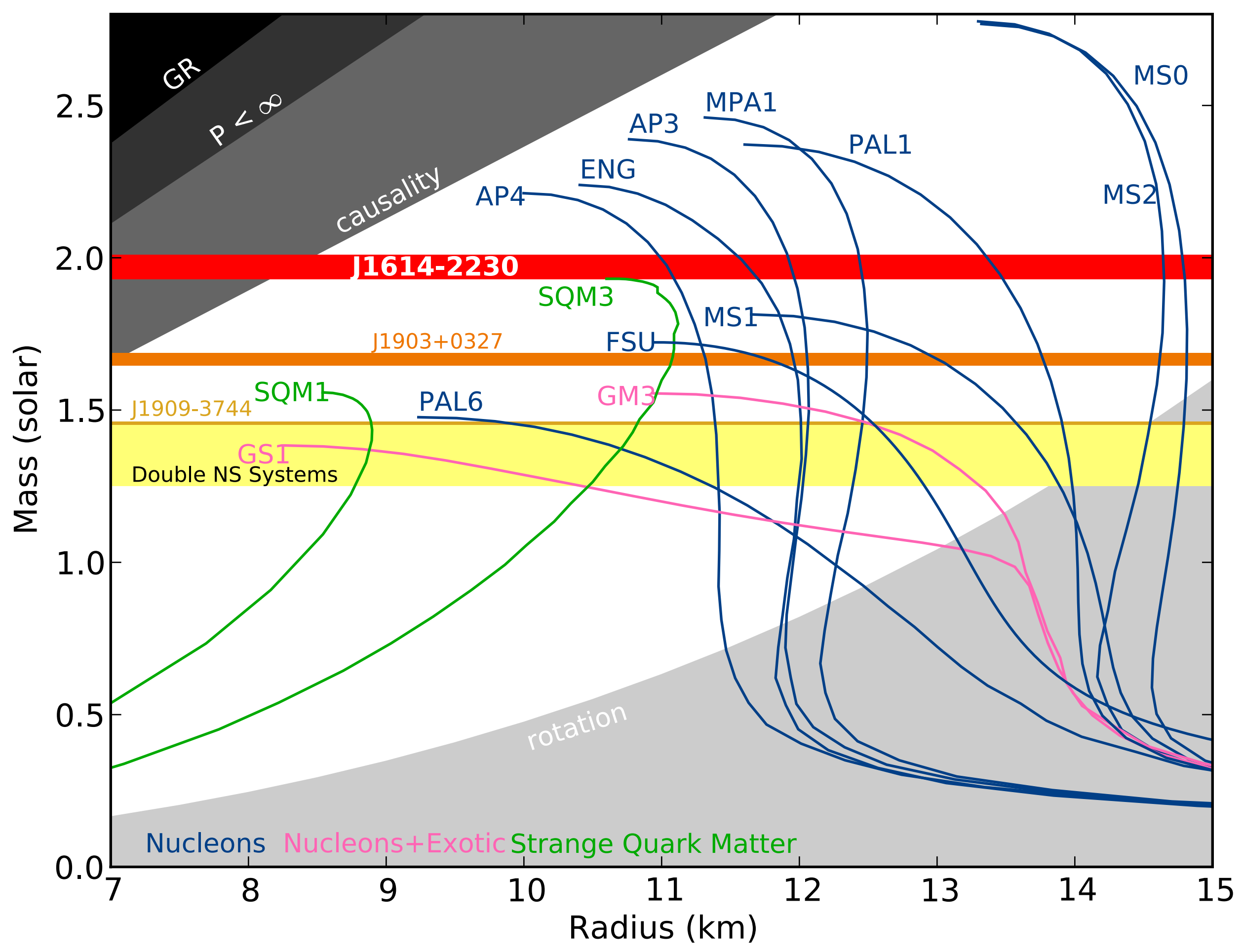
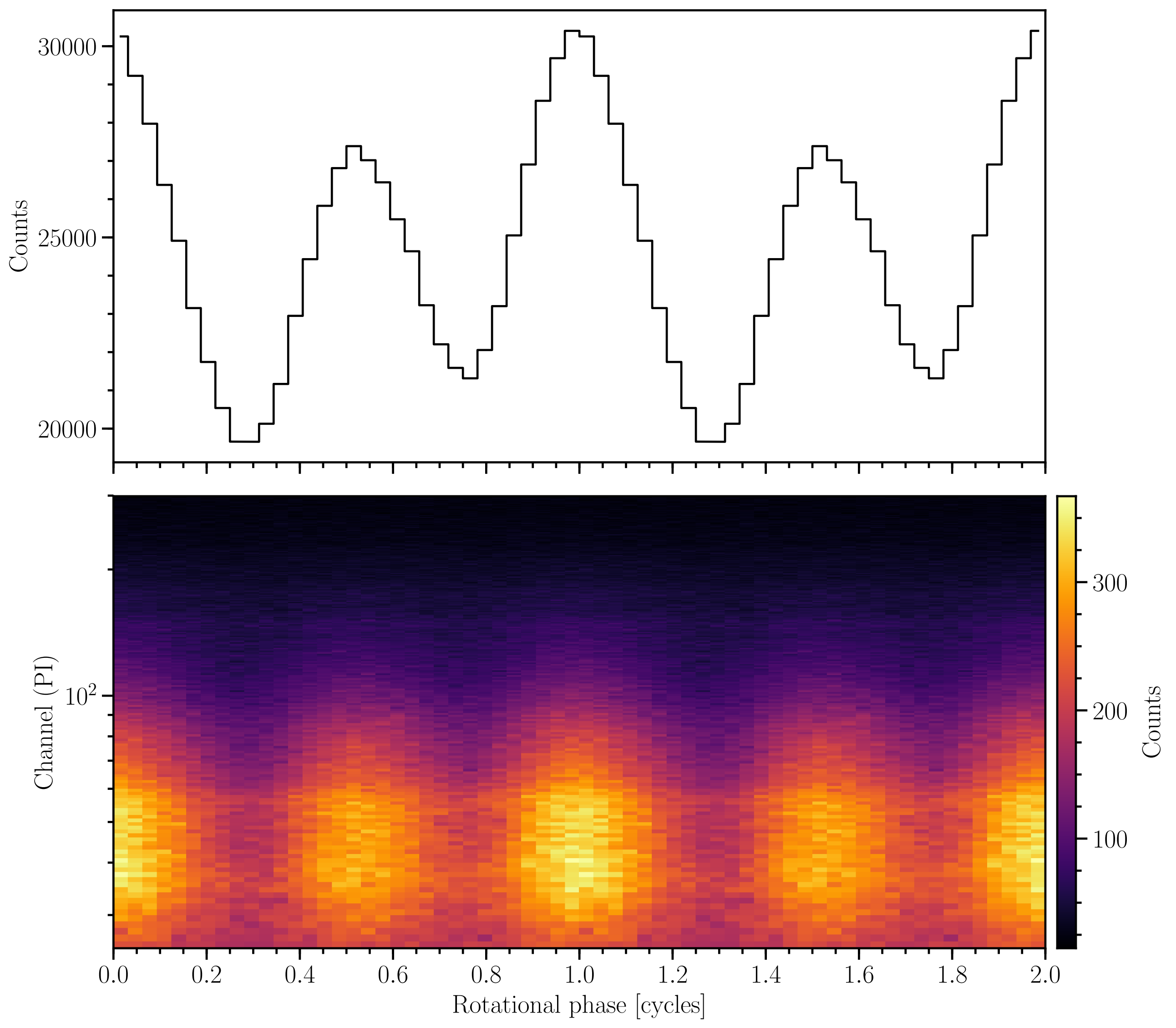
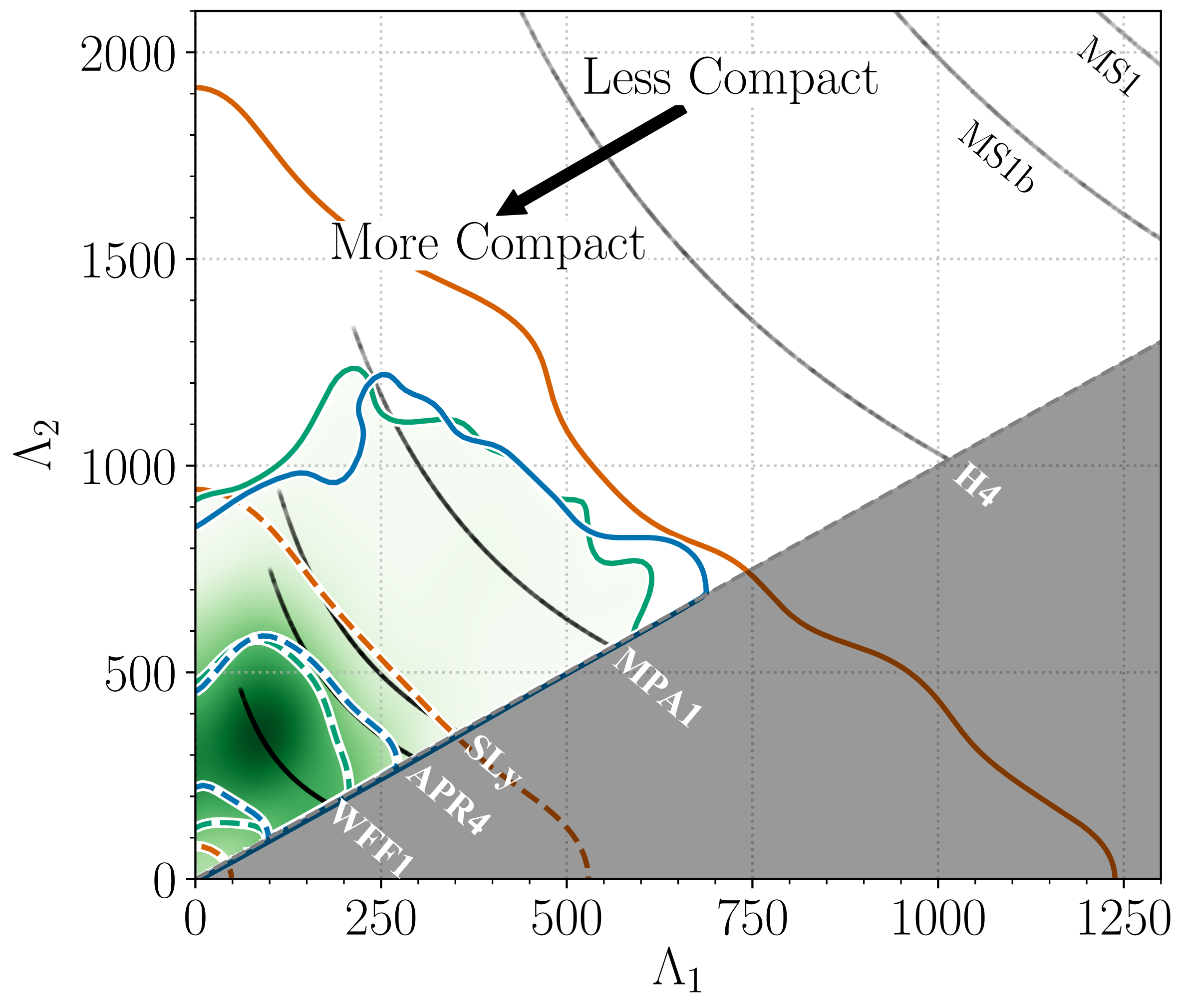


M



R



Λ

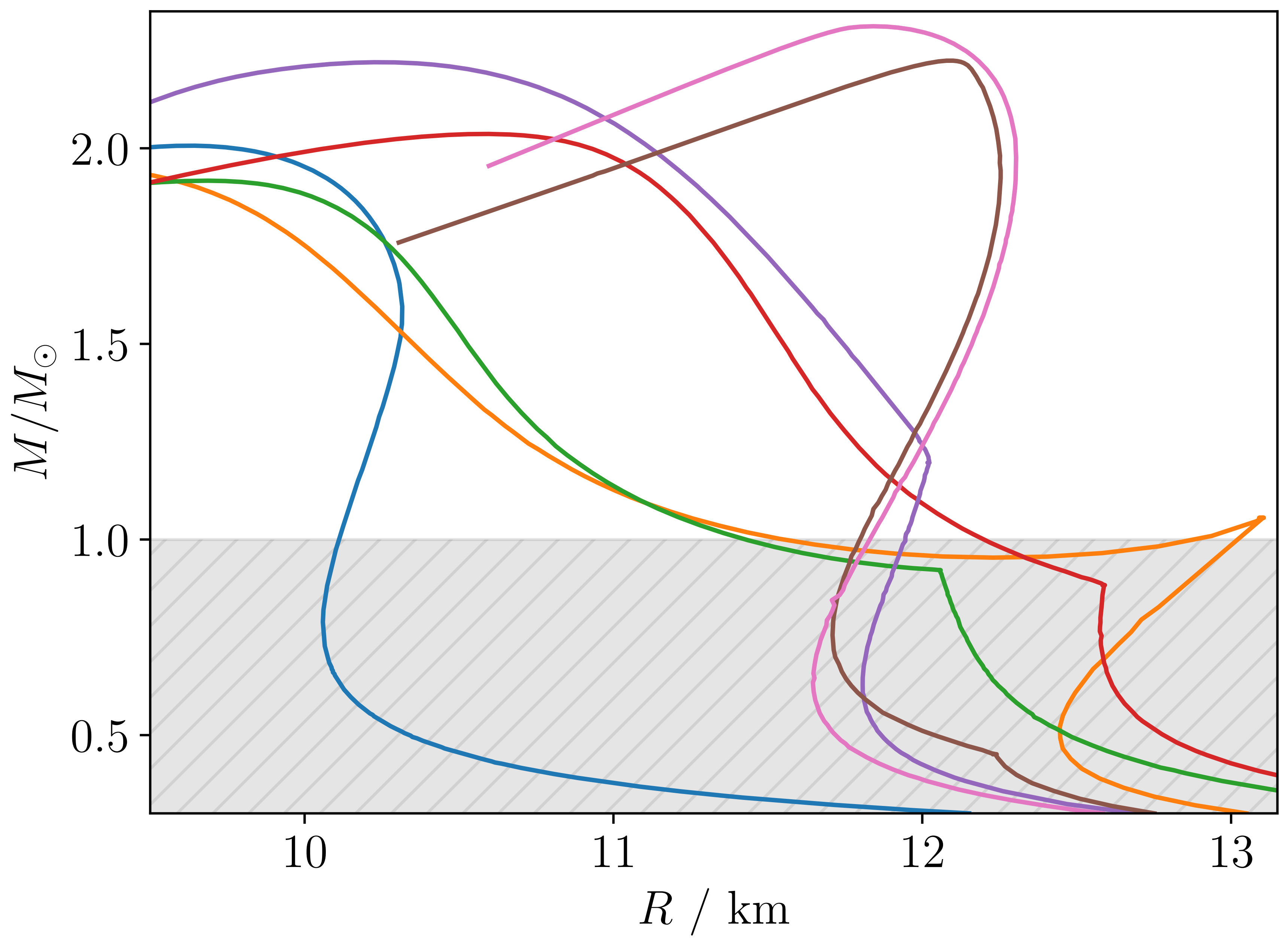
Signatures of phase transitions

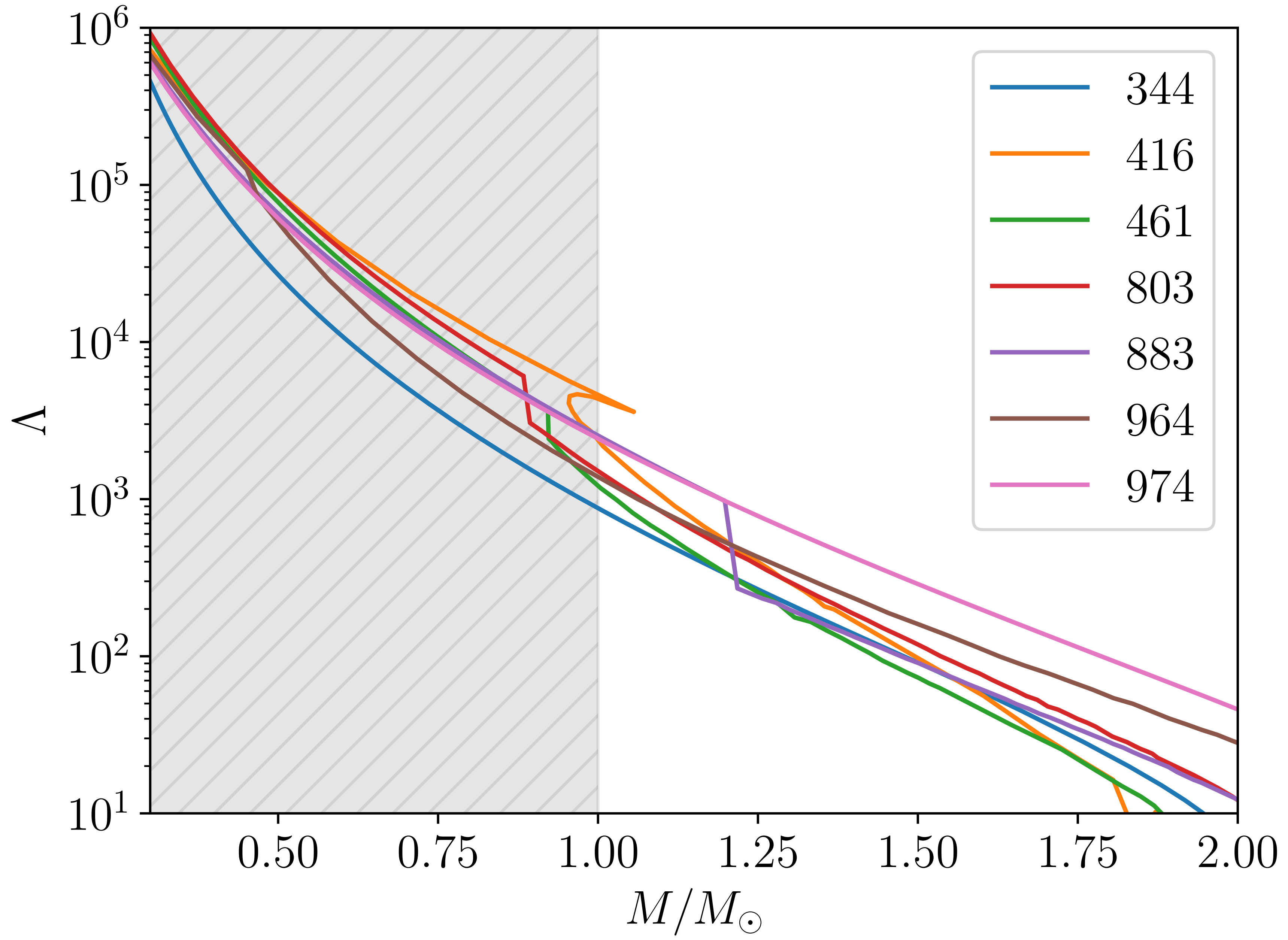
Revealing the transition

- There are two issues with revealing phase transitions from M, R and Λ.

1. The phase transition may occur at lower densities (associated with neutron stars of $M \lesssim M_\odot$). This is a form of the *masquerade problem*.

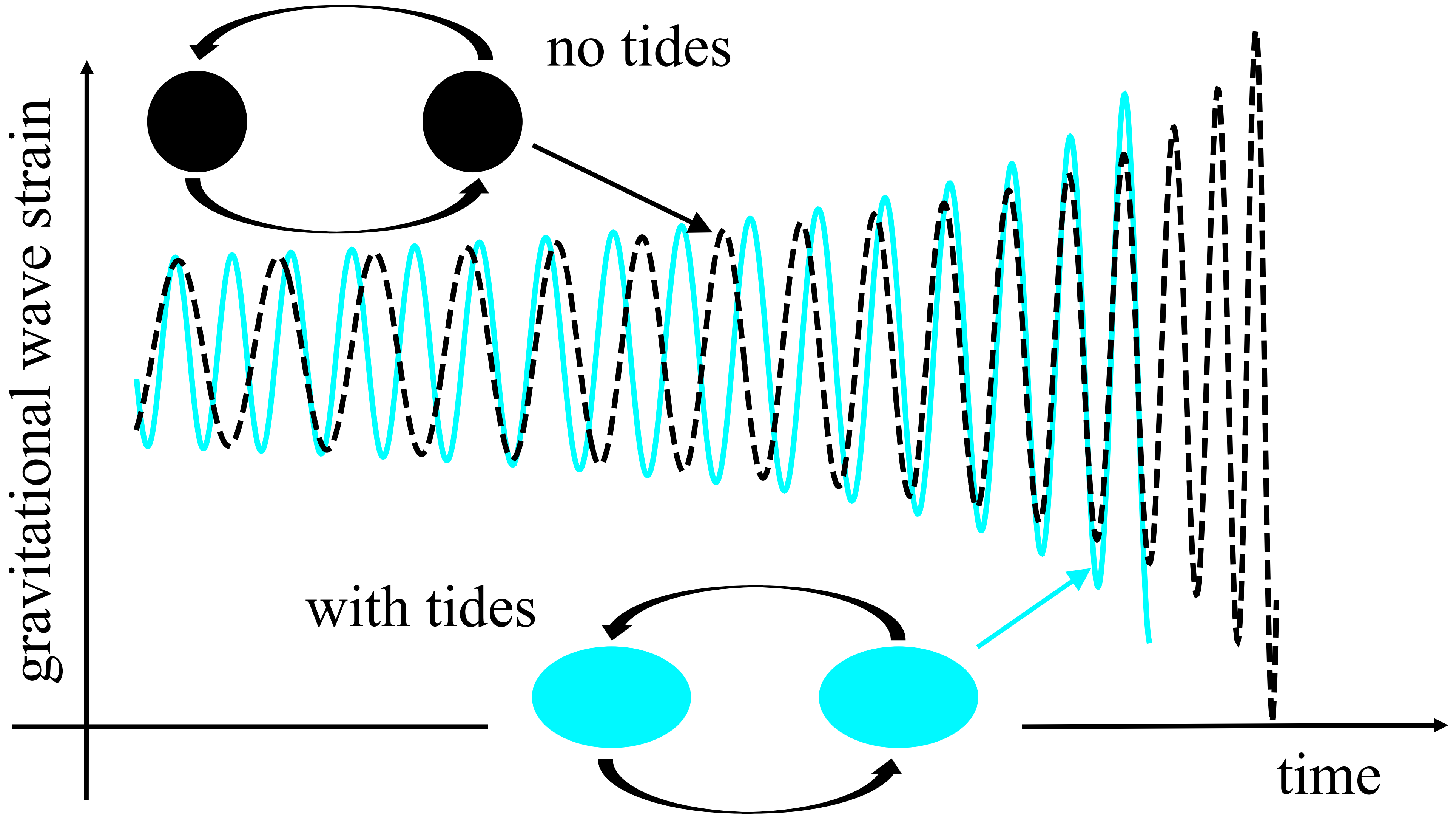
2. Resolving the transition may require many observations and third-generation instruments.





The dynamical tide

- As a compact binary inspirals, the tidal frequency increases and eventually becomes comparable to the neutron star's natural vibrational modes.
- The tidal driving may momentarily match the frequency of an oscillation mode and provoke a resonance, which abruptly extracts energy from the orbit.
- The orbital de-phasing leaves an imprint on the gravitational-wave signal.



The interface mode

- There exists an oscillation mode that arises due to the phase transition: an interfacial *i*-mode.

- A simple, analytical calculation reveals the approximate behaviour:

$$\omega^2 \approx (2\pi \times 686\,\mathrm{Hz})^2 \left(\frac{\epsilon}{0.1}\right) \left(\frac{M}{1.4 M_\odot}\right) \left(\frac{10\,\mathrm{km}}{R}\right)^3 \frac{l(l+1)}{2l+1} \left[1 - \left(\frac{r_\mathrm{i}}{R}\right)^{2l+1}\right],$$

$$Q_l = 10^{-2} \left(\frac{\epsilon}{0.1}\right)^2 M R^l \sqrt{\frac{3}{4\pi}\frac{l(l+1)}{2l+1}} \sqrt{1 - \left(\frac{r_\mathrm{i}}{R}\right)^{2l+1}} \left(\frac{r_\mathrm{i}}{R}\right)^{(2l+1)/2} \left[1 - \left(\frac{r_\mathrm{i}}{R}\right)^3\right].$$

- *Cf.*, *g*-modes have $\omega/(2\pi) \sim 10 - 100\,\mathrm{Hz}$ and $Q_2/(MR^2) \sim 10^{-5} - 10^{-4}$.

Observational prospects

Relativistic calculation

- To quantify the extent to which the associated tidal resonance may be detectable, we compute the *i*-modes in general relativity using a large ensemble of (2000) matter models motivated by chiral EFT.

- The orbital shift due to the resonance is

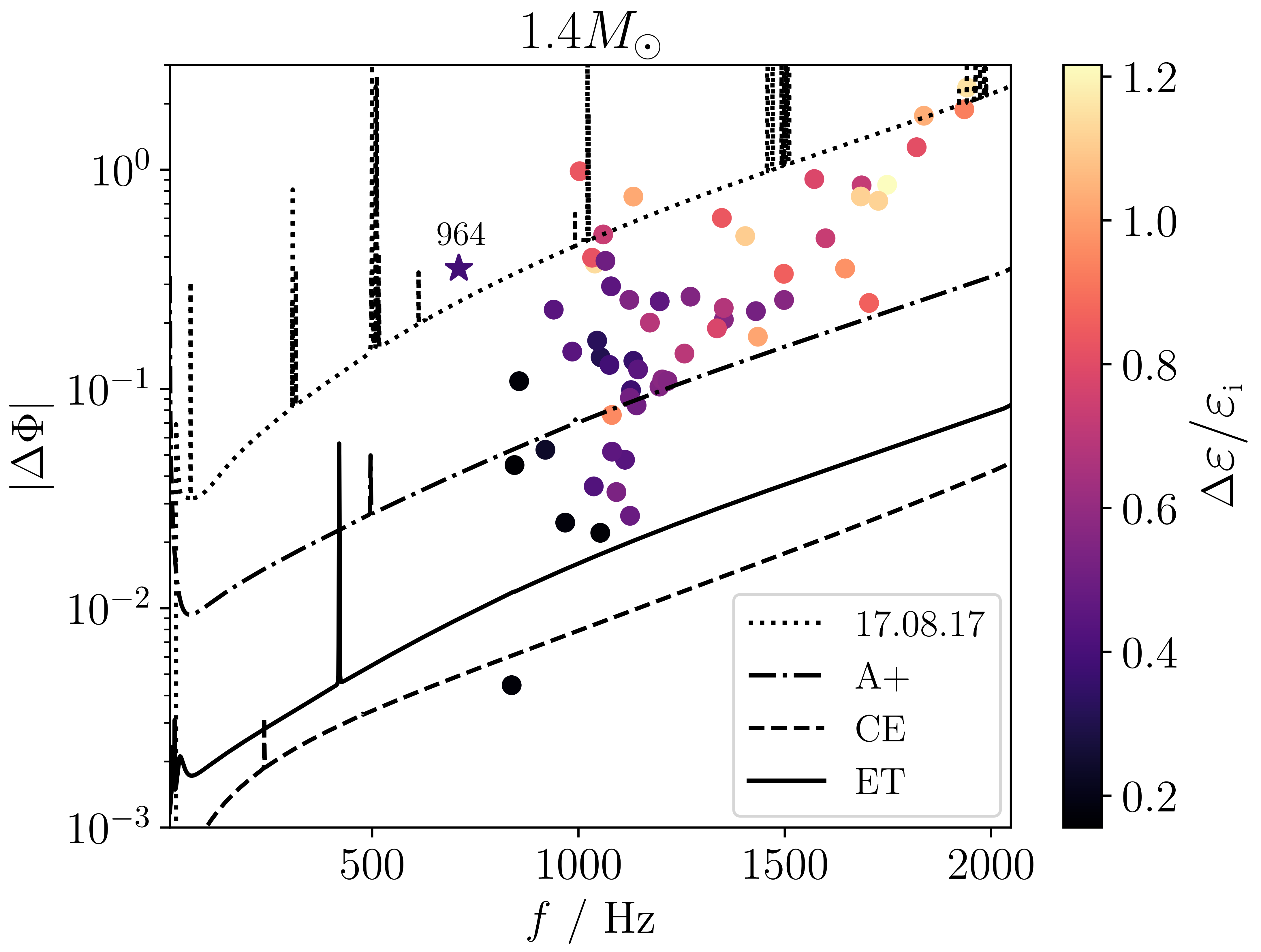
$$\frac{\Delta\Phi}{2\pi} = -\frac{5\pi}{4096}\left(\frac{c^2R}{GM}\right)^5 \frac{2}{q(1+q)}\frac{GM/R^3}{\omega^2}\left(\frac{Q_l}{MR^l}\right)^2 .$$

- We compare these results with estimates of detector sensitivities for a binary at $40\,\mathrm{Mpc}$,

$$|\Delta\Phi(f)| = \frac{\sqrt{S_n(f)}}{2A(f)\sqrt{f}} .$$

Resonance detectability

- The majority of interface-mode resonances would be detectable already by an instrument at the LIGO A+ level.
- The modes grant access to low-density phase transitions.



Conclusions

arXiv arXiv:2504.06181 [gr-qc]

- We report on a *smoking-gun* gravitational-wave signature of a first-order phase transition in a neutron star: the resonant tidal excitation of an interface mode.
- A single event would be sufficient to measure this feature and it would be observable even if the phase transition occurred at lower densities.
- We showed that the interface-mode resonance may be detectable with Cosmic Explorer and the Einstein Telescope, and possibly already with LIGO A+ for sufficiently loud events.
- Future work should more robustly establish the detectability of this feature with realistic waveform models.

Funded by
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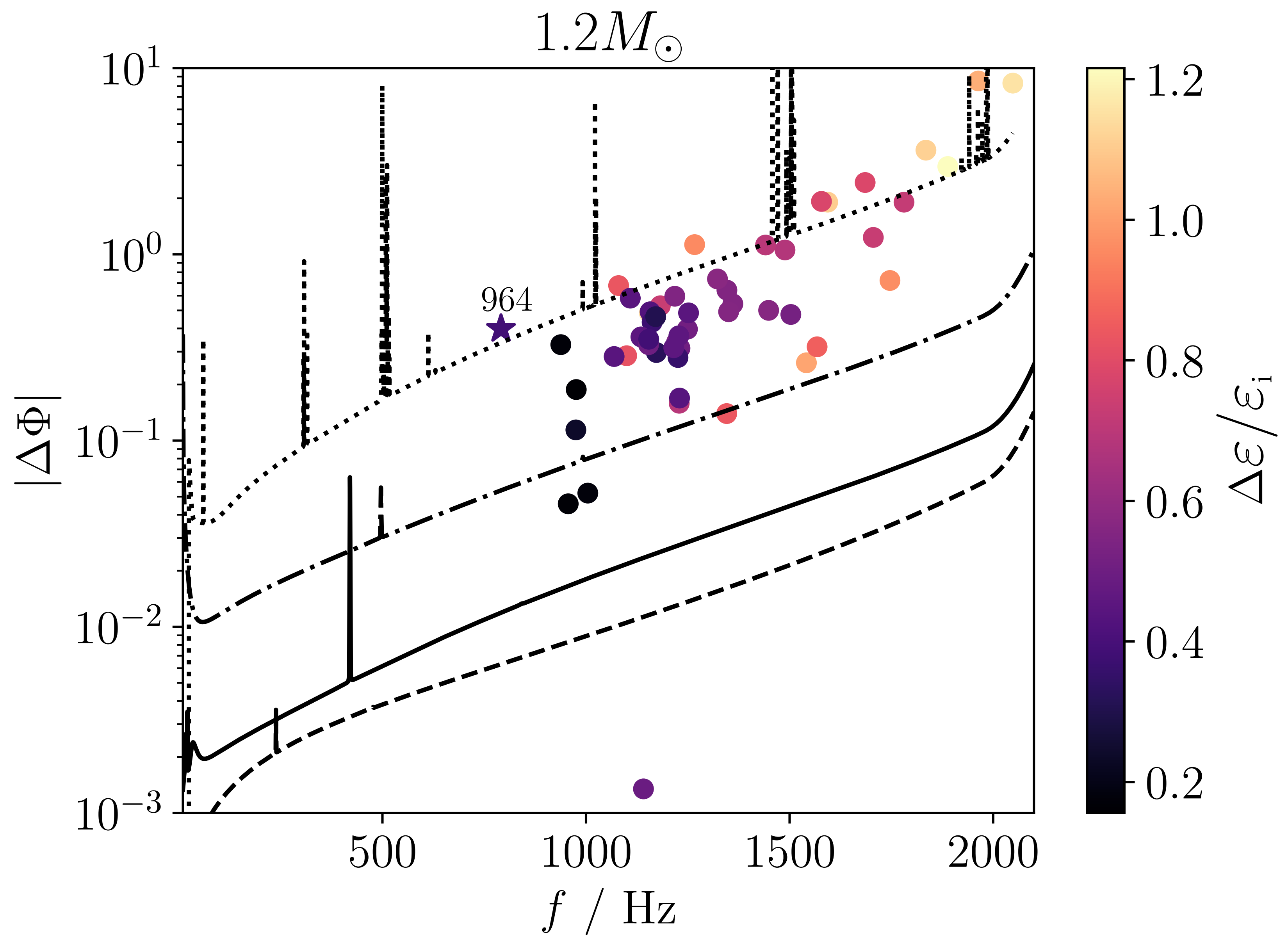
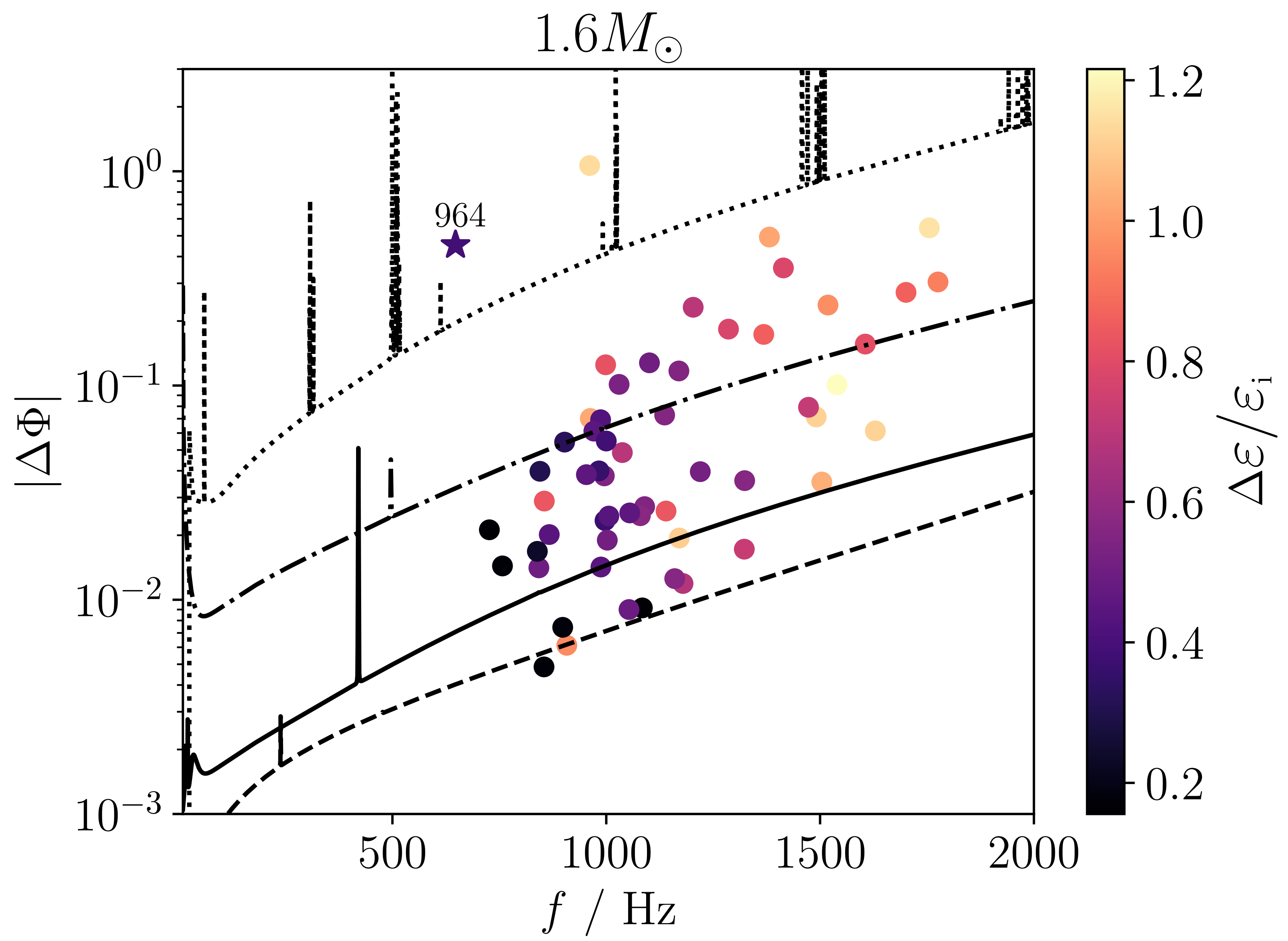
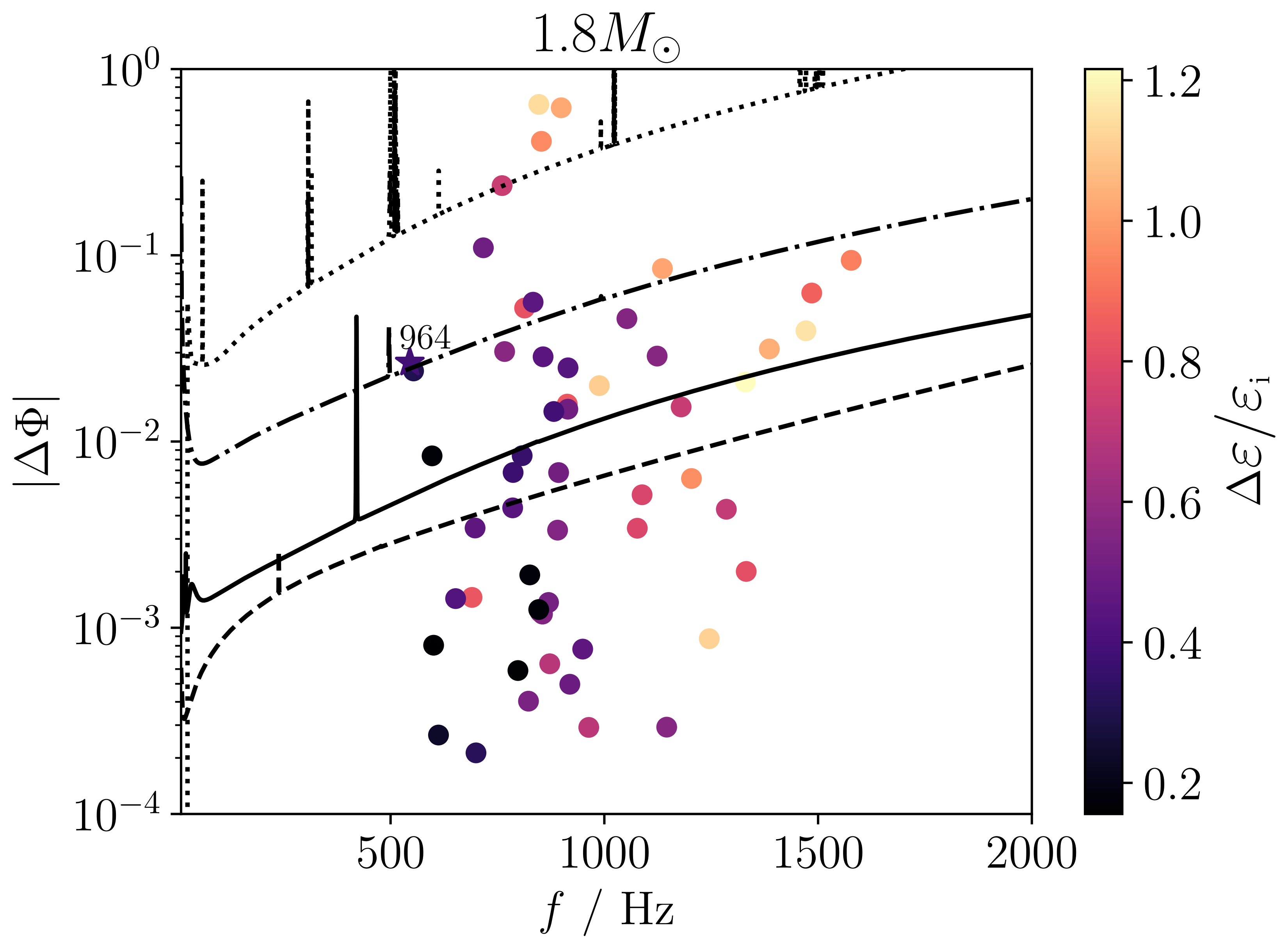
Extra slides

Additional figures I







Additional figures II