Problematic systematics in neutron-star merger simulations

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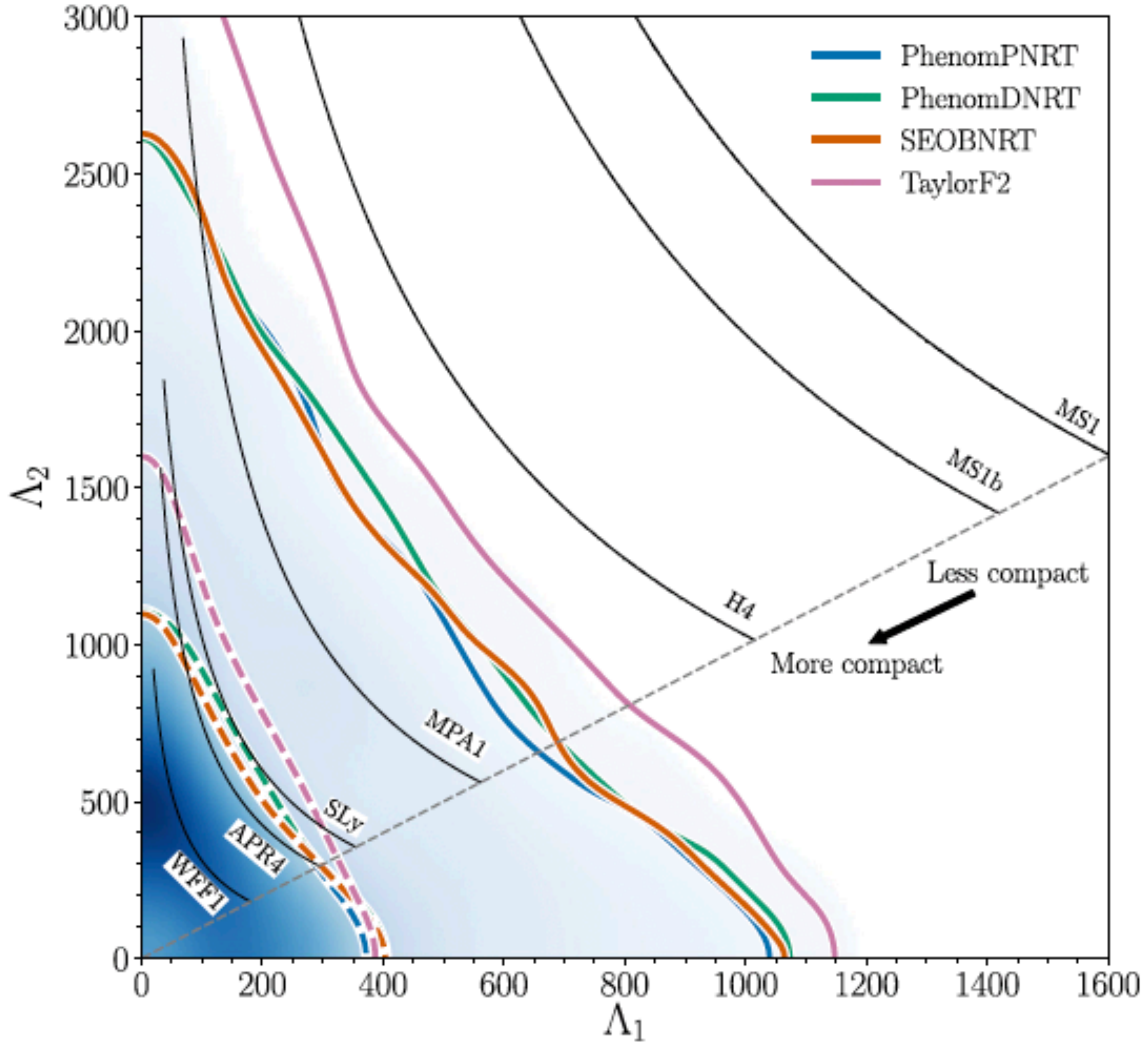
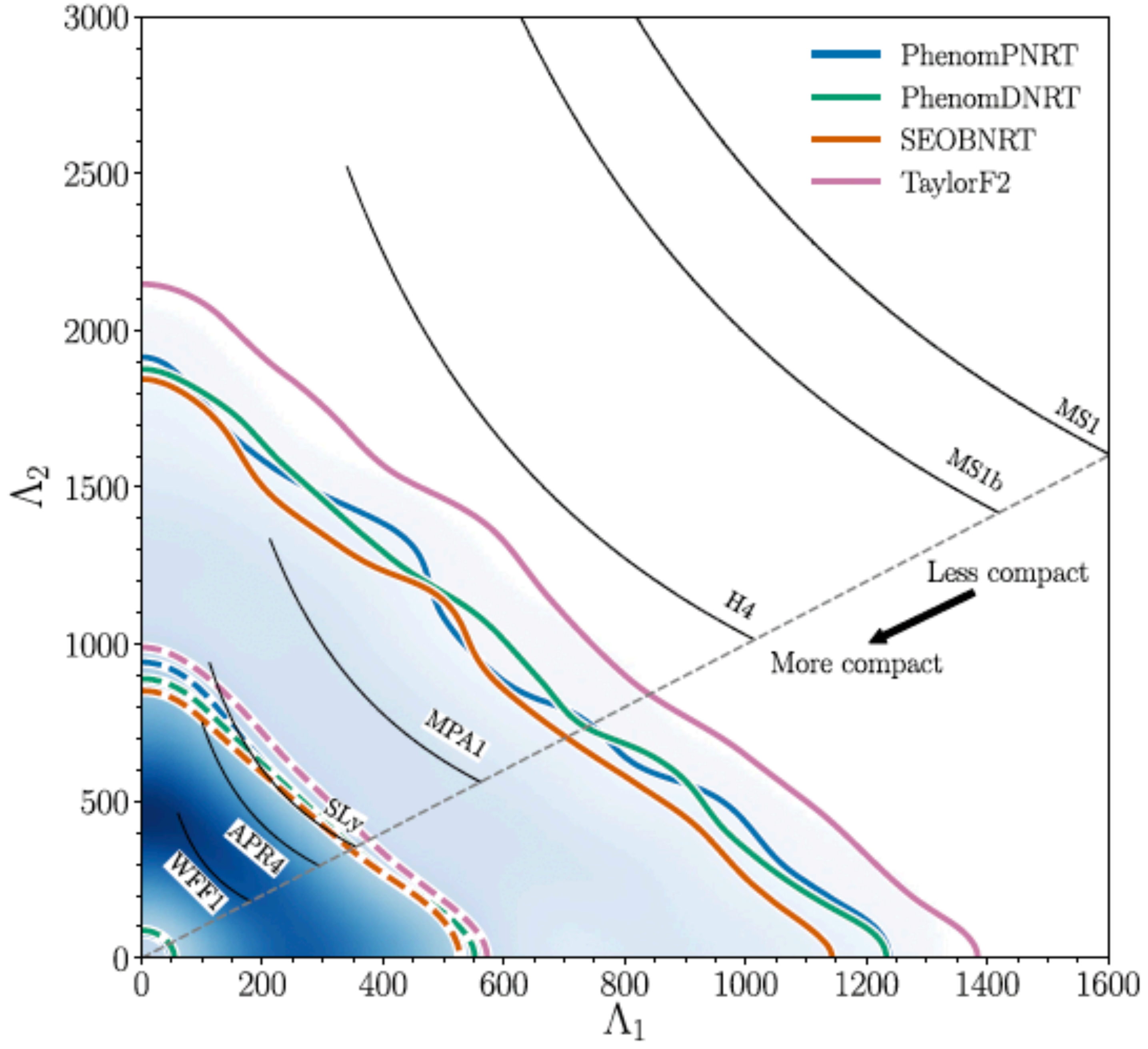
gravitational waves and nuclear matter





[Abbott+, Phys. Rev. X **9**, 011001 (2019)]

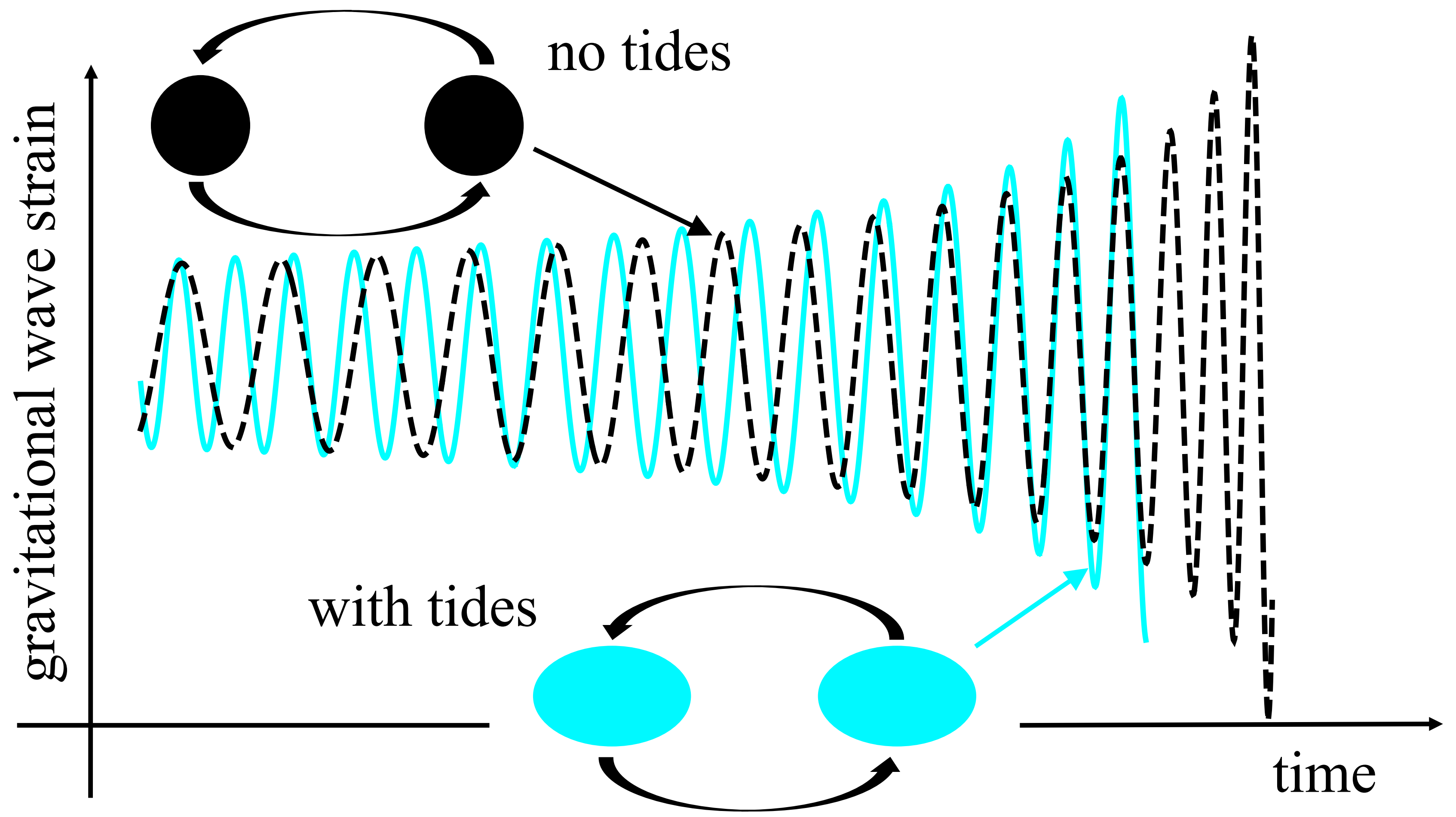
- GW170817 demonstrated that we can use gravitational-wave observations of neutron-star binaries to constrain dense nuclear matter.
- It was the *absence* of a distinguishable imprint in the signal that provided upper limits on the stars' *tidal deformabilities* Λ_1 and Λ_2.
- Although this is the only event for which these constraints have been obtained, this is expected to change with next-generation interferometers, the Einstein Telescope and Cosmic Explorer, designed to be a factor of 50 more sensitive.

- In Newtonian gravity, the tidal susceptibility of the star is characterised by its (gravito-electric/polar) *Love numbers* k_l, which depend on the equation of state of the stellar material.

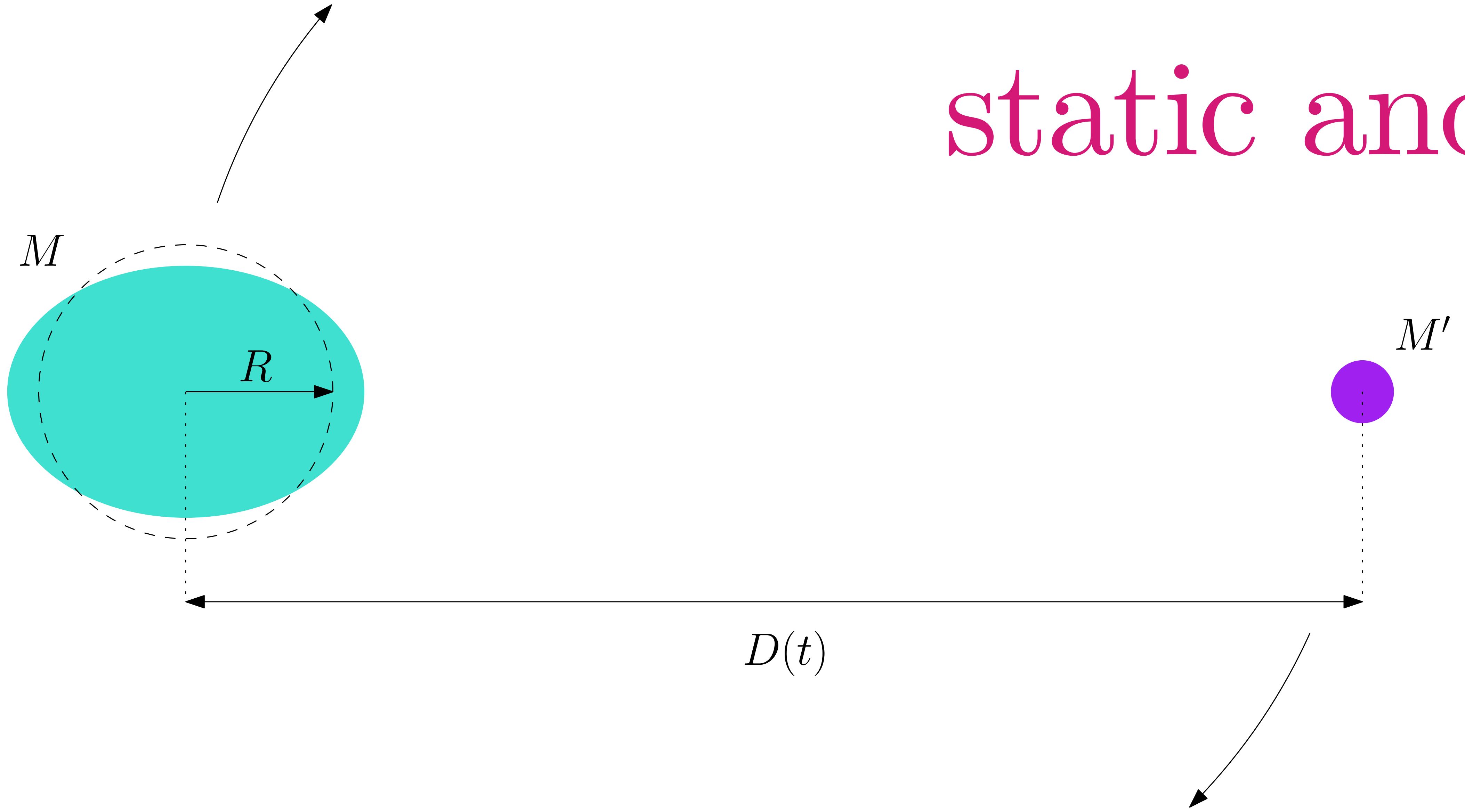
- (In general relativity, new Love numbers manifest, such as the gravito-magnetic/axial and rotational Love numbers.)

- The quadrupolar Love numbers k_2 of the binary components enter the waveform phase Ψ at 5PN, providing a small (but cumulative) contribution throughout the inspiral.

$$Q_{jk} = -\frac{2}{3}k_2 R^5 \mathscr{E}_{jk} = -\Lambda M^5 \mathscr{E}_{jk}$$



static and dynamical tides



- It is useful to decompose the inspiral into two separate regimes.

  (i) *The static tide*: The external field due to the companion is slowly varying, $\lambda = m\dot{\Psi}/\omega_\alpha \ll 1$. This regime is valid when the stars are well separated and is accessible with current instruments; being used to constrain the tidal interaction in GW170817.

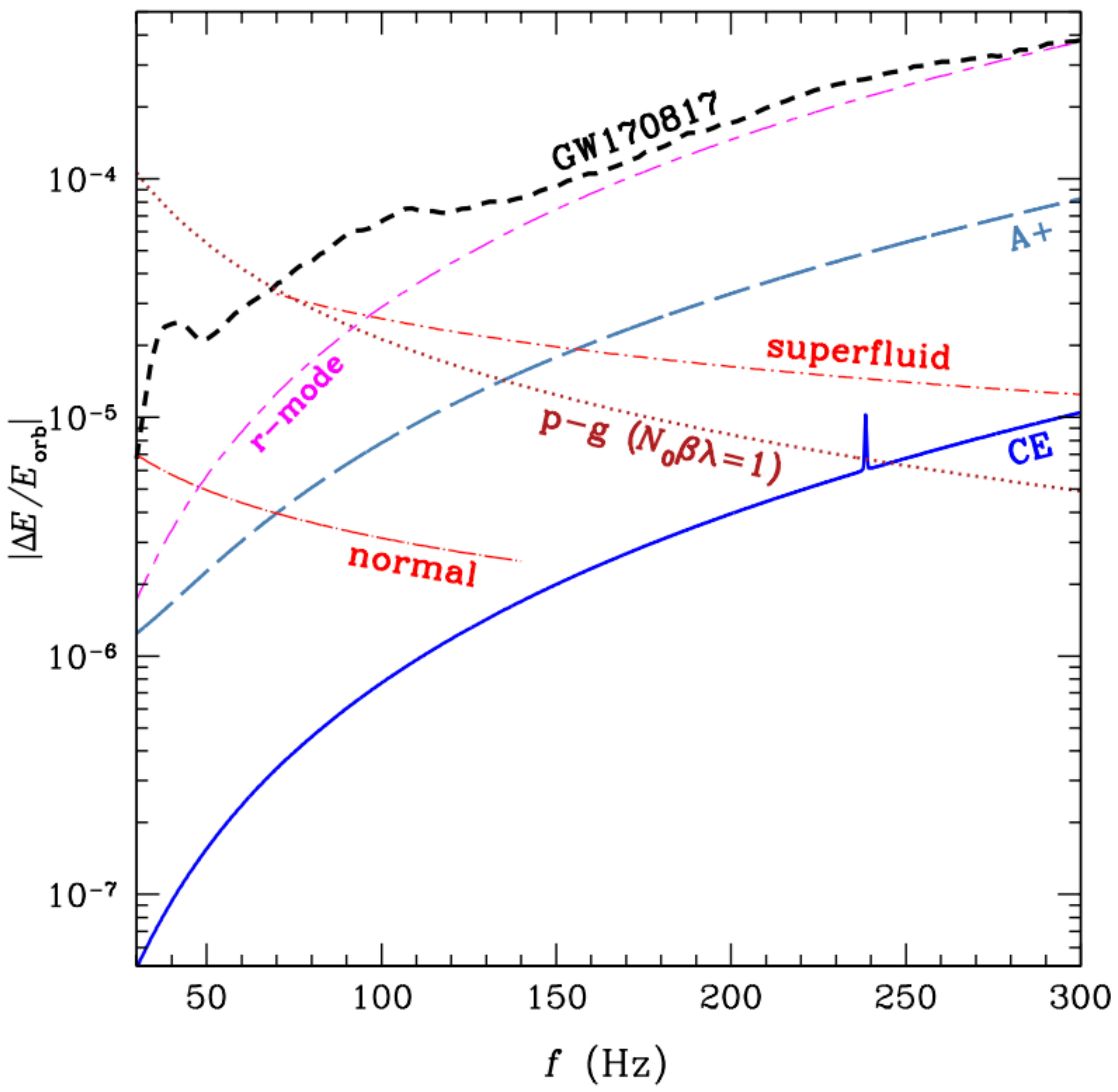
  (ii) *The dynamical tide*: As the compact objects inspiral, the orbital frequency increases such that it eventually becomes comparable to the neutron star's oscillation modes, $\lambda = O(1)$, some of which may become excited.

next-generation observatories

- The dynamical tide contains information about the rich spectrum of neutron-star oscillation modes, which depend on the nuclear microphysics.

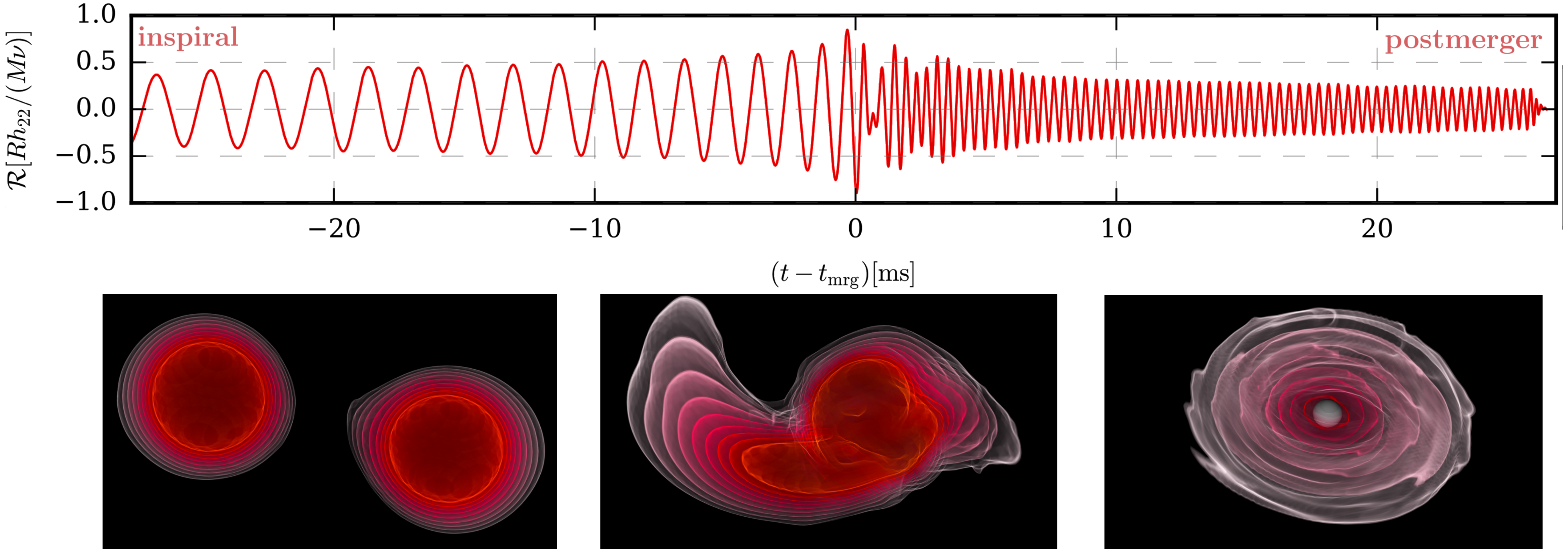
- The Einstein Telescope and Cosmic Explorer will possess even greater sensitivity to the dynamical tide than previously anticipated [Ho+Andersson, Phys. Rev. D **108**, 061104 (2023)].

- Neglecting these effects could introduce severe biases in equation-of-state inference [Pratten+, Phys. Rev. Lett. **129**, 081102 (2022)].



[Ho+Andersson (2023)]

role of simulations



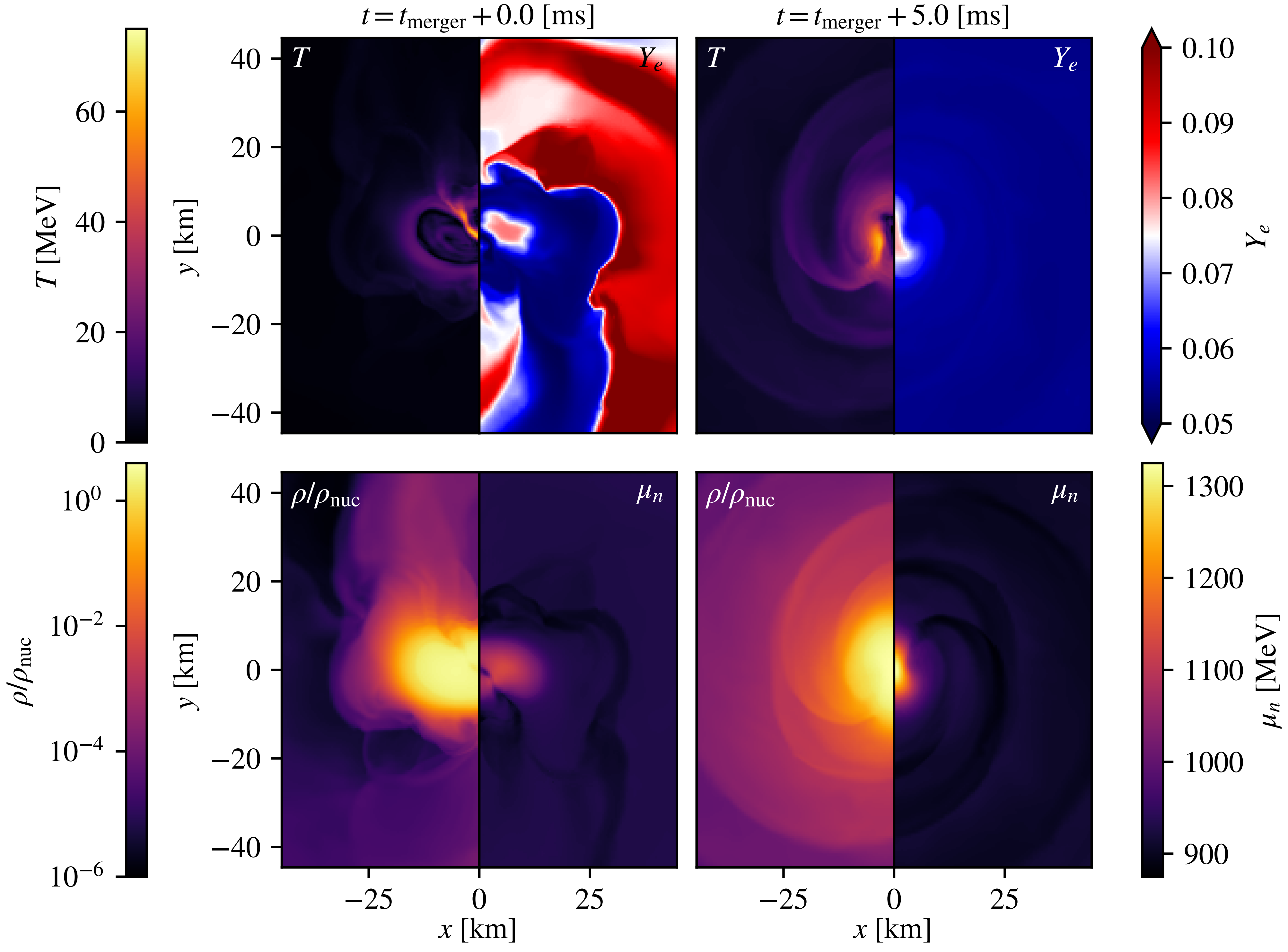
[Dietrich+, Gen. Relativ. Gravit. **53**, 27 (2021)]

- Gravitational-waveform models rely on matching post-Newtonian, inspiral waveforms to those generated from computationally expensive, numerical-relativity simulations.

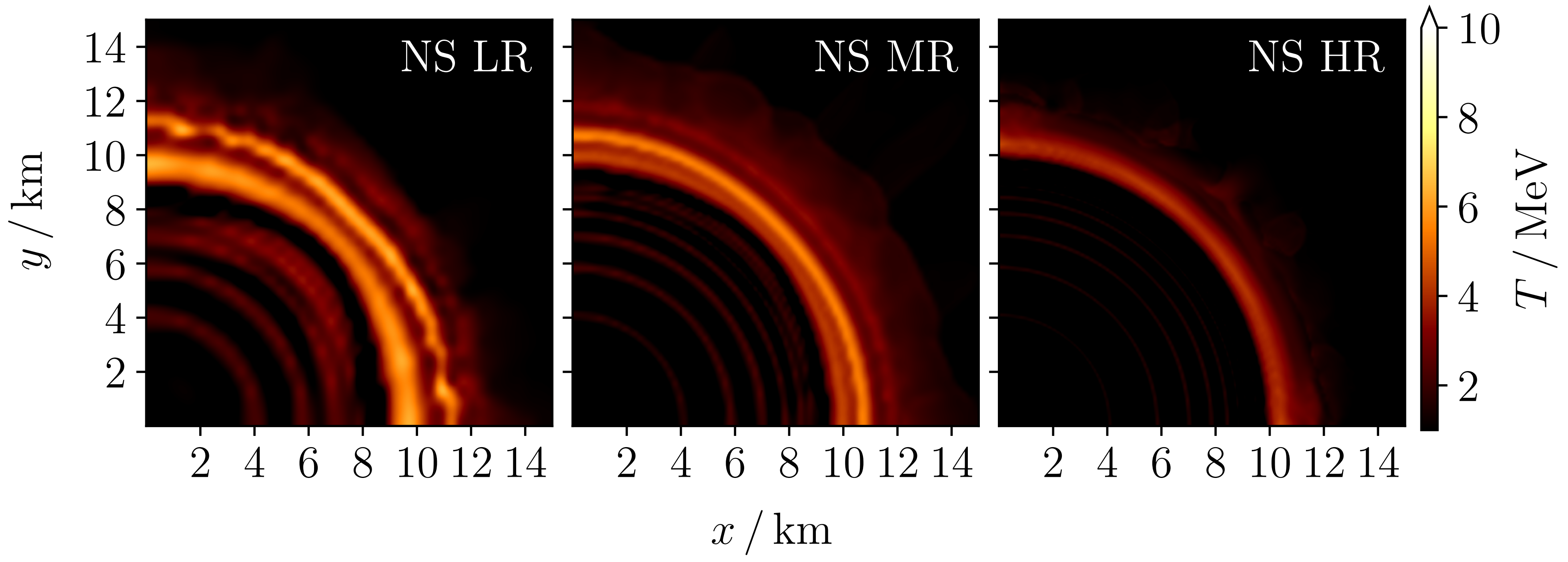
- The state of the art relies on data from simulations that implement piecewise-polytropic fits of one-parameter nuclear models, implicitly assuming the stellar material to be cold and in equilibrium.

- Since realistic mergers are hot, out-of-equilibrium events, we ultimately need to work towards calibrations based on finite-temperature simulations.

hot simulations



[Hammond+ (2021)]



[R. Matur]

- Simulations of neutron-star mergers get *artificially* hot [Perego+, Eur. Phys. J. A **55**, 124 (2021); Endrizzi+, Eur. Phys. J. A **56**, 15 (2020); Prakash+, Phys. Rev. D **104**, 083029 (2021); Hammond+, Phys. Rev. D **104**, 103006 (2021)].

- Shock heating associated with the merger heats the matter up to extreme temperatures.

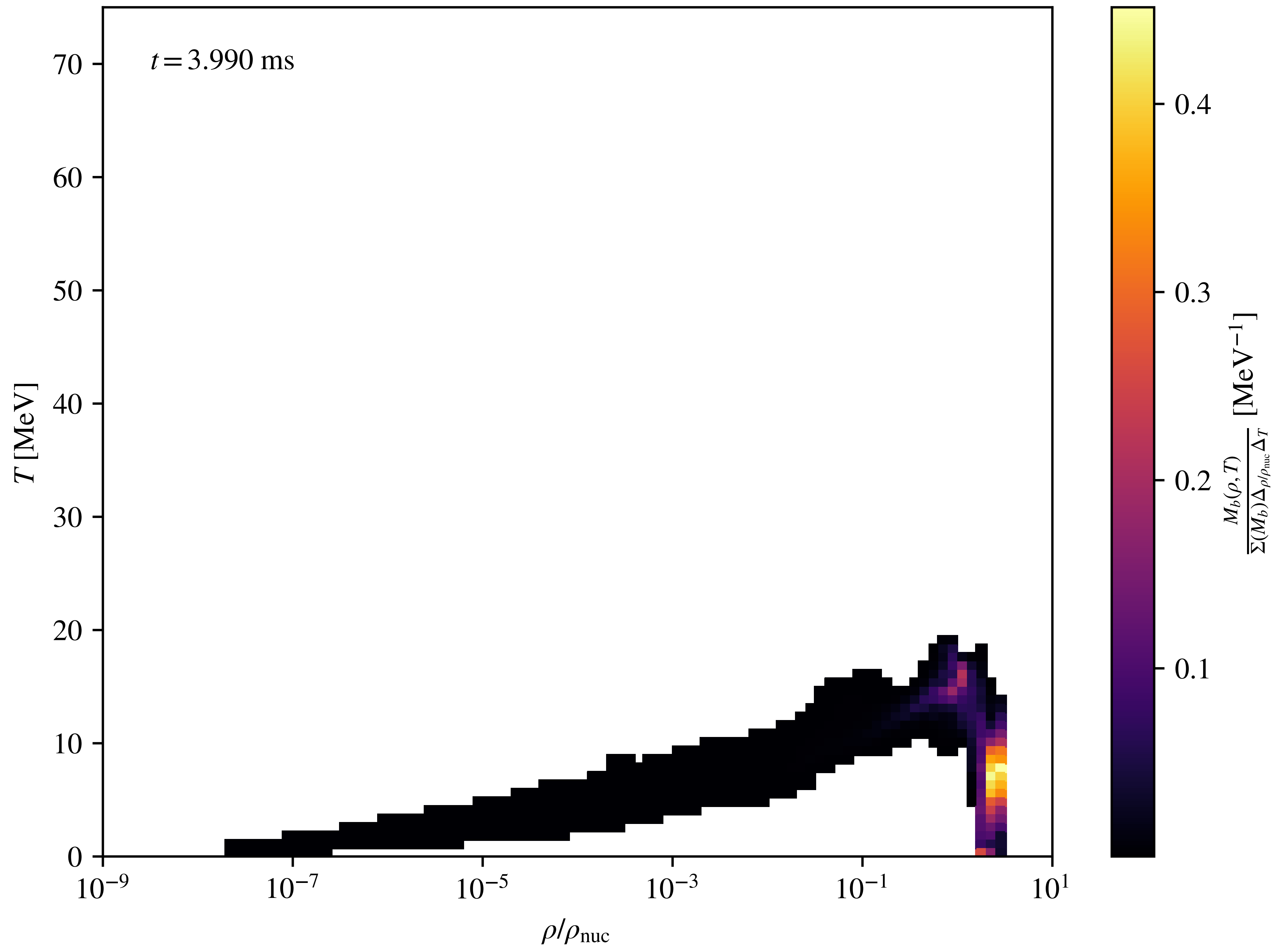
- During the inspiral, the stellar surface reaches order $10\,\mathrm{MeV} \approx 1.16 \times 10^{11}\ \mathrm{K}$. This leads to systematics already at the beginning of the simulations.*

*Cf., mature neutron stars are $\sim 10^6\ \mathrm{K}$.

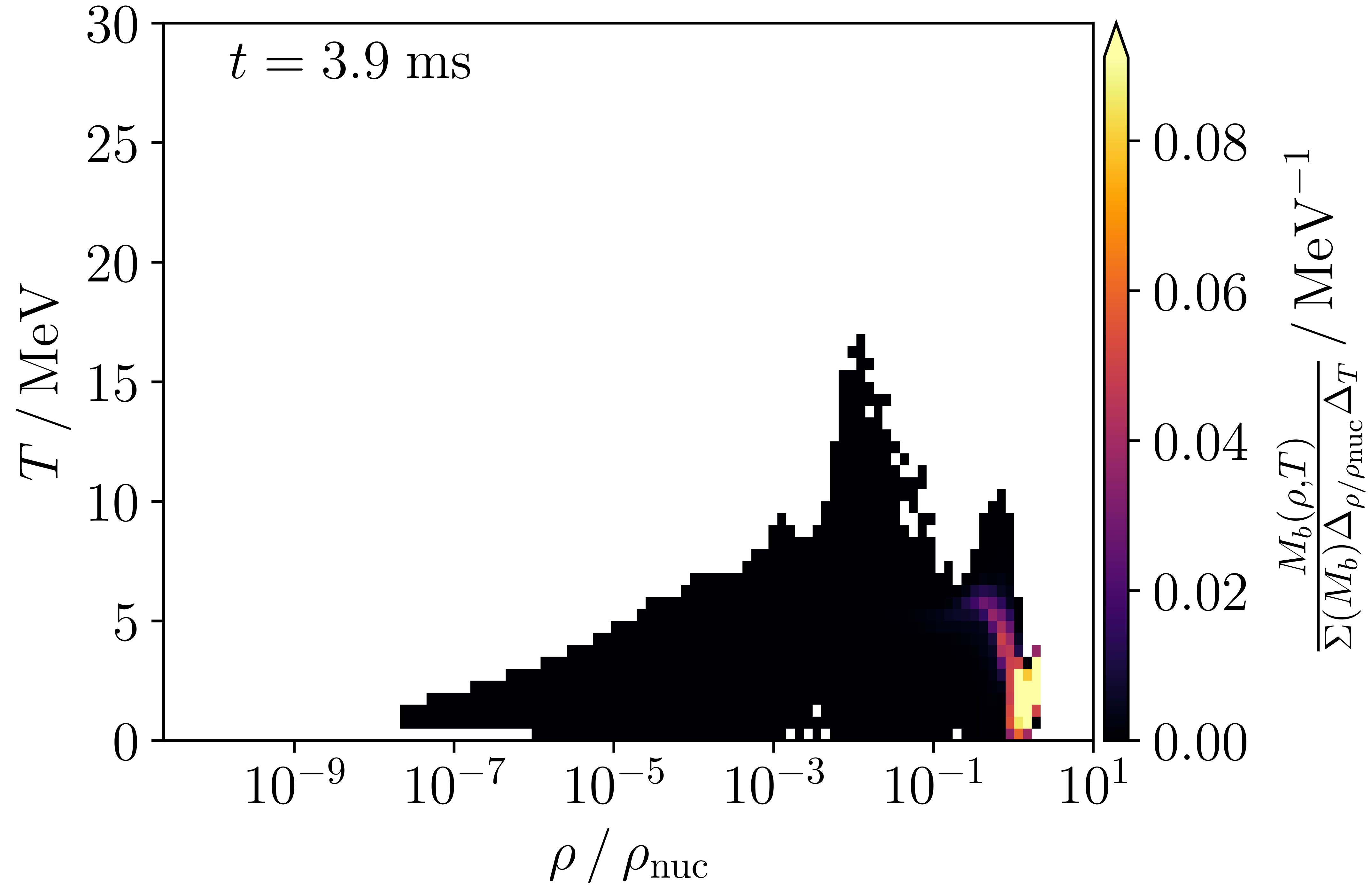
impact on tidal dynamics I

- To explore the effects of temperature, we use results from two separate inspiral-merger simulations.

1. `Einstein Toolkit`, APR matter
2. `WhiskyTHC`, DD2 matter



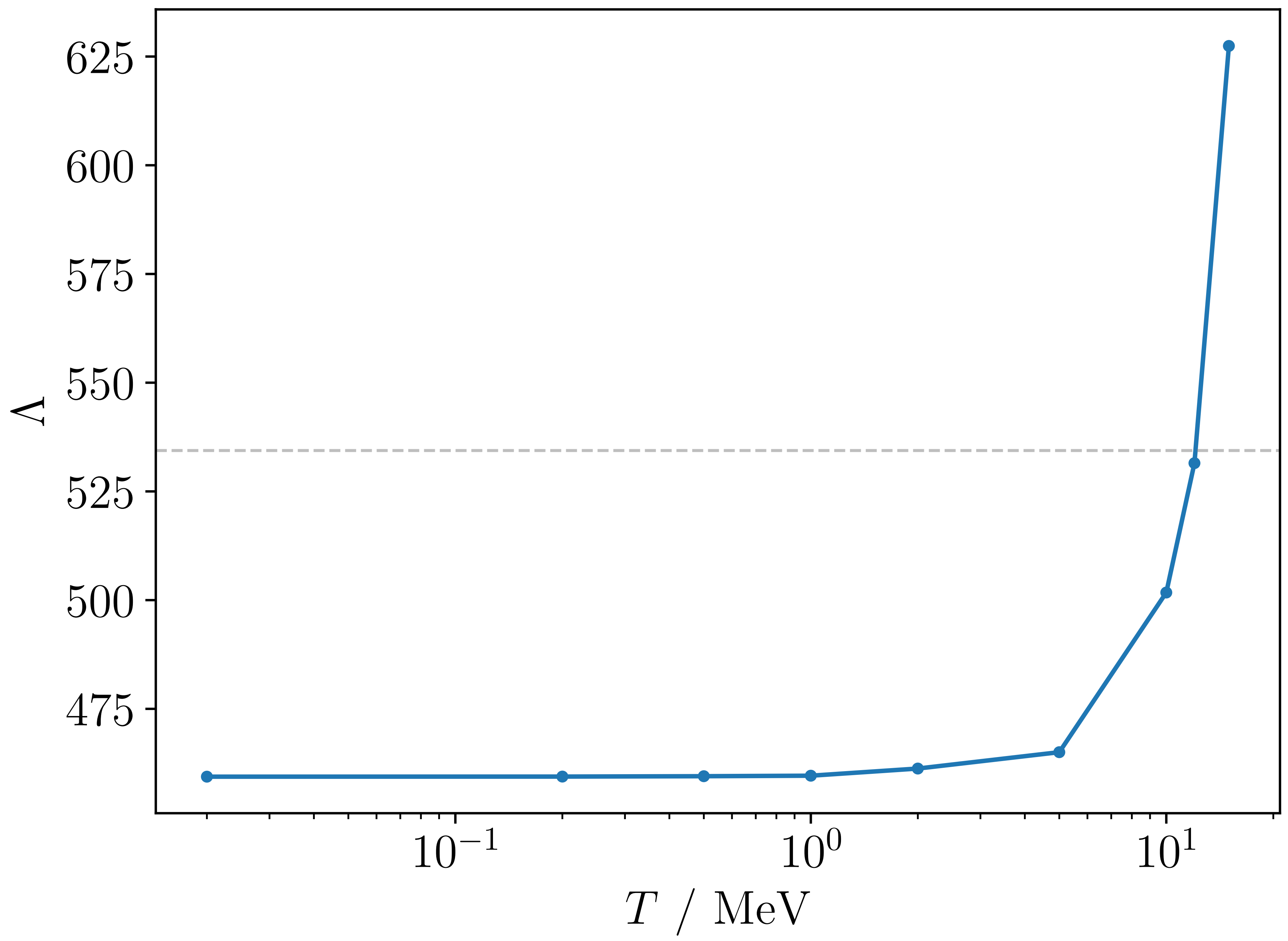
[Hammond+ (2021)]

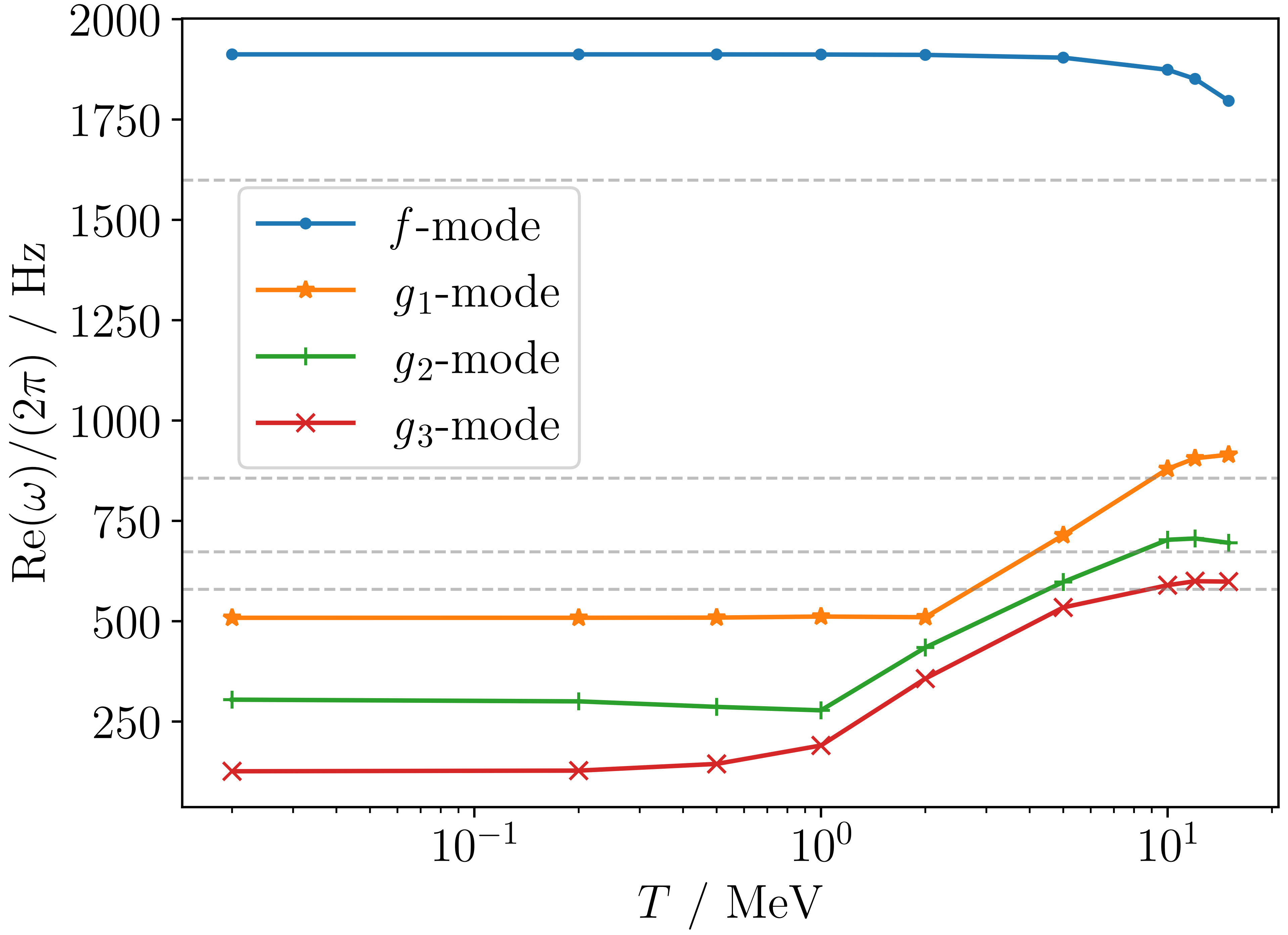


[R. Matur]

impact on tidal dynamics II

- We determine the tidal deformability Λ and the mode frequencies ω_α (to represent the dynamical tide) of a neutron star immersed in the simulation temperature profiles.



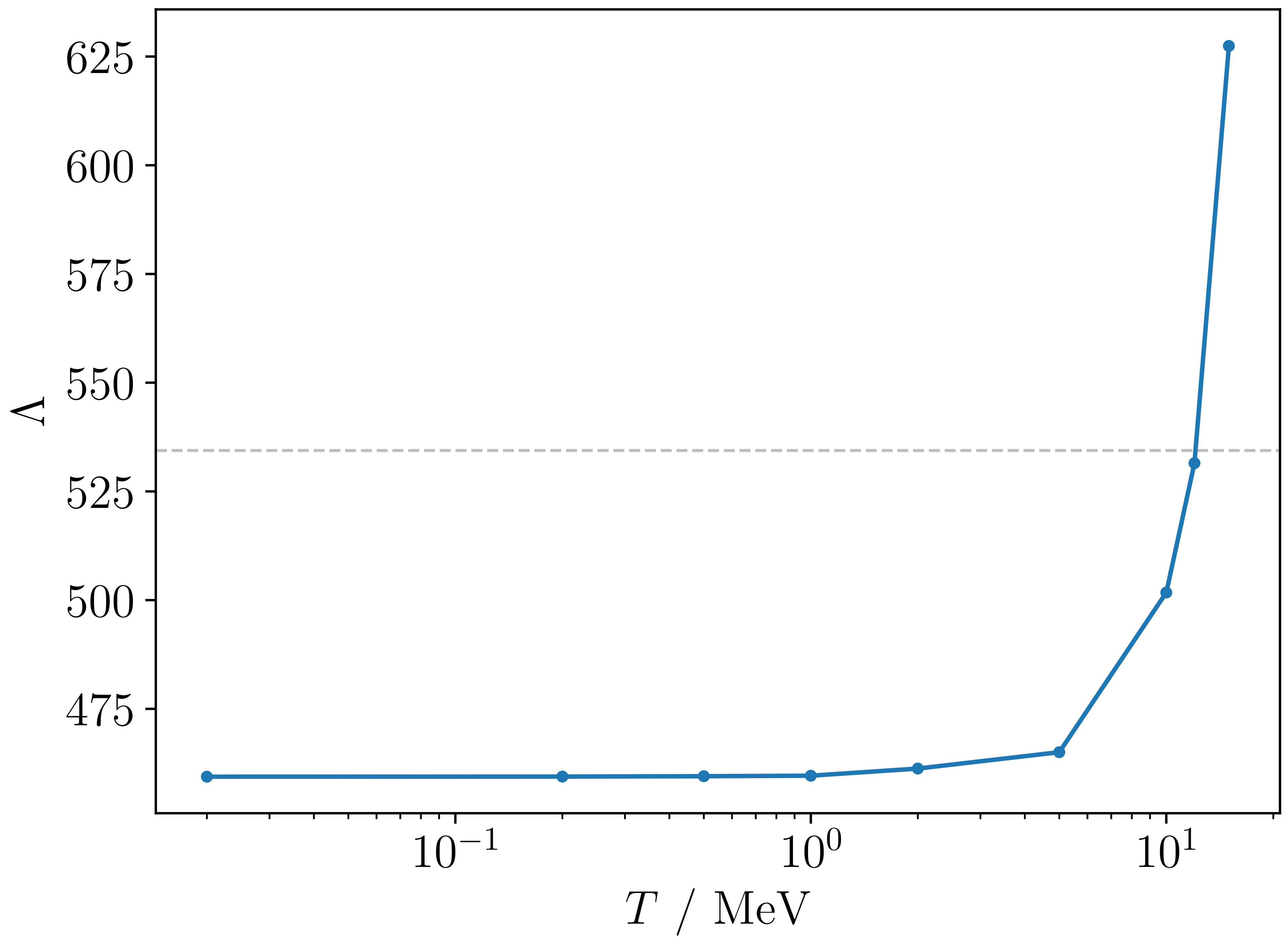


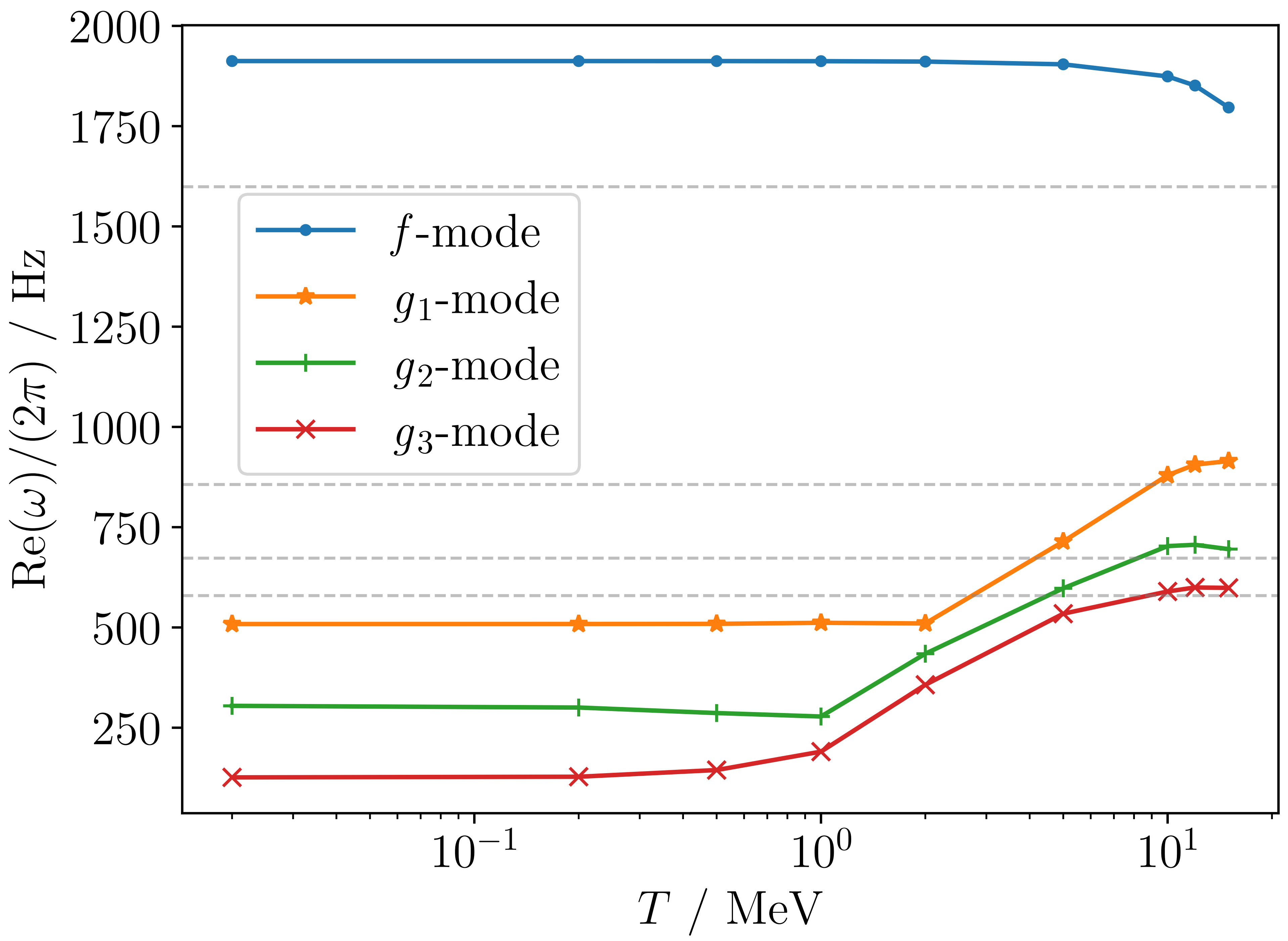
APR Simulation

impact on tidal dynamics III

- The tidal deformability changes by $16\,\%$ with respect to the colder star for the APR simulation. The difference is even starker with DD2, where the increase is by $25\,\%$.

- Therefore, we need to be very careful with systematic errors from simulations with this effect.





APR Simulation

cautionary remarks

- Take-home message: If we were to use results from finite-temperature simulations to calibrate gravitational waveforms, we may incur considerable systematic error in the parameter inference.

- Future work will need to be dedicated to either reducing the systematics or correcting for them in the gravitational-wave analyses.

- We expect these features to be generic for all grid-based numerical-relativity codes. It would be useful to explore the extent to which the features arise in particle-based simulations [Bauswein+, Phys. Rev. D **90**, 023002 (2014); Rosswog+Diener, arXiv:2024.15952 (2024)].

summary

- The Einstein Telescope and Cosmic Explorer will have enhanced sensitivities to neutron-star coalescences and may provide the first measurement of the dynamical tide.
- We have demonstrated how the artificial temperatures encountered in numerical-relativity simulations severely distort the tidal deformability and oscillation spectrum of the neutron star.
- We need to understand the systematics in order to conduct reliable parameter inference with future gravitational-wave detections.