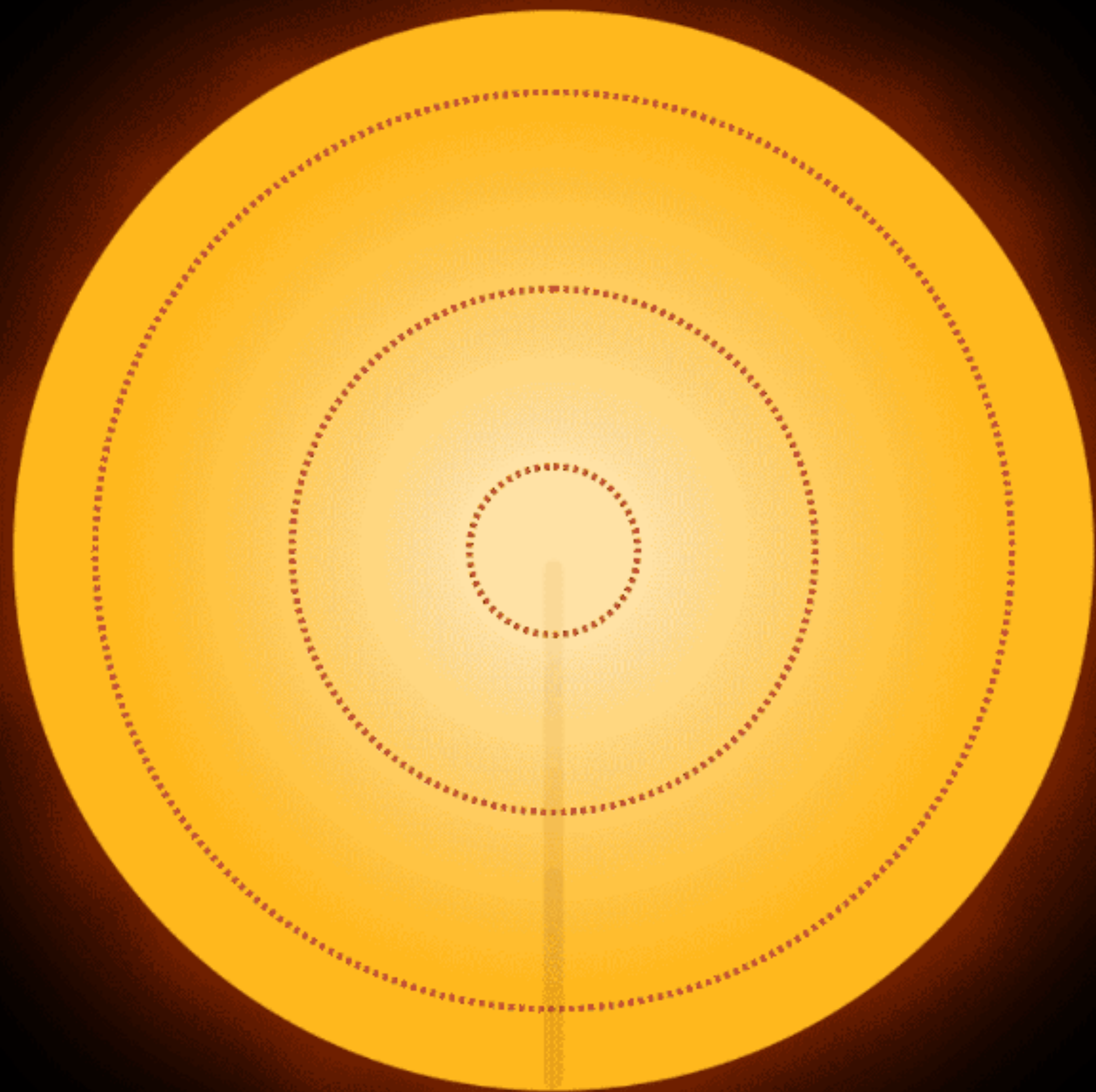


The Hidden Physics Gravitational-Wave Asteroseismology Can Reveal

Fabian Gittins | University of Maryland, Baltimore County — Physics Colloquium | Oct 7, 2026



Funded by
the European Union



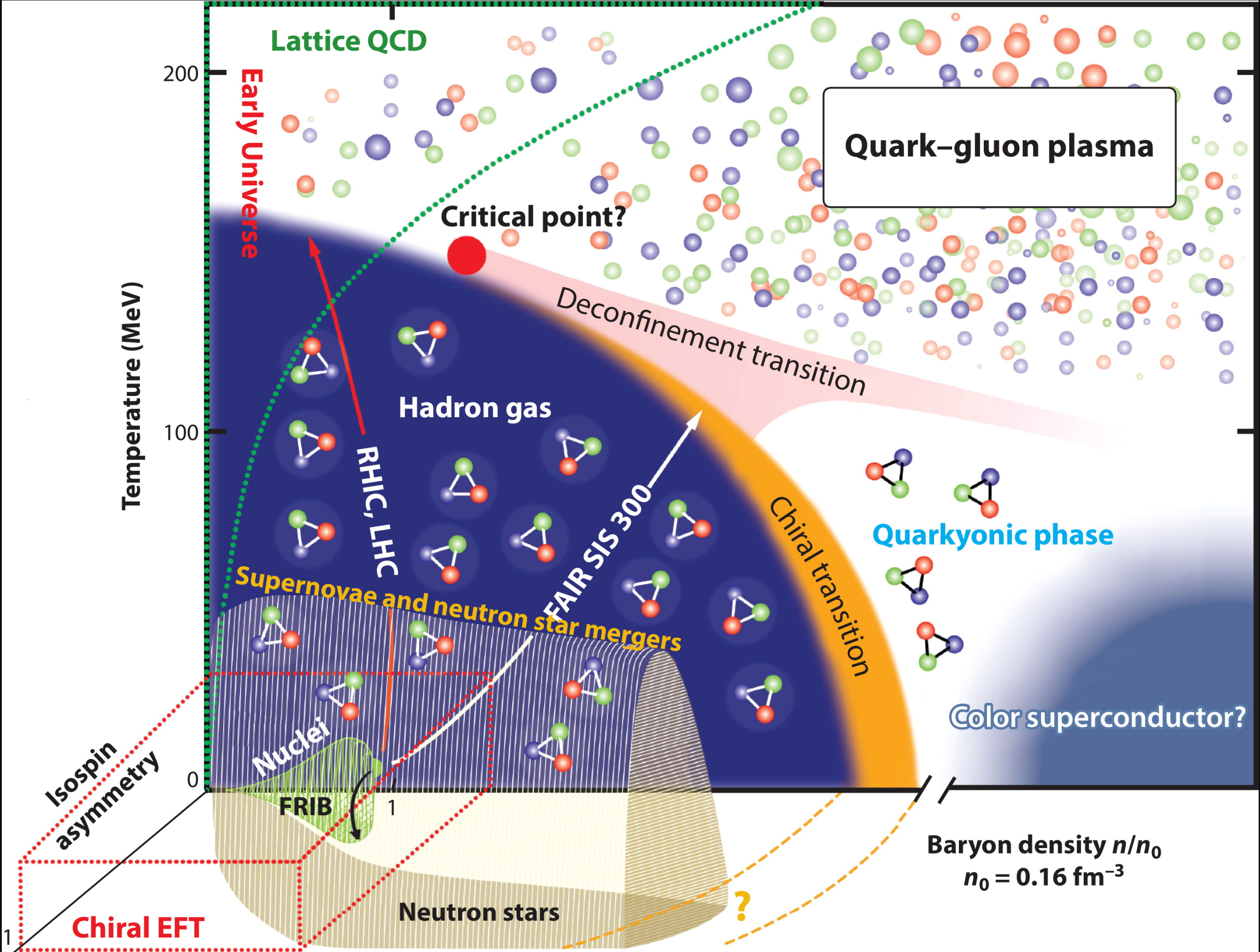
Overview

- Gravitational waves probe *nuclear physics* by observing neutron stars
- Tidal dynamics present opportunity to perform asteroseismology
- Low-frequency oscillation modes become resonantly excited...
- ...and may be measurable with gravitational-wave detectors

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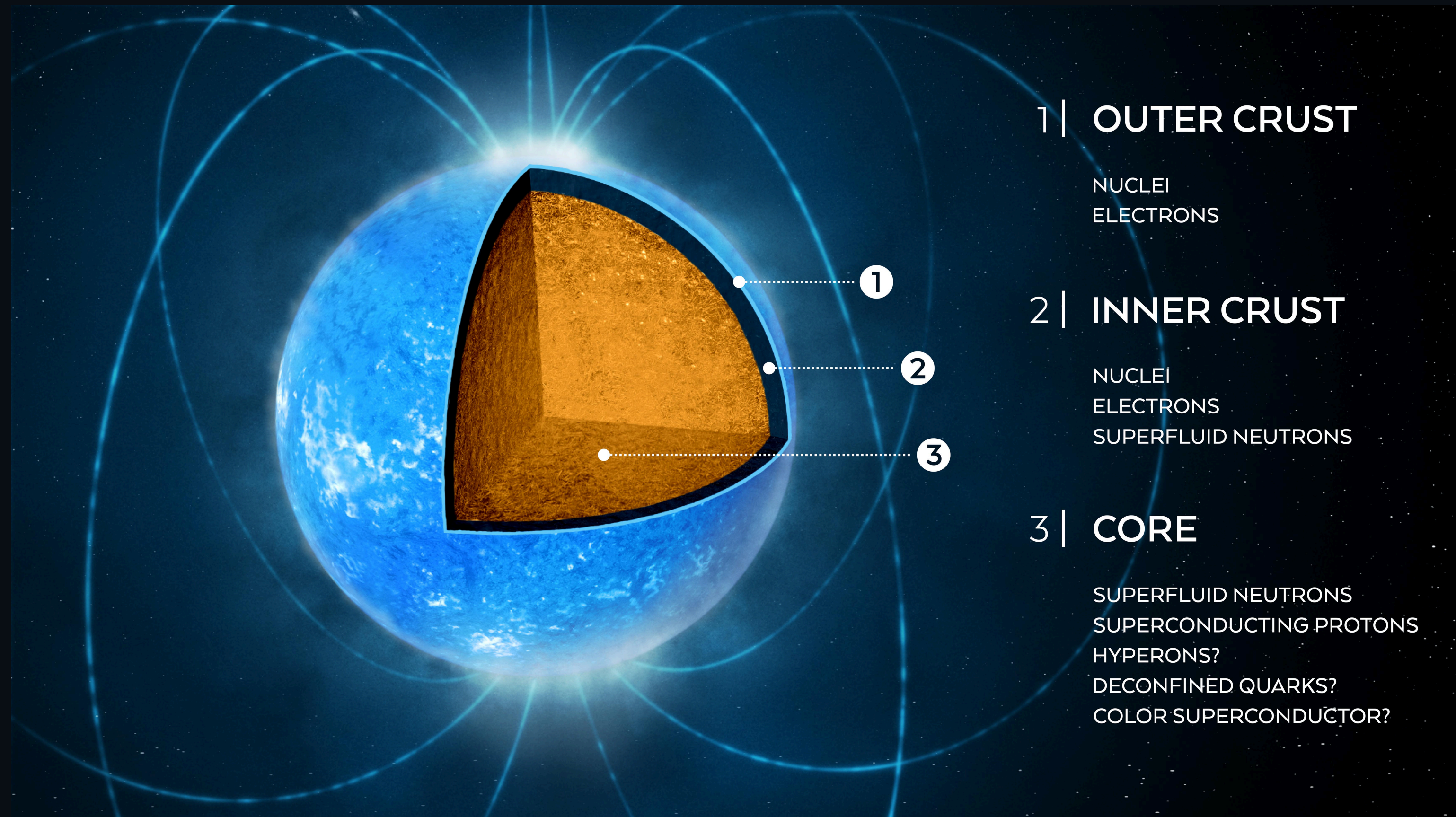
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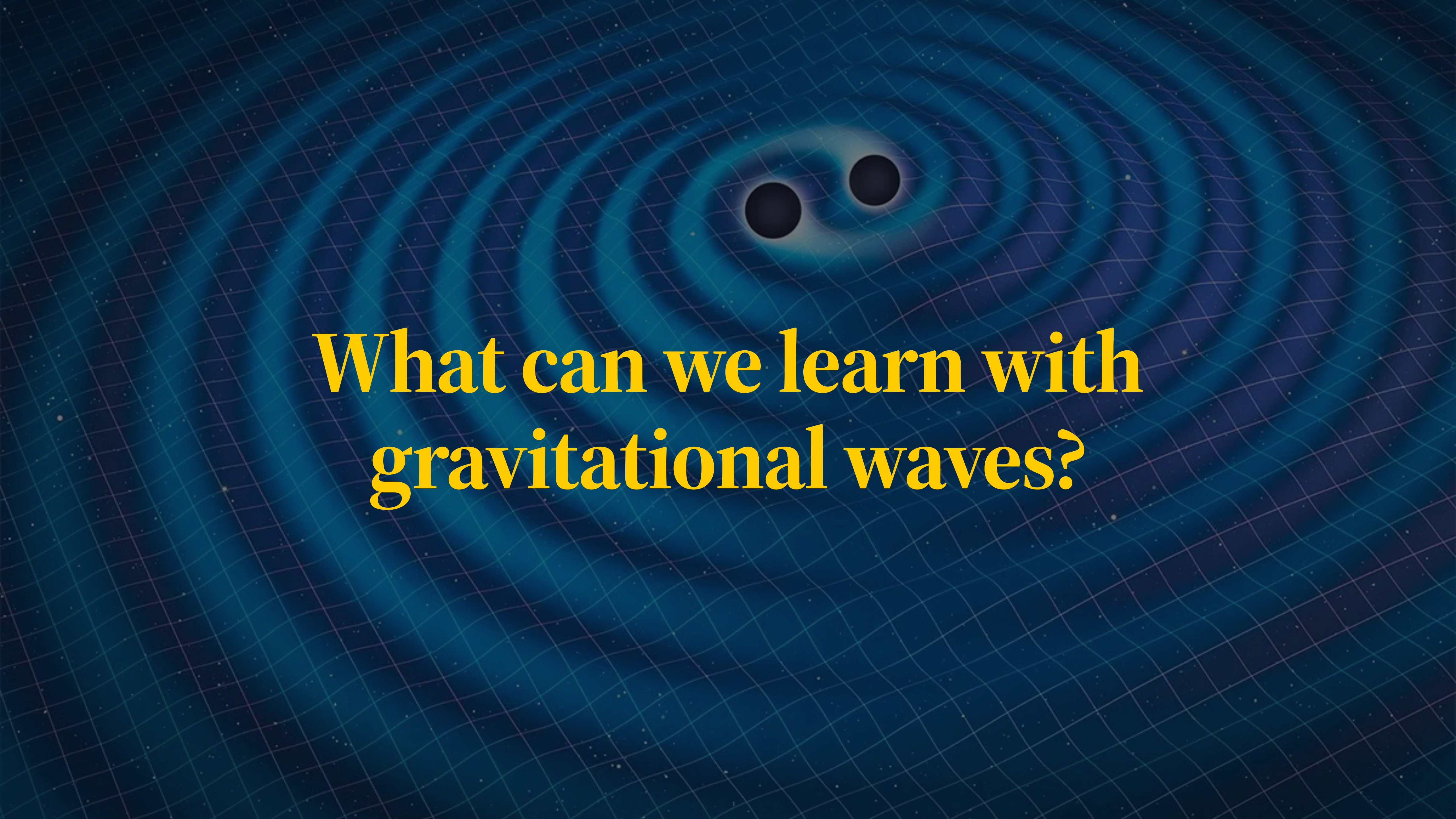
Quantum Chromodynamics (QCD)



Physics of Neutron Stars

- Neutron stars are extreme laboratories
 - Strong-field gravity
 - Dense nuclear matter
 - Rapid rotation
 - Strong magnetic fields
 - Superfluidity
 - Solid crusts

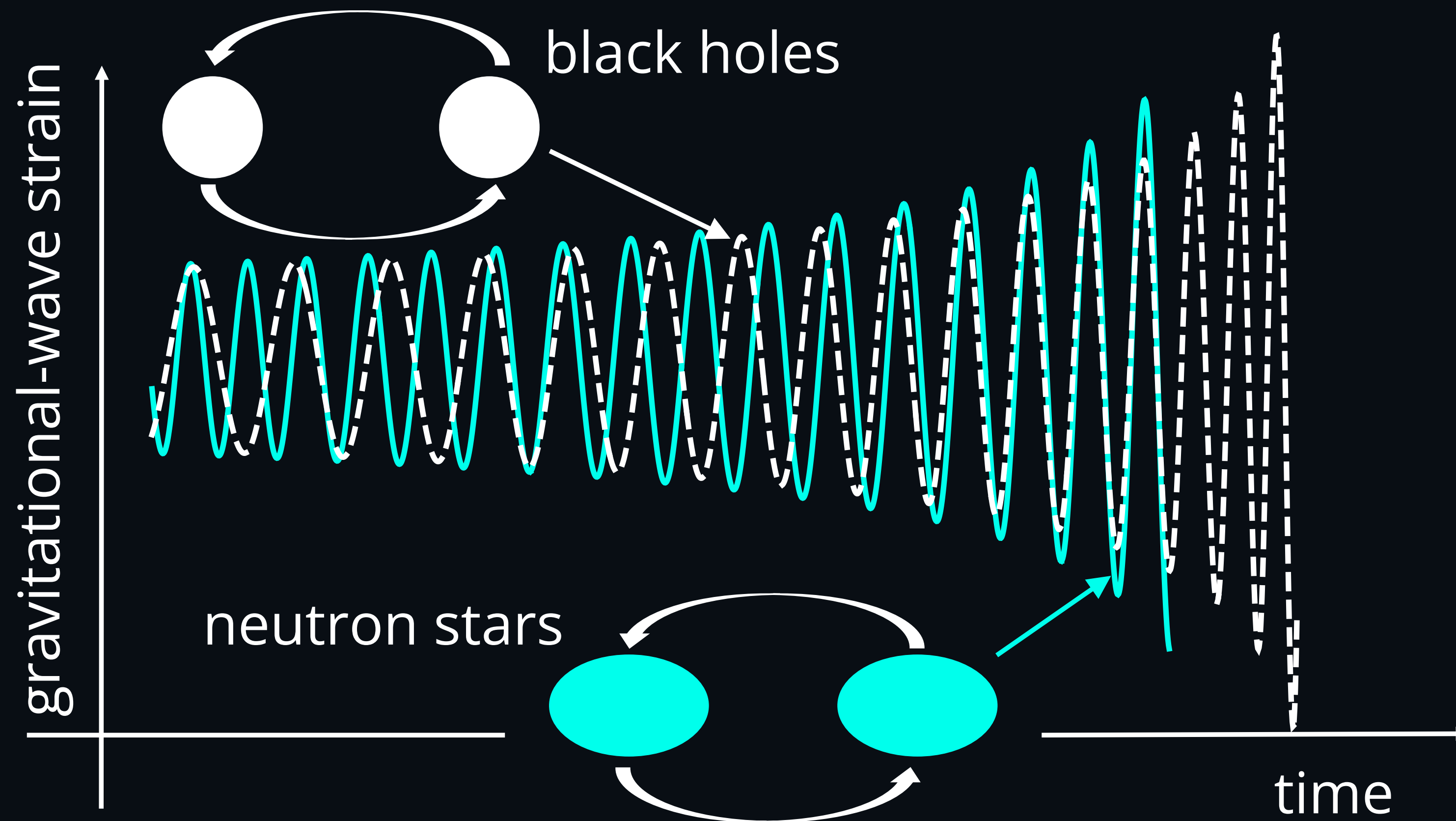


The background of the slide is a visualization of gravitational waves. It features a dark blue, grid-like pattern that represents the fabric of spacetime. In the upper center, two black circles represent merging black holes. Concentric, glowing blue rings emanate from these circles, illustrating the ripples in spacetime as gravitational waves travel outward. The overall effect is a sense of dynamic, curved space.

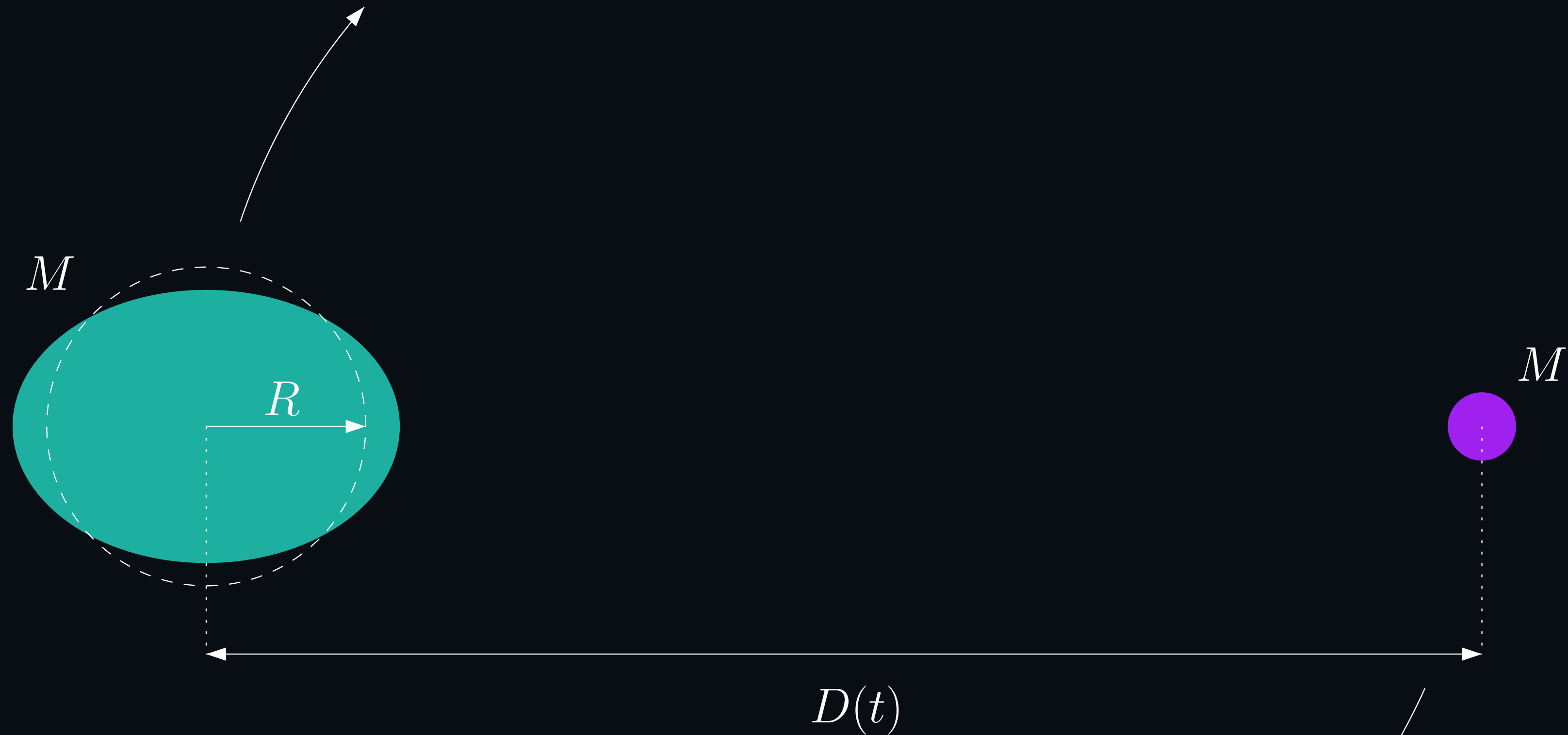
**What can we learn with
gravitational waves?**

Finite-Size Effects

- Consider two compact binaries: one with **black holes**, while the other comprises **neutron stars**

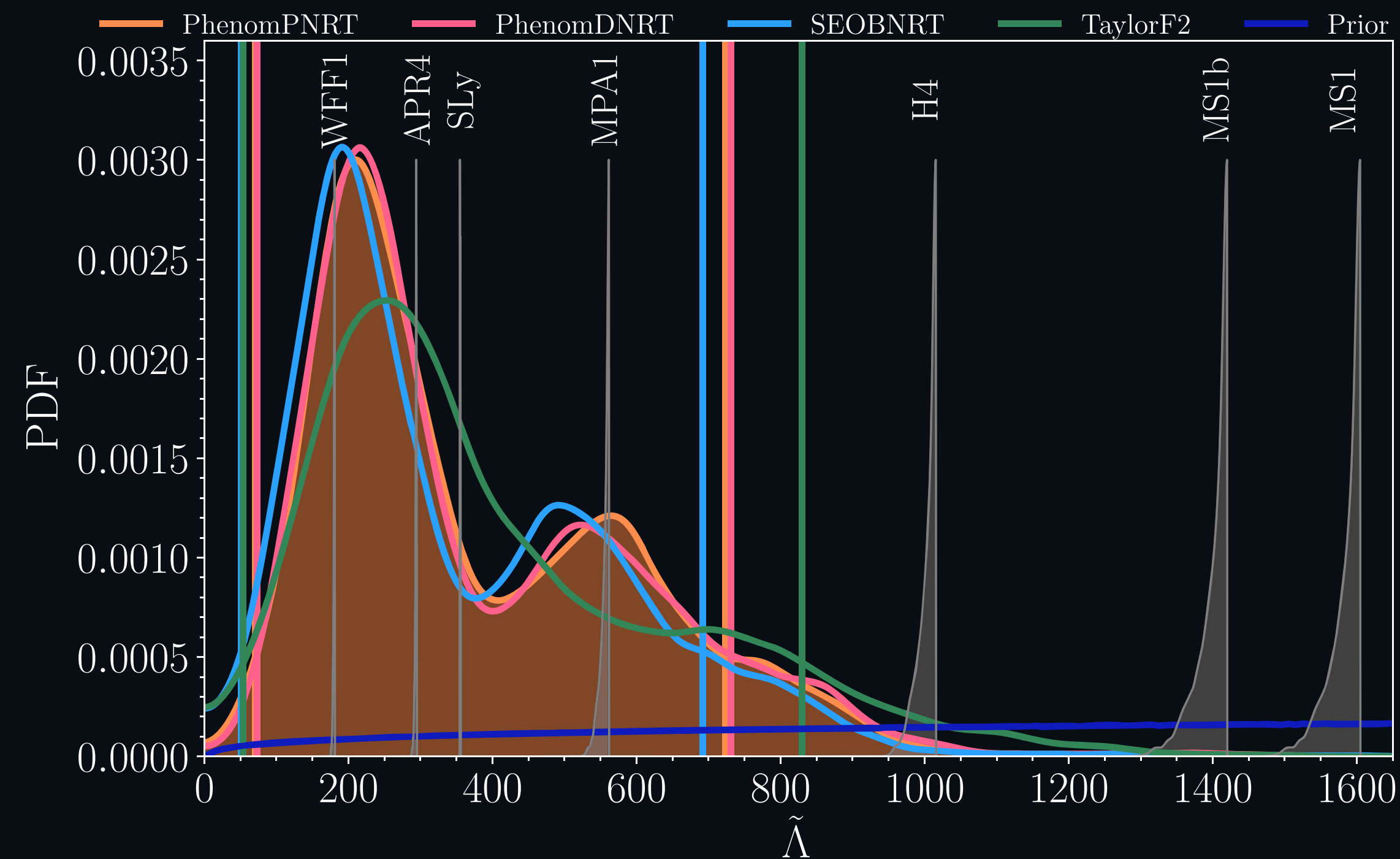


Static Tide

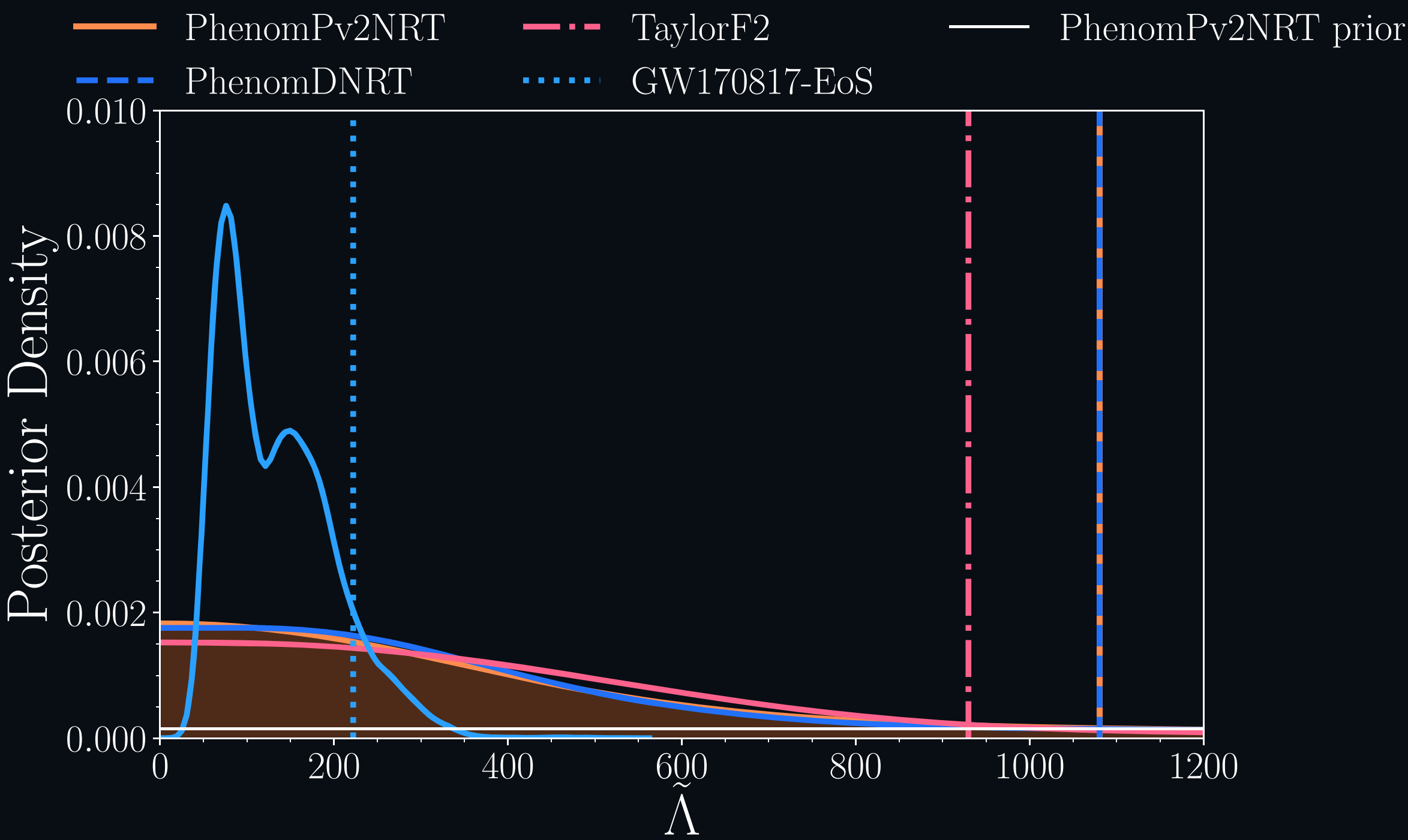


- Assumptions:
 - Components are well separated, $\epsilon = (M'/M)(R/D)^3 \ll 1$
 - Orbital frequency is slow, $\lambda = \dot{\Phi}/\omega_\alpha \ll 1$

GW170817 / GW190425



[LIGO-Virgo Collaboration, Phys. Rev. X **9**, 011001 (2019)]

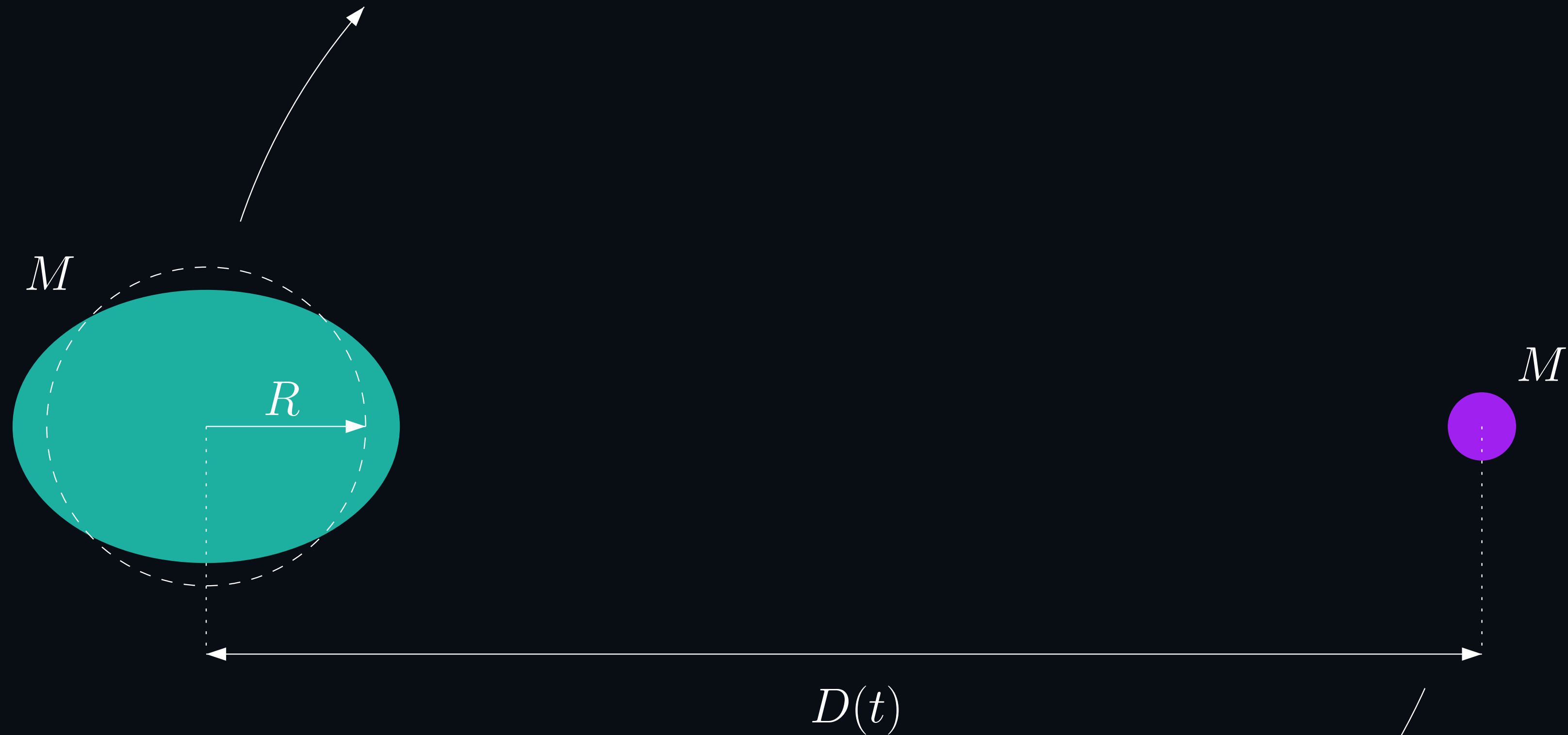


[LIGO-Virgo Collaboration, Astrophys. J. **892**, L3 (2020)]

Overview

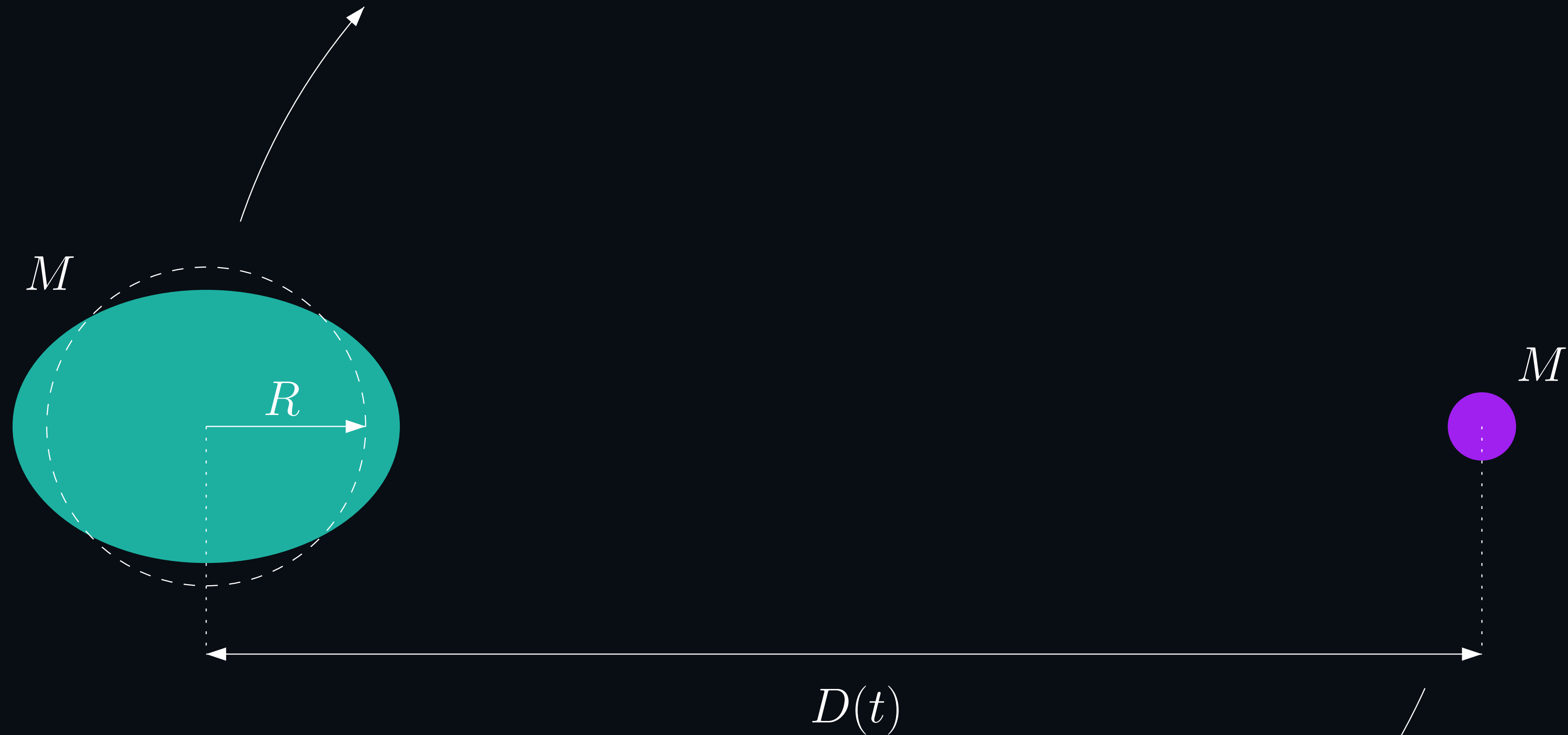
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Static Tide



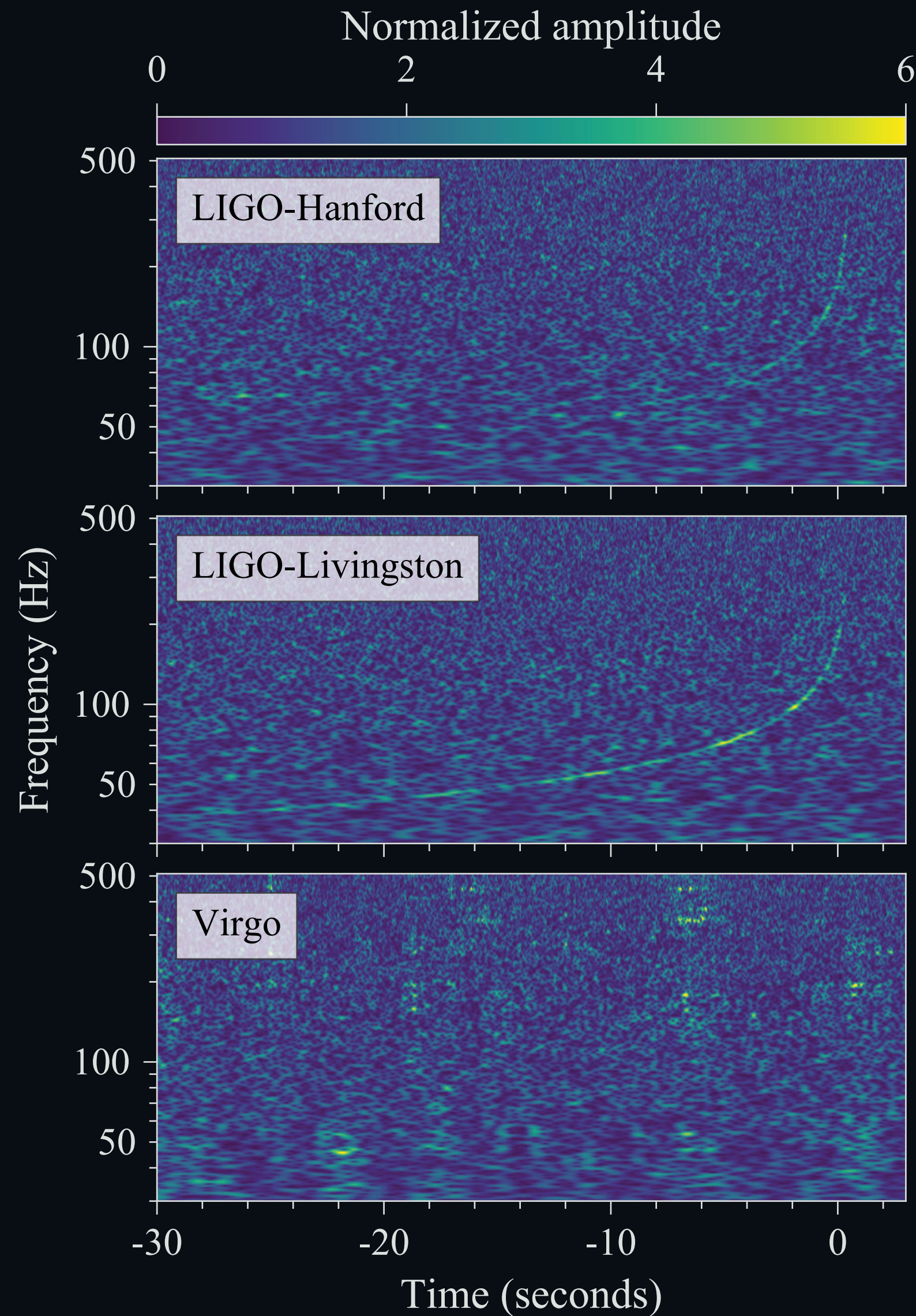
- Assumptions:
 - Components are well separated, $\epsilon = (M'/M)(R/D)^3 \ll 1$
 - Orbital frequency is slow, $\lambda = \dot{\Phi}/\omega_\alpha \ll 1$

Dynamical Tide



- Assumptions:
 - Components are well separated, $\epsilon = (M'/M)(R/D)^3 \ll 1$
 - ~~Orbital frequency is slow, $\lambda = \dot{\Phi}/\omega_\alpha \ll 1$~~

Inspiral



- Static approximation inevitably breaks down,

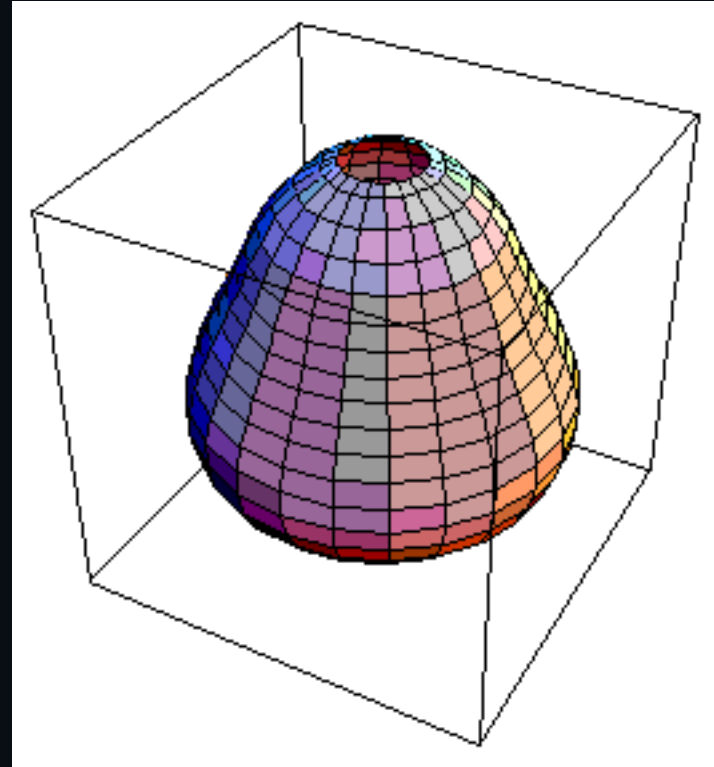
$$\lambda = \dot{\Phi} / \omega_{\alpha} \sim O(1)$$

- Frequency ω_{α} represents a characteristic mode frequency,

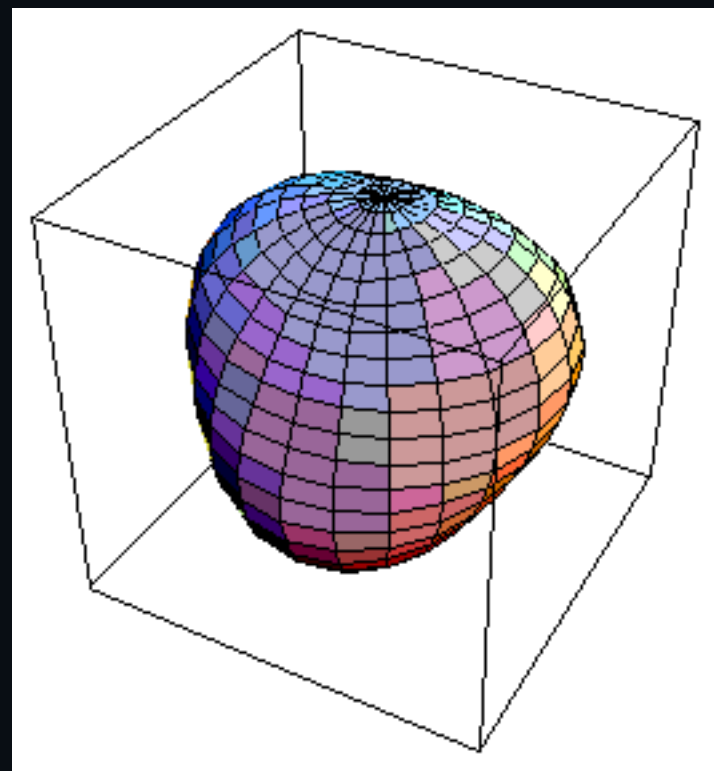
$$\omega_f \sim \sqrt{\frac{GM}{R^3}} \approx 2\pi \cdot 2.2 \text{ kHz} \left(\frac{M}{1.4M_{\odot}} \right)^{1/2} \left(\frac{10 \text{ km}}{R} \right)^{3/2}$$

Mode Compendium

- *f*-mode: scales with average density
- *p*-modes: sound waves in the star (overtones of the *f*-mode)
- *g*-modes: buoyancy waves from thermal/composition gradients
- inertial modes (including *r*-modes): associated with rotation
- *i*-modes: arise from phase transitions
- And many more
 - *w*-modes, *s*-modes, Alfvén modes, ...



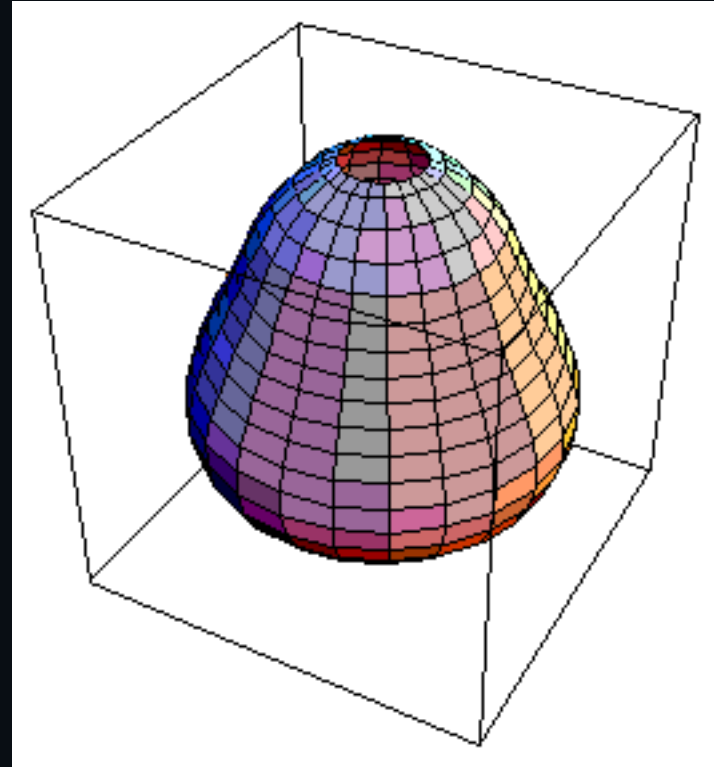
$$(l, m) = (3, 0)$$



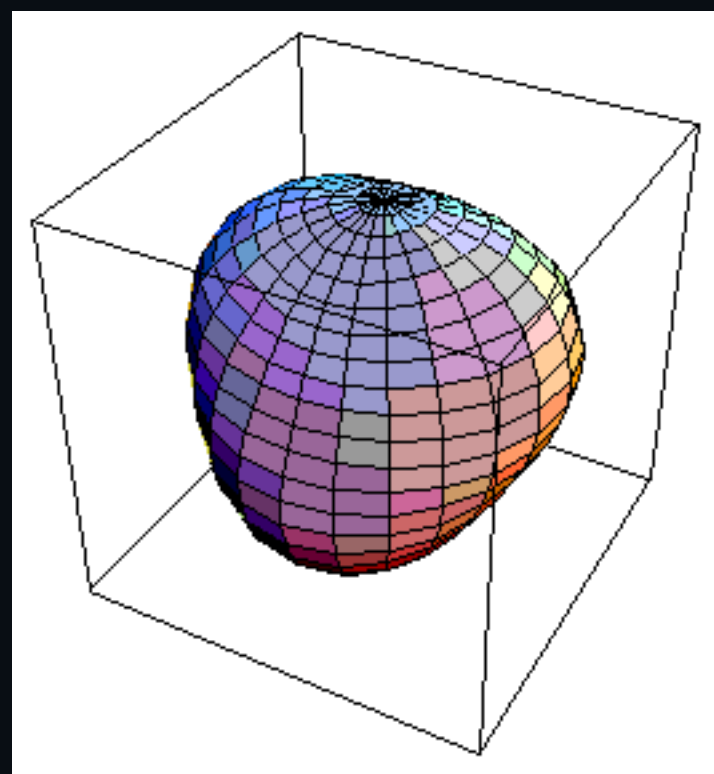
$$(l, m) = (3, 2)$$

Mode Compendium

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- And many more
 - w -modes, s -modes, Alfvén modes, ...



$$(l, m) = (3, 0)$$



$$(l, m) = (3, 2)$$

Mode-Sum Representation

- Normal modes form a complete basis [Chandrasekhar, *Astrophys. J.* **139**, 664 (1964)],

$$\xi(t, \mathbf{x}) = \sum_{\alpha} q_{\alpha}(t) \xi_{\alpha}(\mathbf{x}), \quad \mathbf{C}(\mathbf{x}) \cdot \xi_{\alpha}(\mathbf{x}) = \omega_{\alpha}^2 \xi_{\alpha}(\mathbf{x})$$

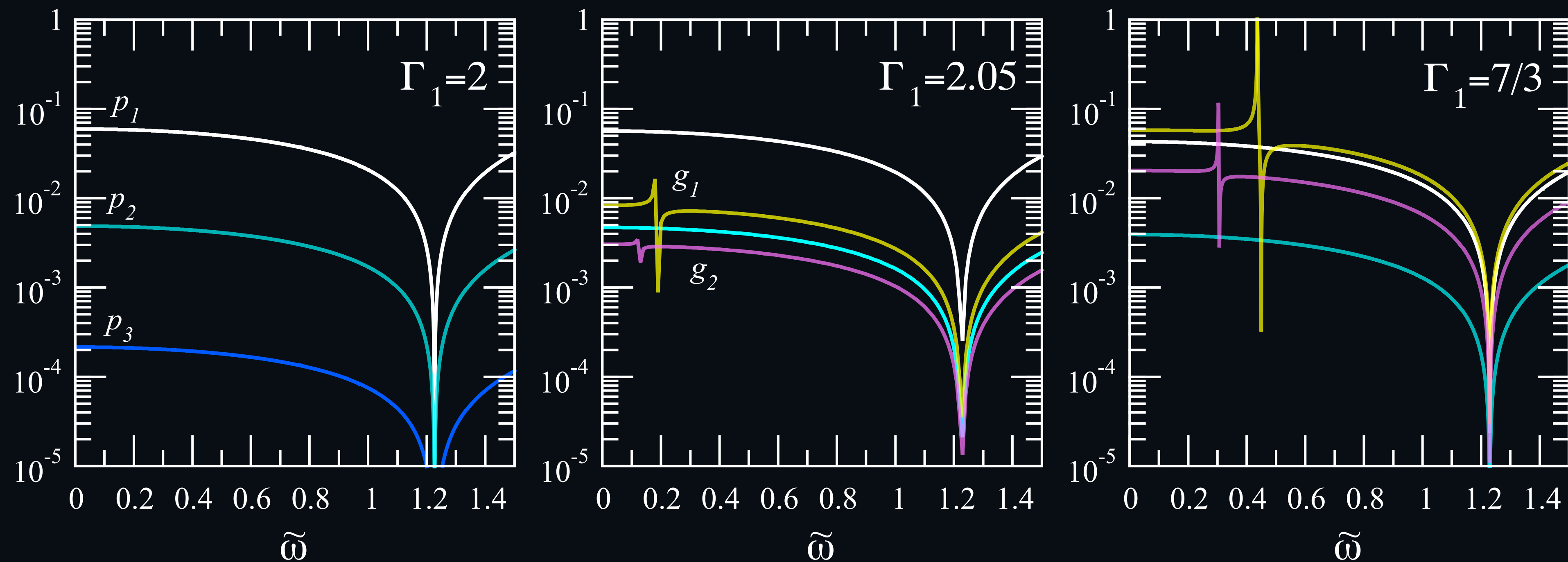
- The tidal equation of motion simplifies to

$$\ddot{q}_{\alpha}(t) + \omega_{\alpha}^2 q_{\alpha}(t) = \frac{Q_{\alpha}(t)}{\mathcal{E}_{\alpha}} \propto e^{-im\Phi(t)}$$

Equilibrium Tide

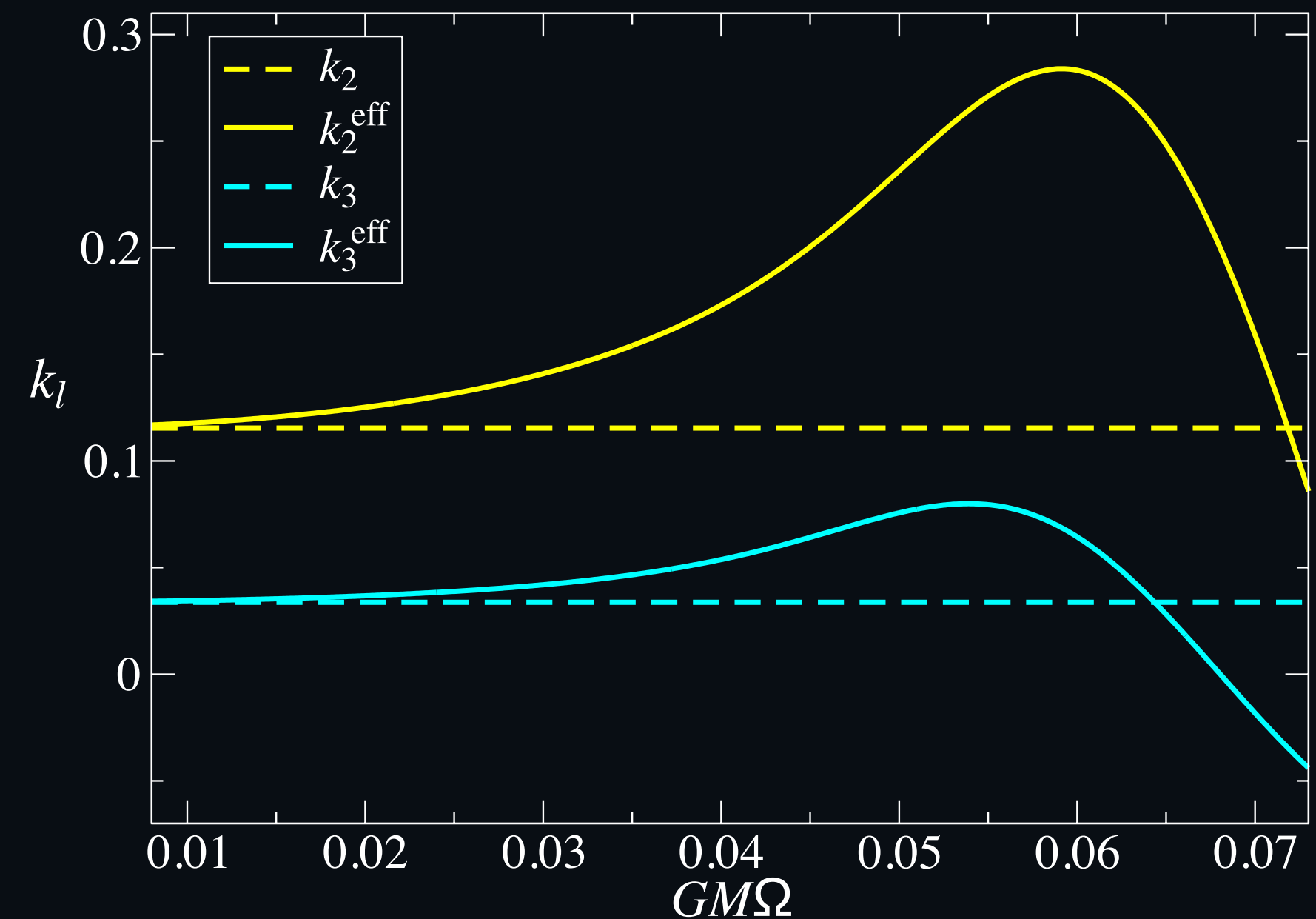
- For an equilibrium orbit, $\dot{\Phi} = \text{const}$,

$$q_{\alpha}(t) = \frac{Q_{\alpha}(t)}{\mathcal{E}_{\alpha}} \frac{1}{\omega_{\alpha}^2 - (m\dot{\Phi})^2}$$



f -mode Approximation

- The dynamical tide is dominated by the f -mode
- There have been models developed for the f -mode dynamical tide that use
 - *effective-one-body* [Steinhoff+, Phys. Rev. D **94**, 104028 (2016)],
 - *Newtonian* [Schmidt+Hinderer, Phys. Rev. D **100**, 021501 (2019)],
 - *phenomenological* approaches [Abac+, Phys. Rev. D **109**, 024062 (2024)]



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Tidal Resonances

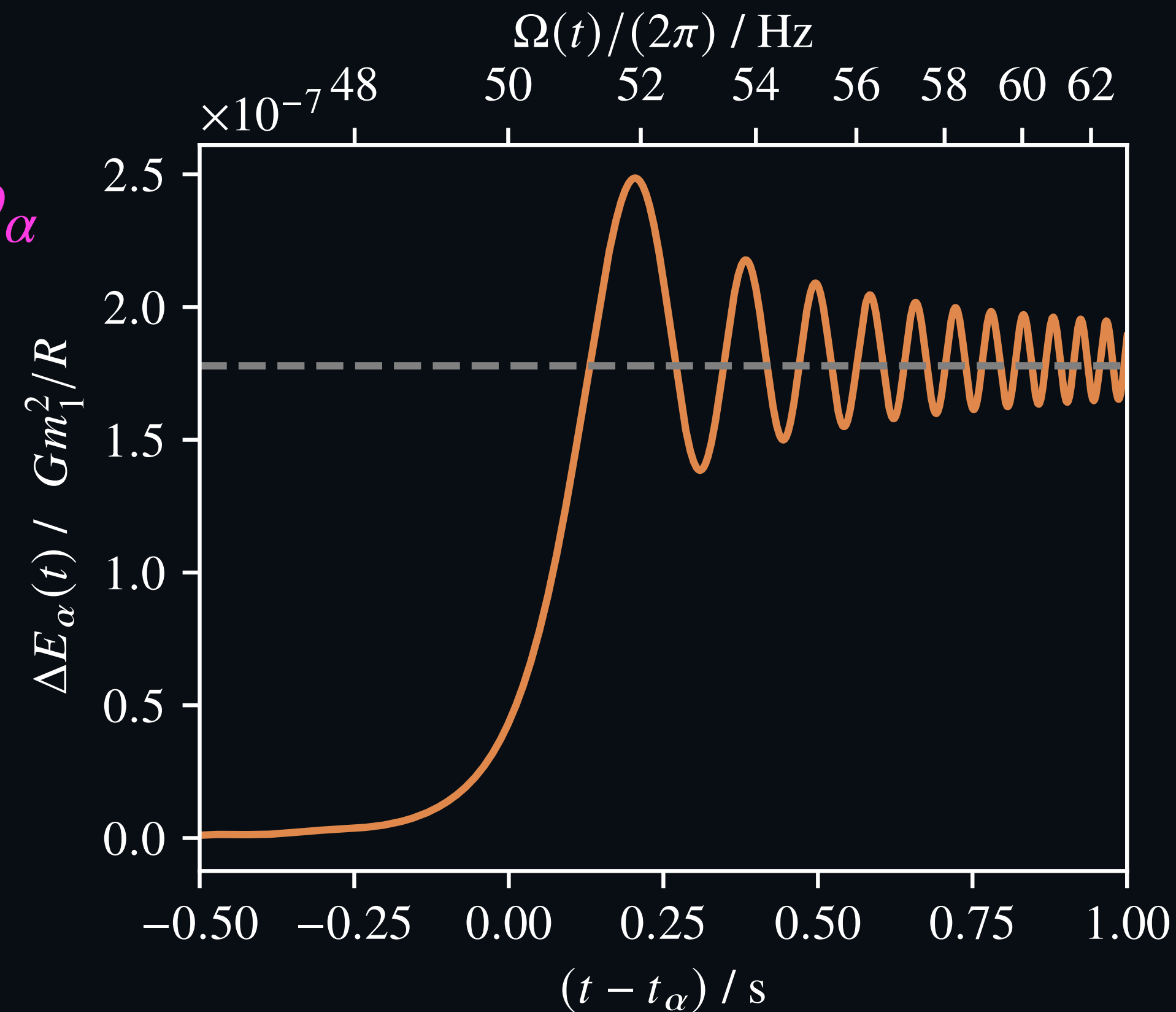
- Low-frequency oscillations will become **resonantly excited** during inspiral,

$$q_\alpha(t) = \frac{Q_\alpha(t)}{\mathcal{E}_\alpha} \frac{1}{\omega_\alpha^2 - (m\dot{\Phi})^2} \implies |m|\dot{\Phi} \approx \omega_\alpha$$

- Energy is extracted from the orbit,

$$\Delta E_\alpha \sim |q_\alpha|^2,$$

which results in a finite phase shift $\Delta\Phi$



g-modes

Composition

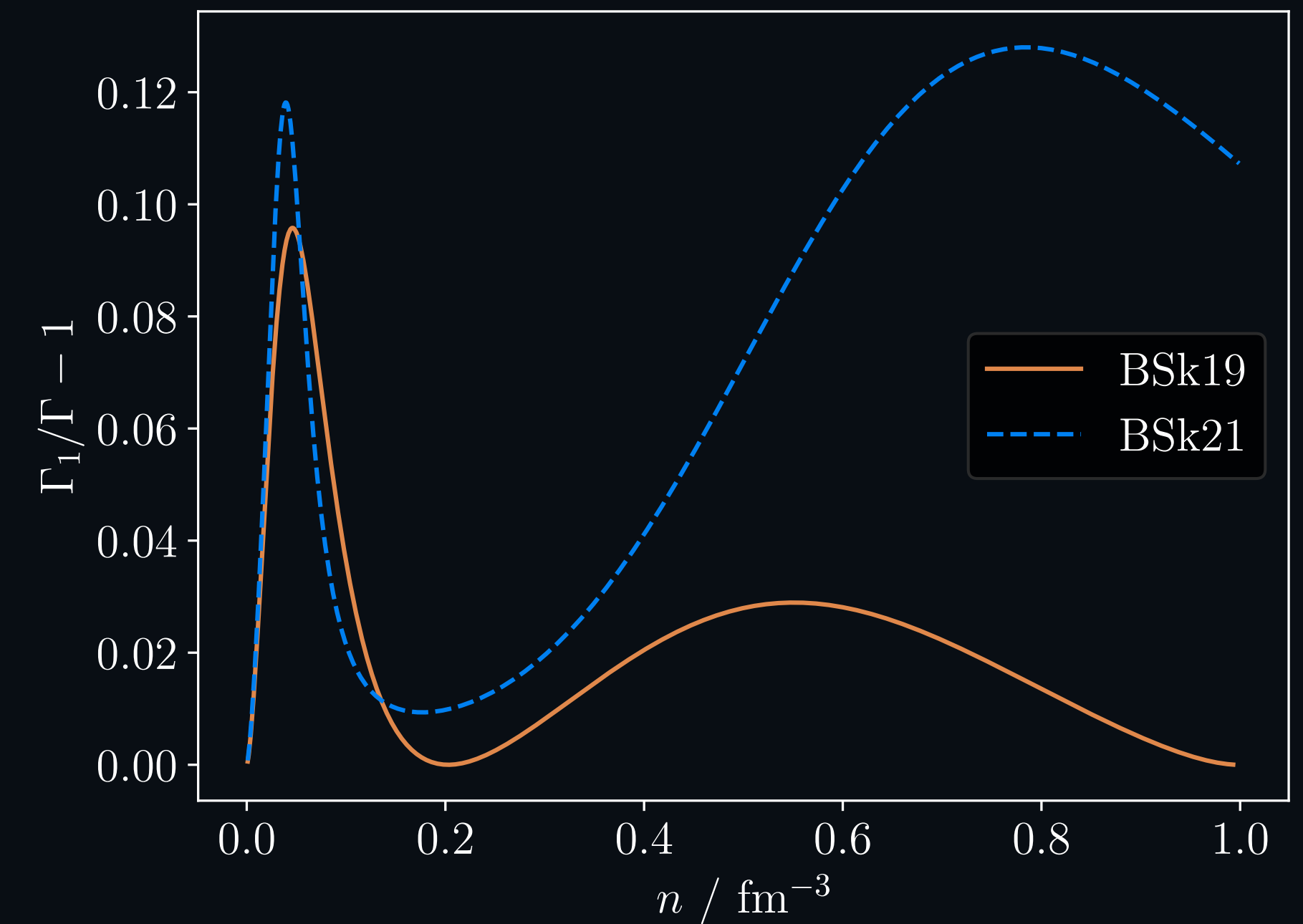
- Instead of

$$d\varepsilon = \frac{\varepsilon + p}{n_b} dn_b \implies \varepsilon = \varepsilon(n_b),$$

the first law is

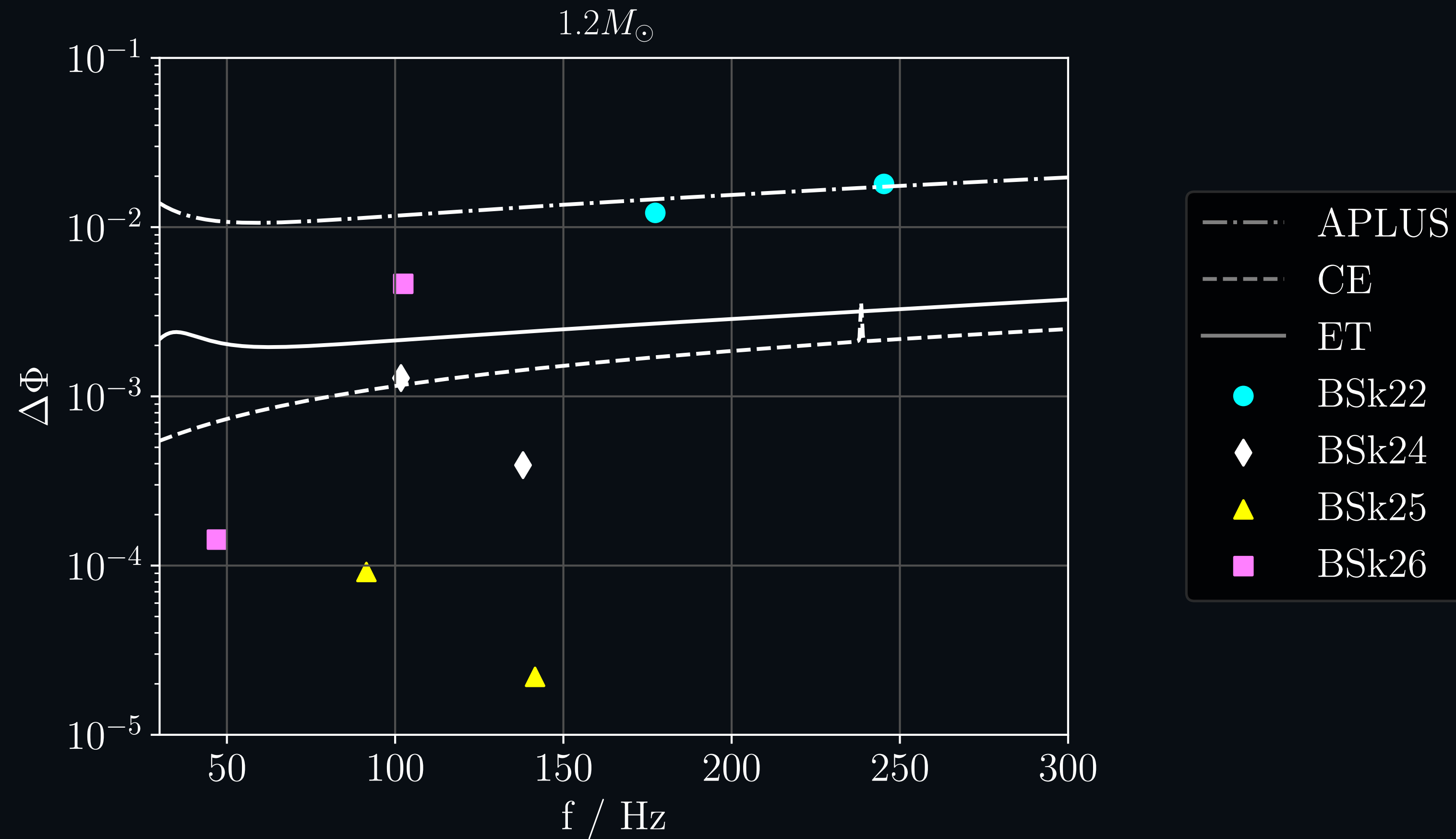
$$d\varepsilon = \frac{\varepsilon + p}{n_b} dn_b + n_b \mu_\Delta dY_e \implies \varepsilon = \varepsilon(n_b, Y_e)$$

- When the weak nuclear reactions are slow, $\mu_\Delta \neq 0$



[FG+Andersson, Mon. Not. R. Astron. Soc. **521**, 3043 (2023)]

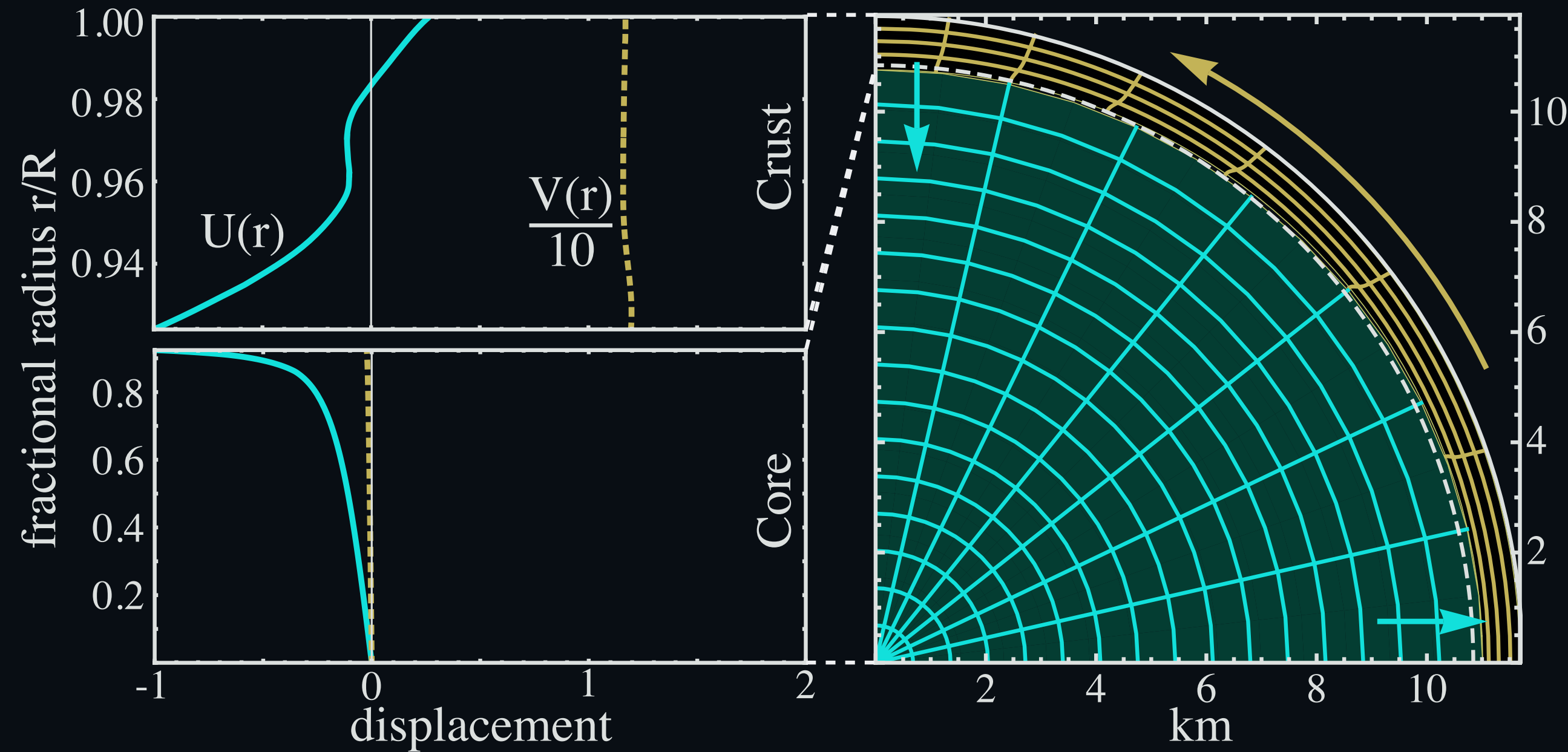
Detectability of g-modes



[Counsell, FG + Andersson, Mon. Not. R. Astron. Soc. **536**, 1967 (2025)]

i-modes

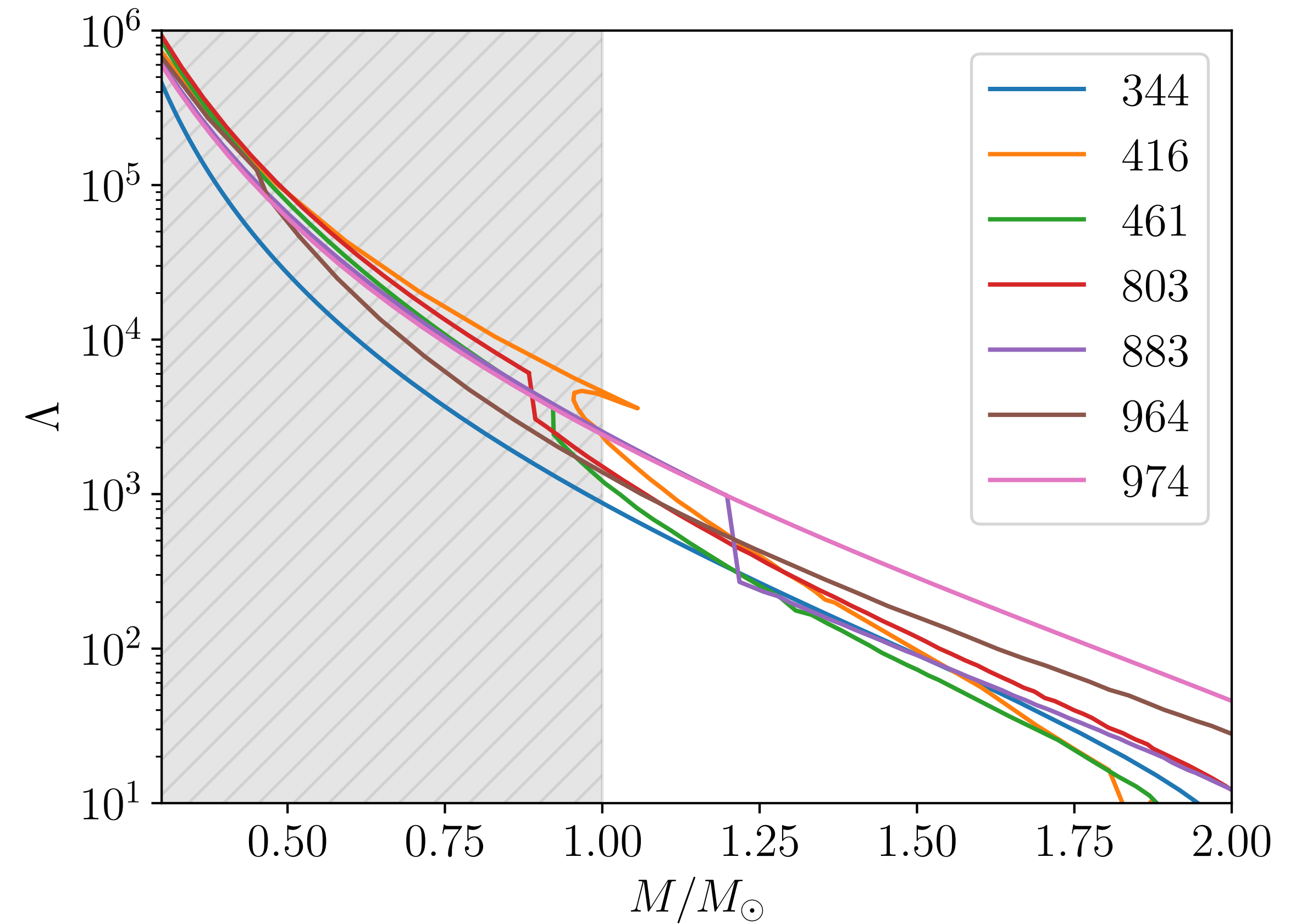
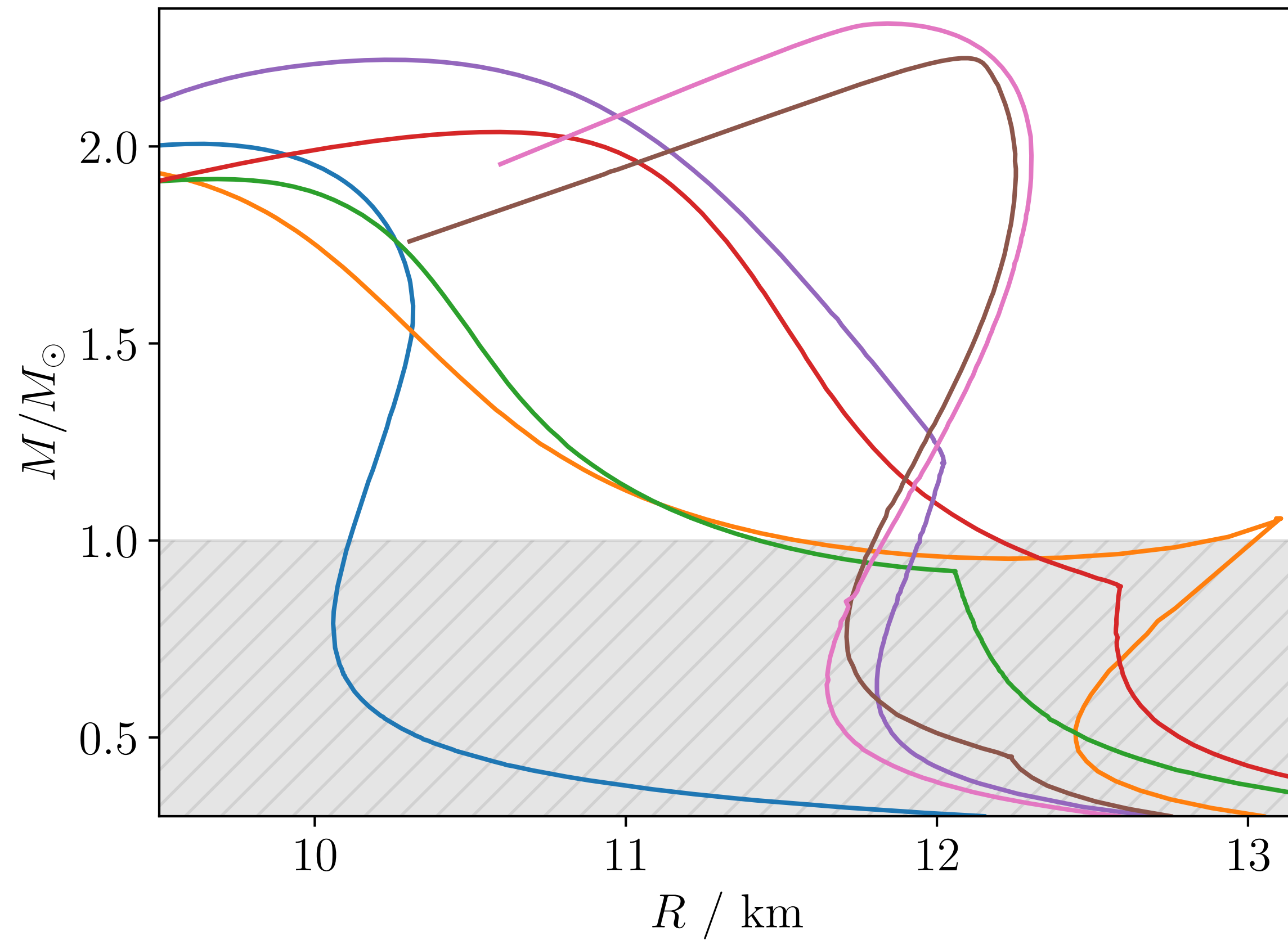
Phase Transitions



[Tsang+, Phys. Rev. Lett. **108**, 011102 (2012)]

- Interfacial *i*-mode arises when there is a first-order phase transition in the star
 - core-crust interface
 - deconfined quark matter

Masquerade Problem



[Counsell, FG+, Phys. Rev. Lett. **135**, 081402 (2025)]

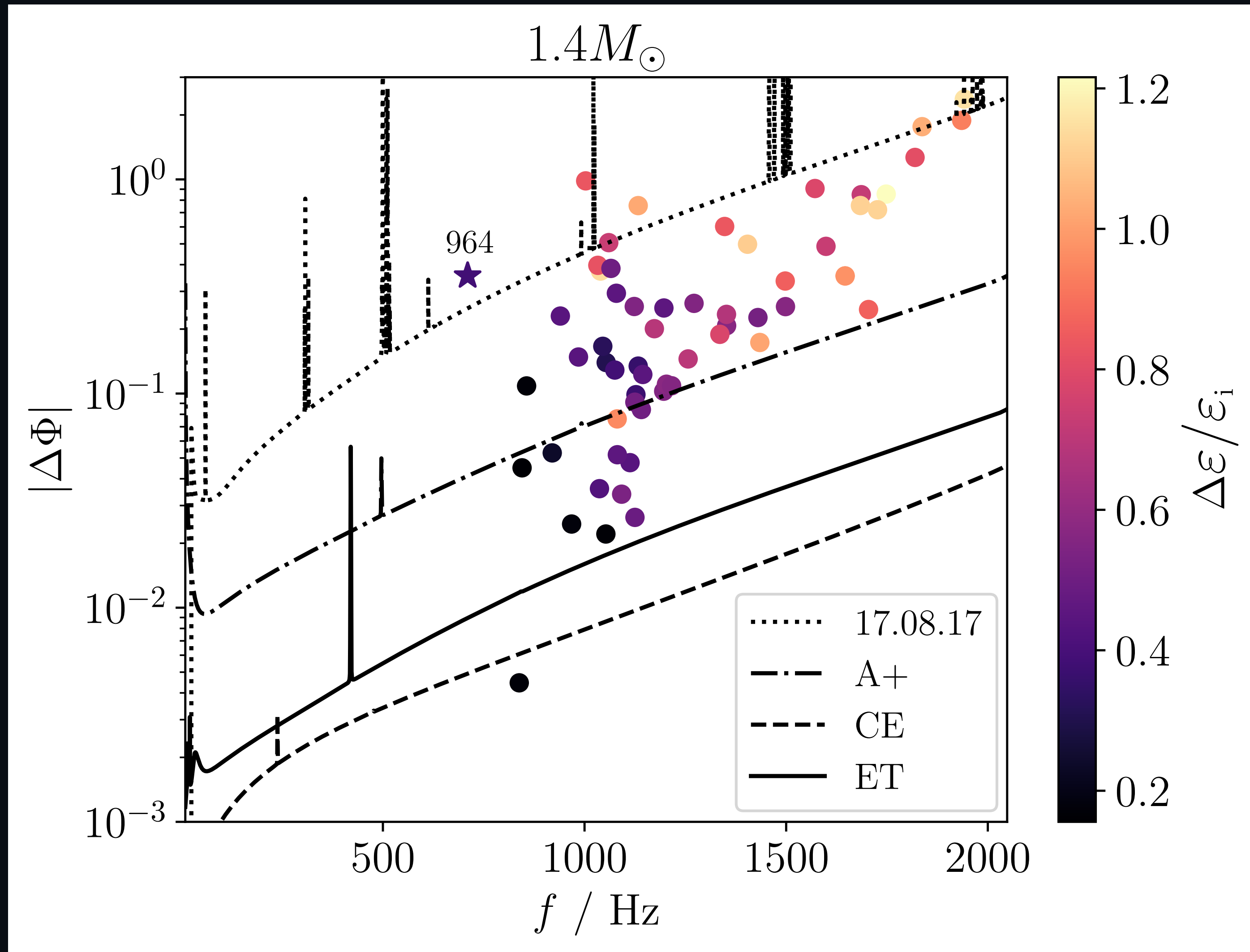
Properties of *i*-modes

- A simple analytical calculation reveals:

$$\omega^2 \approx (2\pi \times 686 \text{ Hz})^2 \left(\frac{\epsilon}{0.1} \right) \left(\frac{M}{1.4M_{\odot}} \right) \left(\frac{10 \text{ km}}{R} \right)^3 \frac{l(l+1)}{2l+1} \left[1 - \left(\frac{r_i}{R} \right)^{2l+1} \right],$$
$$Q_l = 10^{-2} \left(\frac{\epsilon}{0.1} \right)^2 MR^l \sqrt{\frac{3}{4\pi} \frac{l(l+1)}{2l+1}} \sqrt{1 - \left(\frac{r_i}{R} \right)^{2l+1}} \left(\frac{r_i}{R} \right)^{(2l+1)/2} \left[1 - \left(\frac{r_i}{R} \right)^3 \right].$$

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

Detectability of *i*-modes



[Counsell, FG+, Phys. Rev. Lett. **135**, 081402 (2025)]

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Modelling the Resonances

- We investigated the detectability of these features in a **realistic data-analysis setting**
- We modelled the resonance as instantaneous:

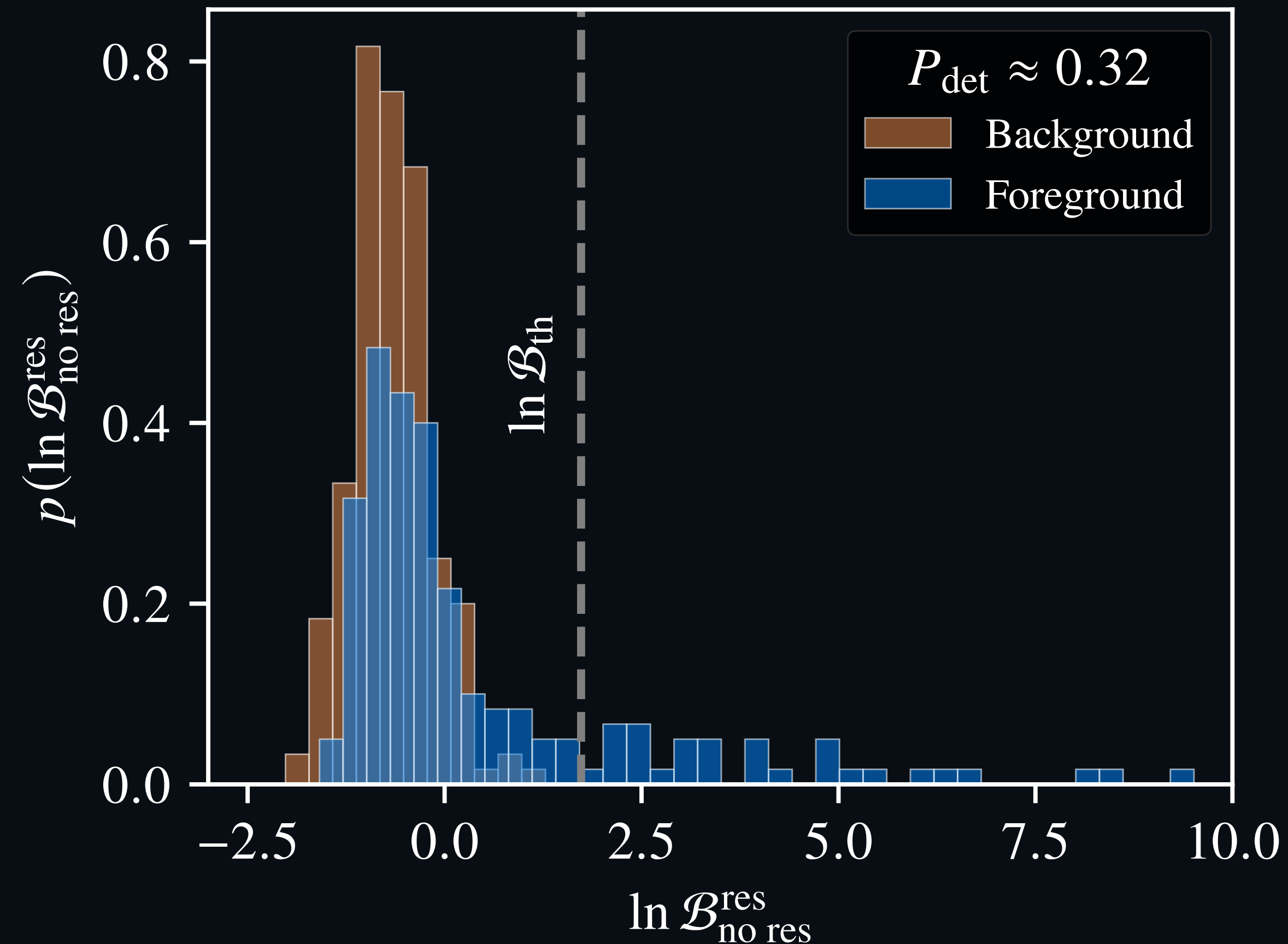
$$\epsilon := \frac{\tau_{\text{res}}}{\tau_{\text{rr}}} \approx 0.07 \left(\frac{\mathcal{M}}{1.2M_{\odot}} \right)^{5/6} \left[\frac{\Omega/(2\pi)}{100 \text{ Hz}} \right]^{5/6}$$

- The abrupt change in the orbital phase leads to

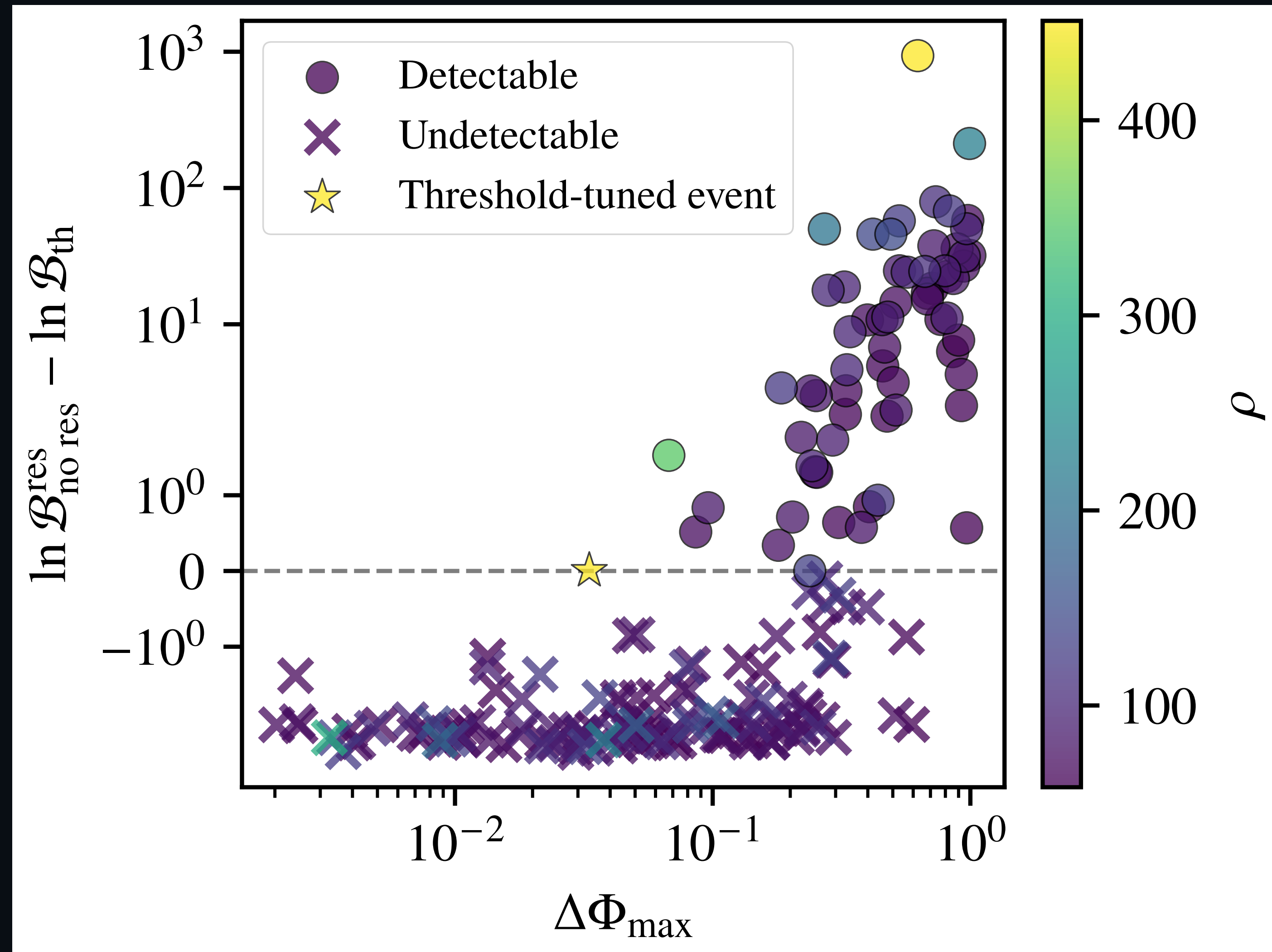
$$\Psi(f) = \Psi_0(f) + \Theta(f - f_{\alpha}) \left(1 - \frac{f}{f_{\alpha}} \right) \Delta\Phi_{\alpha}$$

Gravitational-Wave Population Analysis

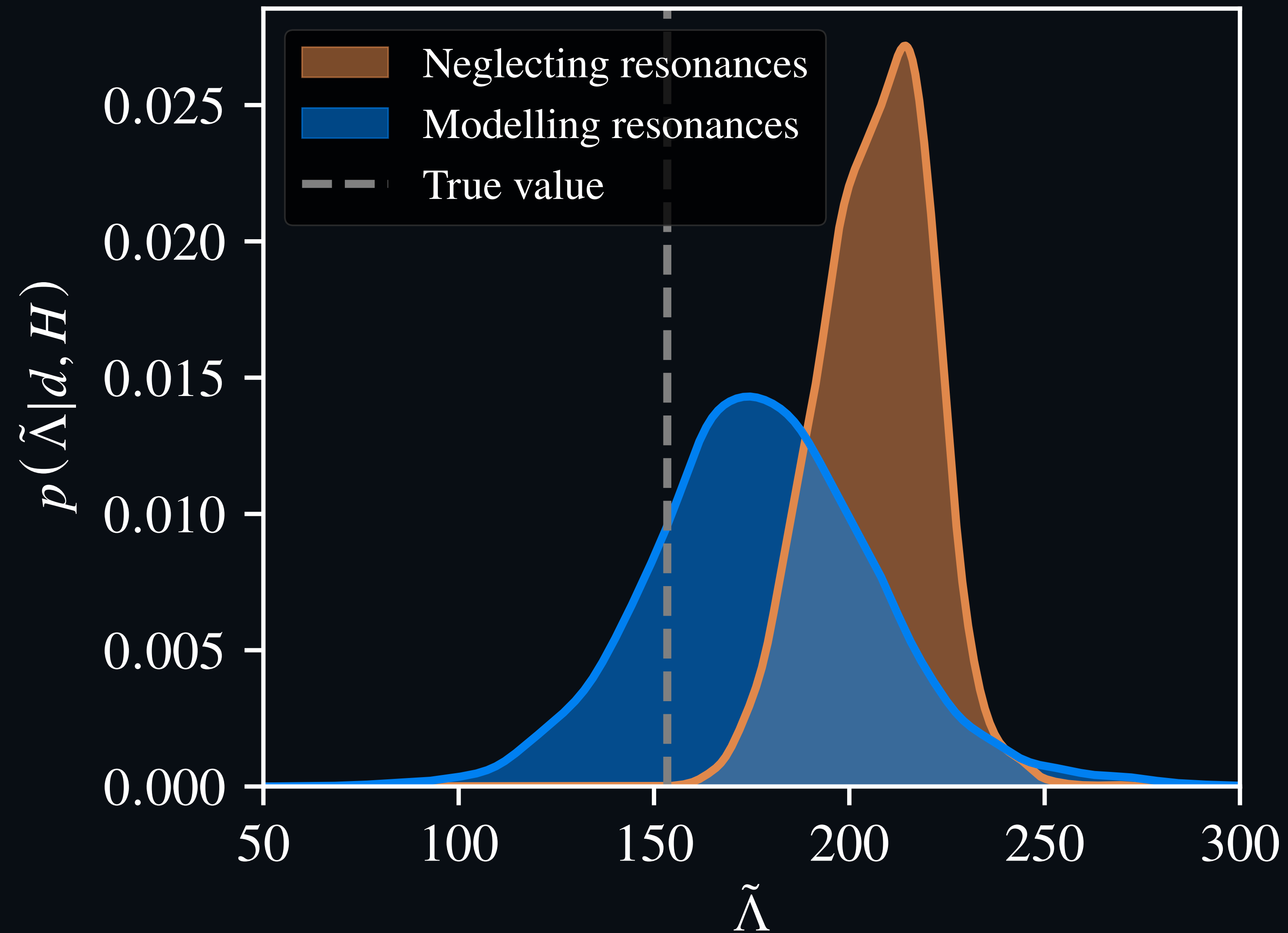
- We simulated an astrophysical population of binary neutron stars observed by the Einstein Telescope over one year and analysed the 200 loudest signals



Dependence on Phase Shift



Neglecting Resonances in Parameter Estimation



Implications for oscillation modes

- Minimum detectable phase shift found to be $\Delta\Phi_\alpha \approx 0.03$
- *g*-modes: up to $\Delta\Phi_\alpha \sim 0.08$ [Counsell, FG + Andersson, Mon. Not. R. Astron. Soc. **536**, 1967 (2025)]
- inertial modes: $|\Delta\Phi_\alpha| \sim 0.02 - 0.20$ [Poisson, Phys. Rev. D. Soc. **101**, 104028 (2020)]
- core-crust *i*-modes: $\Delta\Phi_\alpha \approx 0.002$ [Gao+, Phys. Rev. D. Soc. **112**, 123006 (2025)]

Conclusions

Opportunities	Challenges
Gravitational waves probe dense nuclear matter by encoding fine tidal deformations	Can the mode-sum be formulated in general relativity? [Hegade K R+, Phys. Rev. Lett. 136 , 071401 (2026); Andersson, Counsell, Gittins+ Phys. Rev. D 113 , 06451 (2026)]
The tide presents the opportunity to conduct neutron-star seismology	Develop gravitational-waveform models of resonant oscillation modes
Oscillation modes grant access to rich physics: composition and phase transitions	Connect measurements of modes to dense-matter constraints