Merger-ringdown in the self-force approach

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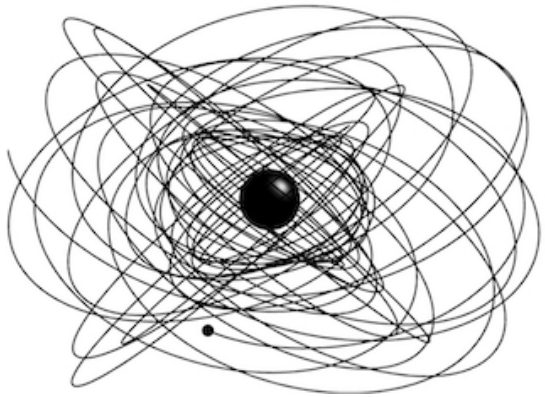
Common Trends in Non-Hermitian Physics:
Black Holes and Quantum Optics

26 March 2025

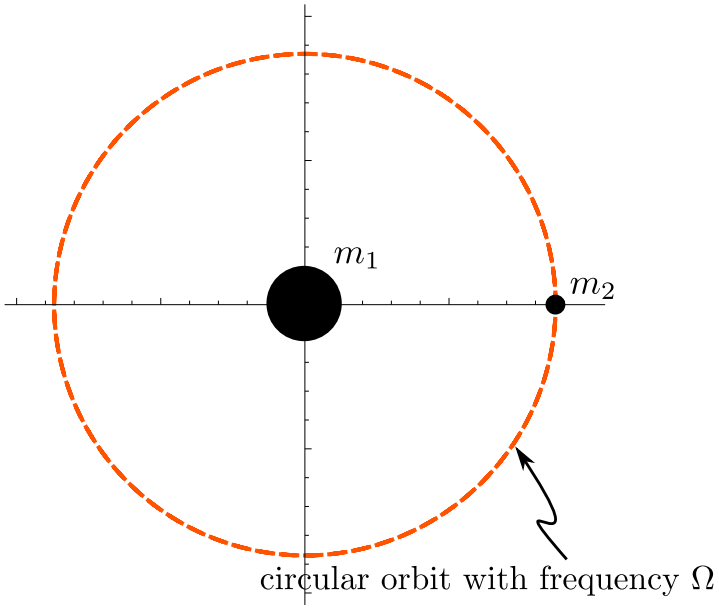
Outline

1. Inspiral, transition, and plunge
2. Merger and ringdown
3. Dissecting the ringdown



[image courtesy of Steve Drasco]

Quasicircular inspiral

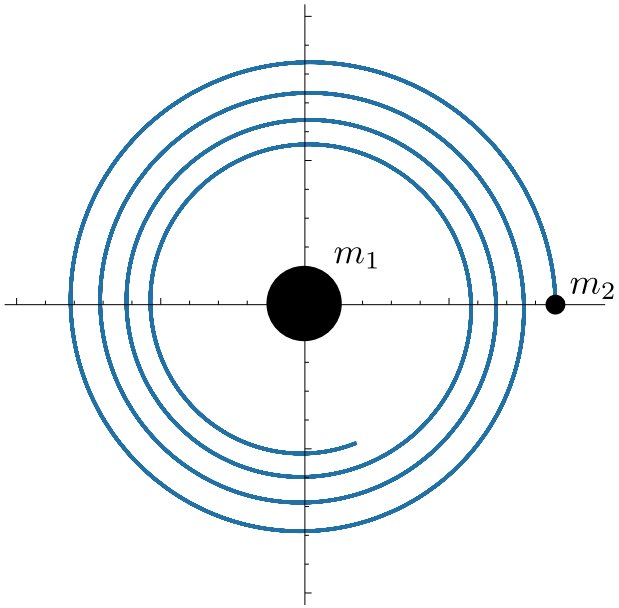


$$\frac{d\phi_p}{dt} = \Omega$$

$$\frac{d\Omega}{dt} = 0$$

$$h_{\ell m} = \sum_{n\geq 1} \epsilon^n h^{(n)}_{\ell m}(\Omega) e^{-im\Omega t}$$

Quasicircular inspiral



$$\frac{d\phi_p}{dt} = \Omega$$

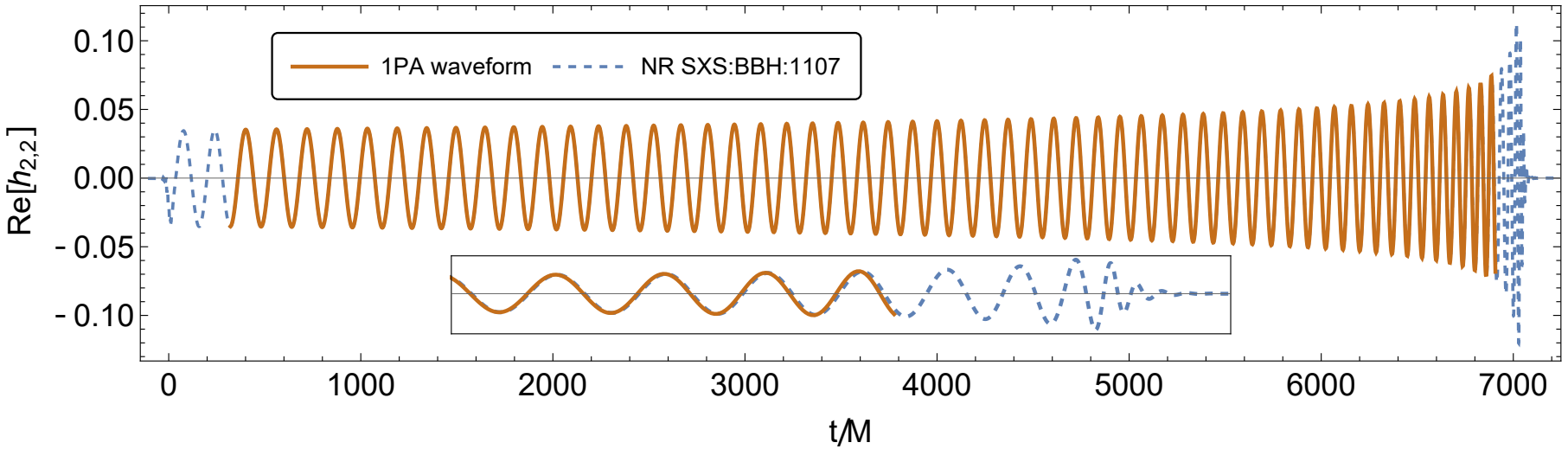
$$\frac{d\Omega}{dt} = \epsilon[F_{(0)}(\Omega) + \epsilon F_{(1)}(\Omega) + \ldots]$$

$$h_{\ell m} = \sum_{n\geq 1} \epsilon^n h^{(n)}_{\ell m}(\Omega) e^{-im\phi_p}$$

Inspiral waveform compared to numerical relativity

Wardell, AP, Warburton+

Mass ratio $\epsilon = 1/10$



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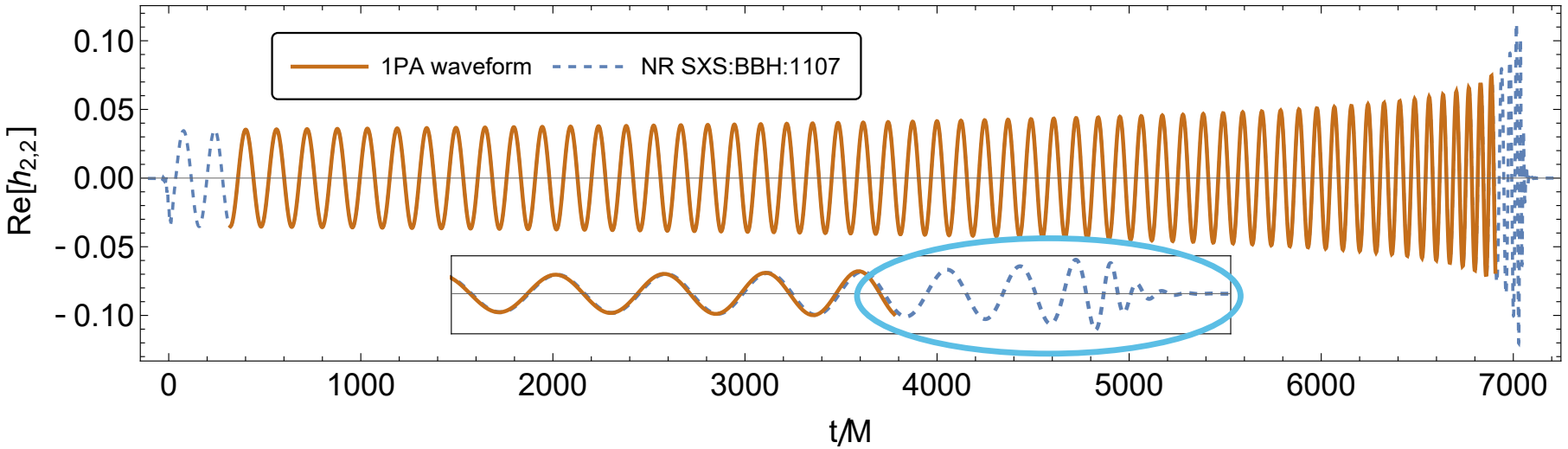


Transition to plunge

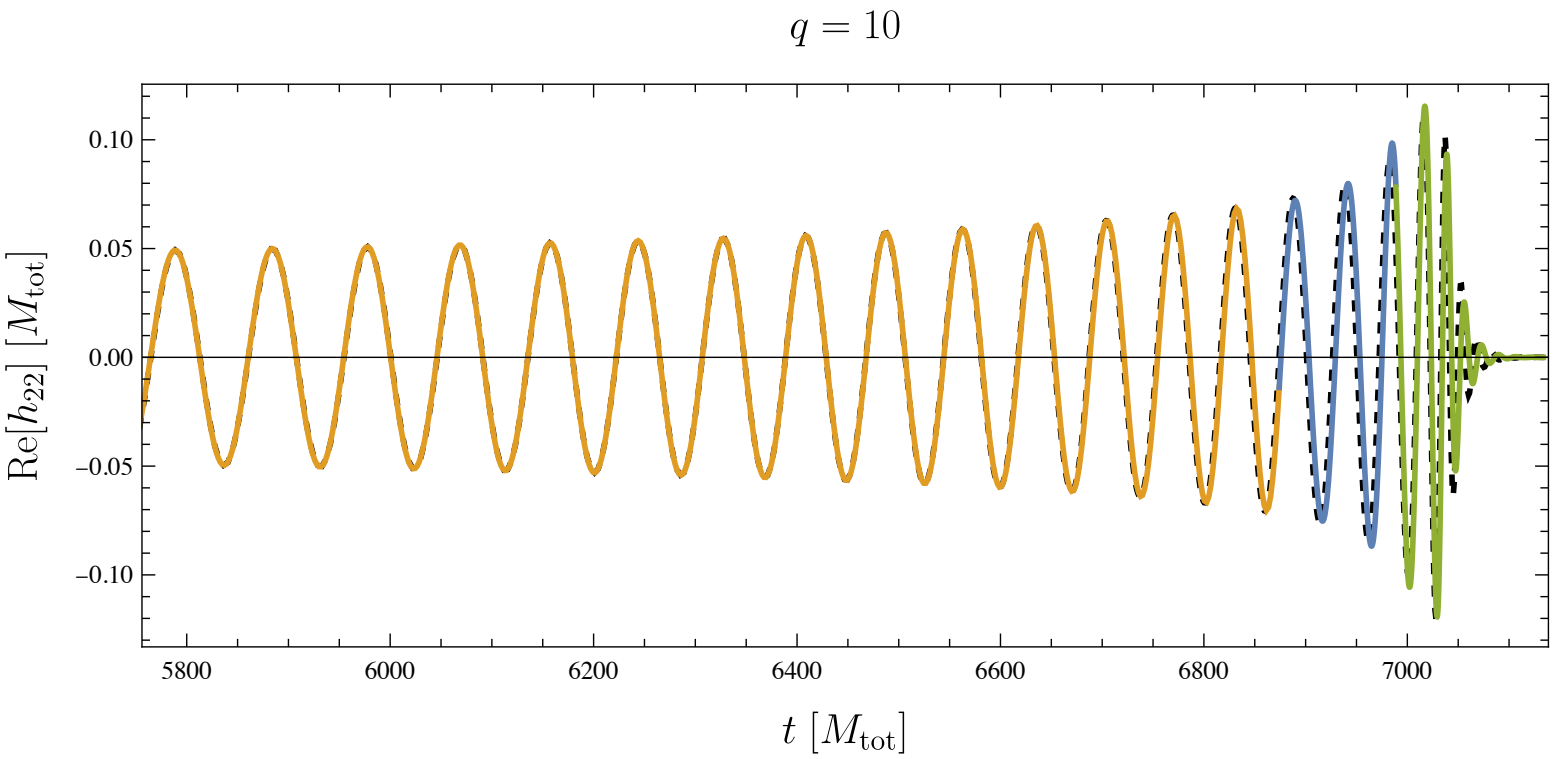
Near innermost stable circular orbit: define $\Delta\Omega := \frac{\Omega - \Omega_{isco}}{\epsilon^{2/5}}$

$$\frac{d\phi_p}{dt} = \Omega$$
$$\frac{d\Delta\Omega}{dt} = \epsilon^{1/5}\left[F^{(0)}_{\Delta\Omega}(\Delta\Omega) + \epsilon^{1/5}F^{(1)}_{\Delta\Omega}(\Delta\Omega) + O(\epsilon^{2/5})\right]$$
$$h_{\ell m} = \epsilon \sum_{n\geq 0} \epsilon^{n/5} j^{(n)}_{\ell m}(\Delta\Omega) e^{-im\phi_p}$$

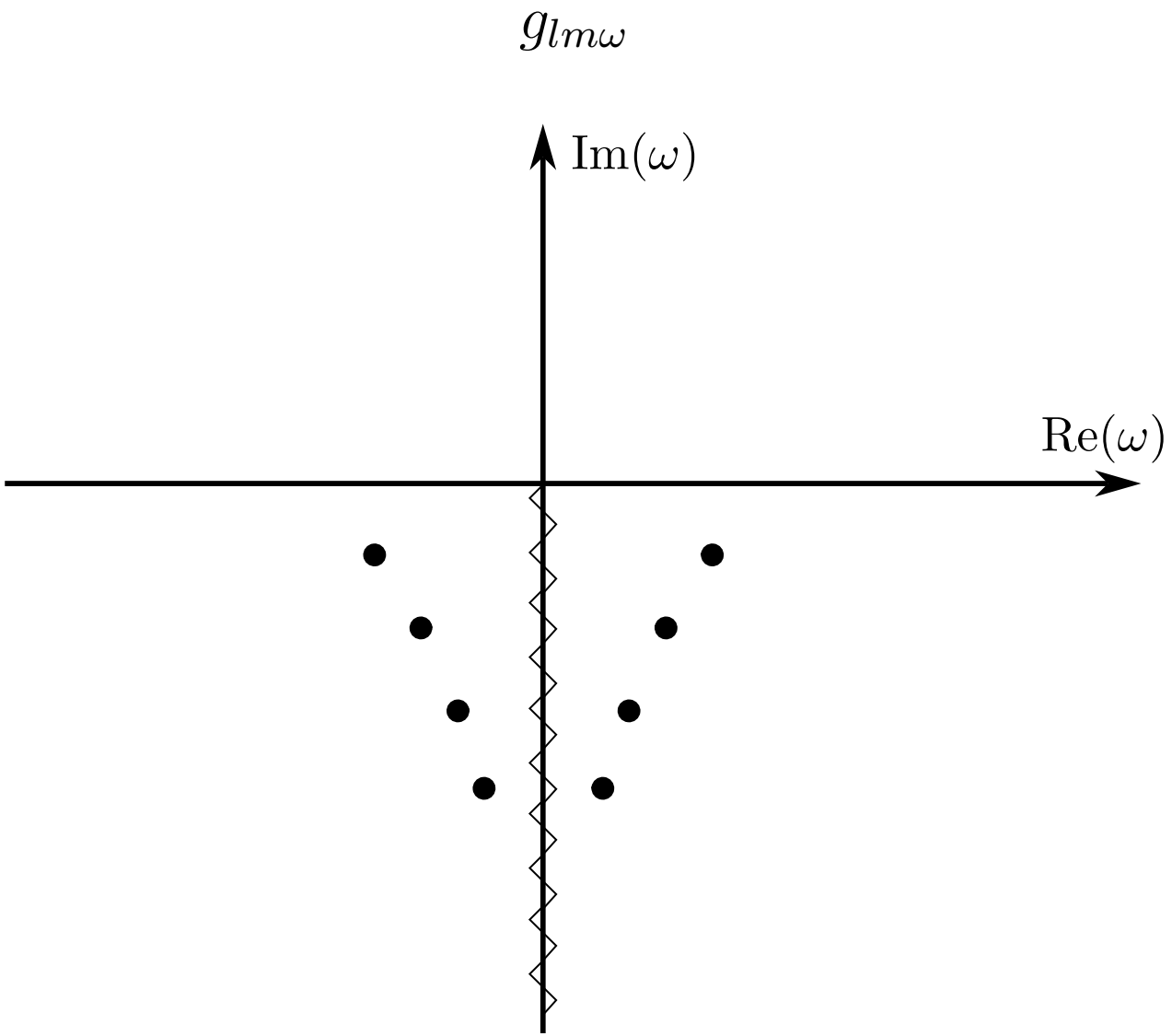
Final plunge

$$\frac{d\phi_p}{dt} = \Omega$$
$$\frac{d\Omega}{dt} = F_\Omega^{(0)}(\Omega) + \epsilon F_\Omega^{(1)}(\Omega) + O(\epsilon^2)$$
$$h_{\ell m} = \sum_{n\geq 1} \epsilon^n h_{\ell m}^{(n)}(\Omega) e^{-im\phi_p}$$

Complete inspiral-merger ringdown waveform Kuchler, Compere, AP

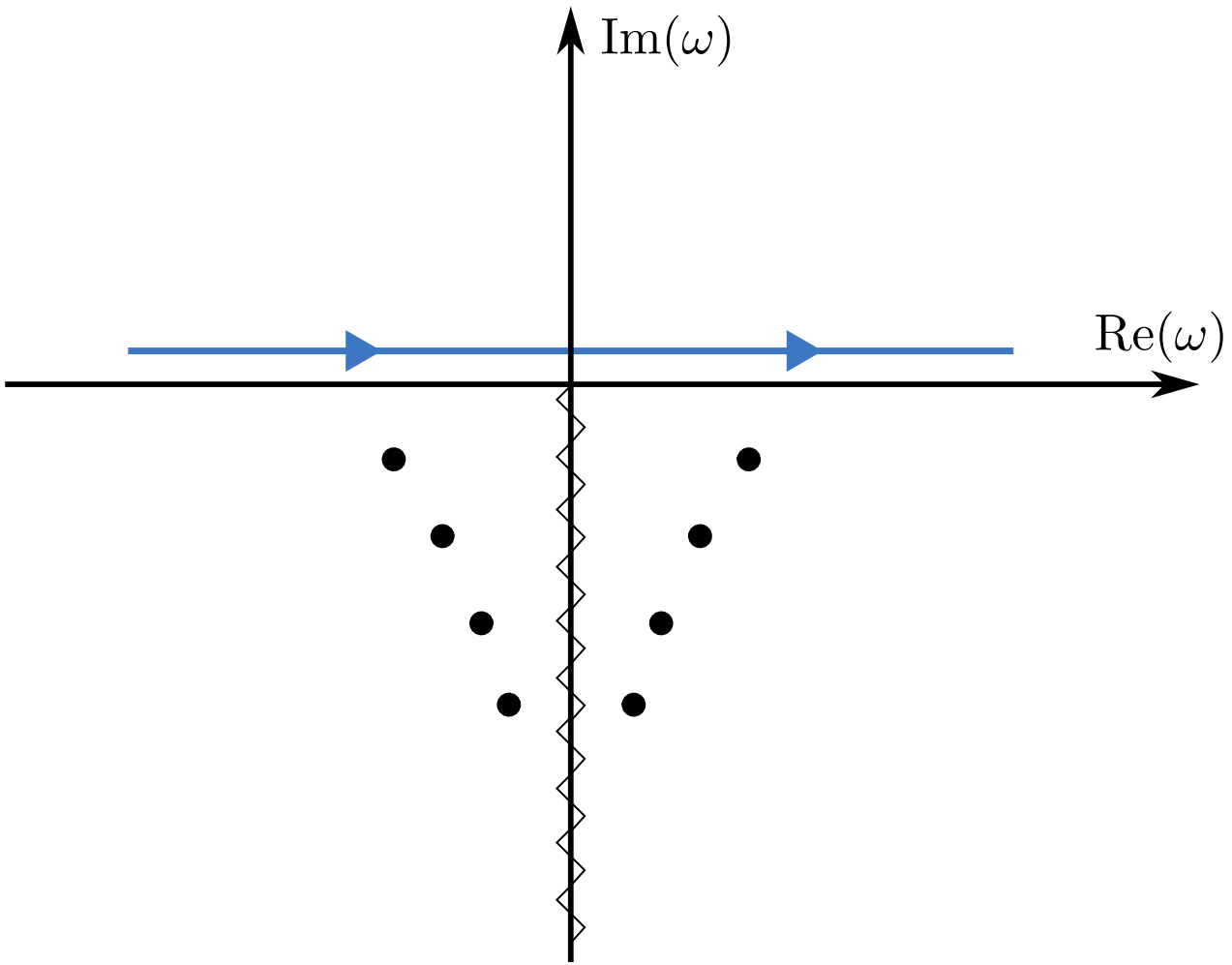


QNMs from residues



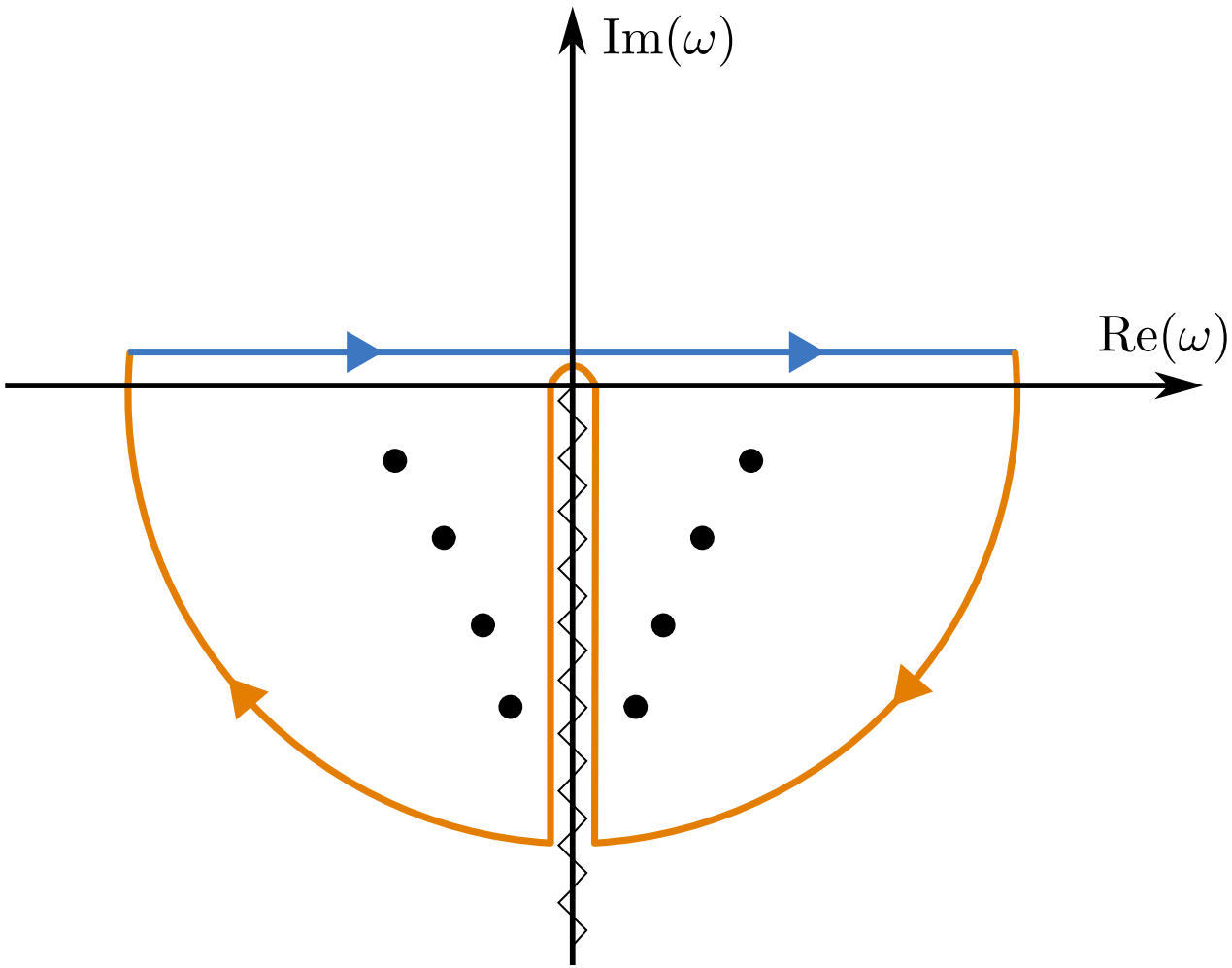
QNMs from residues

$$\psi_{lm}(t,r) = \int_{-\infty}^{\infty} d\omega e^{-i\omega t} \int g_{lm\omega}(r,r') T_{lm\omega}(r') dr'$$

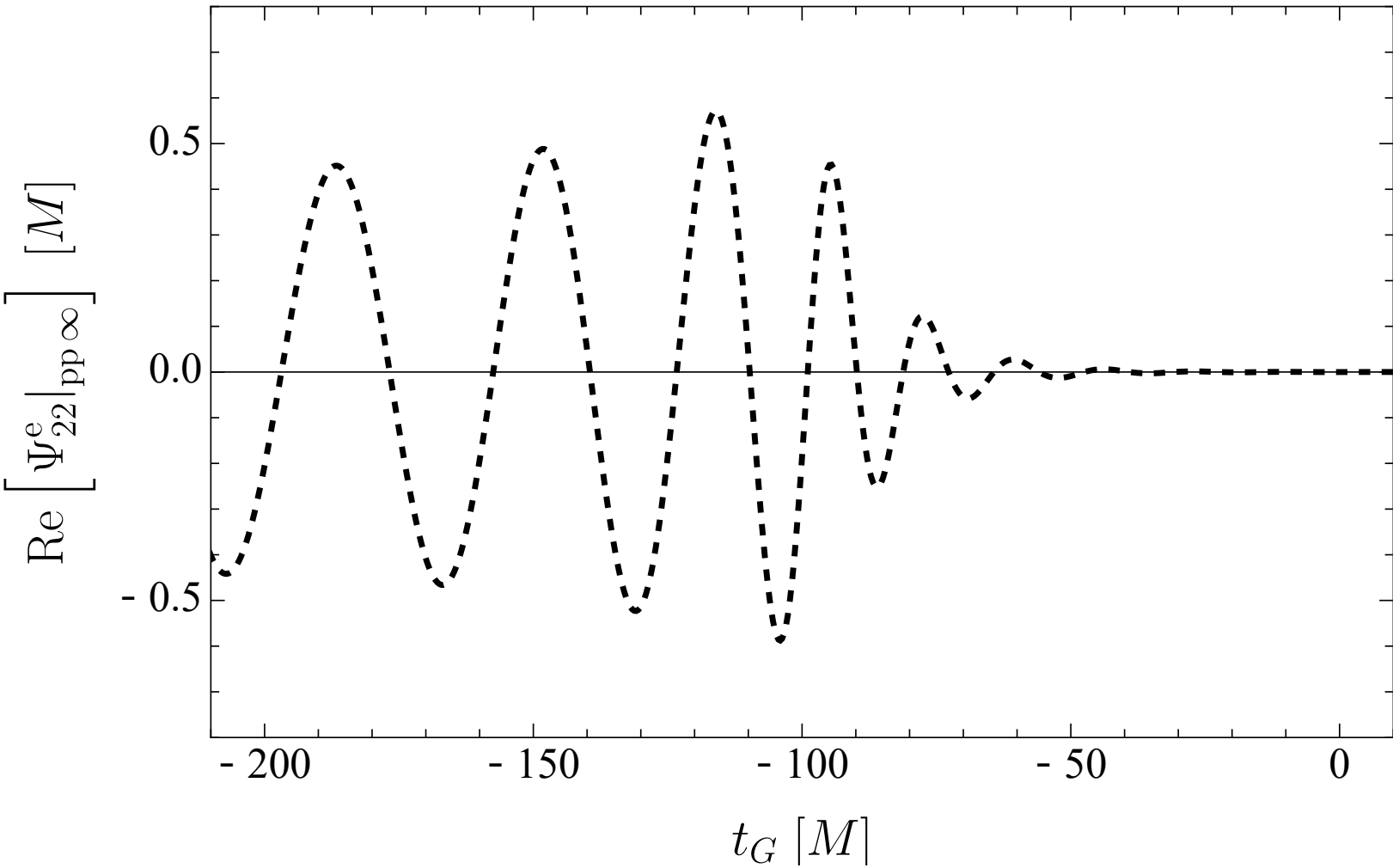


QNMs from residues

$$\int_{-\infty}^{\infty} d\omega = \text{residues} - \int_{\text{arcs}} d\omega - \int_{\text{branch cut}} d\omega$$



Dissecting the ringdown



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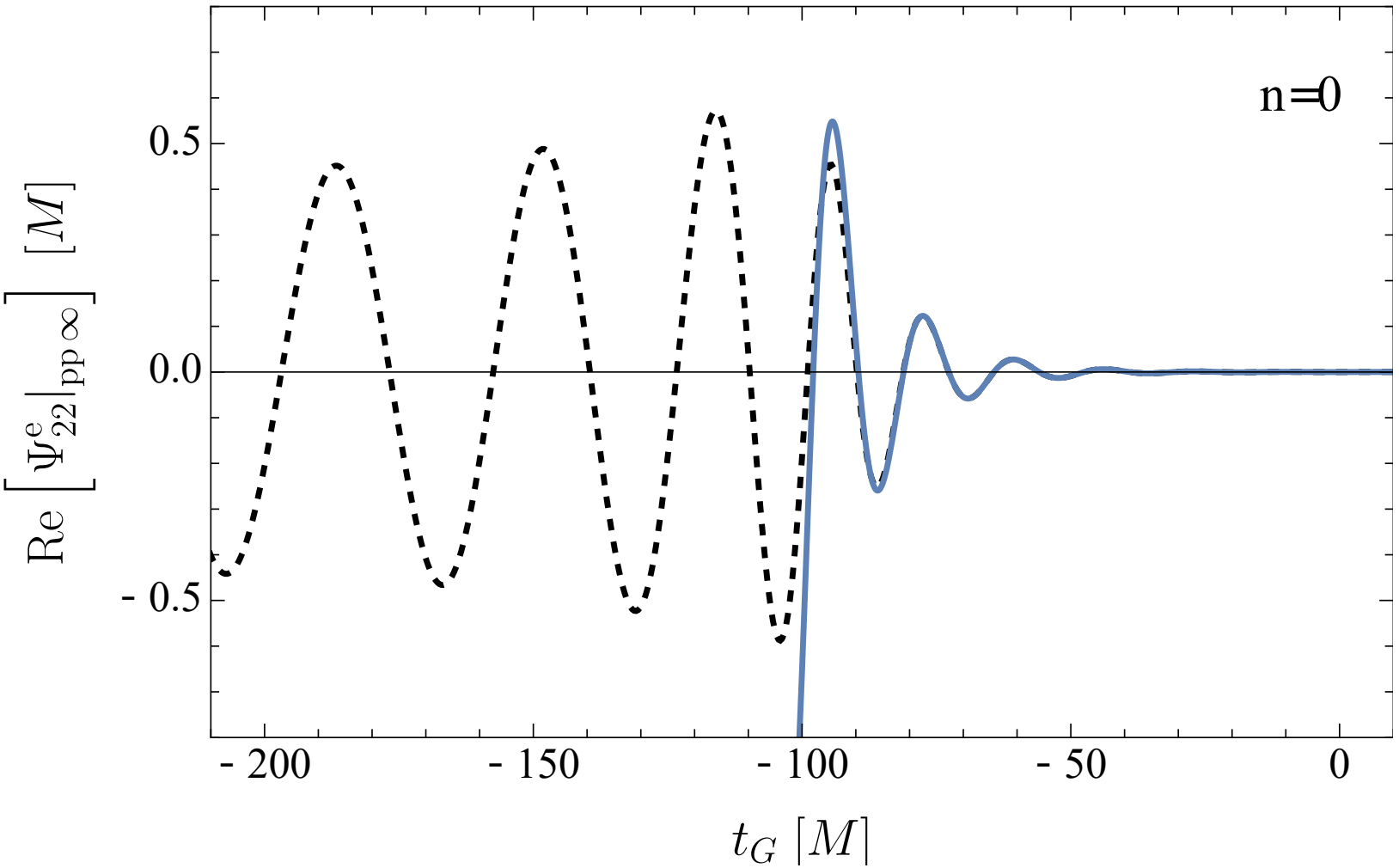

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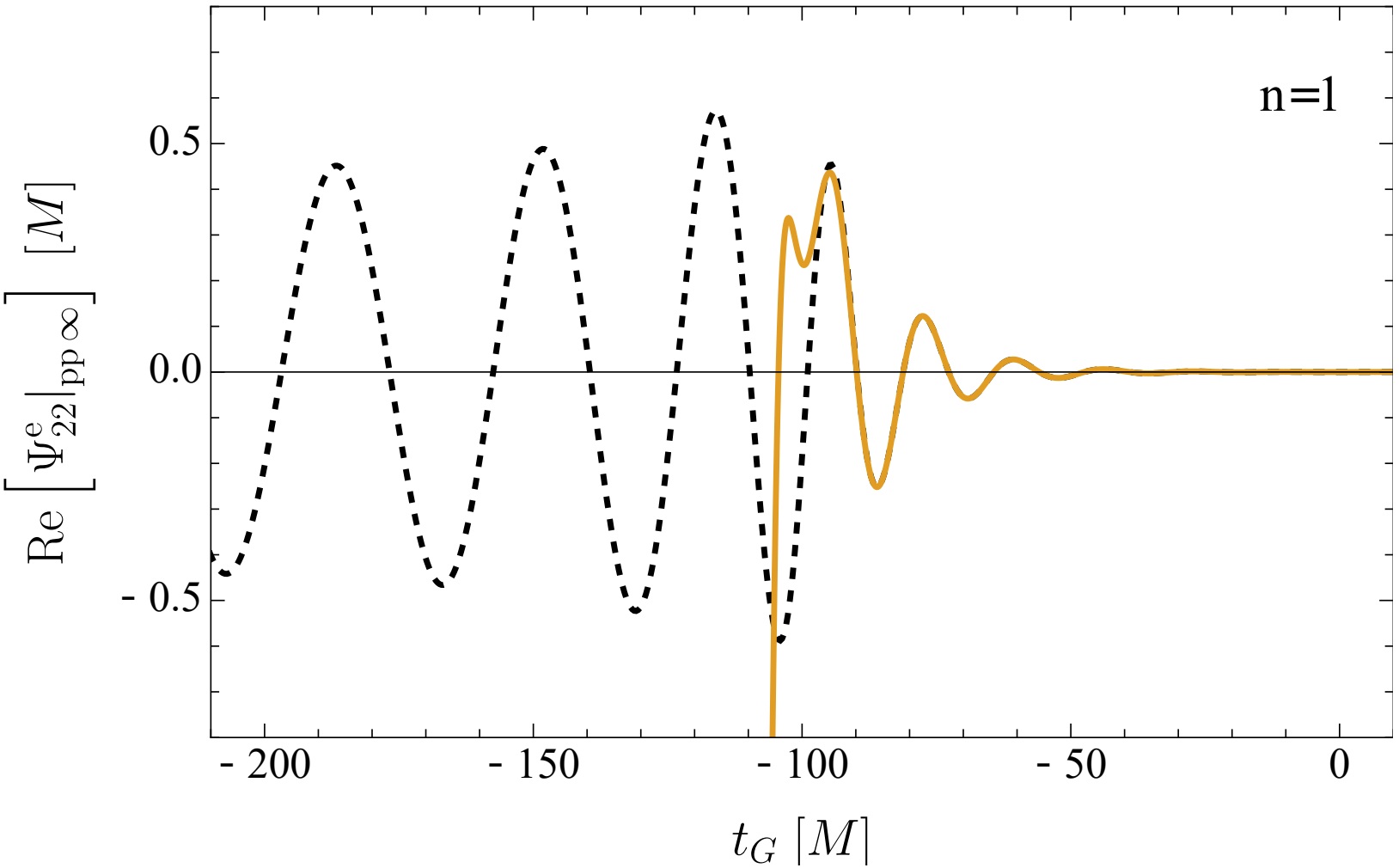

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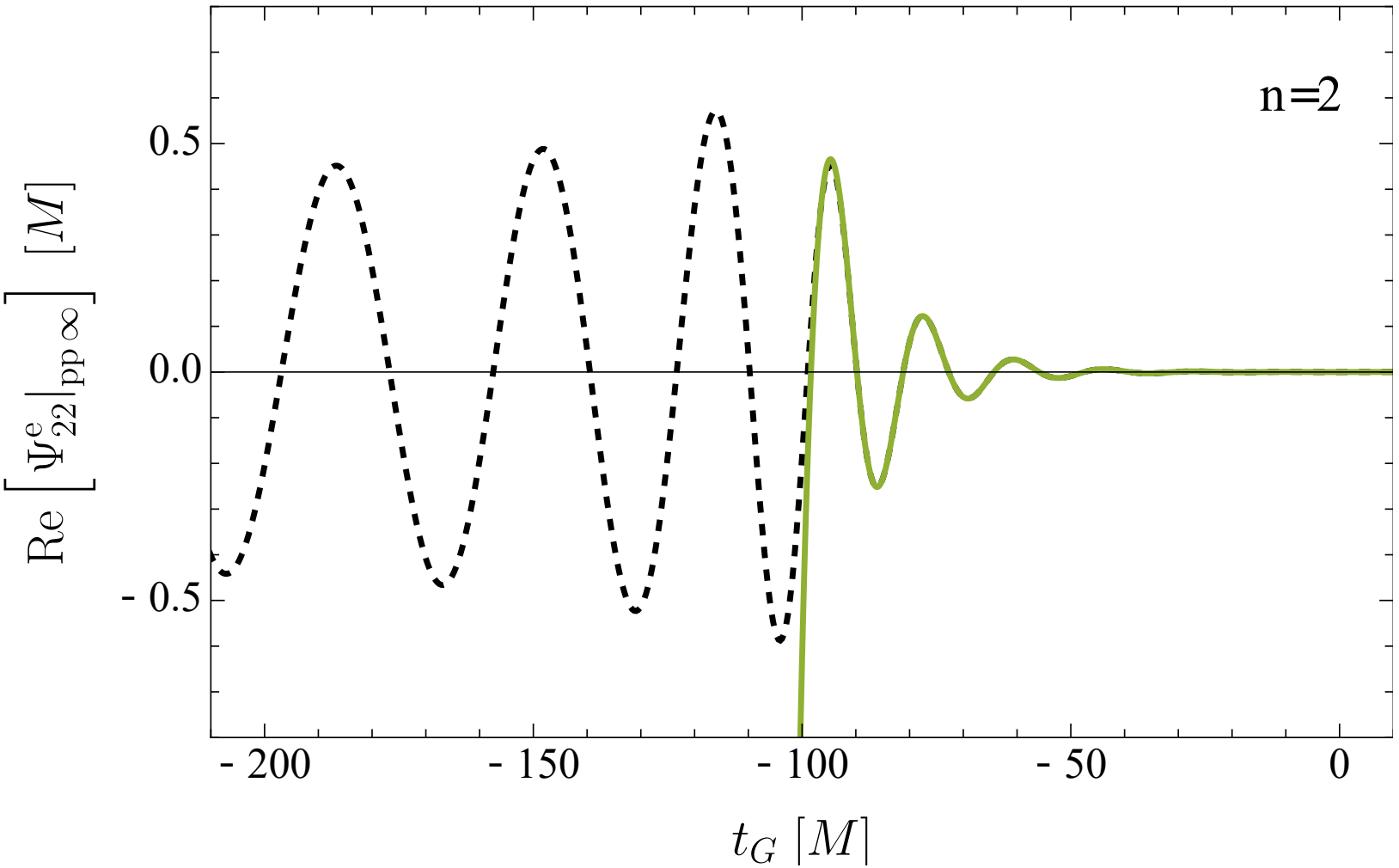

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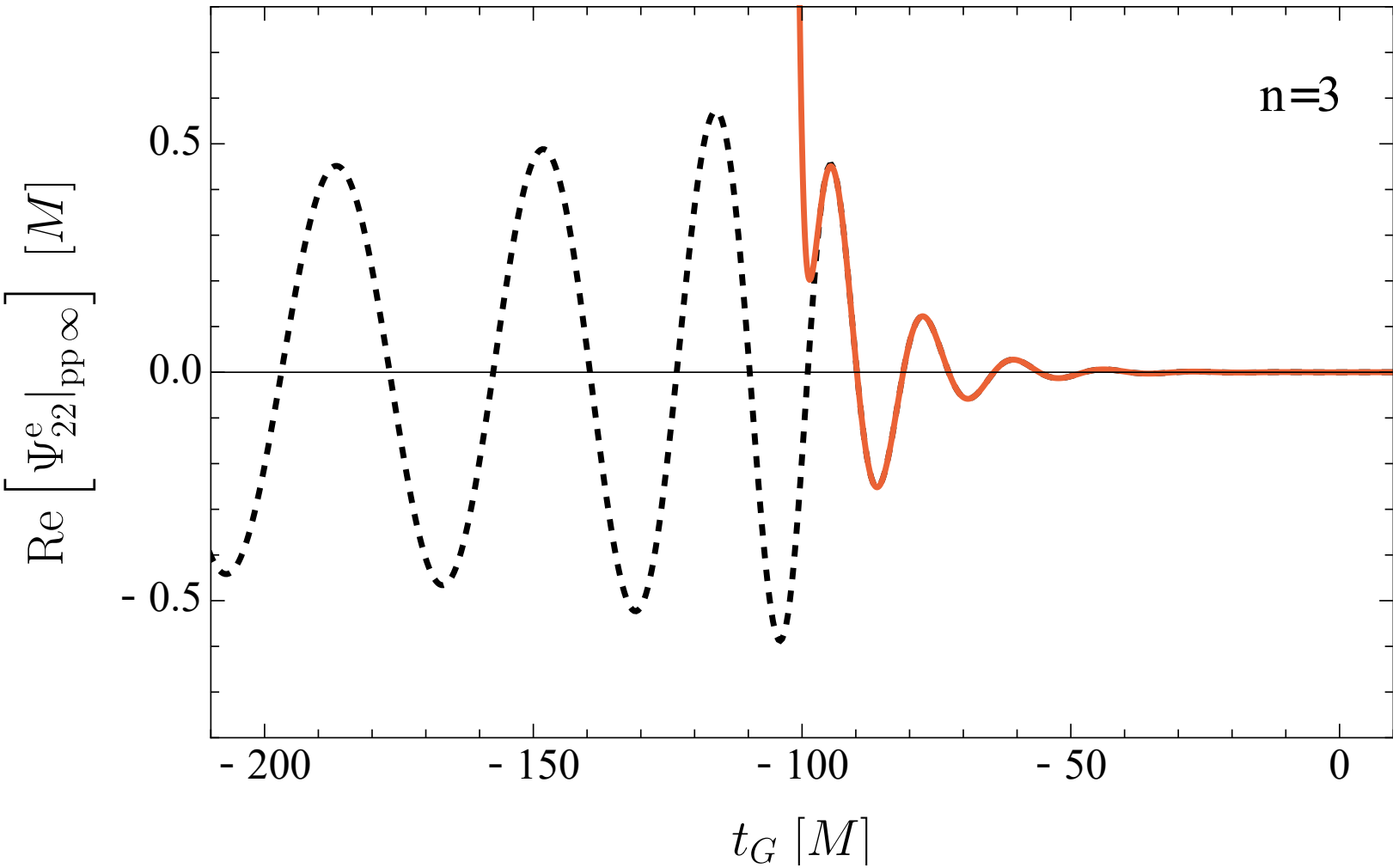

Conclusion

- self-force theory: fast, accurate waveforms for $\epsilon \lesssim 0.1$
- new systematic understanding of merger-ringdown
- QNM sum's convergence is erratic and does not reach the merger waveform's peak