Black hole ringdown modelling: linking the horizon dynamics to the gravitational wave observations

Xisco Jiménez Forteza

Maastricht. 2023

The Black Hole Ringdown: Characteristic 'chords' of BHs

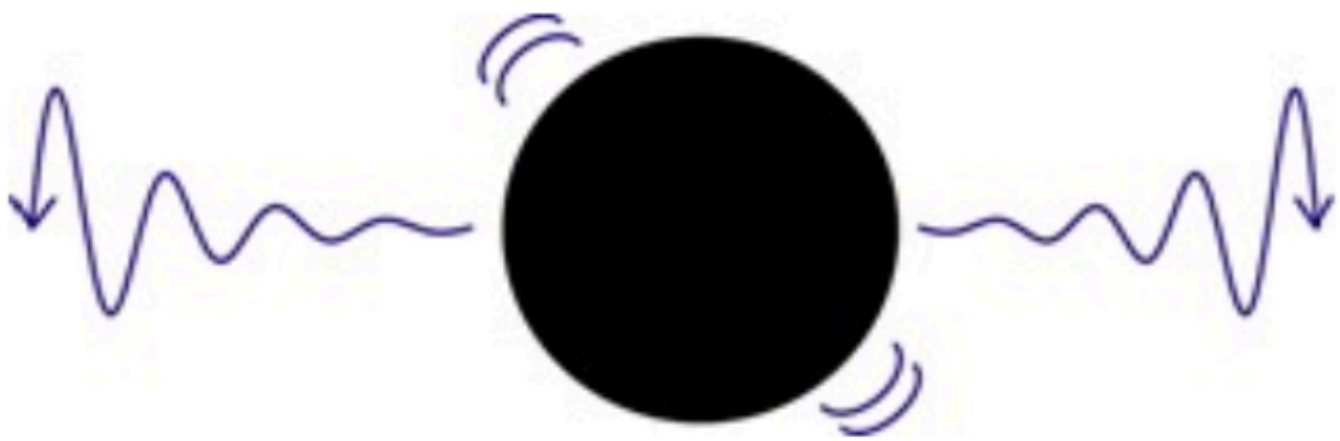


Image source: Porter Glanville

Particles or radiation in close orbits of the BH horizon, same particles falling-in, matter being accreted or even BHs merging with BHs will make the BH space time tremble in a characteristic way.

$$g_{ab} = g^0_{ab} + h_{ab} \qquad |h_{ab}| << |g^0_{ab}|$$

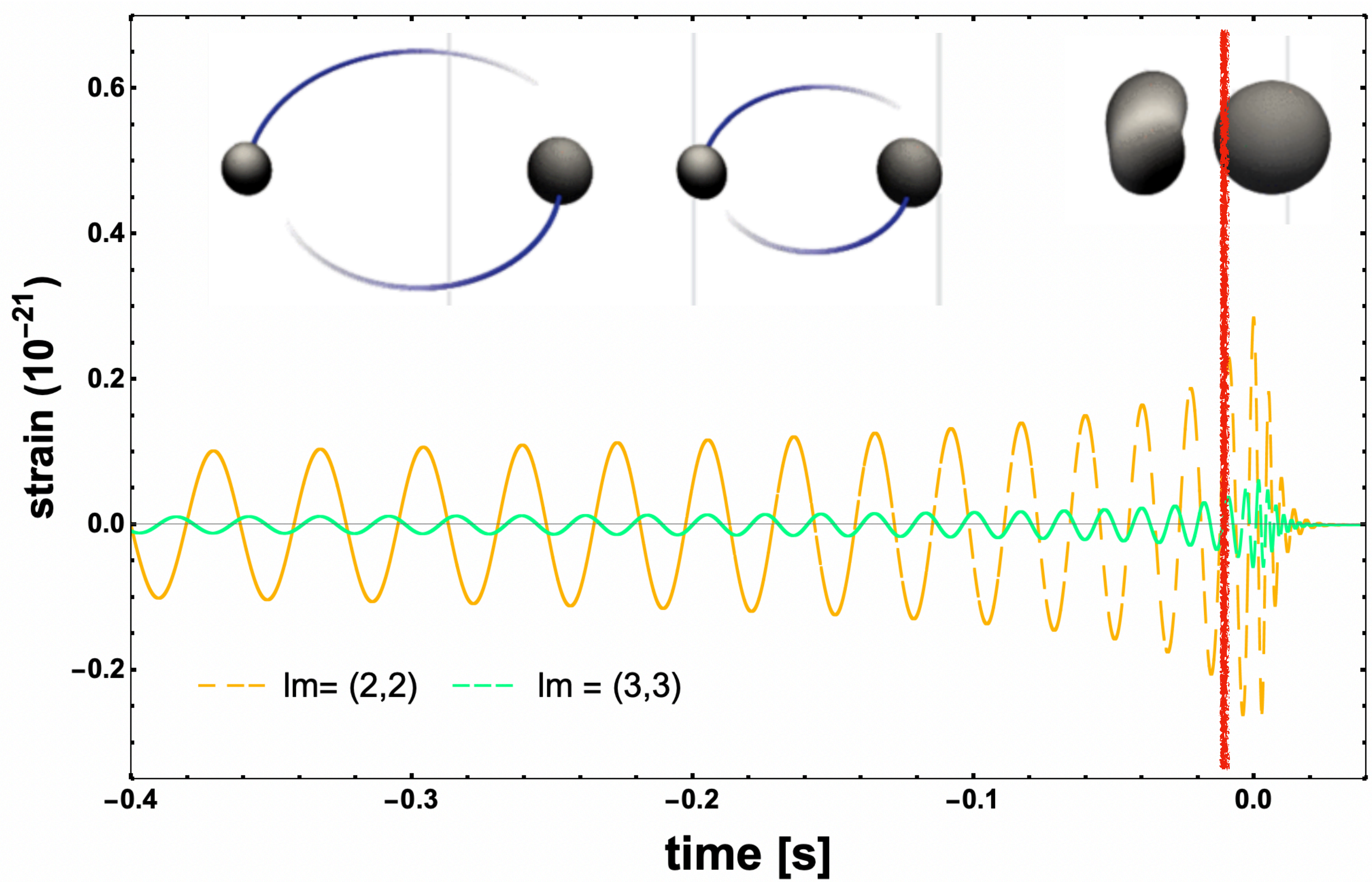
This characteristic trembling is the BH ringdown and it appears in BBH mergers.

Introduction

~ v/c expansions

~ Nonlinear regime

~ Linear regime



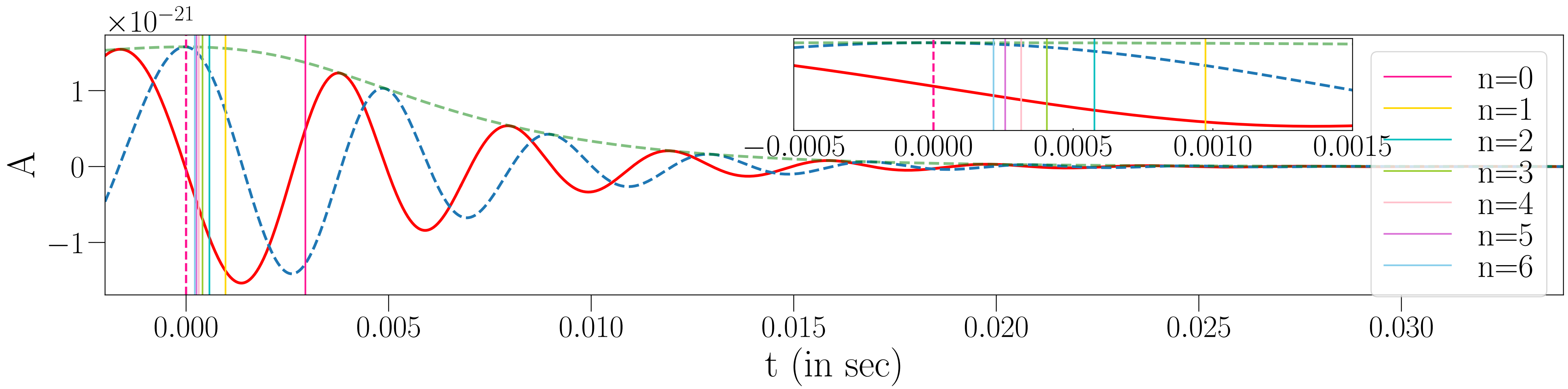
Well described by PT

Teukolsky, Chandrasekhar, Ferrari,

Kokkotas, Berti, Cardoso…

Linear perturbation theory predicts its shape —> discrete set of eigenmodes: quasi-normal modes (QNMs)

$$h_+ + i\,h_\times = \Sigma_{lmn} \mathcal{C}_{lmn} e^{-\iota\omega_{lmn}(t-t^0_{lmn})} e^{-(t-t^0_{lmn})/\tau_{lmn}} \mathcal{Y}_{lm} \quad C_{lmn} = A_{lmn} e^{\iota\phi_{lmn}}$$



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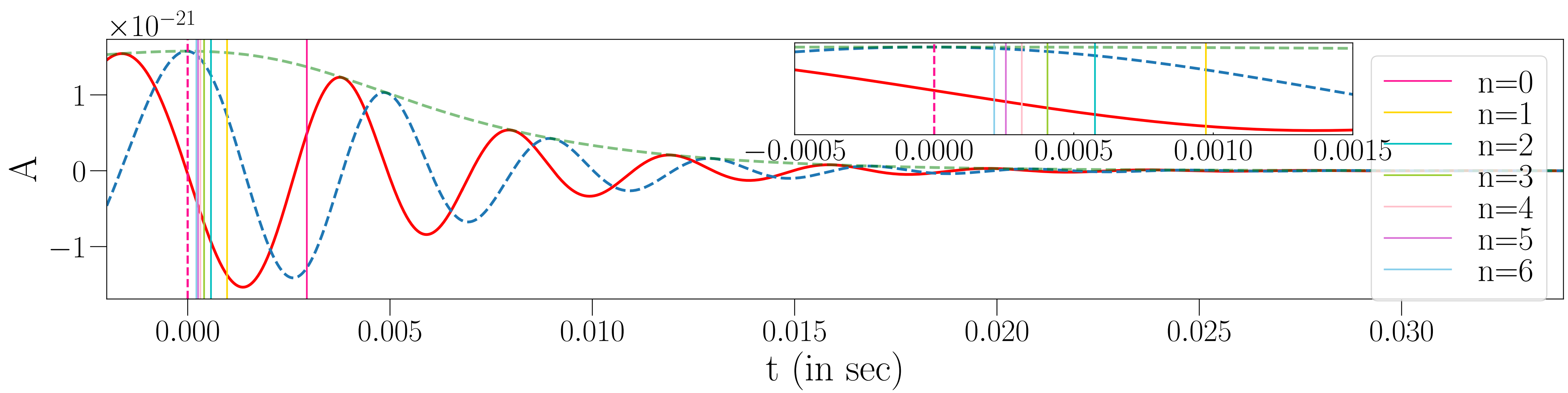

Black hole uniqueness / no-hair theorem in GR: axisymmetric, asymptotically flat, vacuum spacetimes, the QNMs are characterized by mass, angular momentum and charge. [Israel, Hawking, Carter…]

What can we test with the RD ???

Black hole no-hair theorem test — [Israel, Hawking, Carter…]

A BH spacetime in general relativity (GR) is uniquely defined by at most three parameters: the mass, the angular momentum and the electric charge.

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Astrophysical BHs in general relativity (GR) are expected to be chargeless: the mass, the angular momentum and the ~~electric charge~~.

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Part of the perturbative dynamics parametrizable by its mass and spins

$$\omega_{lmn} = f(M_f, a_f) \qquad \tau_{lmn} = g(M_f, a_f)$$

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If not GR

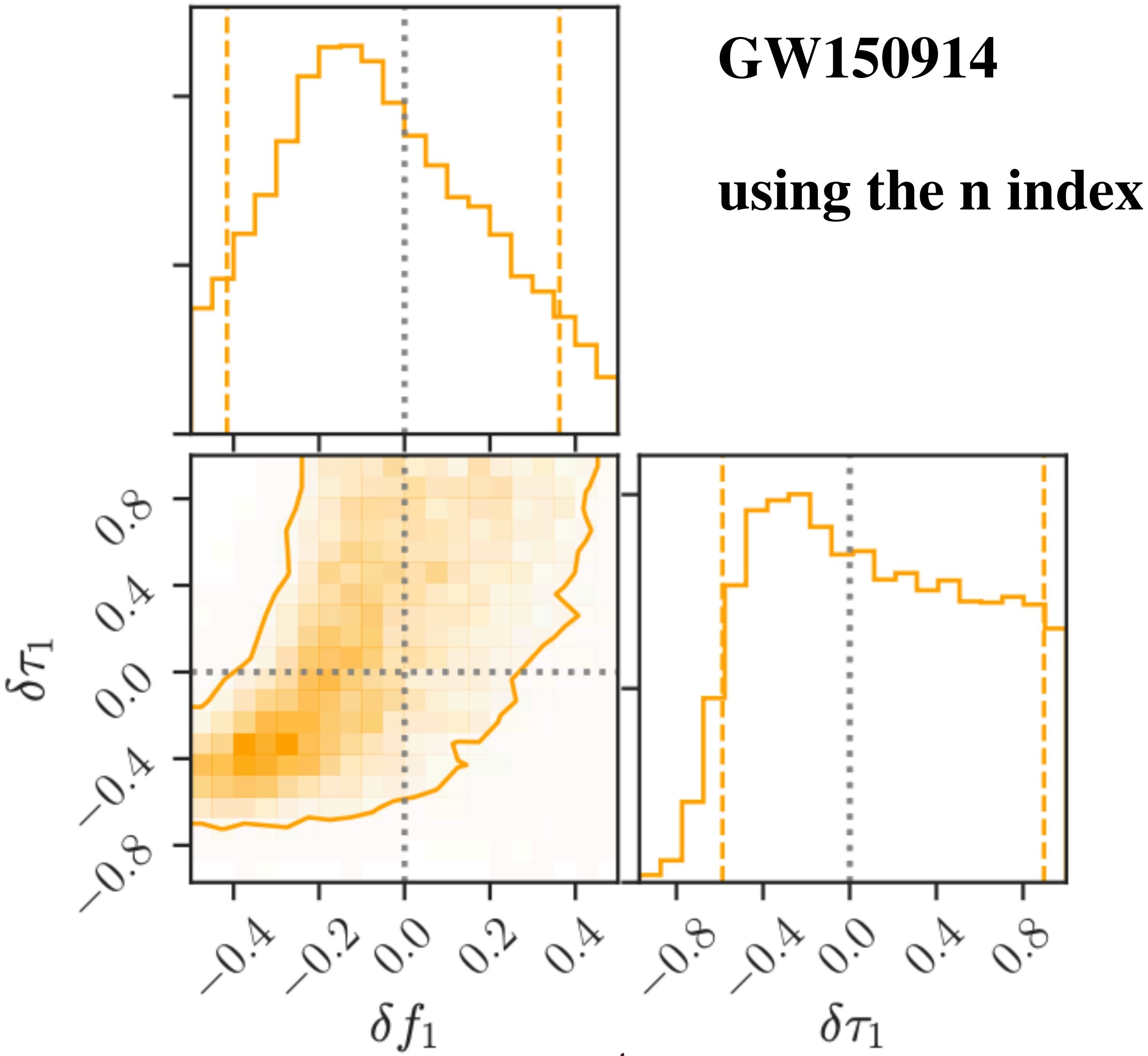
If not BH

Has the black hole no hair theorem been tested?

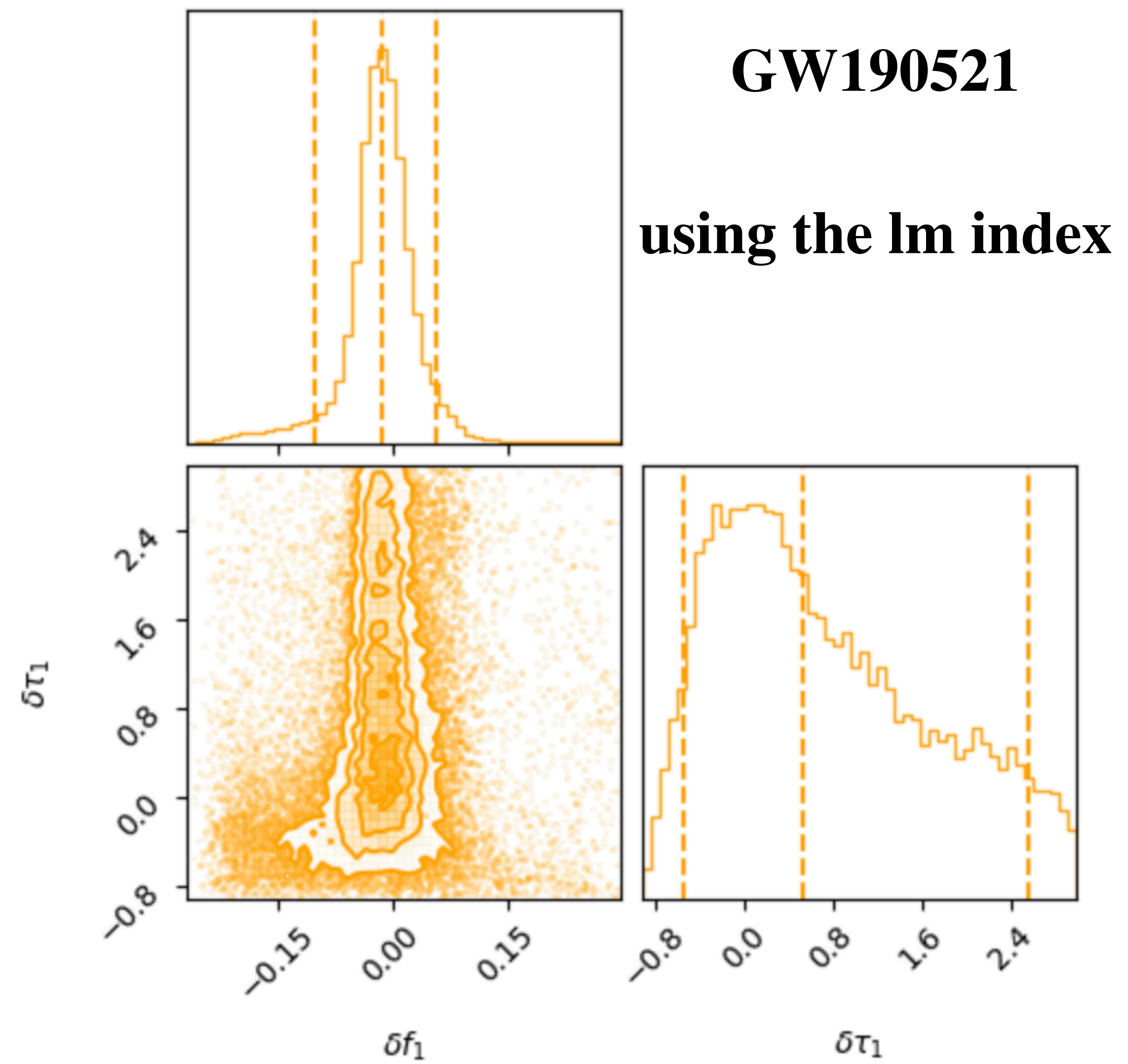
$\delta f, \delta\tau$ measure the BH or GR deviations.

$$\omega_{lmn} \to \omega_{lmn}^{GR}(1+\delta f)$$

$$\tau_{lmn} \to \tau_{lmn}^{GR}(1+\delta\tau)$$

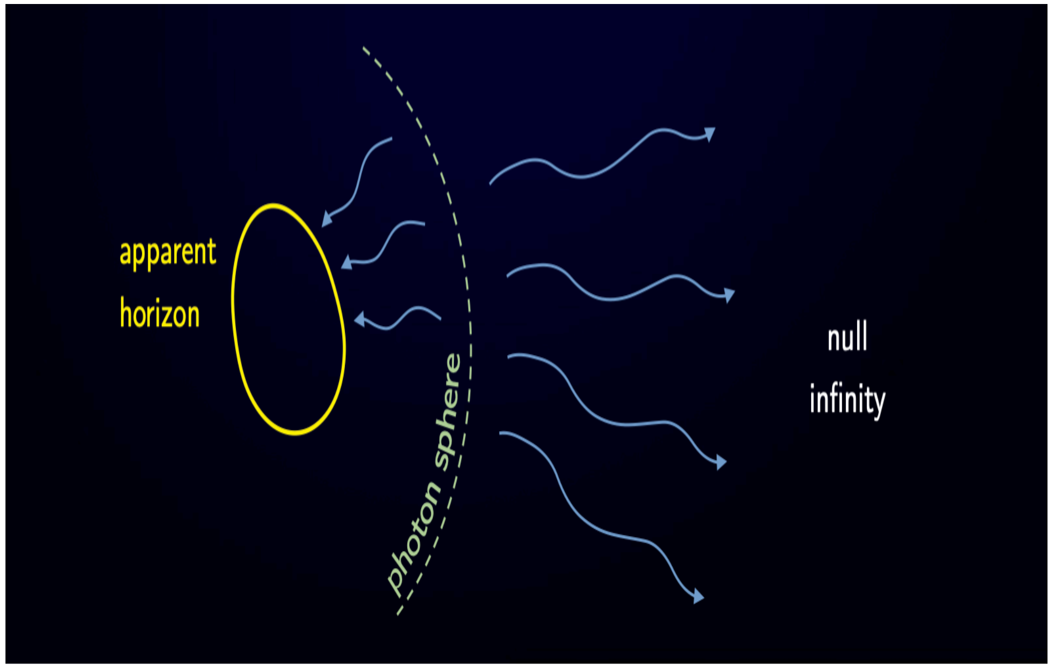


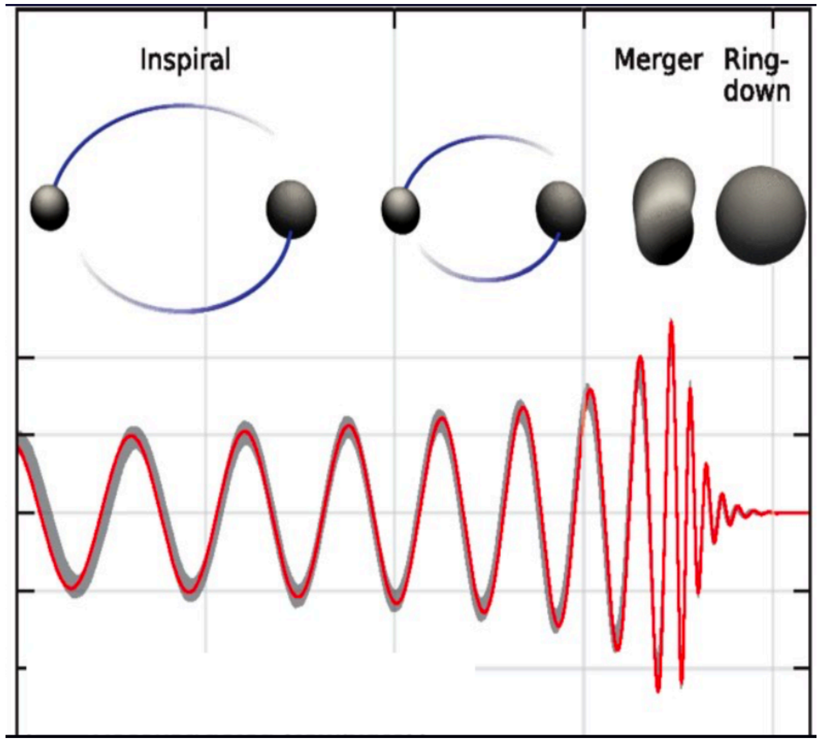
Isi et al. 2019



Capano et al. 2021

- But BHs also absorb radiation!





- The ingoing flux depends on the geometrical properties of the horizon as the shear of the outgoing null rays at the horizon (it is spin-2 field).

$$\sigma = m^a m^b \nabla_a l_b \qquad \sigma = \sum_{l=2} \sigma_{l\ 2}\mathcal{Y}_{lm}$$

$$\mathcal{F}_{\text{infalling}} \sim |\sigma|^2 \qquad \longleftrightarrow \qquad \mathcal{F}_{\text{outgoing}} \sim \mathcal{N}^+ \sim |\frac{dh}{dt}|^2$$

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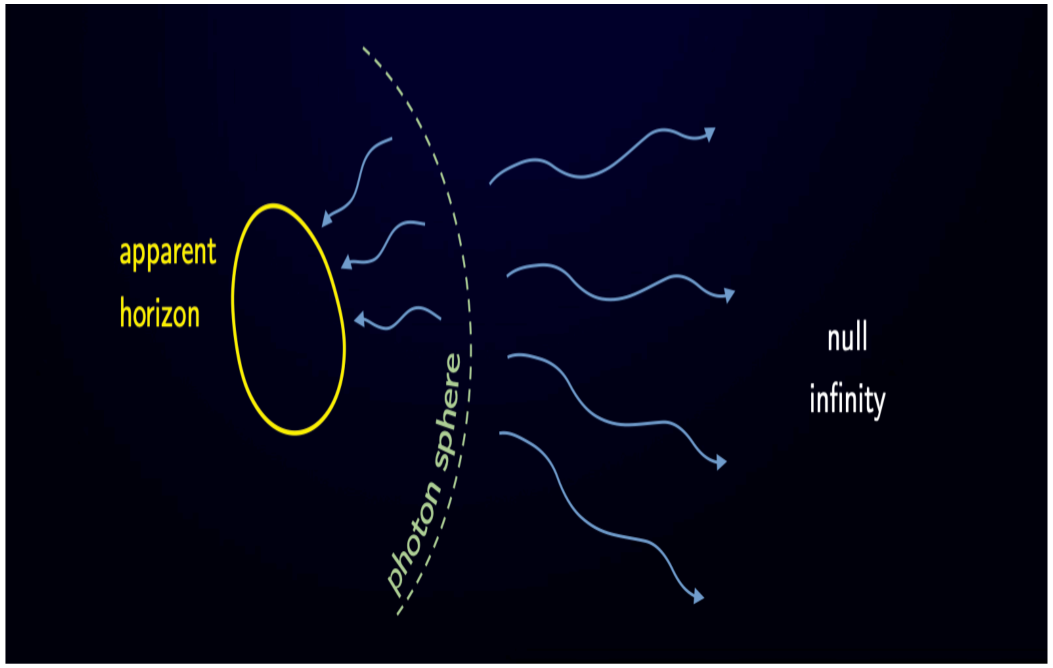
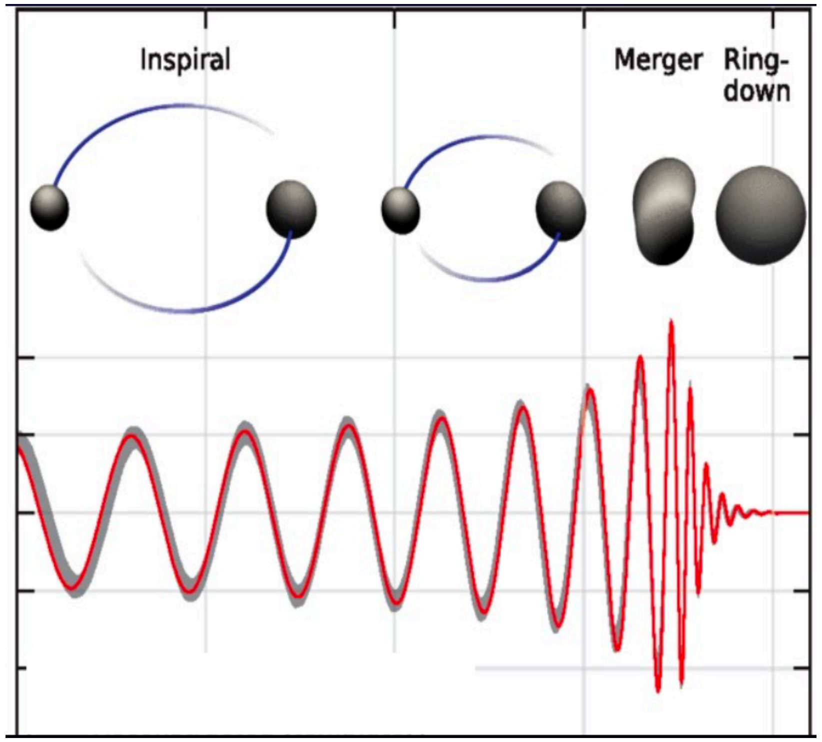


???



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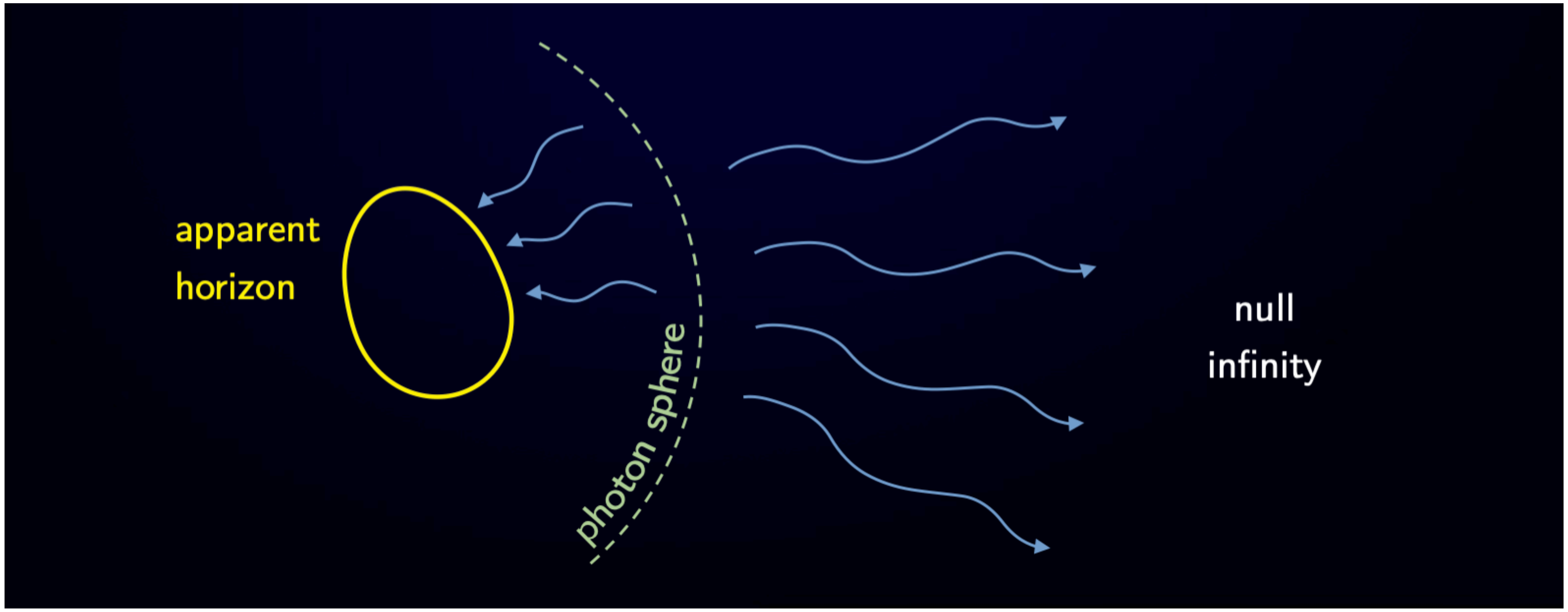

i) Has the horizon anything to do with the actual observable quantity, namely the outgoing GWs?
Are the horizons not causally disconnected from the outside observers and thus observationally irrelevant?

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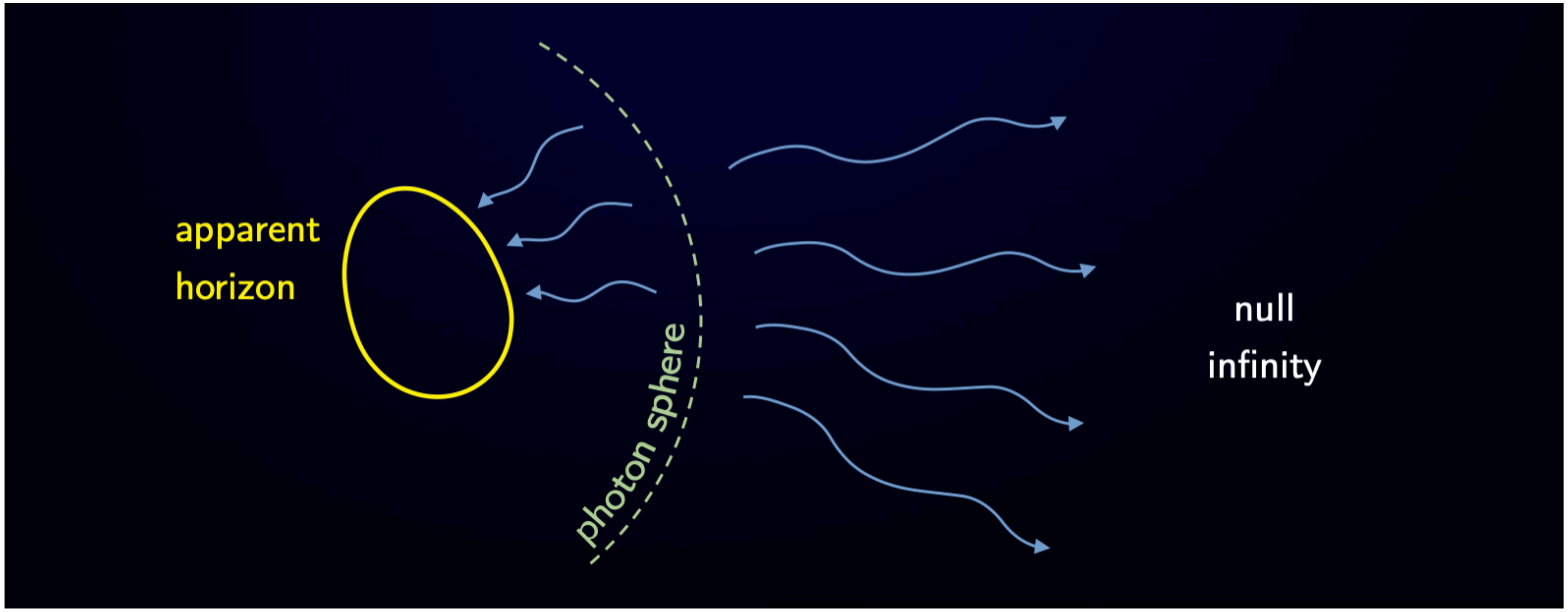

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i-a) Remarkable correlations observed between the outgoing radiation and the in-falling radiation that could be seen by a hypothetical observer living near the horizon *(Ashtekar (2002), Rezzolla (2010), Jaramillo (2012), Gupta (2018), Vaishak Prasad (2020))*.

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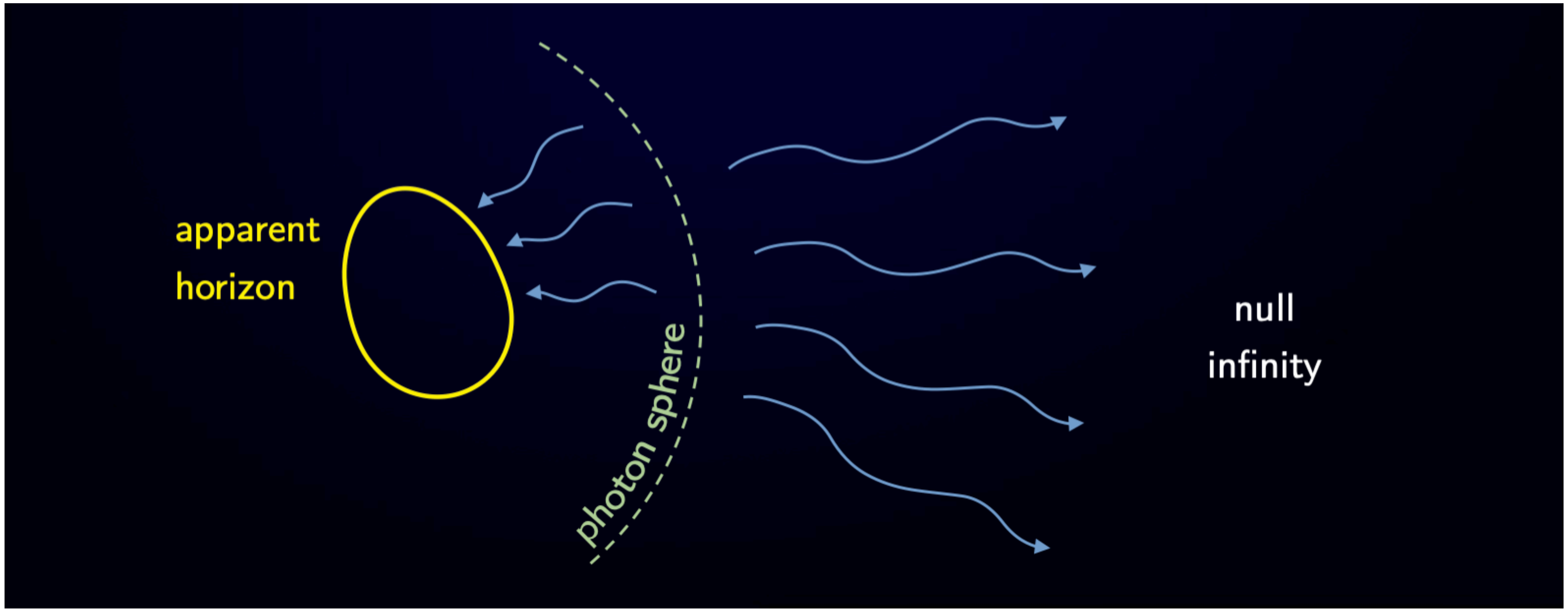

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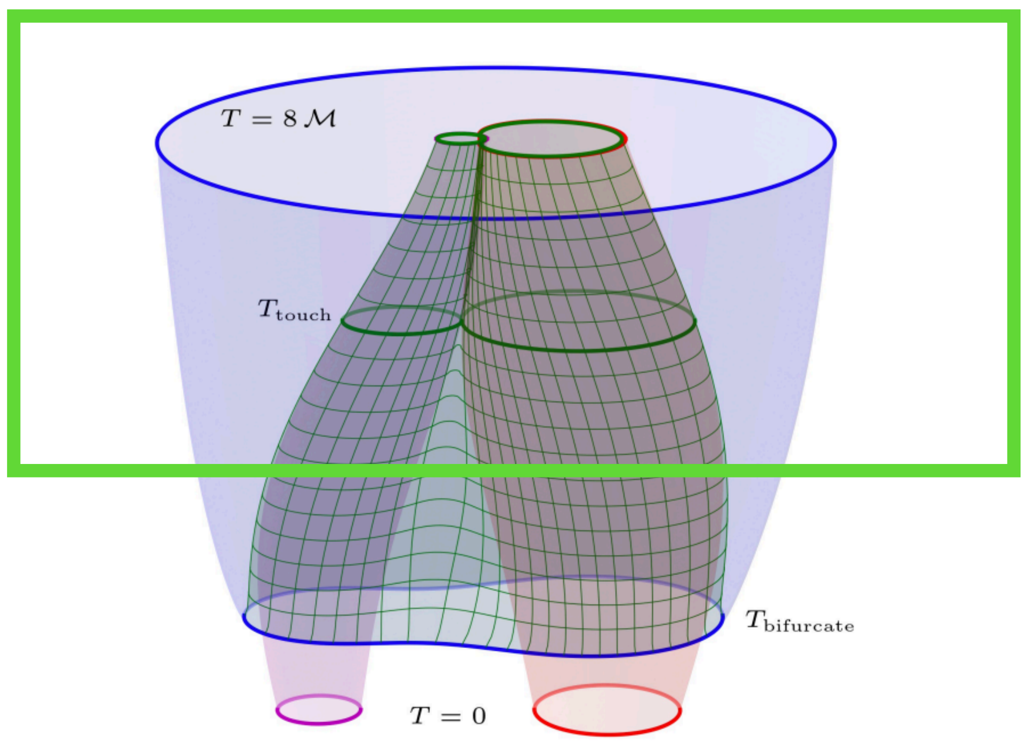
i-b) Actually since, the gravitational radiation they would see comes from the same source, it is thus not a surprise that both observers will see qualitatively similar features.

But is this correlation also valid during the late regime?



Pook-Kolb et al (2020), Pook-Kolb et al (2021), Mourier et al (2021)

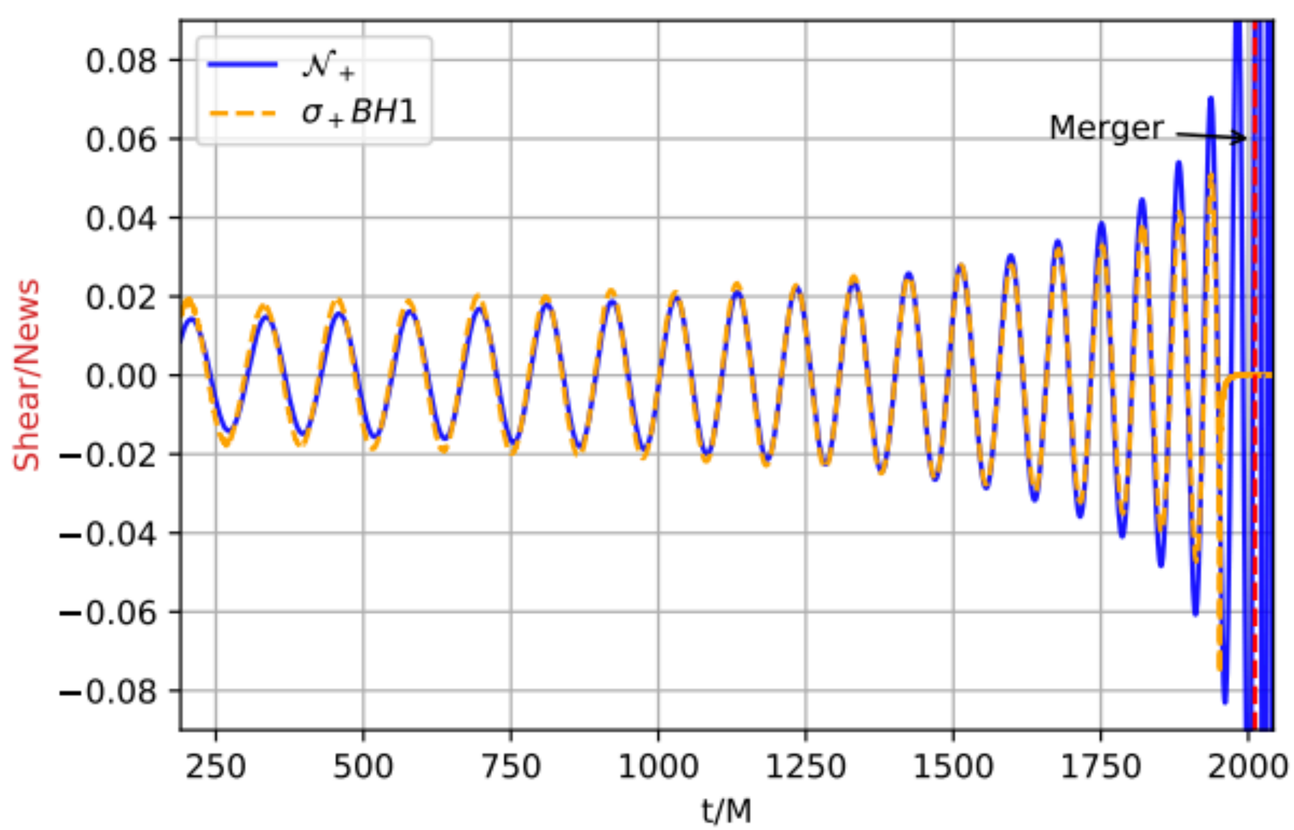
Evidence of correlations

Near the horizon

Remarkable correlations observed between the infalling gravitational wave flux and the outgoing flux.

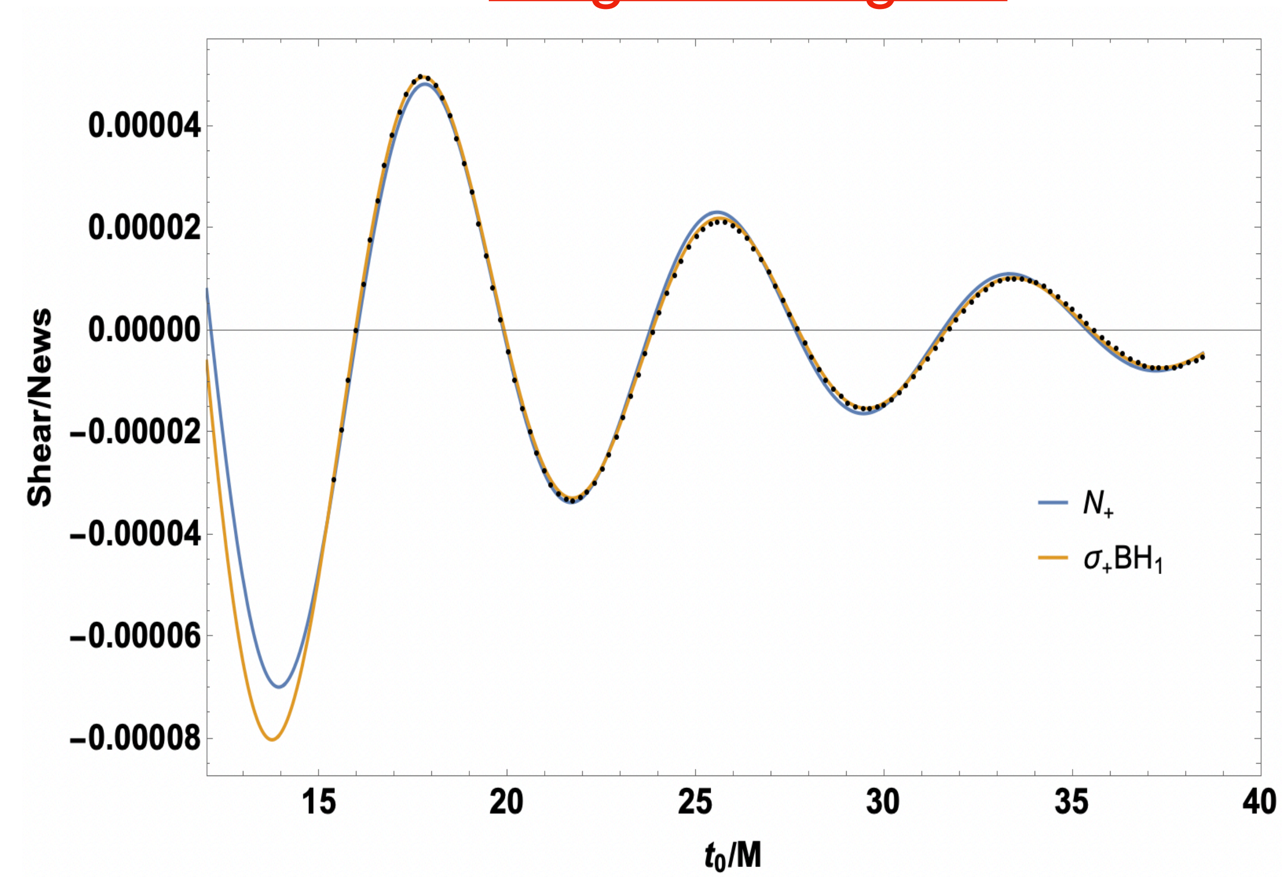
$$\mathcal{F}_{\text{infalling}} \sim |\sigma|^2 \quad \xleftrightarrow{\;V\;} \quad \mathcal{F}_{\text{outgoing}} \sim \mathcal{N}^{+} \sim \left|\frac{dh}{dt}\right|^2$$

Inspiral regime



Vaishak Prasad et al (2020)

Ringdown regime



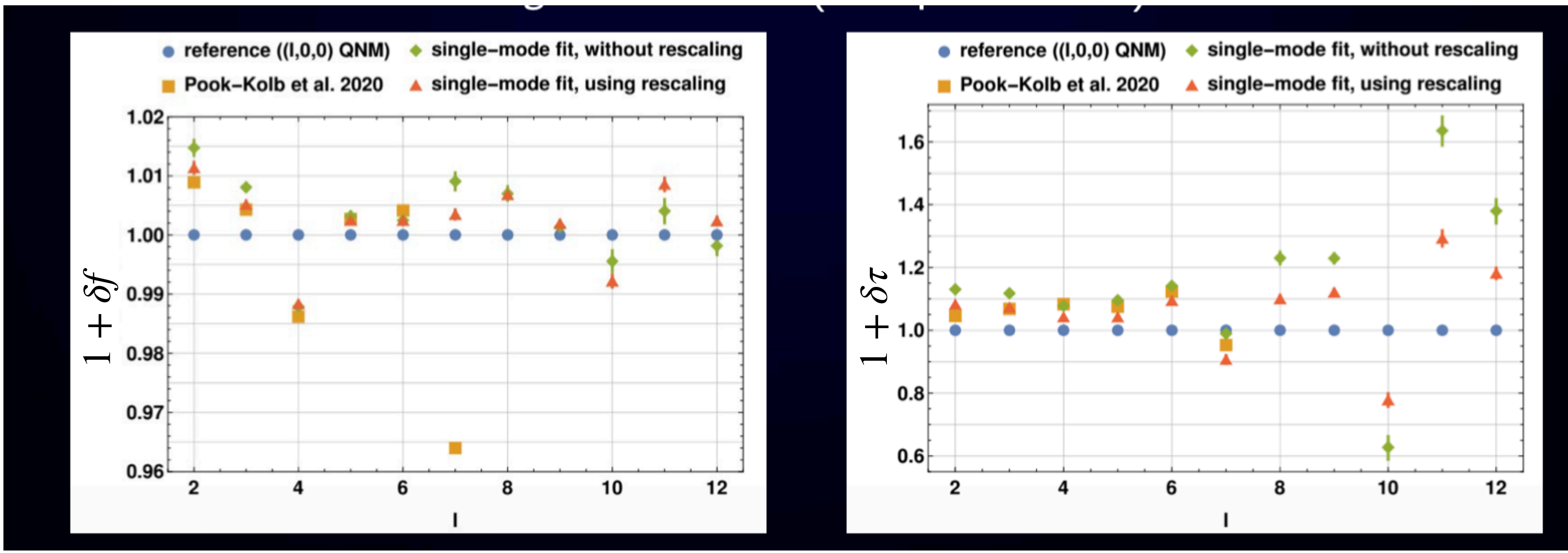
Pool Mourier-Jimenez, Ribes - Jimenez

Results

- Recovering the fundamental QNM at late times t_0.

$$\omega_{lmn} \to \omega_{lmn}^{GR}(1+\delta f) \qquad \tau_{lmn} \to \tau_{lmn}^{GR}(1+\delta\tau)$$

- Fractional deviation of the shear spectrum.



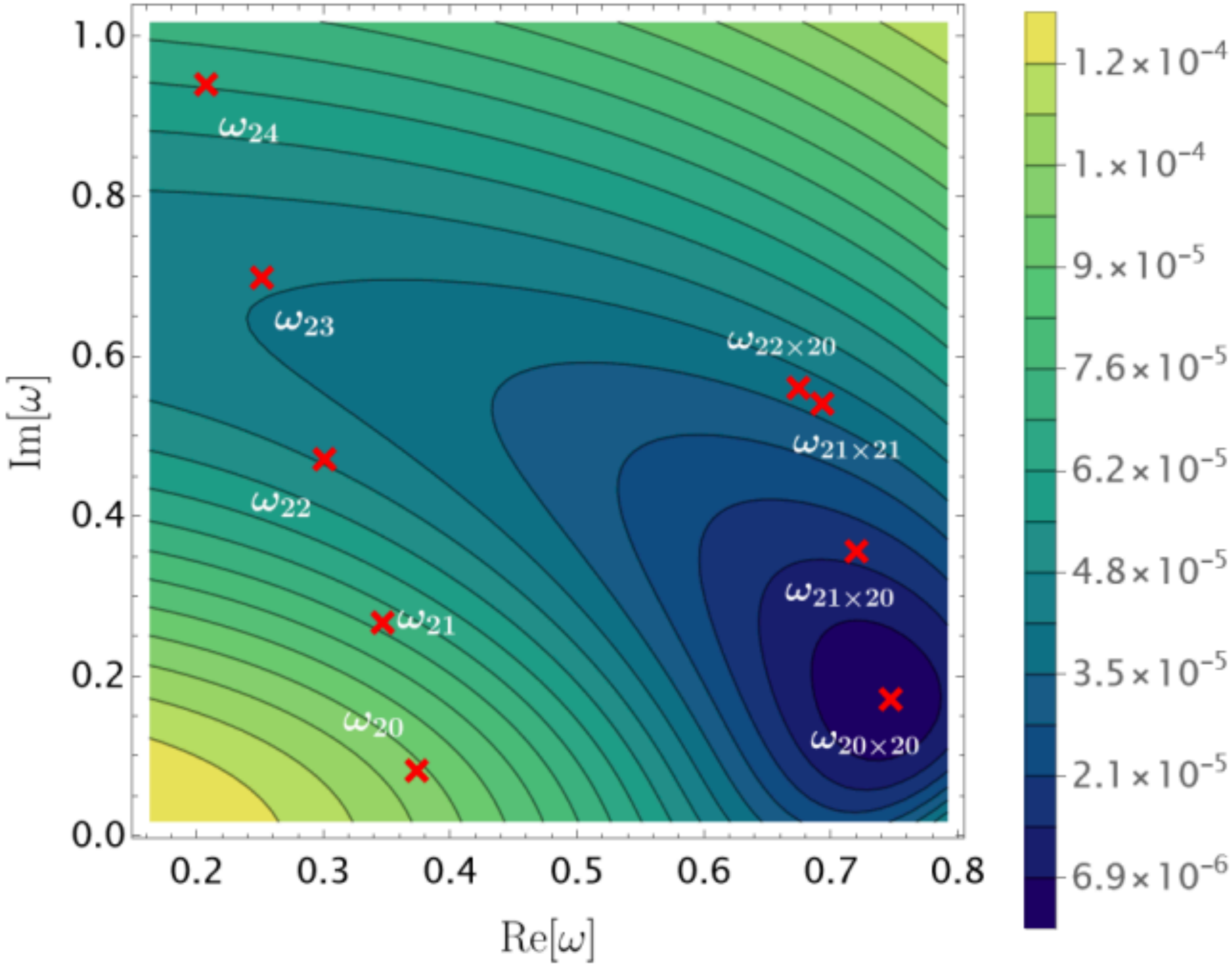
- The shear, a property of the horizon, shows the n=0 tone spectrum at the few % level.

- Recently, evidences of quadratic correlations (Neev-Ribas 2023).

Results

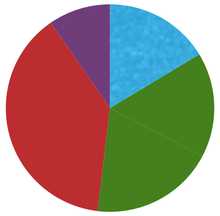
- Recently, evidences of quadratic correlations (Neev-Ribas 2023).

$$h_{RD} \sim h_L + h_L^2 \qquad \omega_q = \omega_L^1 + \omega_L^2$$



Neev-Ribes (PRL, 2023)

Conclusions + future work



1. The no-hair theorem to be tested soon with better accuracy.

2. Evident correlations between the waveforms and the horizon quantities.

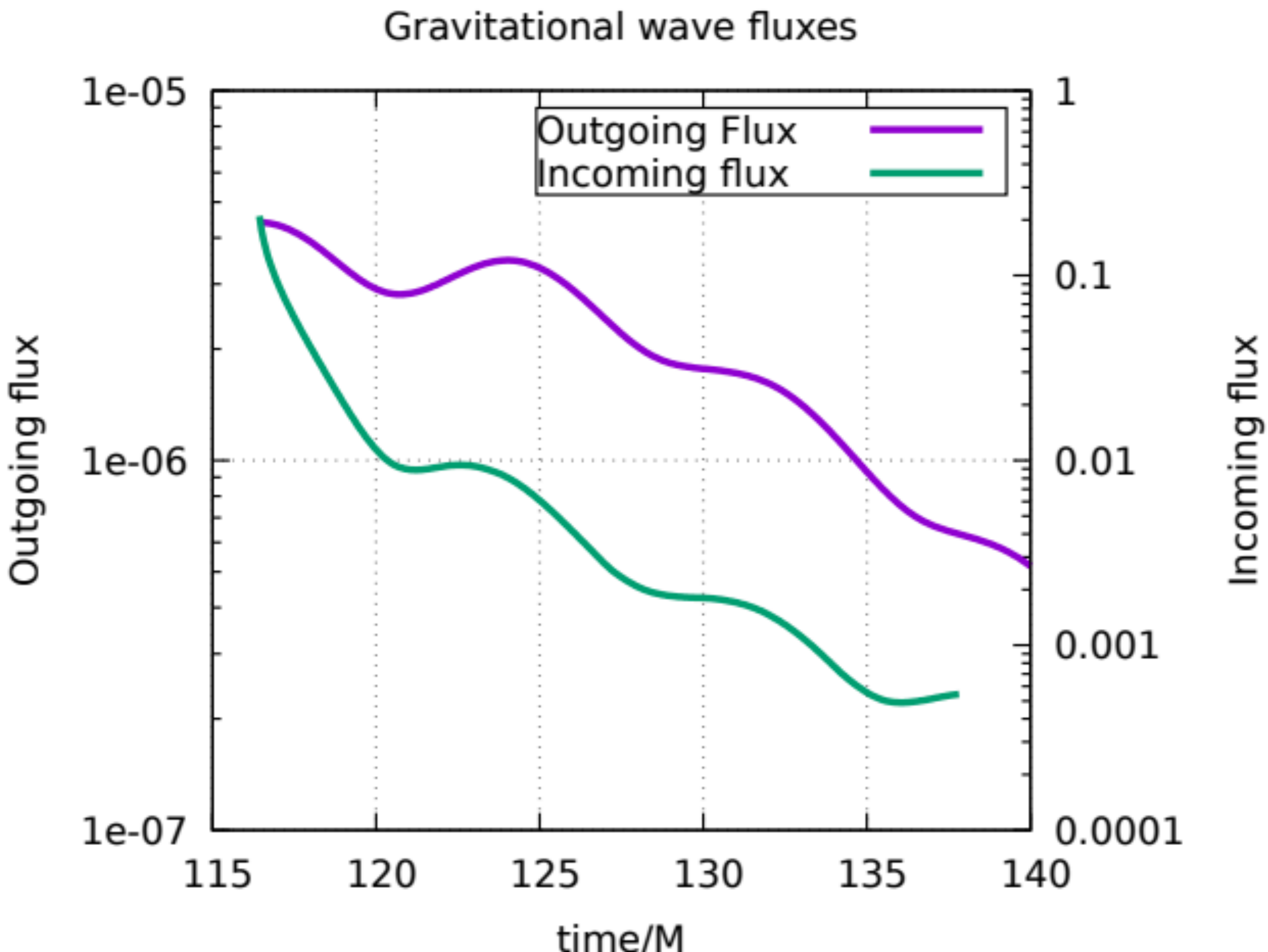
3. Can we touch the causally disconnected horizon with GWs?

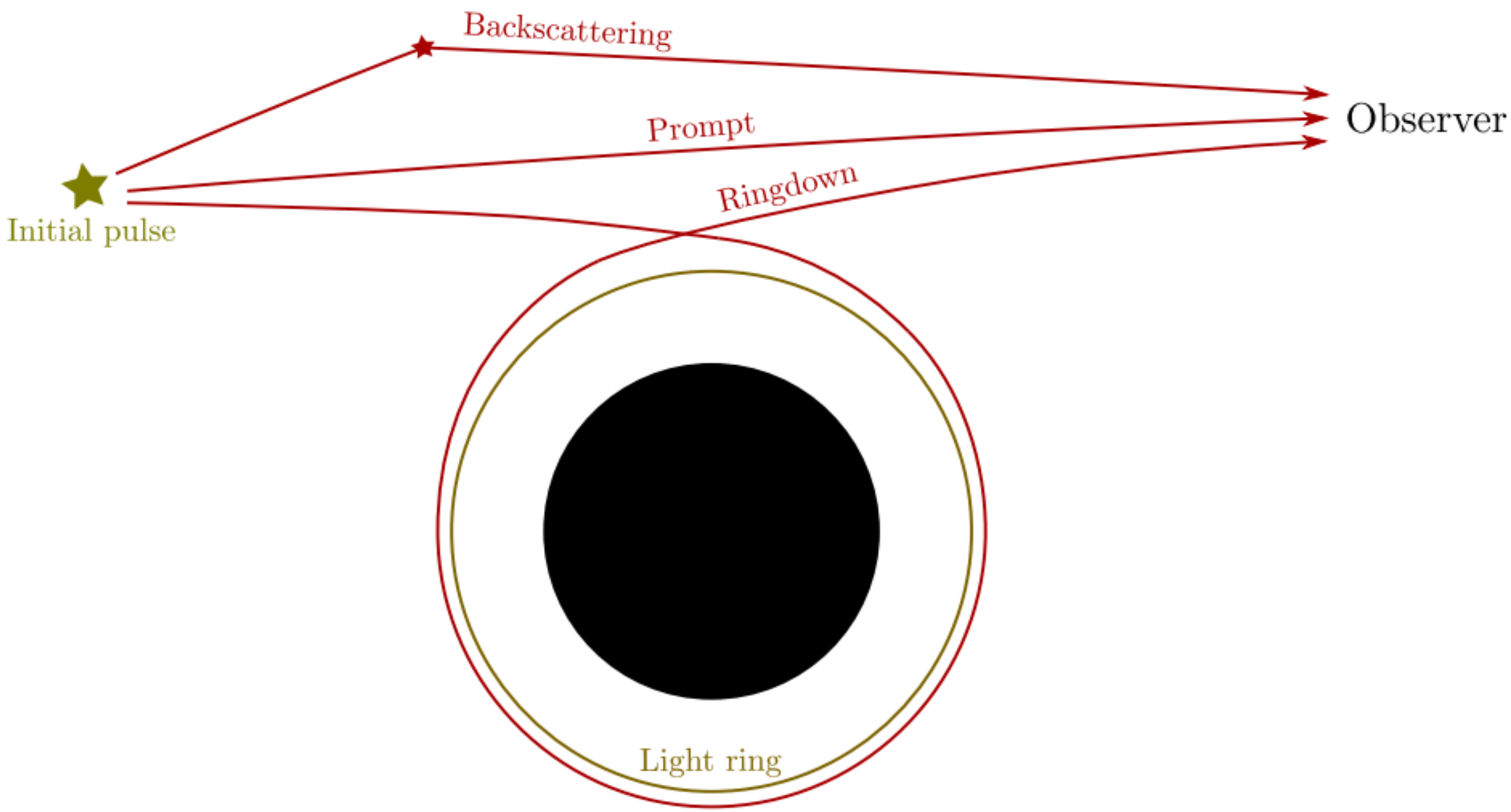
4. Do near-horizon exotic object surfaces of show a similar behaviour?

5. Useful for waveform modelling?

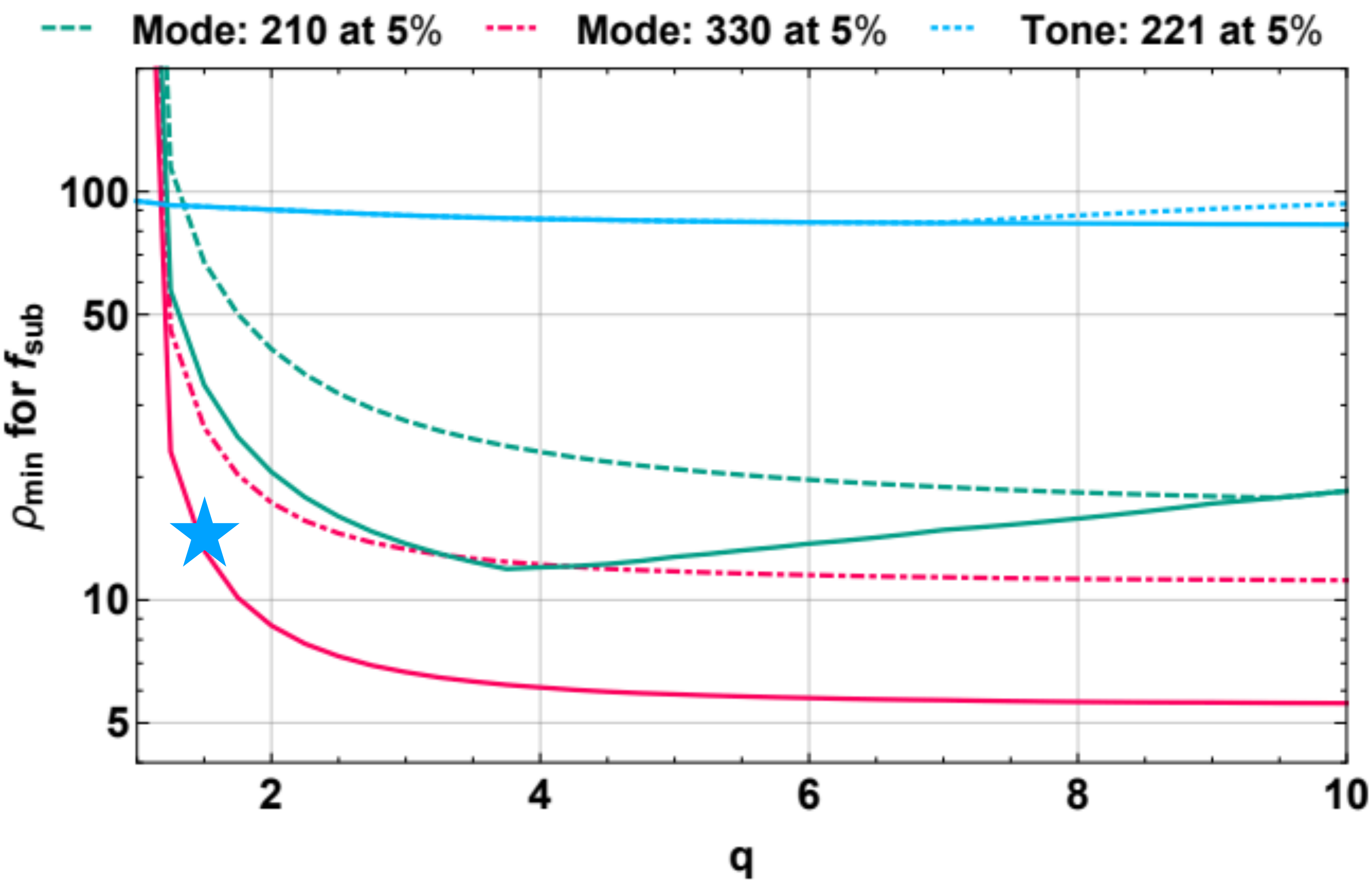
Evidence of correlations

Outgoing fraction




Backscattering
Observer
Prompt
Ringdown
Initial pulse
Light ring

★ **GW210521**



Jimenez et al. 2020

Introduction

· RD pops up naturally in numerical relativity.

· The frequency and damping time of the fundamental mode n=0 well observed in NR.