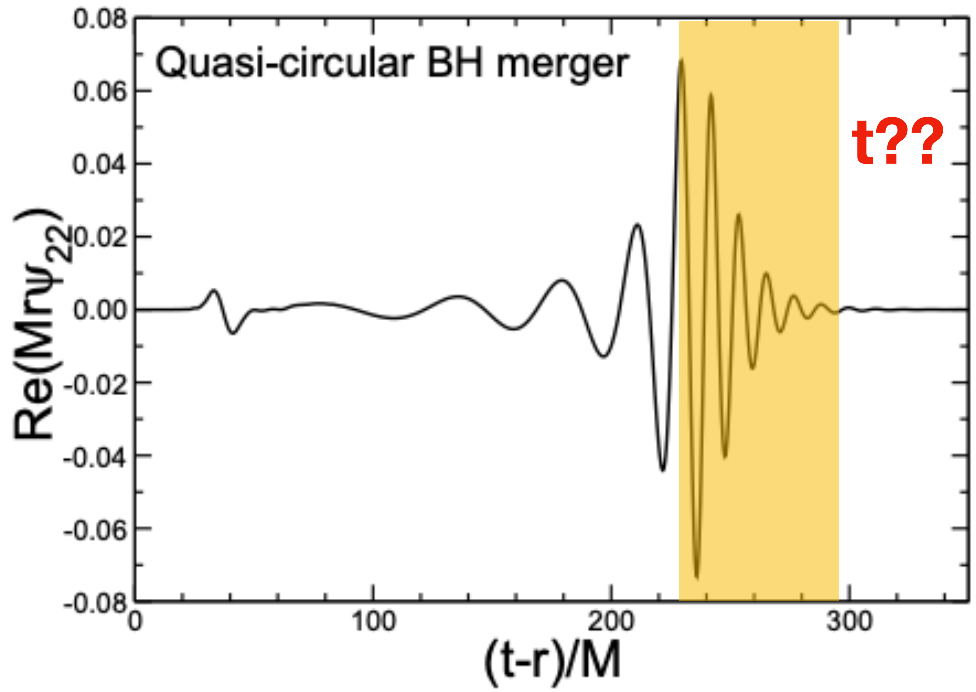
Understanding the black hole ringdown using numerical relativity

Xisco Jiménez Forteza

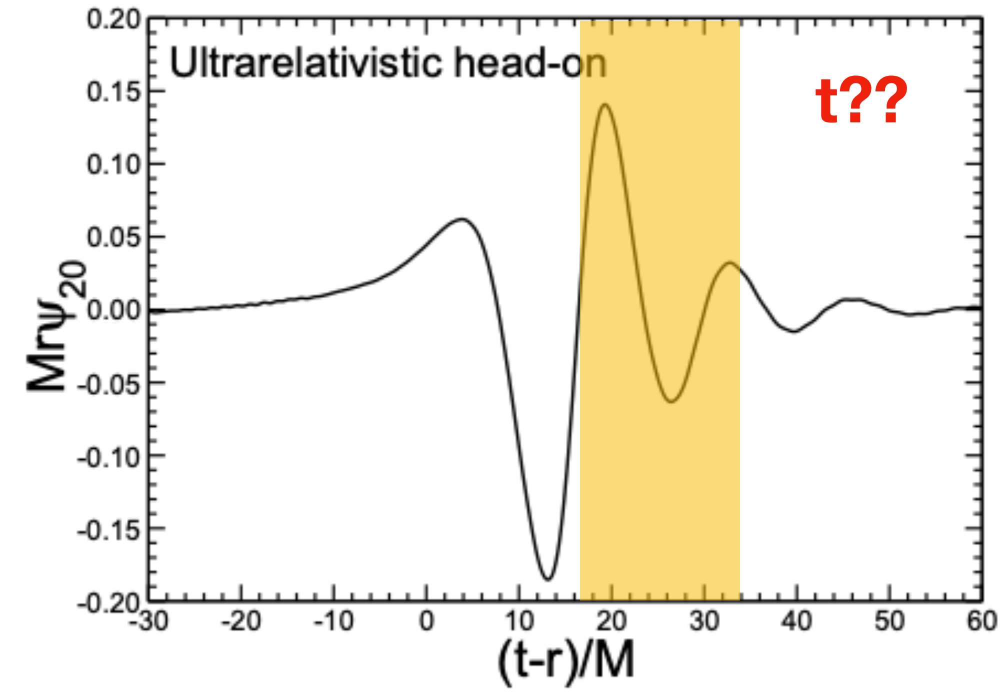
Black Holes workshop 2025

BBH merger: A historical review

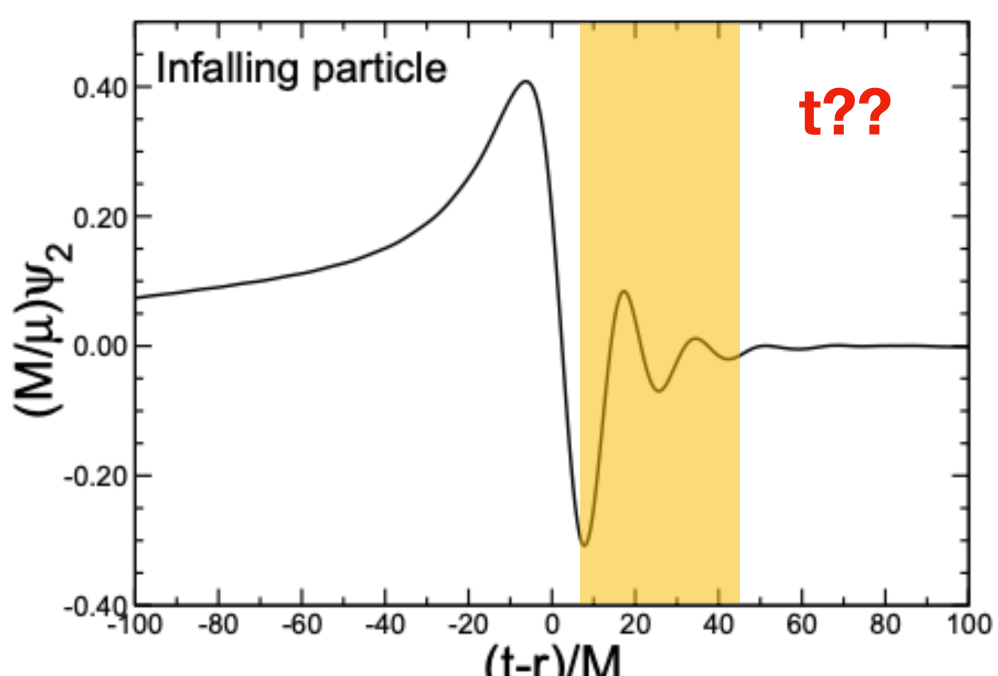
Sperhake, Hannam, Husa, Bruegmann 2008



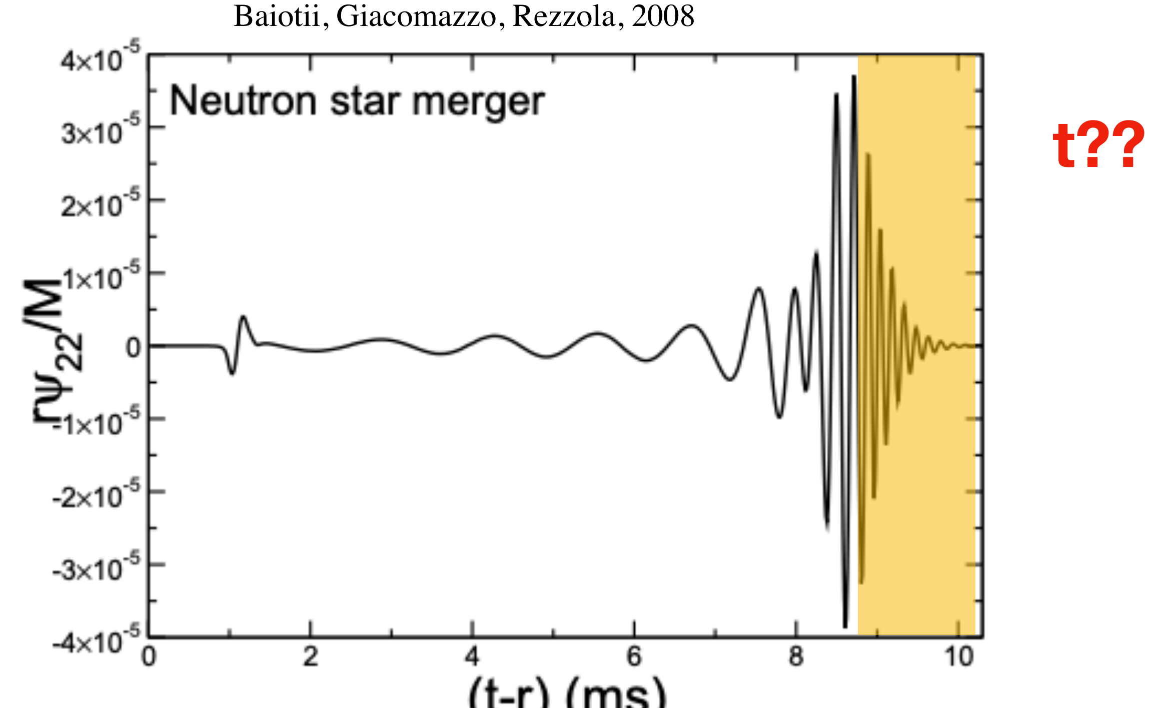
Sperhake, 2008



C. V. Vishveshwara 1970



Baiotii, Giacomazzo, Rezzola, 2008



The BH ringdown

The solution to this equation is normally expressed in terms of QNMS… which are obtained by solving the BH linear perturbation equations. But is it all? We will try to answer this.

$$h(t-x) = \frac{1}{2\pi}\int_{-\infty+i\epsilon}^{\infty+i\epsilon} d\omega \tilde{\xi}(\omega, x) e^{-i\omega t} = \sum_n B_n^{(\mathrm{SN})} T_n e^{-i\omega_n (t-x)}$$
$$+ \,(\text{prompt response term}) + (\text{branch cut term}),$$

The QNM spectrum: unique to the mass & spin of the BH $\longrightarrow$ ω_n

Amplitudes depend on both. $\longrightarrow$ $C_n = B_n T_n$

$\nearrow B_n$ Depend on BH

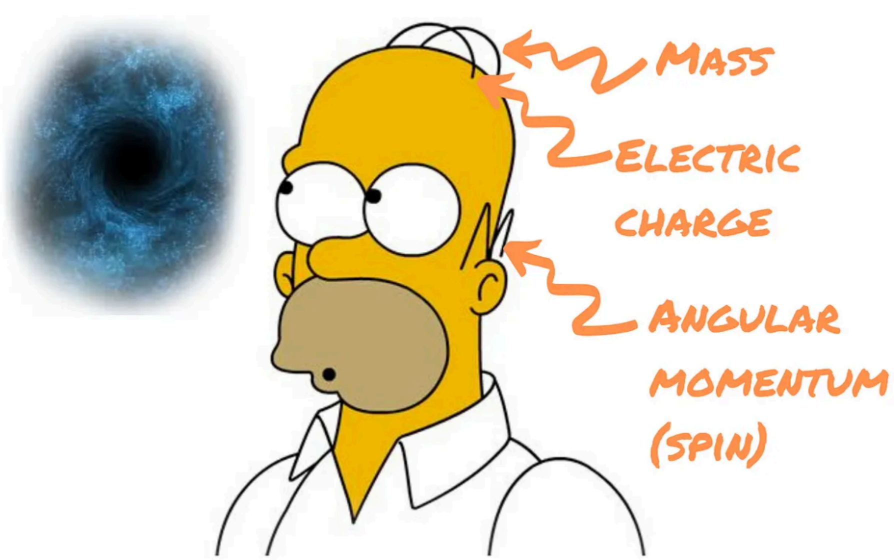
$\searrow T_n$ Depend also on IC

BH spectroscopy

RD spectroscopy aims the independent observation of the spectra of two modes.

An eventual (maybe also speculative) observation of such relations would indicate:

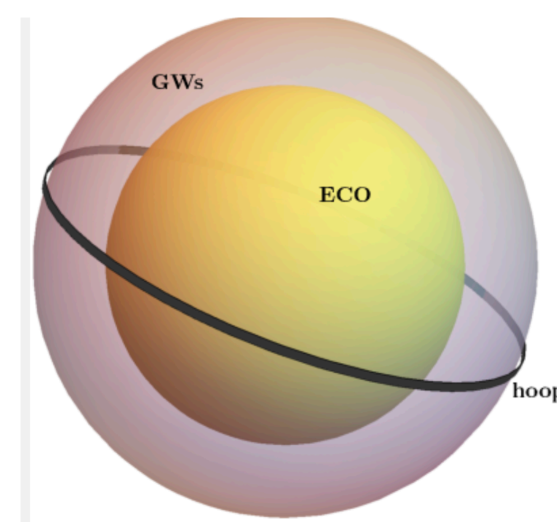
We are observing a non-GR BH (hairy)



From Juan Calderon

We are not observing a BH

- NS? - ECO?

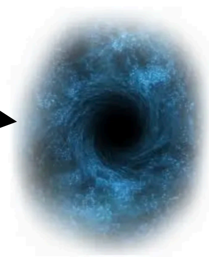


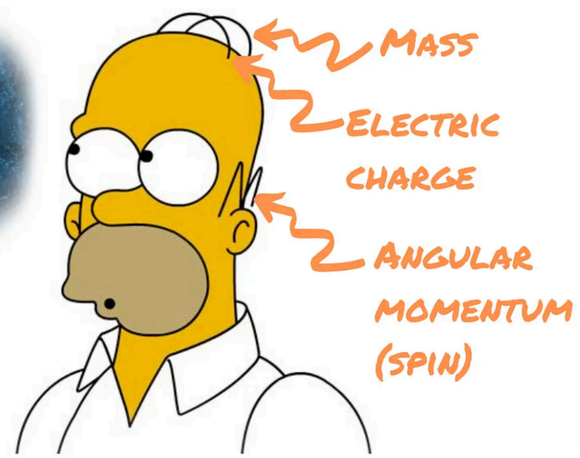
BH amplitudescopy

RD amplitude depends on both, initial conditions and the BH space-time properties

Exploration of alternative theories of GR via amplitudes:

Crescimberi, Jimenez et al (See Francesco' talk)



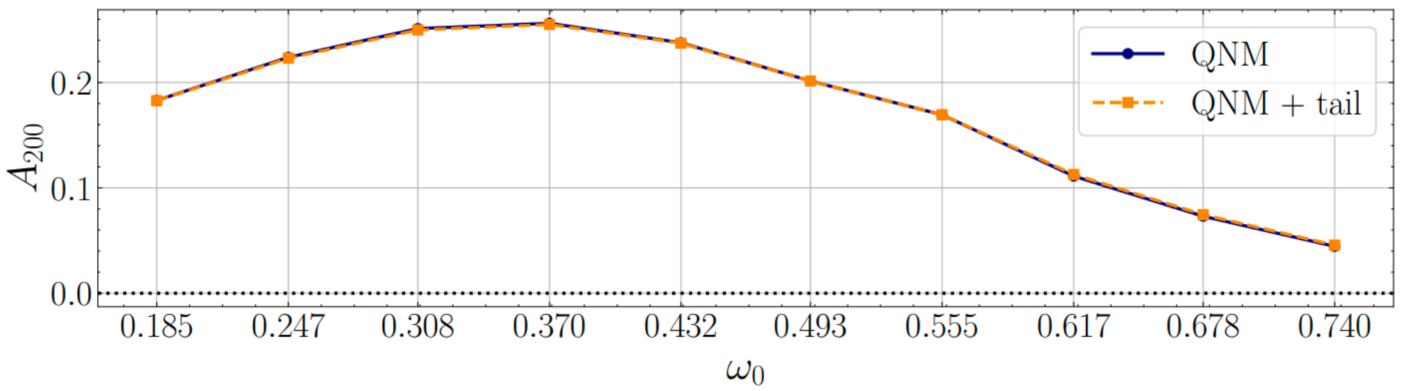


Exploration of the BH mass and spin with amplitudes:

Romeo's talk

Exploration of the BH amplitudes and BH resonances depending on initial conditions:

Alejandro's talk



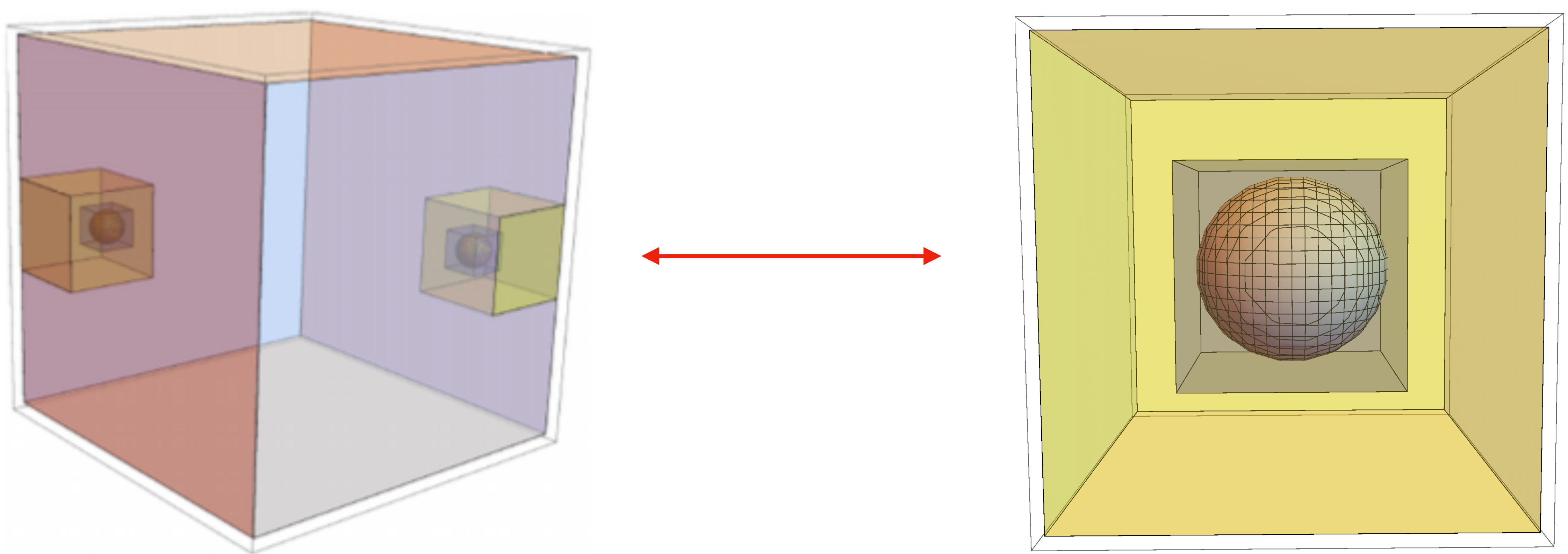
Numerical relativity as tool vs Perturbation theory

A full 3+1 formalism is required to reach the ringdown regime.

There are several codes that allow us to simulate these events: SPEC, Einstein Toolkit, MHDuet etc.

Problem: Computationally very expensive.

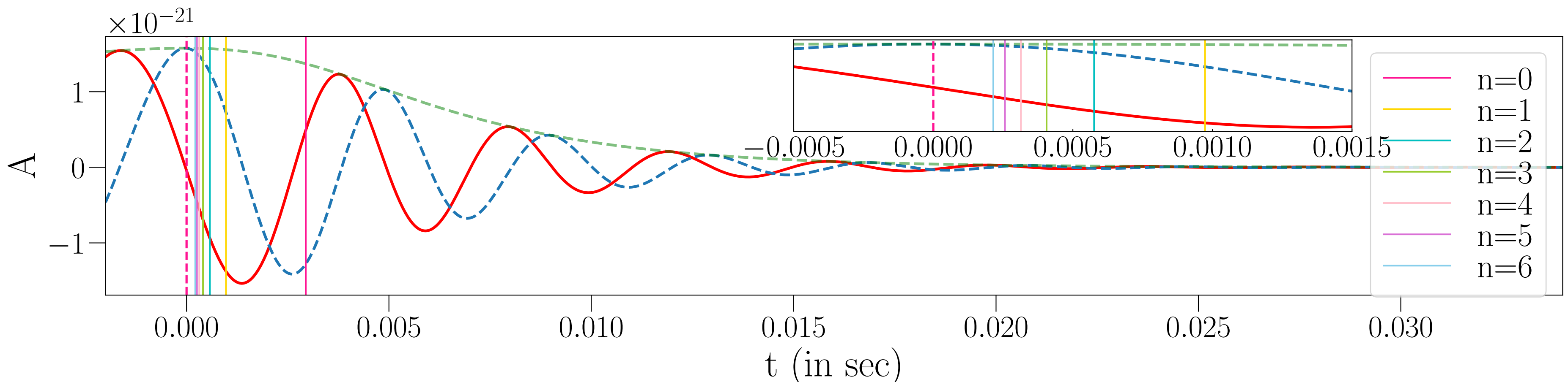
Wave zone $\mathcal{O}$(100M). ***Near zone $\mathcal{O}$(1-10M).***



Modes and overtones modelling

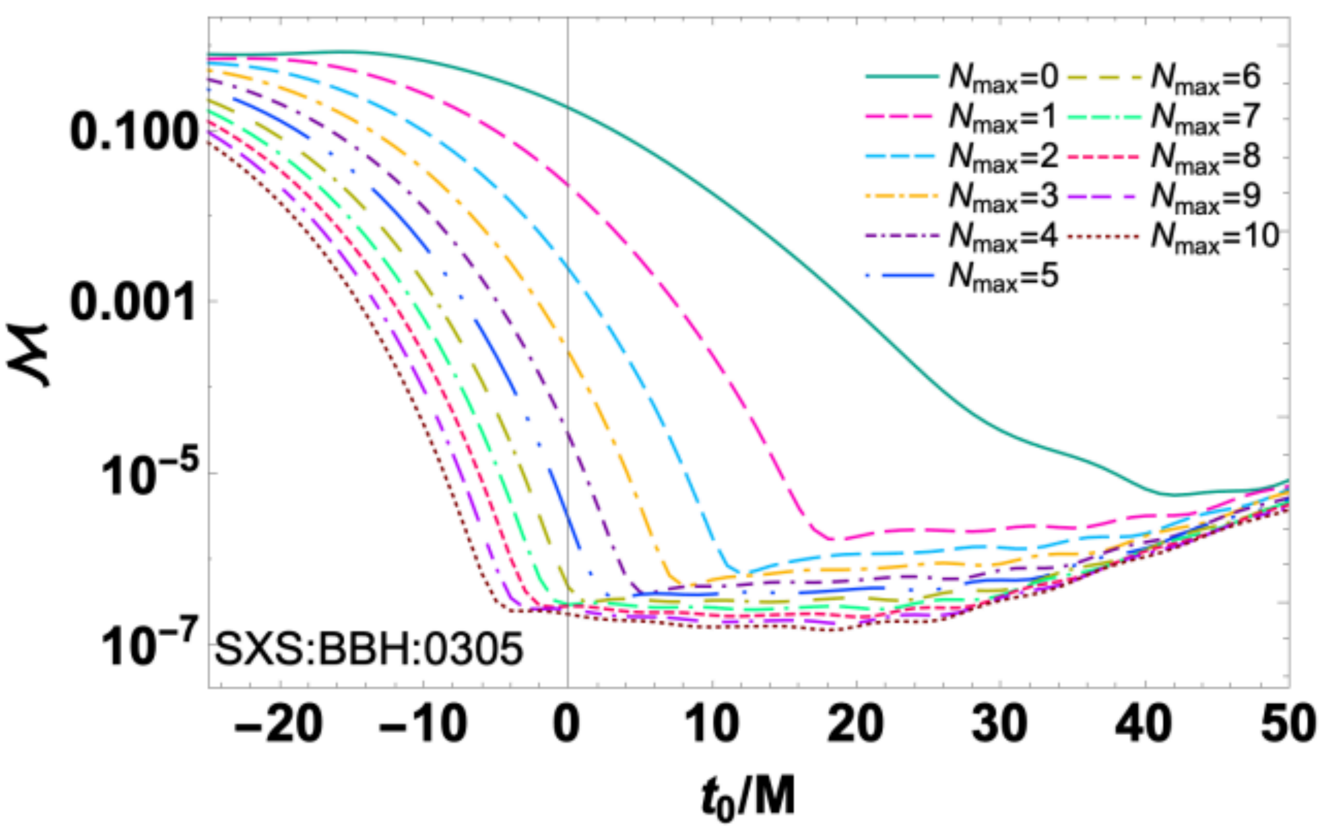
Before asking if we can detect ringdown modes in GW data…

Can we detect linear modes in NR or LPT data?



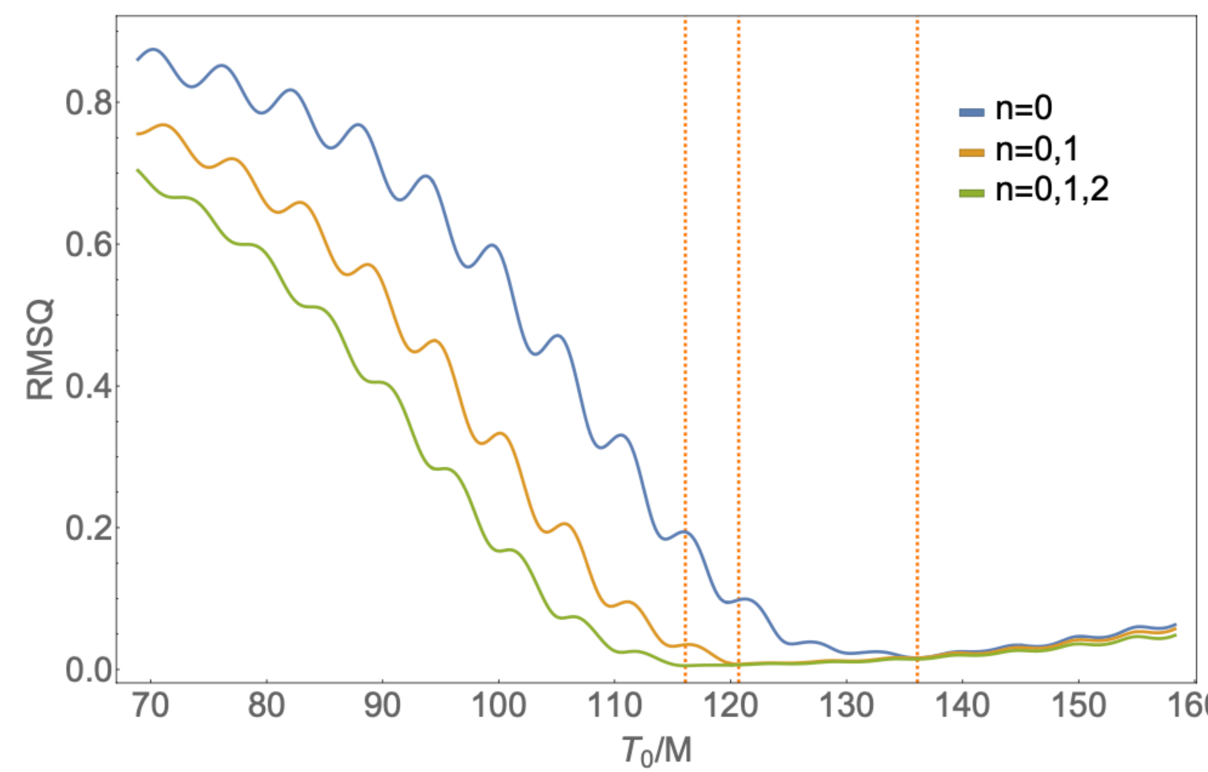
You start adding modes ('tones') and you fit to see if the fit gets better… Indeed but

NR data



Jimenez+ 2021

Solving the perturbative equations



Rita Fiorini, Jimenez, Pani, Ferrari + 2018

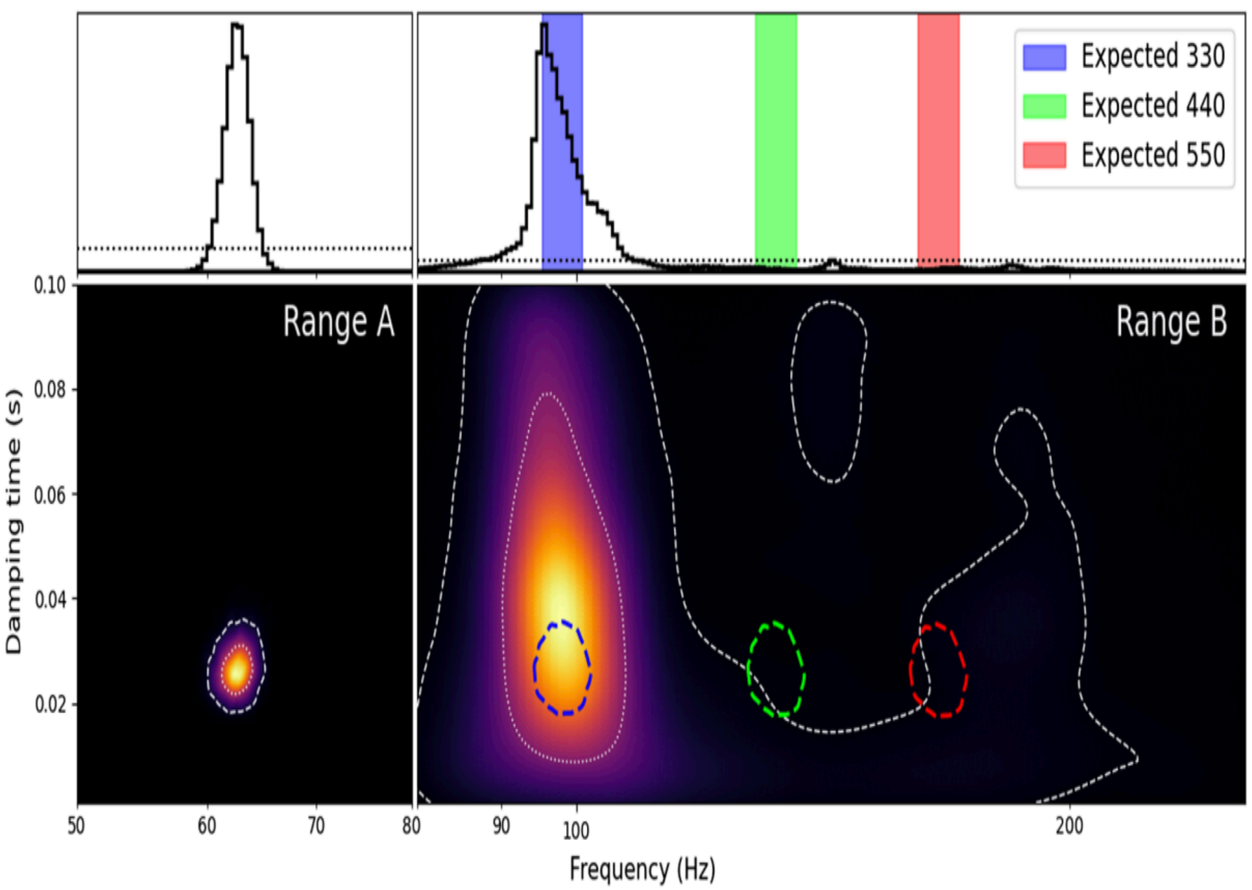
Tones: $\tau_{lm0} \sim \tau_{220}$ large and $\omega_{lm0} \sim l/2\, \omega_{220}$

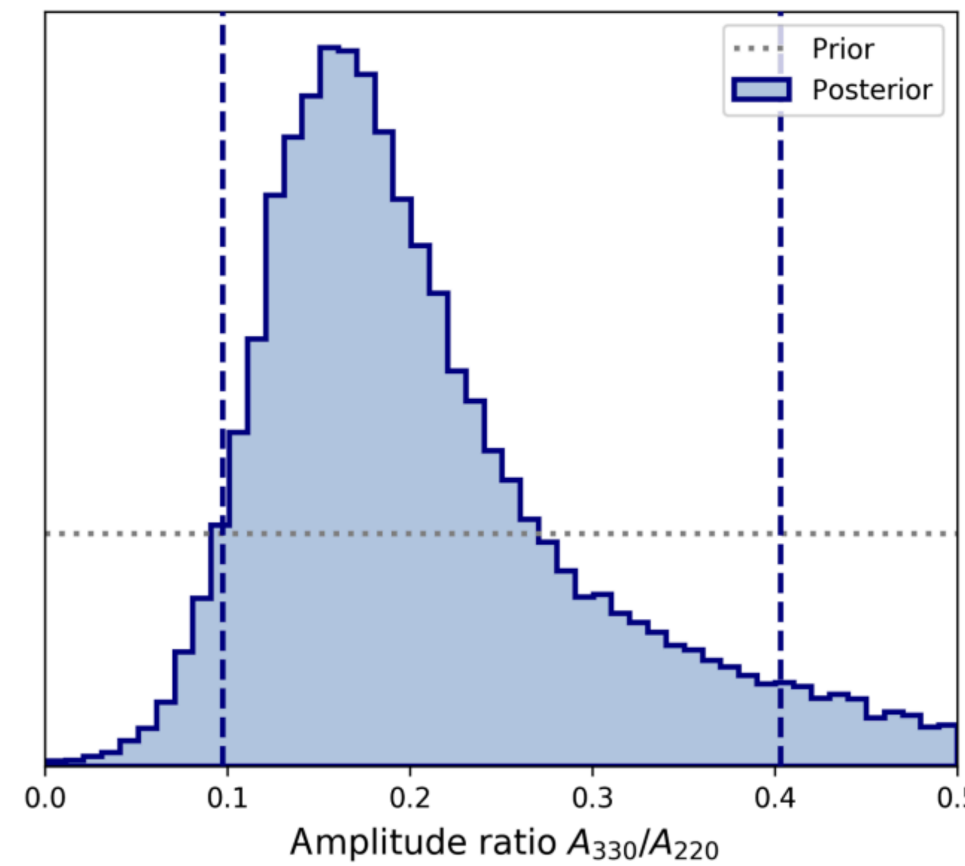
Modes. **lmn's = 220, 330**

Starting time: 6ms off the peak.

Distributions on the amplitude ratio between modes

Merger-Ringdown consistency tests.





Capano et al. + (2021)

Amplitudes (phases) are useful for: GW190521

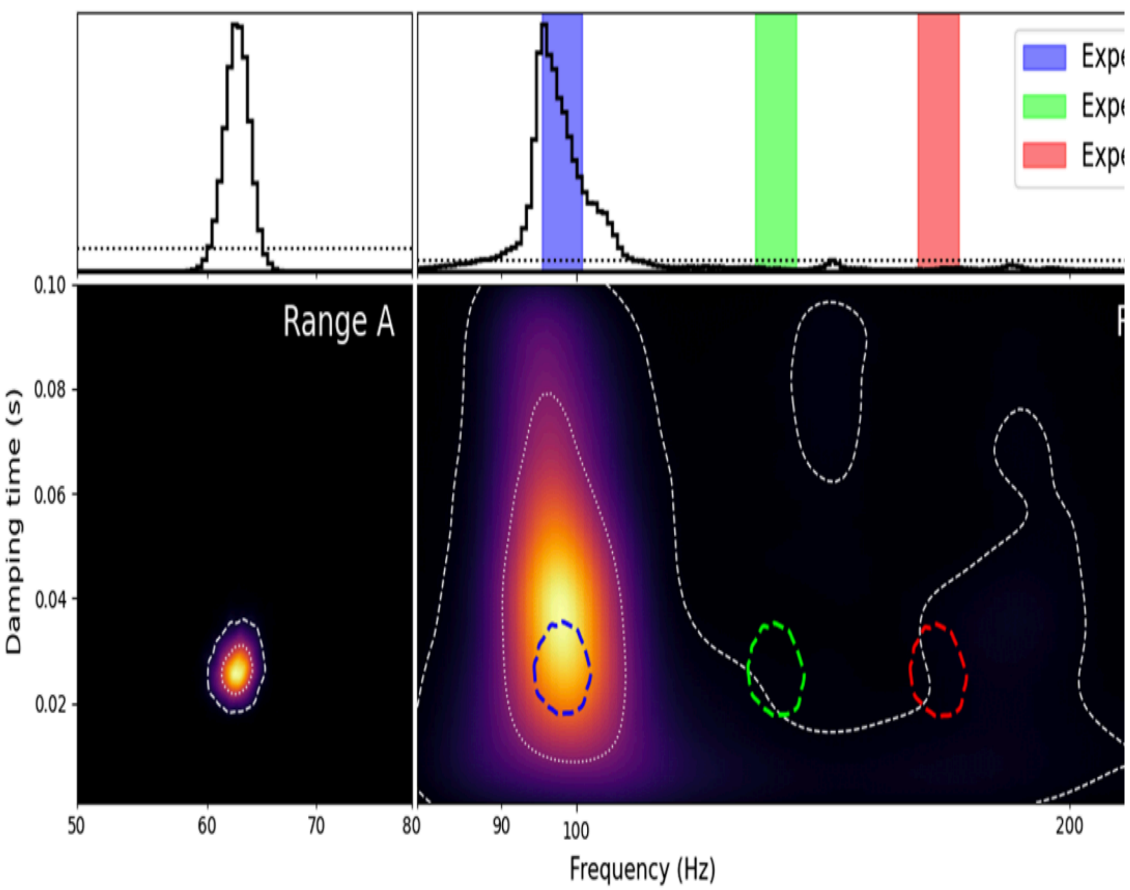
Tones: $\tau_{lm0} \sim \tau_{220}$ large and $\omega_{lm0} \sim l/2\, \omega_{220}$

Modes. **lmn's = 220, 330**

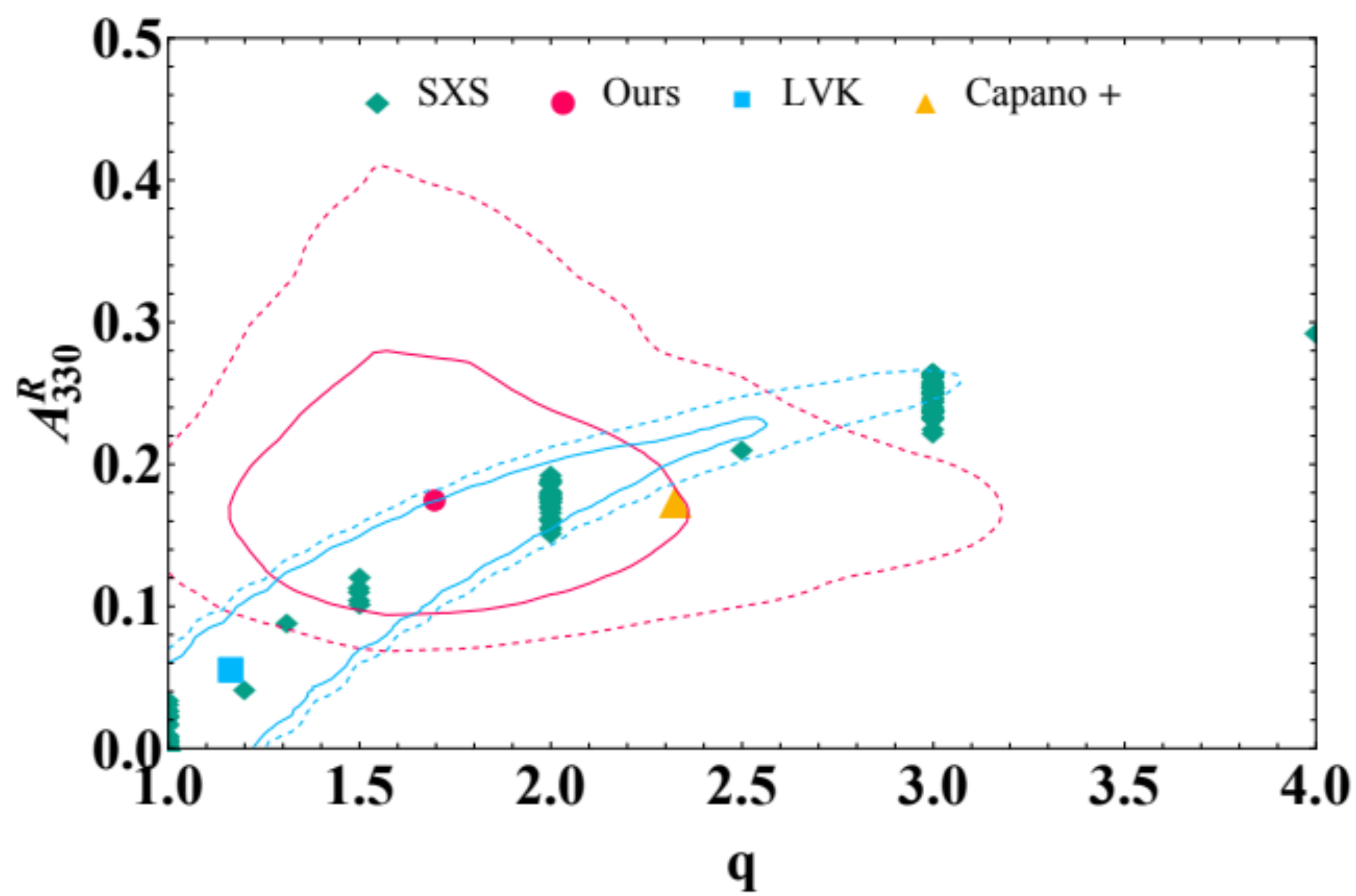
Starting time: 6ms off the peak.

Distributions on the amplitude ratio between modes

Merger-Ringdown consistency tests.



Capano et al. + (2021)

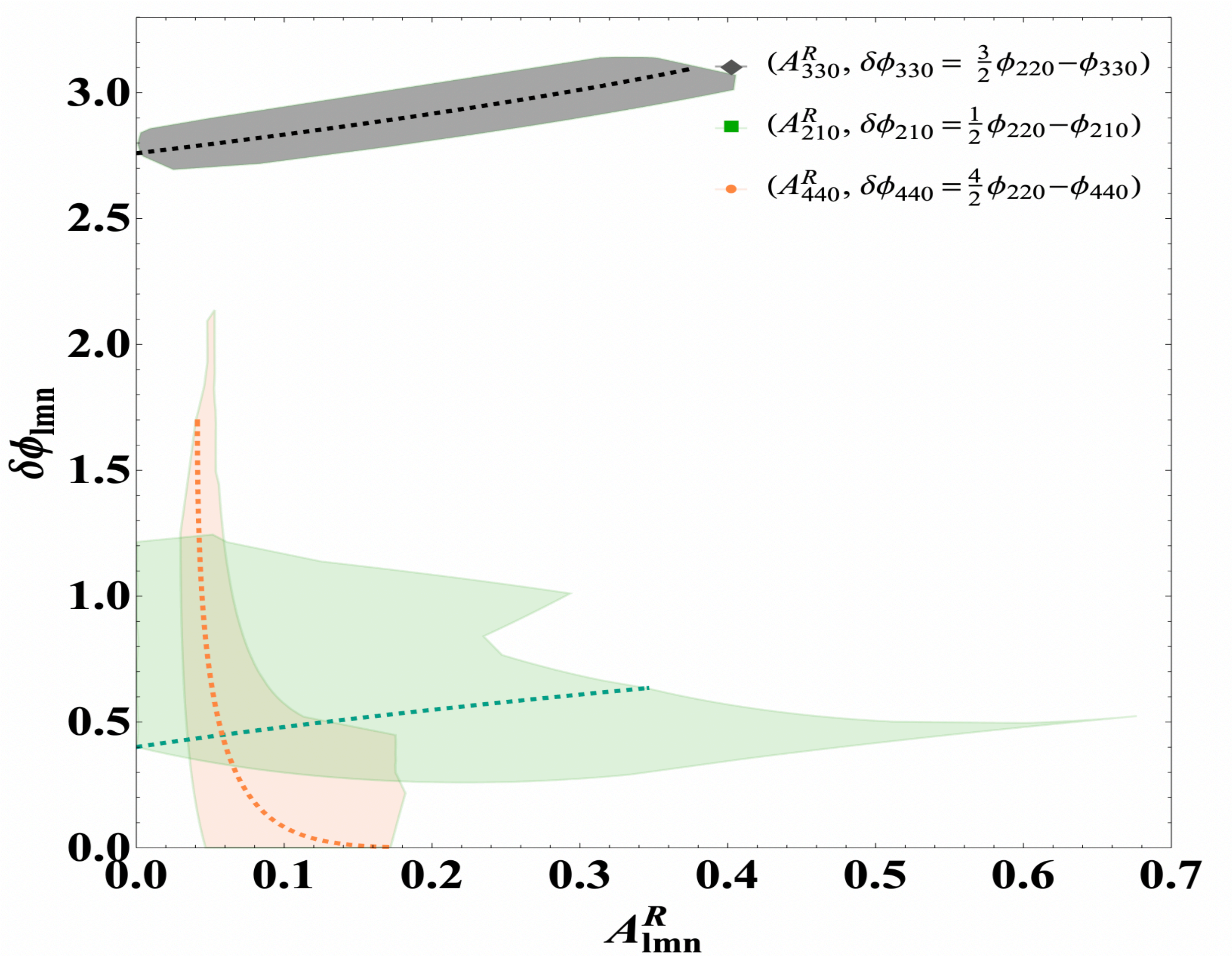


Jimenez+ 2023. PRL

Mode amplitudes. What can we learn?

Take the whole SXS quasi-circular catalogue and fit for amplitudes and phases

Amplitude ratio: $A^R_{lmn} = \frac{A_{lmn}}{A_{220}}$ **Phase difference:** $\delta\phi_{lmn} = \frac{m}{2}\phi_{220} - \phi_{lmn}$



Jimenez+ 2023. PRL

1- Amplitude- phase found in bands.

2- Bands depend on spin and massratio

$$\delta_\phi, A_R \leftrightarrow q, \chi?$$

3- Quasi-circular, precessing, head-on

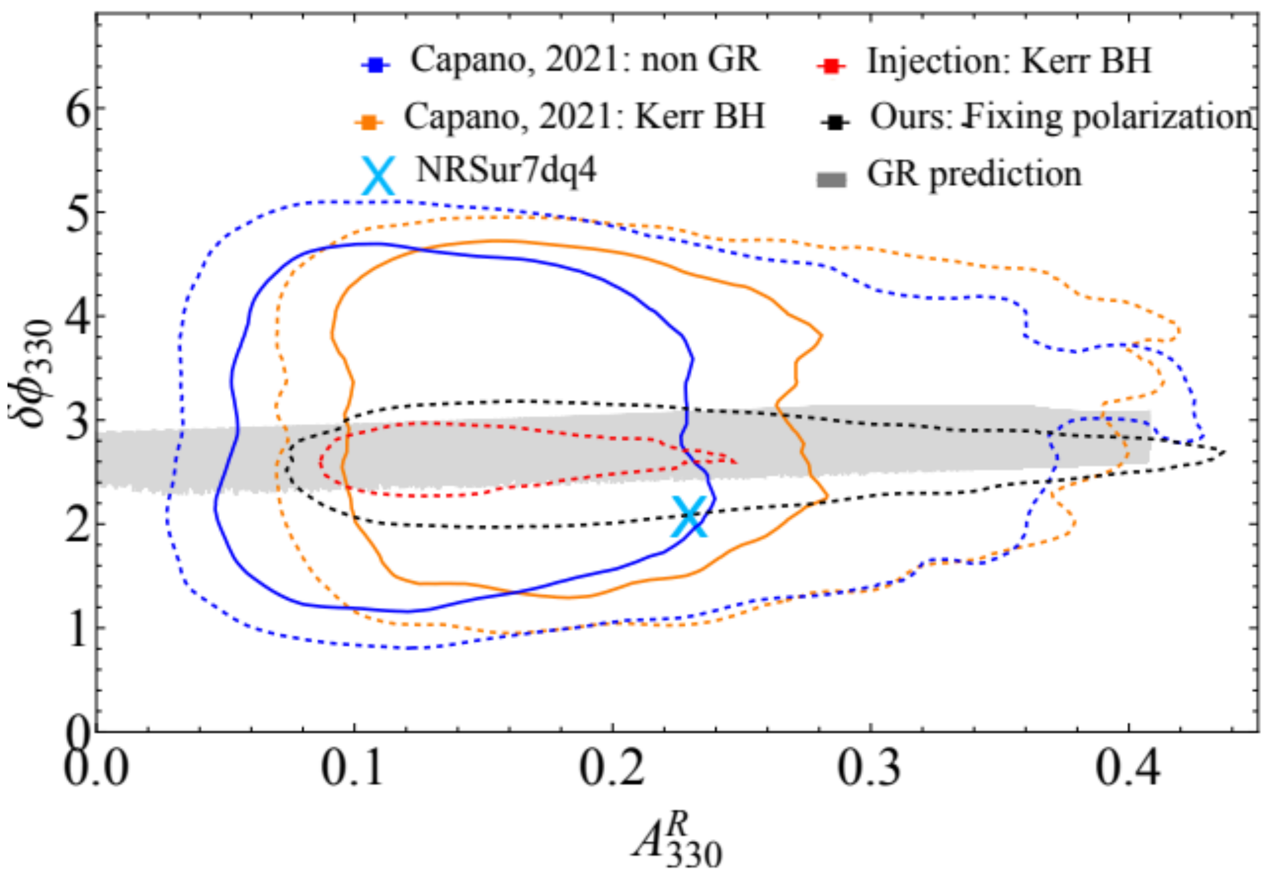
will show different bands.

4- But also extra fields will modify them.

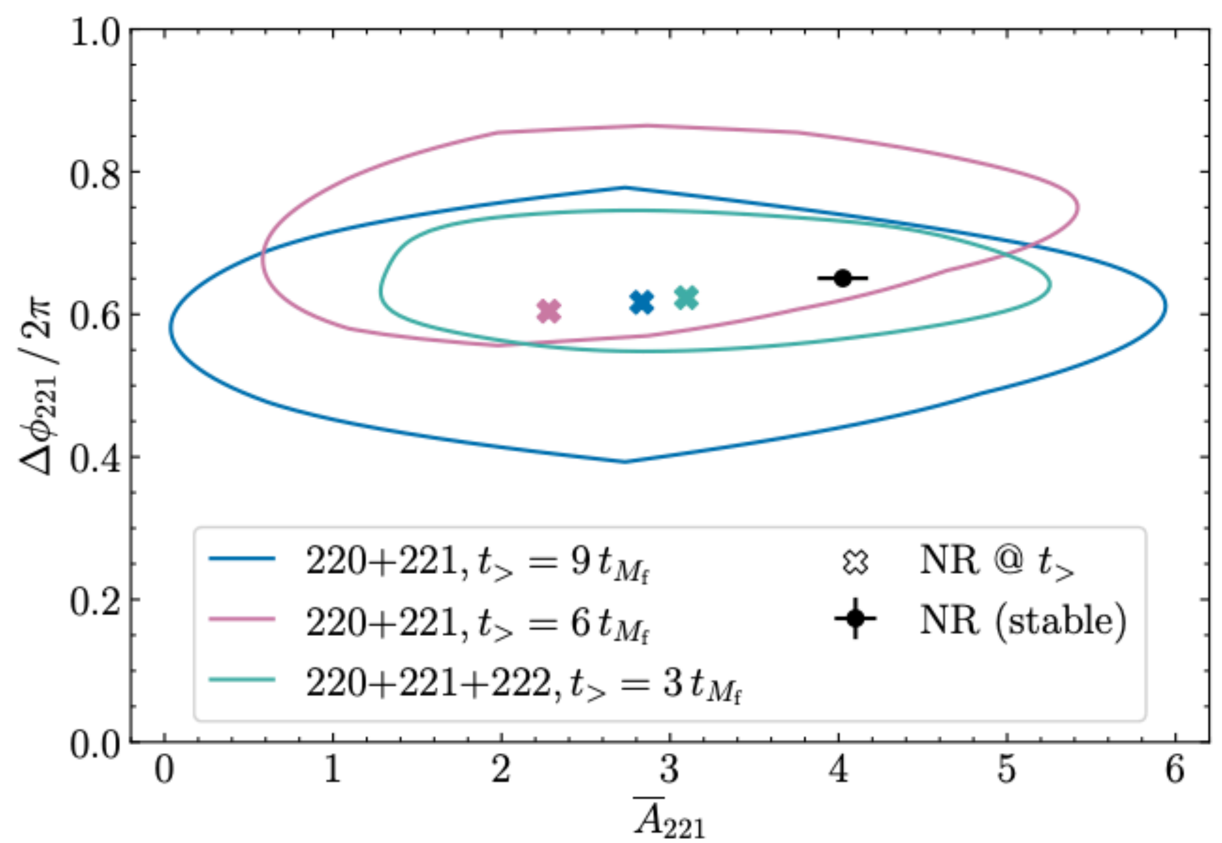
Mode amplitudes. What can we learn?

Take the whole SXS quasi-circular catalogue and fit for amplitudes and phases

Amplitude ratio: $$A^R_{lmn} = \frac{A_{lmn}}{A_{220}}$$ **Phase difference:** $$\delta\phi_{lmn} = \frac{m}{2}\phi_{220} - \phi_{lmn}$$



Jimenez+ 2023. GW190521



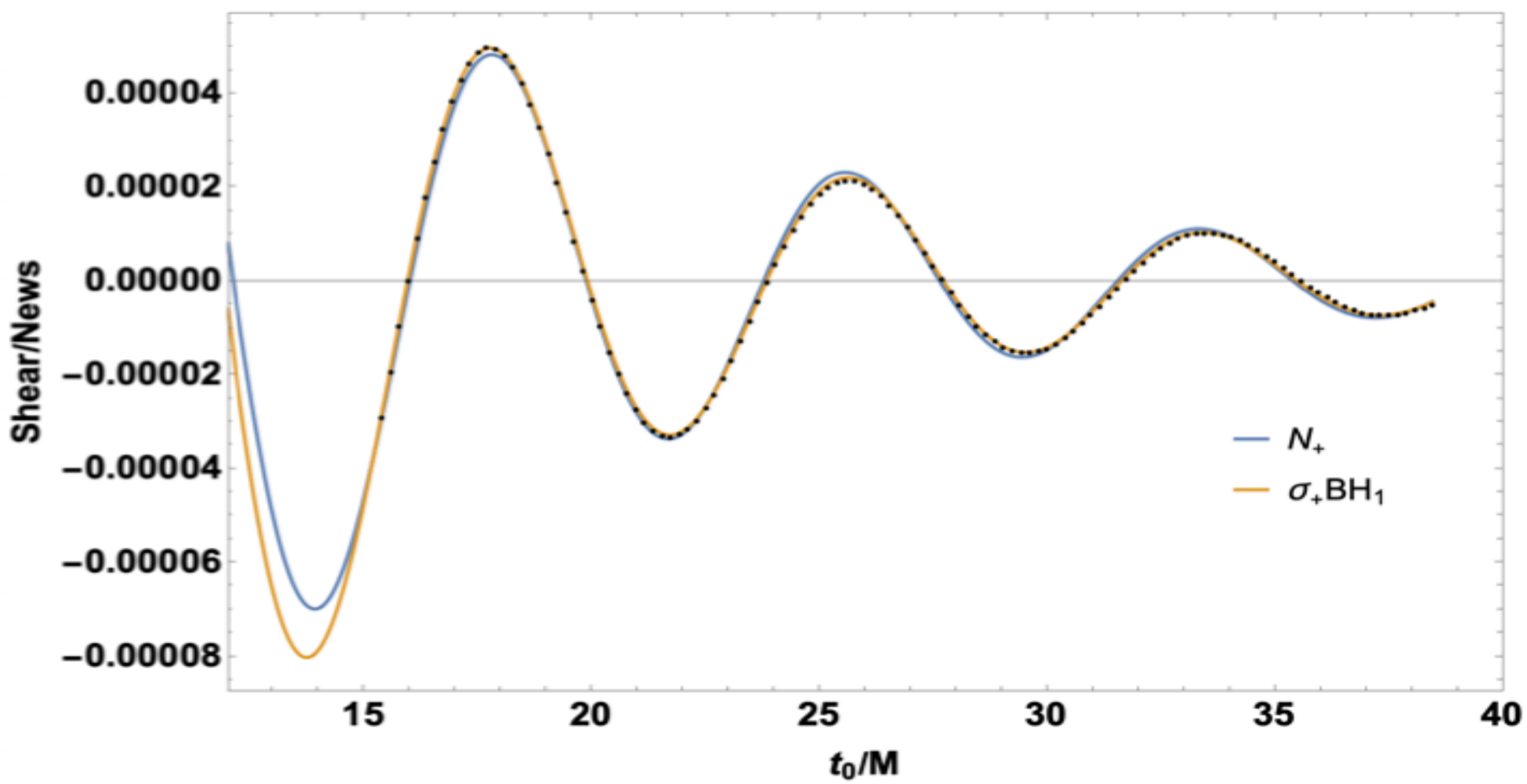
LVK. on GW250114

Our geometric analysis on the BH horizon

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

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

Linear Ringdown regime

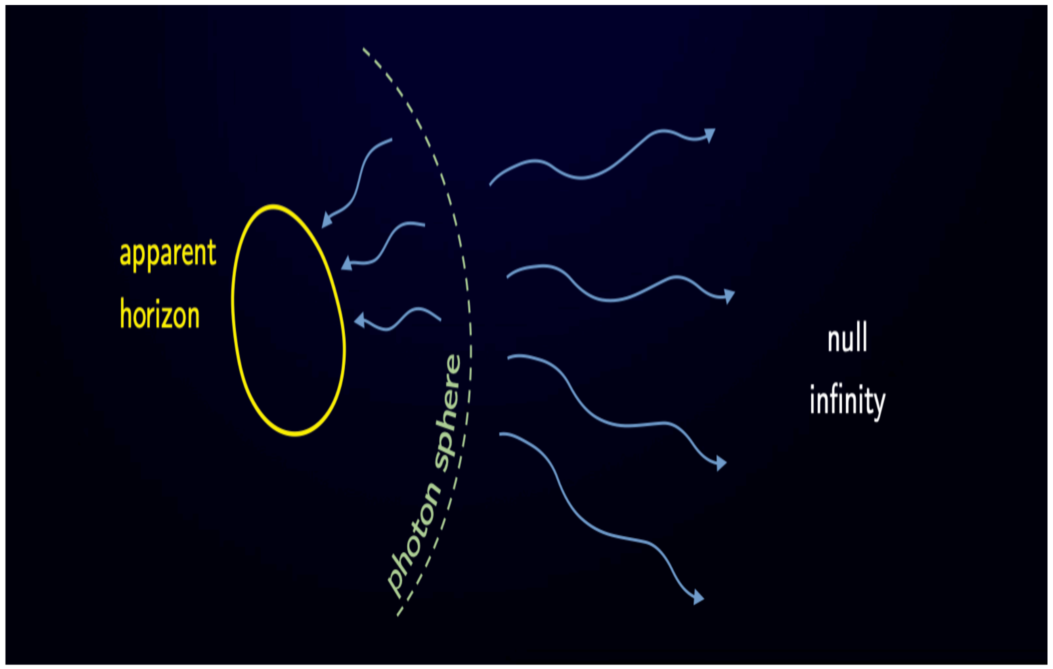


Pool Mourier-Jimenez, Ribes - Jimenez

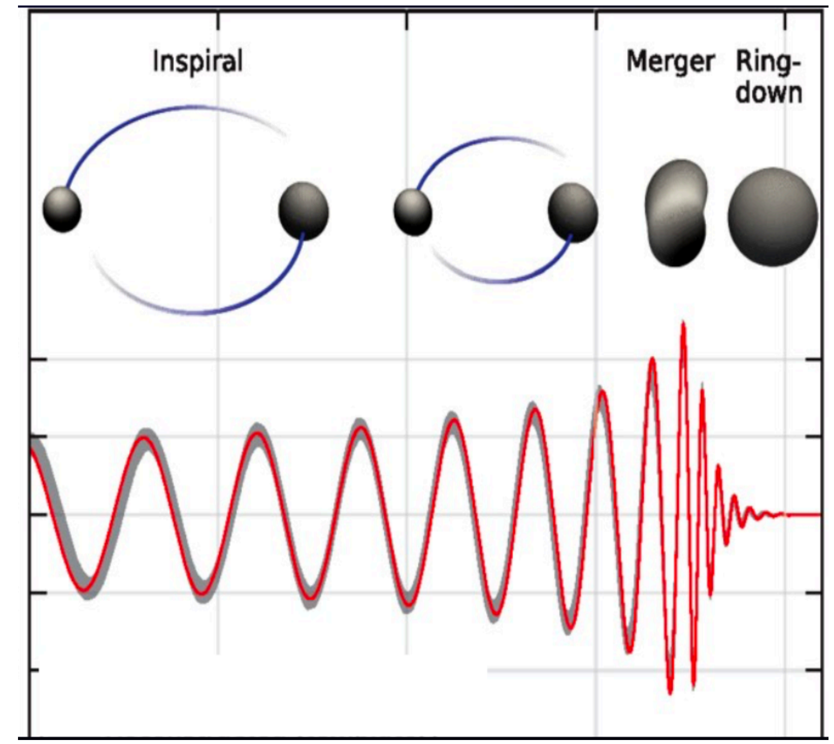
Our geometric analysis on the BH horizon

· But BHs also absorb radiation!

- Pool-Kolp, Mourier-Jimenez, Ofek + 2021.



???



· 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).

$$\sigma = m^a m^b \nabla_a l_b$$

$$\sigma = \sum_{l=2} \sigma_l \, {}_2\mathcal{Y}_{lm}$$

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

Conclusions

1. Numerical relativity is needed to understand the astrophysical GW ringdown.

2. RD amplitudes also useful for tests of GR

3. Correlations observed at the horizon level. Direct proxy of H morphology?

4. Work in progress for addressing the quasi-circular scenario (Alejandro).

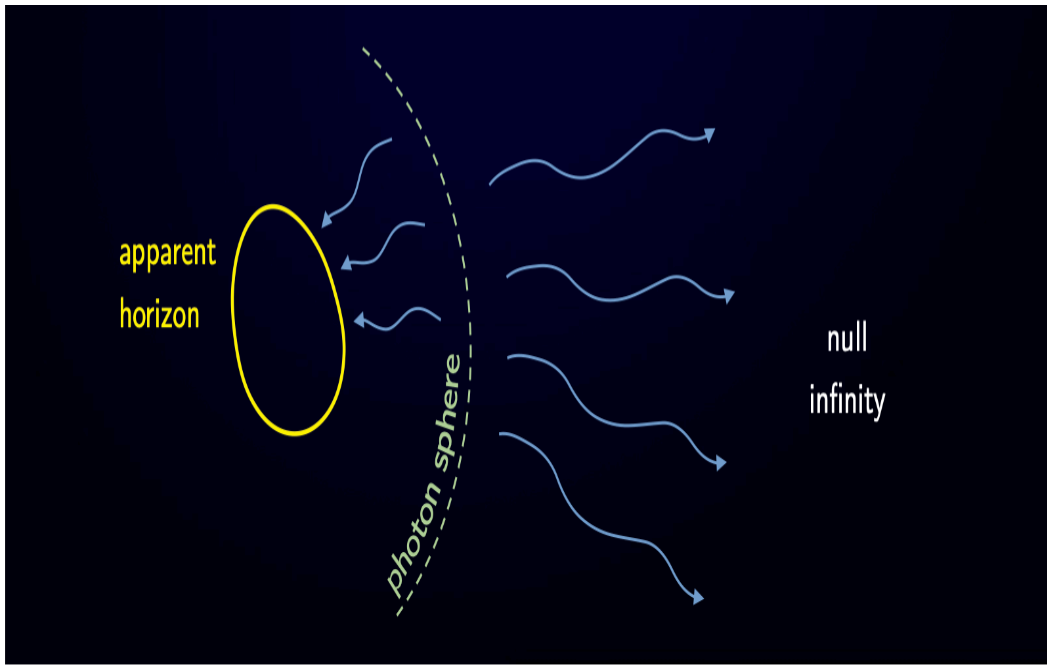
Acknowledgements

Xisco Jimenez Forteza. acknowledges funding from the Spanish Agencia Estatal de Investigacion, ´ grant IJC2019-041385. This work was supported by the Universitat de les Illes Balears (UIB); the Spanish Agencia Estatal de Investigacion, grants PID2022-138626NB-I00, PID2019-106416GB- ´ I00, RED2022-134204-E, RED2022-134411-T, funded by MCIN/AEI/10.13039/501100011033; the MCIN with funding from the European Union NextGenerationEU/PRTR (PRTR-C17.I1); Comunitat Autonoma de les Illes Balears through the Direcci ` o General de Recerca, Innovaci ´ o I ´ Transformacio Digital with funds from the Tourist Stay Tax Law (PDR2020/11 - ITS2017-006), ´ the Conselleria d'Economia, Hisenda i Innovacio grant number SINCO2022/6719, co-financed ´ by the European Union and FEDER Operational Program 2021-2027 of the Balearic Islands; the "ERDF A way of making Europe." LIGO Laboratory and Advanced LIGO are funded by the United States NSF as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. Virgo is funded, through the European Gravitational Observatory (EGO), by the French Centre National de Recherche Scientifique (CNRS), the Italian Istituto Nazionale di Fisica Nucleare (INFN) and the Dutch Nikhef, with contributions by institutions from Belgium, Germany, Greece, Hungary, Ireland, Japan, Monaco, Poland, Portugal, Spain. KAGRA is supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan Society for the Promotion of Science (JSPS) in Japan; National Research Foundation (NRF) and Ministry of Science and ICT (MSIT) in Korea; Academia Sinica (AS) and National Science and Technology Council (NSTC) in Taiwan. This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation

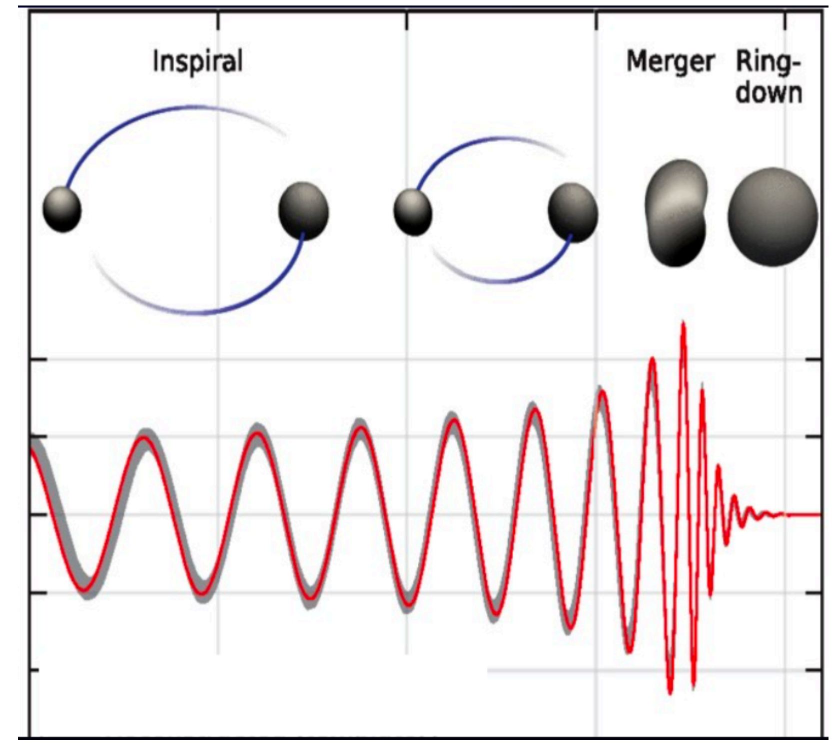
Our geometric analysis on the BH horizon

· But BHs also absorb radiation!

- Pool-Kolp, Mourier-Jimenez, Ofek + 2021.



???



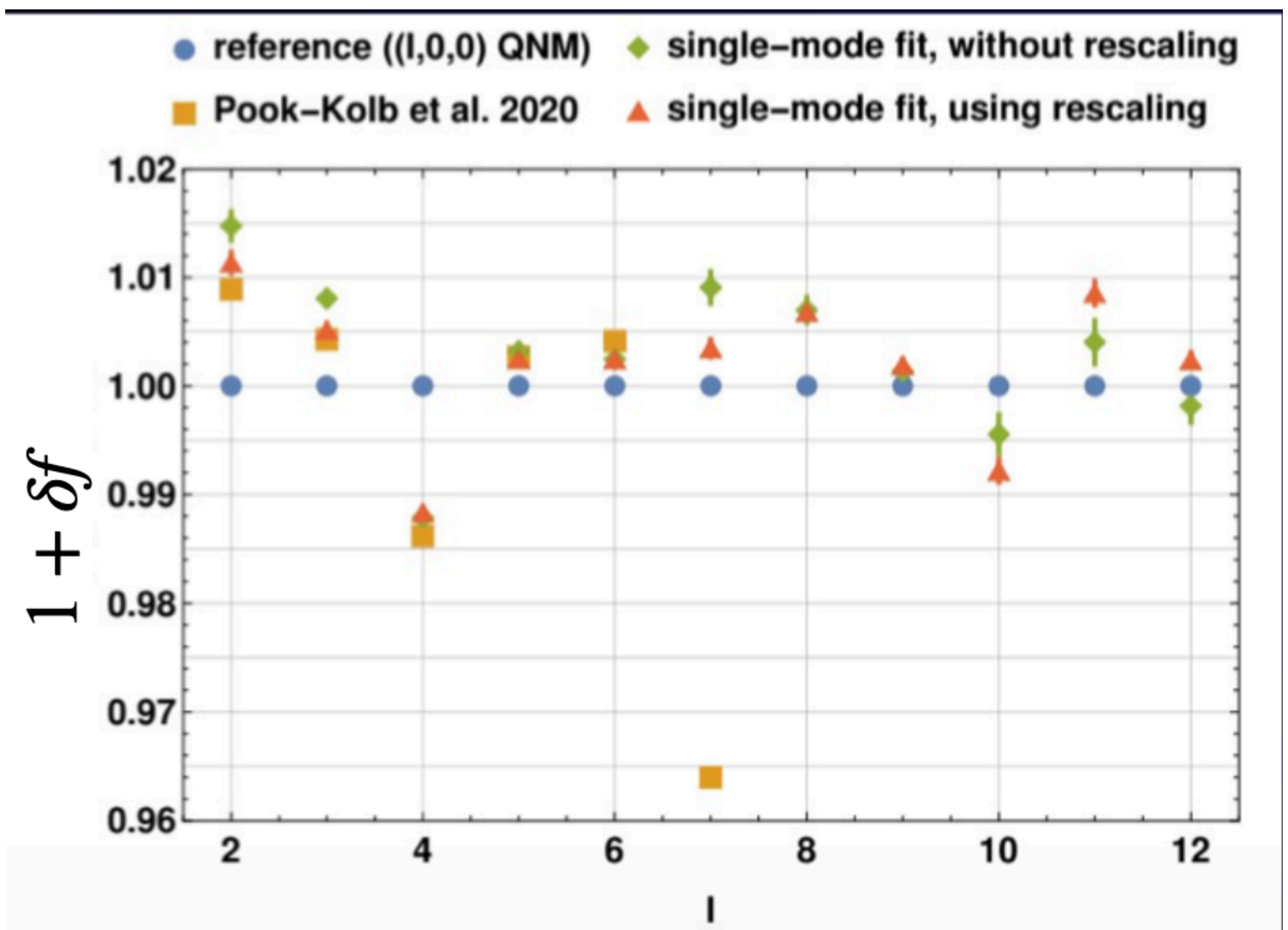
· The ingoing flux depends on the geometrical properties of the horizon as the shear of the outgoing null rays at the horizon (it is spin-2 field).

$$\sigma = m^a m^b \nabla_a l_b \qquad \sigma = \sum_{l=2} \sigma_l \, {}_2\mathcal{Y}_{lm}$$

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

BH Tomography: Spectroscopy of the BH horizon

<u>Linear Ringdown regime</u>

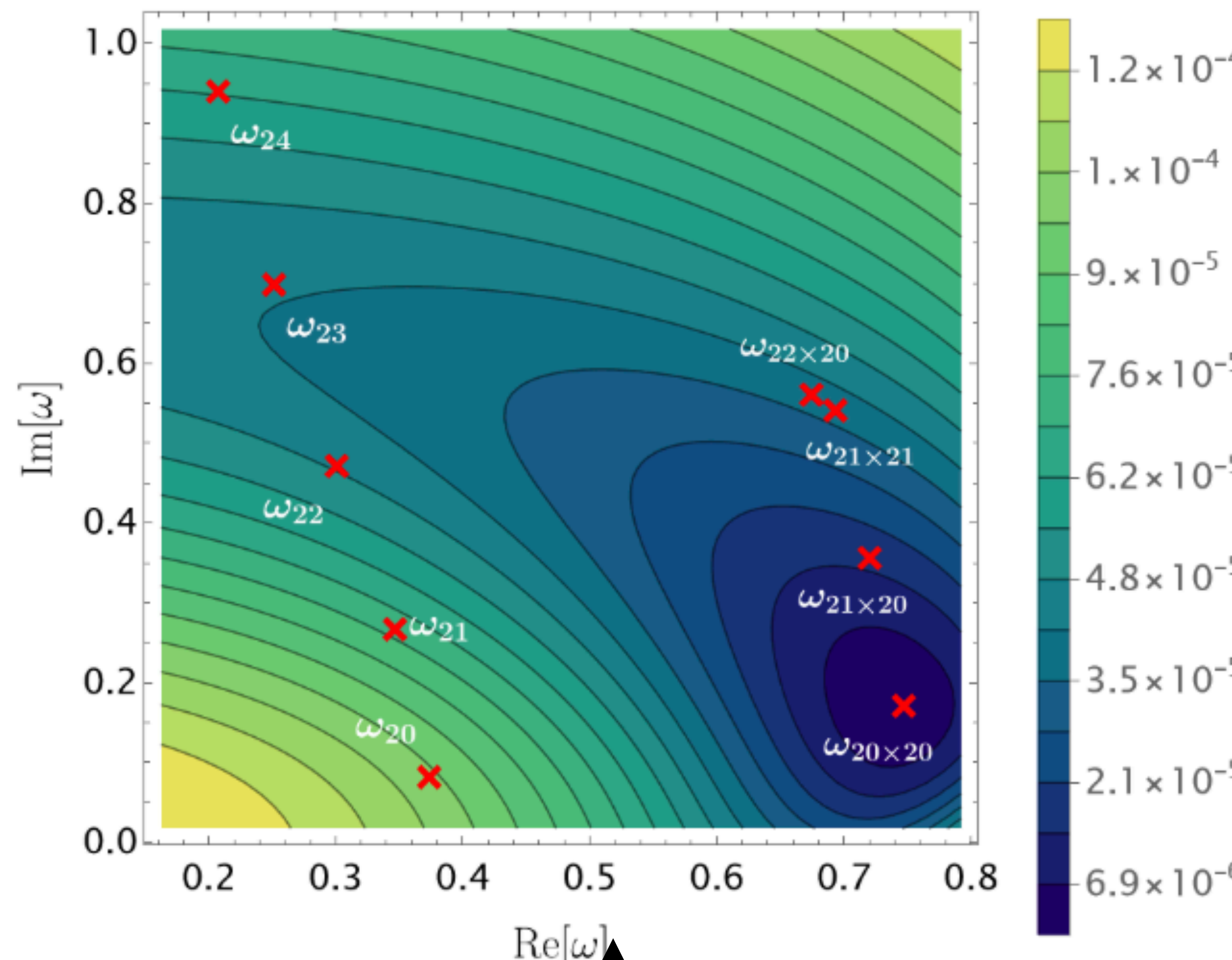


Pierre Mourier, X. Jimenez-Forteza (2021)

$$h_L \sim A e^{-t/\tau_l} cos(f_l\,(1+\delta f_l)\,t\,+\phi_l)$$

<u>Linear spectrum at the horizon!</u>

<u>Non linear Ringdown regime</u>



Neev Khera, Ribas, Bonga, Jimenez-Forteza + (2023)

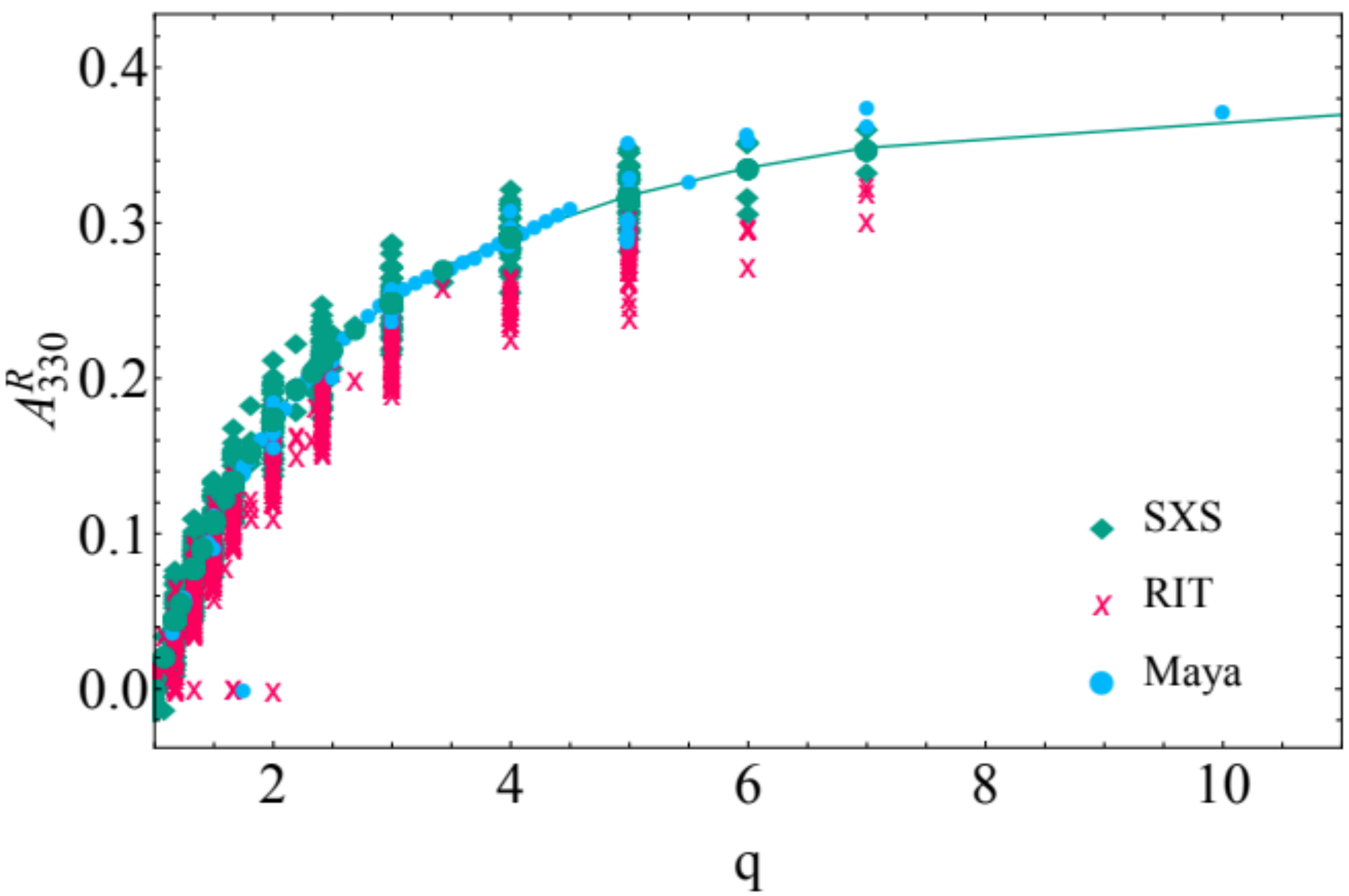
$$h_q \sim A e^{-t/\tau_{l\times l'}} cos(f_{l\times l'}\,t + \phi_{l\times l'})$$

<u>Quadratic spectrum at the horizon!</u>

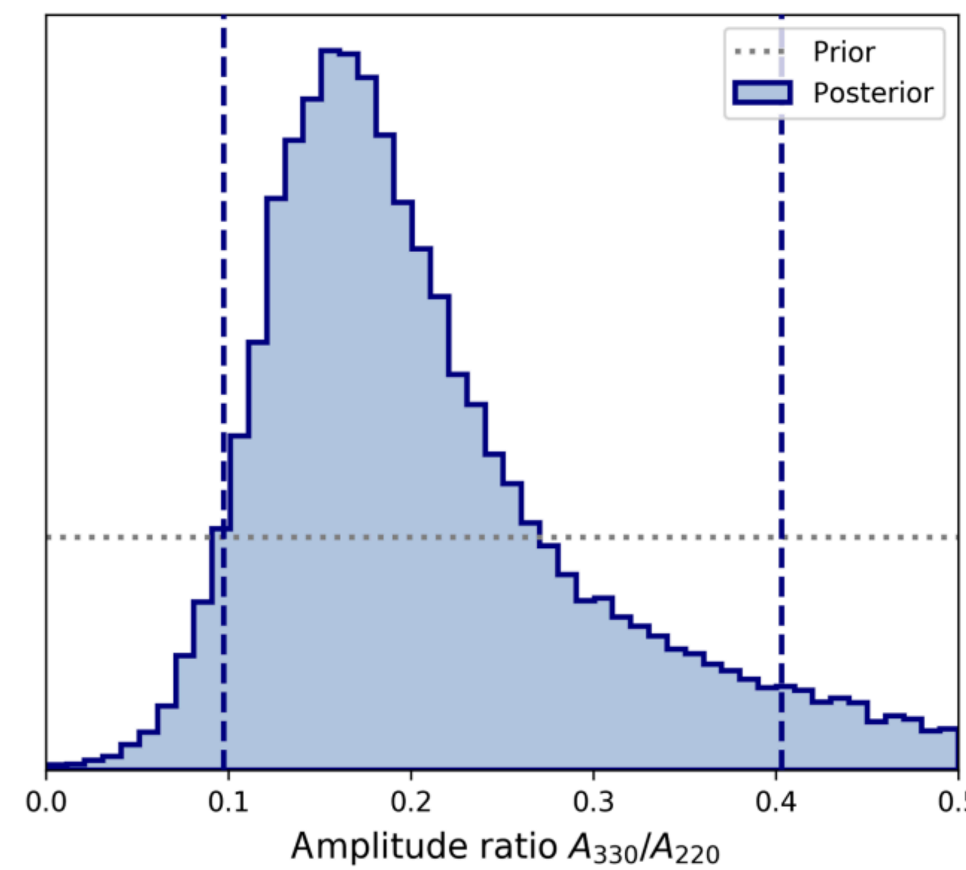
Mode amplitudes. What can we learn?

Take the whole SXS quasi-circular catalogue and fit for amplitudes and phases

Amplitude ratio: $A^R_{lmn} = \frac{A_{lmn}}{A_{220}}$ **Phase difference:** $\delta\phi_{lmn} = \frac{m}{2}\phi_{220} - \phi_{lmn}$



Jimenez, Bhagwat et al. + (2022)



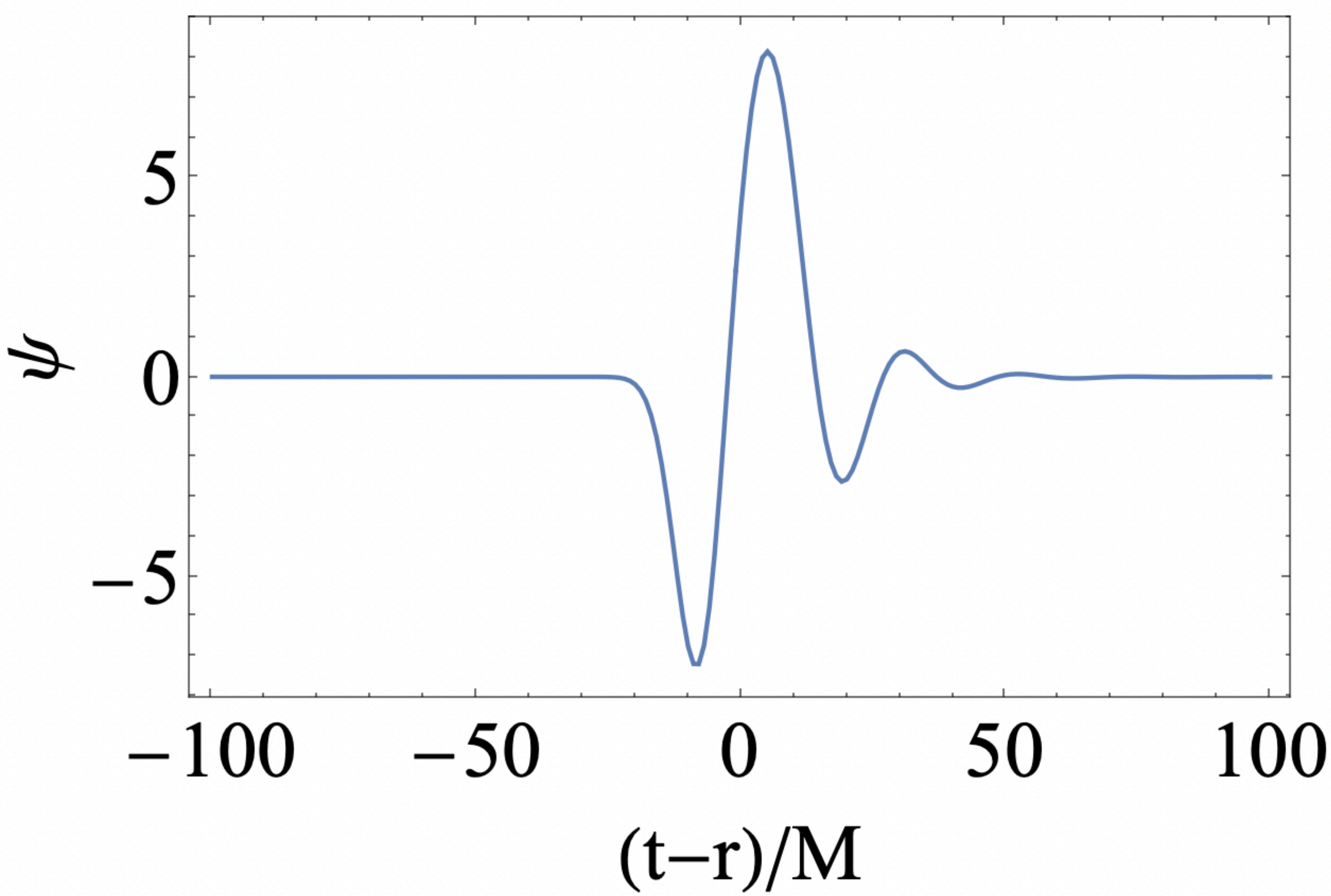
Capano et al. + (2021)

Back to the 70's, 80's and 90's.

Let's do an exercise and let's go back to the 70's and look to solve this. For a Schwarzschild BH:

$$\left[\frac{d^2}{dr_*^2} + \omega^2 - V_l(r)\right]\psi(r_*, \omega) = -\frac{d\psi}{dt}\Big|_{t=0} + \psi\Big|_{t=0} \qquad V_l(r) = (1-\frac{2M}{r})\left[\frac{l(l+1)}{r^2} + (1-s^2)\frac{2M}{r^3}\right]$$

C. V. Vishveshwara (1970)



Send Gaussian pulse with a given amplitude.

He found that the oscillations were independent on the properties of the pulse.

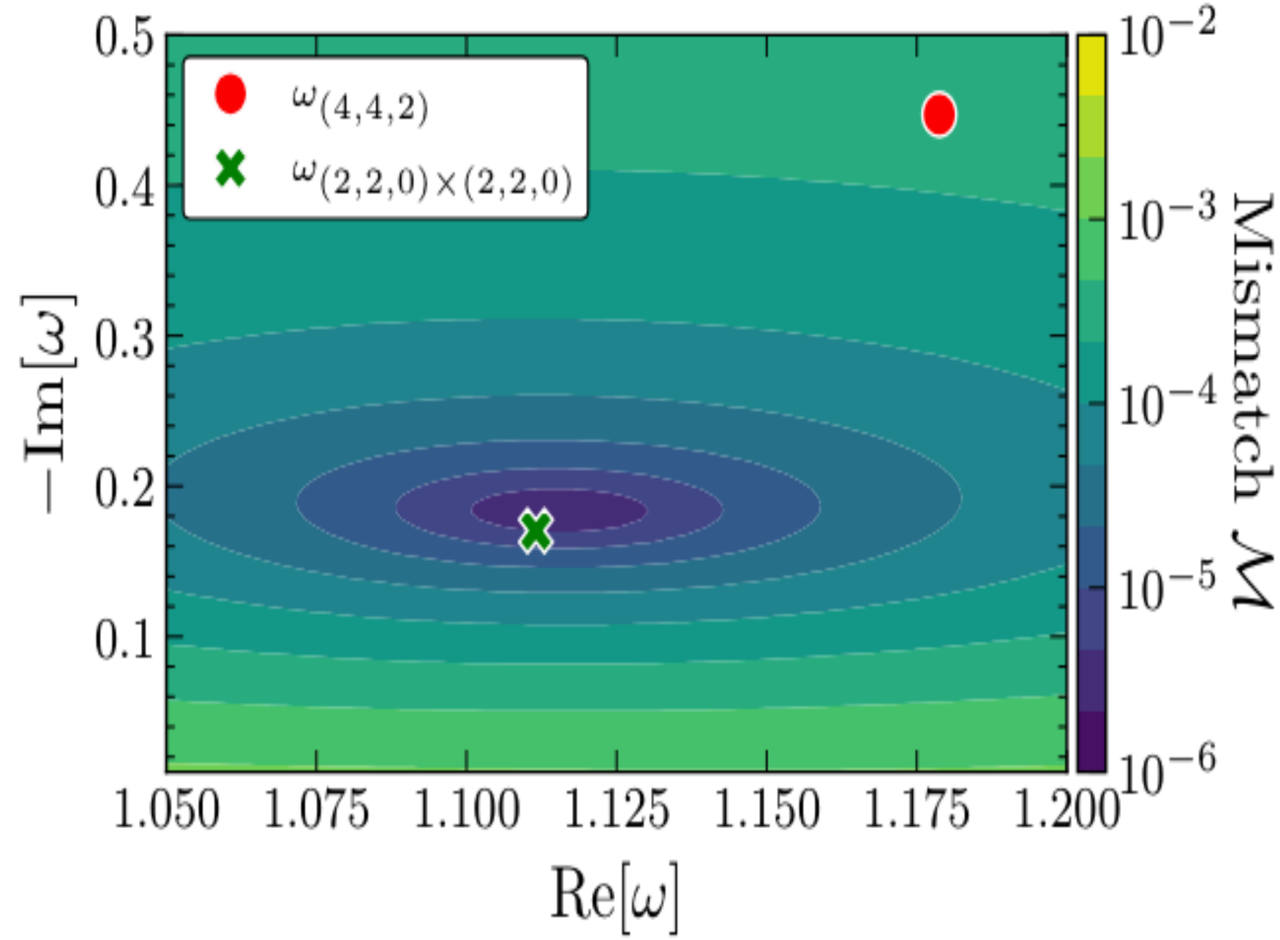
The ringdown battle: Linear be or not be that is the question

But there are more terms that just the linear ones.

And by 2on order PT

$$h_+ + \imath h_\times = \sum_{22,n=0,1} A_{22n} e^{\imath\phi_{22n}} e^{\imath\omega_{22n}(t)} e^{\imath\frac{(t)}{\tau_{22n}}} Y_{22n} \quad + A_q e^{\imath\phi_q} e^{\imath\omega_q(t)} e^{\imath\frac{(t)}{\tau_q}} C_q$$

$$g_{\mu\nu} = g^0_{\mu\nu} + h_{\mu\nu} + h^{(2)}_{\mu\nu}$$



Properties of the quadratic modes:

Amplitude: $A_{lm}A_{l'm'}C_{lm,l'm',l''m''} \sim A^2C$

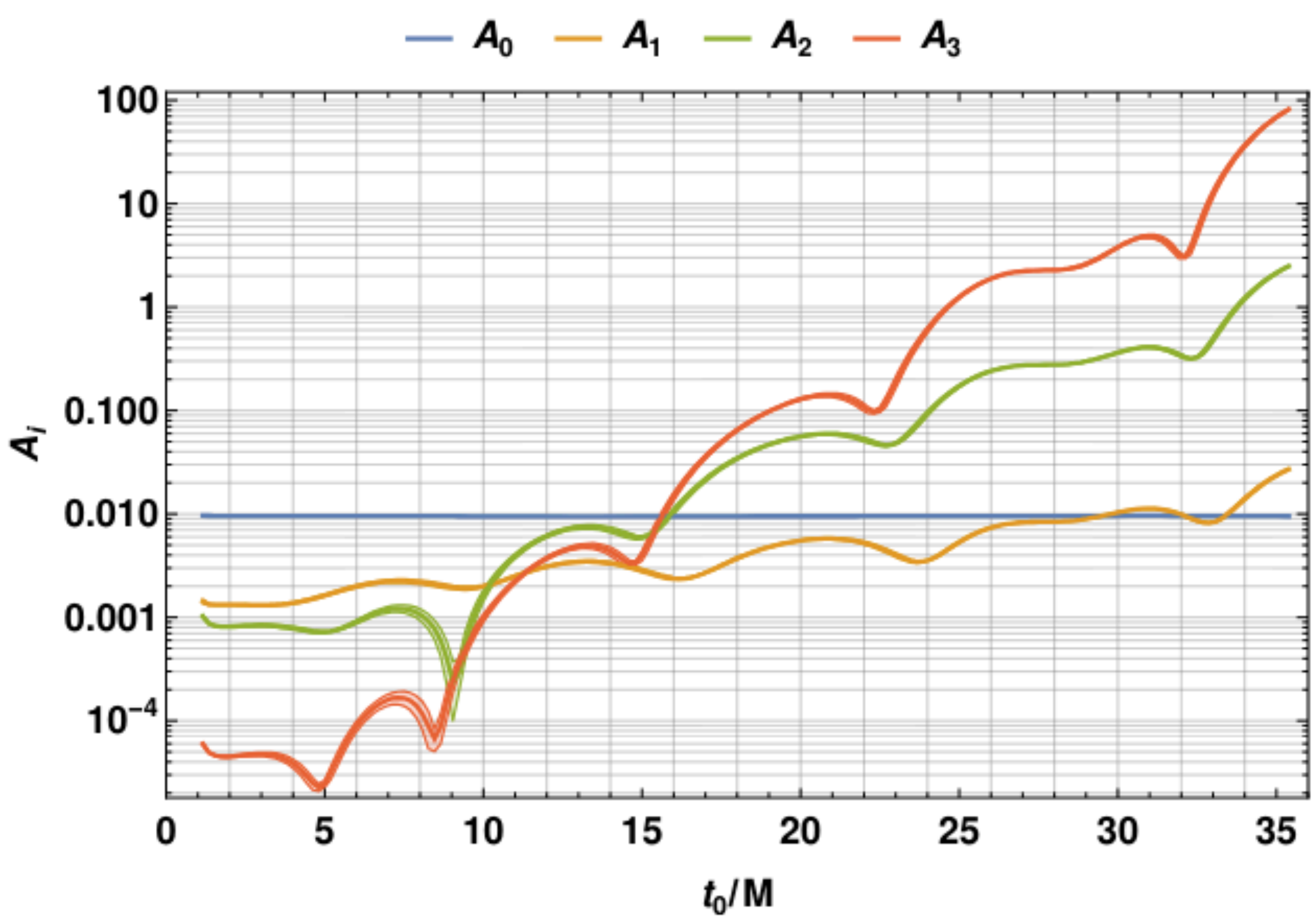
Frequency $\omega_{lm} = \omega_{l'm'} + \omega_{l''m''}$

Keefe Mitman et al. 2023 Cheung et al. et al. 2023

Spectroscopy of the BH horizon

But what is next? - Wave zone-horizon amplitudes comparison.

- Amplitudes in a head-on for the horizon.

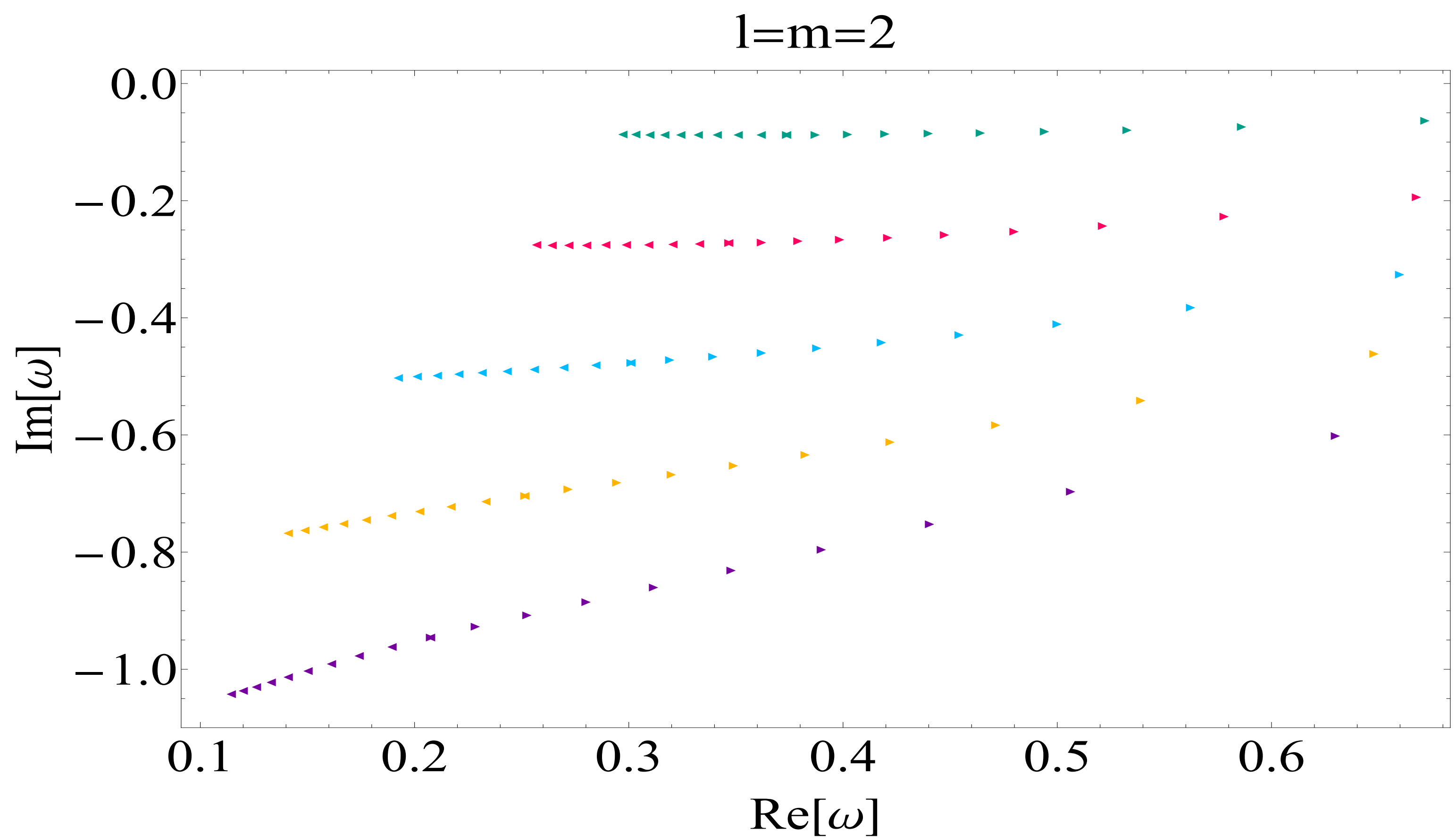


- Amplitudes in a head-on for the waves

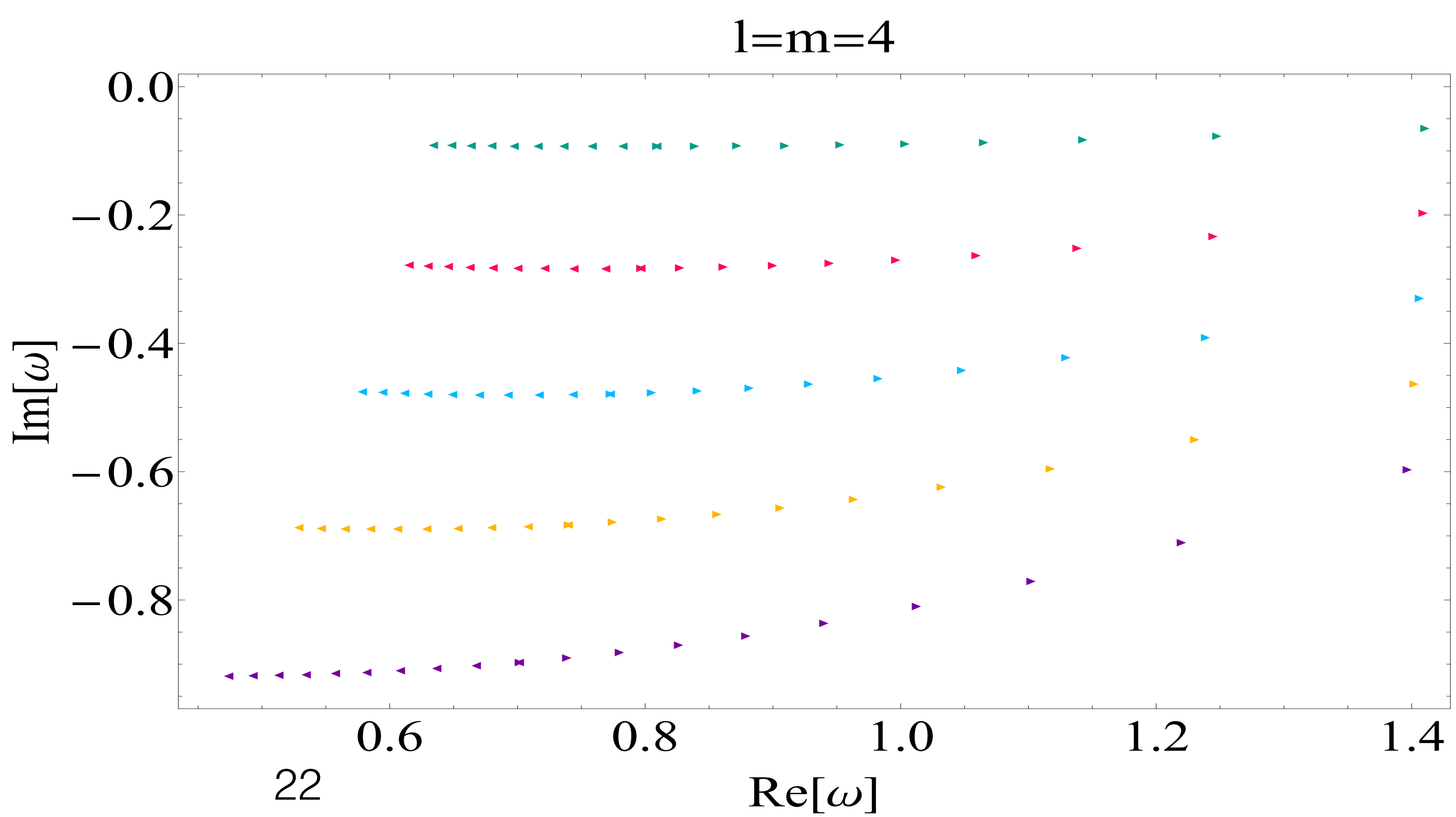
- To be filled.

Introduction

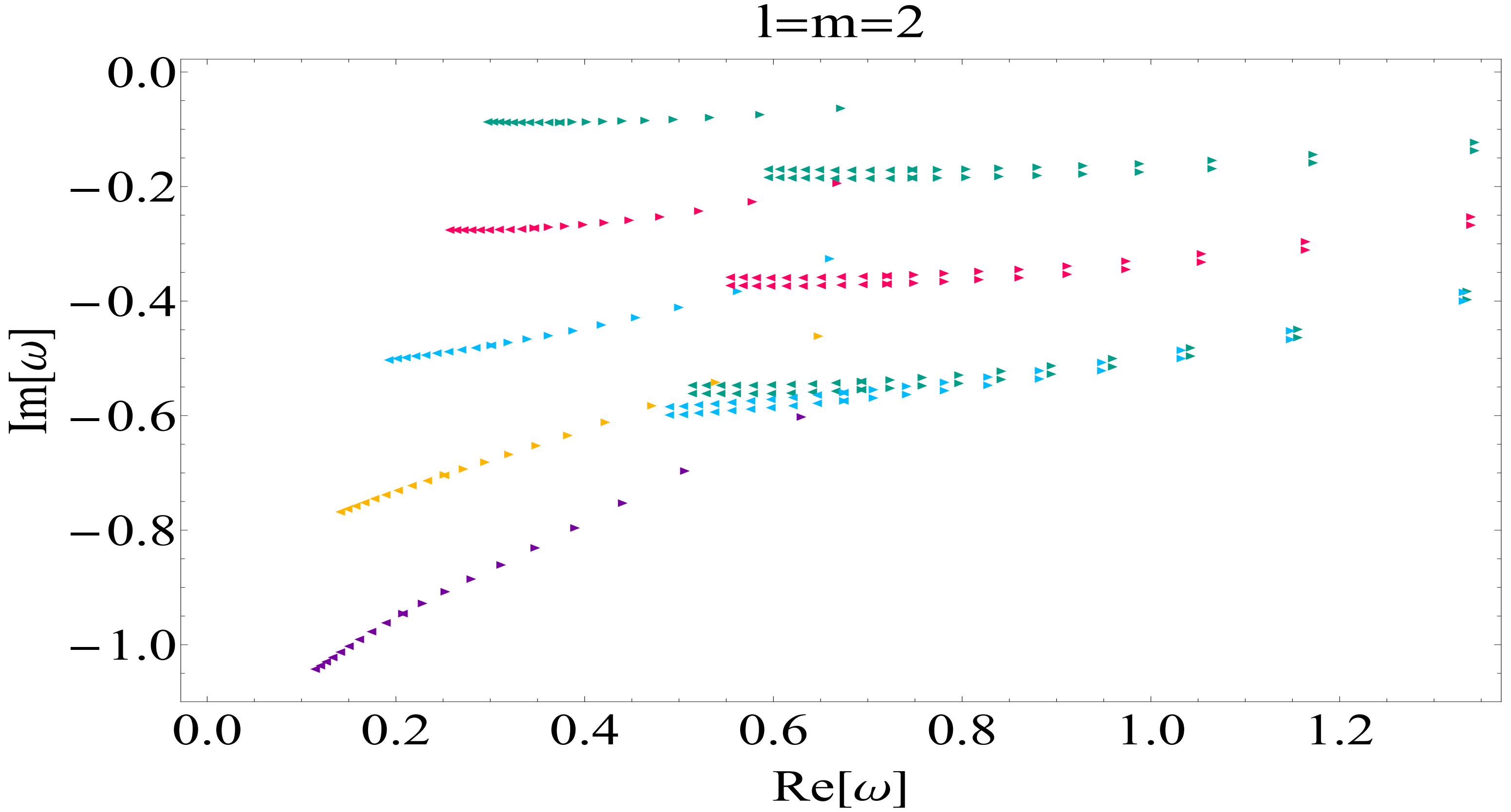
The overtone family on the 22 mode



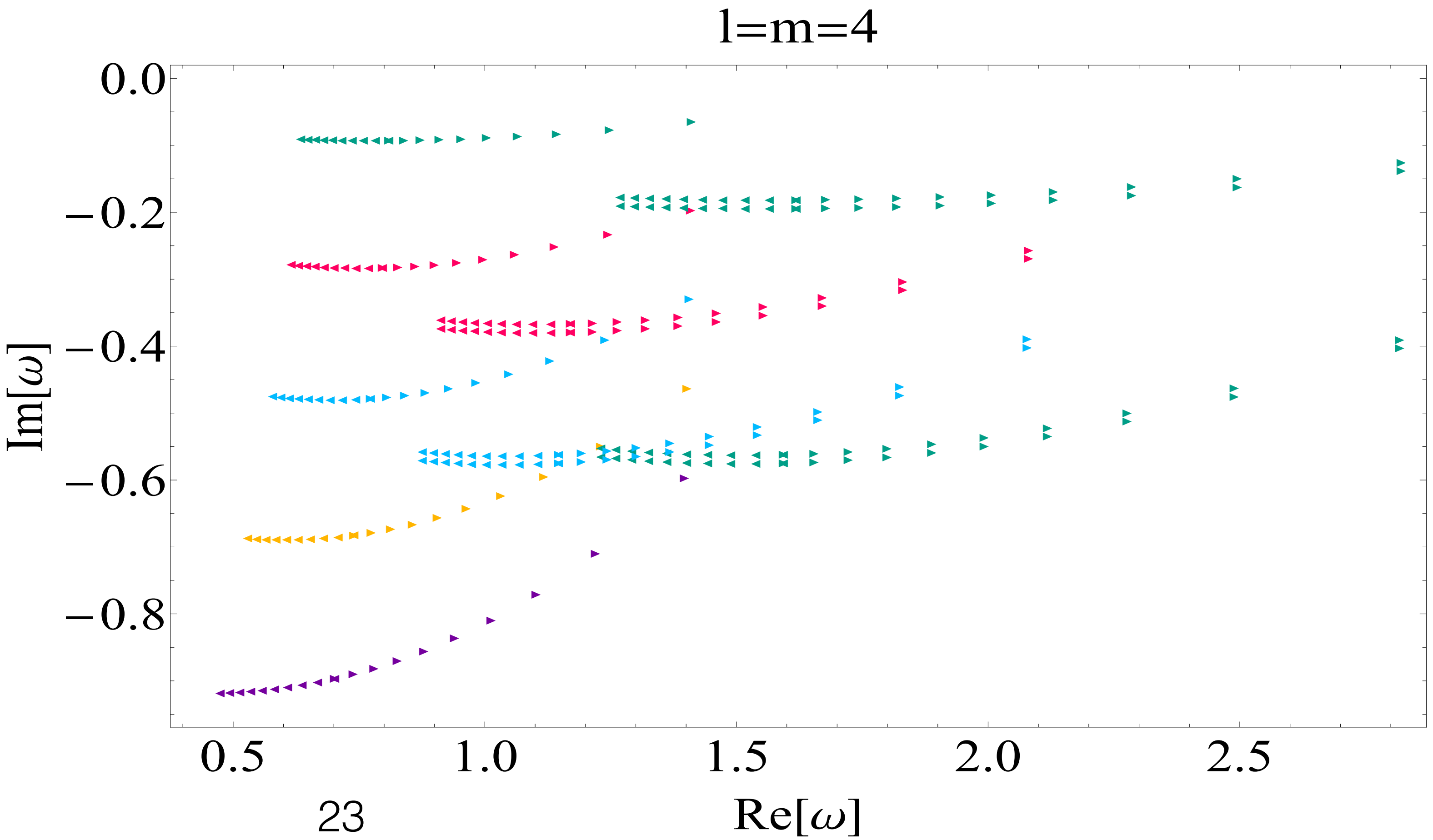
The overtone family on the 44 mode



The overtone family on the 22 mode

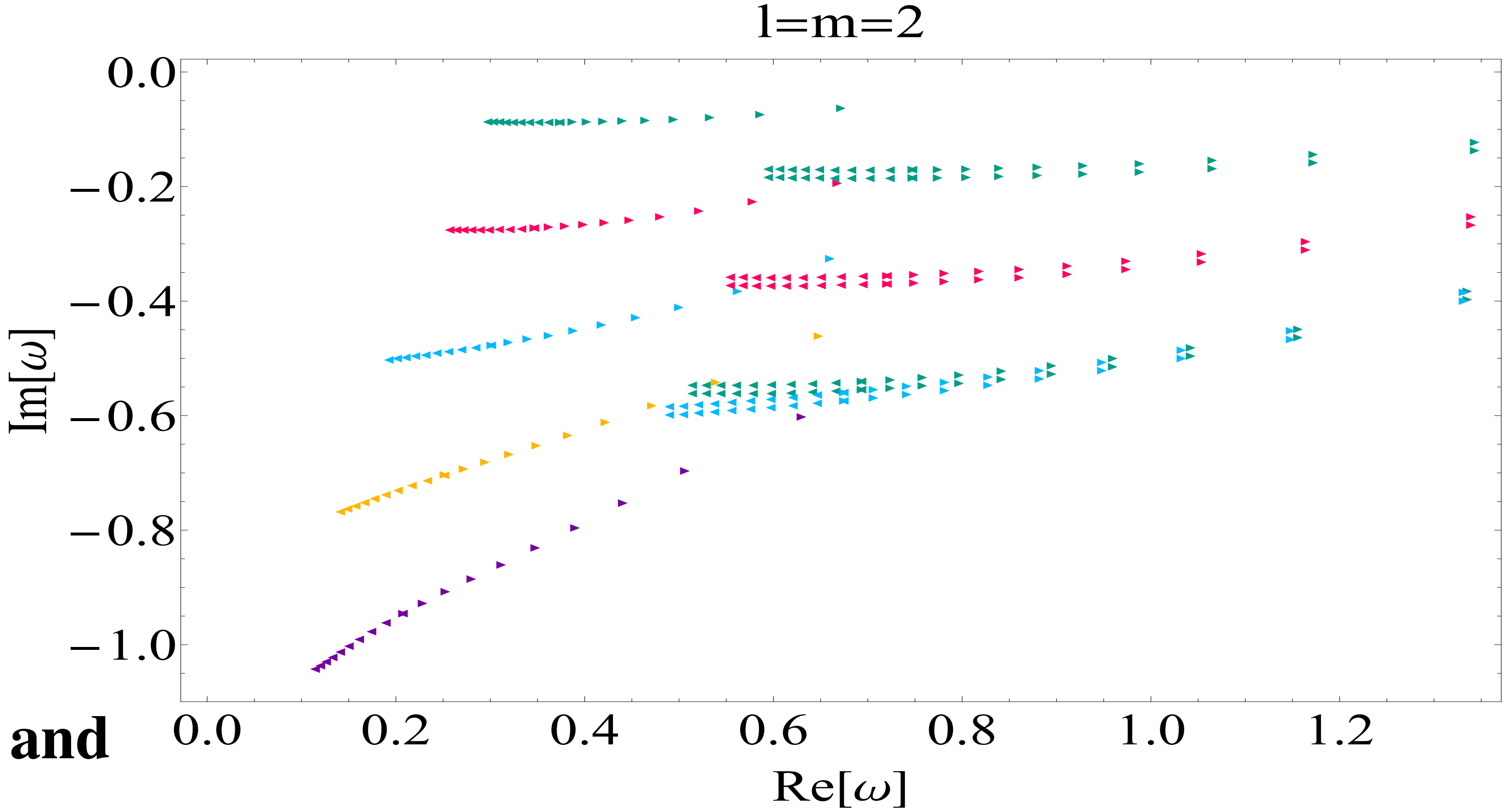


The overtone family on the 44 mode



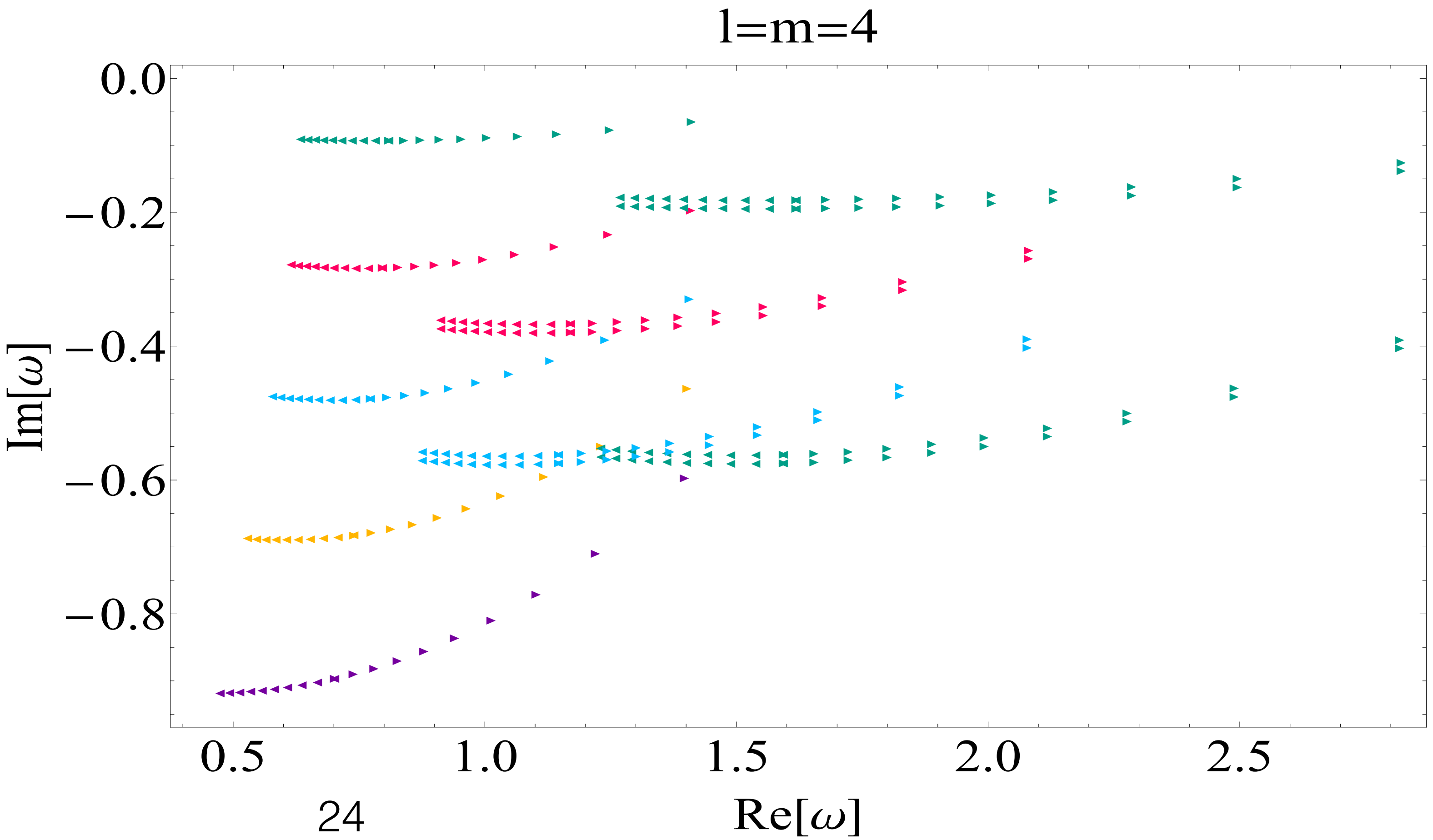
Introduction

The overtone family on the 22 mode



We have foundear evidence of linear and quadratic modes in NR

The overtone family on the 44 mode



The ringdown battle: Linear be or not be that is the question

Linear perturbation theory vs non-linear effects: Choose your team.

<u>Team non linear models</u>

- Phenom, EOB, NR Surrogate models are non-linear.

- Kerr properties of the space-time not satisfied locally.

… They have to be there!! yeye, but where?

<u>Team linear models</u>

-Models from PT

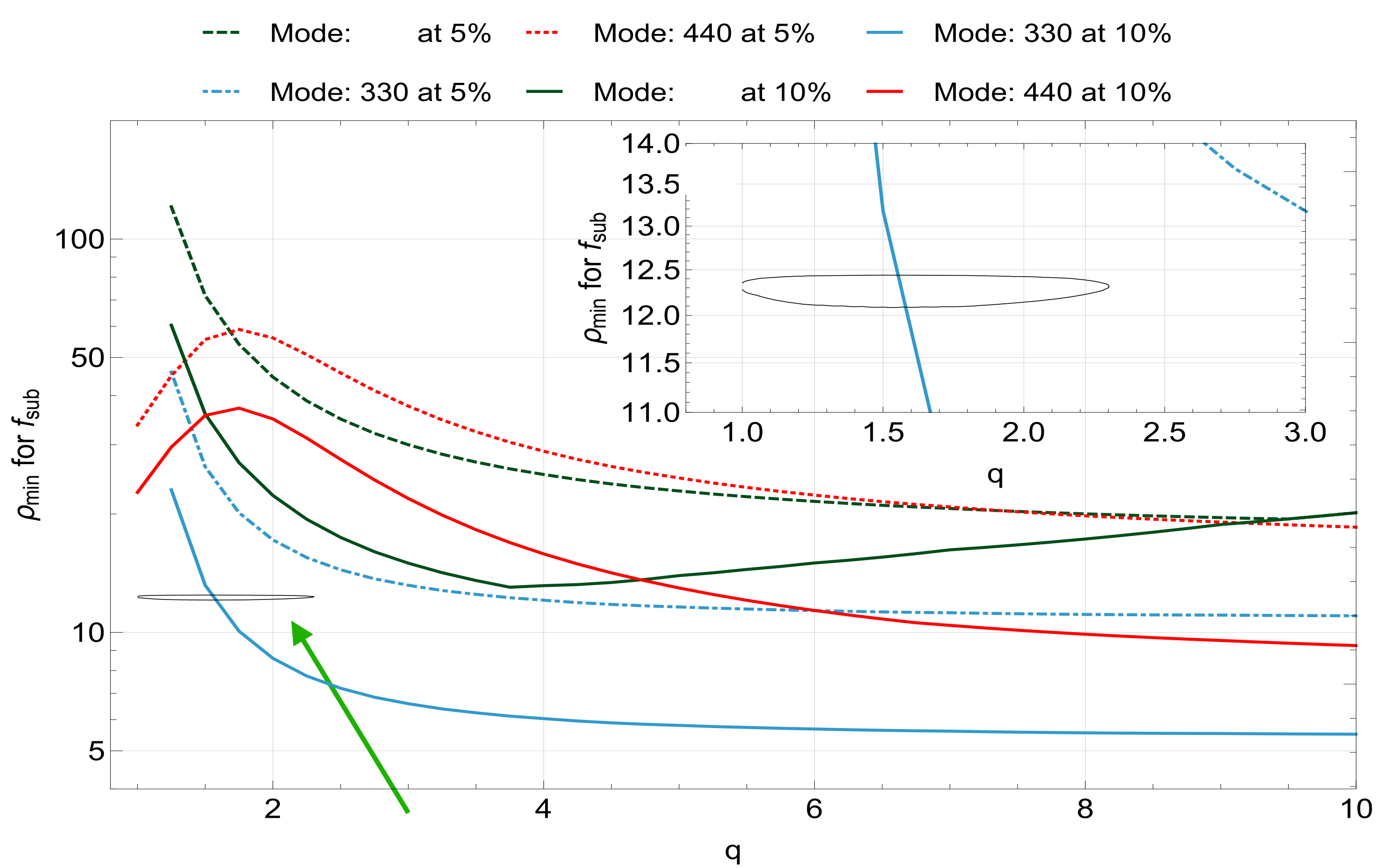
- They fit really well

Today in LIGO/Virgo observatories…

Recipe to detect a subdominant mode and why amplitudes are important:

- Its frequencies are diff. enough from the fundamental mode

- It has enough amplitude



GW190521 with modes 22-33

Jimenez, Bhagwat +

Amplitudes are known from fitting your ansätz to NR data

About the non-linearities

- NR simulations show the QNM structure

- Late time tails have been also recently found in NR simulations

- Prompt emission arises naturally by solving the scattering of field in a Schwarzschild space time

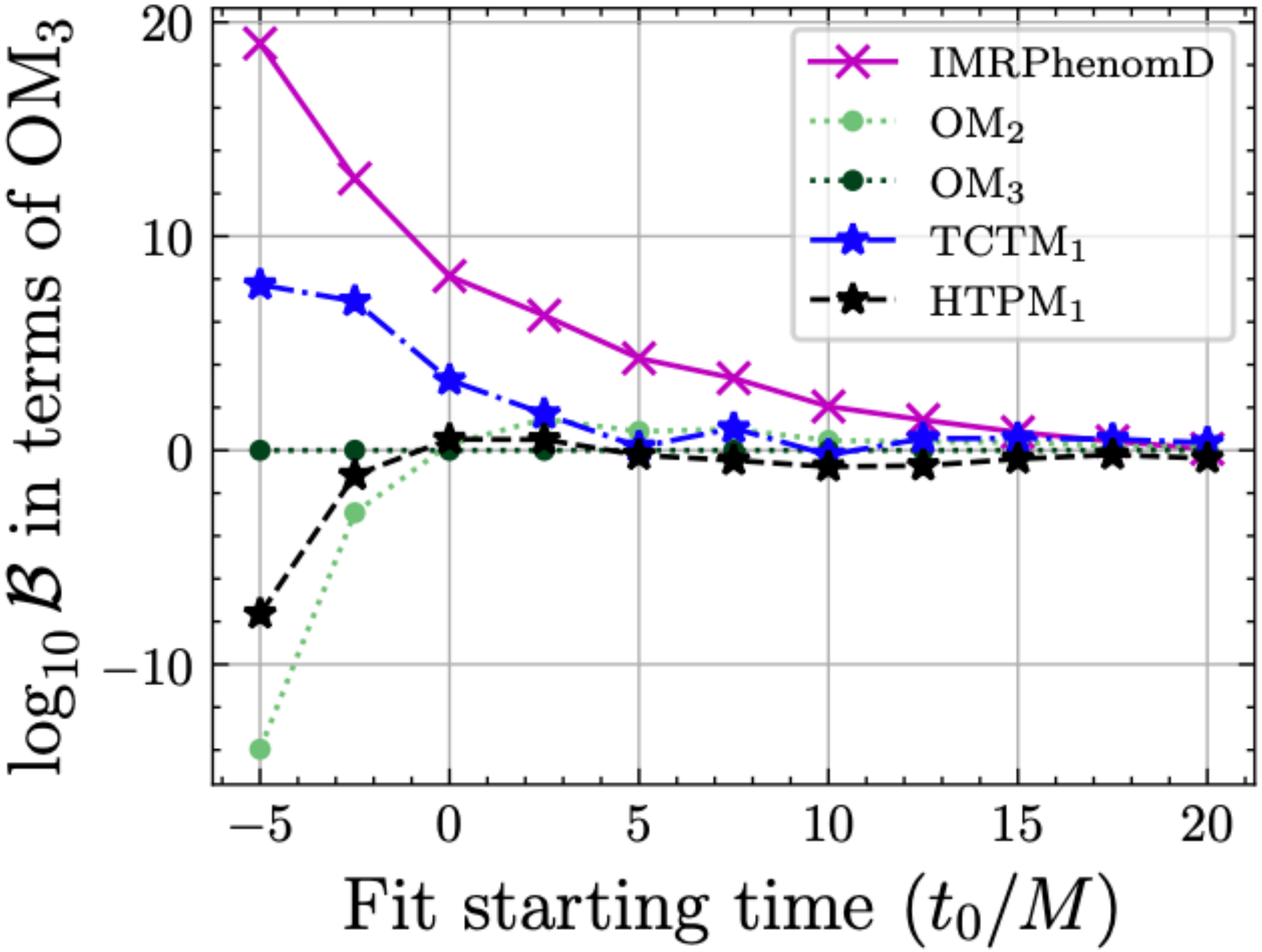
- All three types of emission are excited at different times: Direct emission, light-ring excitation and field backscattering.

- All together forms a rich but complex RD in which linear and non-linear terms appear… even in the linearized case.

About the non-linearities

- Comparing NR full non-linear models to the typical solutions show a preference for non-linear models at t>~10M

- Is this consistent with the direct propagation or prompt emission? Ongoing.



Yi, Jimenez (2023)

GW190521: Quite a controversial event

Overtone instability