8TH KAGRA INTERNATIONAL WORKSHOP (KIW8) - JULY 09 2021

PROSPECTS FOR OBSERVING MULTIPLE QUASINORMAL MODES WITH GRAVITATIONAL WAVE DETECTORS

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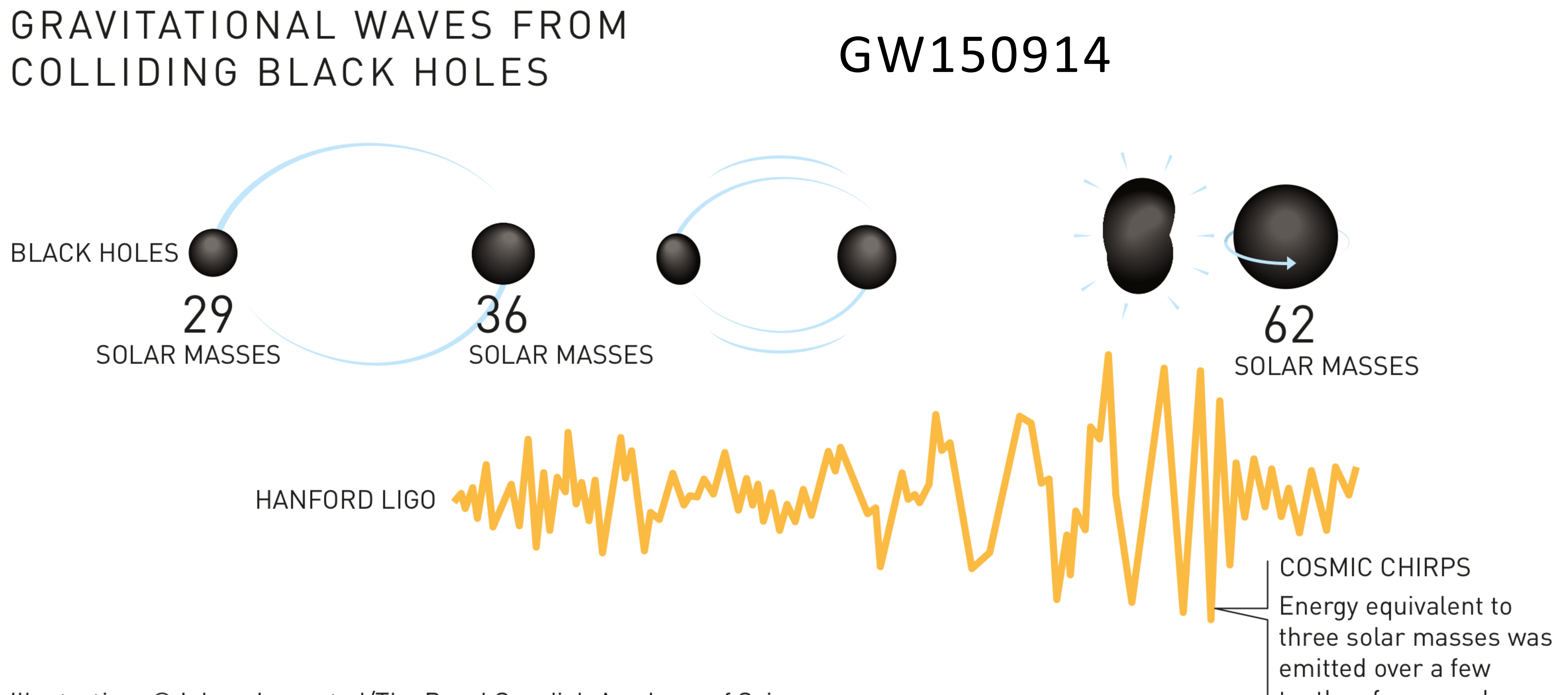
BINARY BLACK HOLE MERGER

- Most LIGO sources are binary black hole mergers
- 3 stages: inspiral, merger and ringdown
- Ringdown is well approximated by *quasinormal modes*



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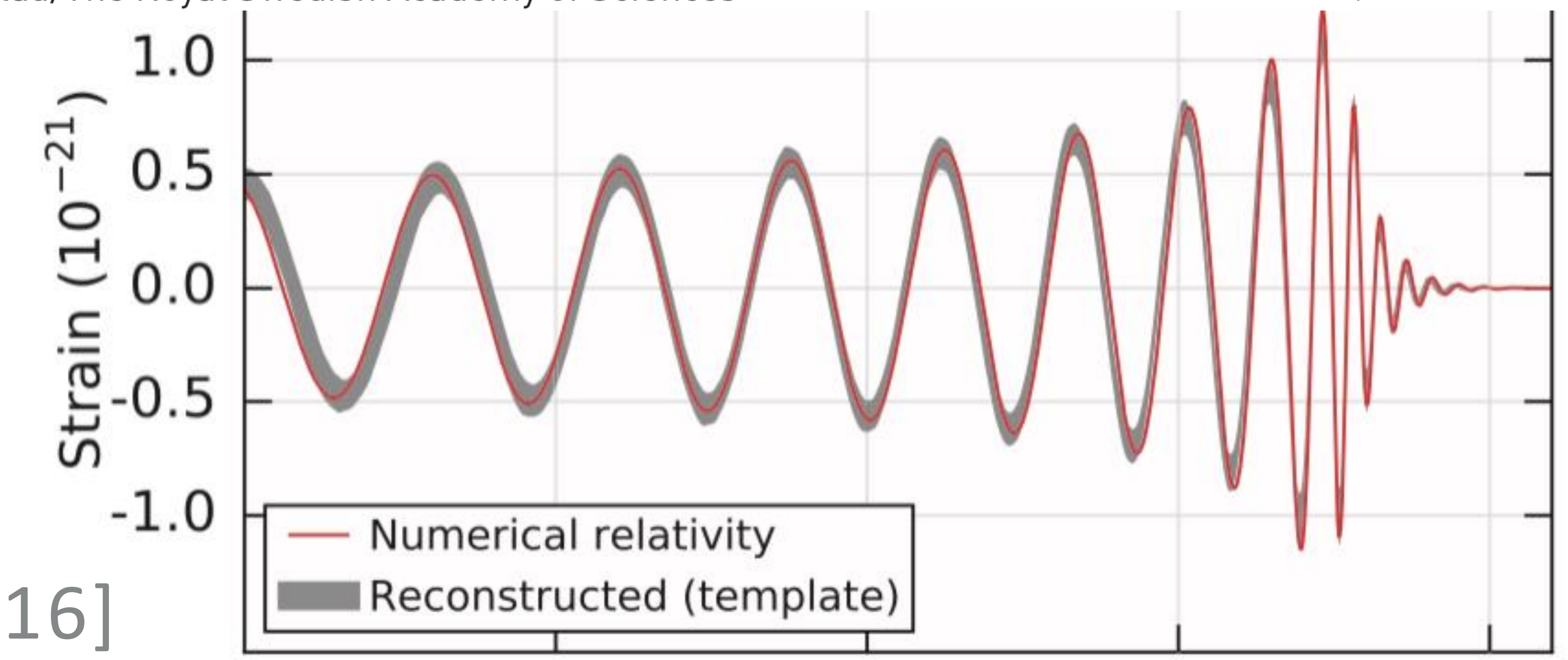
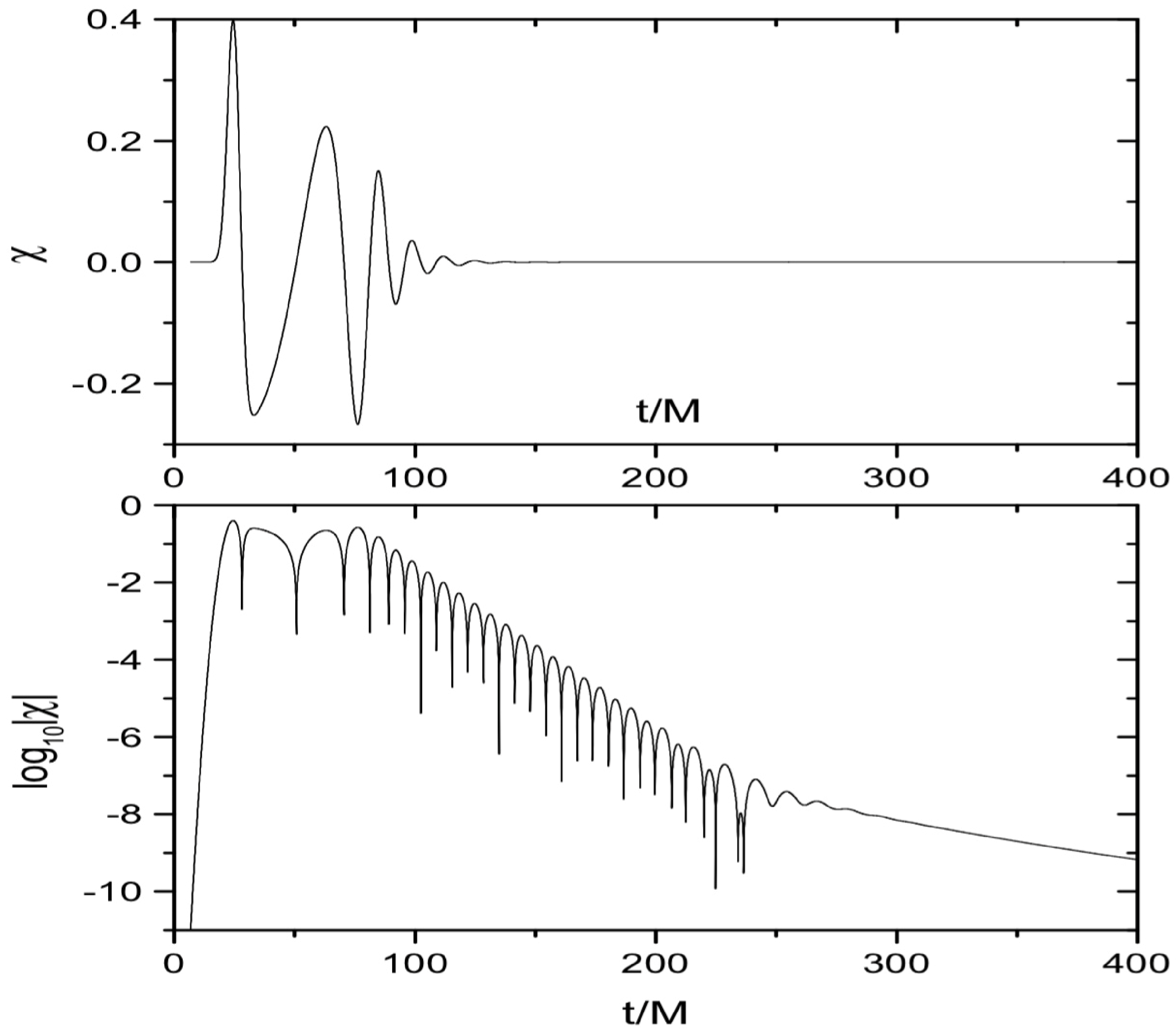


[Abbott et al., 2016]

BLACK HOLE LINEAR PERTURBATION

1. *Transient:* depends on initial perturbation
2. *Quasinormal modes (QNMs):* characteristic frequency of oscillation and damping time - encode information about the black hole
3. *Power law tail:* oscillation ceases



[Kokkotas and Schmidt, 1999]

THE NO-HAIR THEOREM

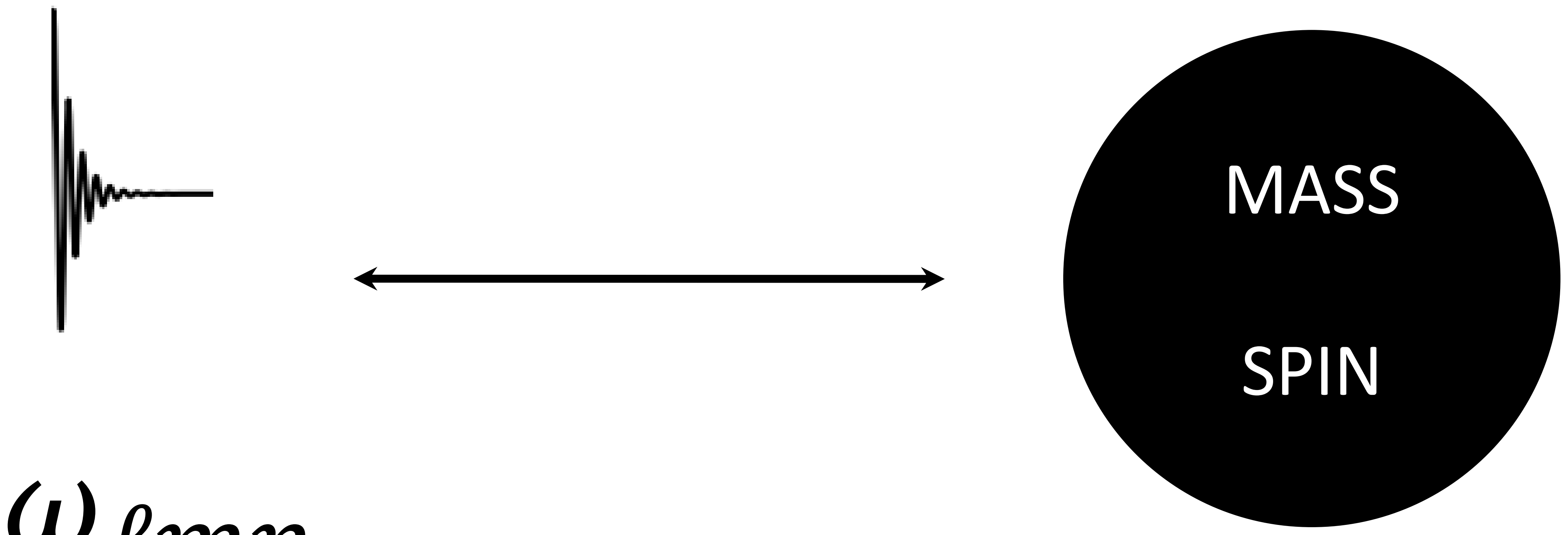
- *The no-hair theorem*: black holes are described by 3 numbers. Astrophysical black holes are described by only 2.

- QNMs frequencies depend only on mass and spin.

QNM waveform:

$$\psi = \sum \psi_{\ell mn} = \sum A_{\ell mn} e^{i\omega_{\ell mn} t + \phi_{\ell mn}}$$

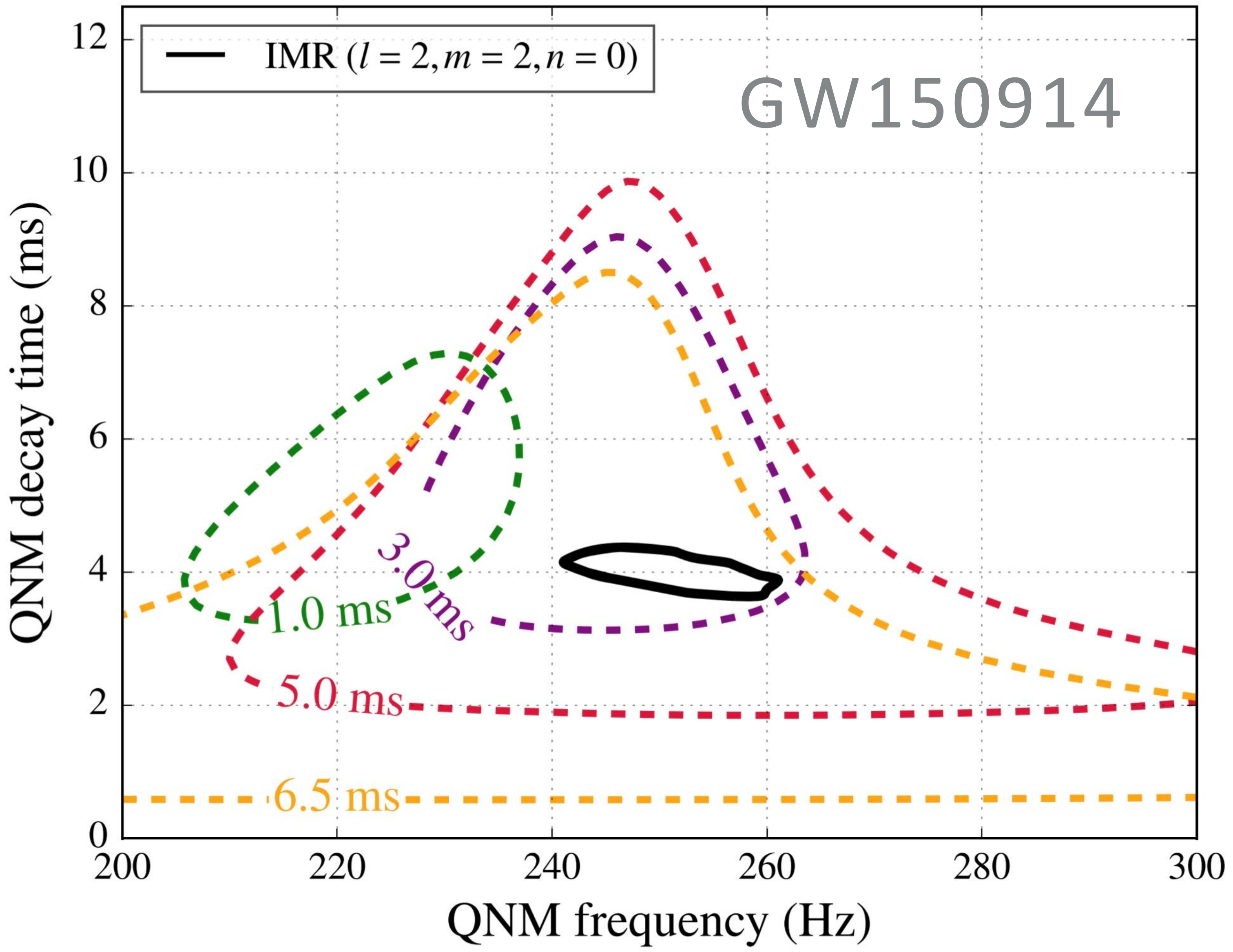
complex frequency: $\omega_{\ell mn} \equiv 2\pi f_{\ell mn} + i/\tau_{\ell mn}$



$\omega_{\ell mn}$

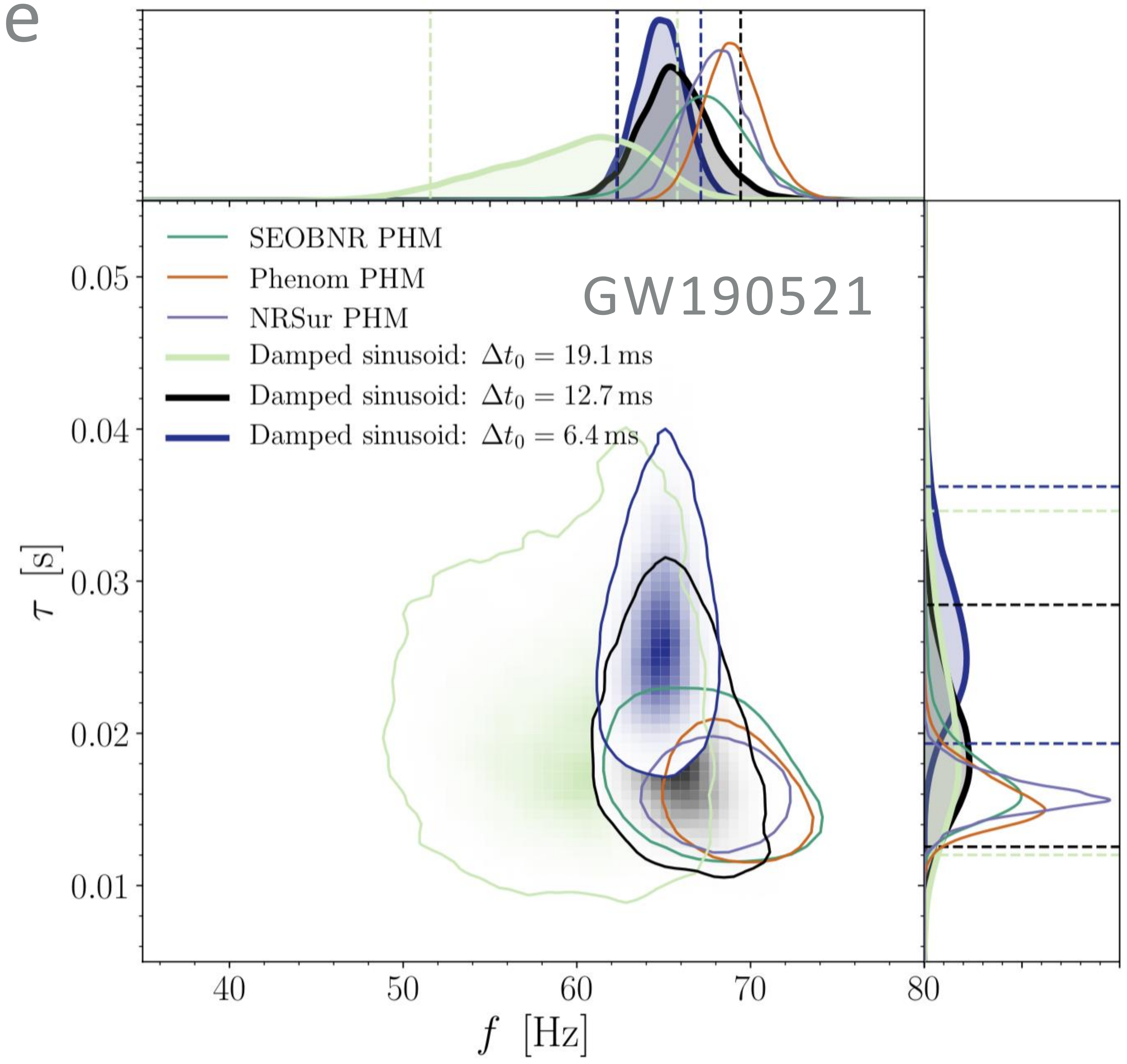
DETECTION OF QUASINORMAL MODE

- The frequency and damping time of the dominant mode (2,2,0) can be determined in some LVC detections



[Abbott et al., 2016]

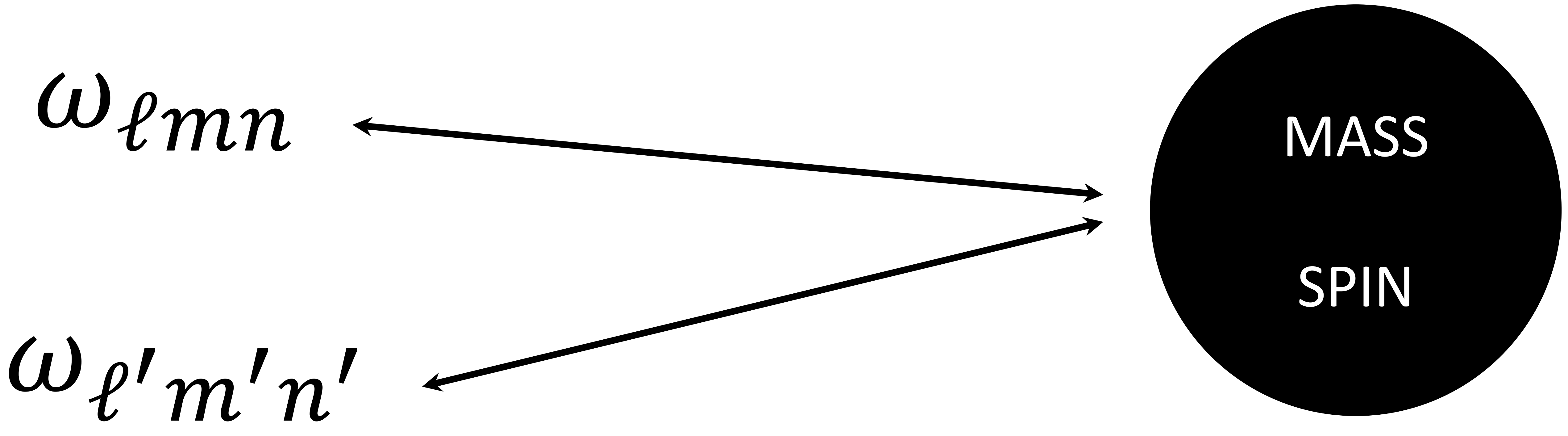
- This is a consistency test and not a test of the no-hair theorem



[Abbott et al., 2020]

BLACK HOLE SPECTROSCOPY [Dreyer et al., 2004]

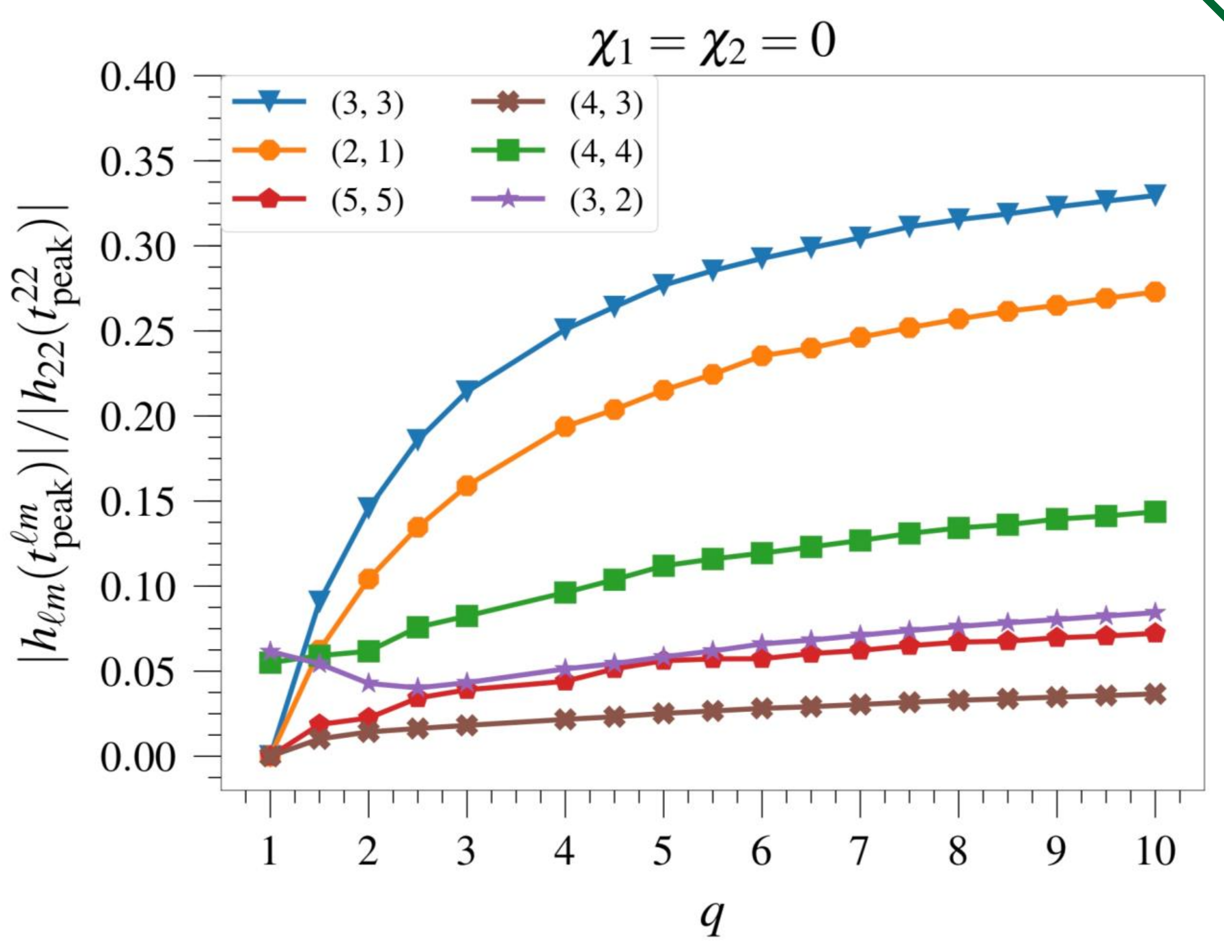
- Detection of 2 or more modes to test the no-hair theorem.
- Check if the remnant black hole is described by the Kerr metric.
- Independent test.
- Dominant mode: $(\ell, m, n) = (2,2,0)$



$$\omega_{\ell m n} \equiv 2\pi f_{\ell m n} + i/\tau_{\ell m n}$$

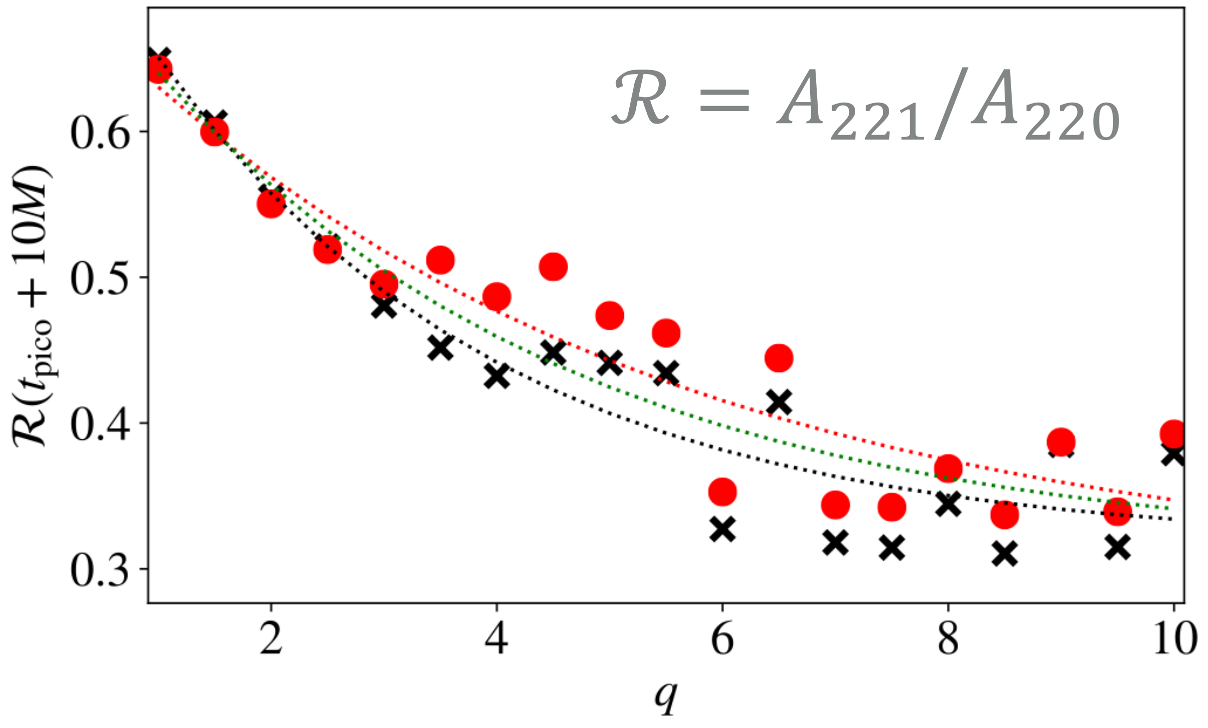
SUB-DOMINANT MODES

(binaries with no initial spin and eccentricity)



[Cotesta et al., 2018]

higher harmonics $(\ell, m, 0) \neq (2,2,0)$ are more relevant for unequal mass binaries

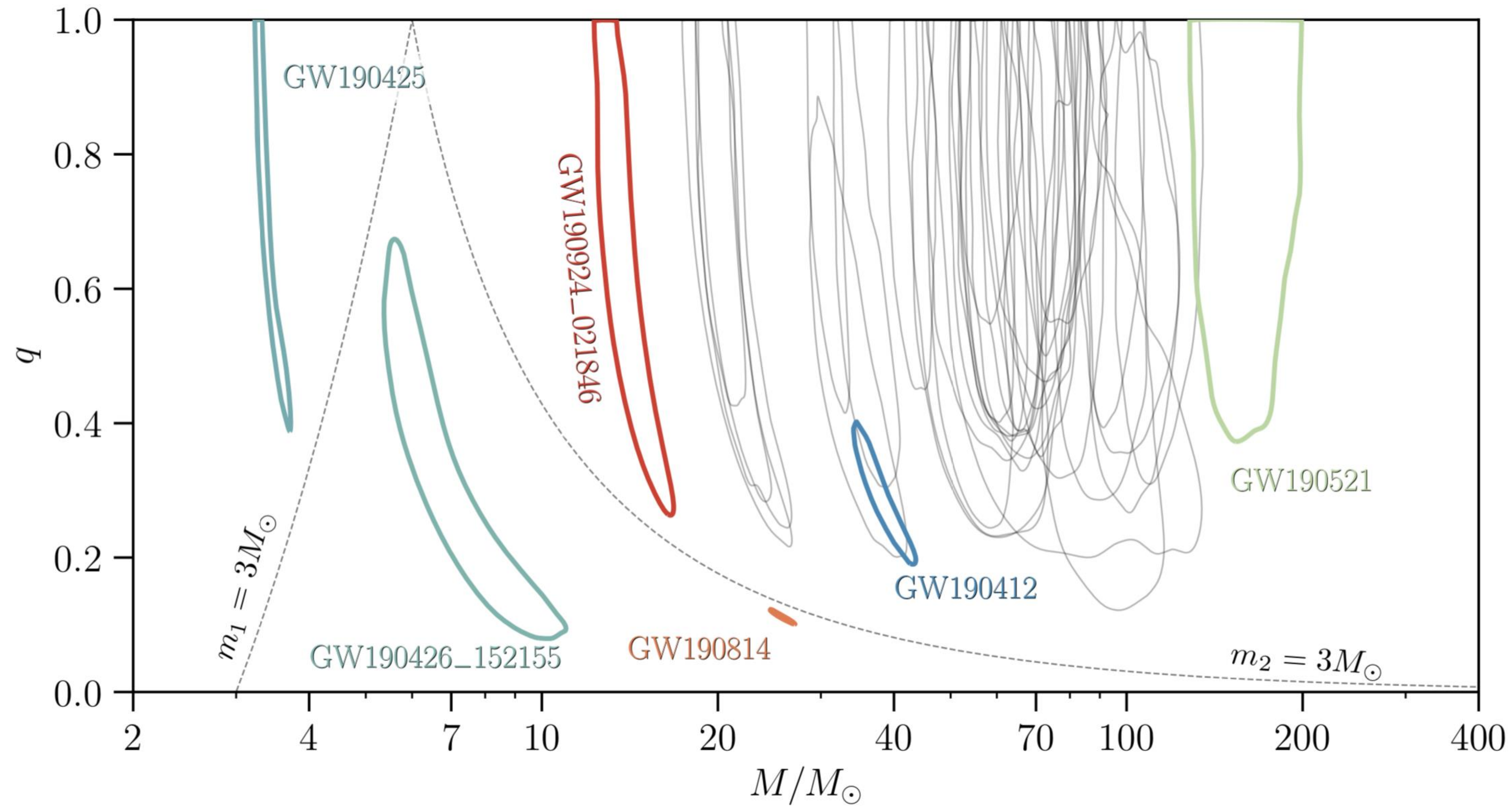


[Ota and Chirenti, 2020]

the first overtone $(\ell, m, n) = (2,2,1)$ are more relevant for equal mass binaries

see also [Forteza et al., 2020]

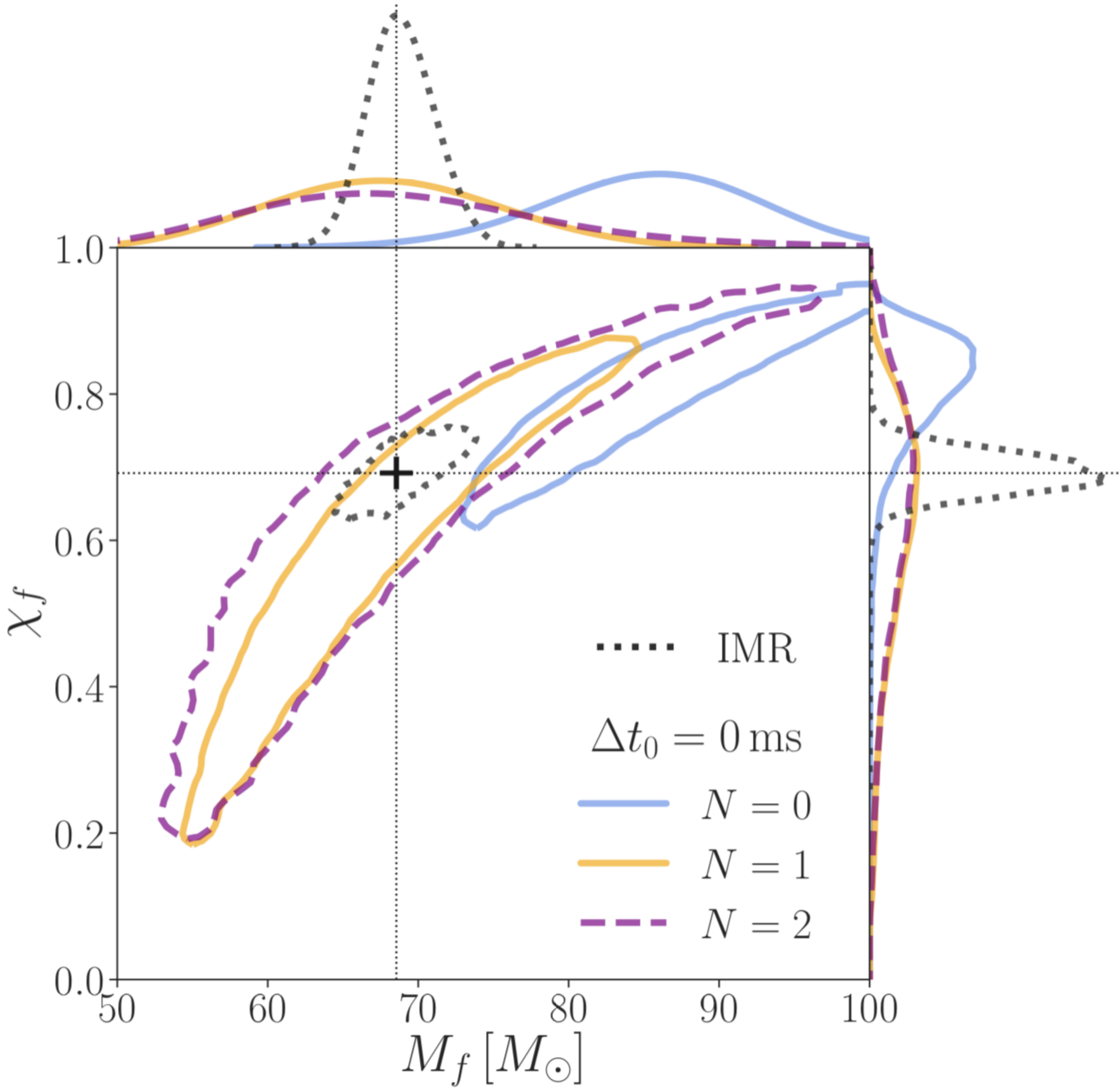
most LIGO sources are compatible with equal masses



[Abbott et al., 2020]

SUB-DOMINANT MODES IN THE DATA

GW150914 $z \sim 0.09$



[Isi et al., 2019]

the inclusion of sub-dominant modes in the analyses decreases the error in the mass and spin but the data do not provide enough evidence for a second mode

[Carullo et al., 2019]

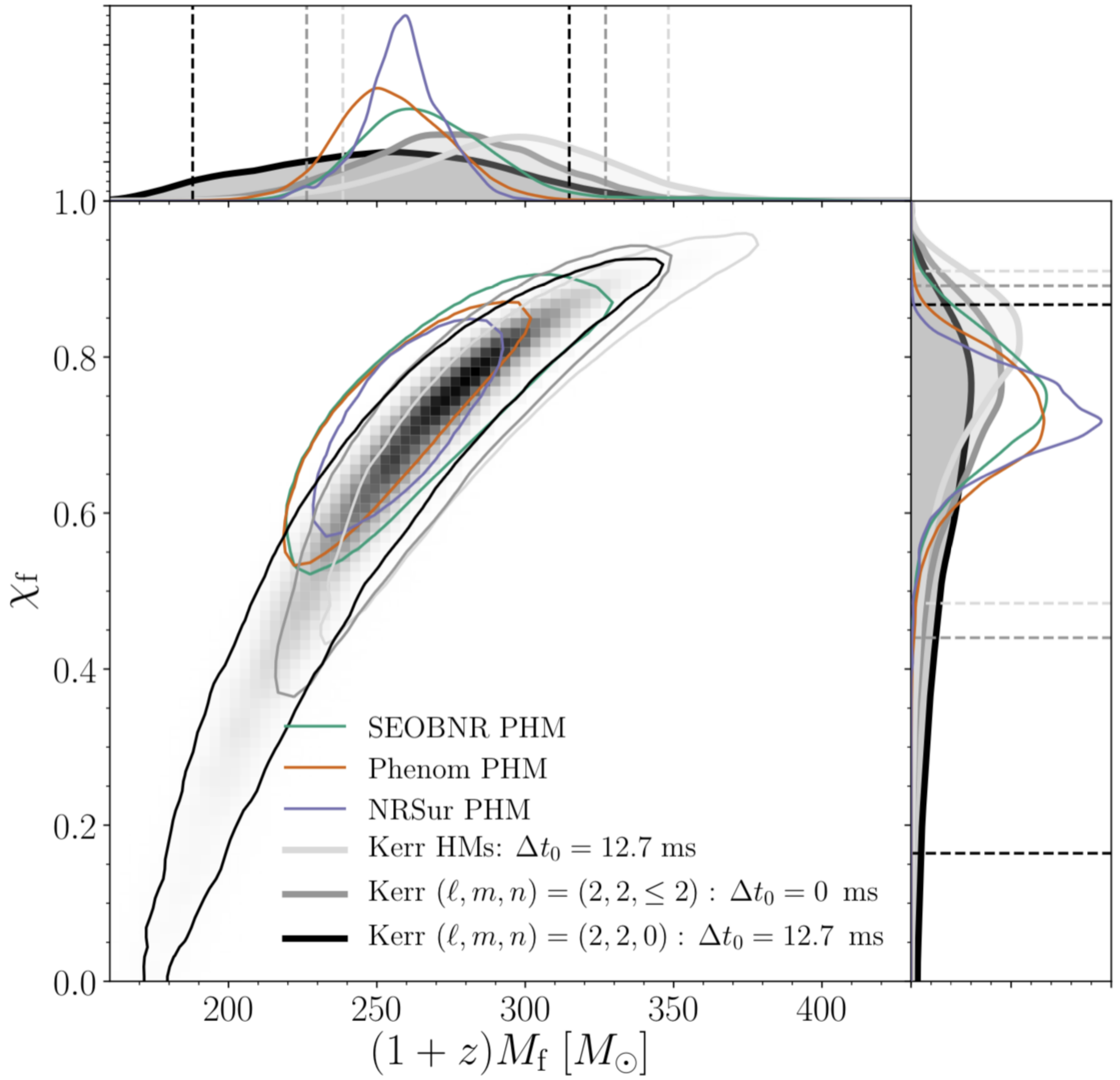
[Abbott et al., 2020]

[Bustillo et al., 2020]

[Isi et al., 2021]

[Capano et al., 2021]

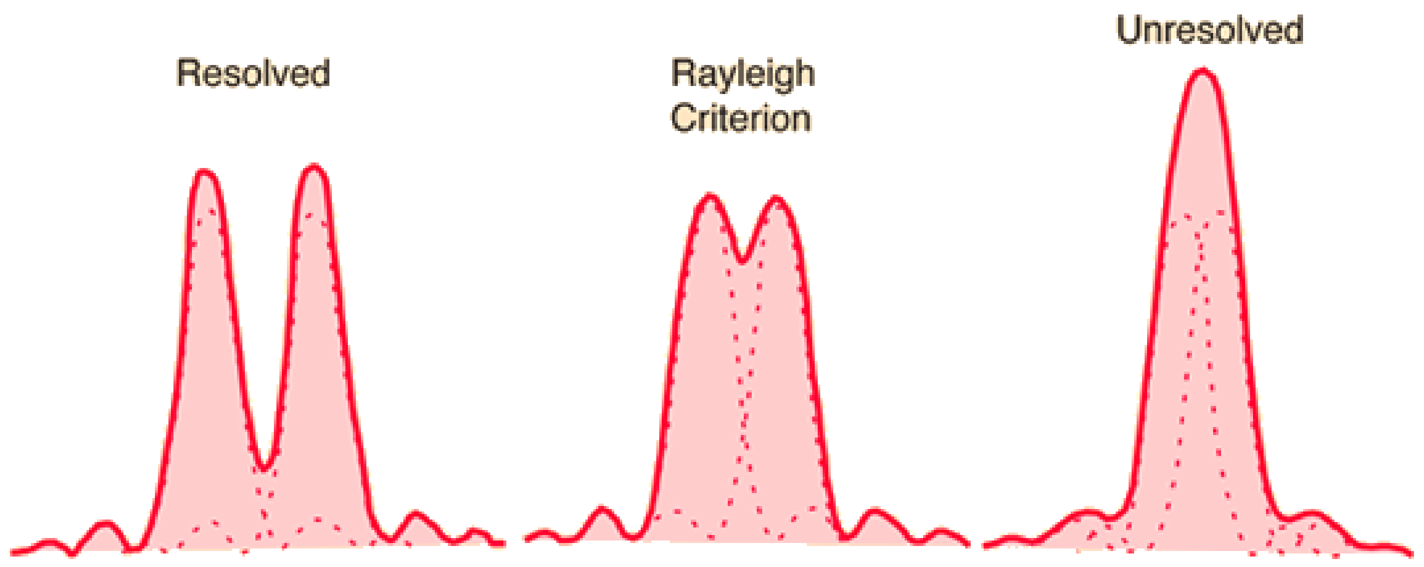
GW190521 $z \sim 0.7$



[Abbott et al., 2019]

RESOLVABILITY: RAYLEIGH CRITERION

- Detectability is not enough for an independent test of the no-hair theorem!



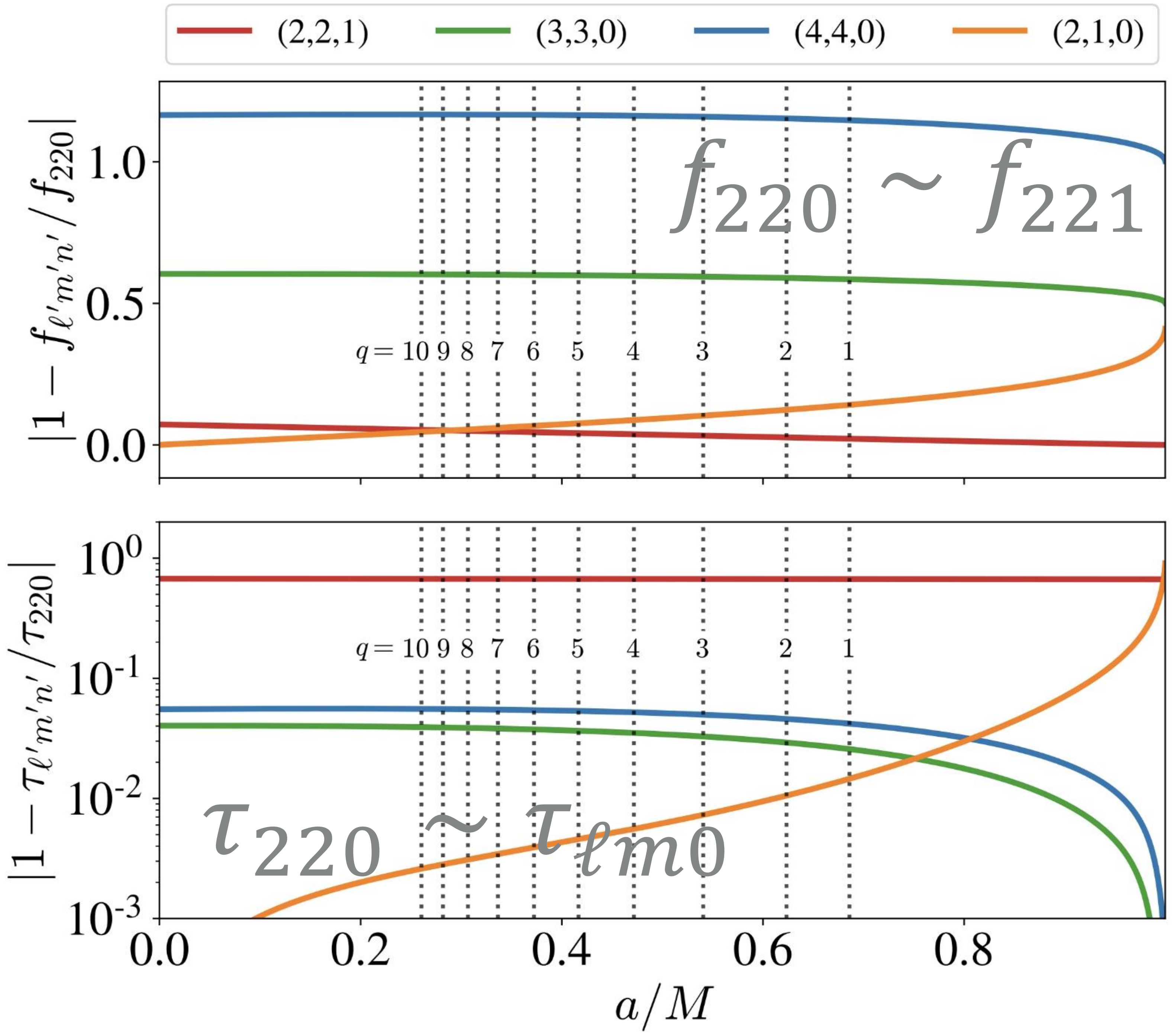
[hyperphysics.phy-astr.gsu.edu]

$$|f_{\ell mn} - f_{\ell' m' n'}| > max(\sigma_{f_{\ell mn}}, \sigma_{f_{\ell' m' n'}})$$

$$|\tau_{\ell mn} - \tau_{\ell' m' n'}| > max(\sigma_{\tau_{\ell mn}}, \sigma_{\tau_{\ell' m' n'}})$$

[Berti et al., 2006]

The Rayleigh criterion require resolvability of two modes for an independent test of the no-hair theorem



[Ota and Chirenti, in preparation]

errors computed using Fisher Matrix

BAYESIAN INFERENCE AND MODEL COMPARISON

Signal:

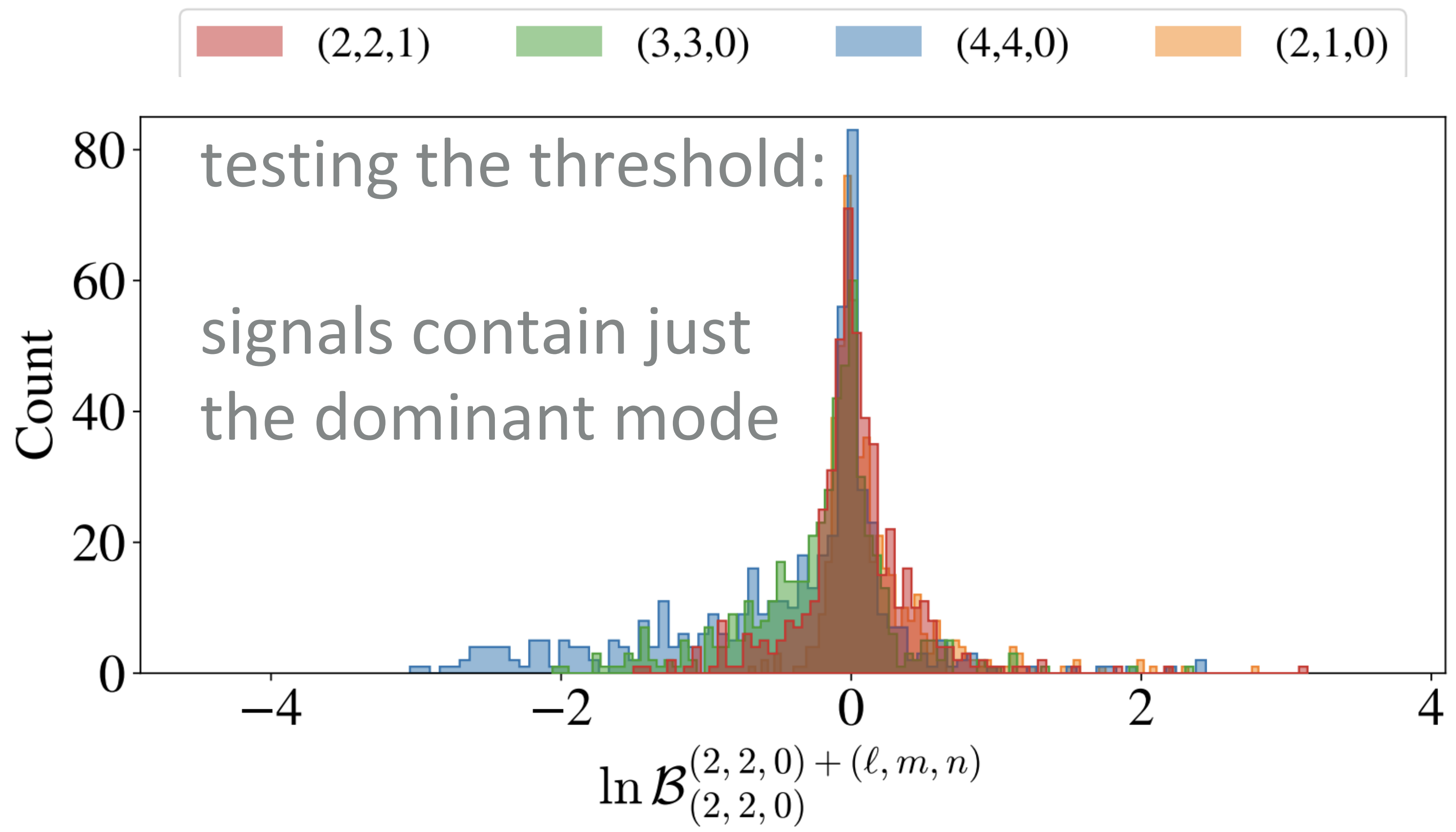
$s = \psi_{220} + \psi_{\ell mn} + n$

QNMs inject in the signal have parameters informed by NR simulations

Models:

1) one mode: $M_1 = \psi_{220}$

2) two modes: $M_2 = \psi_{220} + \psi_{\ell mn}$



[Ota and Chirenti, in preparation]

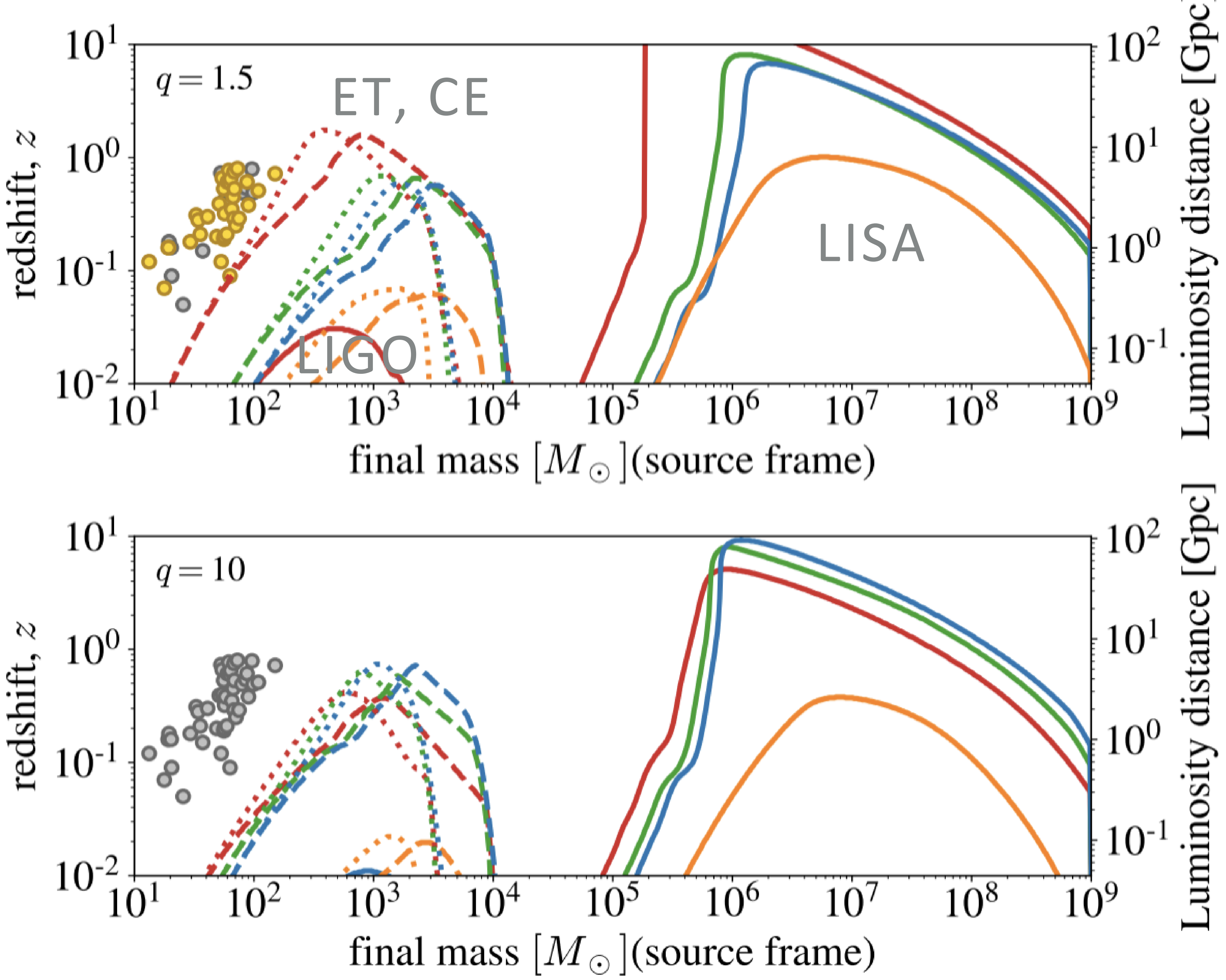
Model comparison:

We require $\ln\mathcal{B} > 8$ as our threshold to favor of 2 modes over 1 mode.

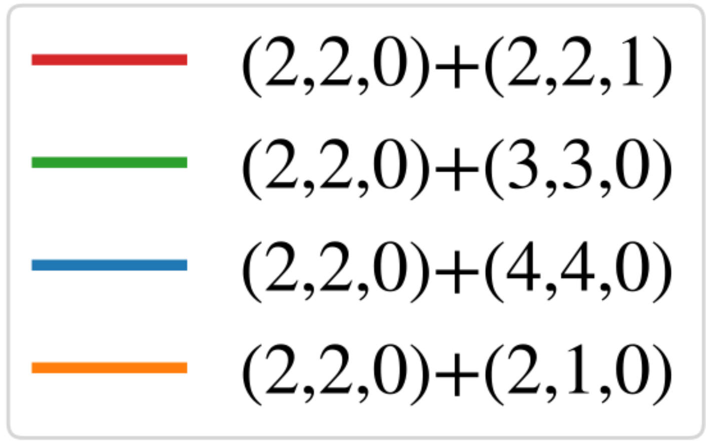
No cases with only one mode had a $\ln\mathcal{B}$ in favor of two modes larger than 4.

TWO MODES BH SPECTROCOPY HORIZONS

RAYLEIGH CRITERION

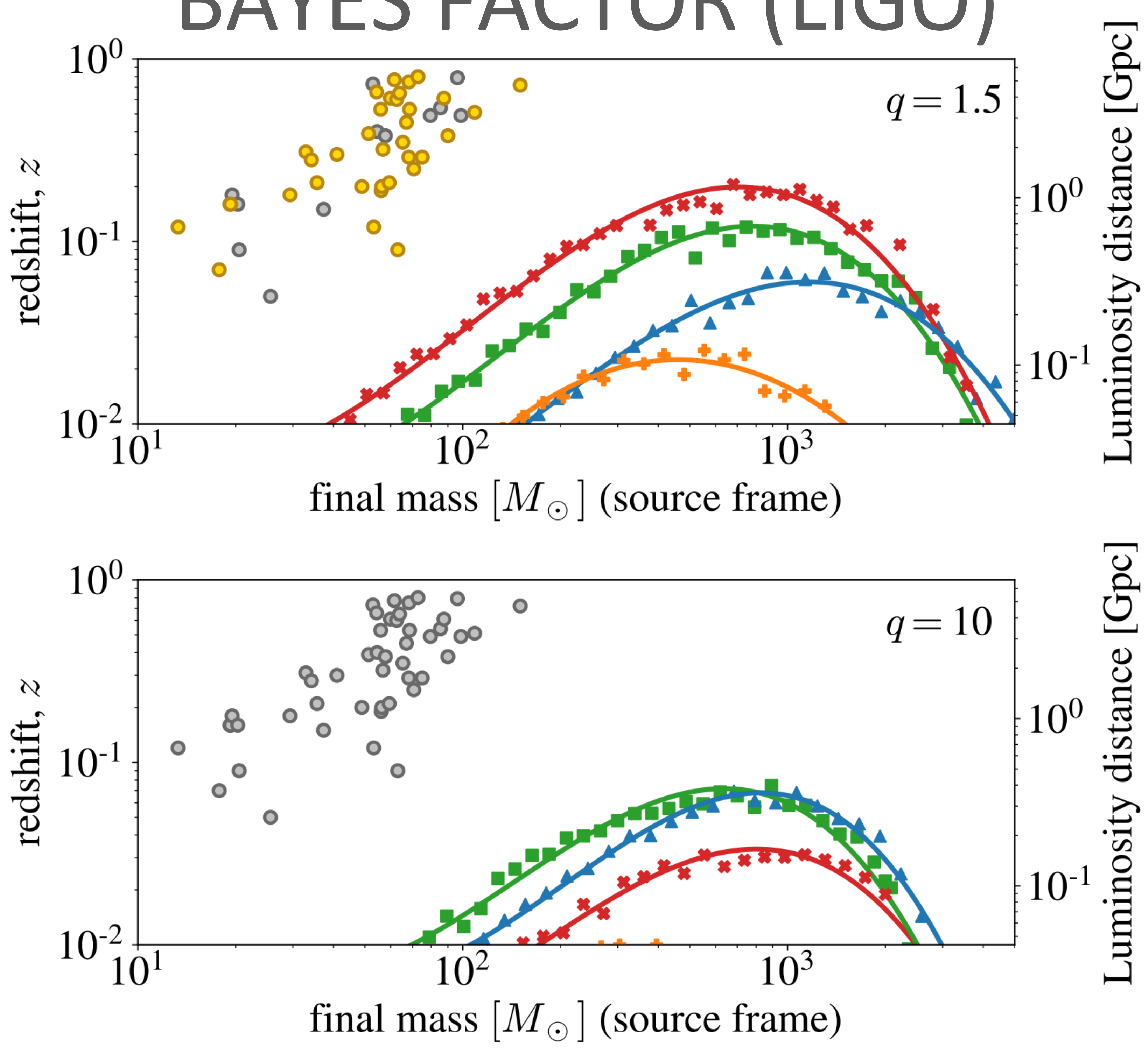


[Ota and Chirenti, in preparation]



- The detection of the first overtone is favored for low mass ratios
- Higher harmonics are favored for high mass ratios

BAYES FACTOR (LIGO)

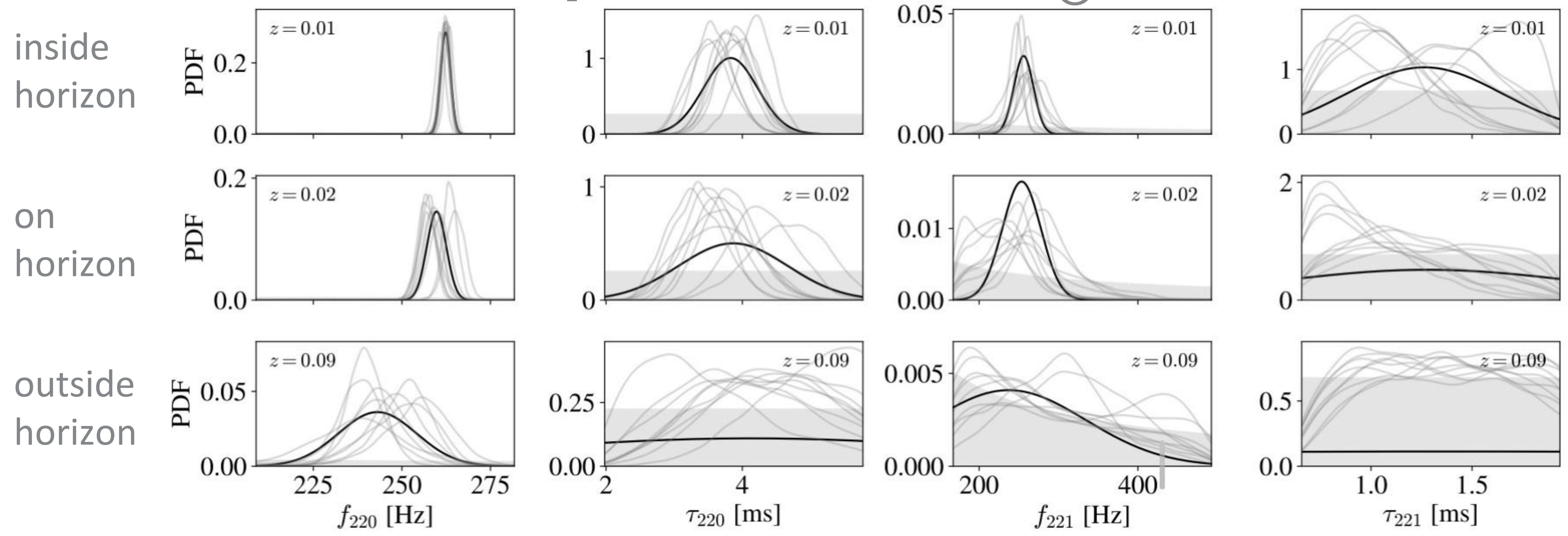


[Ota and Chirenti, in preparation]

The Rayleigh criterion is too restrictive!

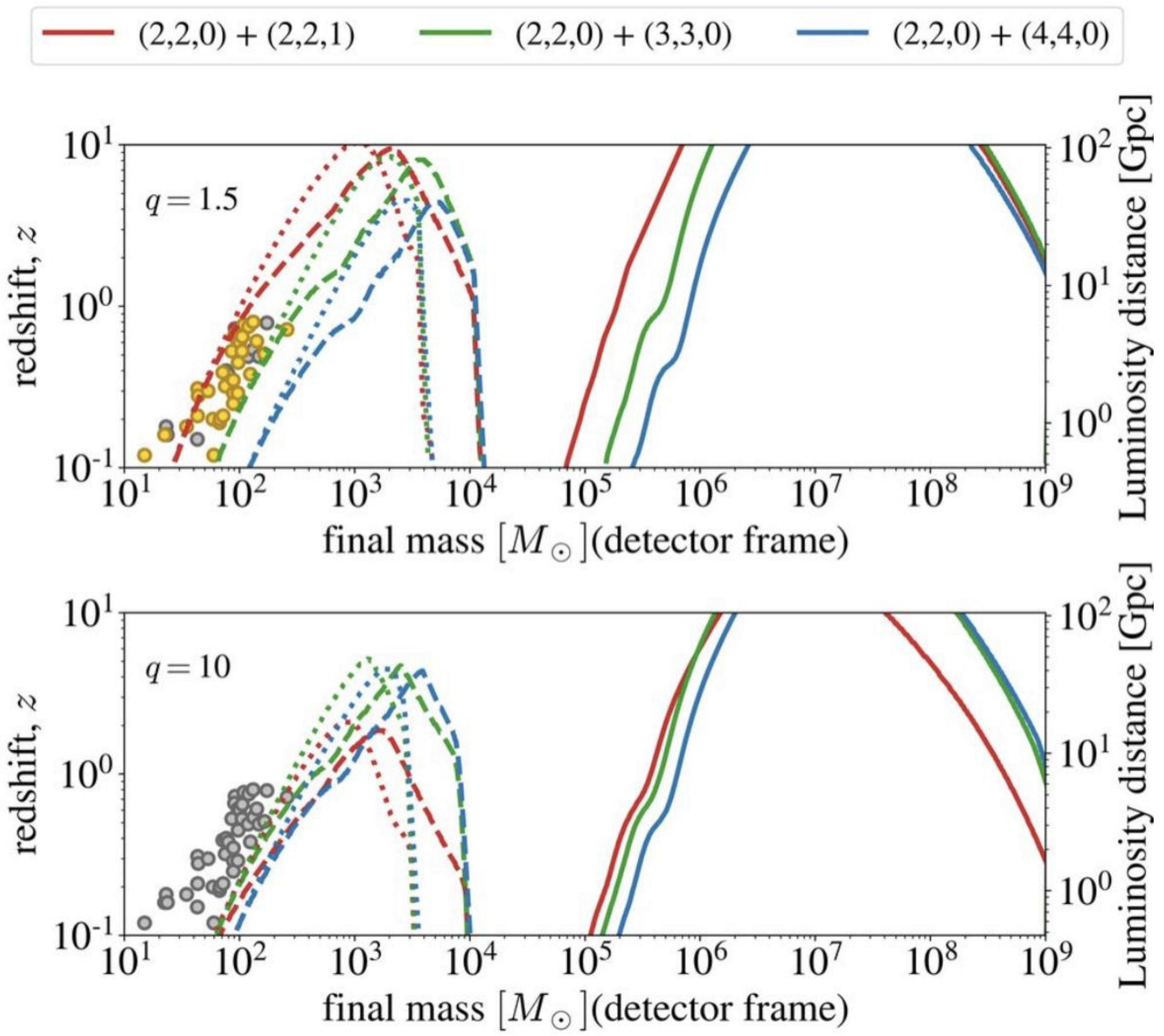
PARAMETER ESTIMATION: BAYESIAN VS FISHER MATRIX

$q = 1.5, M = 63\ M_{\odot}$



[Ota and Chirenti, in preparation]

Rescaling Rayleigh criterion based on LIGO Bayes factor horizon



The errors estimated with Fisher Matrix for the damping time are too big!

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MULTIMODE BH SPECTROCOPY HORIZONS (LIGO)

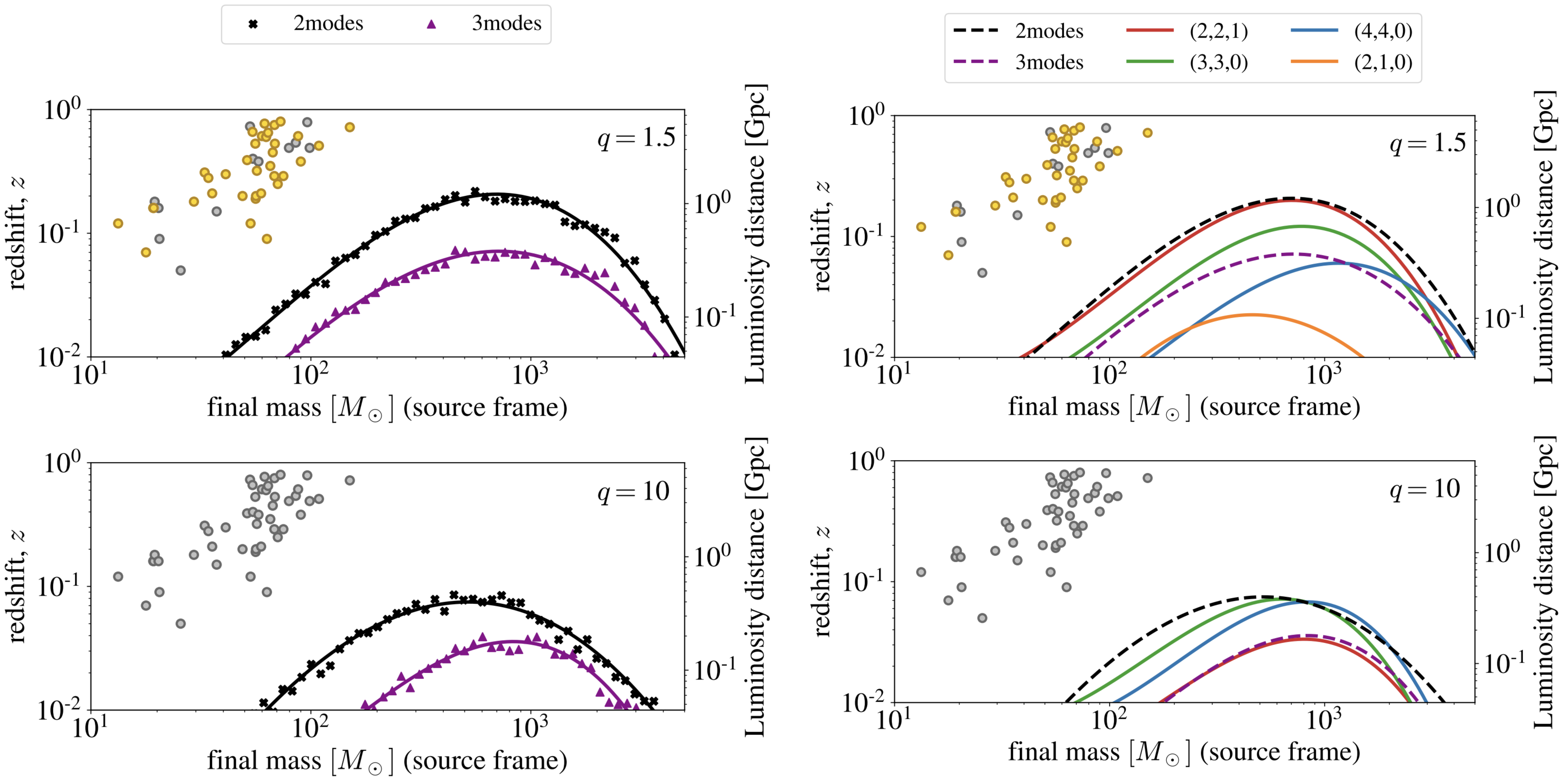
Signal: $s = \psi_{220} + \psi_{221} + \psi_{330} + \psi_{440} + \psi_{210} + n$

Models:

1) one mode: $M_1 = \psi_{220}$

2) two modes: $M_2 = \psi_{220} + \psi_{\ell mn}$

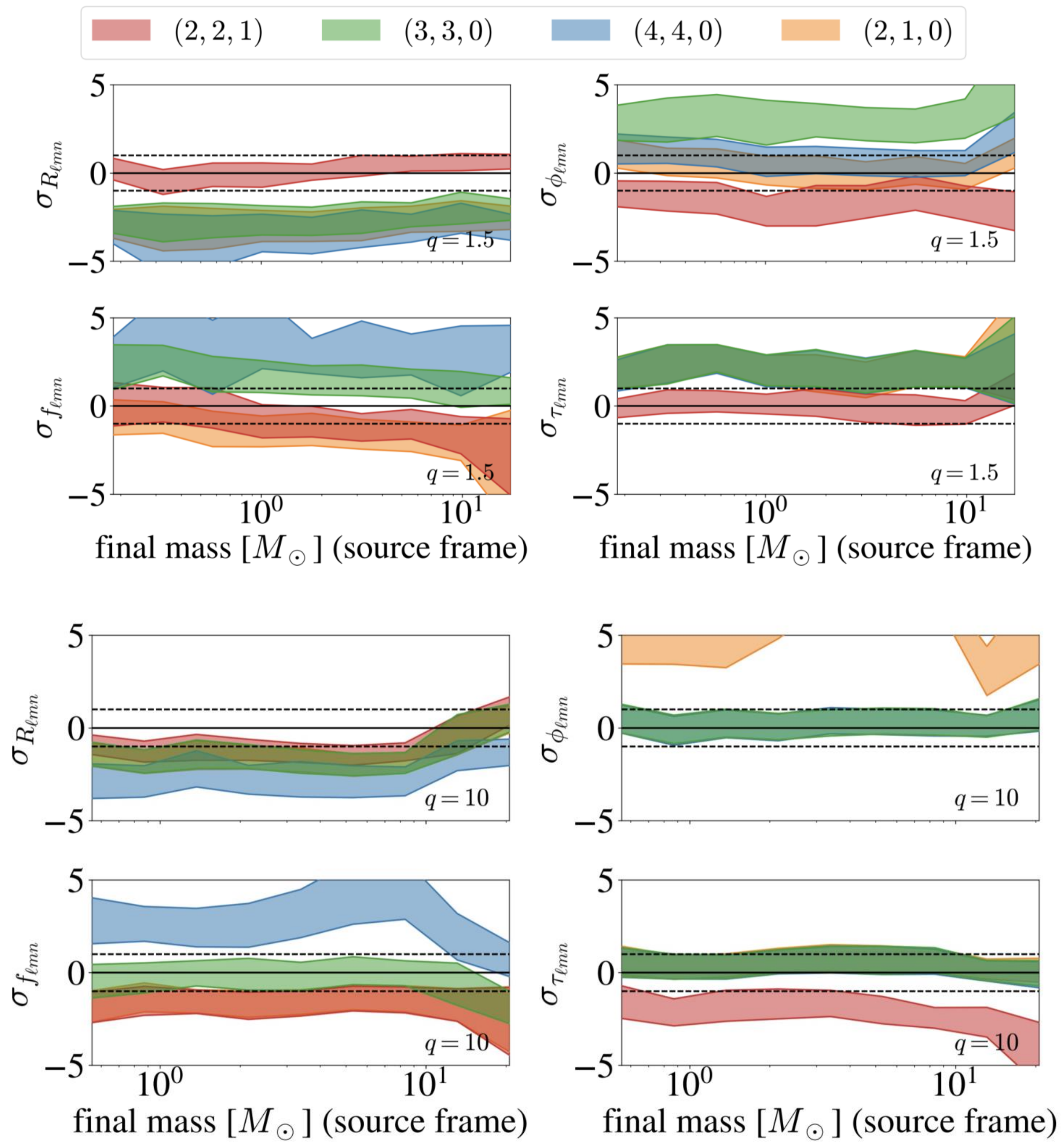
3) three modes: $M_3 = \psi_{220} + \psi_{\ell mn} + \psi_{\ell' m' n'}$



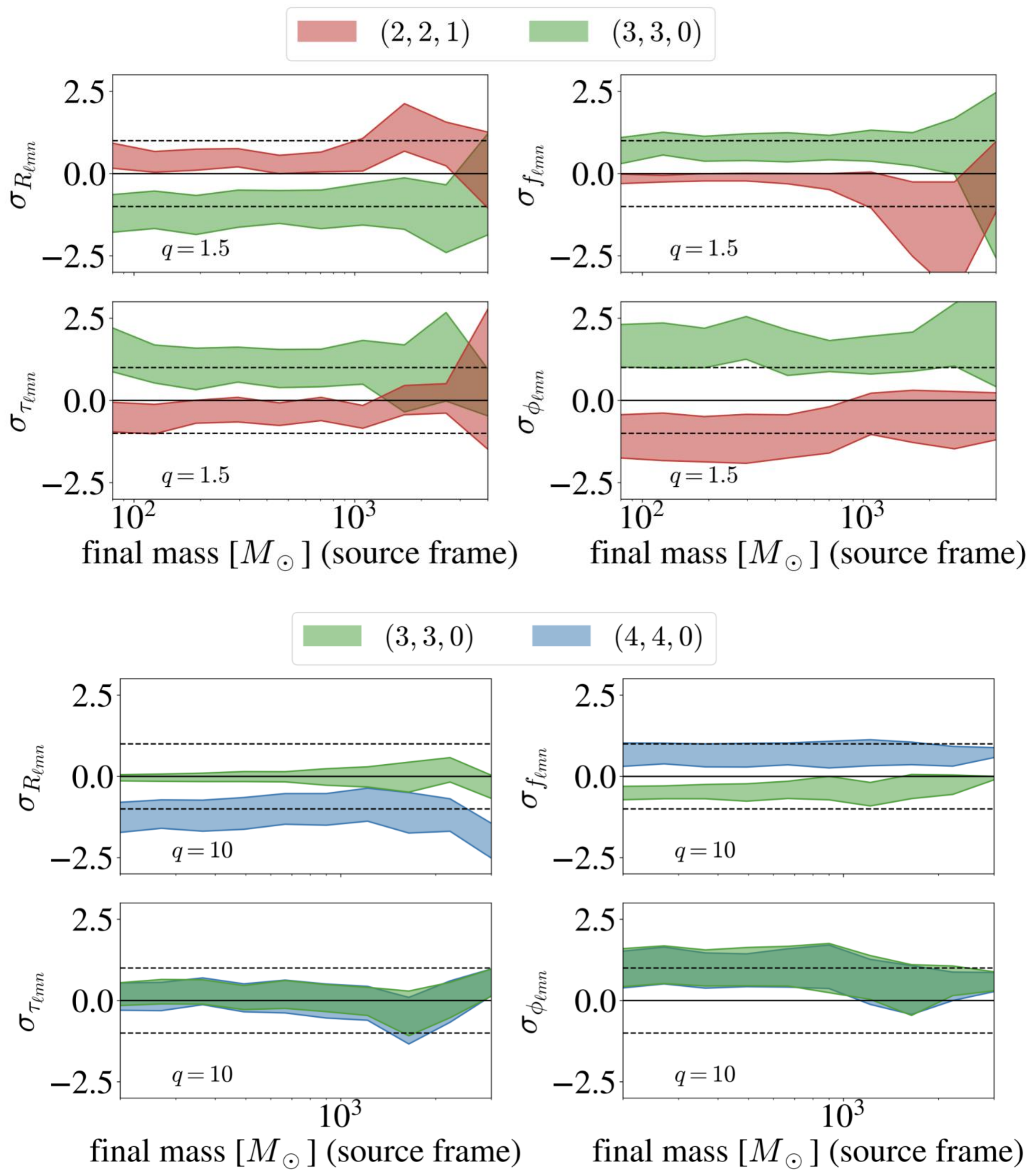
[Ota and Chirenti, in preparation]

PARAMETER ESTIMATION: MULTIMODE HORIZONS

TWO-MODES HORIZON



THREE-MODES HORIZON



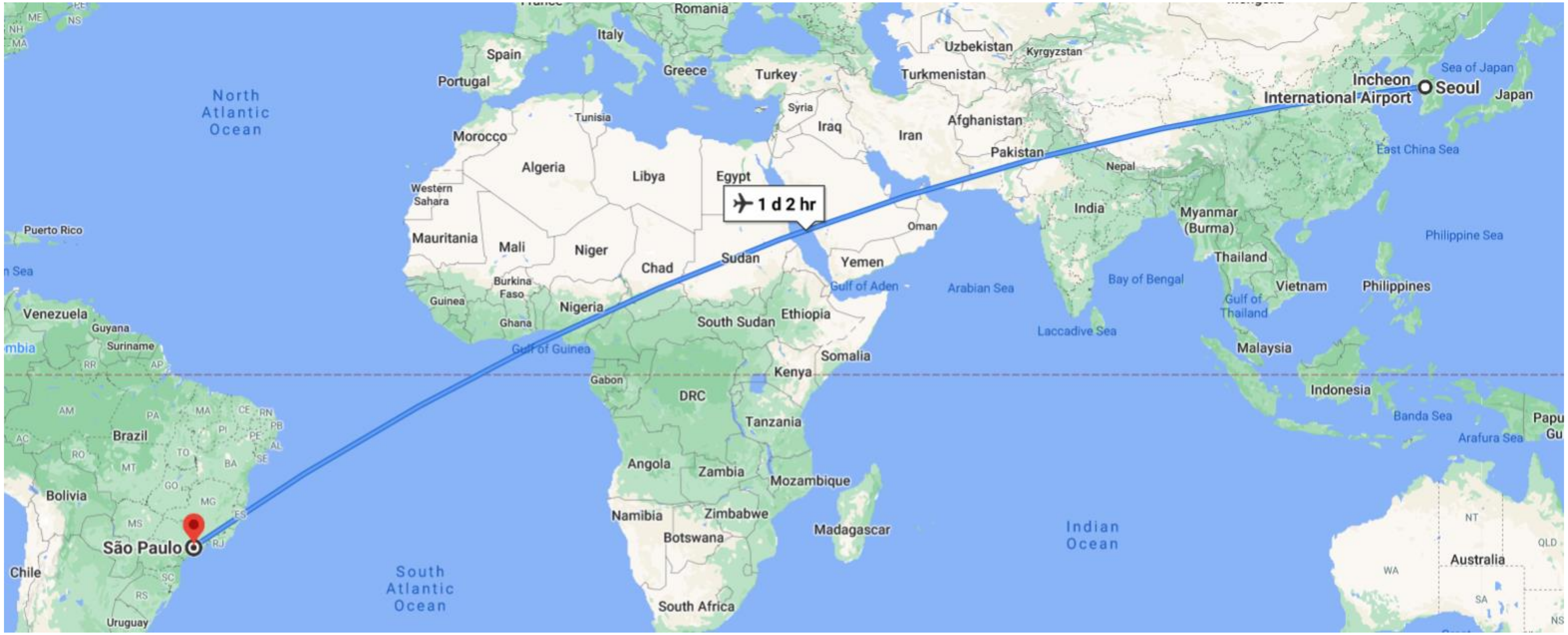
- For low mass ratios the overtone is the first mode detected followed by the (3,3,0) mode
- For high mass ratios it is easier to detect the (3,3,0) than the (4,4,0) mode

[Ota and Chirenti, in preparation]

FINAL REMARKS

- There are exciting prospects for testing the nature of black holes with gravitational waves!
- Black hole spectroscopy provides an independent test of the no-hair theorem using information contained in the ringdown of a binary black hole merger.
- The first overtone is favored for binaries with more symmetric masses ($q = 1$) and higher harmonics are favored for less symmetric masses ($q = 10$).
- Einstein Telescope and Cosmic Explorer will be sensitive enough to resolve events similar to the events detected so far.
- LISA black hole spectroscopy horizons are very big, but its sources are still uncertain.
- Closer sources will be needed to perform black hole spectroscopy with a single LIGO. Multiple detections analysis and mode stacking may compensate the low sensitivity.

QUESTIONS AT THE SLACK CHANNEL



[google.com/maps]