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BLACK HOLE SPECTROSCOPY: PROSPECTS FOR TESTING THE NATURE OF BLACK HOLES WITH GRAVITATIONAL WAVE OBSERVATIONS

arXiv:2208.07980

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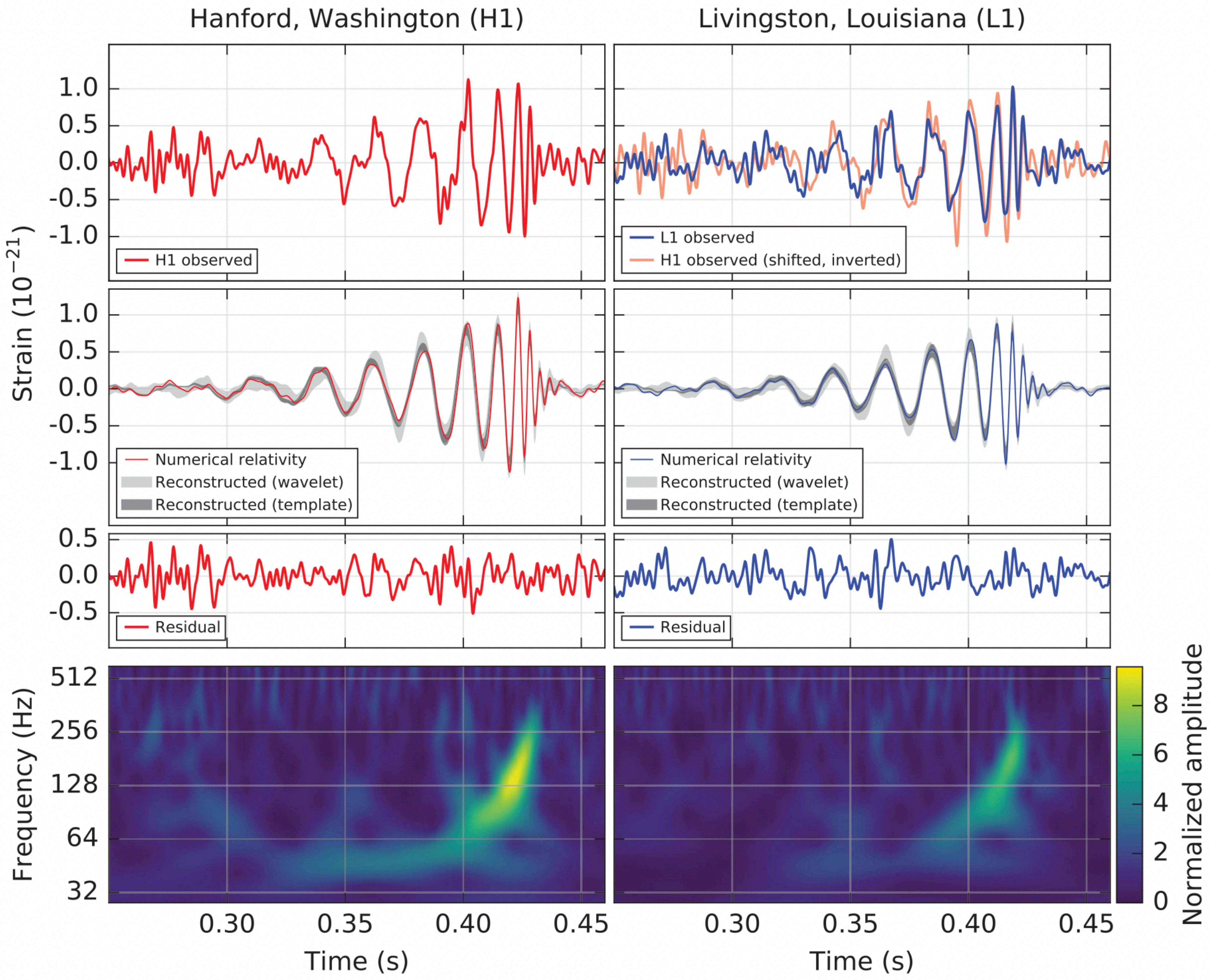
14 SEPTEMBER 2015 – FIRST DIRECT DETECTION OF GRAVITATIONAL WAVES

- Gravitational waves are ripples of spacetime
- Nobel Prizes in Physics:
  - 1993: Hulse and Taylor
  - 2017: Weiss, Thorne and Barish
- GW observation: new window to the universe!



[Abbott et al., 2016]

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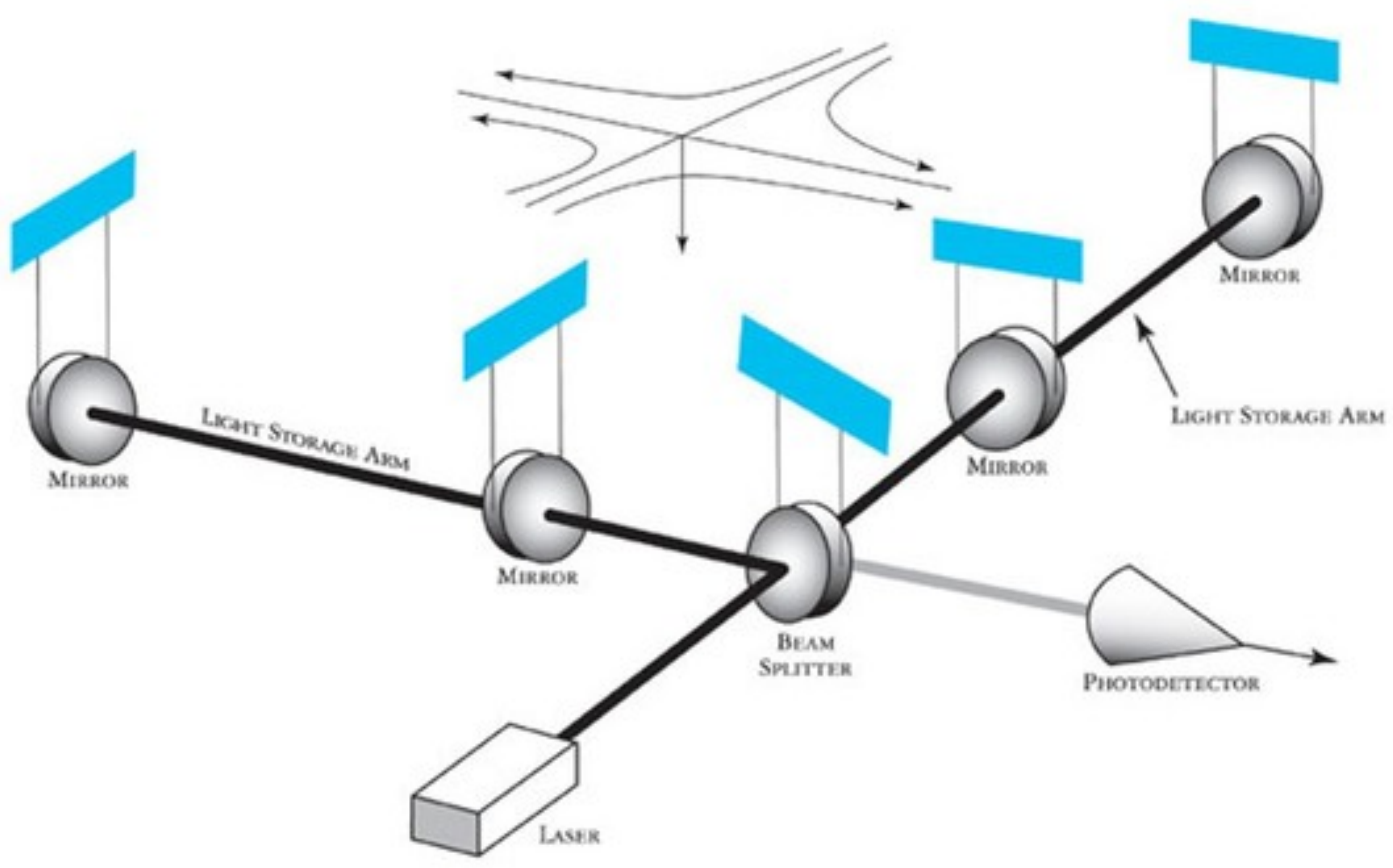
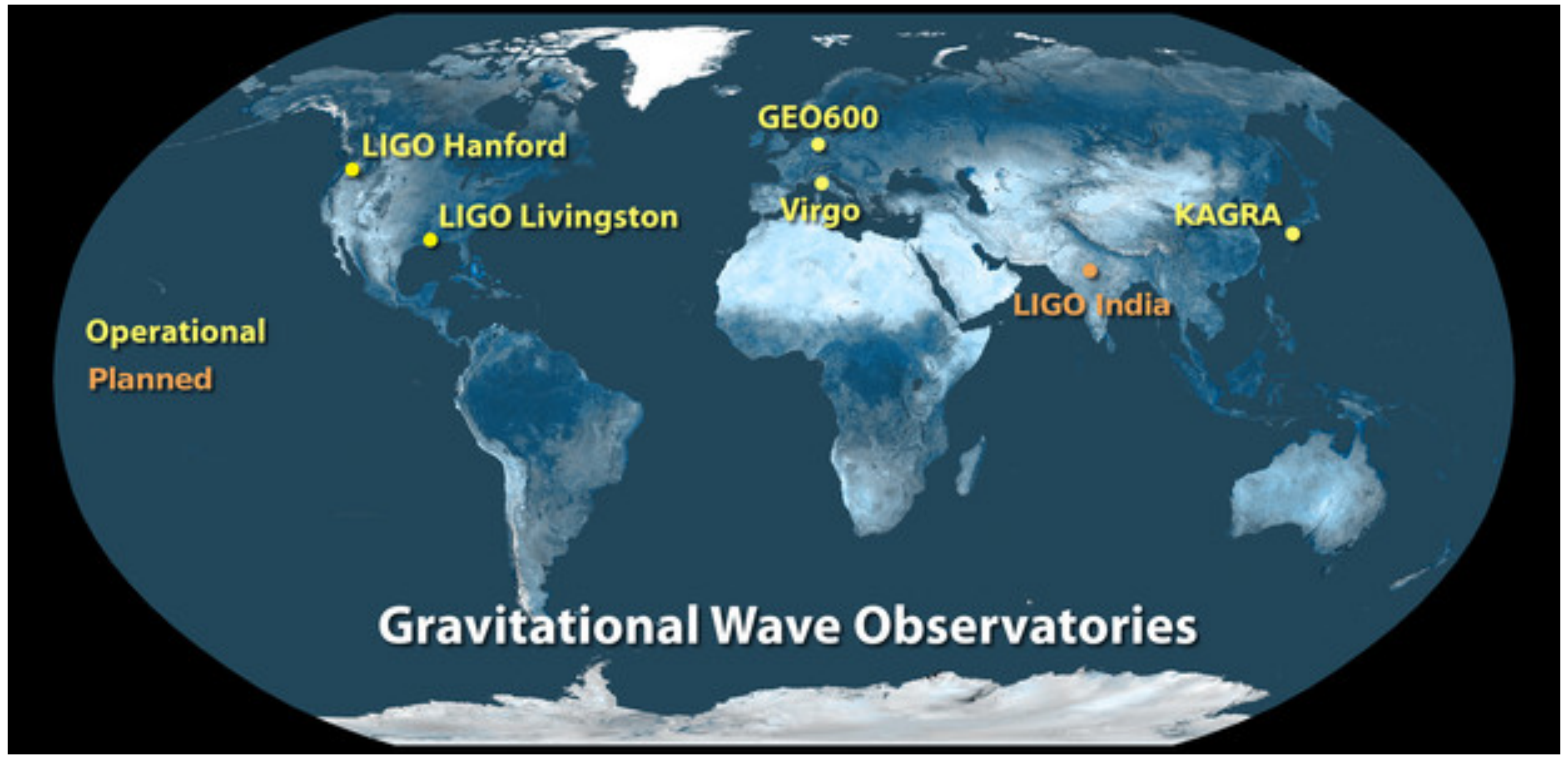
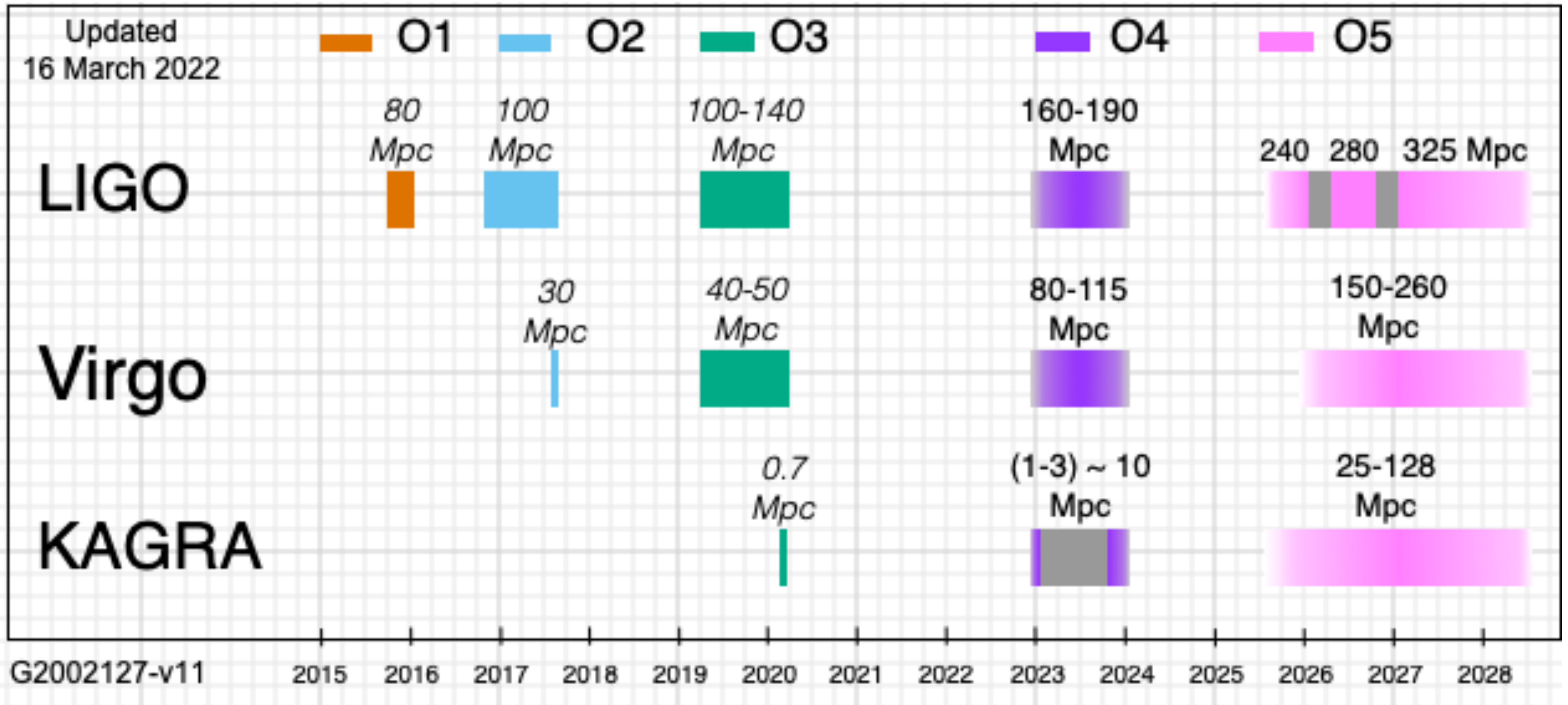
GRAVITATIONAL WAVE DETECTORS



[ligo.caltech.edu]





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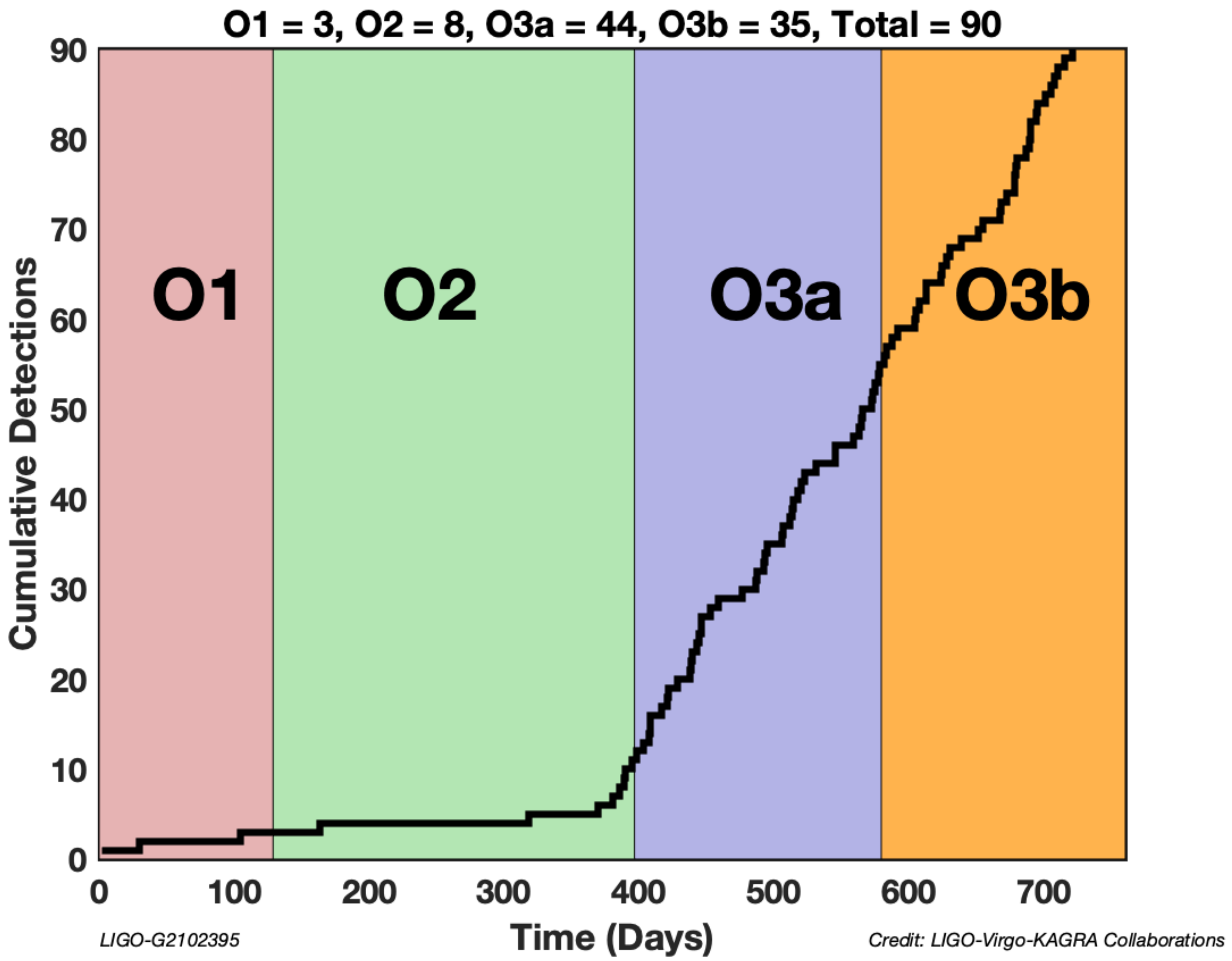
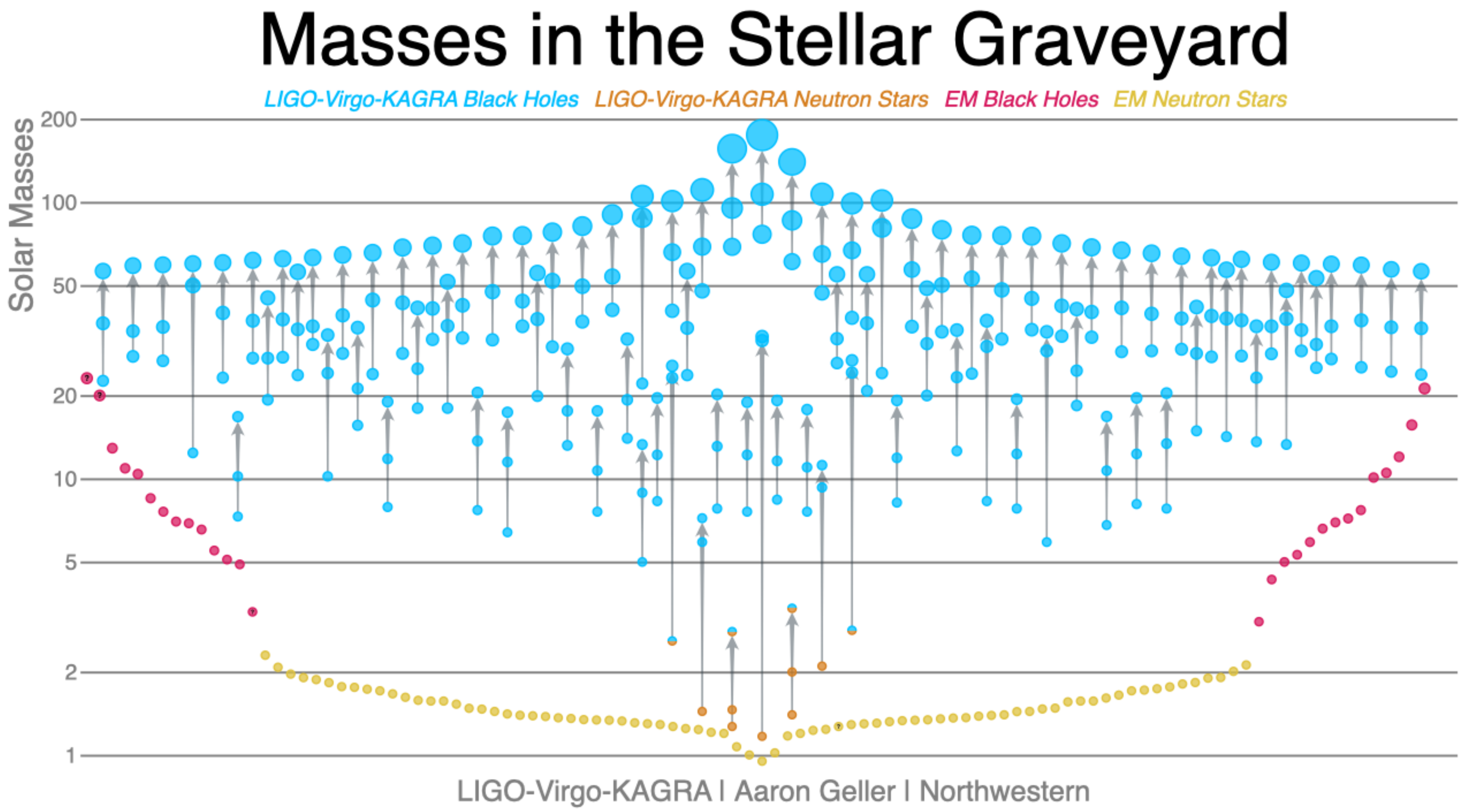
LIGO-VIRGO-KAGRA DETECTIONS

- 83 BBH + 5 NSBH or BBH
- 2 BNS





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BINARY BLACK HOLE MERGER

- 3 stages: inspiral, merger and ringdown
- Ringdown is well approximated by *quasinormal modes*

GW150914 [Abbott et al., 2016]

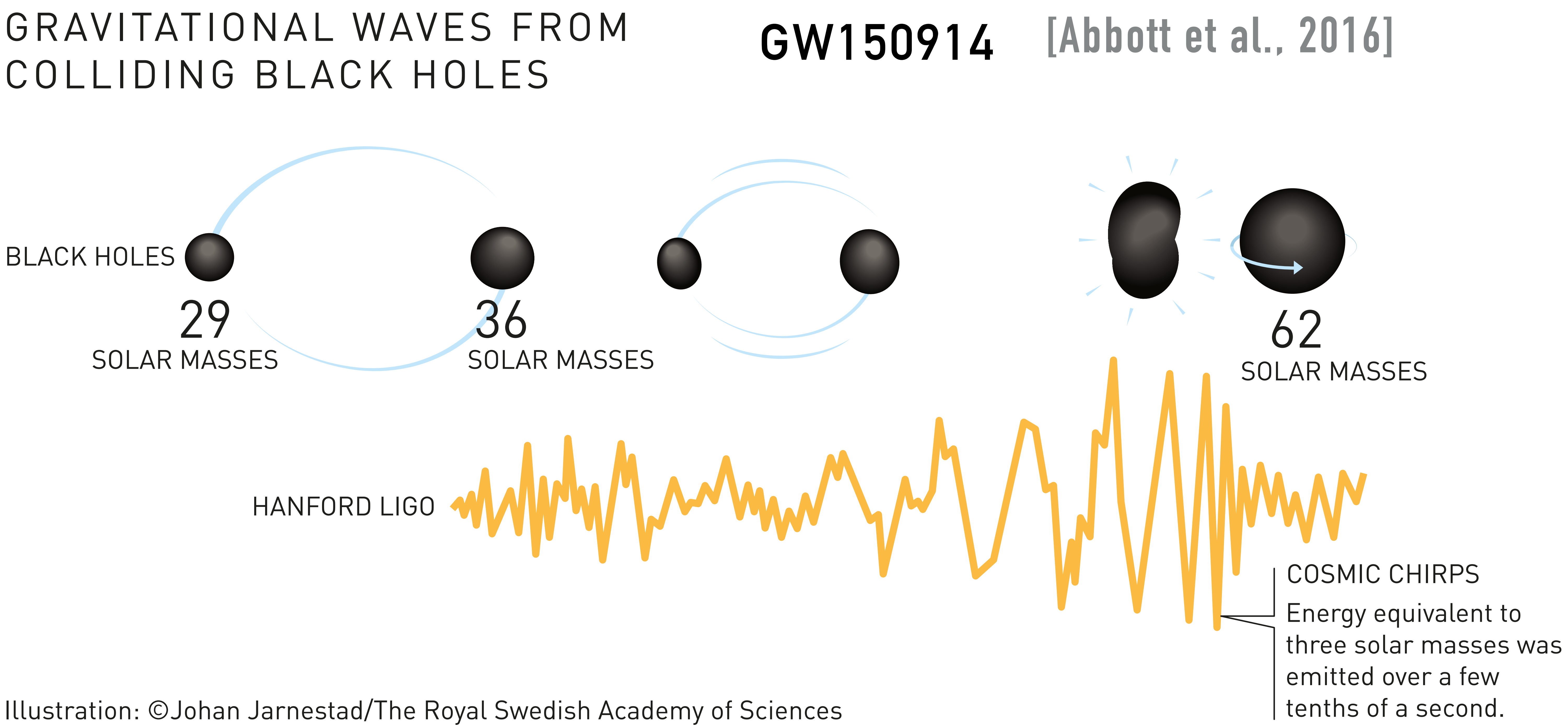
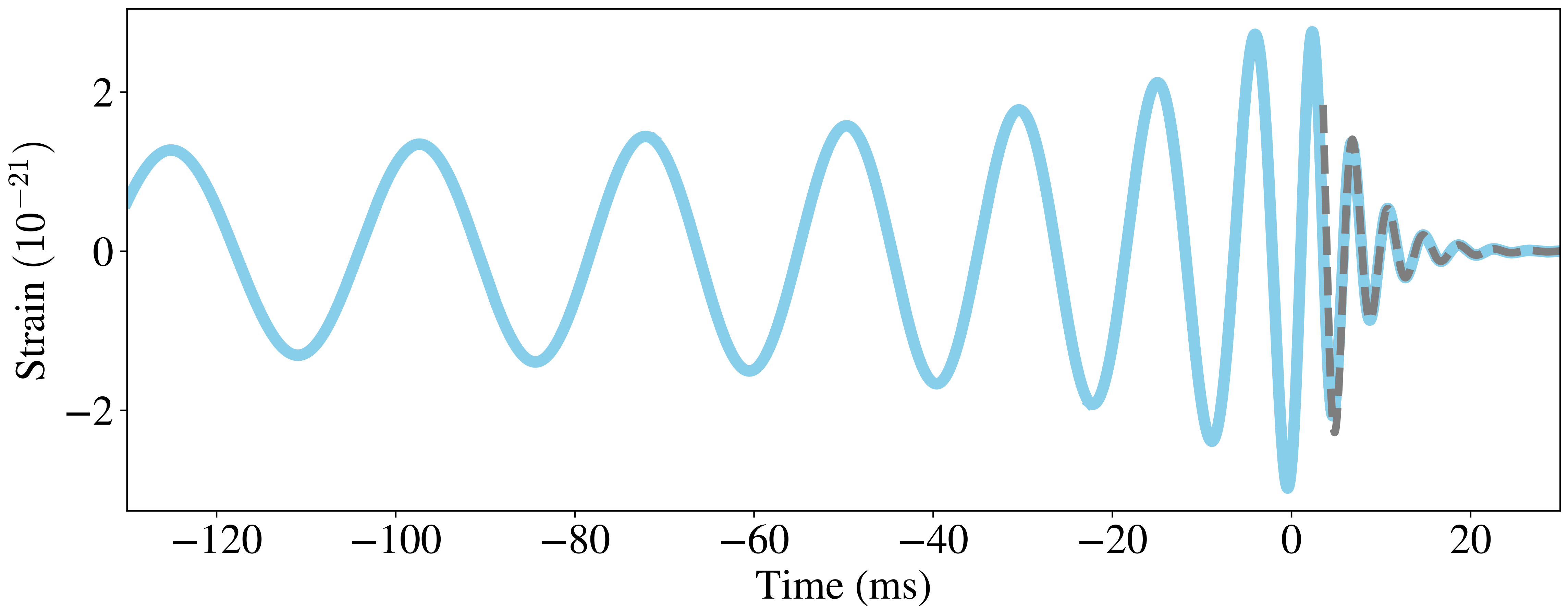
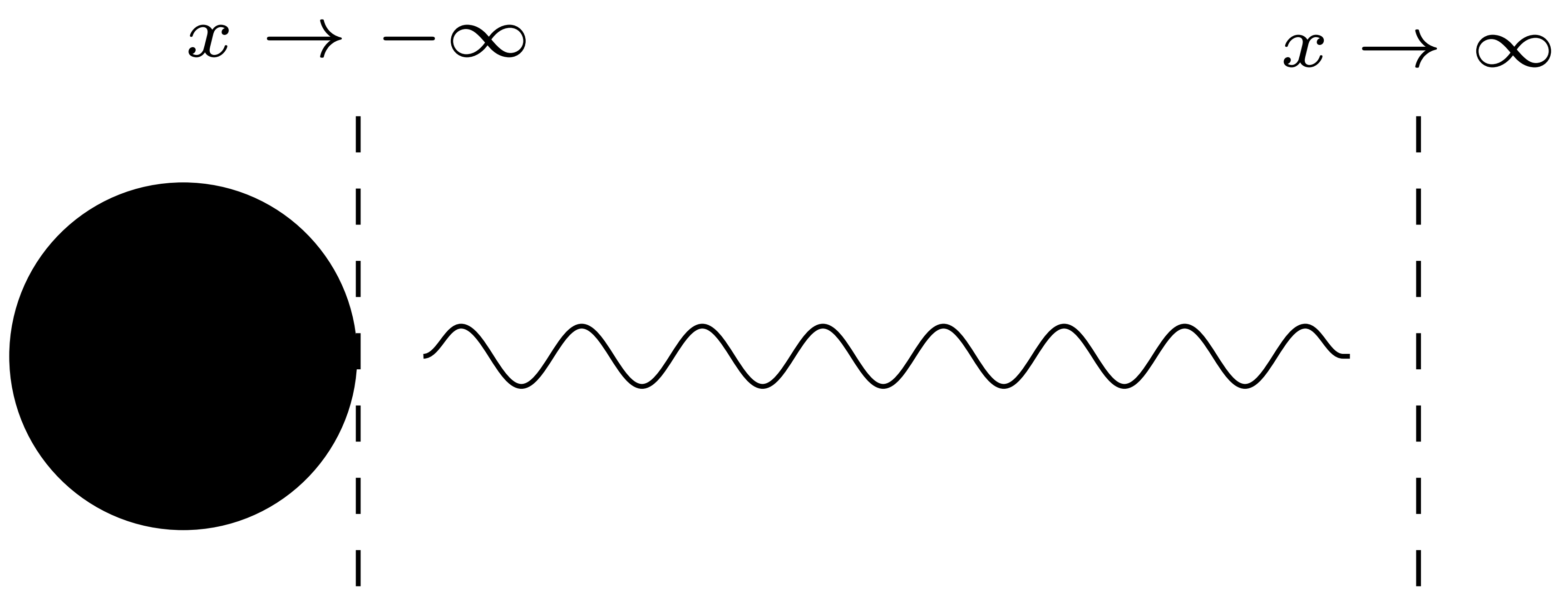


Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences



QUASINORMAL MODE



open system

outgoing at infinity

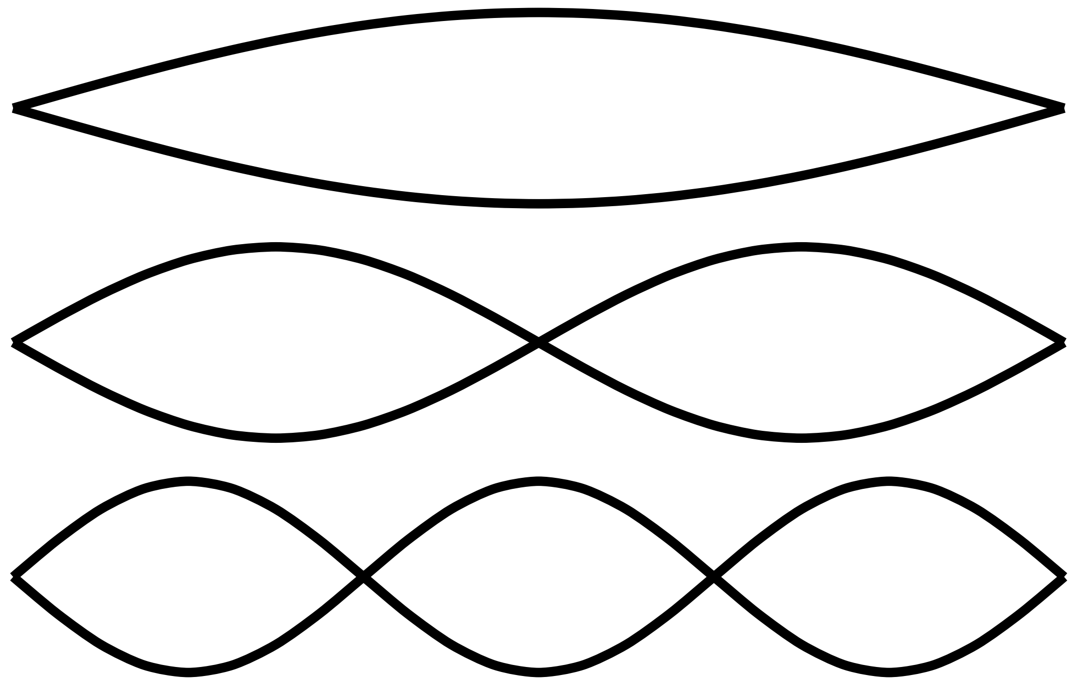
ingoing at the event horizon

[Kokkotas and Schmidt, 1999]
[Nollert, 1999]
[Berti et al., 2009]
[Konoplya and Zhidenko, 2011]

$$h = \sum h_{\ell mn}$$

$$h_{\ell mn} \propto e^{i\omega_{\ell mn} t}$$

NORMAL MODE



closed system

vanishes at boundary

complex frequency $\rightarrow$ damped oscillation

real frequency $\rightarrow$ constant oscillation

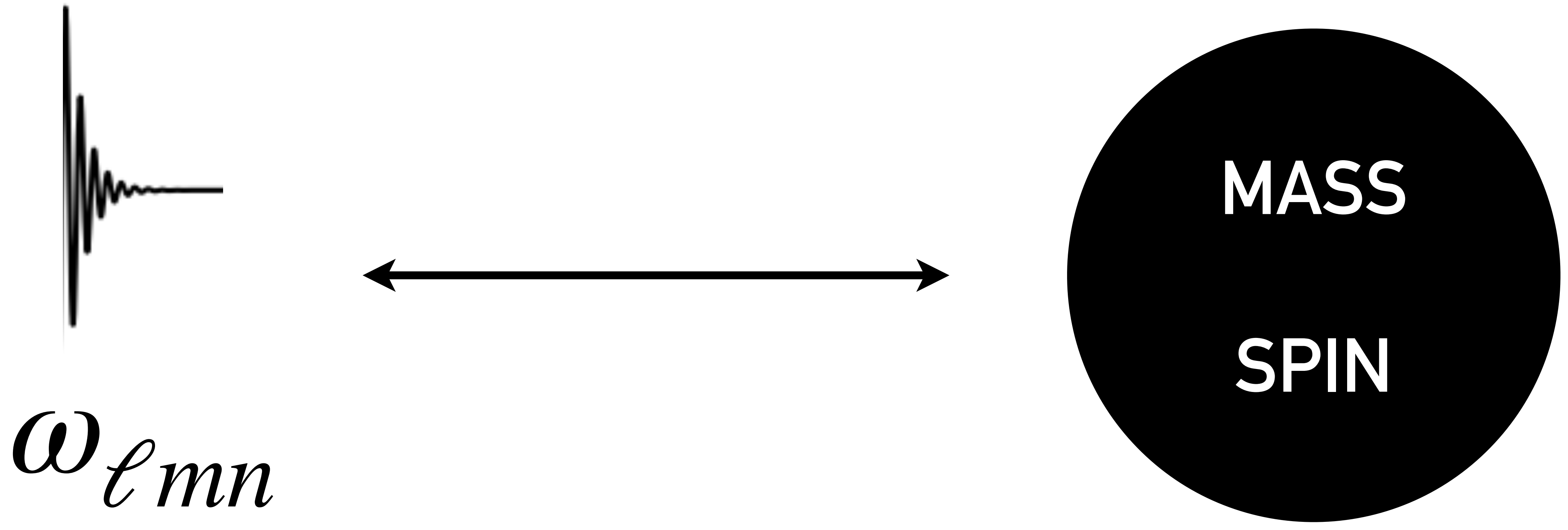
THE NO-HAIR THEOREM

- *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:

$$h = \sum h_{\ell mn} = \sum A_{\ell mn} e^{i\omega_{\ell mn}(t-t_i)+\phi_{\ell mn}} {}_{-2}S_{\ell m}(a\omega_{\ell mn})$$

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



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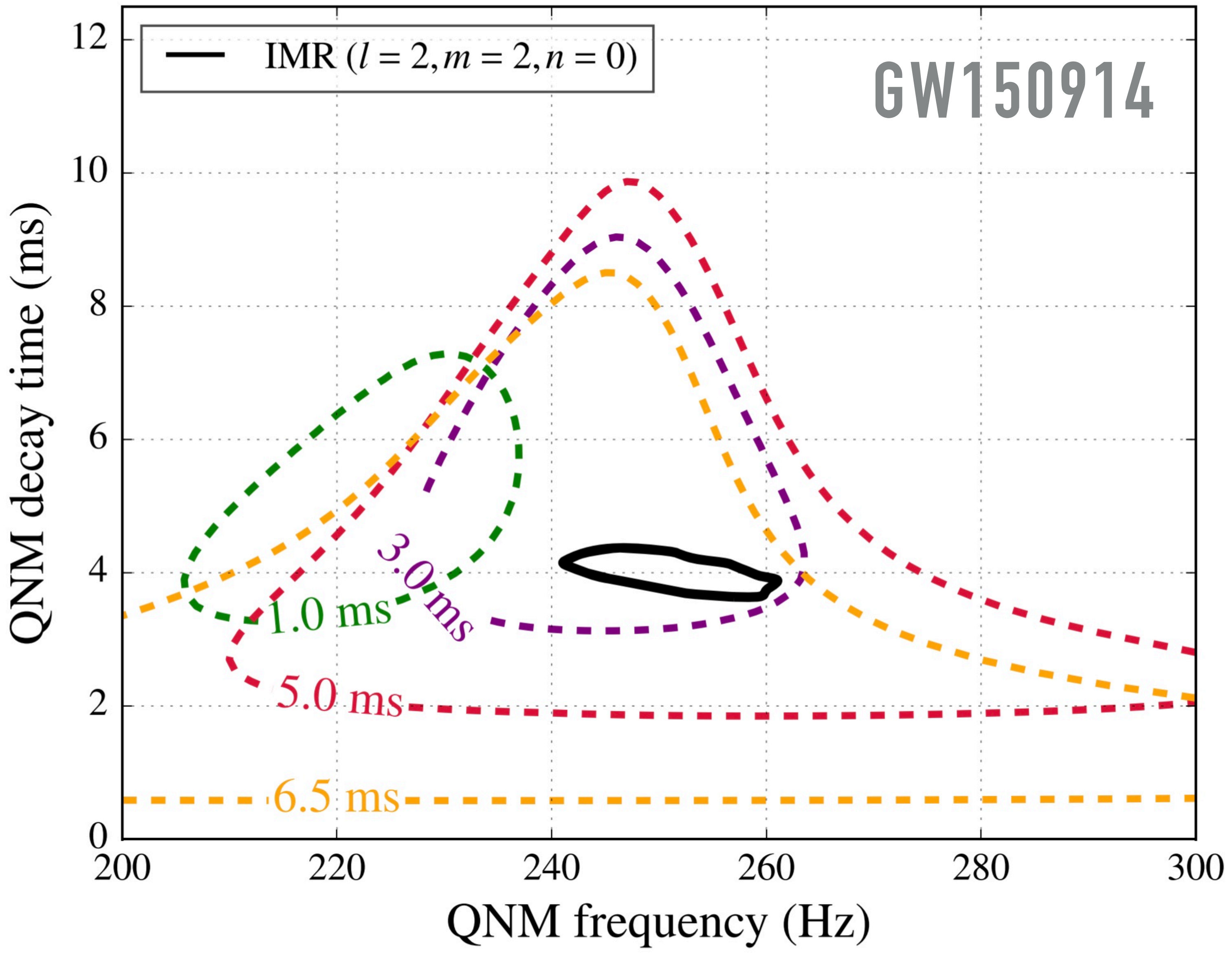
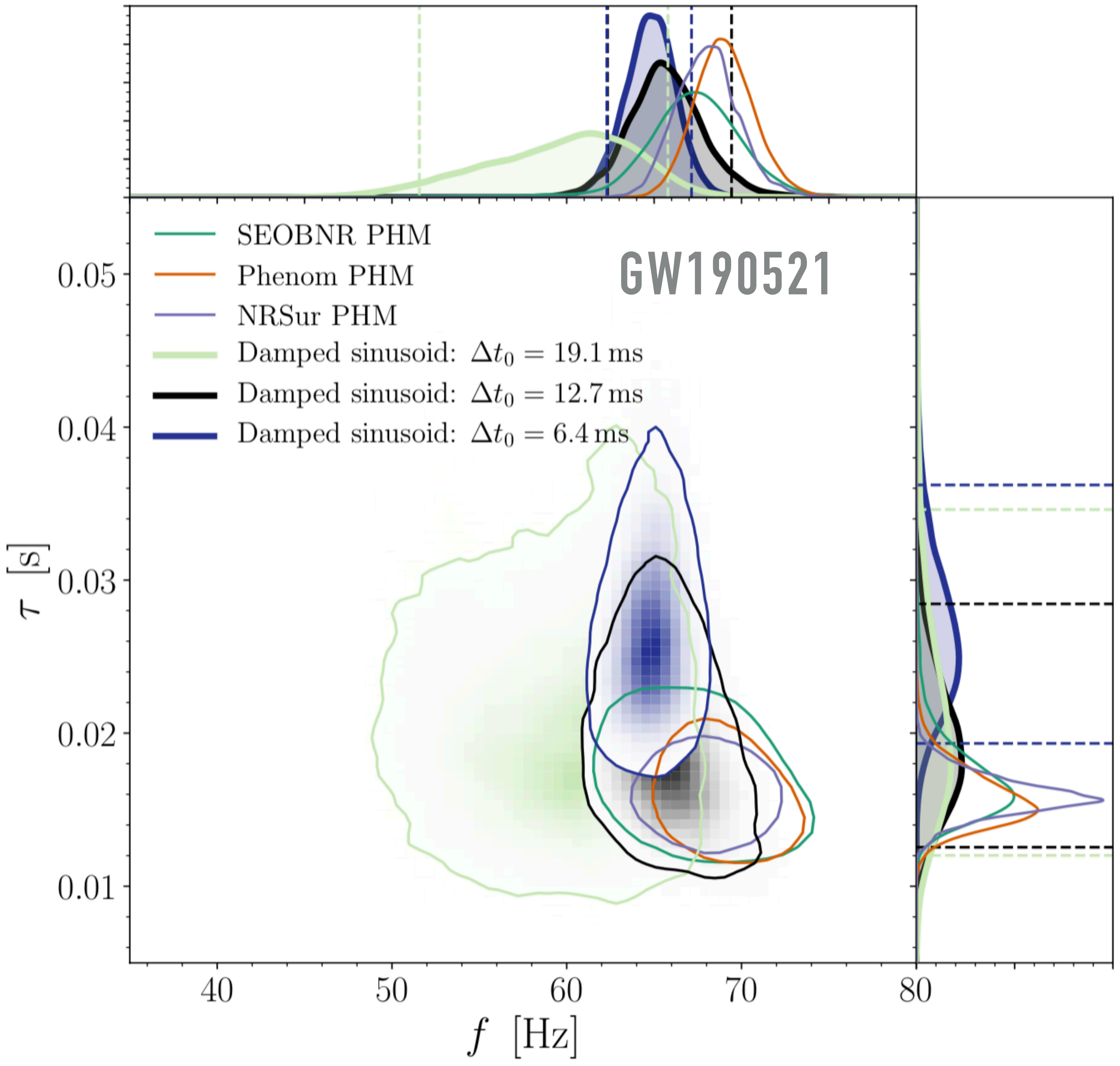
DETECTION OF QUASINORMAL MODE

- 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



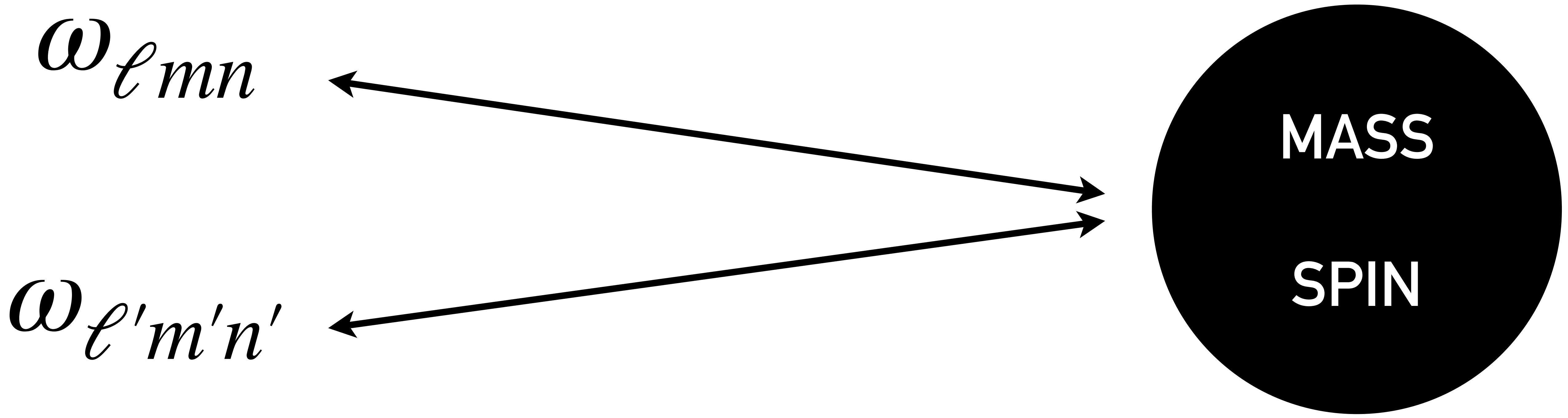
[Abbott et al., 2020]

BLACK HOLE SPECTROSCOPY

[Dreyer et al., 2004] [Berti et al., 2006] [Berti et al., 2007] [Kamaretsos et al., 2012] [Berti et al., 2016] [Thrane et al., 2017] [Baibhav et al., 2018]

- Detection of two 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: $(\ell, m, n) = (2{,}2{,}0)$

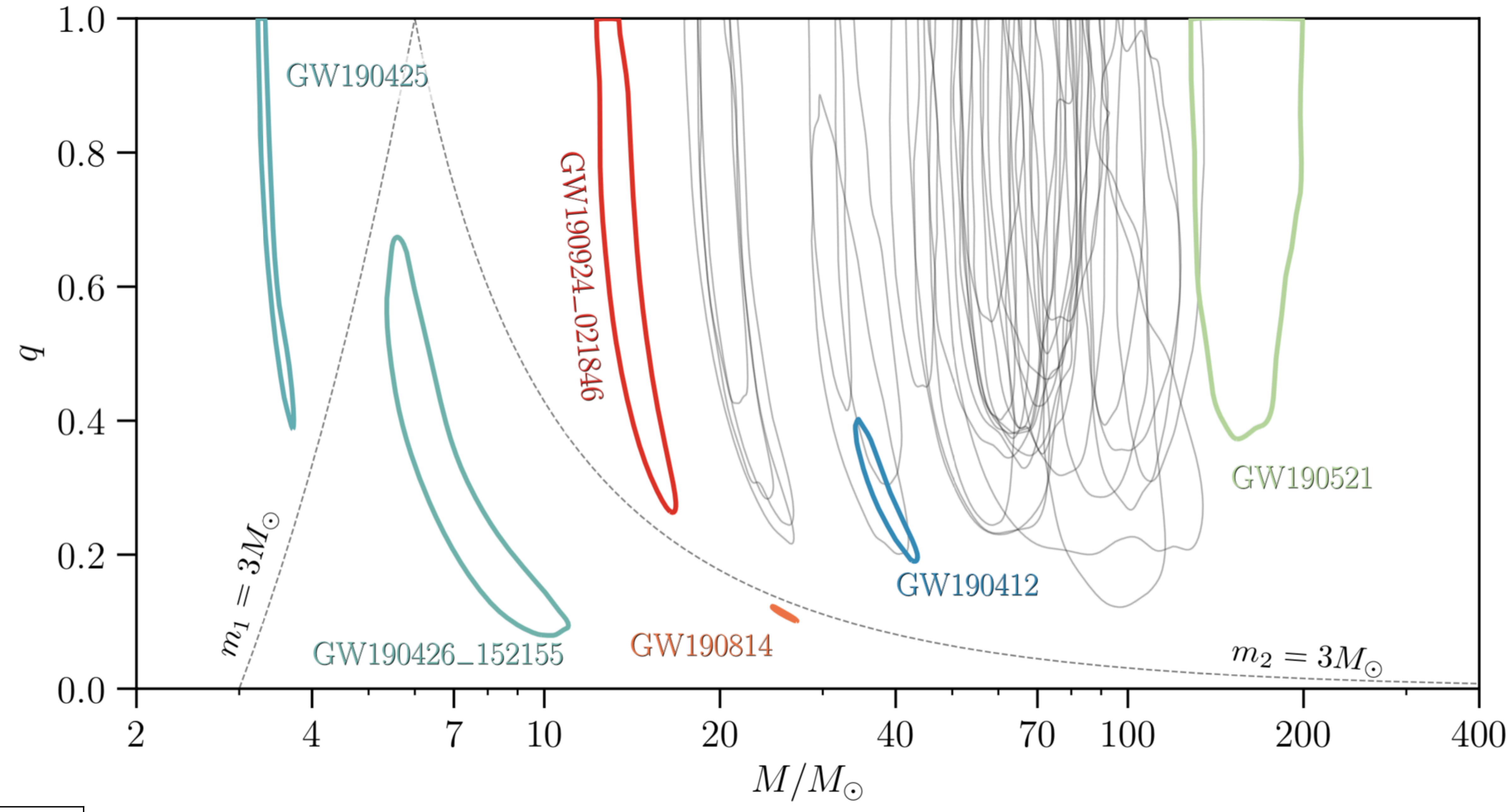
$$\omega_{\ell mn} \equiv 2\pi f_{\ell mn} + i/\tau_{\ell mn}$$



SUB-DOMINANT MODES

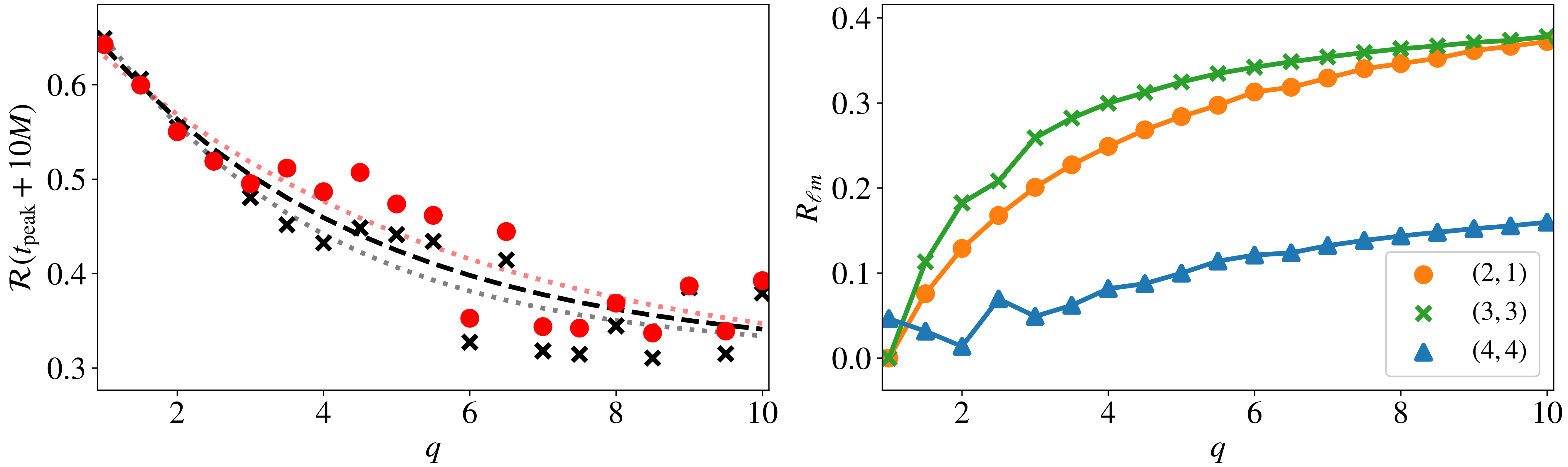
overtones
$(\ell, m, n) = (2,2,1)$
are more relevant for equal mass binaries

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



[Abbott et al., 2020]

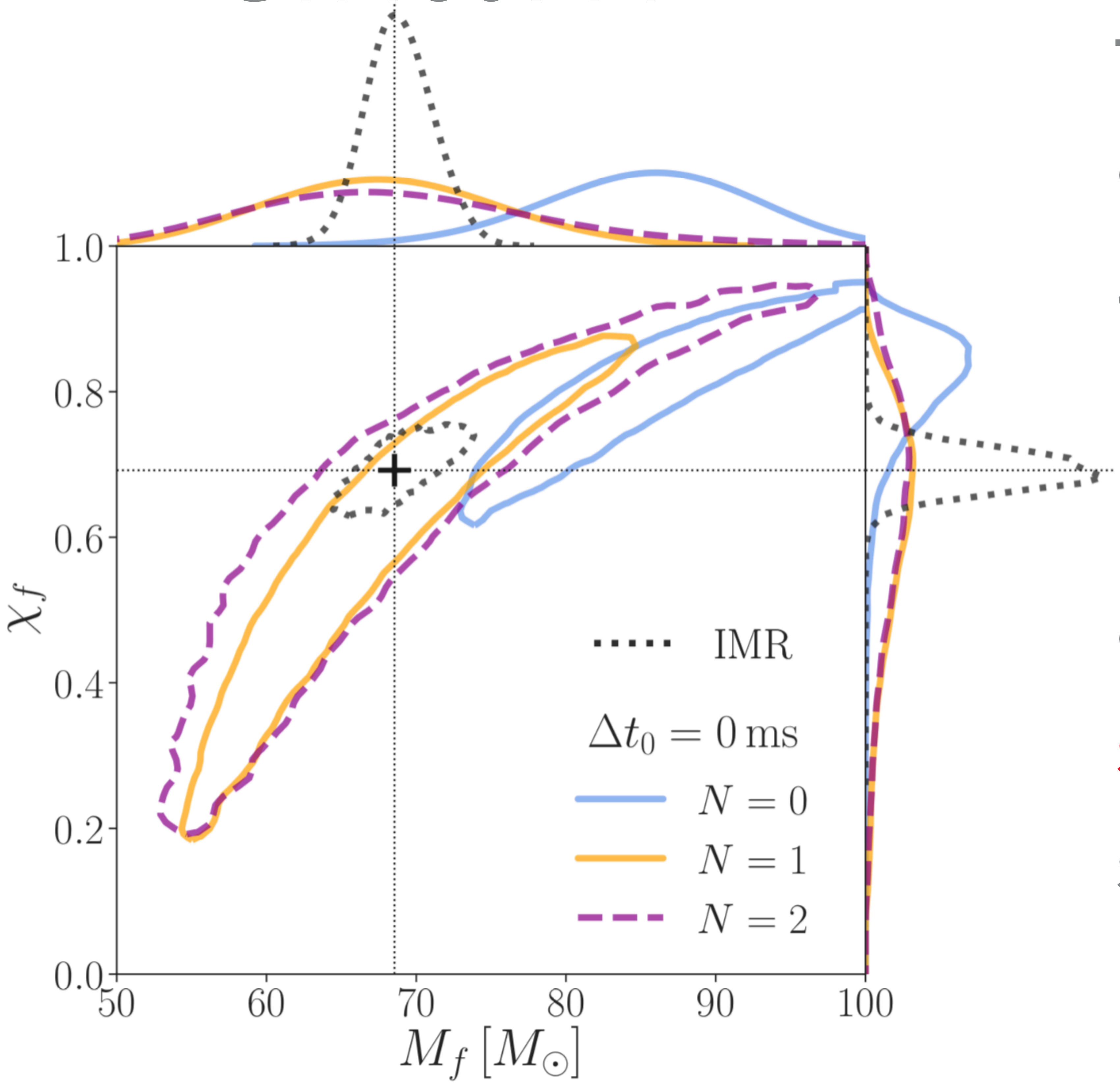
most LIGO sources are compatible with equal masses



[Ota and Chirenti, 2020]

SUB-DOMINANT MODES IN THE DATA

GW150914 $z \sim 0.09$

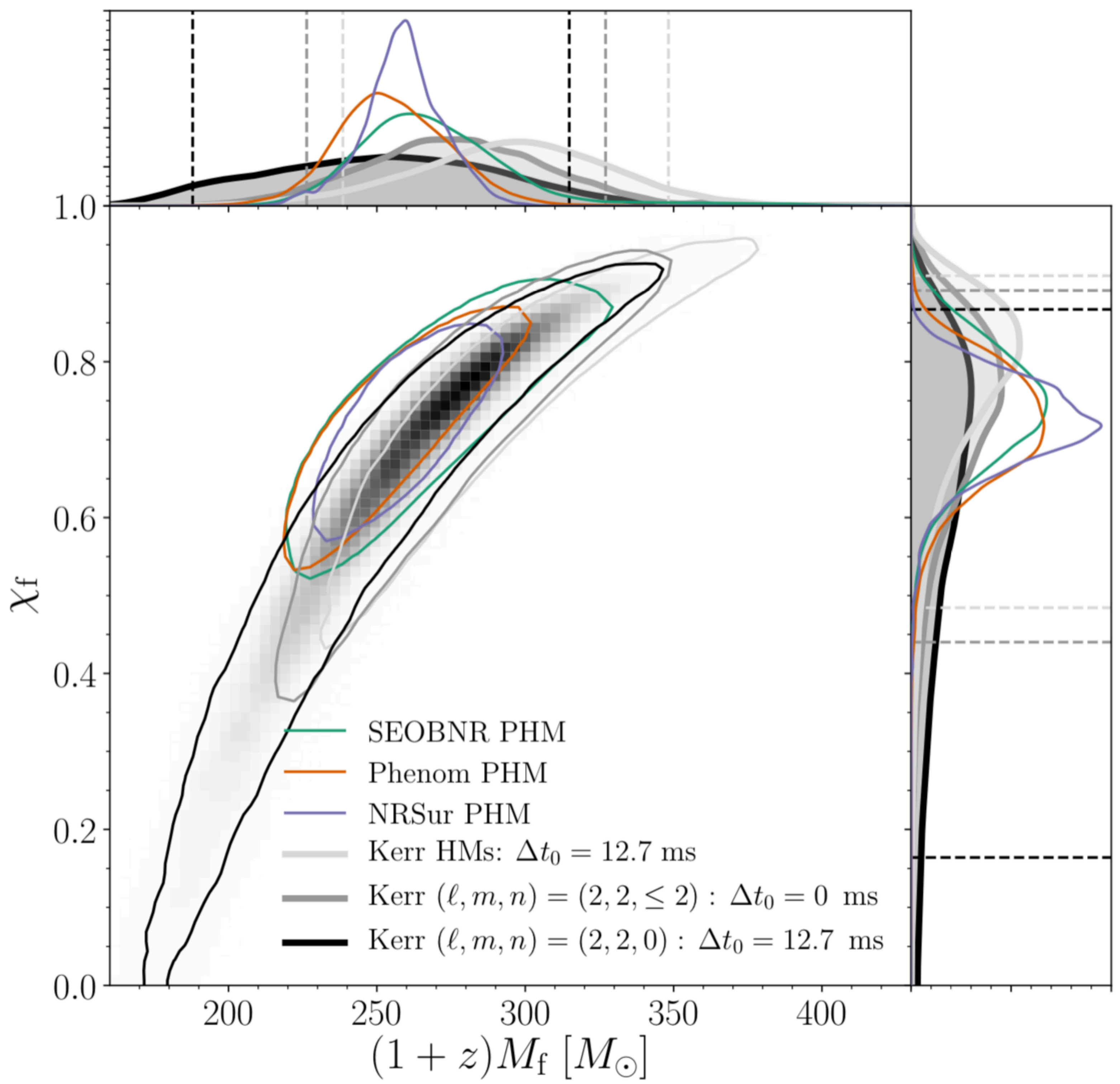


[Isi et al., 2019]

the inclusion of sub-dominant modes in the analyzes decreases the uncertainties for the mass and spin but the data does not provide strong evidence for a second mode

[Carullo et al., 2019]
[Bustillo et al., 2020]
[Isi et al., 2021]
[Capano et al., 2021]
[Cotesta et al., 2022]

GW190521 $z \sim 0.8$



[Abbott et al., 2019]

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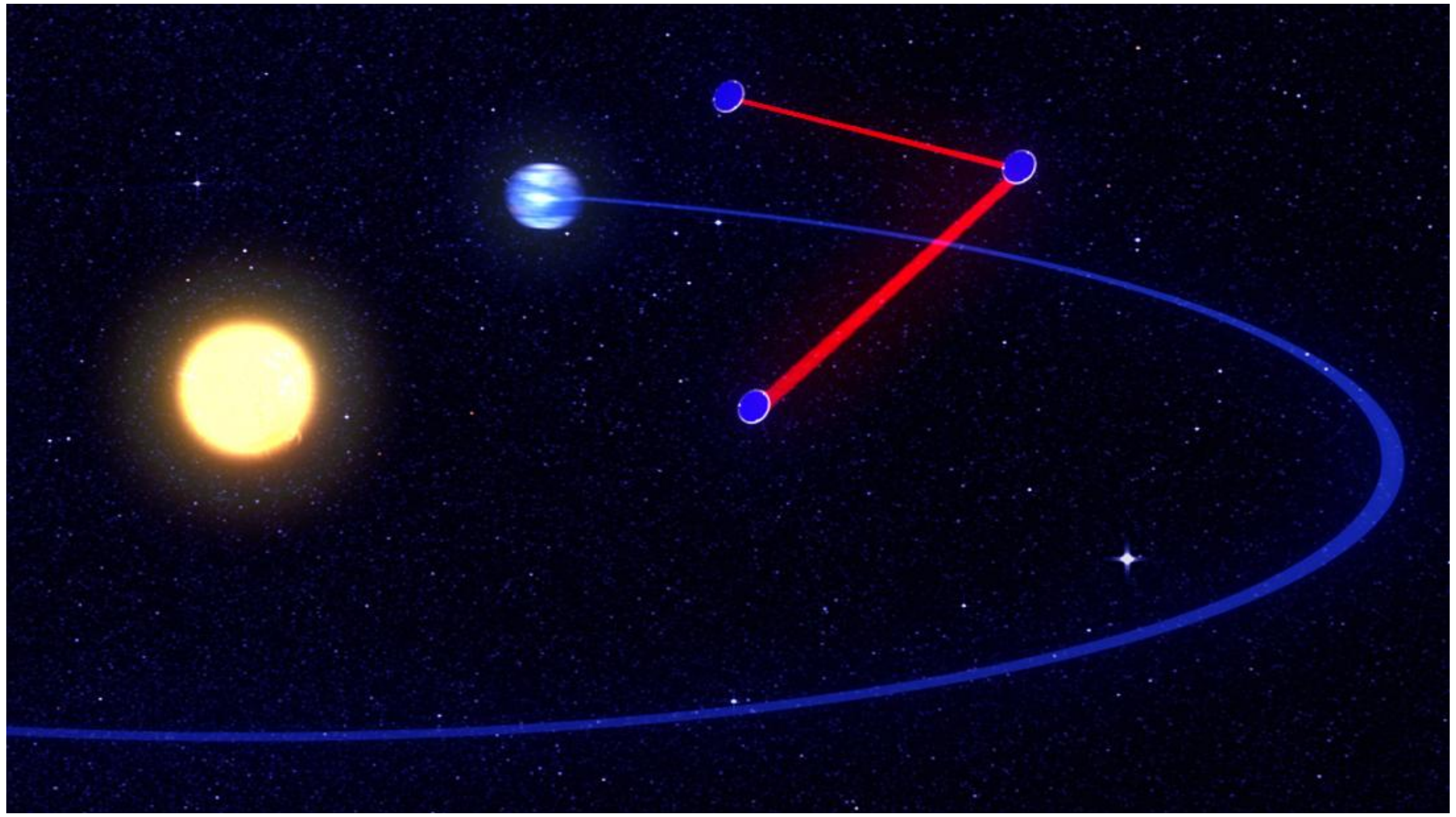
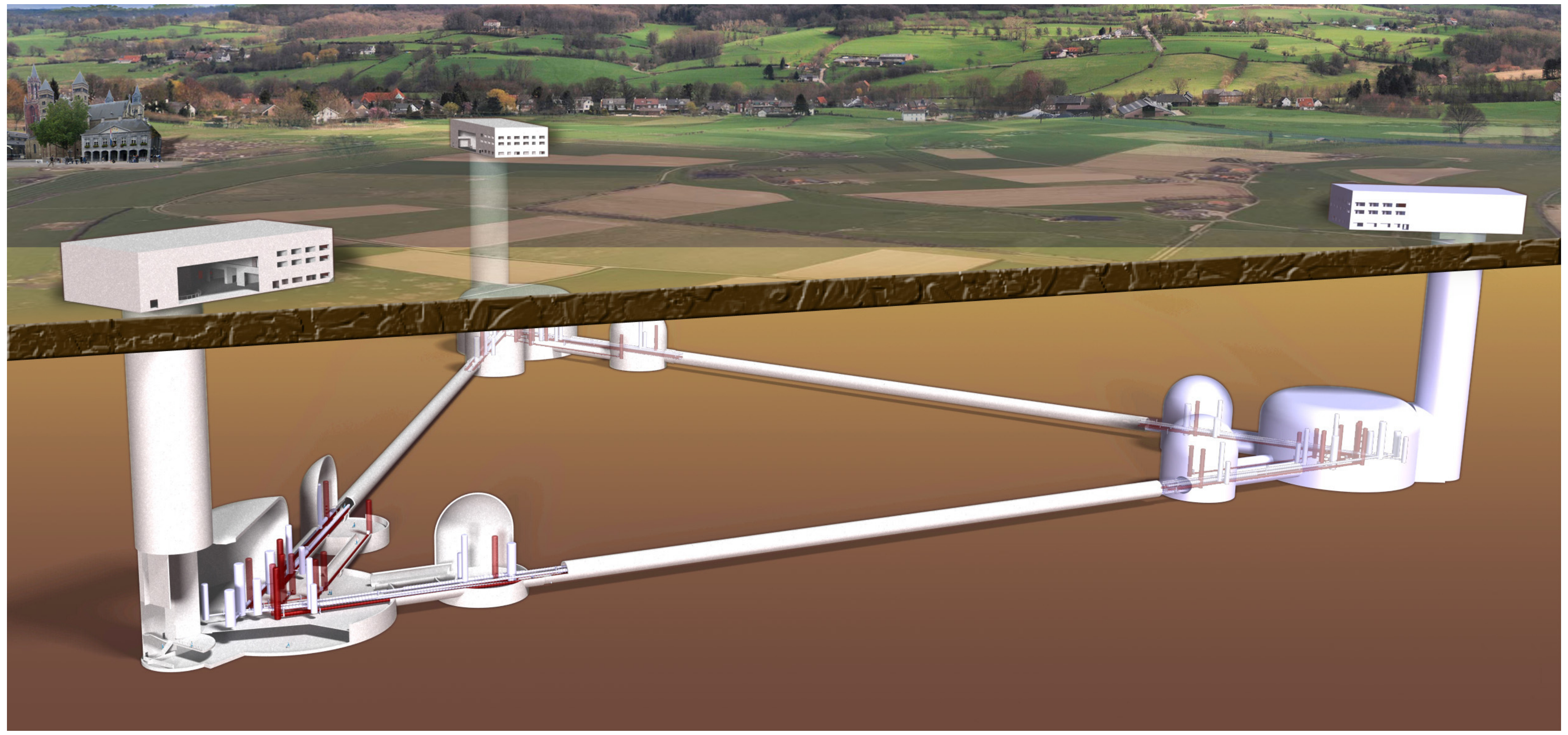
FUTURE DETECTORS

- Ground-based:
  - Einstein Telescope (ET)
  - Cosmic Explorer (CE)
  - Neutron Star Extreme Matter Observatory (NEMO)

[elisascience.org]





[et-gw.eu]

- Space-based:
  - Laser Interferometer Space Antenna (LISA)
  - TianQin

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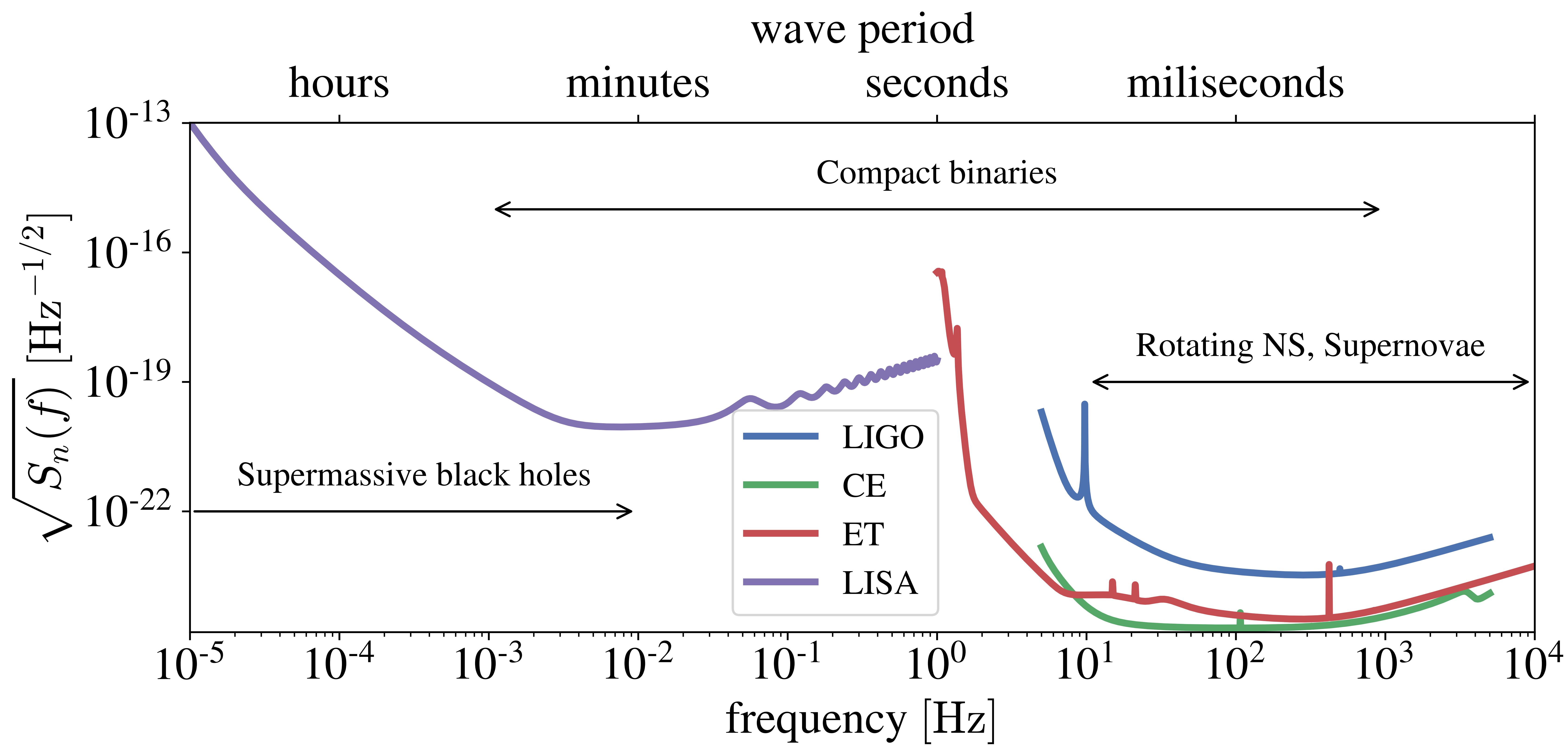
FUTURE DETECTORS

Amplitude spectral density



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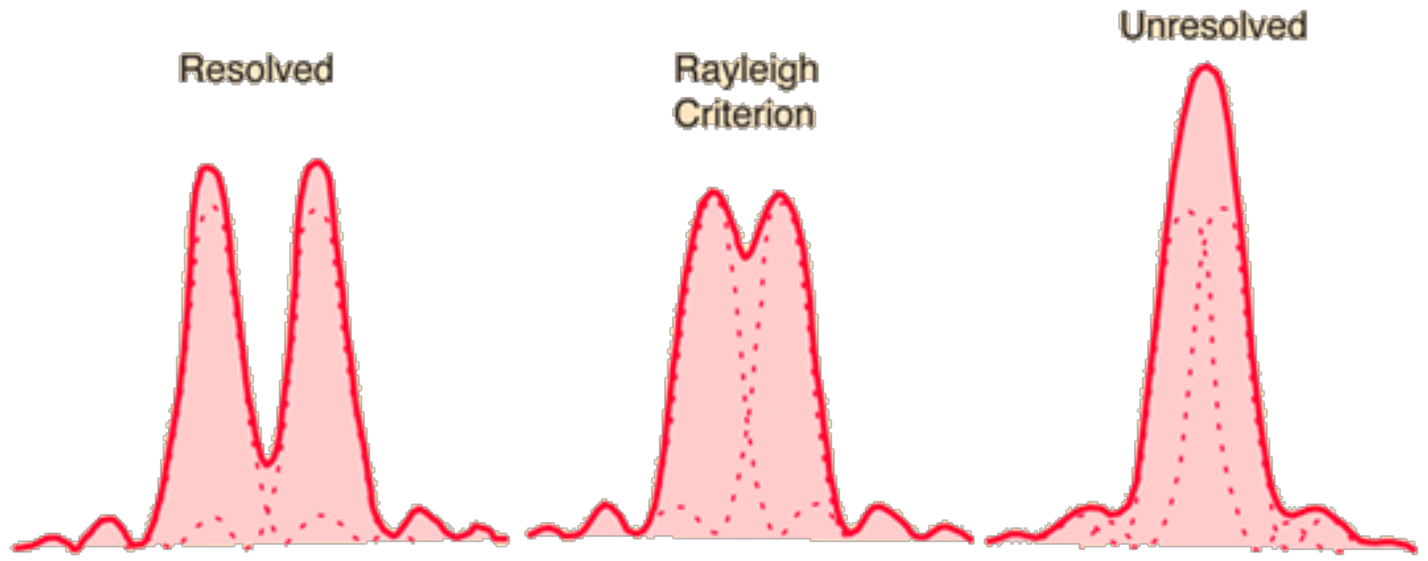
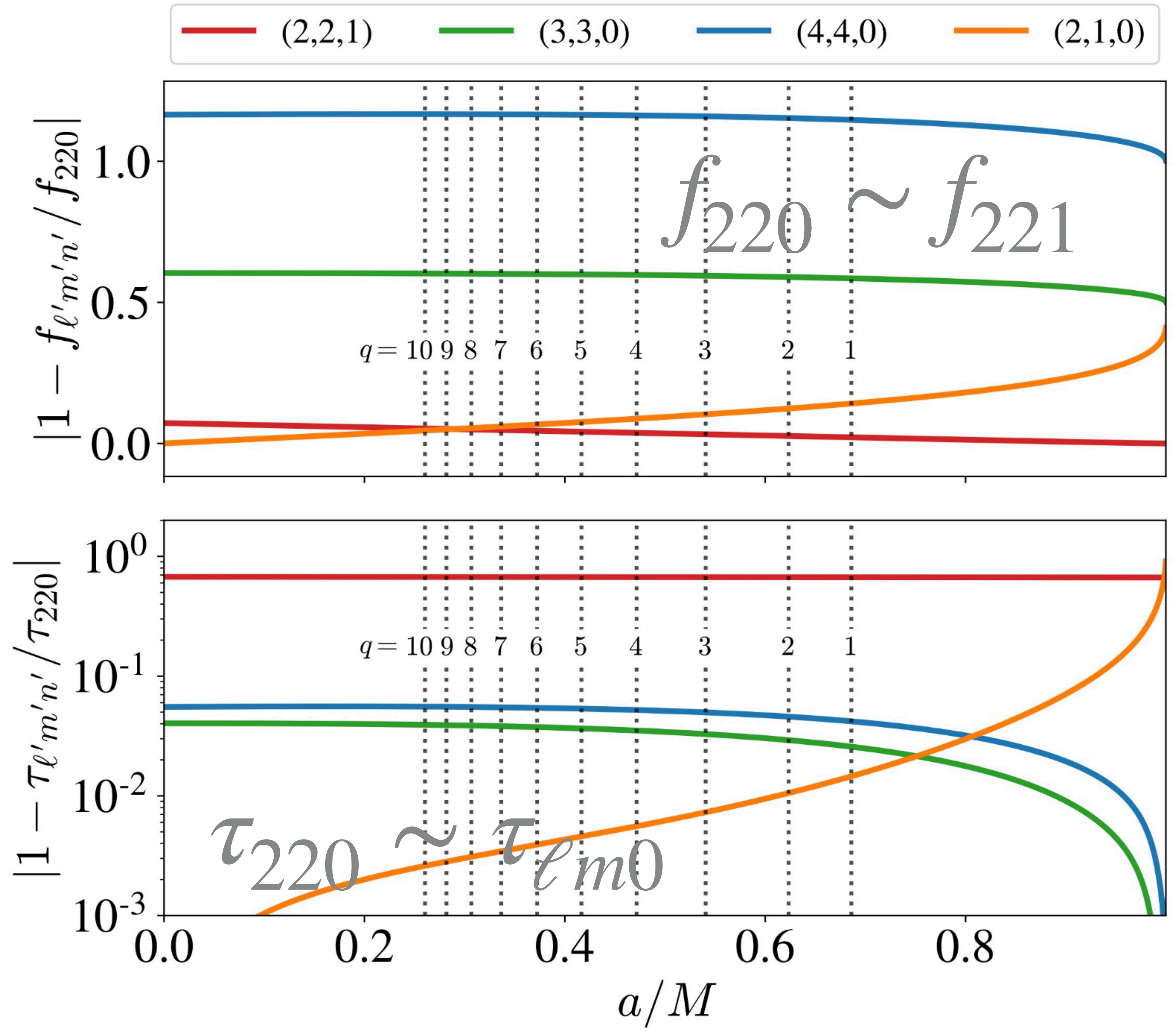
RESOLVABILITY: RAYLEIGH CRITERION



[hyperphysics.phy-astr.gsu.edu]

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



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

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

[Berti et al., 2006]

[Ota and Chirenti, 2022]

errors are computed using Fisher Matrix

BAYESIAN INFERENCE AND MODEL COMPARISON

Signal:

$$d_2 = h_{220} + h_{\ell mn} + n$$

QNMs injected in the signal have parameters informed by NR simulations

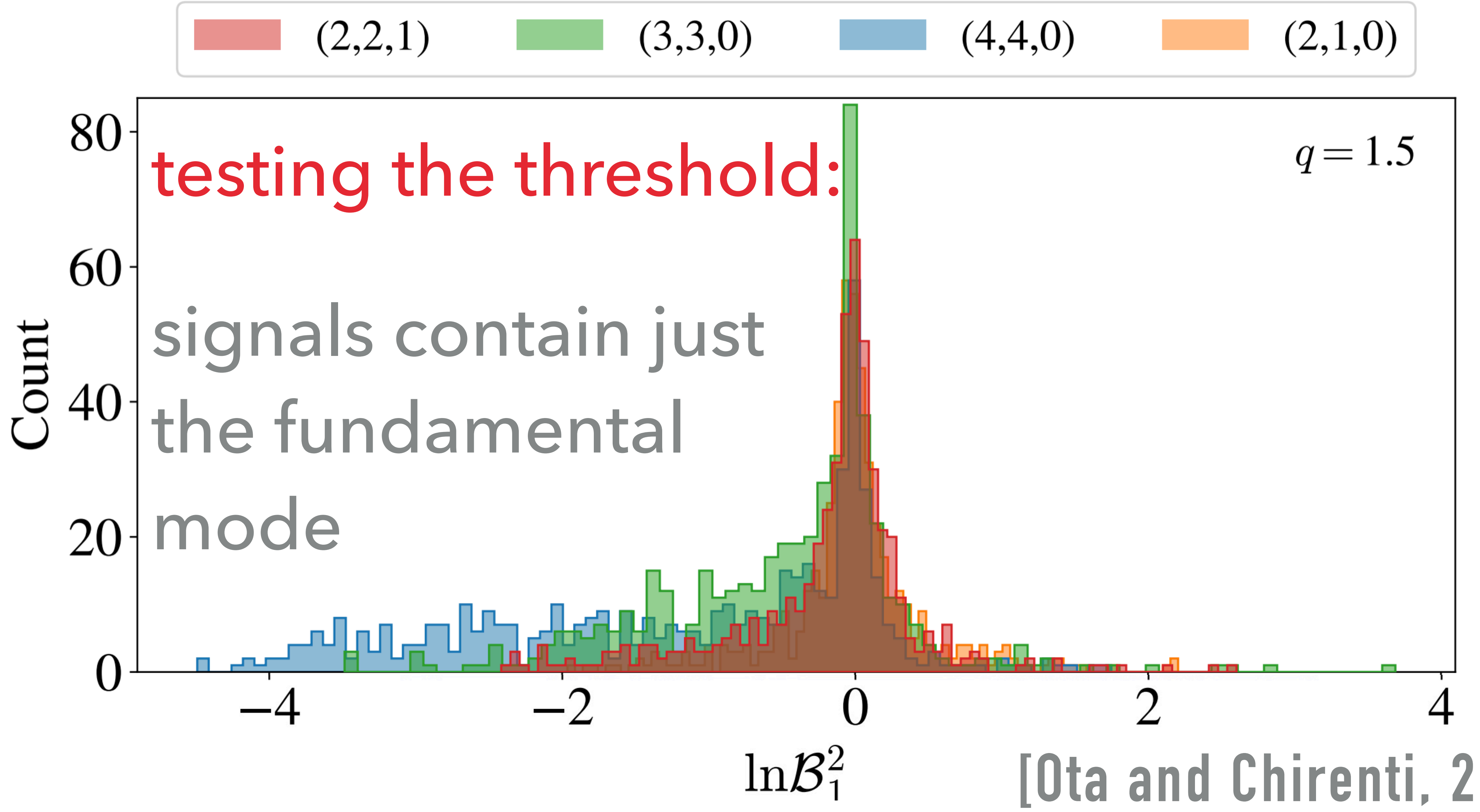
Models:

1) one mode: $\mathscr{M}_1 = h_{220}$

2) two modes: $\mathscr{M}_2 = h_{220} + h_{\ell mn}$

Model comparison:

We require $\ln \mathscr{B} > 8$ as our threshold to favor the $\mathscr{M}_2$ over $\mathscr{M}_1$.



[Ota and Chirenti, 2022]

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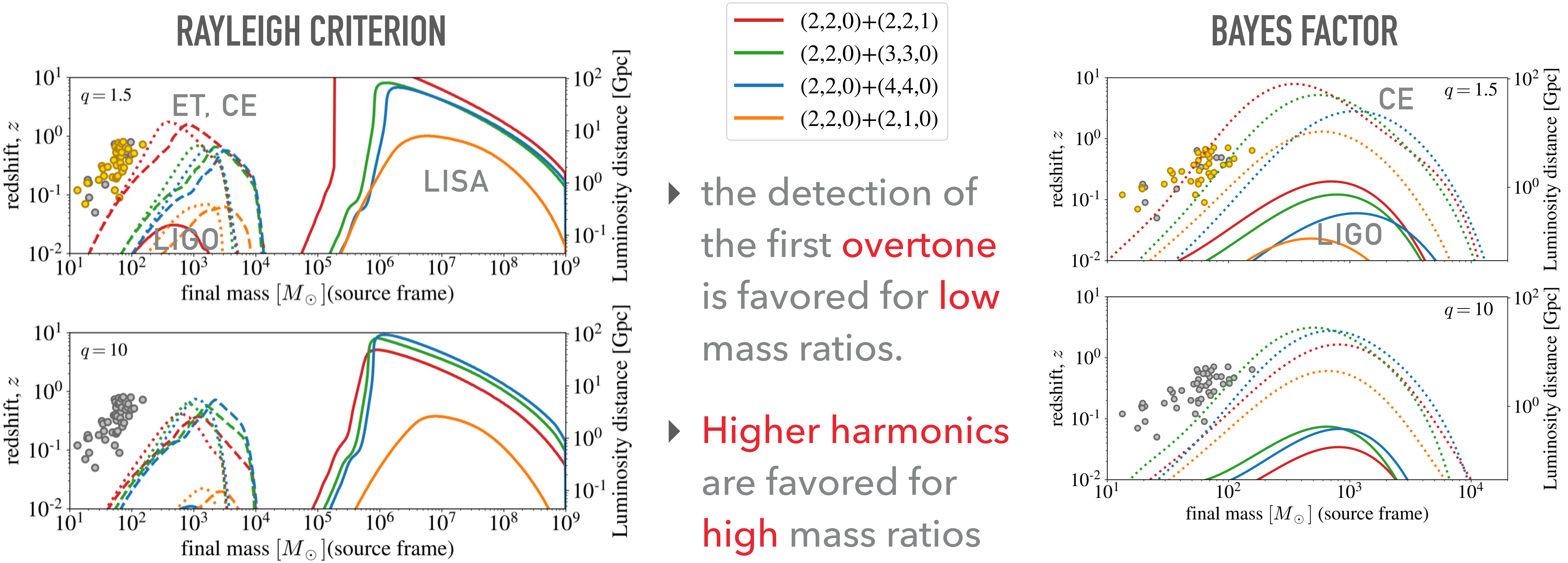
TWO MODES BH SPECTROCOPY HORIZONS



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

The Rayleigh criterion is too restrictive to assess detectability [Ota and Chirenti, 2022]

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MULTIMODE BH SPECTROCOPY HORIZONS (LIGO)

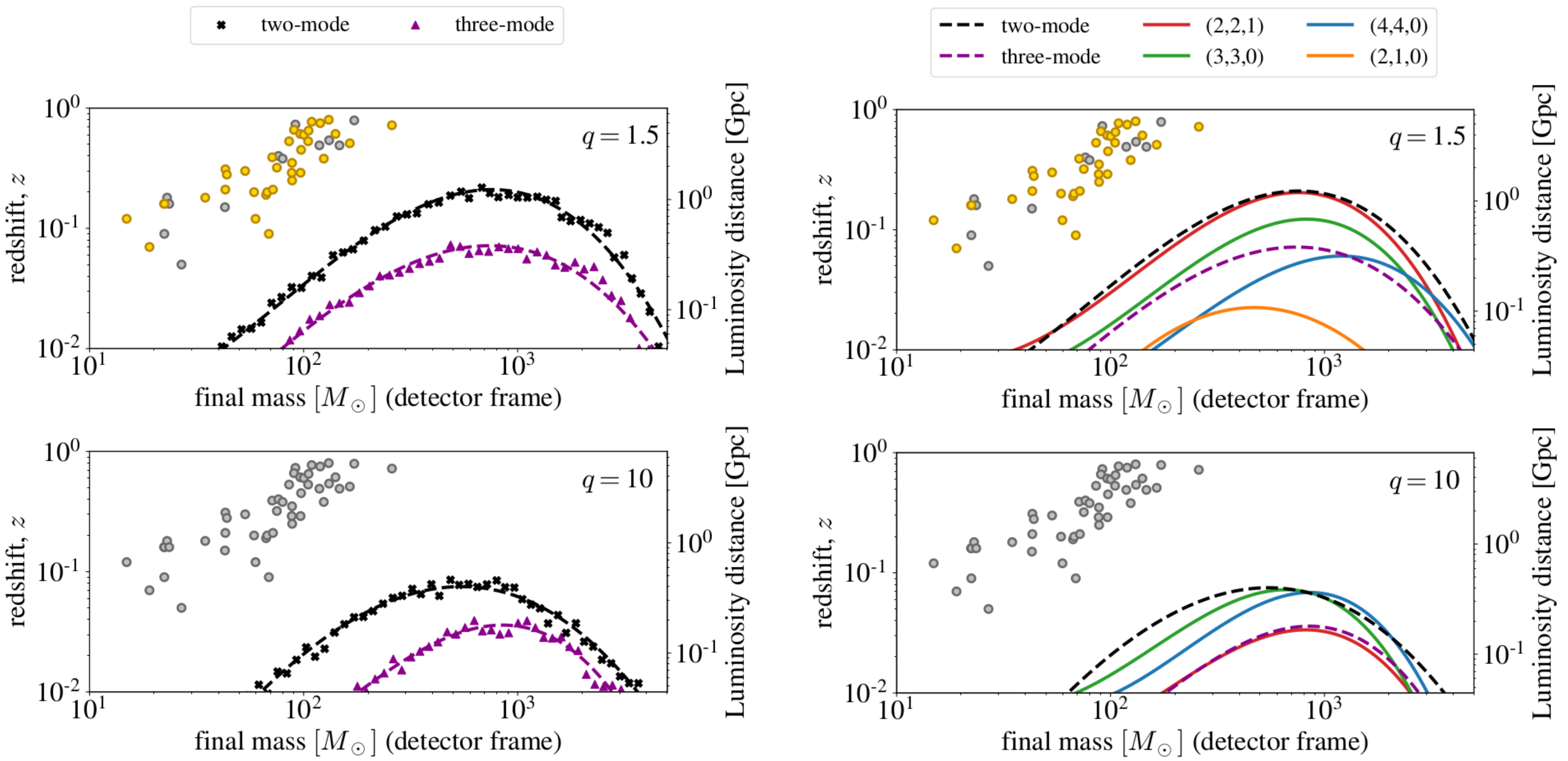
Signal: $d = h_{220} + h_{221} + h_{330} + h_{440} + h_{210} + n$

Models:

1) single-mode: $\mathscr{M}_1 = h_{220}$

2) two-mods: $\mathscr{M}_2 = h_{220} + h_{\ell mn}$

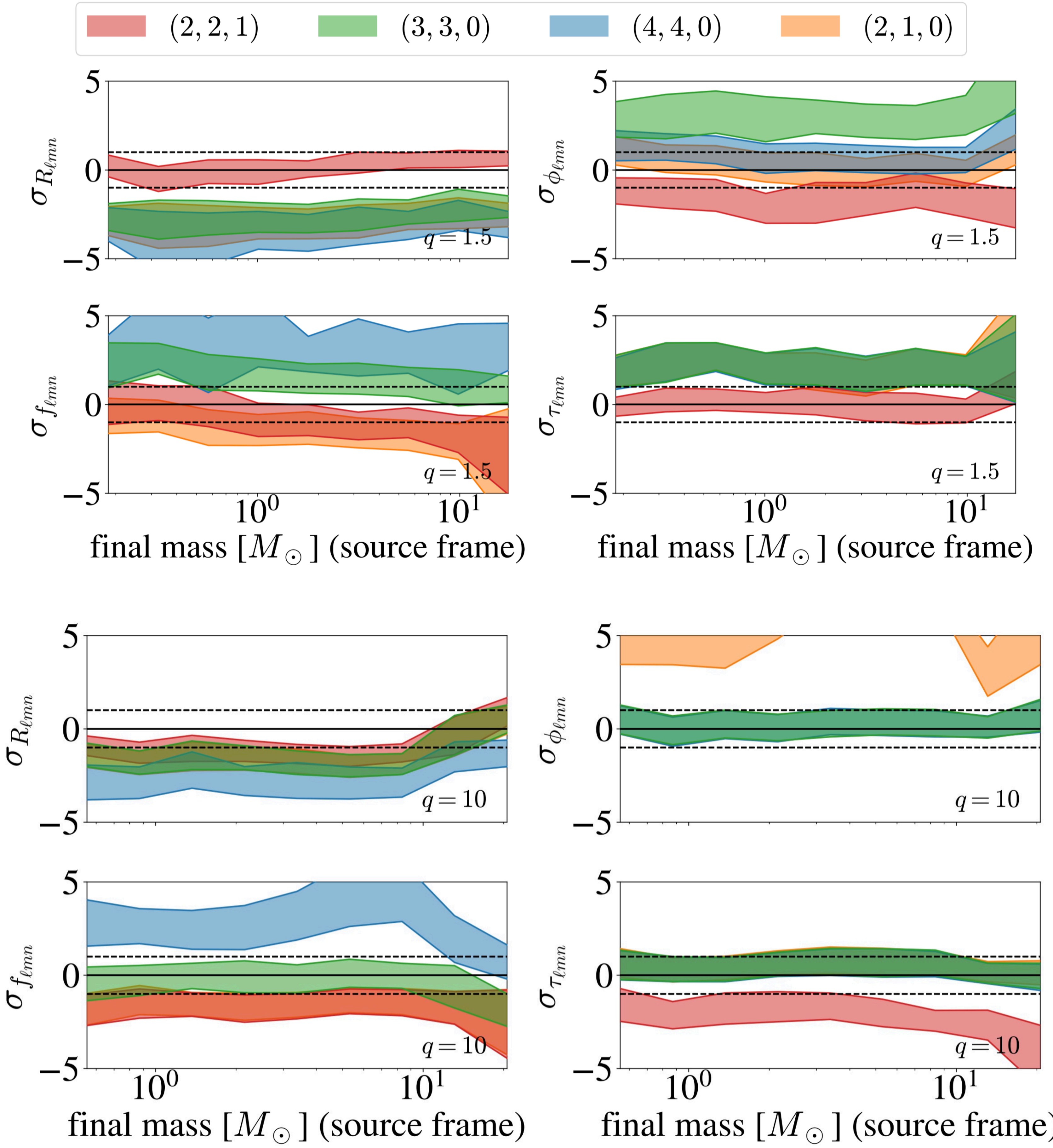
2) three-mode: $\mathscr{M}_3 = h_{220} + h_{\ell mn} + h_{\ell' m' n'}$



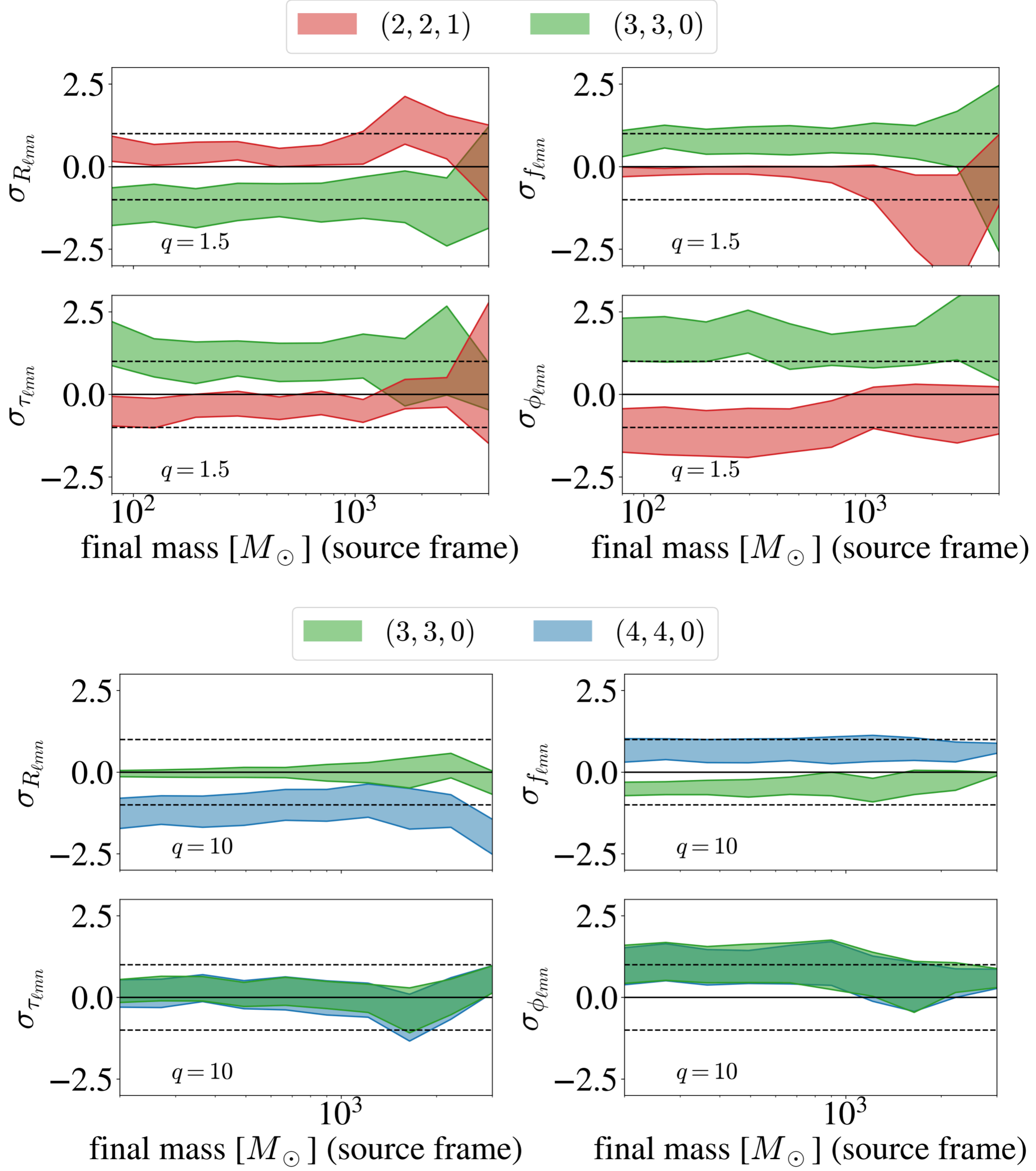
[Ota and Chirenti, 2022]

TESTING THE NO-HAIR THEOREM

TWO-MODE HORIZON



THREE-MODE HORIZON



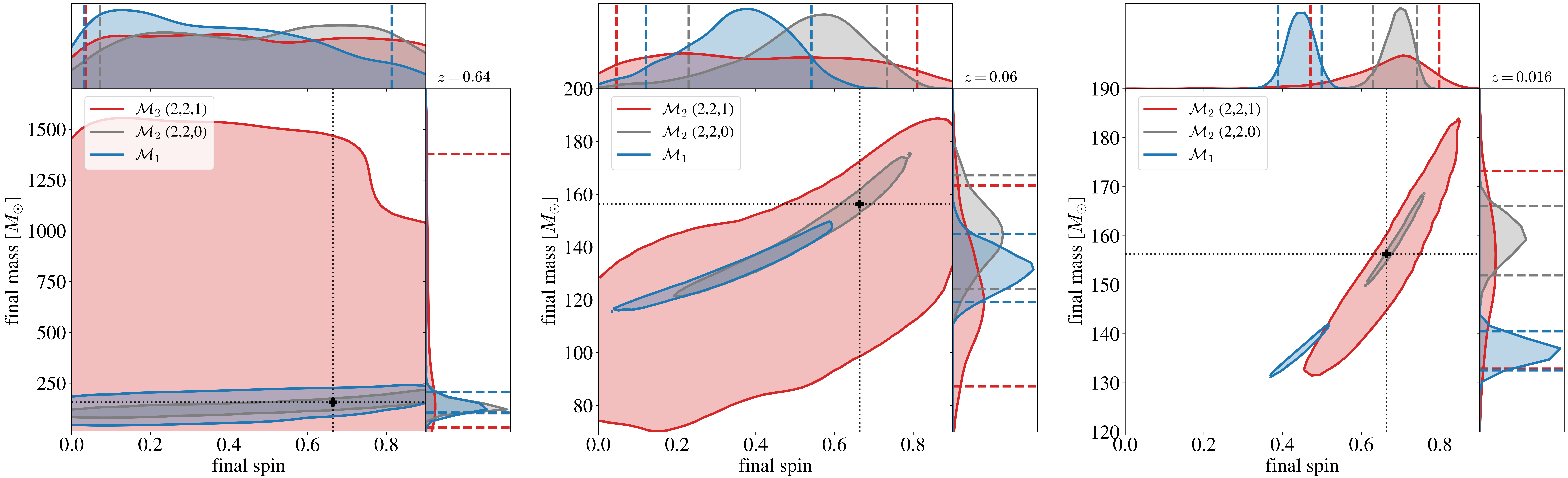
[Ota and Chirenti, 2022]

- For low mass ratios the overtone is the first mode detected followed by the (3,3,0) mode
- For high mass ratios the (3,3,0) is the secondary mode and the (4,4,0) tertiary mode

PARAMETER ESTIMATION: MULTIMODE HORIZONS

The contours enclose 90% of the posterior distribution

outside horizon | on Bayes horizon | on Rayleigh horizon



$$q = 1.5, \quad M = 156.3 M_\odot$$

The secondary mode is not negligible at the horizon distance!

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 large, but its sources are still uncertain.
- Closer sources will be needed to perform black hole spectroscopy with a single LIGO detector. Multiple detections analysis and mode stacking may compensate the low sensitivity.