

APP Seminar  
13 November 2025

# Testing general relativity with the ringdown of gravitational-wave observations

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MAX-PLANCK-GESELLSCHAFT



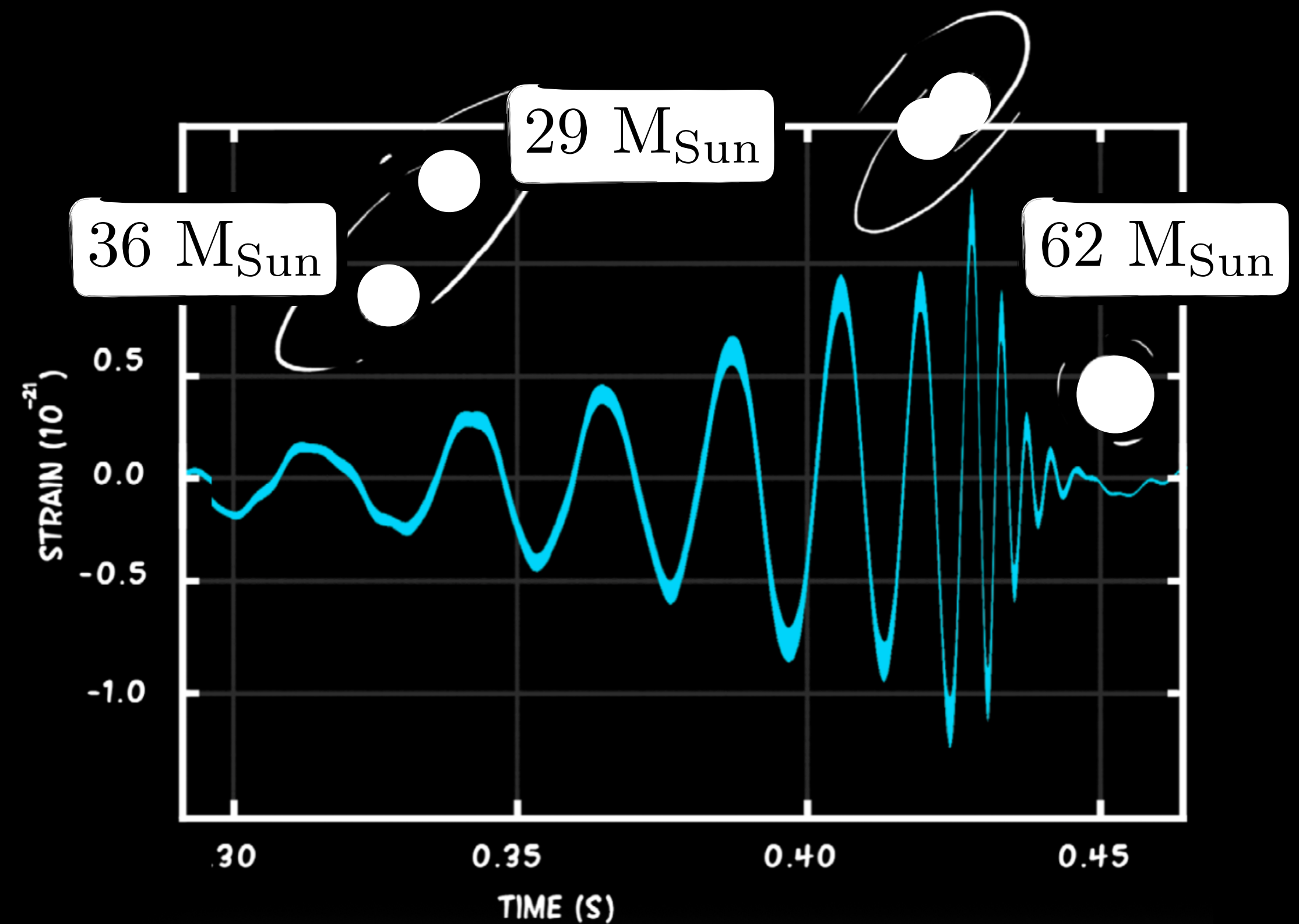
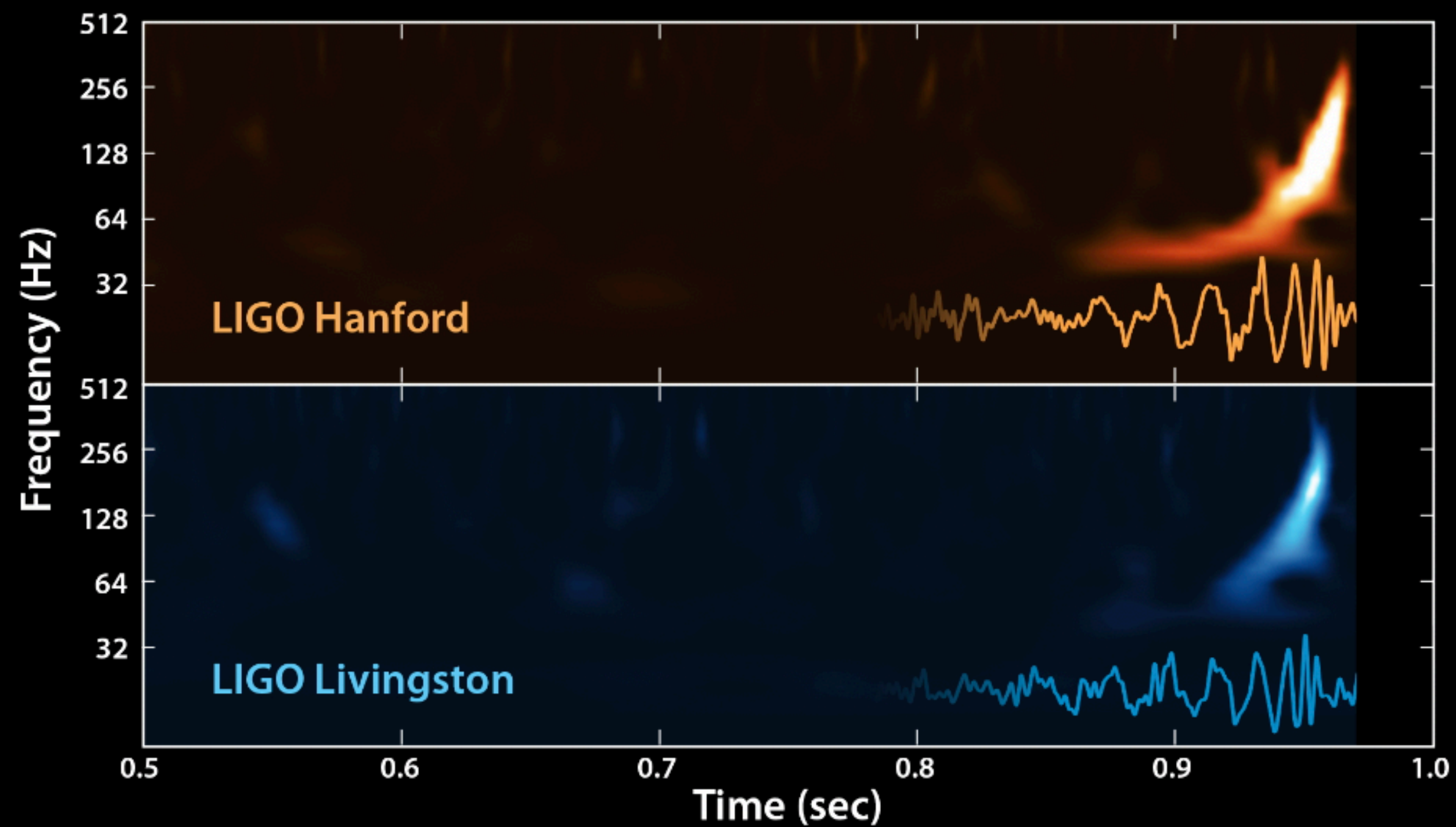
MARIE CURIE



Funded by  
the European Union

# GW150914

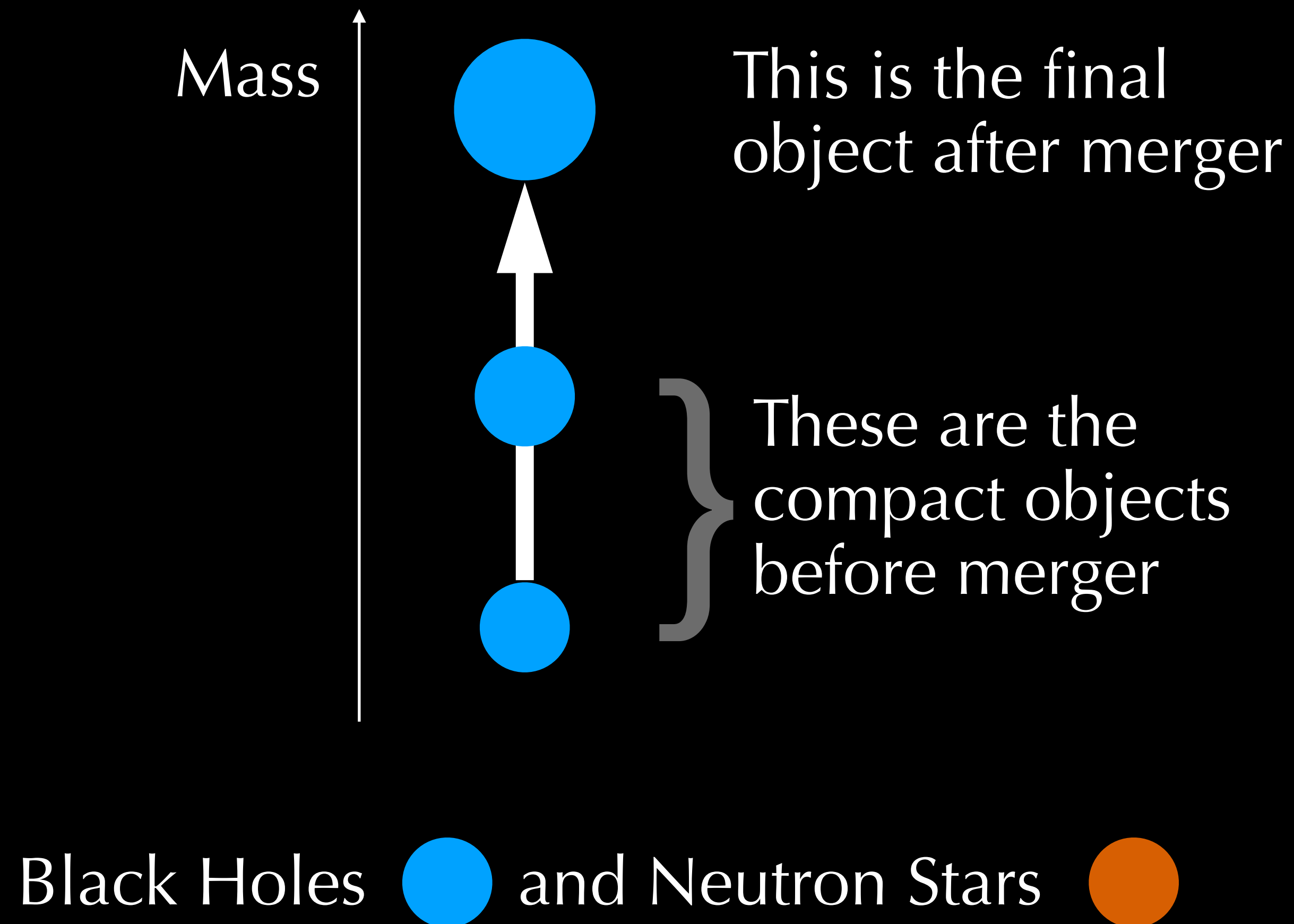
The first observation of gravitational waves from a binary black hole merger



Signal-to-noise ratio = 24

<https://www.ligo.org/magazine/LIGO-magazine-issue-8.pdf>

# How many detections have we had?

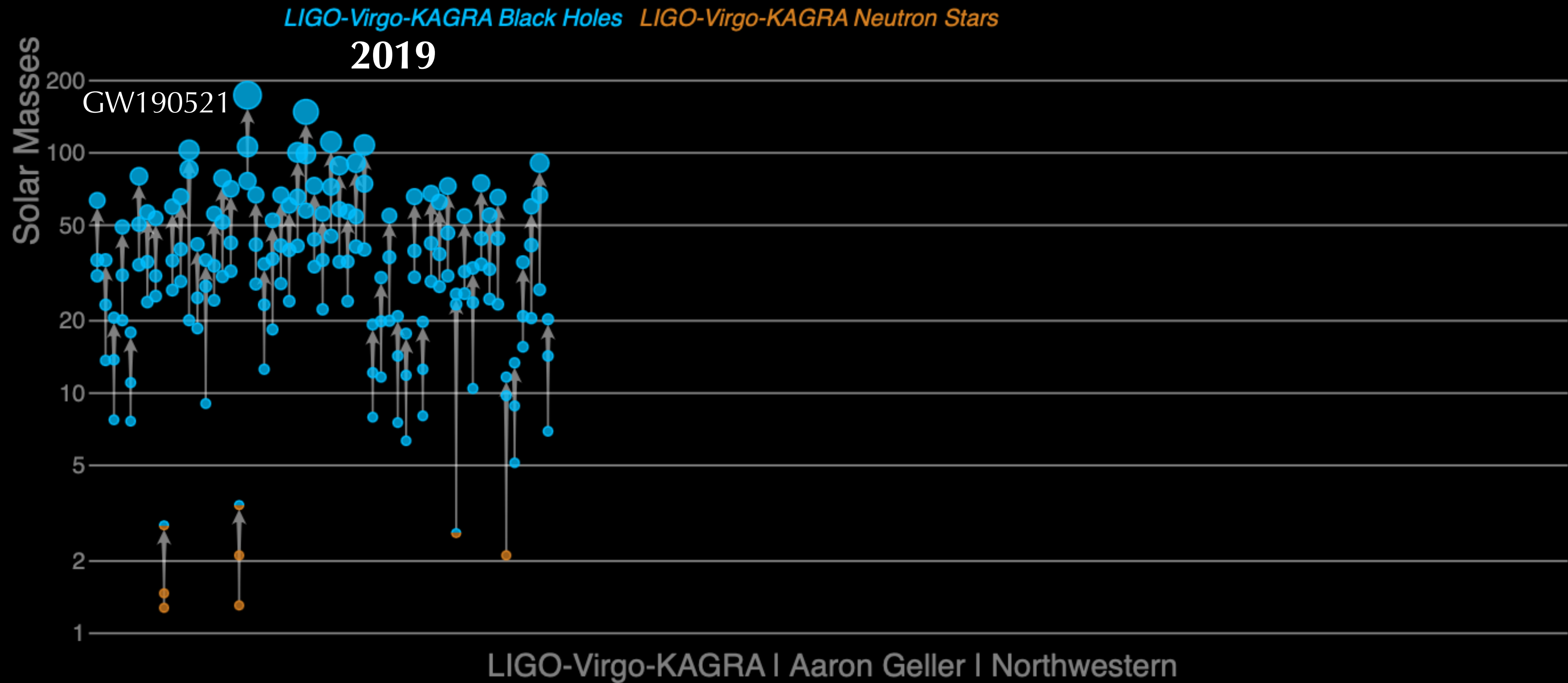


# Gravitational-wave events

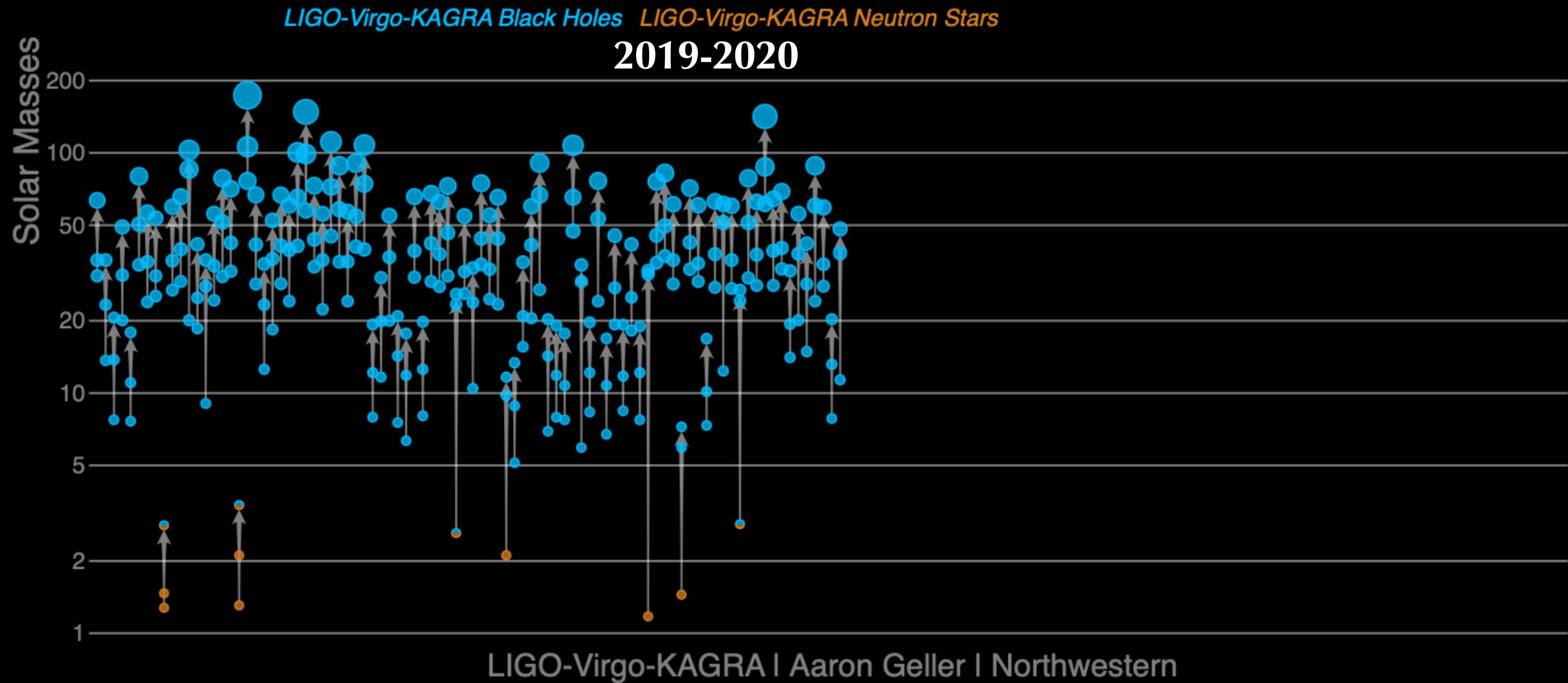


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

# Gravitational-wave events



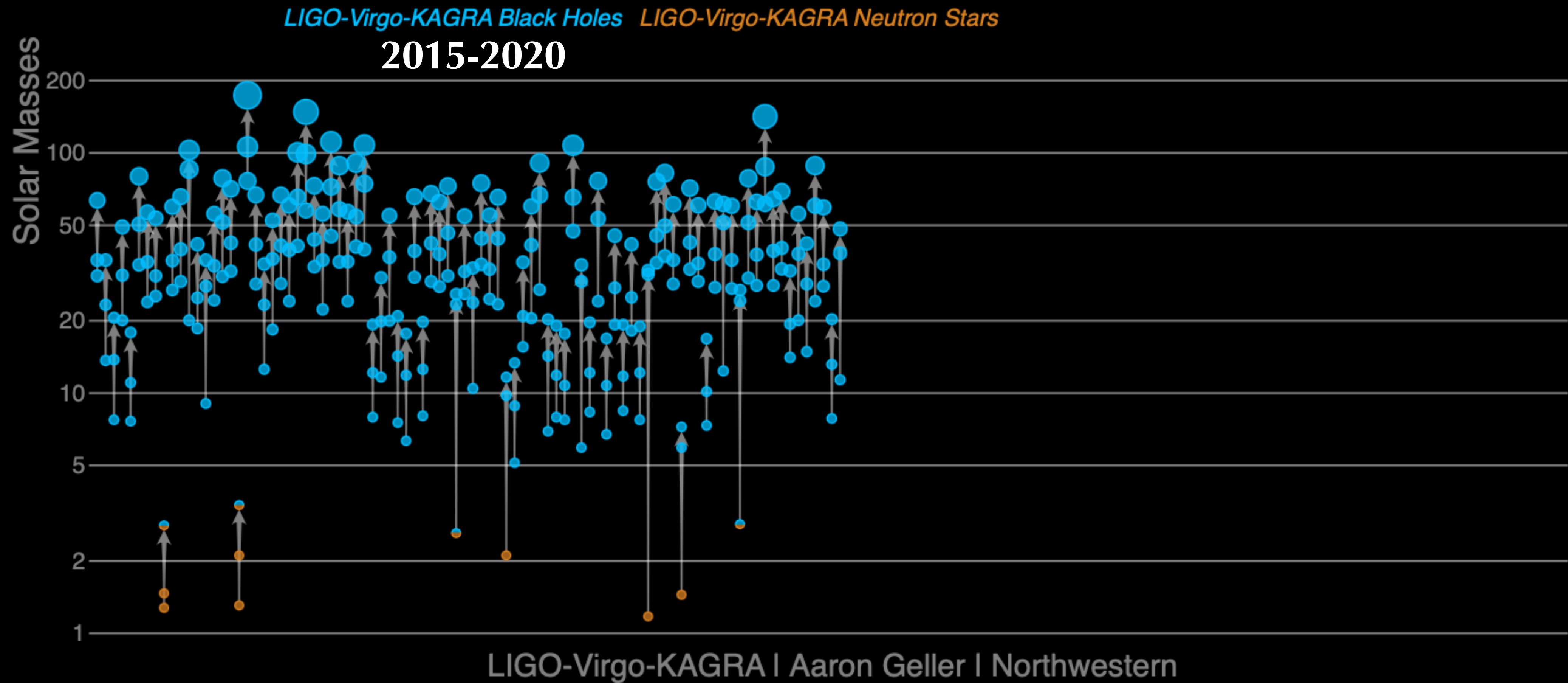
# Gravitational-wave events



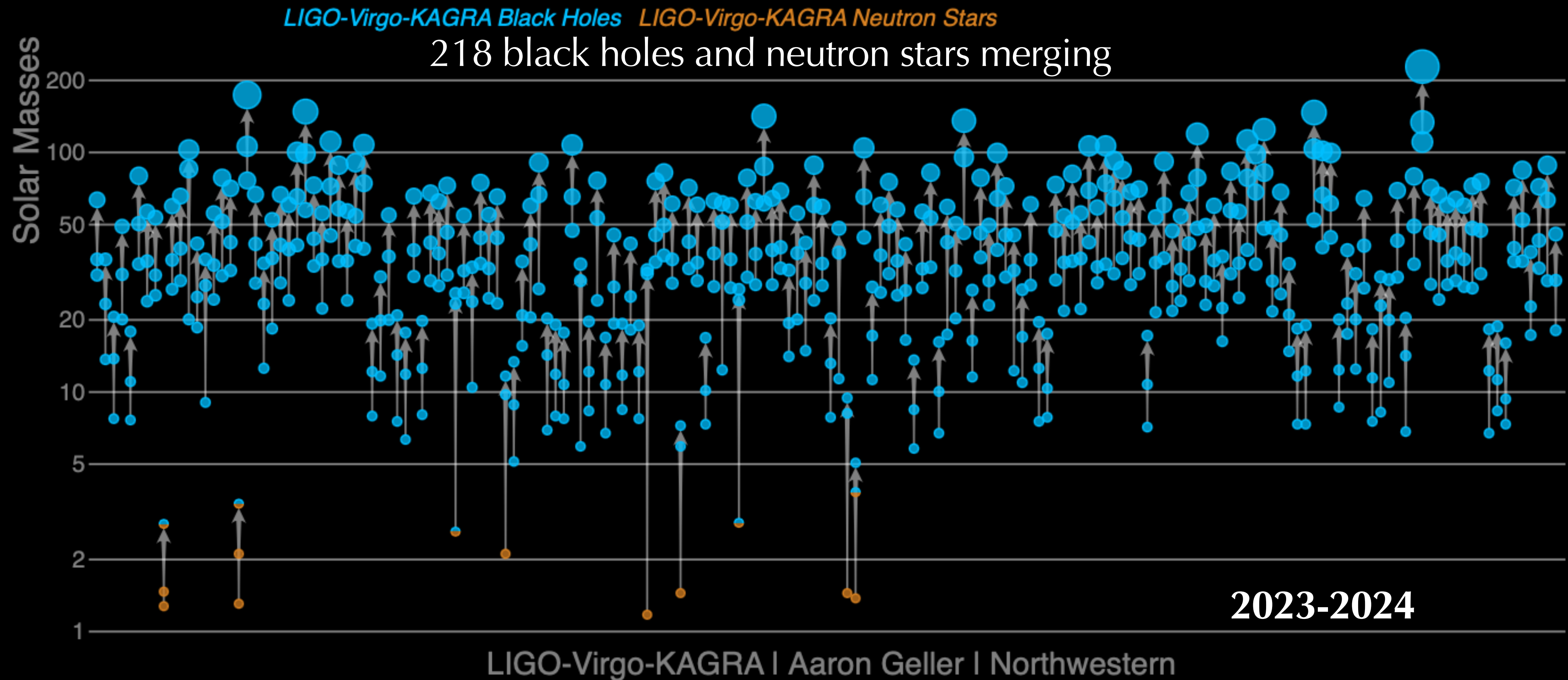
# New Results from the LIGO-Virgo-KAGRA Collaboration

Abac et al., arXiv:2508.18082

# Gravitational-wave events



# Gravitational-wave events

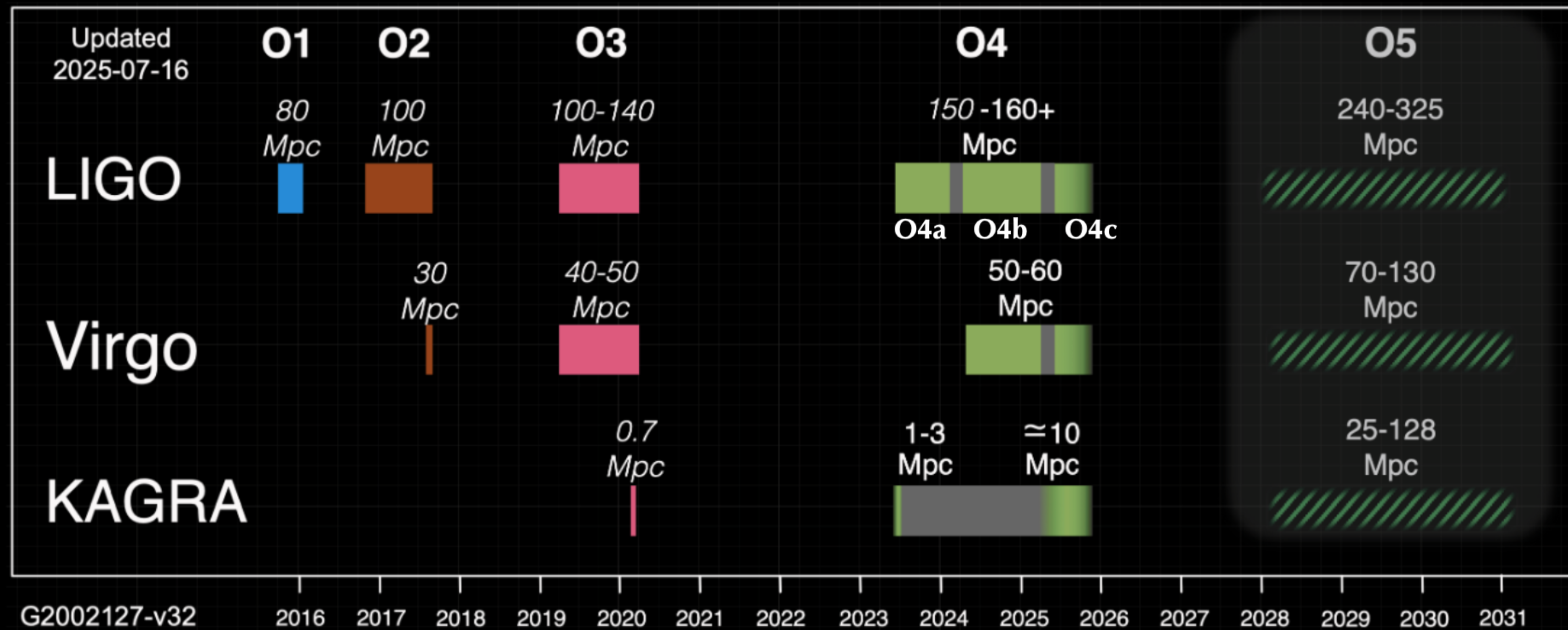


# The observing runs

**O4a:** May 2023 - January 2024

**O4b:** April 2024 - January 2025

**O4c:** January 2025 - November 2025



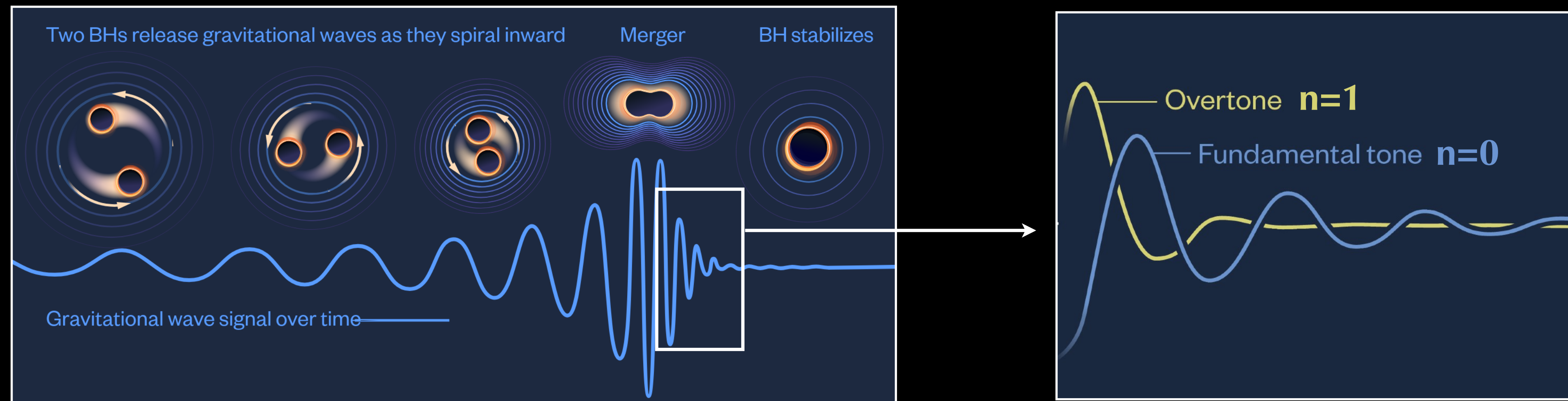
<https://observing.docs.ligo.org/plan/>

# The ringdown

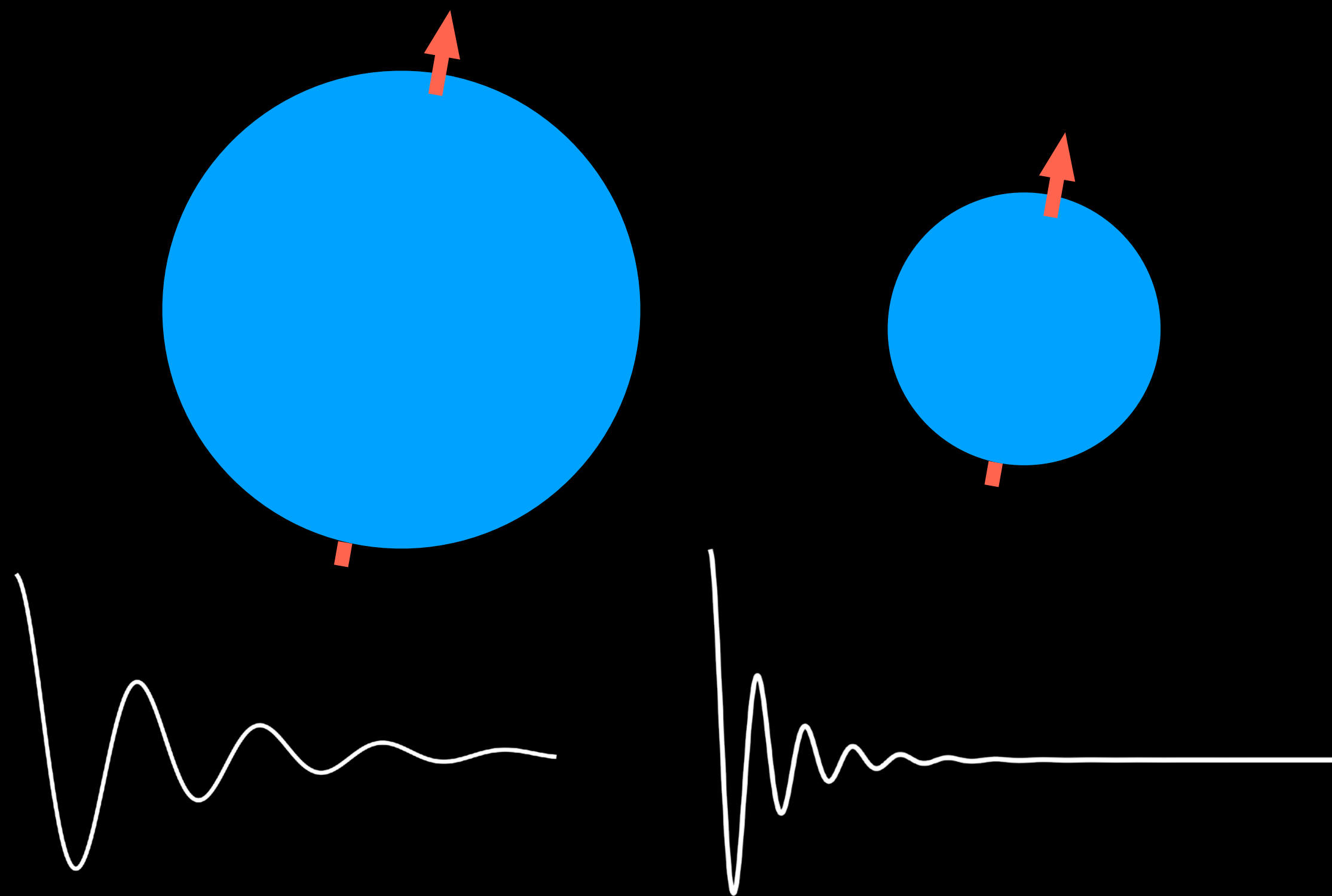
The ringdown is dominated by characteristic oscillations known as **quasi-normal modes**:

$$\omega_{lmn} = \omega_{R,lmn} + i\omega_{I,lmn}$$

It is modeled as a sum of exponentially damped sinusoids:  $f_{lmn} = \frac{\omega_{R,lmn}}{2\pi}$ ,  $\tau_{lmn} = -\frac{1}{\omega_{I,lmn}}$



# Black holes ringdown



Credit: L. Pompili

Kerr black holes are determined uniquely by two parameters:

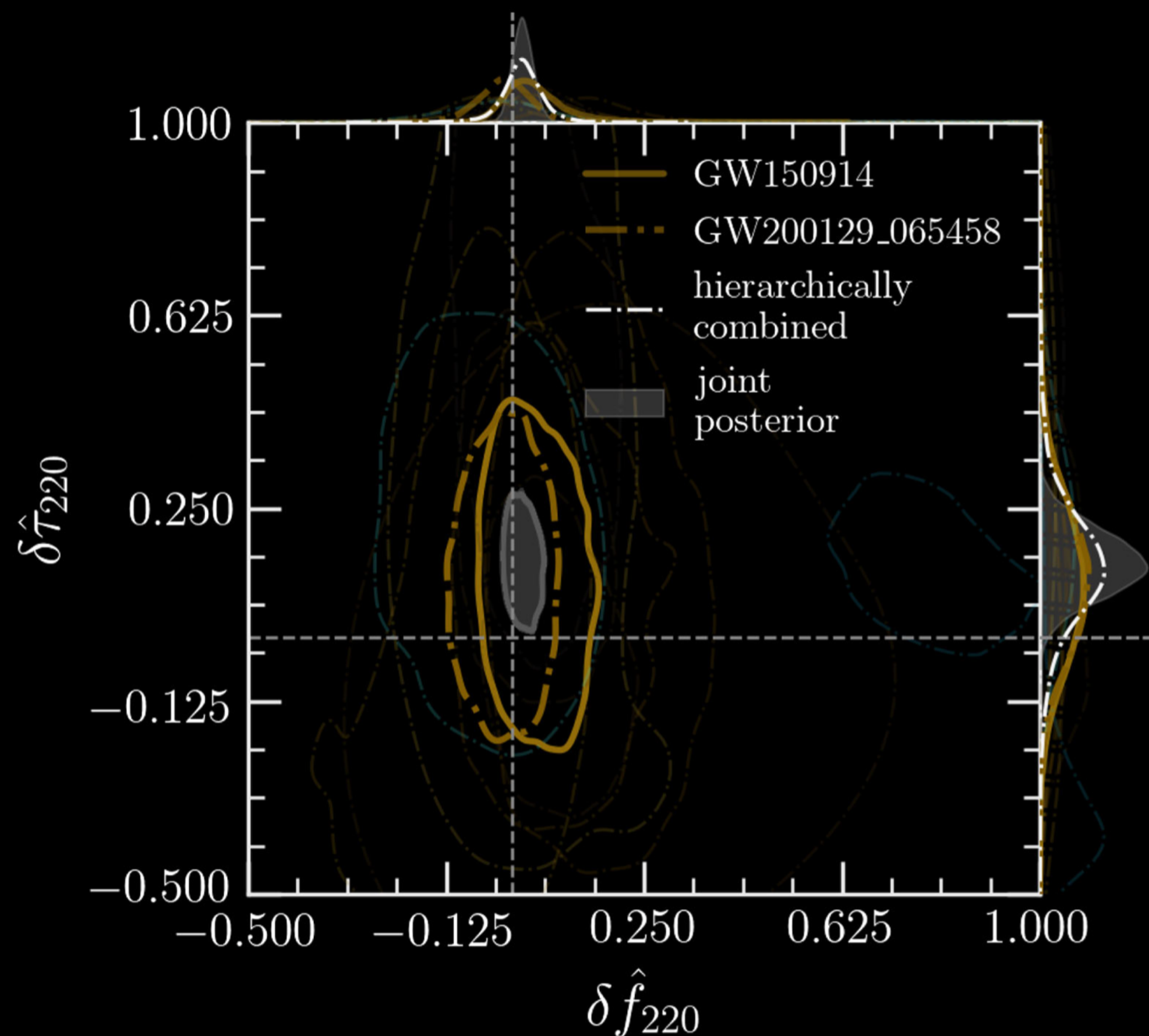
- Mass
- Angular momentum

Carter, PRL **26**, 331 (1971); Robinson, PRL **34**, 905 (1975)

A test of the black-hole paradigm requires the identification of at least 2 quasinormal modes.

# Ringdown tests

The fundamental quasi-normal mode ( $\ell = m = 2, n = 0$ ) has been observed in the ringdown of  $\mathcal{O}(10)$  gravitational-wave events.



The ringdown observations are compatible with Kerr black hole remnants with:

$$\delta f_{220} = 0.02^{+0.07}_{-0.07}$$

$$\delta \tau_{220} = 0.13^{+0.21}_{-0.22}$$

Abac et al., PRD **112**, 084080 (2025)

# Testing the nature of compact objects

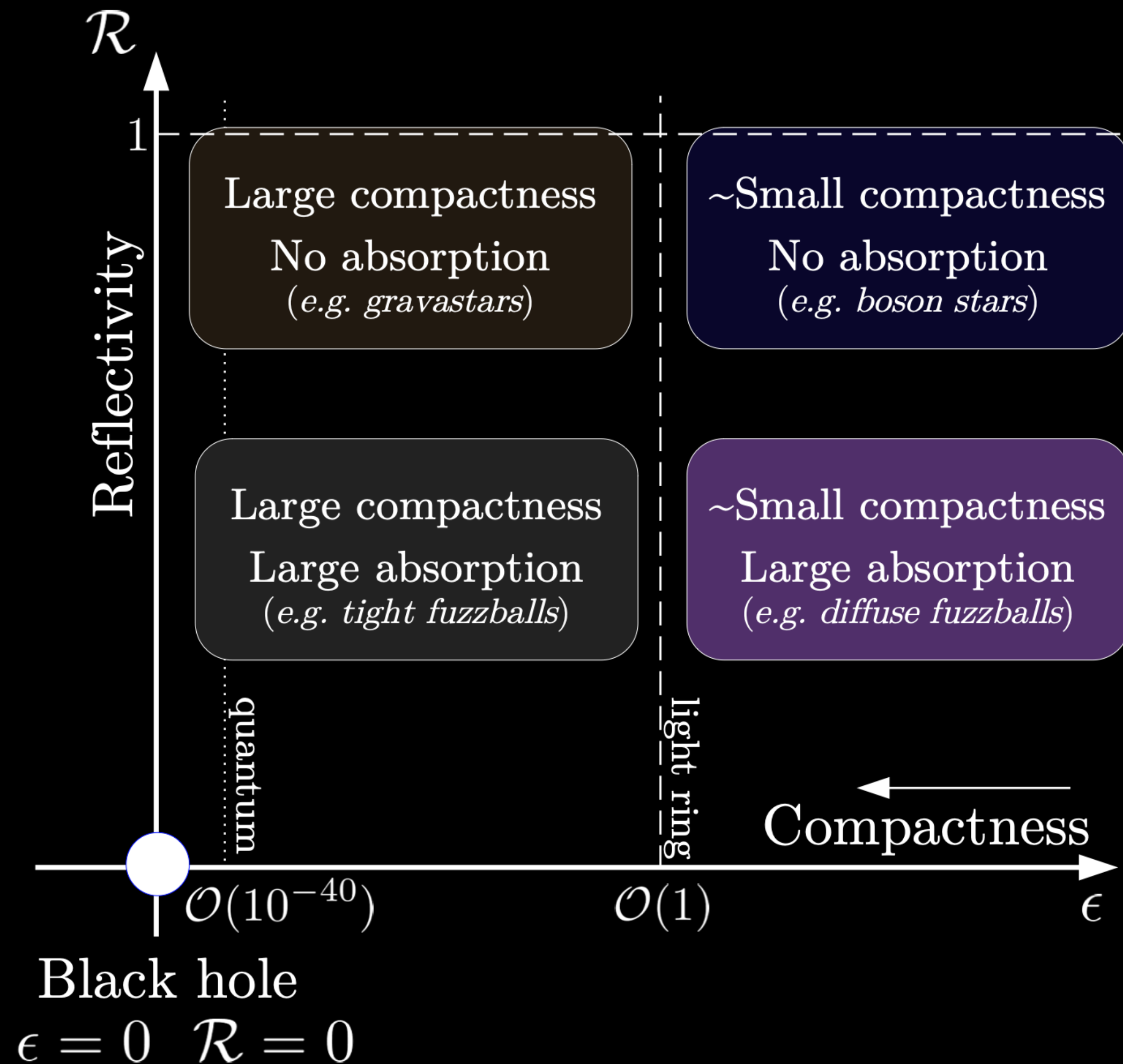
New physics can prevent the formation of the horizon:

- 
- In quantum-gravity extensions of general relativity  
(e.g. fuzzballs Mathur, Fortsch. Phys. **53**, 793-827 (2005) )
  - In general relativity with dark matter or exotic fields  
(e.g. boson stars Liebling+, LRR **20**, 5 (2017) )

**Horizonless compact objects** can quantify the existence of horizons.

Giudice+, JCAP **10** (2010) 001; Cardoso+, LRR **22**:4 (2019); EM+, Handbook for GW Astronomy, Springer (2021)

# Horizonless compact objects

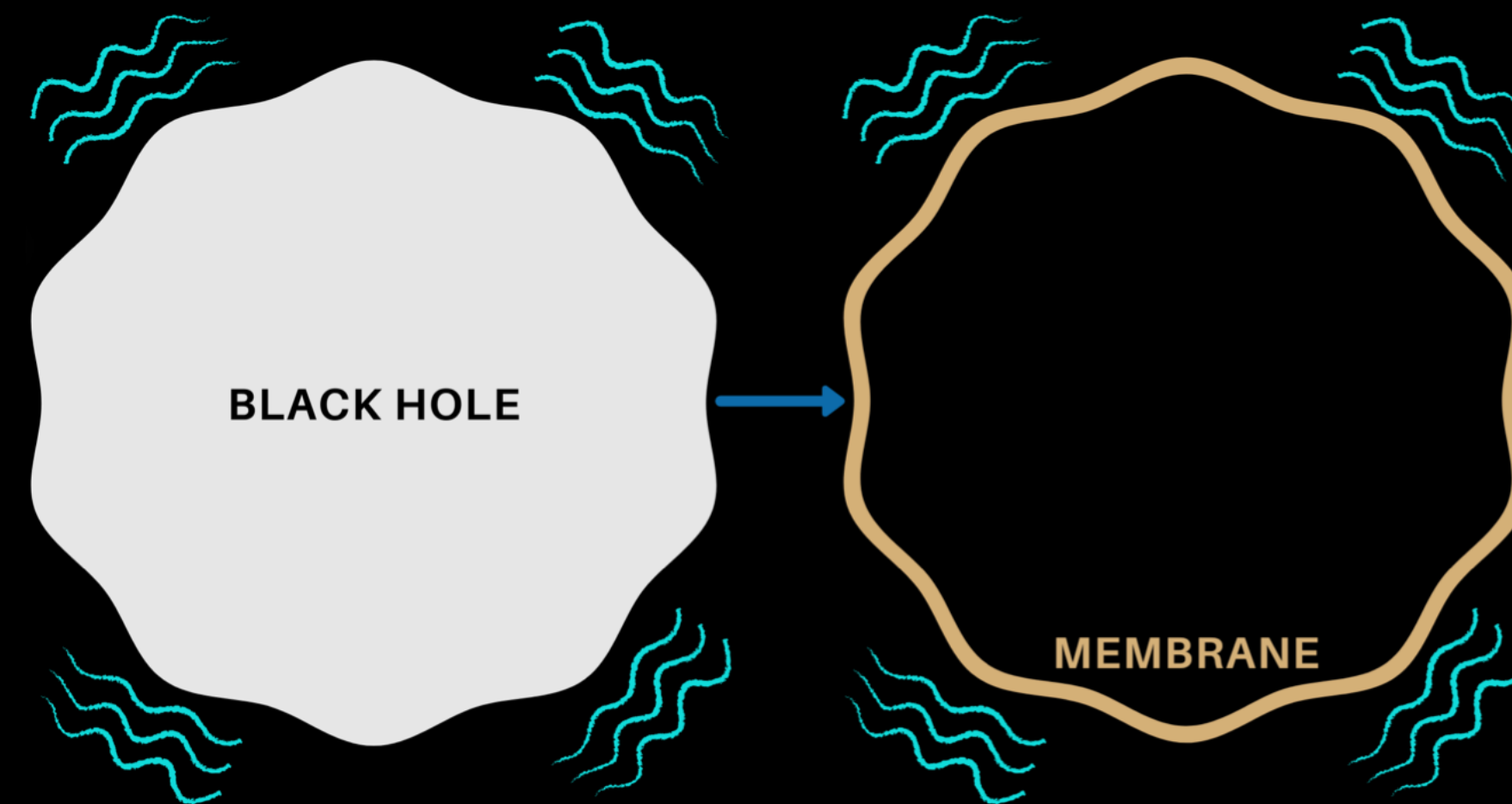


They deviate from black holes for their:

- **Compactness**  
since the object's radius is at  $r_0 = r_+(1 + \epsilon)$
- **Reflectivity**  
different from a totally absorbing black hole

# Membrane paradigm

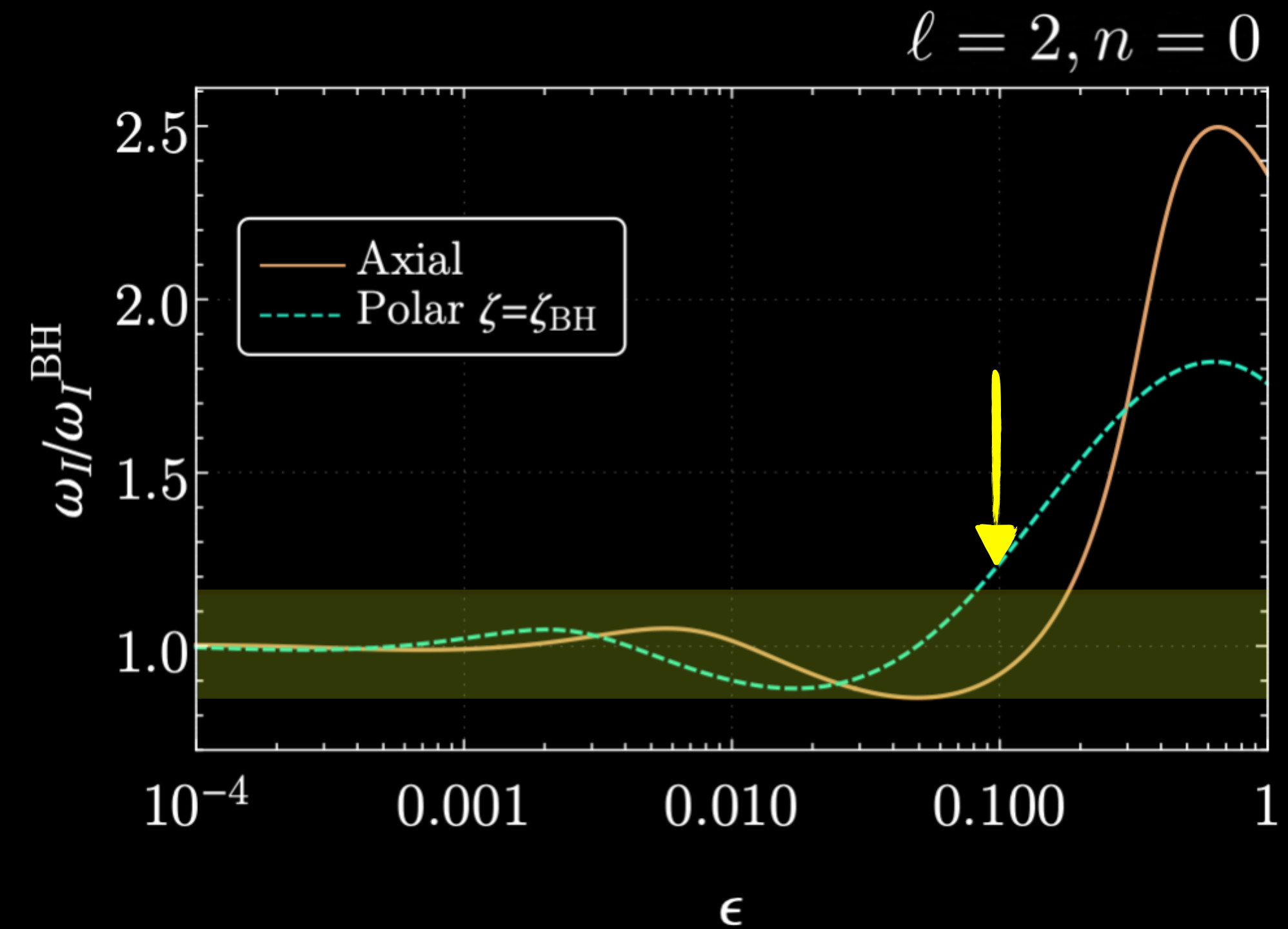
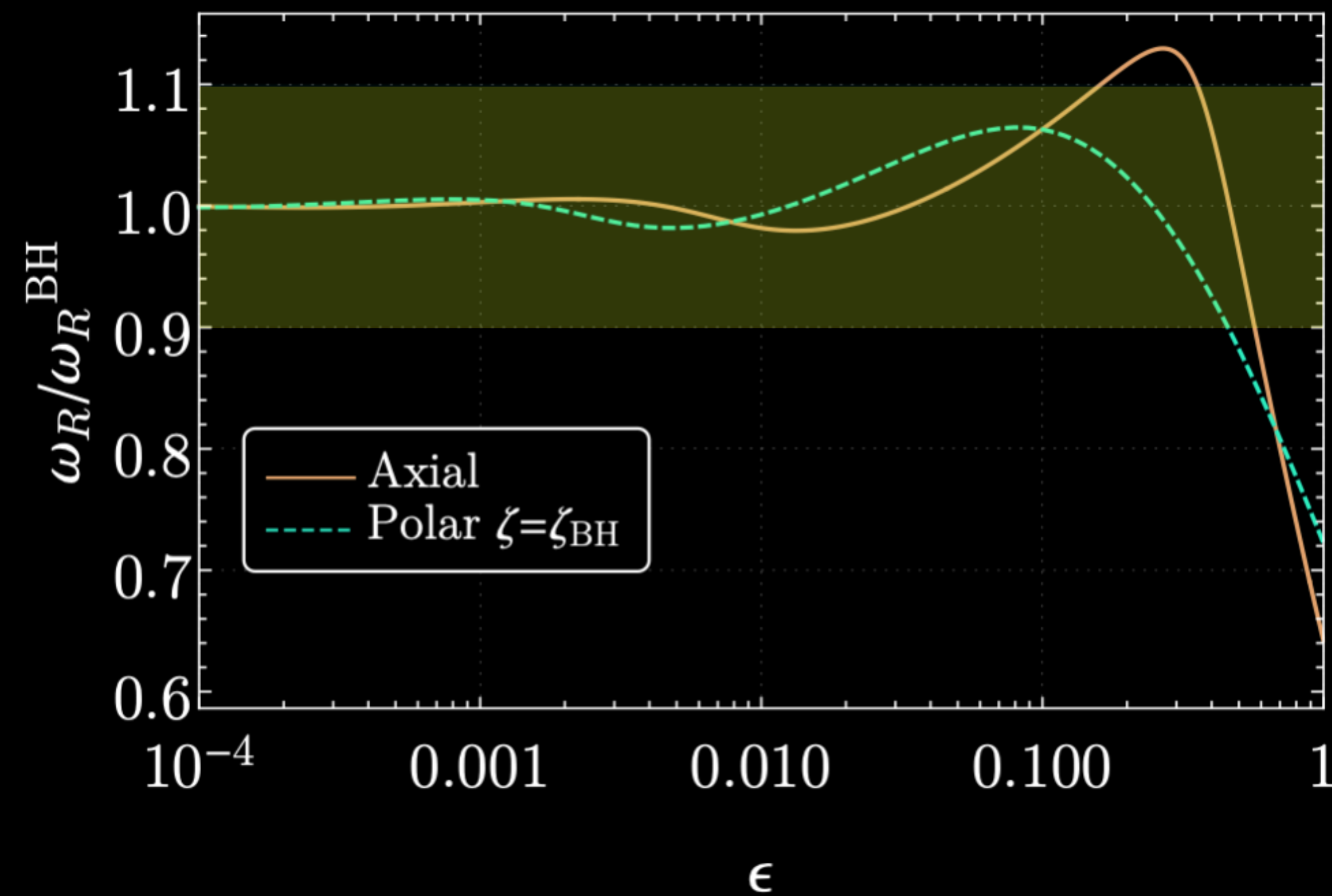
The interior of a black hole can be mapped into a fictitious membrane located at the horizon, which is a viscous fluid with shear  $\eta$  and bulk viscosity  $\zeta$ . Damour, PRD **18**, 10 (1978); Price, Thorne, PRD **33**, 4 (1986)



We generalized the membrane paradigm to any compact object with a Schwarzschild exterior and a Kerr metric at the linear order in spin.

# Quasinormal mode spectrum

Totally absorbing compact object:

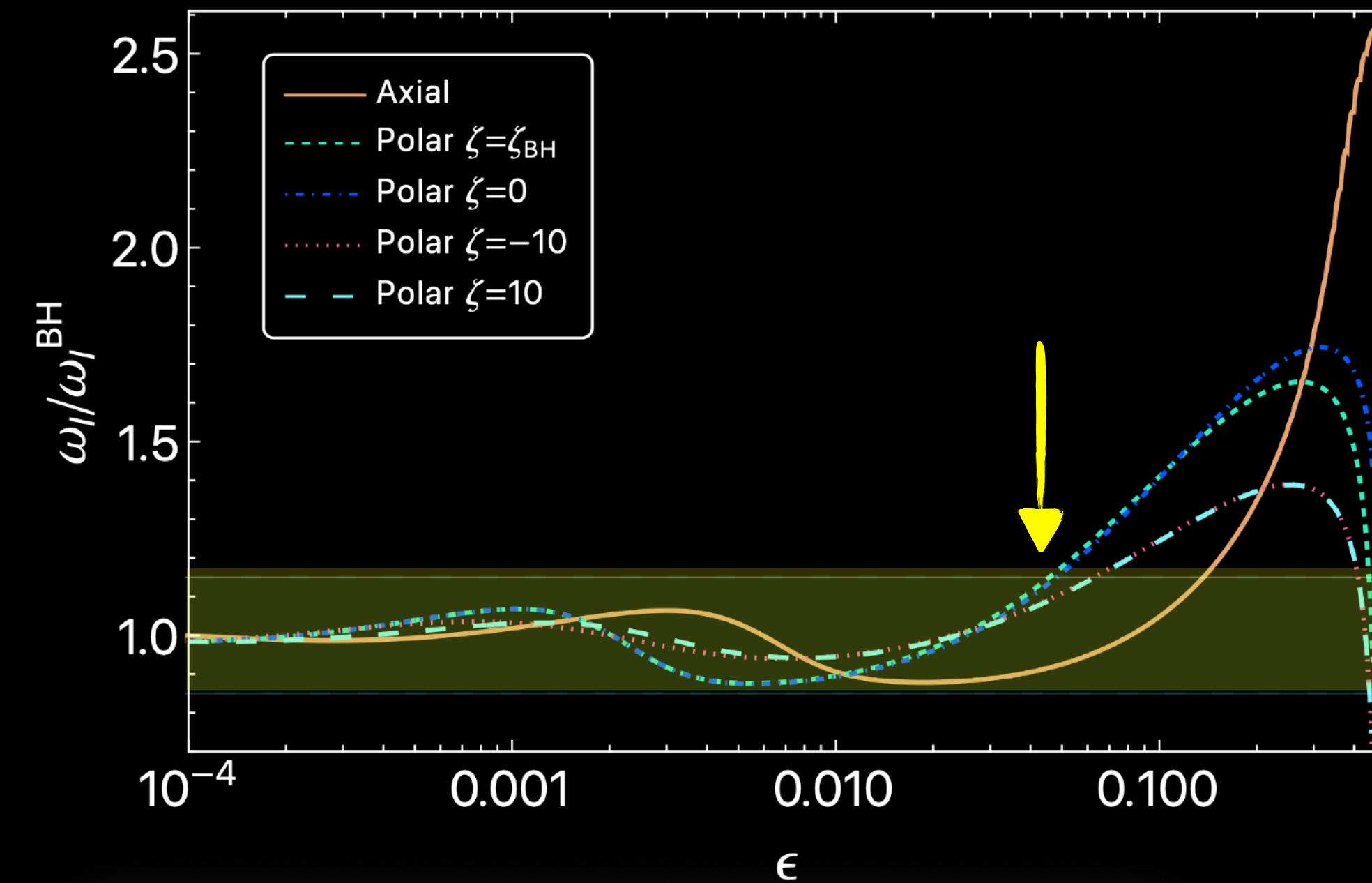


Horizonless compact objects with  $\epsilon \lesssim 0.1$  are compatible with the measurement accuracy of the fundamental quasi-normal mode in GW150914.

# Spinning remnant

Including the linear order in spin makes the constraint more stringent with  $\epsilon \lesssim 0.4$ .

Saketh, EM, PRD 110, 084038 (2024)

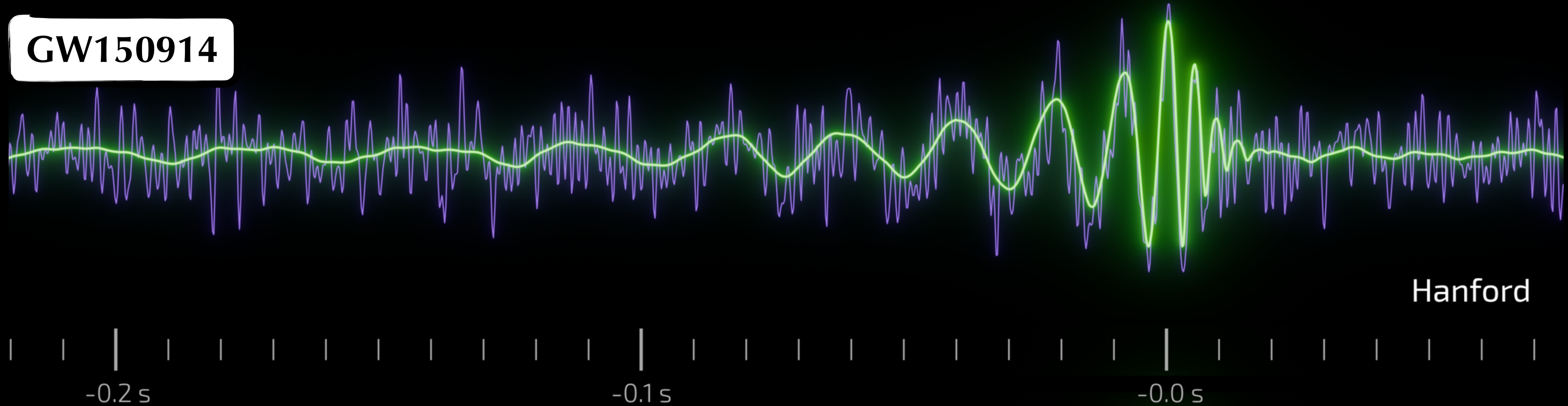


The generalization to high values of the spin is under development. EM, Wagle, in prep.

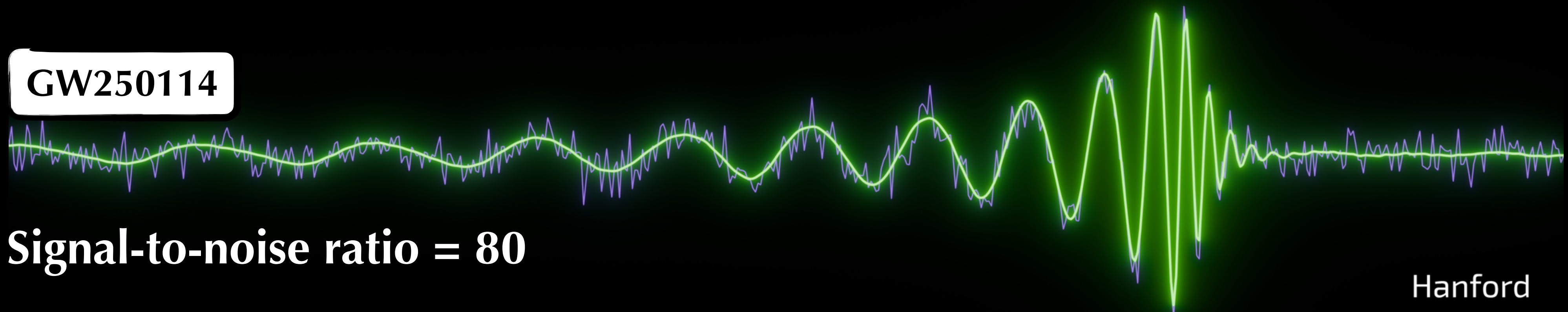
# GW250114

The clearest view yet of merging black holes Abac et al., PRL 135, 111403 (2025)

**GW150914**

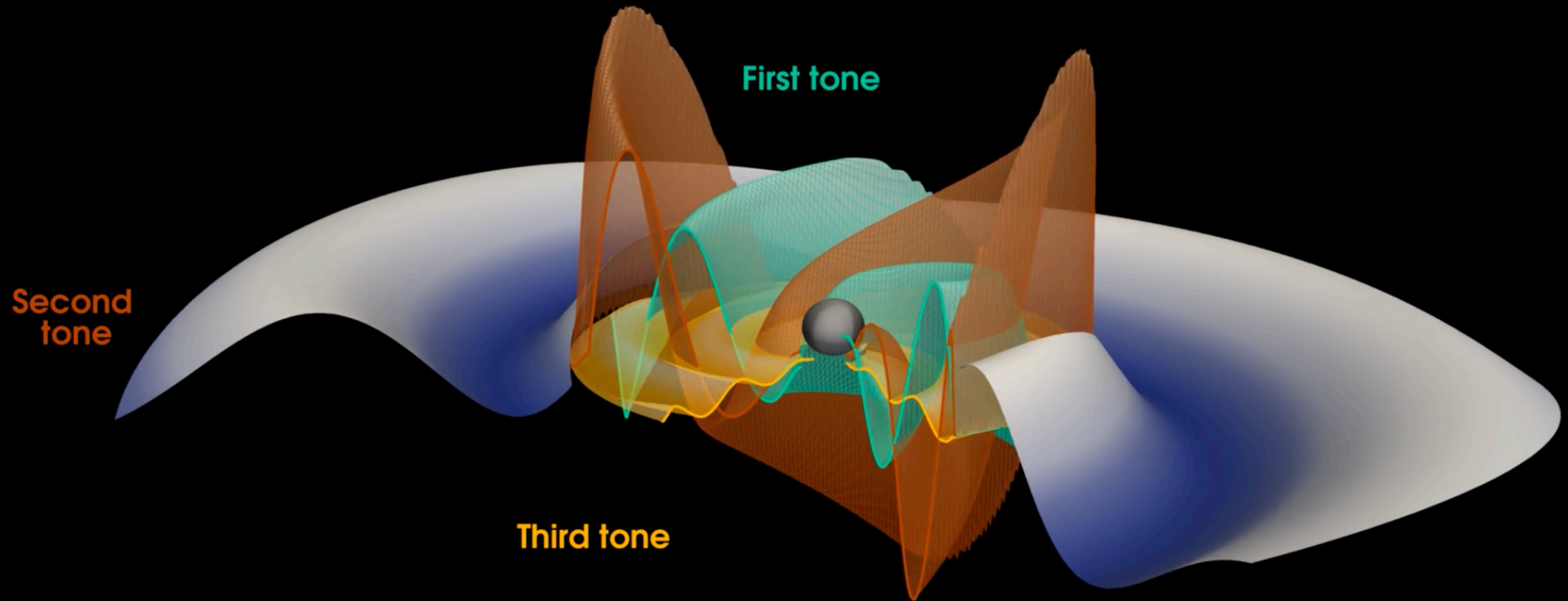


**GW250114**

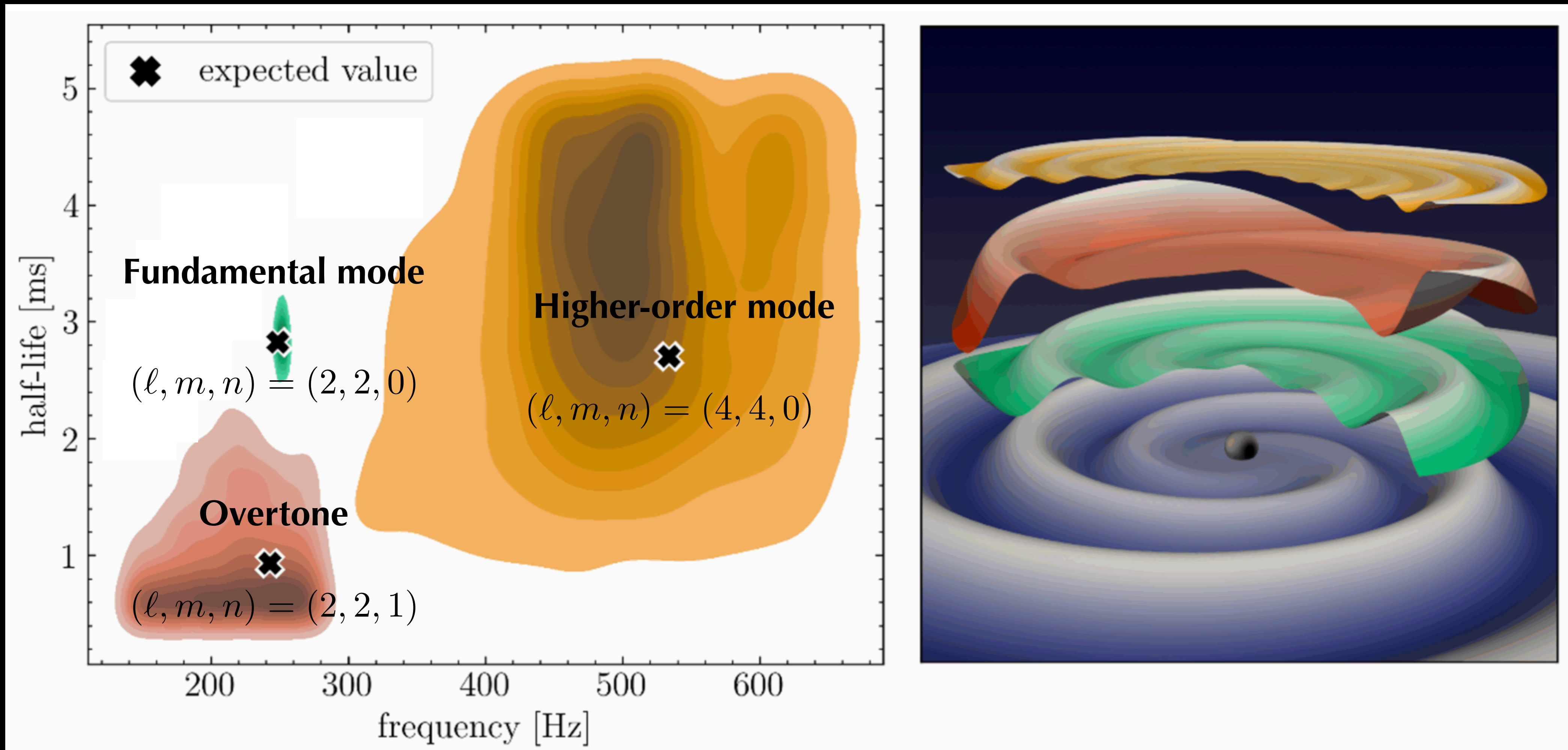


**Signal-to-noise ratio = 80**

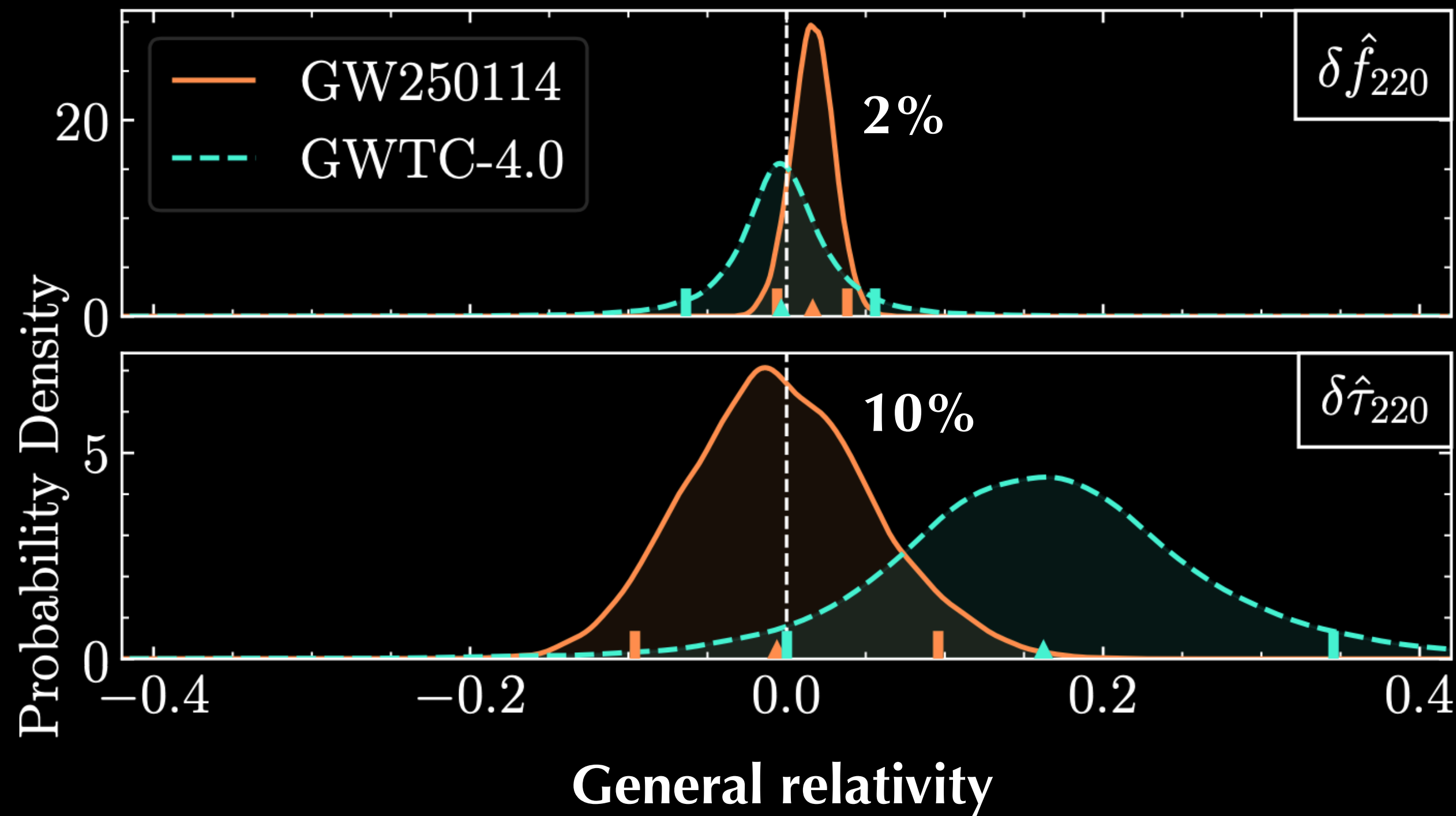
# GW250114



# The ringdown of GW250114

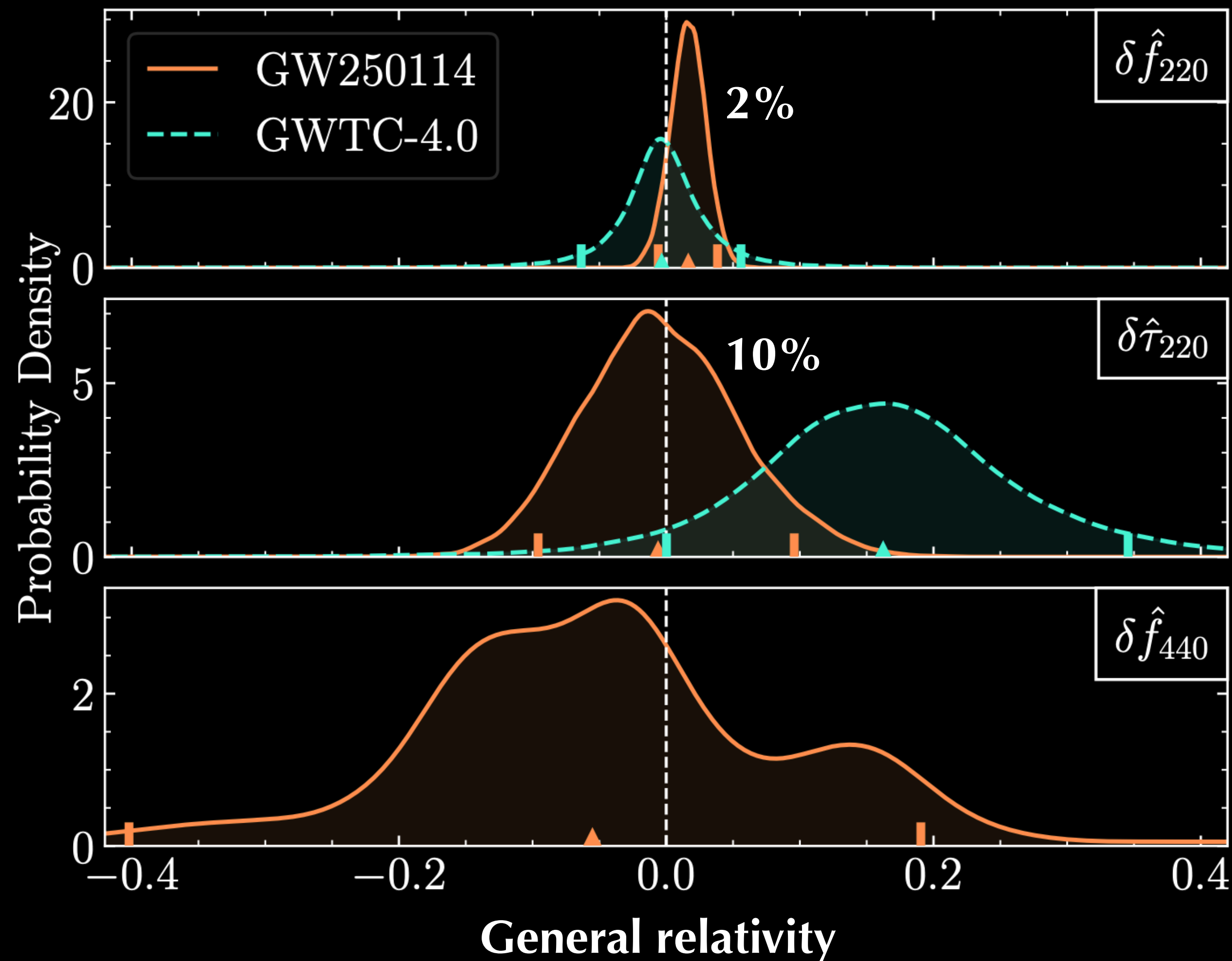


# The ringdown of GW250114



The fundamental mode is constrained twice as strictly as combining events from the fourth catalog.

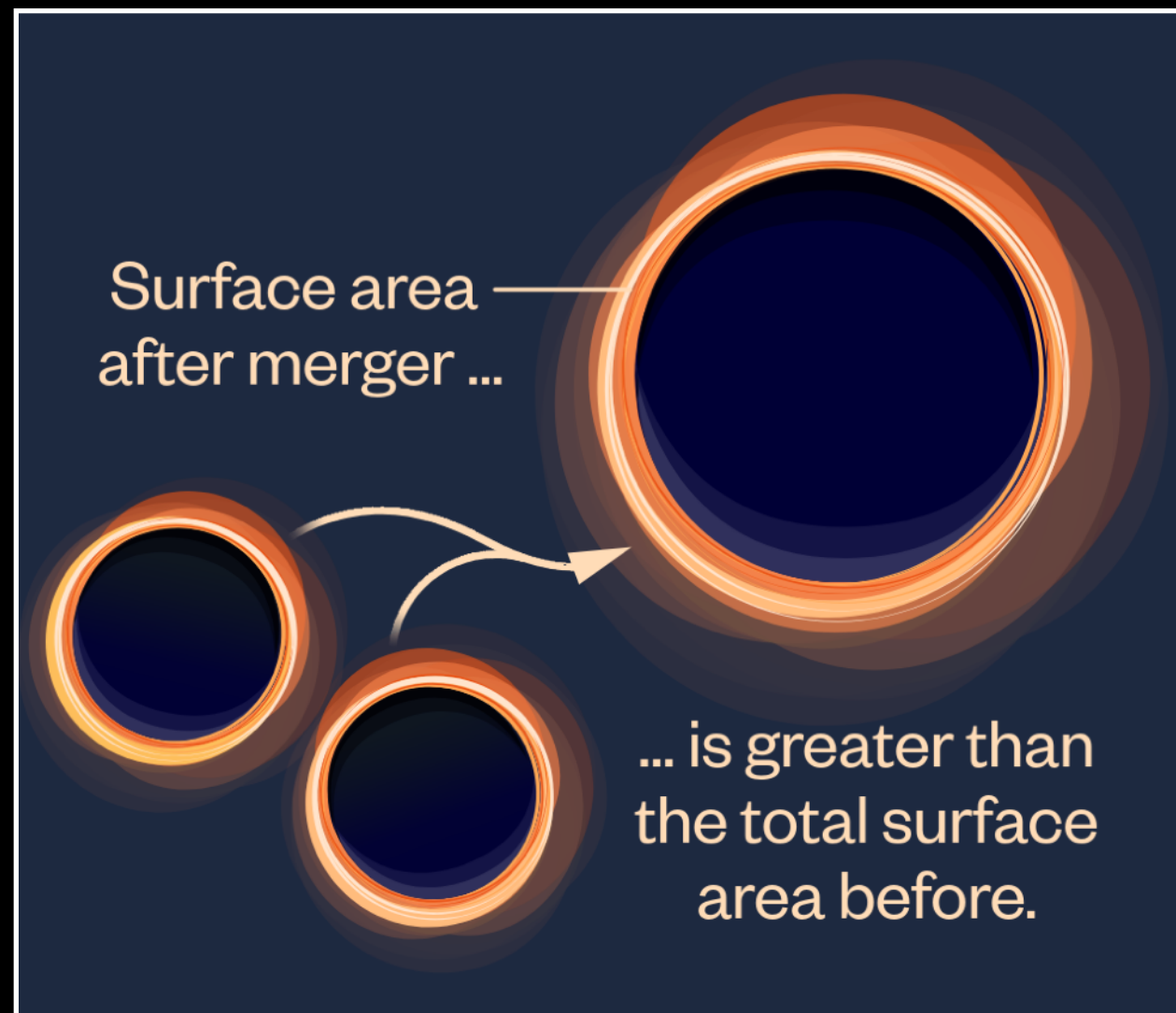
# The ringdown of GW250114



The fundamental mode is constrained twice as strictly as combining events from the fourth catalog.

For the first time, the frequency of the (4,4,0) quasinormal mode is constrained.

# Testing Hawking's area law

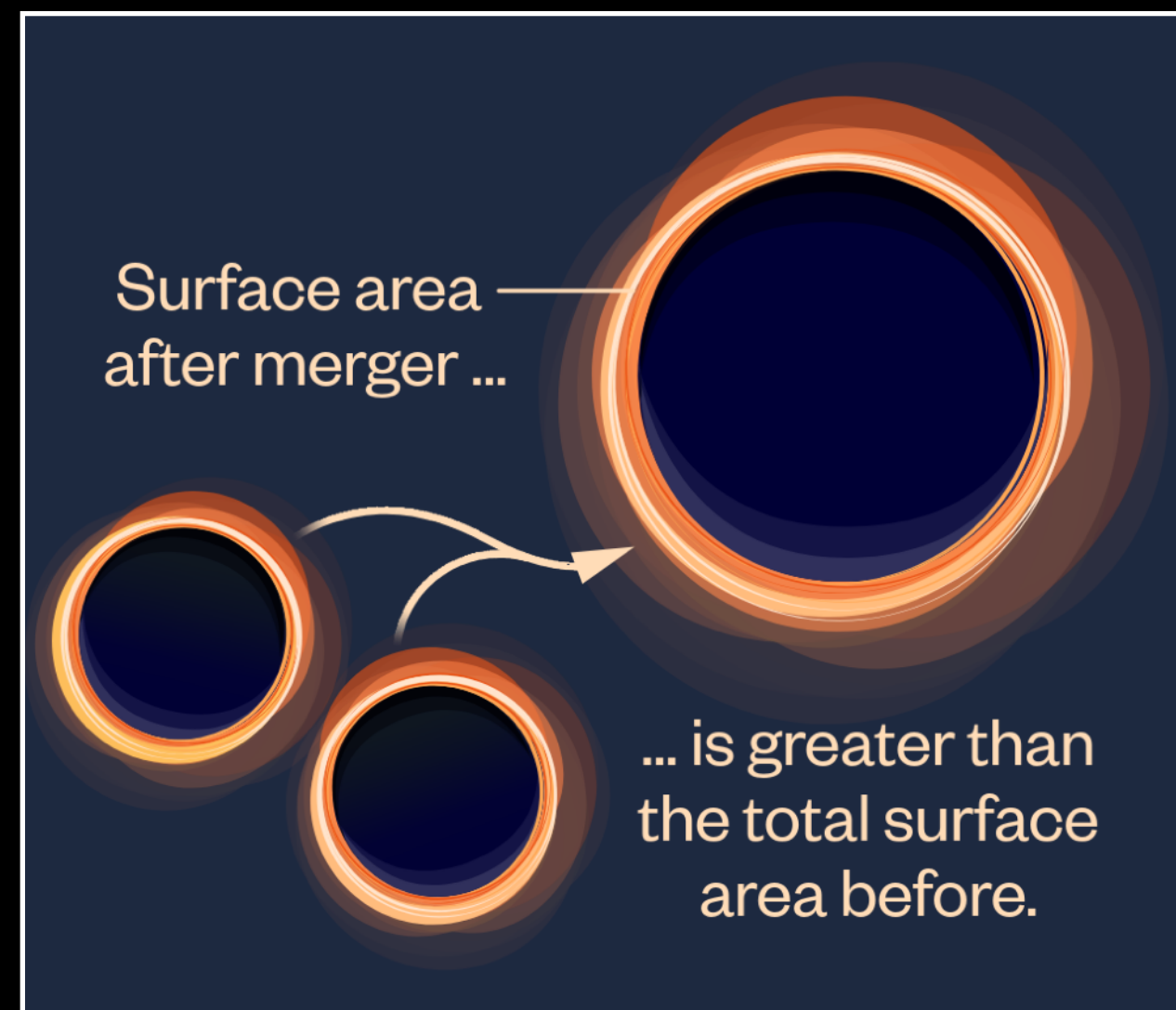


The black hole horizon area cannot decrease in time:

$$\mathcal{A} = 8\pi \left( \frac{GM}{c^2} \right)^2 \left( 1 + \sqrt{1 - \chi^2} \right)$$

Mass Spin

# Testing Hawking's area law

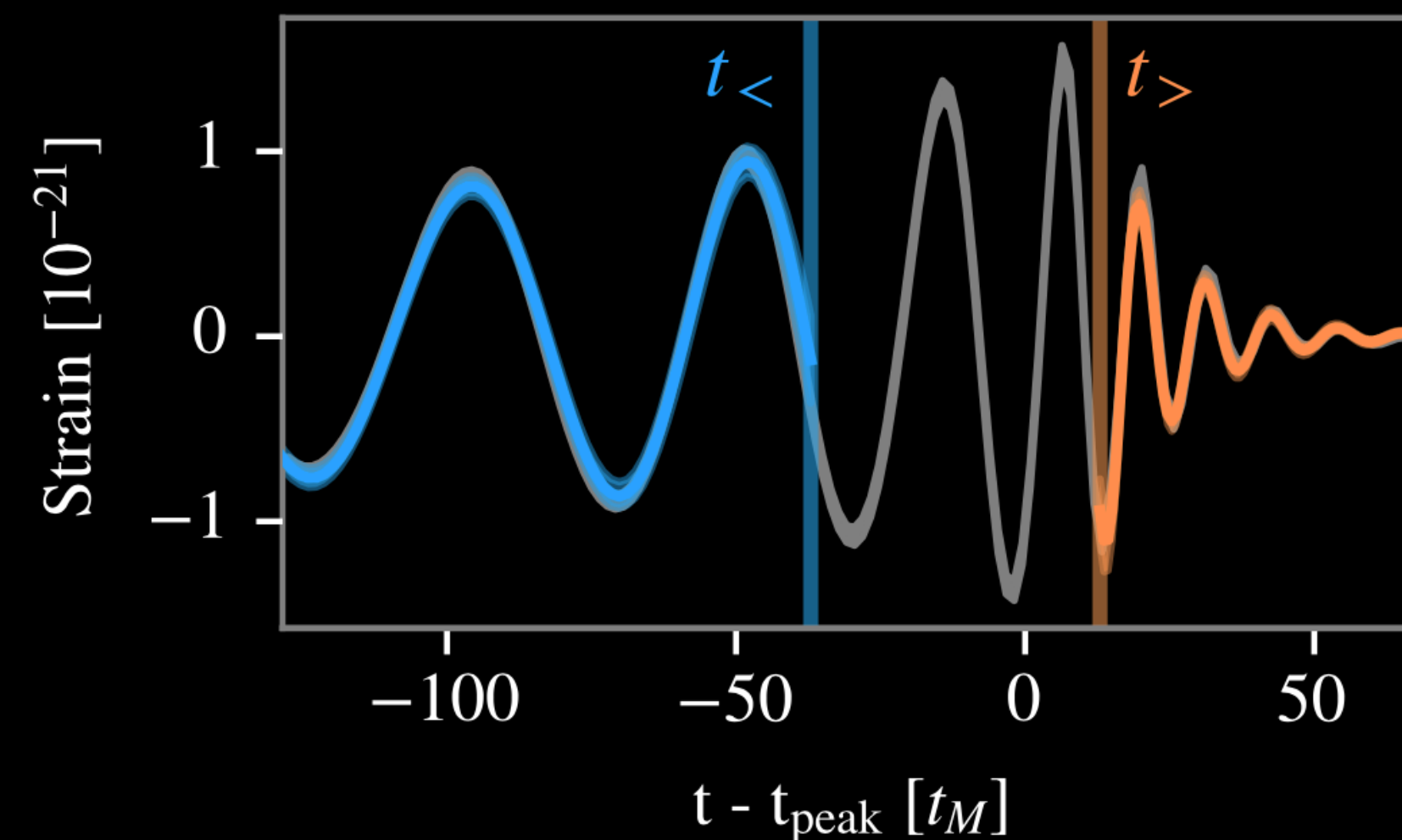


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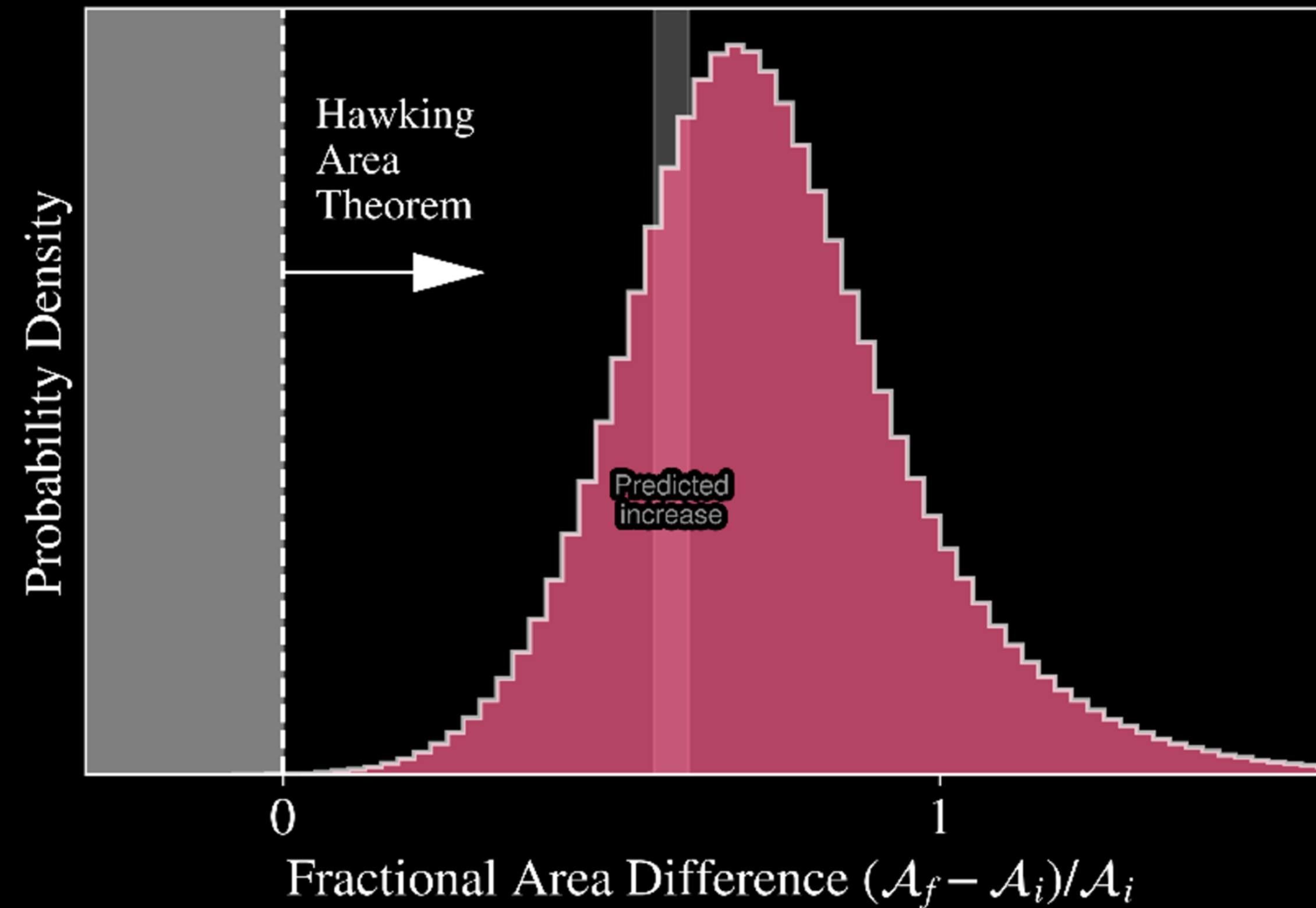
Mass Spin

We compare the areas of the black holes before and after the merger.



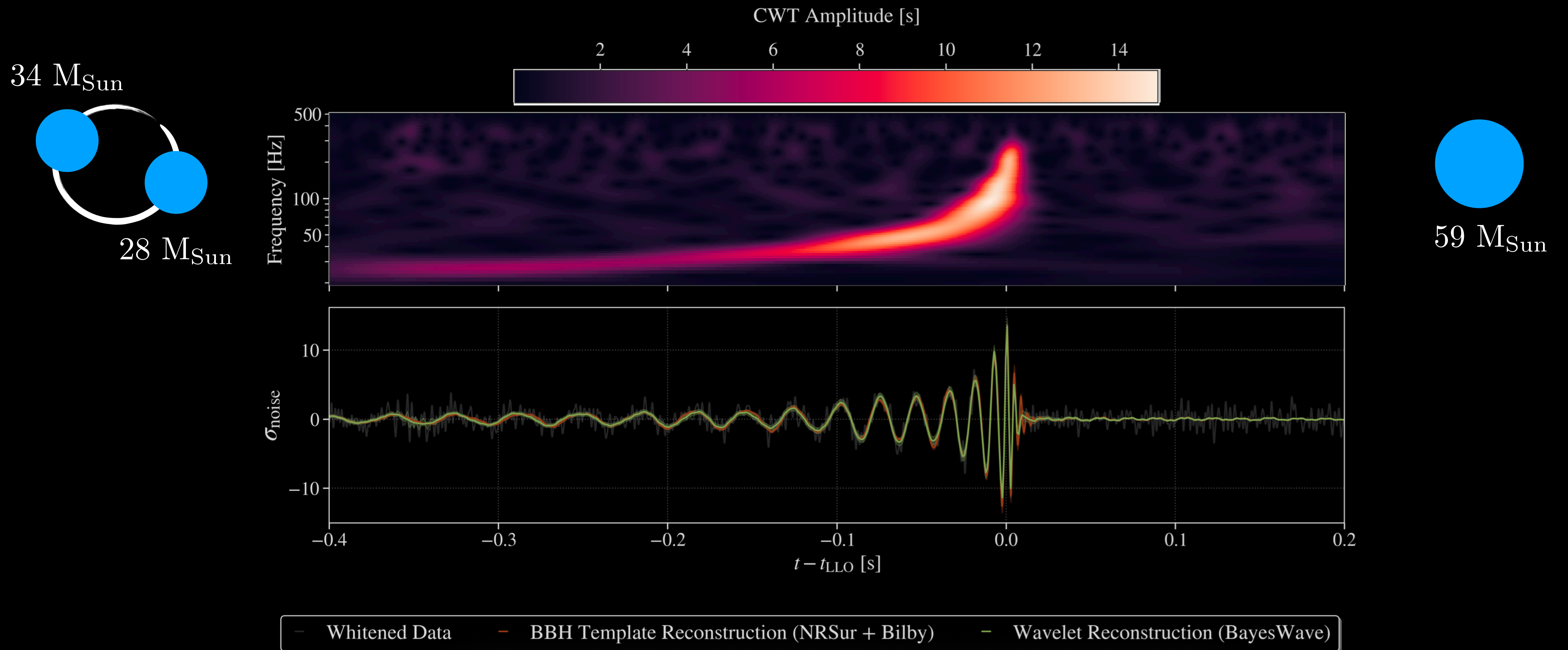
# Testing Hawking's area law

GW250114 confirms that the remnant area is larger than the sum of the initial areas.

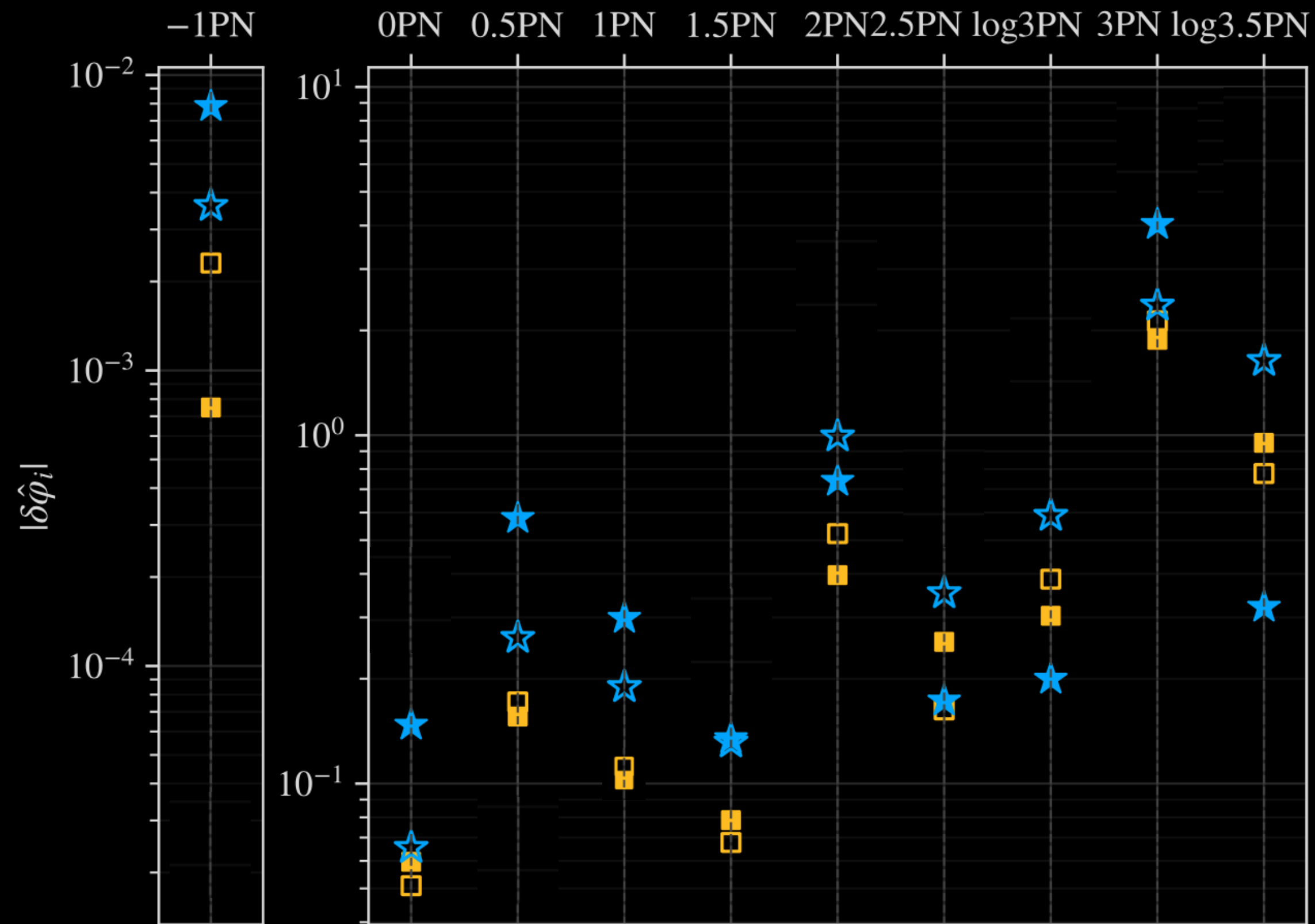


# GW230814

The loudest gravitational-wave signal in the fourth catalog detected by LIGO Livingston, with signal-to-noise ratio of 42.4.



# The inspiral of GW230814



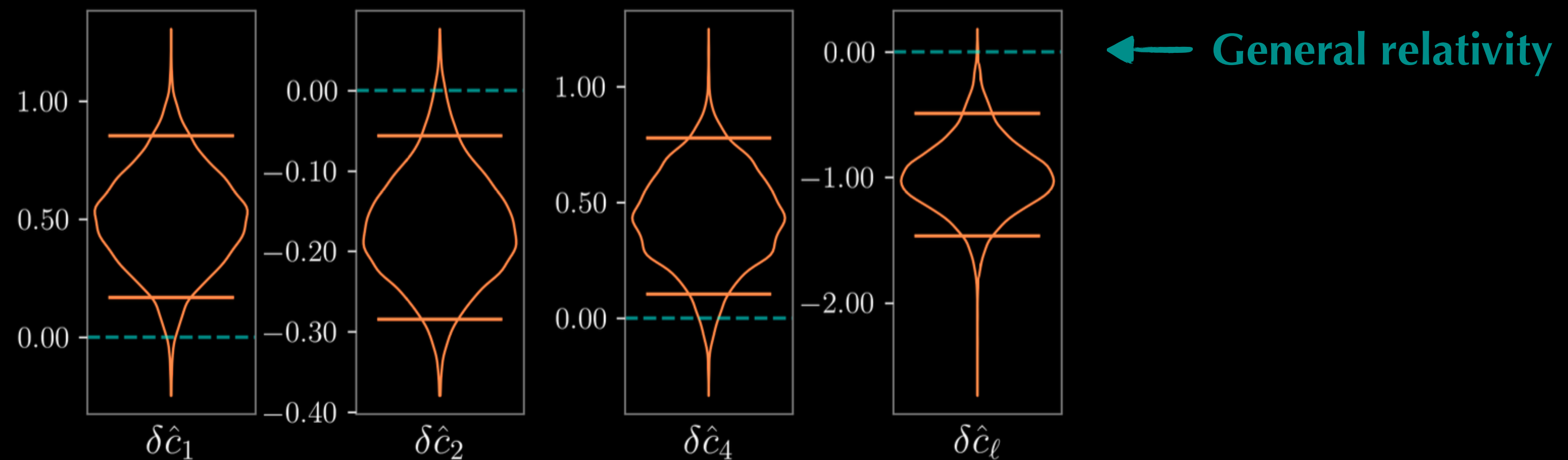
The inspiral parameters are consistent with general relativity.

- ★ GW230814 (FTI)
- ★ GW230814 (TIGER)
- GWTC-3 (FTI)
- GWTC-2 (TIGER)

# The merger-ringdown of GW230814

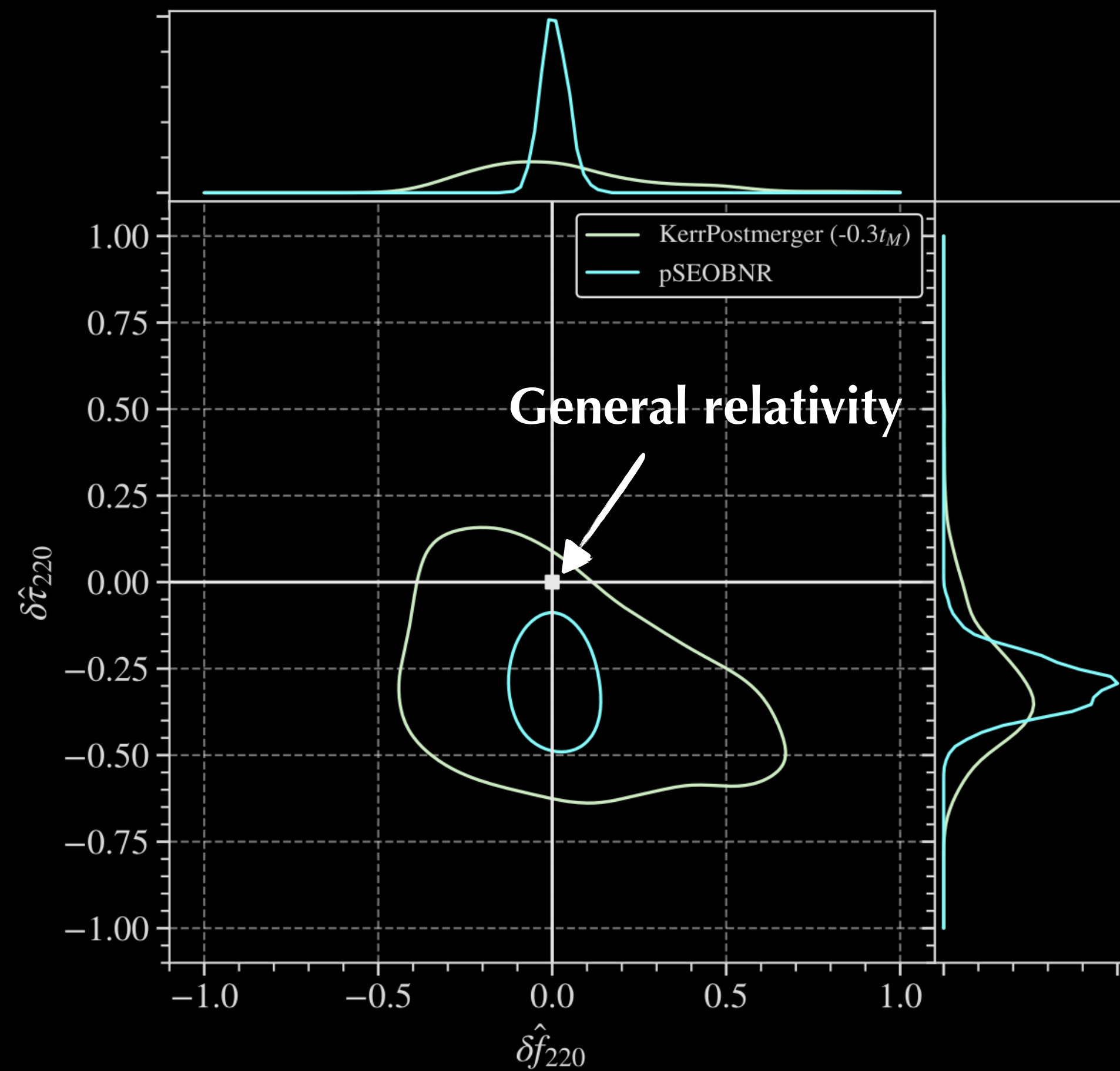
We constrain fractional deviations from general relativity in the merger-ringdown part.

*Merger-ringdown  
parameters*



The posteriors are shifted from general relativity, with negative  $\log_{10}$  Bayes factors.

# The ringdown of GW230814



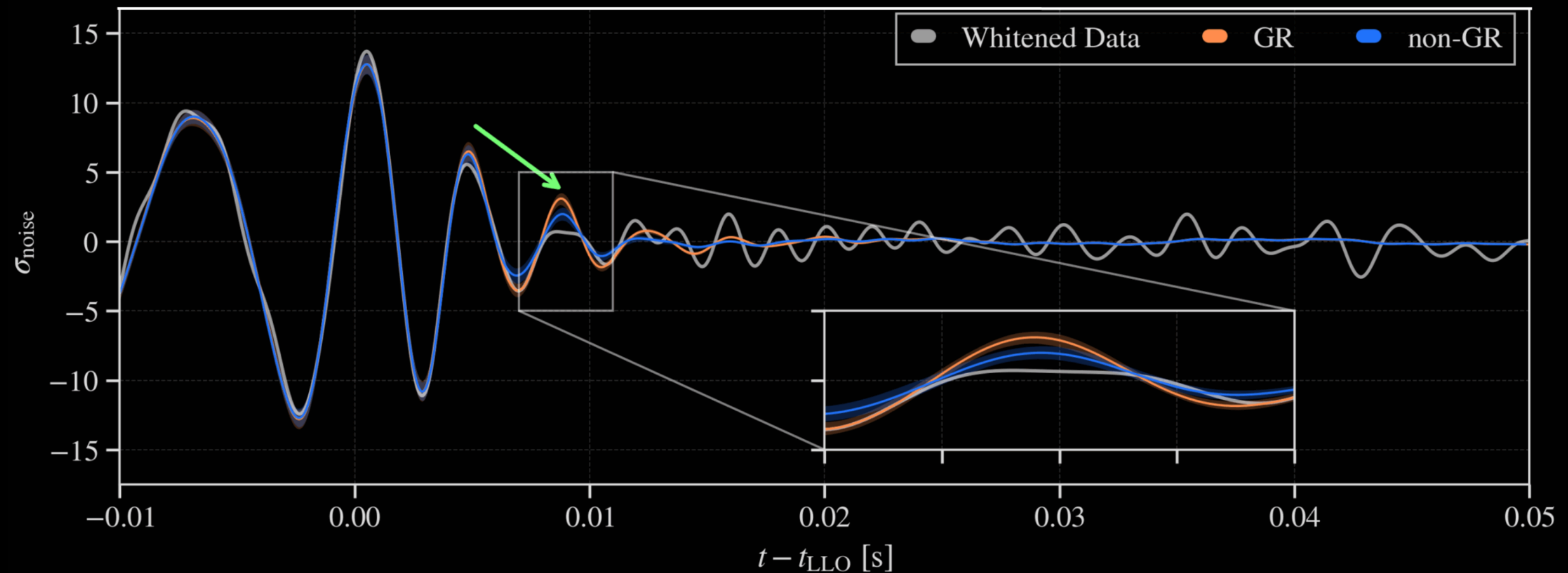
The data supports a damping time smaller than expected from general relativity:

$$\delta \hat{\tau}_{220} = -0.3^{+0.15}_{-0.12}$$

The  $\log_{10}$  Bayes factor is -0.43.

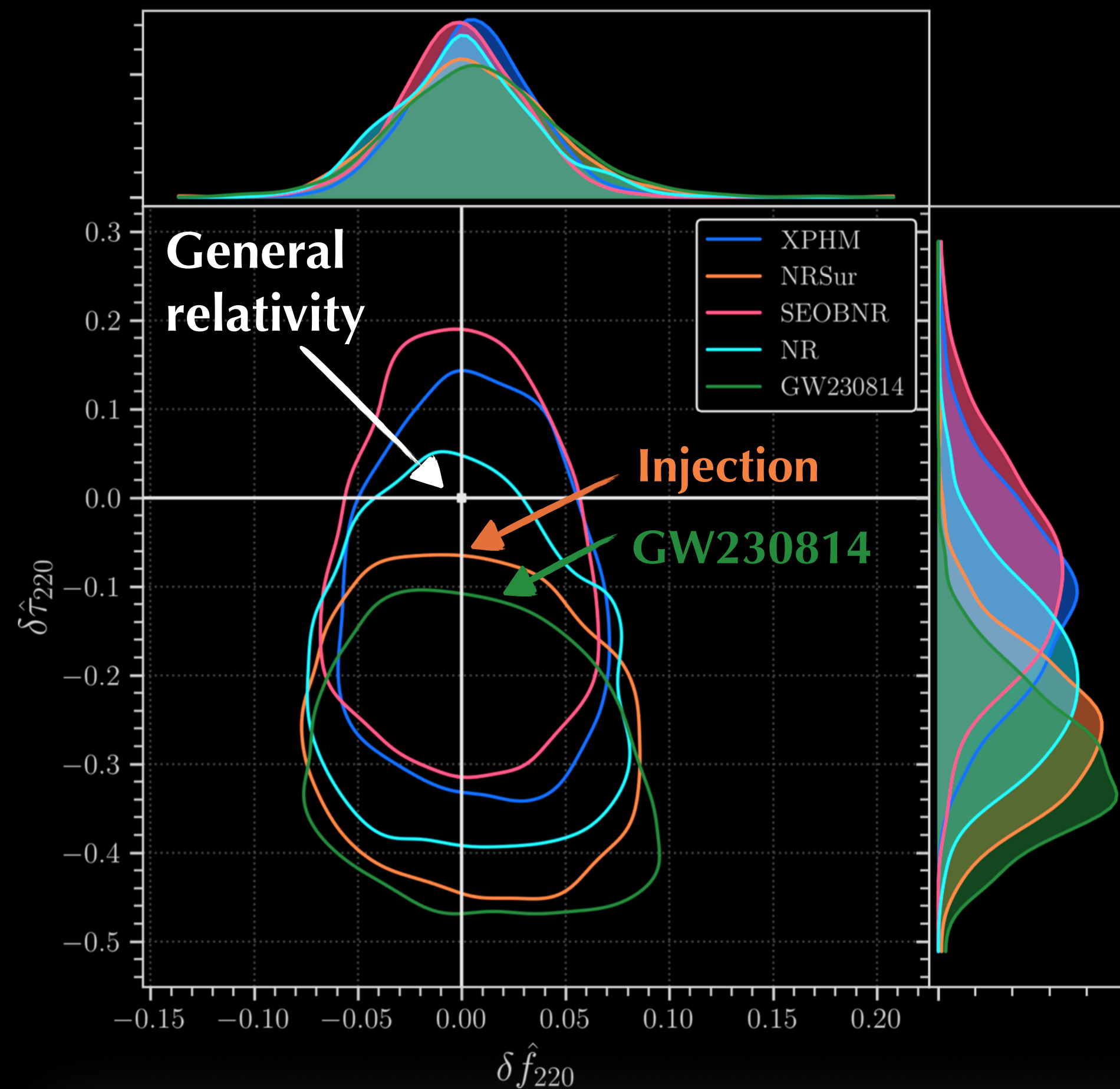
# The ringdown of GW230814

The ringdown analysis provides a visibly better fit to the data. *What causes this deviation?*



# Assessing waveform systematics

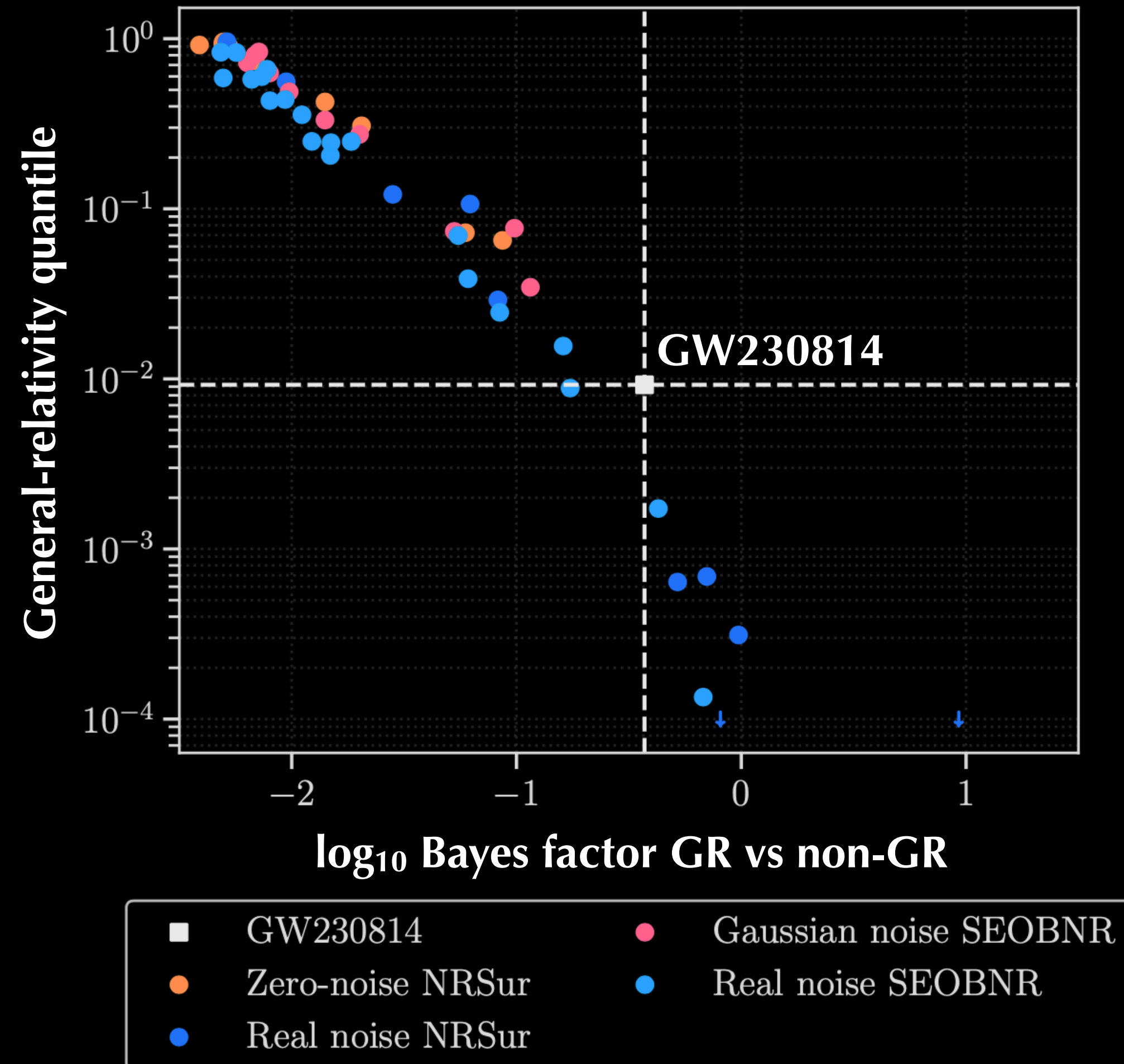
We perform injections with different waveform models in zero noise.



*Waveform systematics could contribute to the observed bias in the ringdown damping time.*

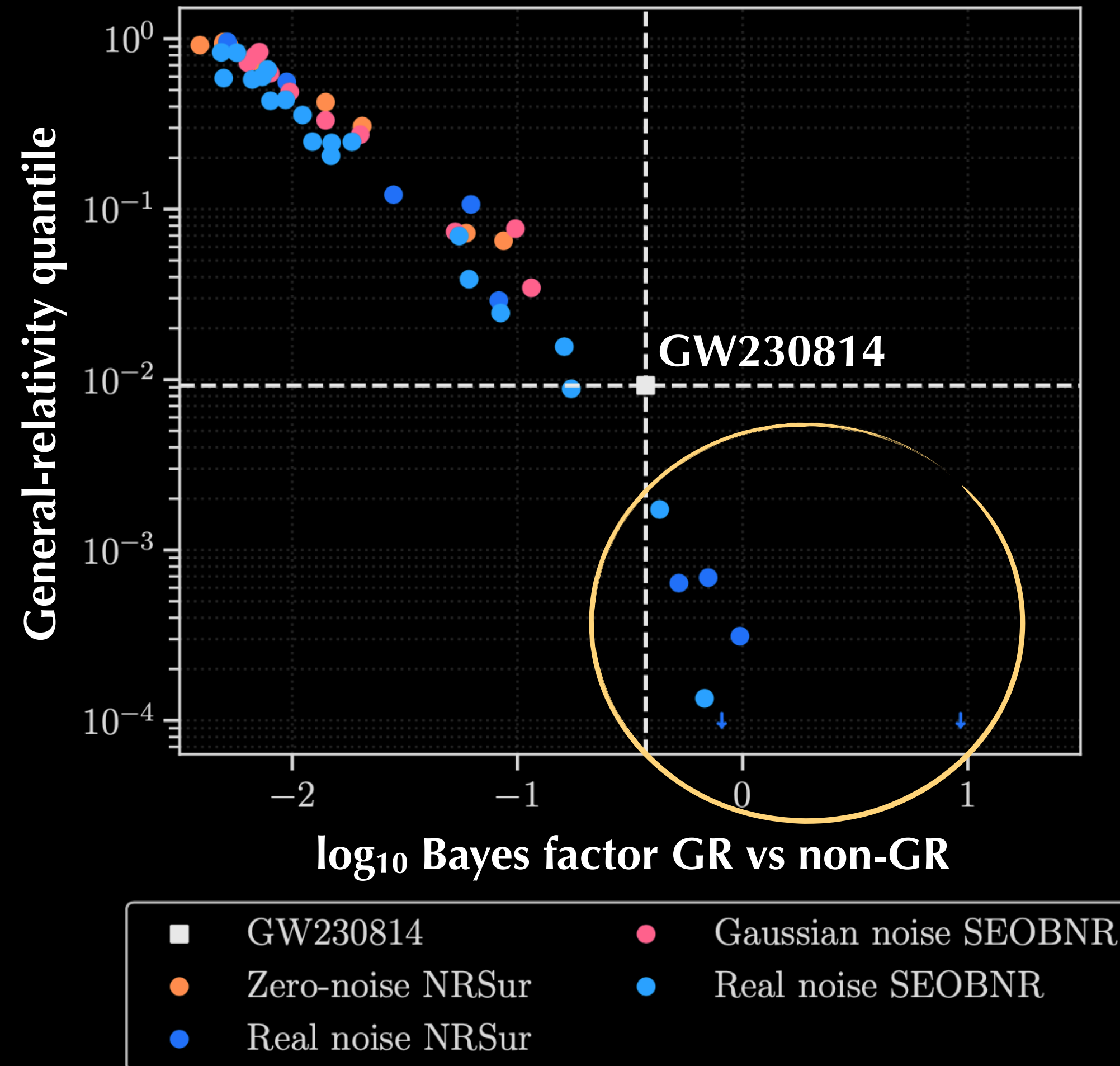
# Assessing detector effects

We perform injections in the real noise of the detector at various times around the event.



# Assessing detector effects

We perform injections in the real noise of the detector at various times around the event.



*Statistical fluctuations in real detector noise can be responsible for apparent deviations from general relativity in the ringdown.*

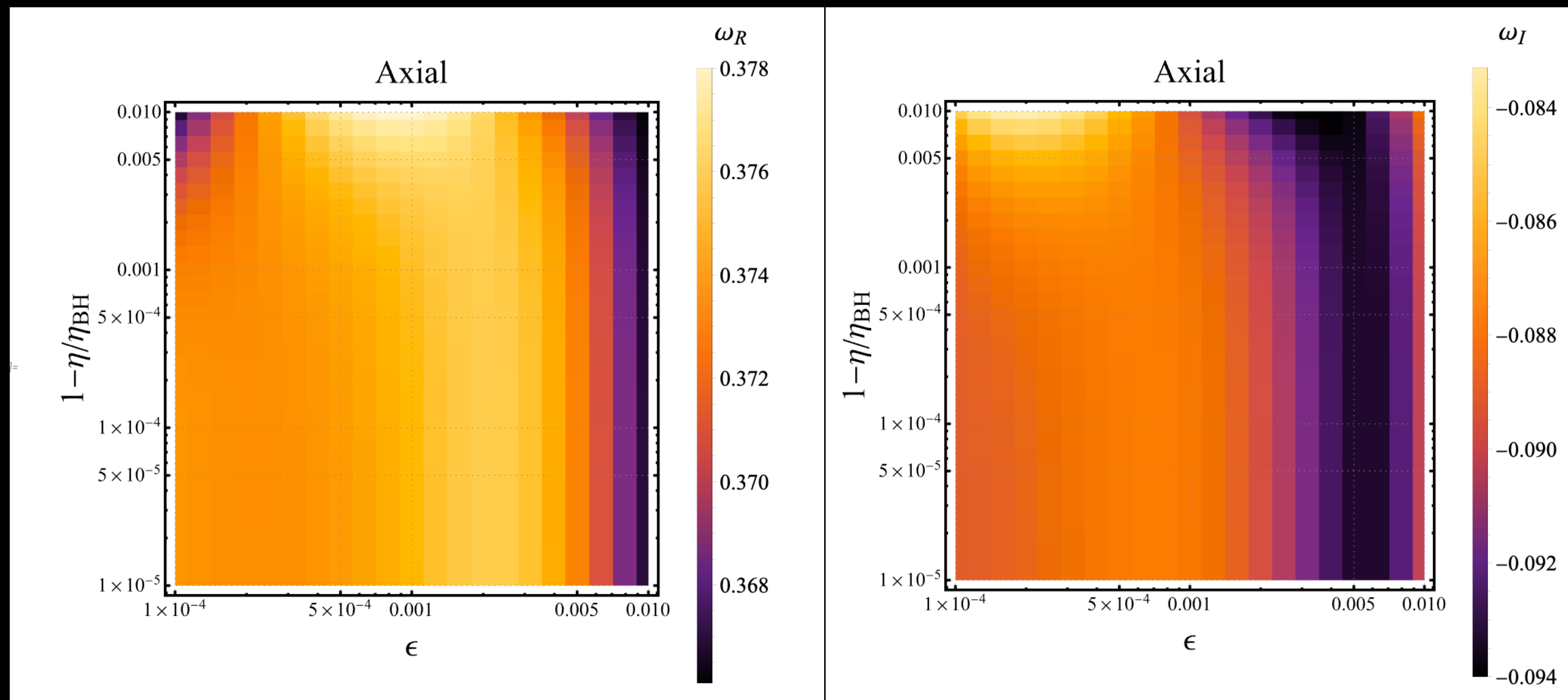
# What have we learnt?

- GW230814 highlights the need for a global network of gravitational-wave observatories for robust tests of fundamental physics.
- We need accurate studies of waveform systematics and noise.

# Prospects with next-generation detectors

LISA could constrain the quasinormal modes of heavy massive black-hole binaries at 0.1%.

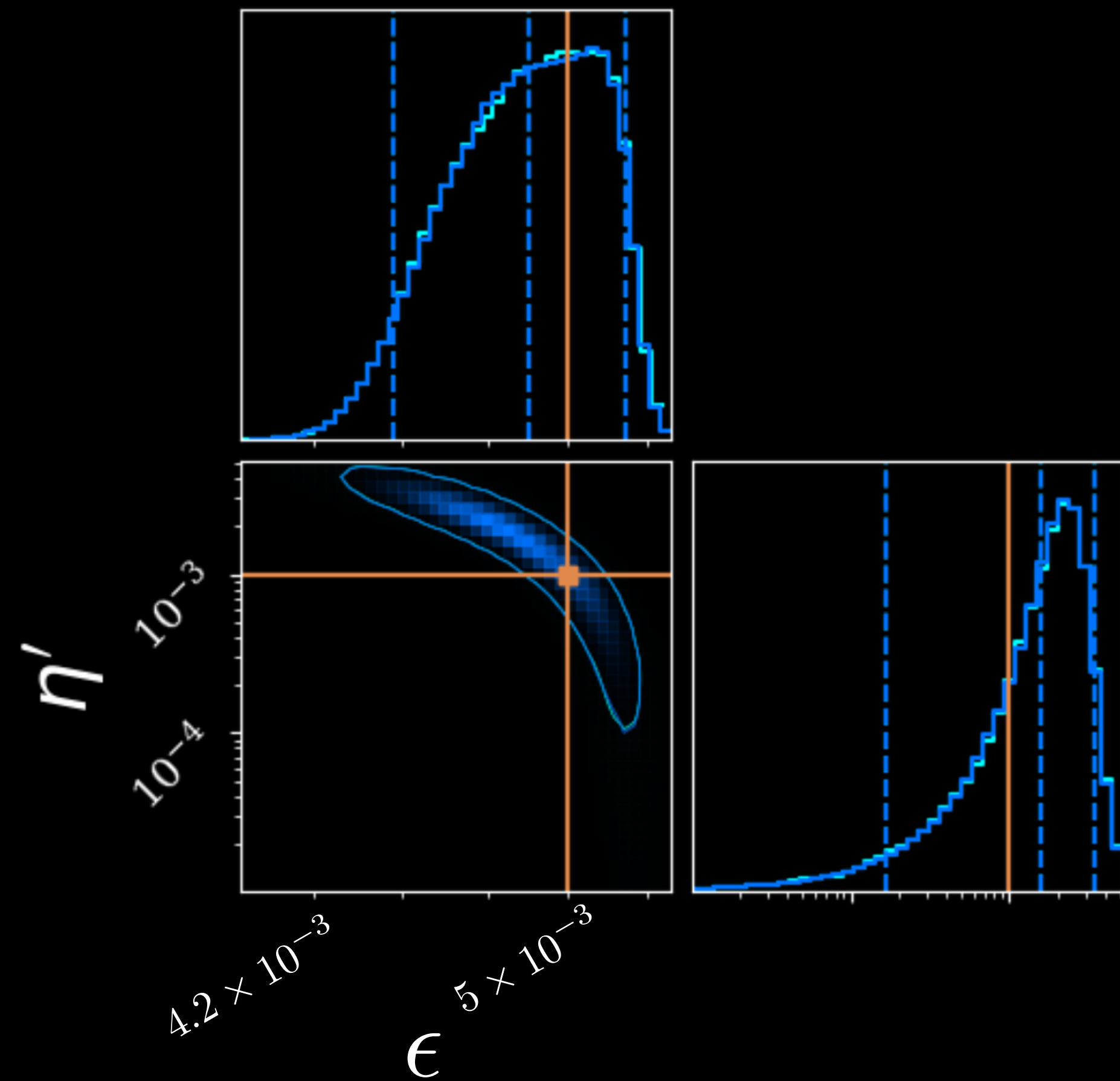
Toubiana+, PRD 109, 104019 (2024)



The quasinormal modes of compact objects depend on their compactness and reflectivity.

Muller, EM, Toubiana, in prep.

# Prospects with next-generation detectors



We can infer the compactness and the reflectivity of the merger remnants with accurate precision.

# Conclusions and future prospects

- We can test the physics at the horizon scale with gravitational waves.
- Horizonless compact objects are not excluded by current observations.
- Next-generation detectors will allow us to perform unprecedented tests of the black hole paradigm.
- Improve the modeling of horizonless compact objects (including spin, inspiral-merger-ringdown waveforms).
- Develop strategies to mitigate waveform and noise systematics.