New Frontiers in Strong Gravity

21 July 2026

How to assess false general relativity violations in gravitational-wave observations?

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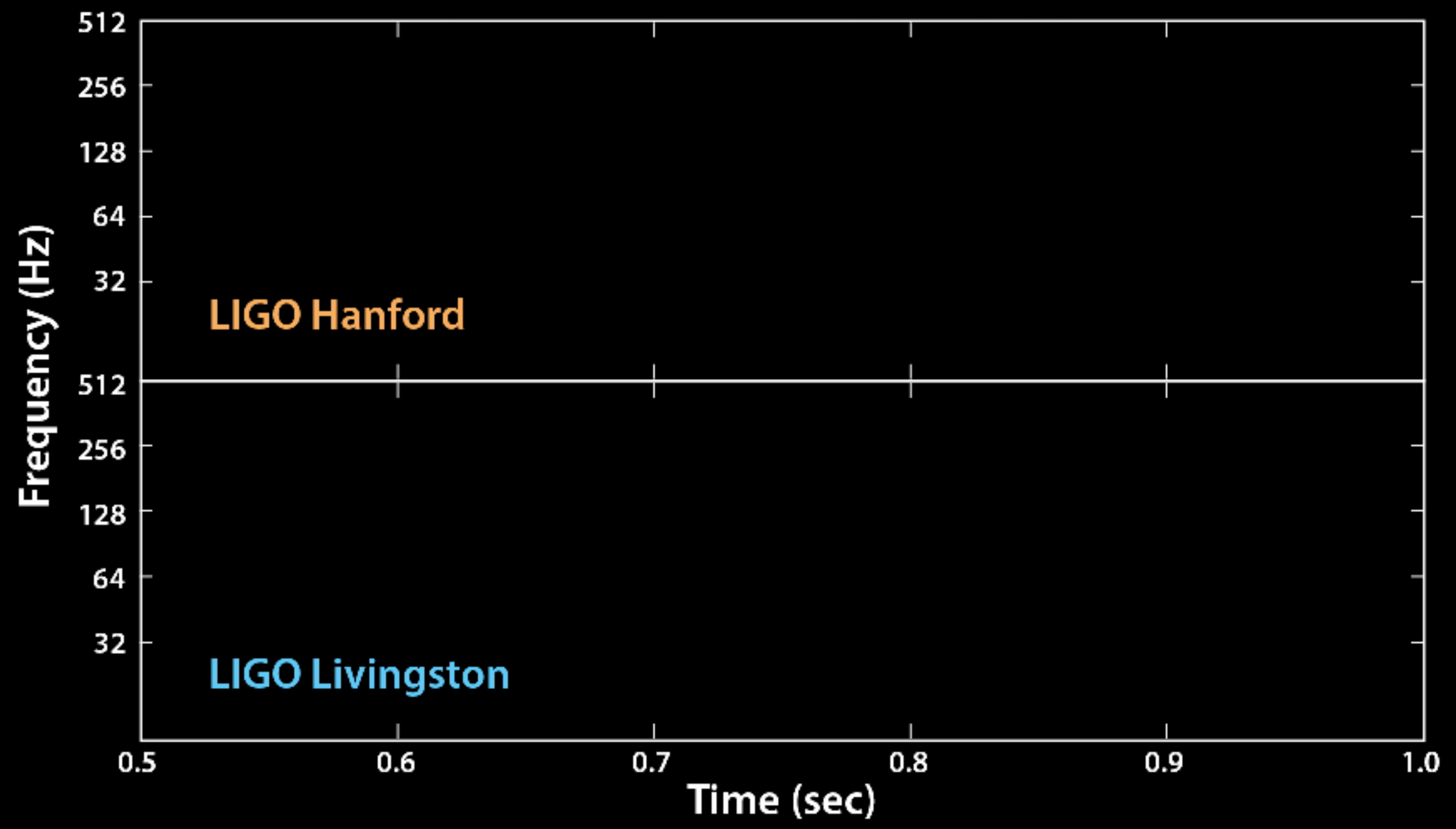
INFN

FONDO ITALIANO PER LA SCIENZA

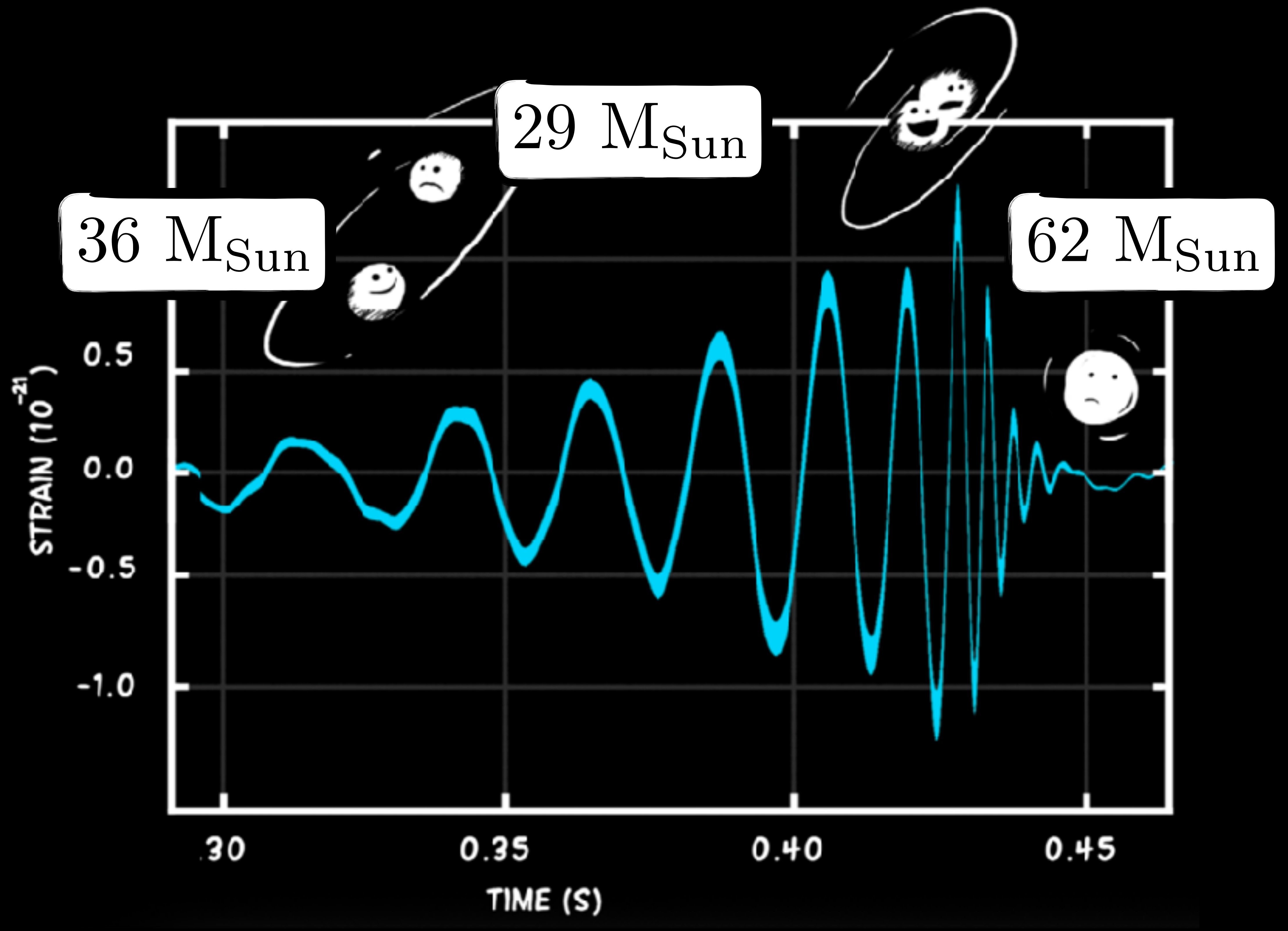
MUR

GW150914

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

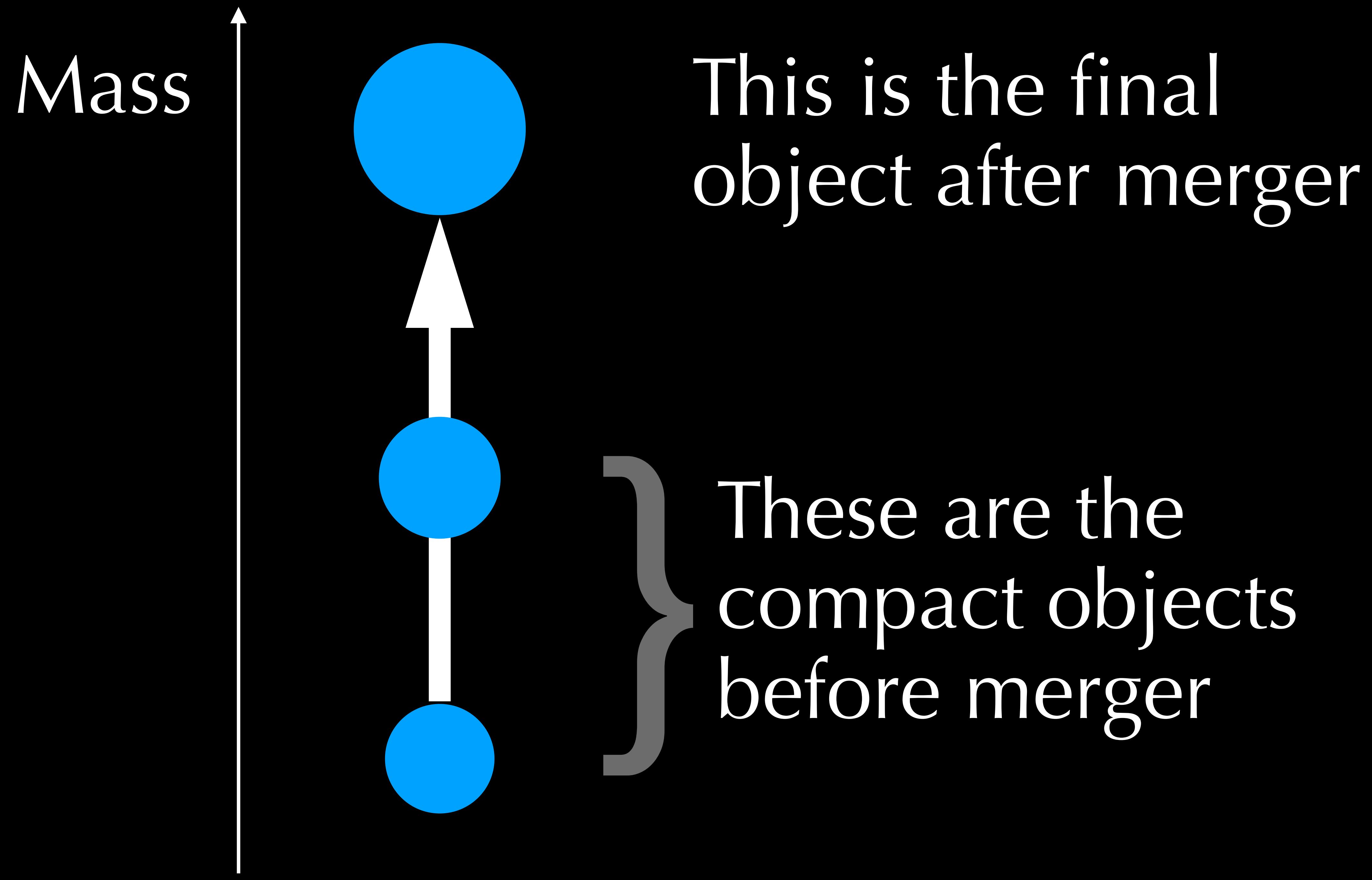


Signal-to-noise ratio = 24



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

How many detections have we had?



Black Holes and Neutron Stars

Gravitational-wave events

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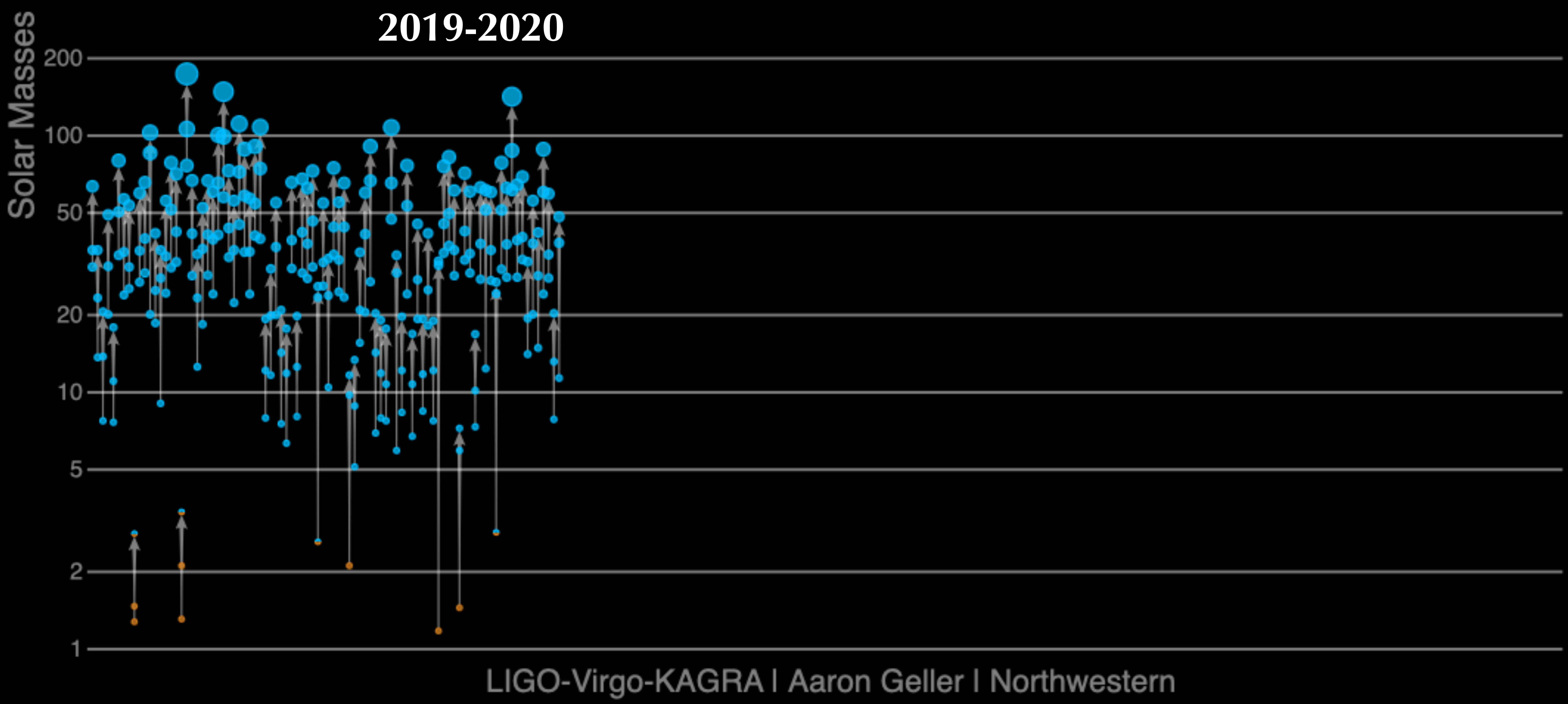
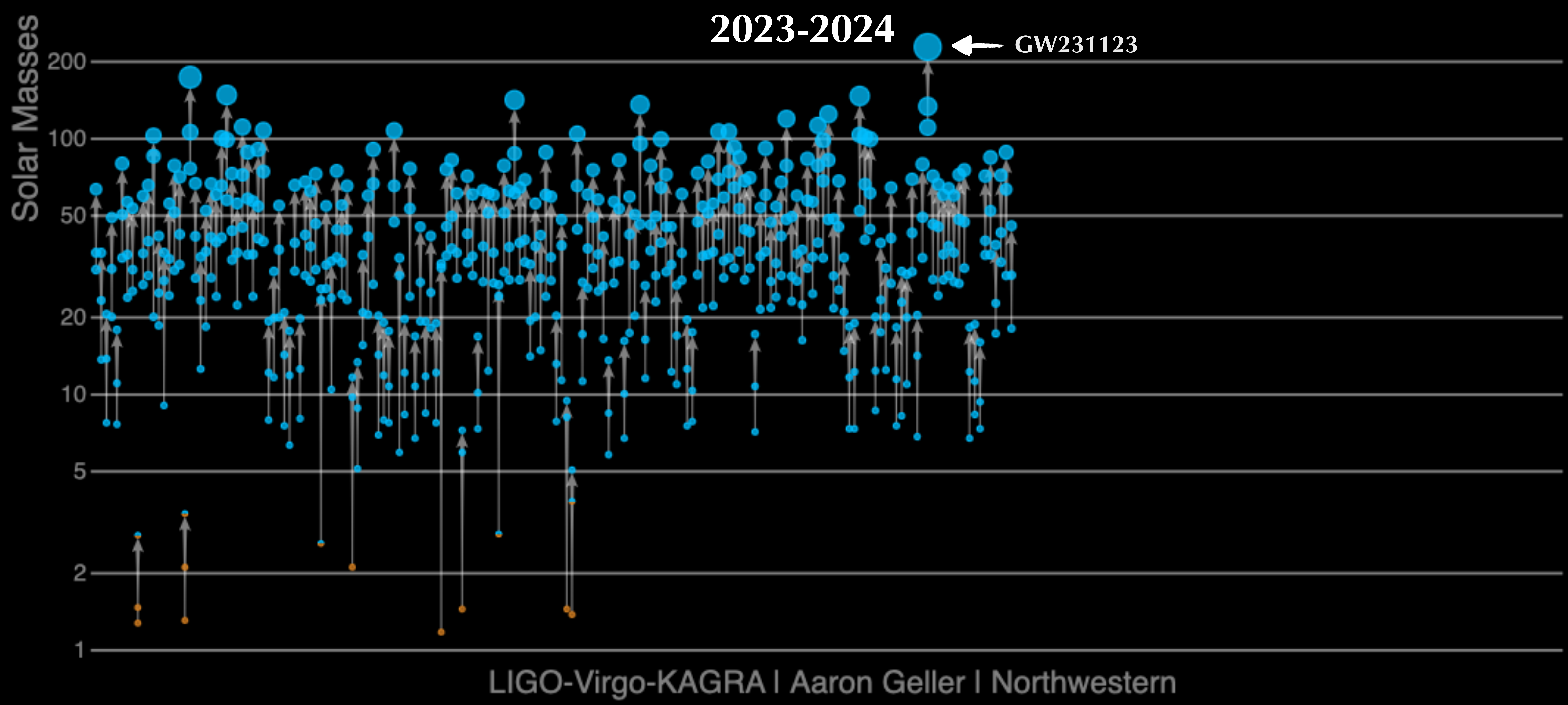
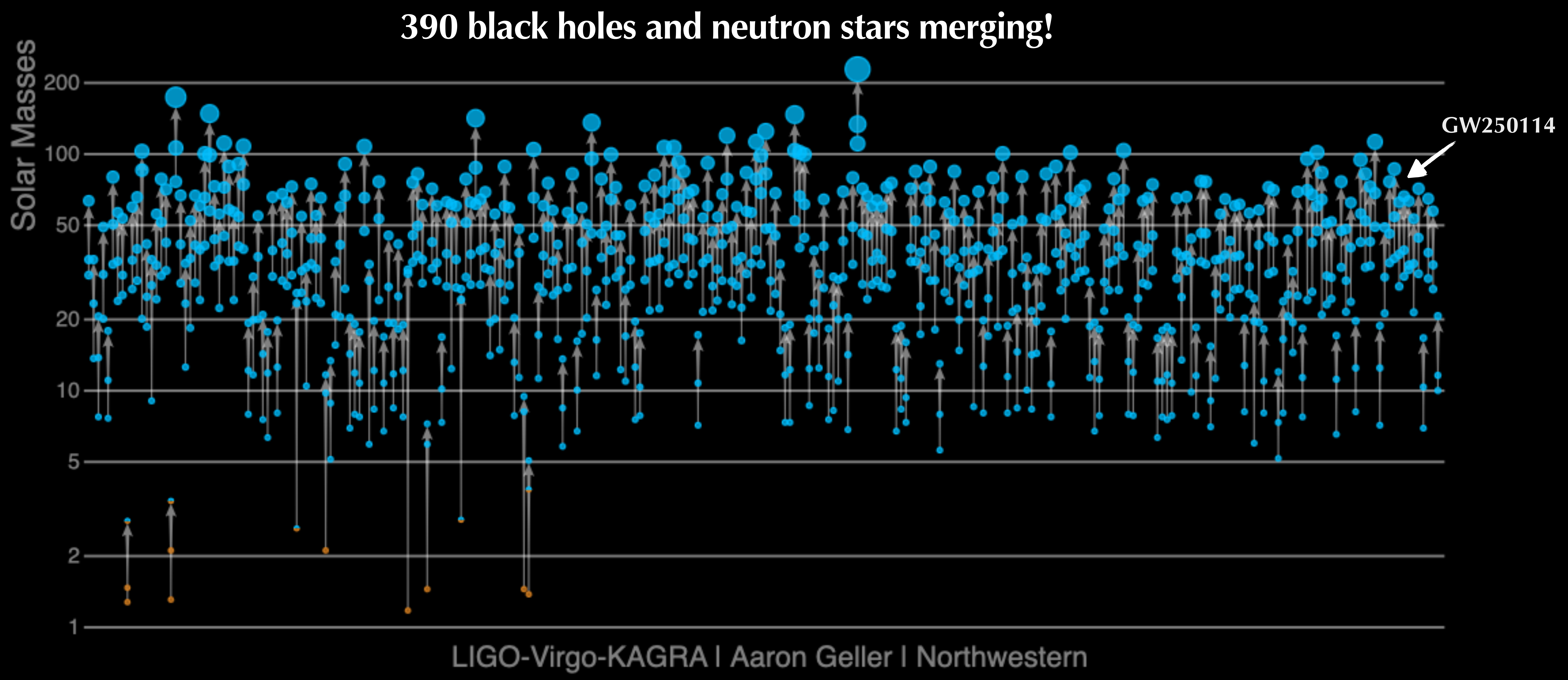


Gravitational-wave events



New Results from the LIGO-Virgo-KAGRA Collaboration

Gravitational-wave events

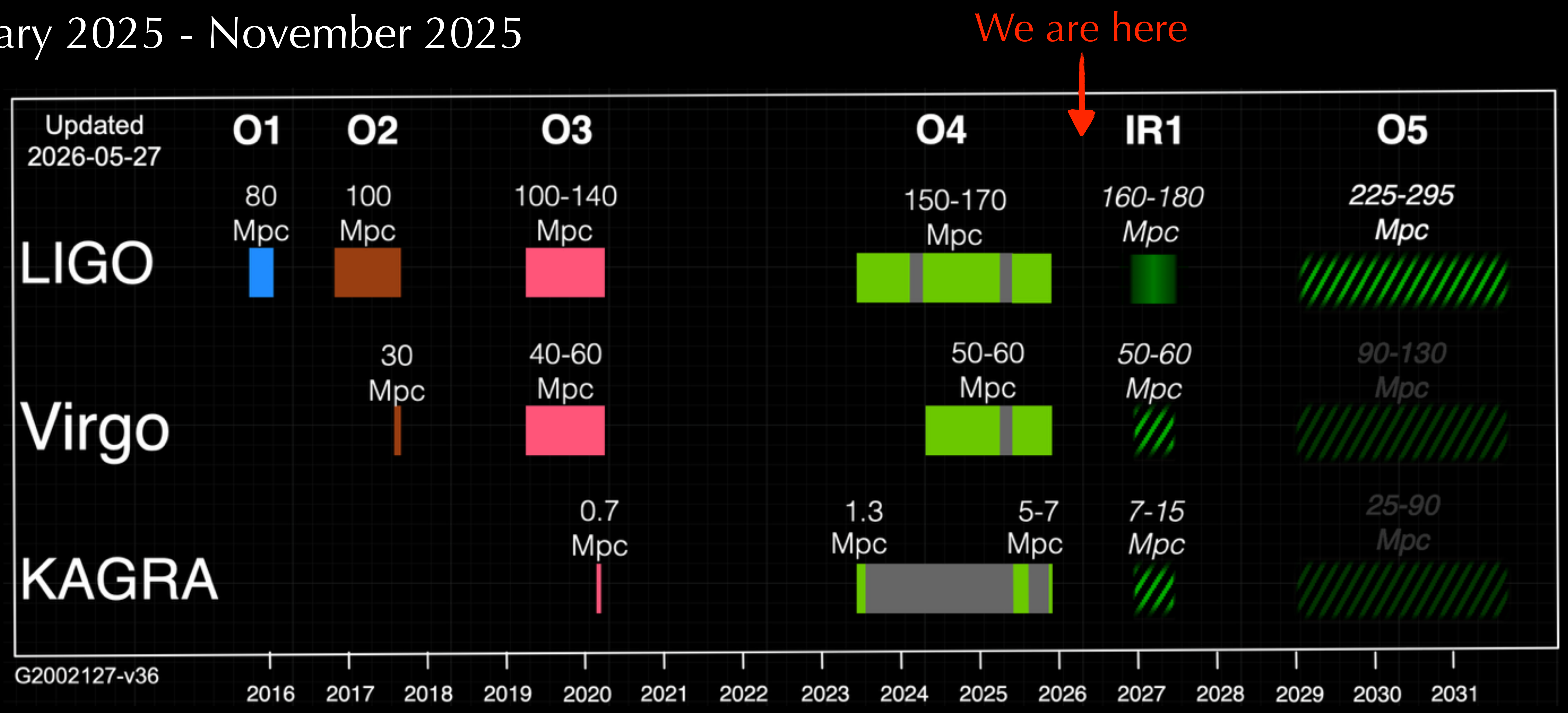


The observing runs

O4a: May 2023 - January 2024

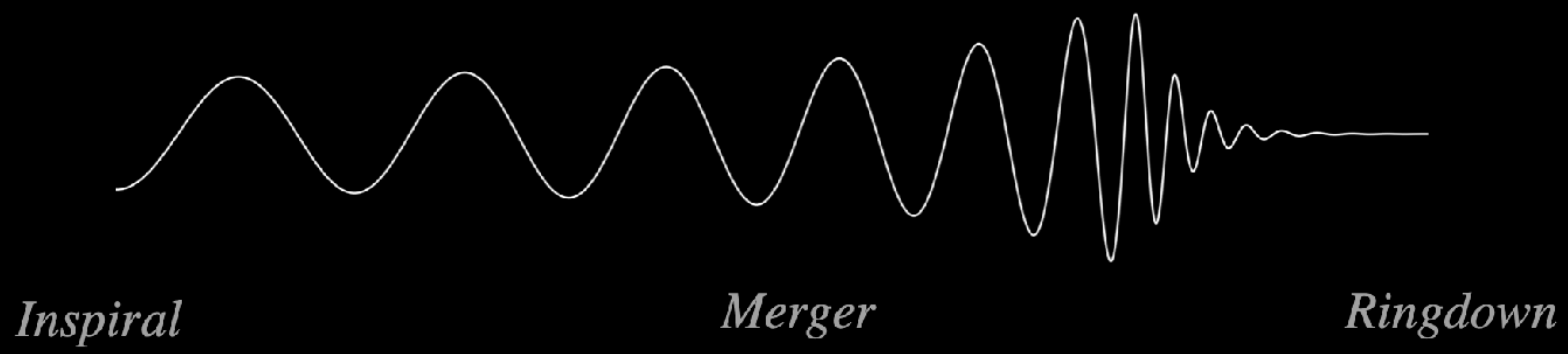
O4b: April 2024 - January 2025

O4c: January 2025 - November 2025



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

Compact binary coalescences



Gravitational waves provide a unique channel for probing gravity in the strong and dynamical regime.

Abbott+, PRD **100**, 104036 (2019); Abbott+, PRD **103**, 122002 (2021); Abbott+, arXiv: 2112.06861 (2021); Abac+, arXiv: 2603.19019, 2603.19020, 2603.19021 (2026)

Tests of general relativity

There are two approaches:

- Rely on waveforms in modified theories of gravity — Few template banks
- Look for generic departures from GR — Sensible to unmodelled physics within GR

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Gravitational waves can differ from general relativity in:

- Generation
- Propagation
- Polarization

LVK webinar

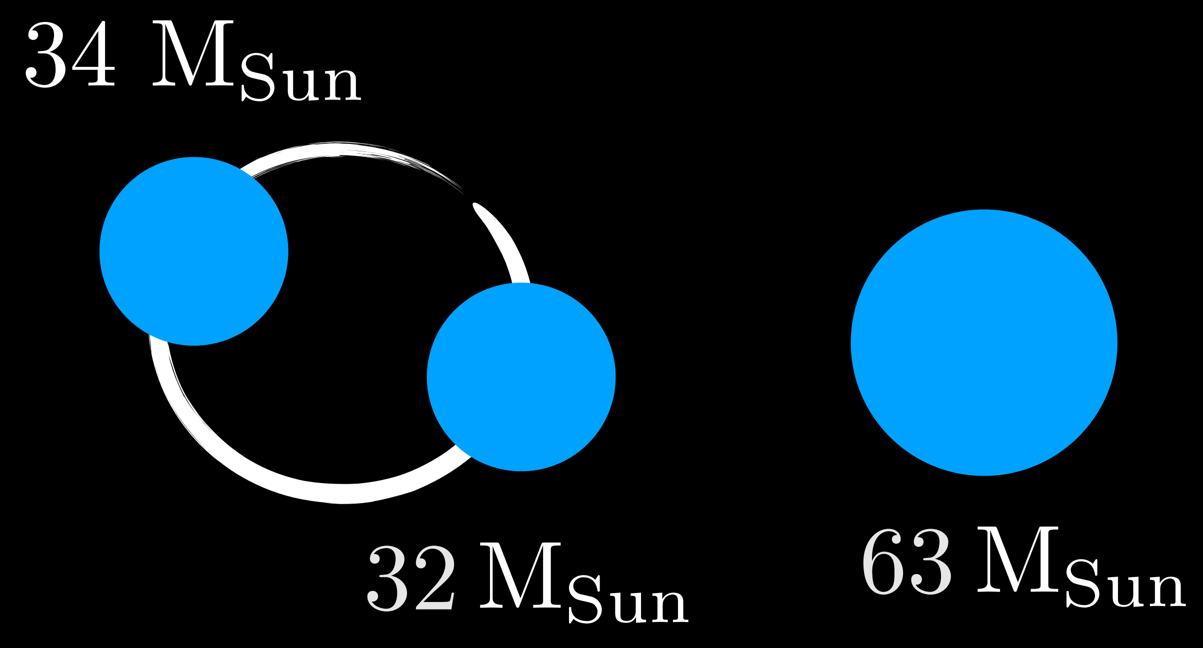
“GWTC-5:0: Tests of general relativity” & “Open Data from LVK through the O4b run”

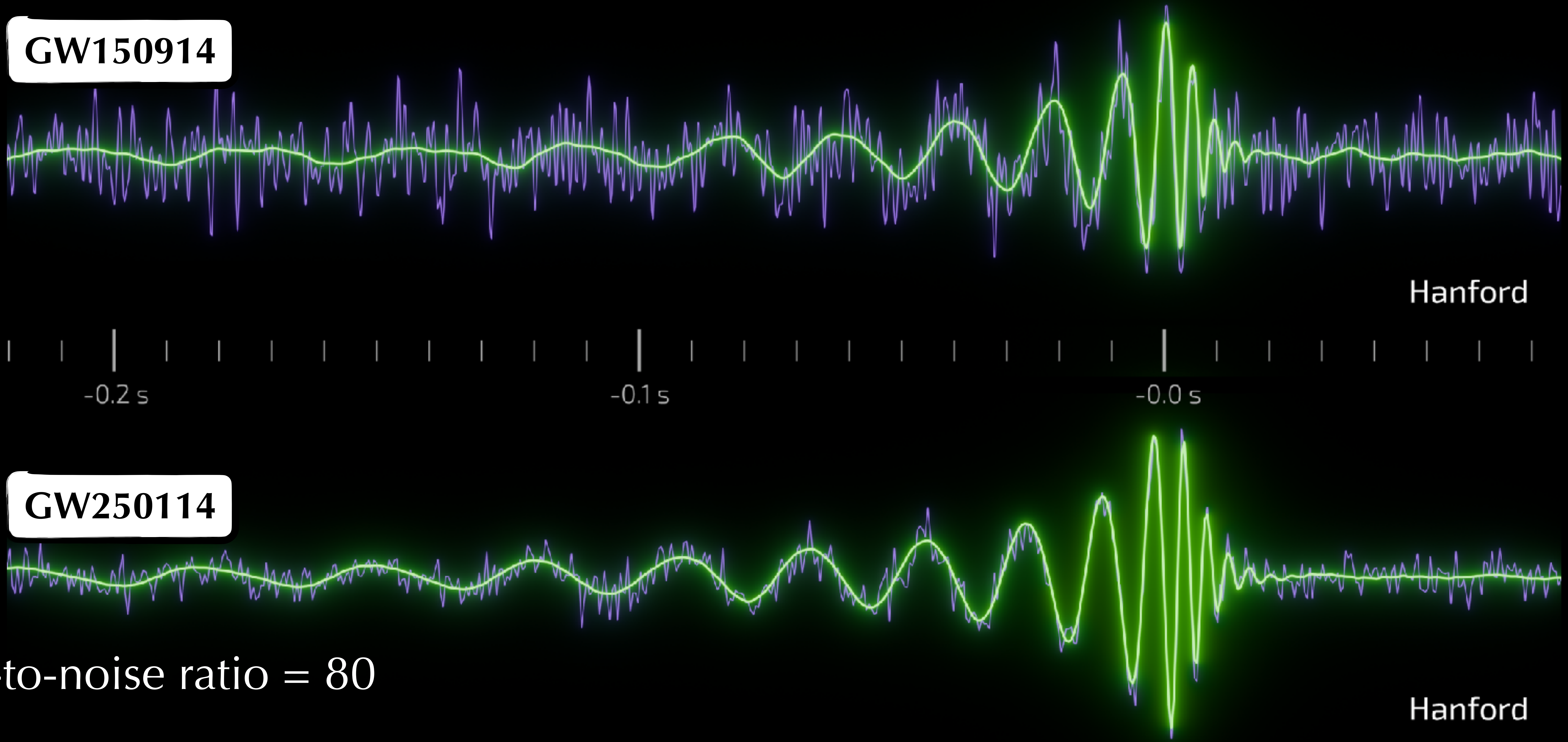
On Thursday 23 July at 4 pm CEST

Register for the webinar here

GW250114

The clearest view of merging black holes





Signal-to-noise ratio = 80

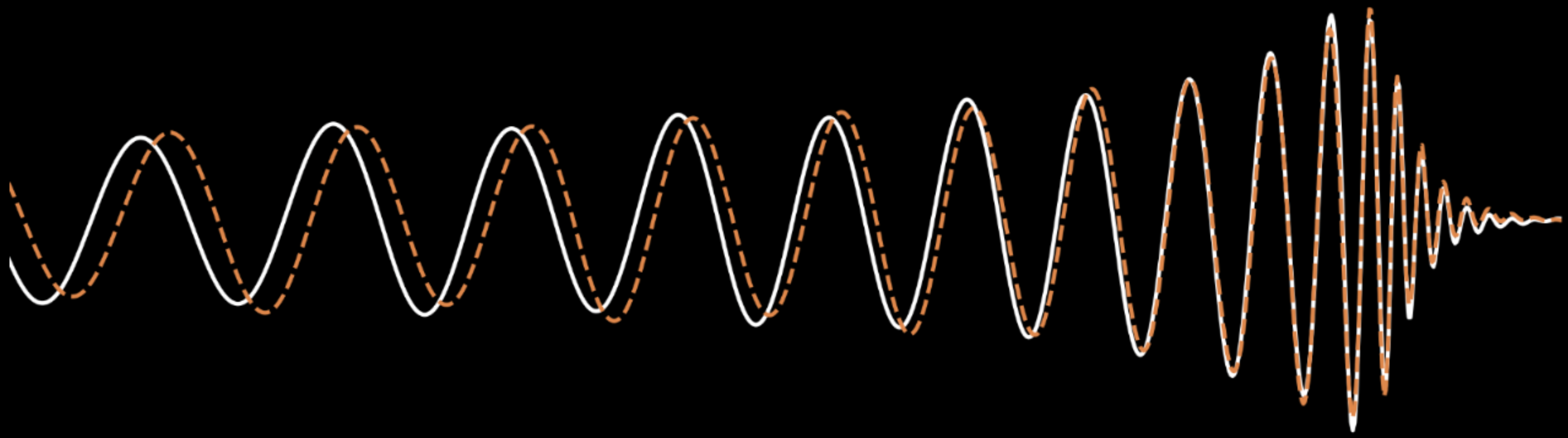
Abac et al., PRL **135**, 111403 (2025); Abac et al., arXiv:2509.08099

Inspiral tests

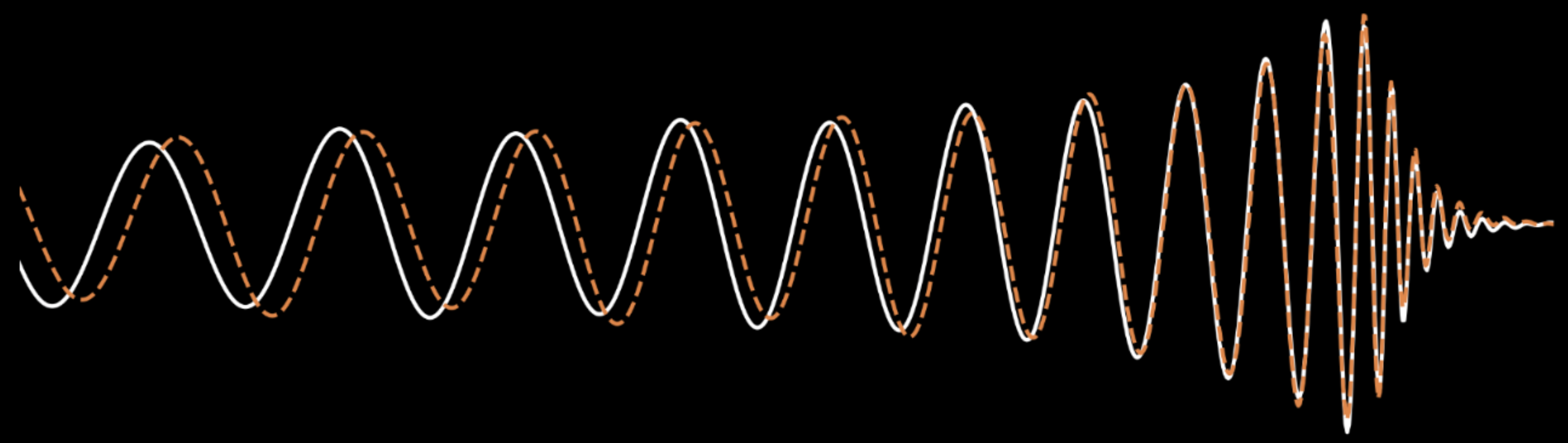
The inspiral stage is treated perturbatively in the **post-Newtonian** framework in powers of v/c.

The GW phase is: $\Psi_{\ell m}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3c^5}{128\eta v^5} \frac{|m|}{2} \sum_{n=0}^{7} \left(\psi_n + \psi_{nl} \log \frac{v}{c}\right) \frac{v^n}{c^n}$

We allow for deviations from GR



Inspiral tests



Flexible Theory Independent Method (FTI)

Mehta, PRD **107**, 044020 (2023)

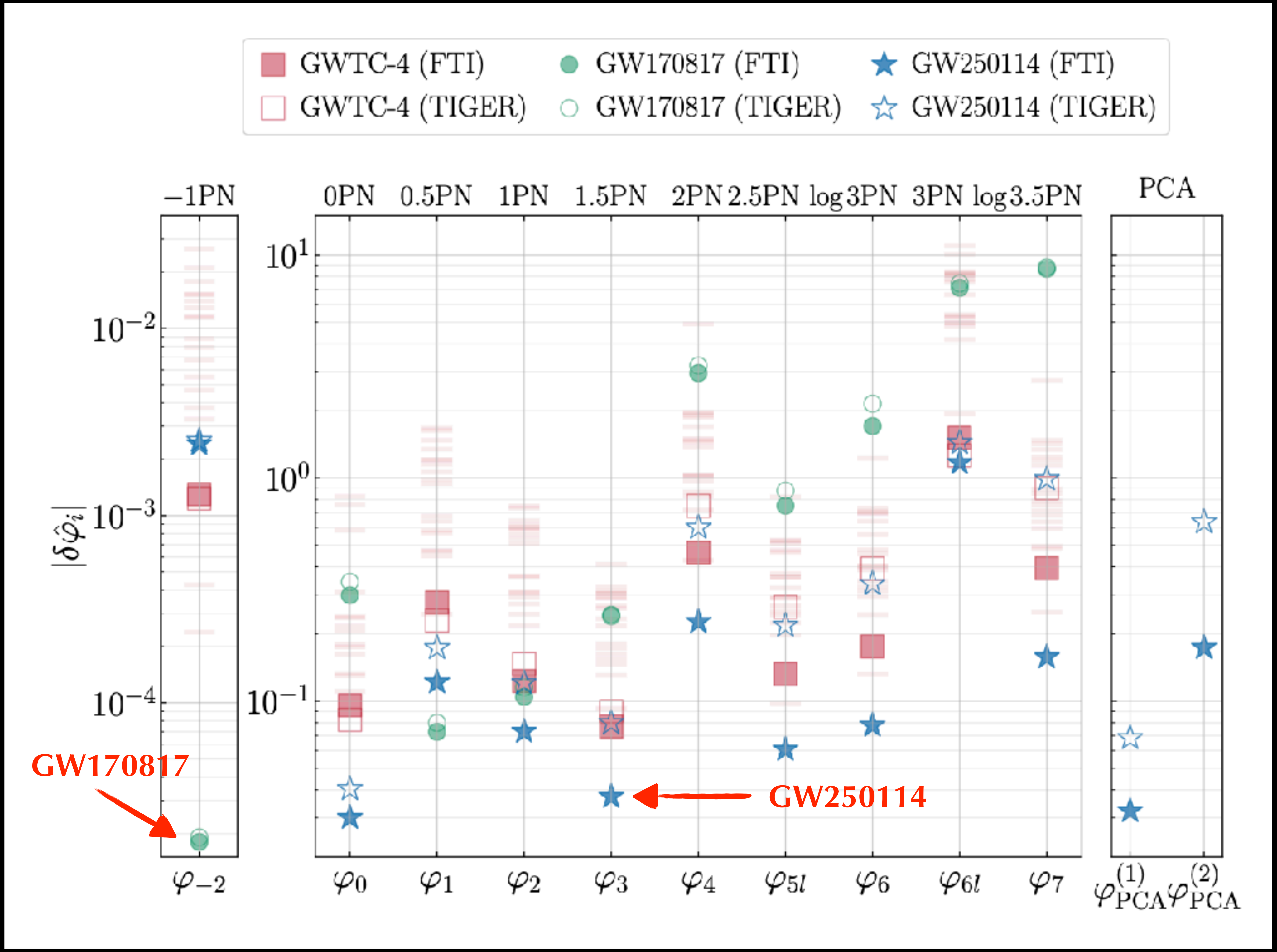
- Based on SEOBNRv5HM_ROM (nonprecessing)
- Inspiral ends around frequency of peak in dominant (2,2) mode

Test Infrastructure for GEneral Relativity (TIGER)

Agathos+, PRD **89**, 082001 (2014); Roy+, PRD **113**, 024016 (2026)

- Based on IMRPhenomXPHM
- Inspiral ends close to the minimum energy circular orbit frequency

Inspiral tests with GW250114



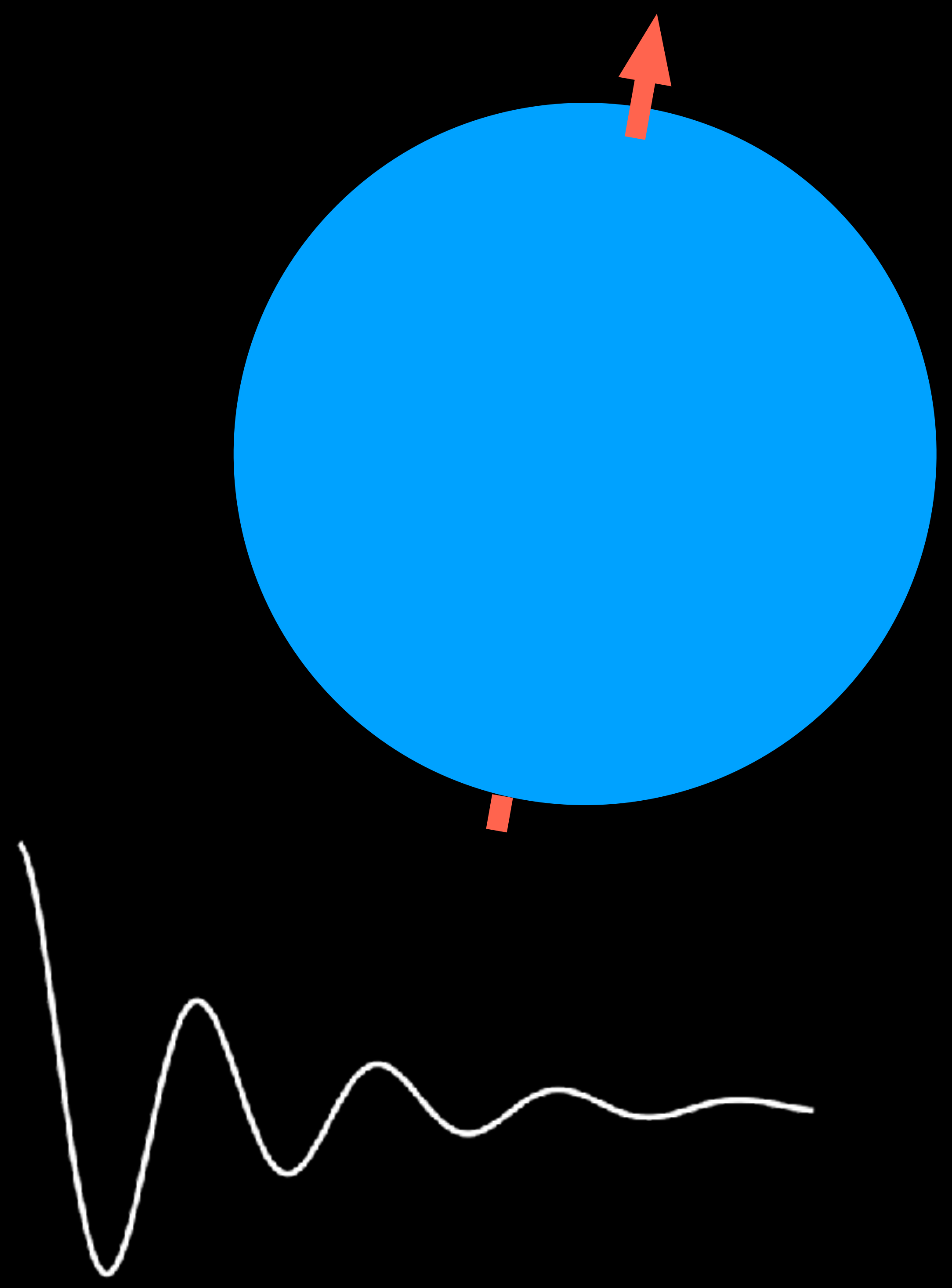
Due to its high SNR, GW250114 provides constraints on a subset of deviations that are 2–3 times more stringent than the joint constraints of the GWTC-4 results.

Abac et al., arXiv:2509.08099

The ringdown

The ringdown is dominated by characteristic oscillations of the remnant, known as **quasi-normal modes**:

$$\omega_{\ell mn} = \omega_{R,\ell mn} + i\omega_{I,\ell mn}$$



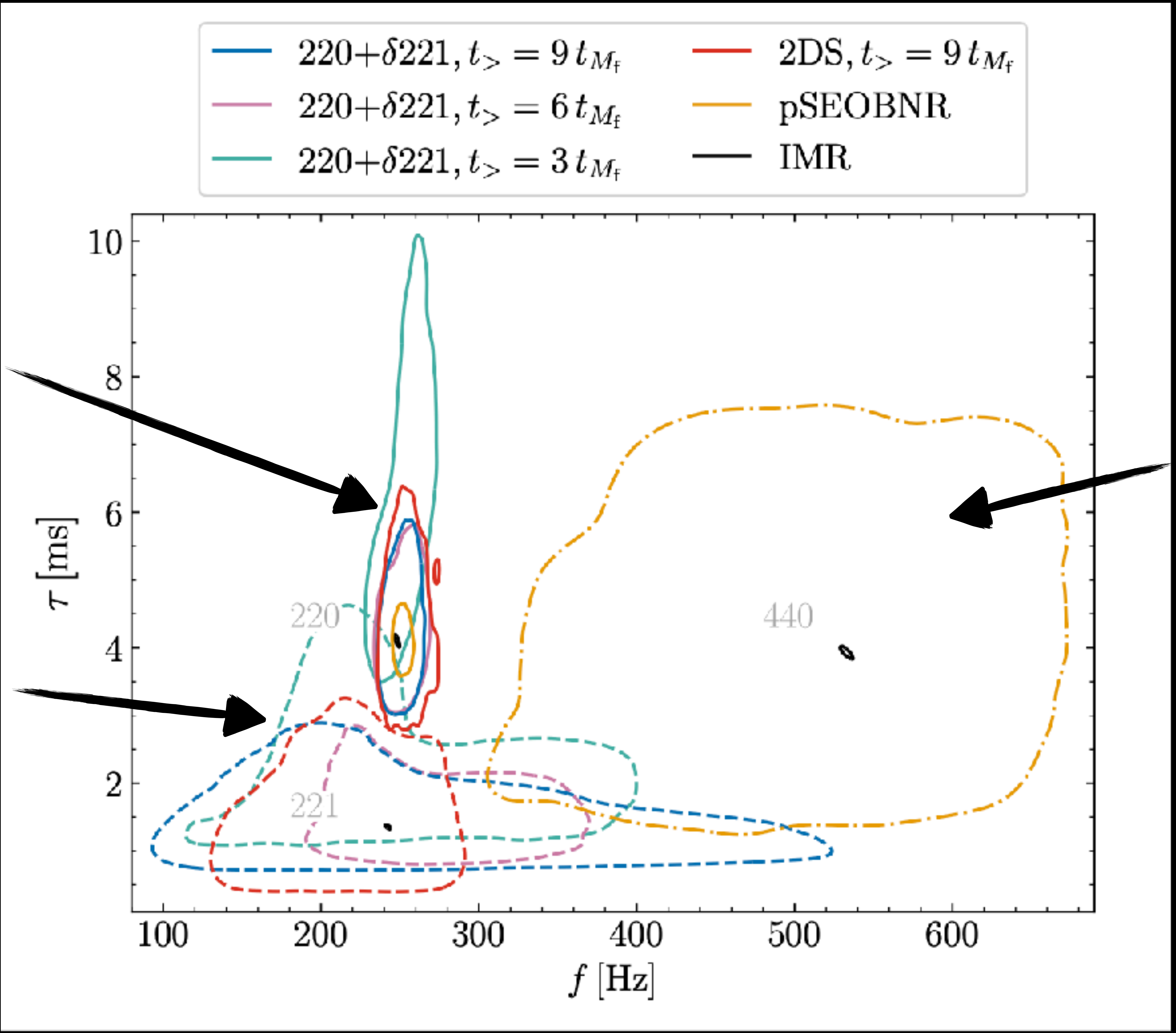
It is modeled as a sum of exponentially damped sinusoids:

$$f_{\ell mn} = \frac{\omega_{R,\ell mn}}{2\pi} \qquad \tau_{\ell mn} = -\frac{1}{\omega_{I,\ell mn}}$$

The ringdown of GW250114

Fundamental mode
$(2, 2, 0)$

Overtone
$(2, 2, 1)$



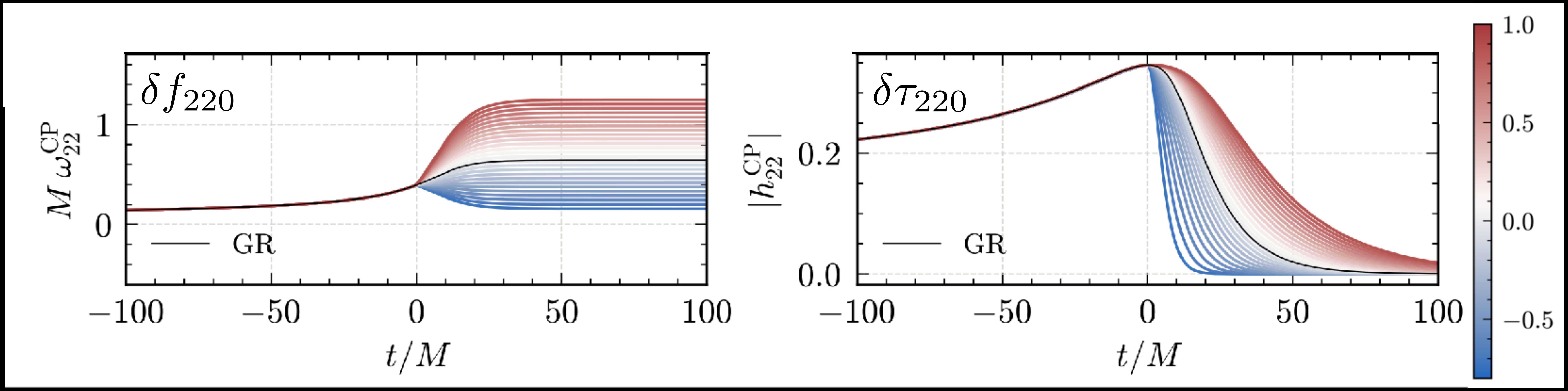
Higher-order mode
$(4, 4, 0)$

Abac et al., arXiv:2509.08099

The pSEOBNR analysis

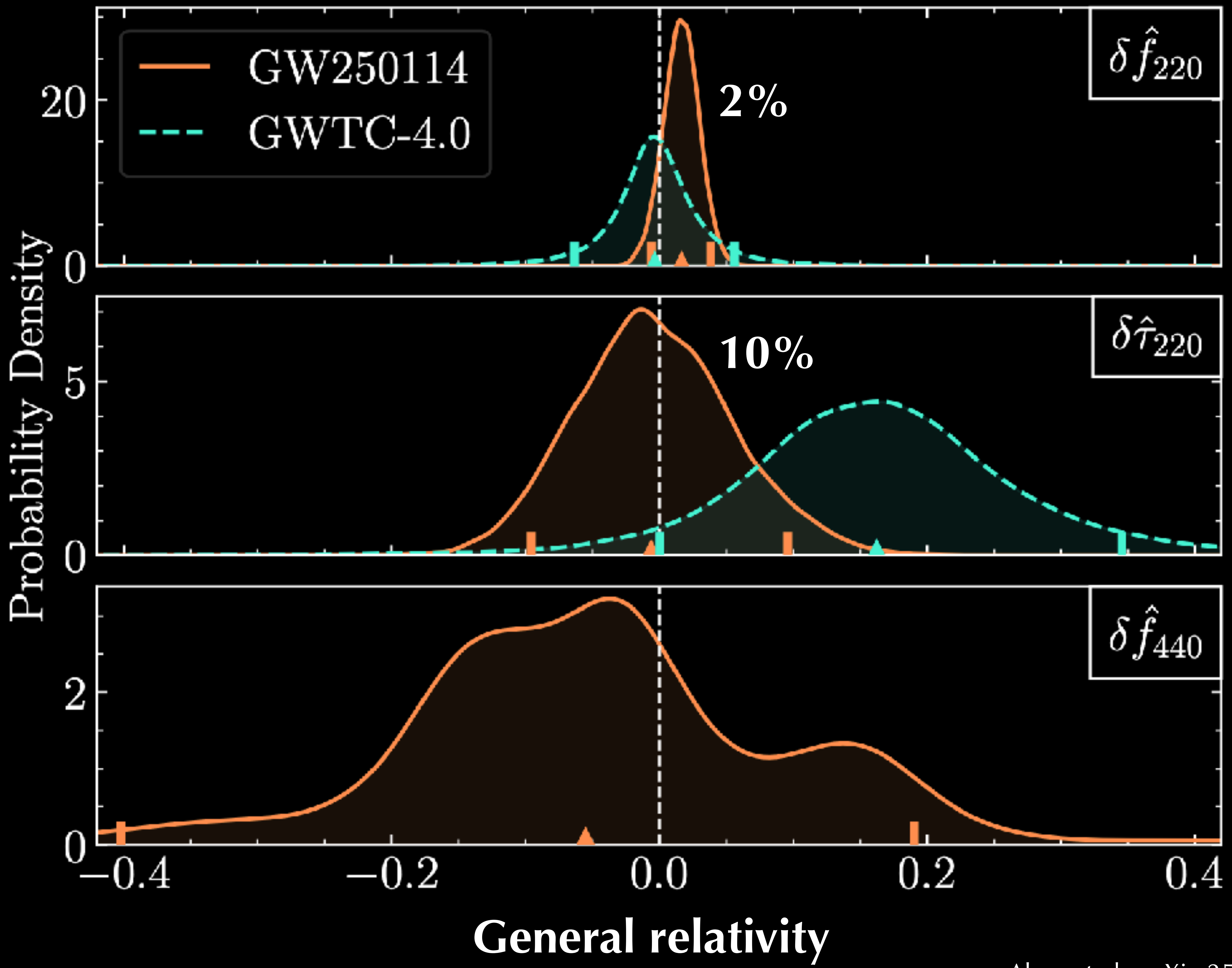
The pSEOBNR test introduces fractional deviations to the frequency and decay time of the quasinormal modes in an inspiral-merger-ringdown waveform as:

$$f_{\ell m0} = f_{\ell m0}^{\mathrm{GR}}\,(1 + \delta f_{\ell m0}) \qquad \tau_{\ell m0} = \tau_{\ell m0}^{\mathrm{GR}}(1 + \delta\tau_{\ell m0})$$



Grimaldi+, PRD **113**, L061506 (2026); Pompili+, PRD **111**, 124040 (2025); Maggio+, PRD **108**, 024043 (2023); Ghosh+, PRD **103**, 124041 (2021); Brito+, PRD **98**, 084038 (2018)

The ringdown of GW250114

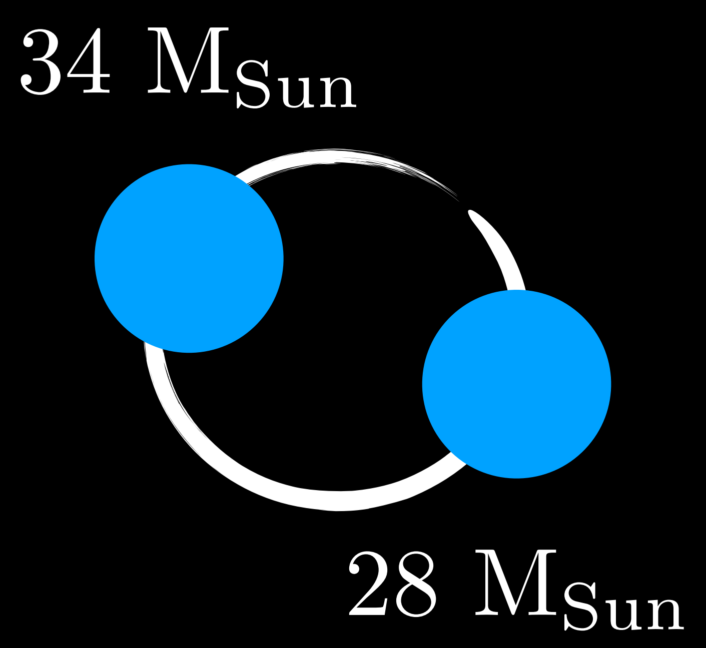


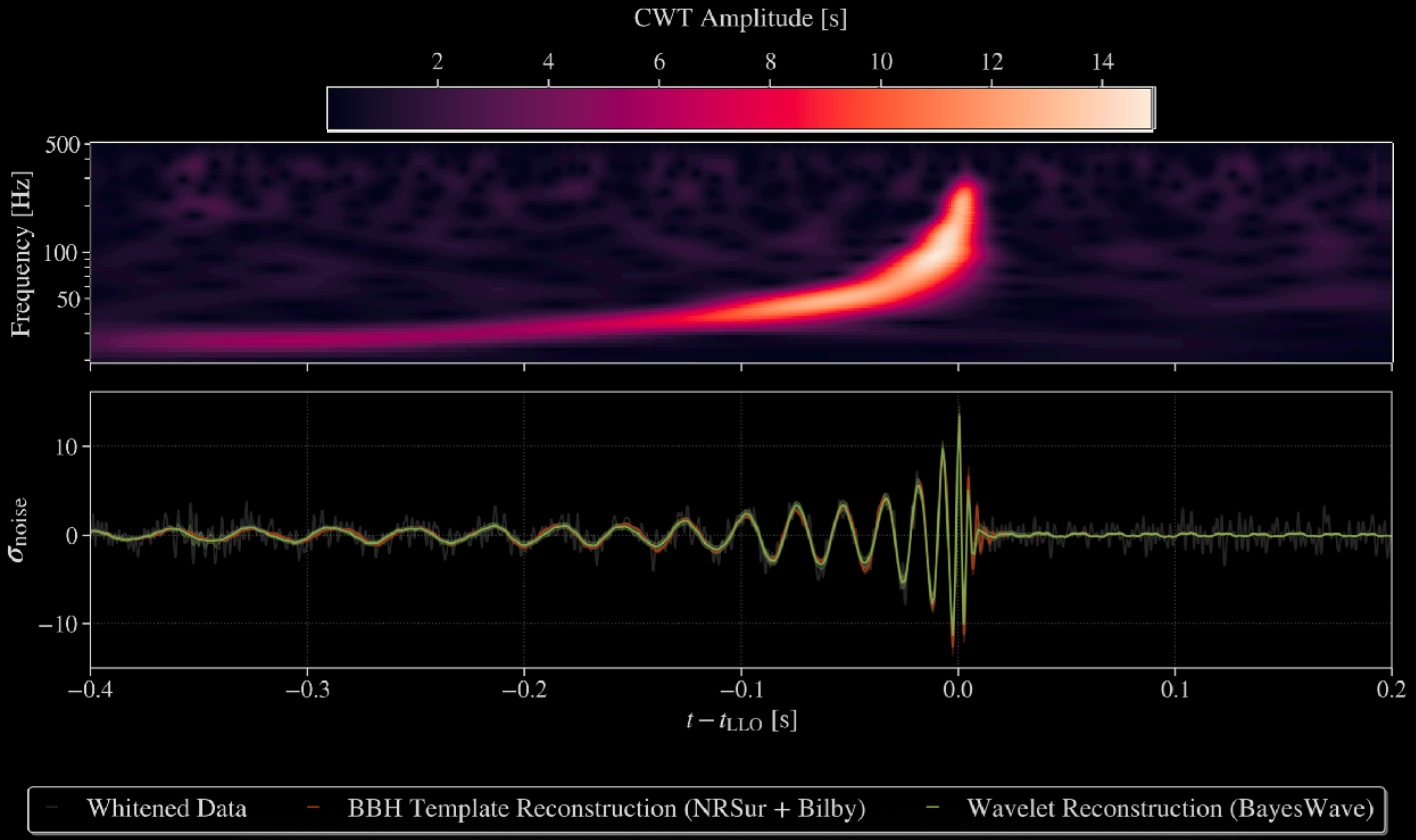
Abac et al., arXiv:2509.08099

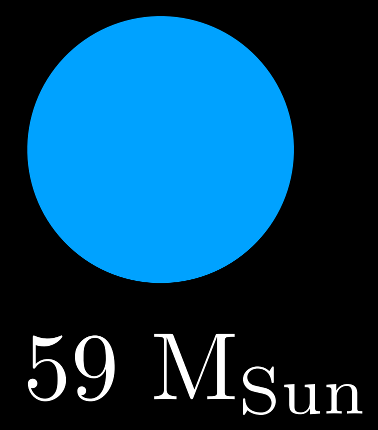
The fundamental mode is constrained twice as strictly as combining events from the fourth catalog.

GW230814

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

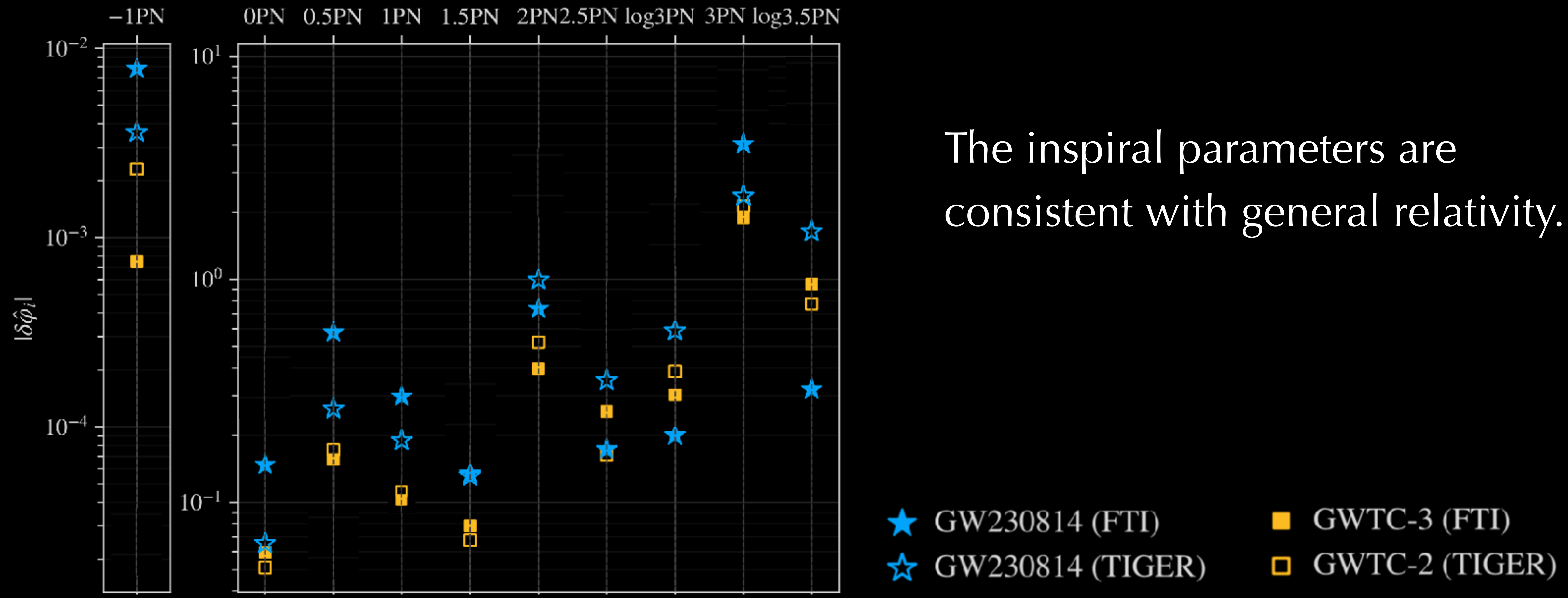






Abac et al., Astrophys.J.Lett. **1004** (2026) 2, L23

The inspiral of GW230814



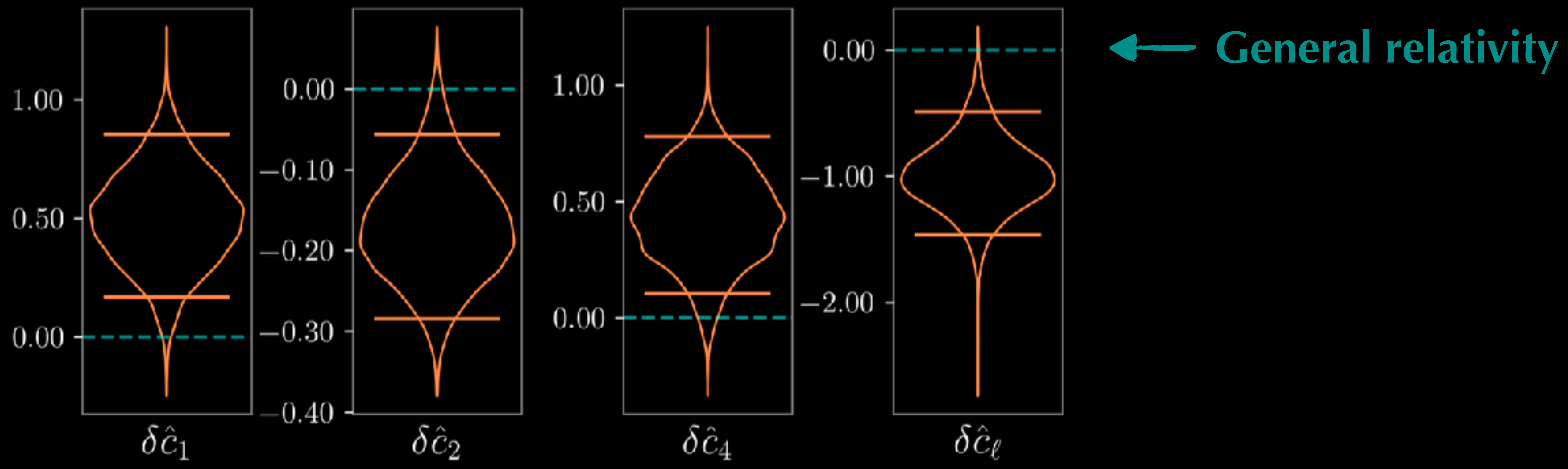
The inspiral parameters are consistent with general relativity.

Abac et al., Astrophys.J.Lett. **1004** (2026) 2, L23; Mehta+ 2023; Agathos+ 2024; Meidam+ 2018; Roy+ 2025

The merger-ringdown of GW230814

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

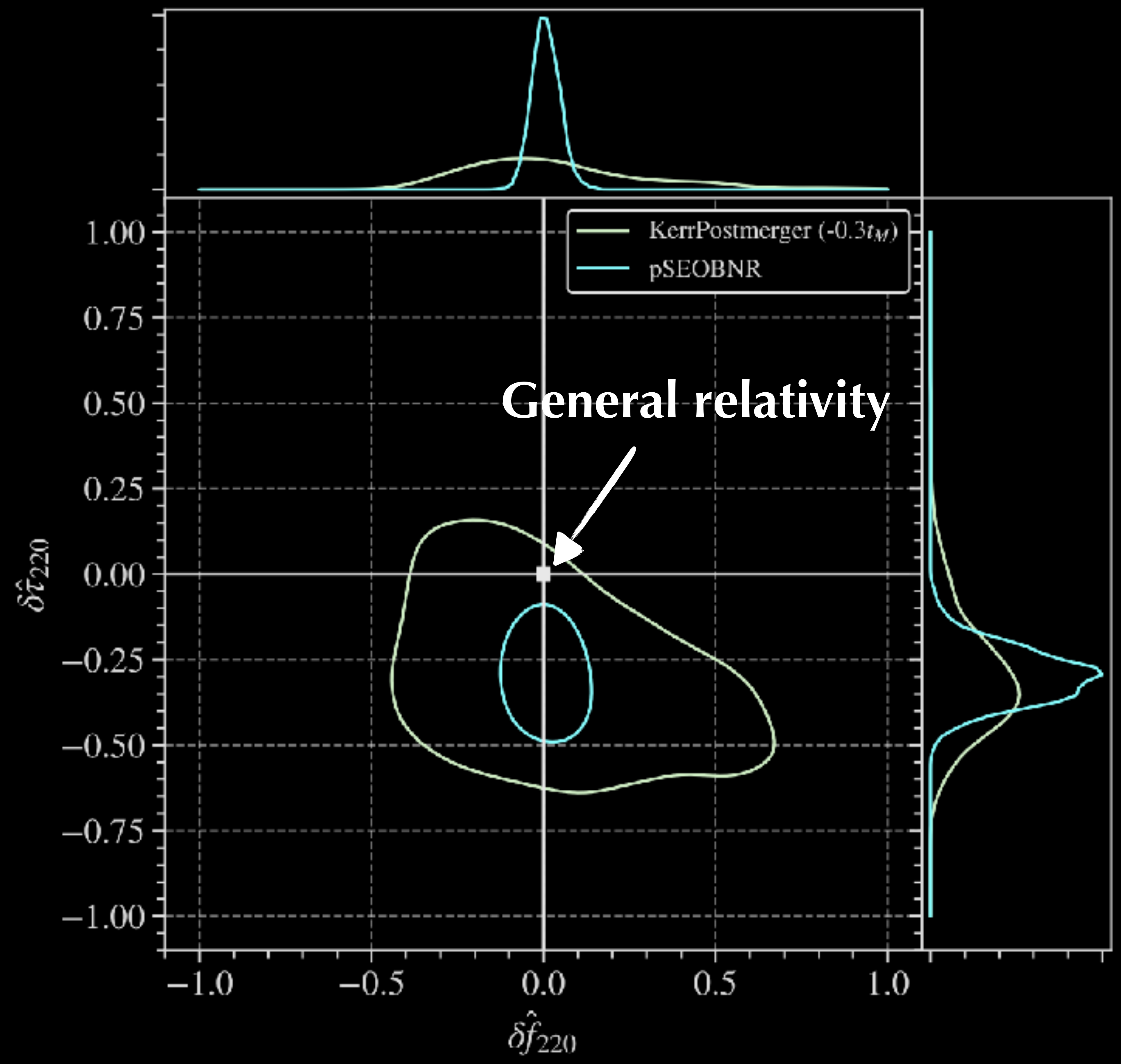
Merger-ringdown parameters



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

Abac et al., Astrophys.J.Lett. **1004** (2026) 2, L23; Agathos+ 2024; Meidam+ 2018; Roy+ 2025

The ringdown of GW230814



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

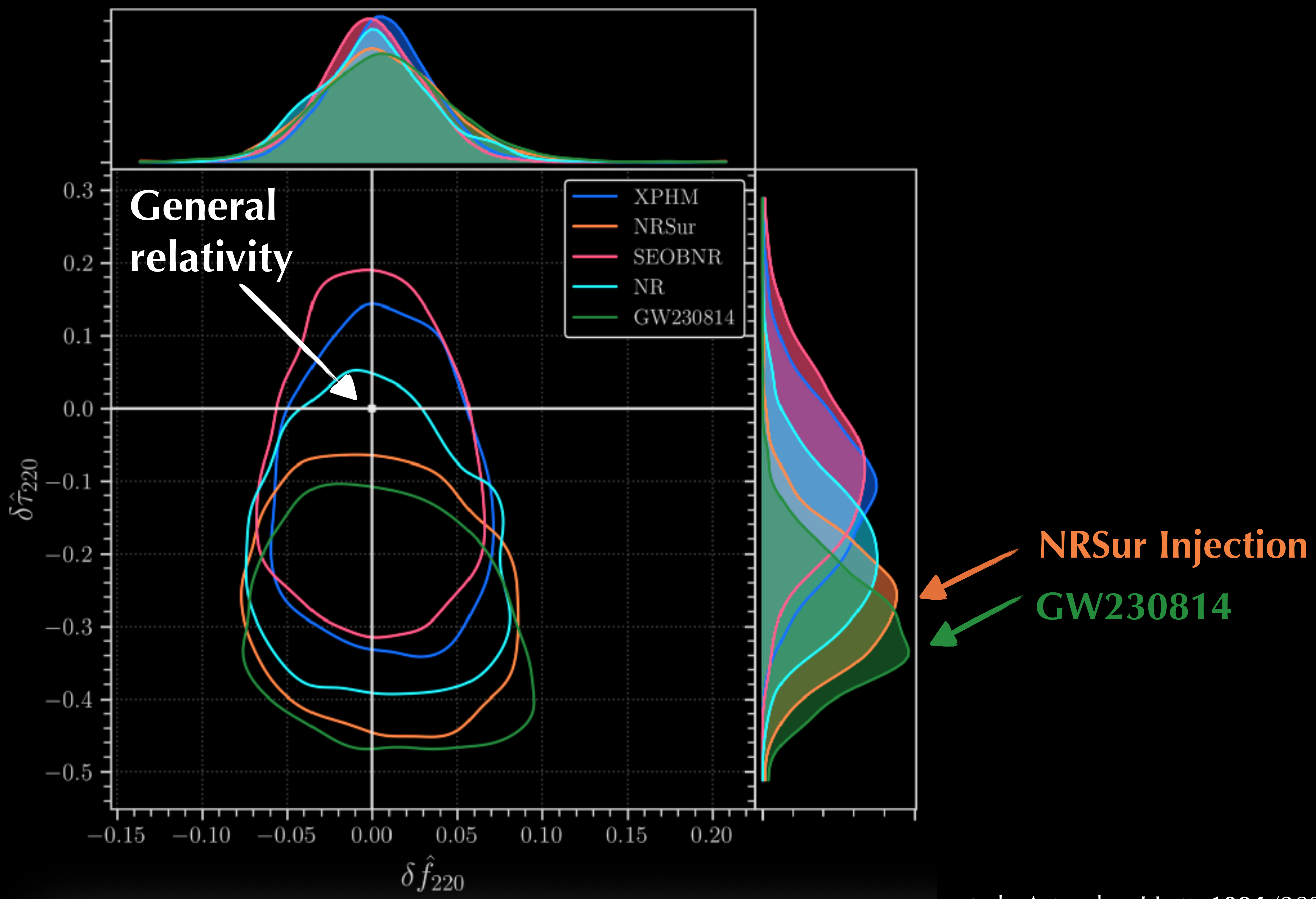
$$\delta\hat{\tau}_{220} = -0.3^{+0.15}_{-0.12}$$

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

Abac et al., Astrophys.J.Lett. **1004** (2026) 2, L23; Brito+ 2018; Ghosh+ 2021; Maggio+ 2023; Pompili+ 2025; Carullo+ 2019; Isi+ 2021; Gennari+ 2024

Assessing waveform systematics

We perform injections with different waveform models in zero noise.



Abac et al., Astrophys.J.Lett. **1004** (2026) 2, L23

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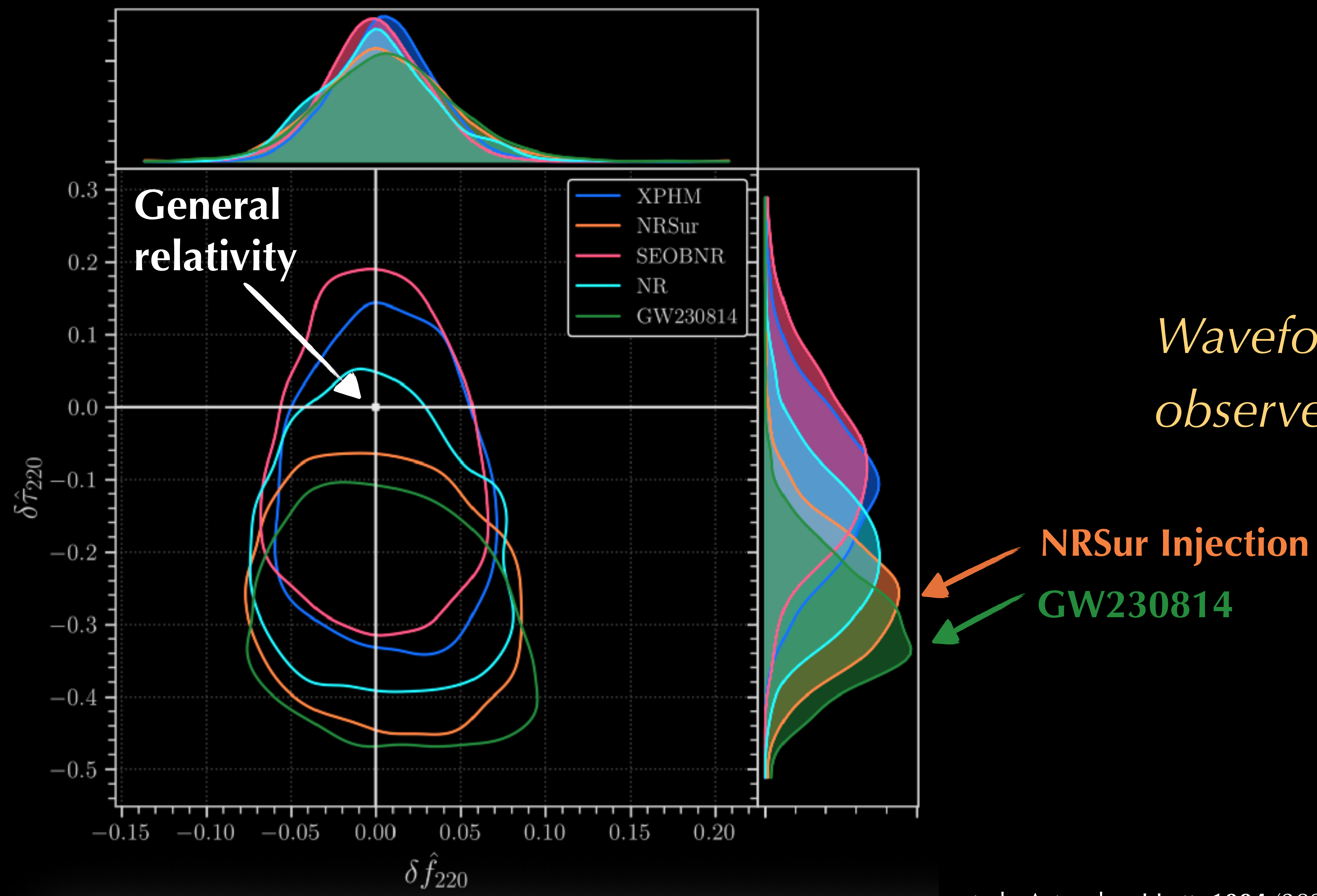
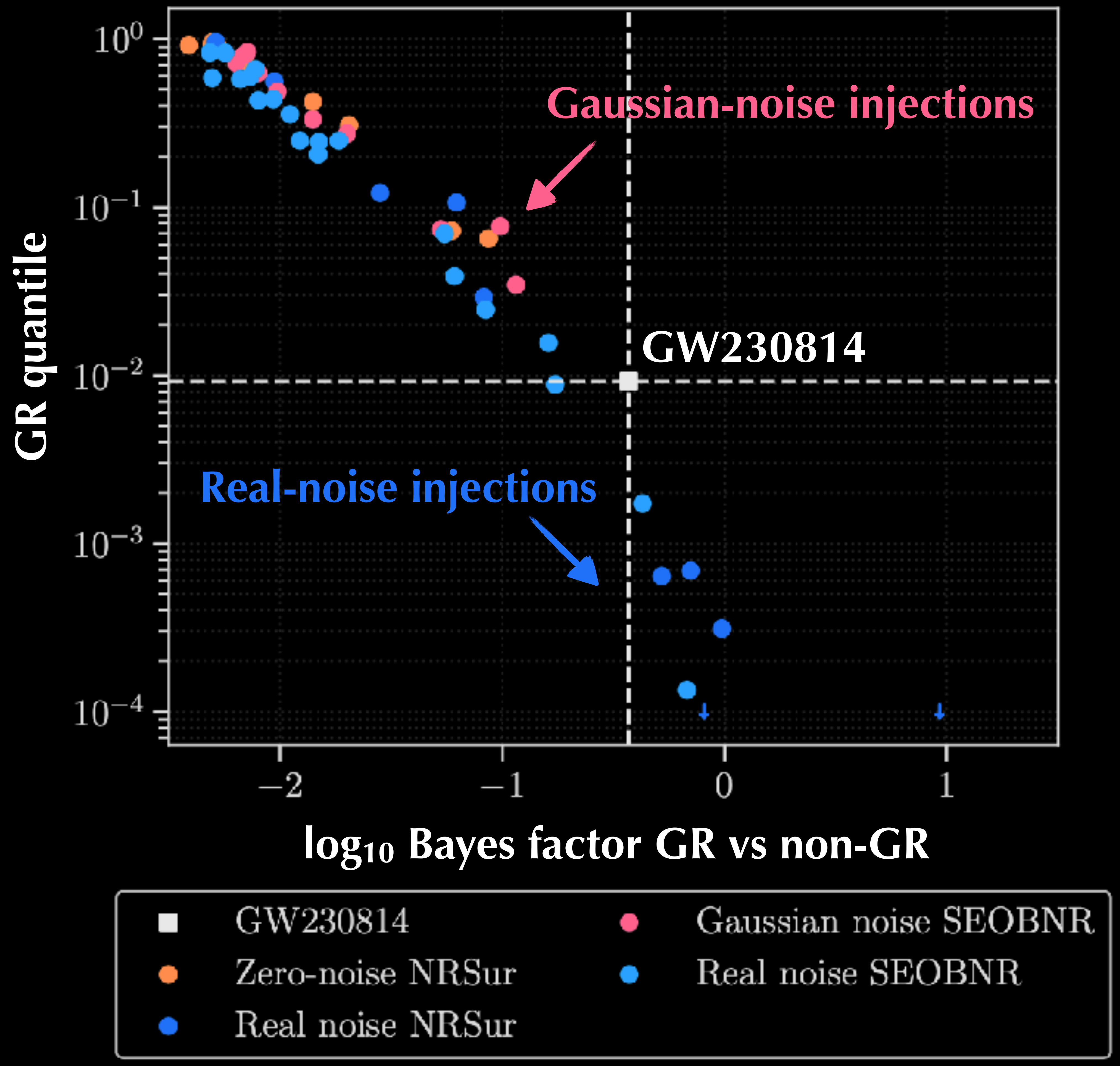


Waveform systematics could contribute to the observed bias in the ringdown damping time.

Abac et al., Astrophys.J.Lett. **1004** (2026) 2, L23

Assessing detector effects

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



Abac et al., Astrophys.J.Lett. **1004** (2026) 2, L23

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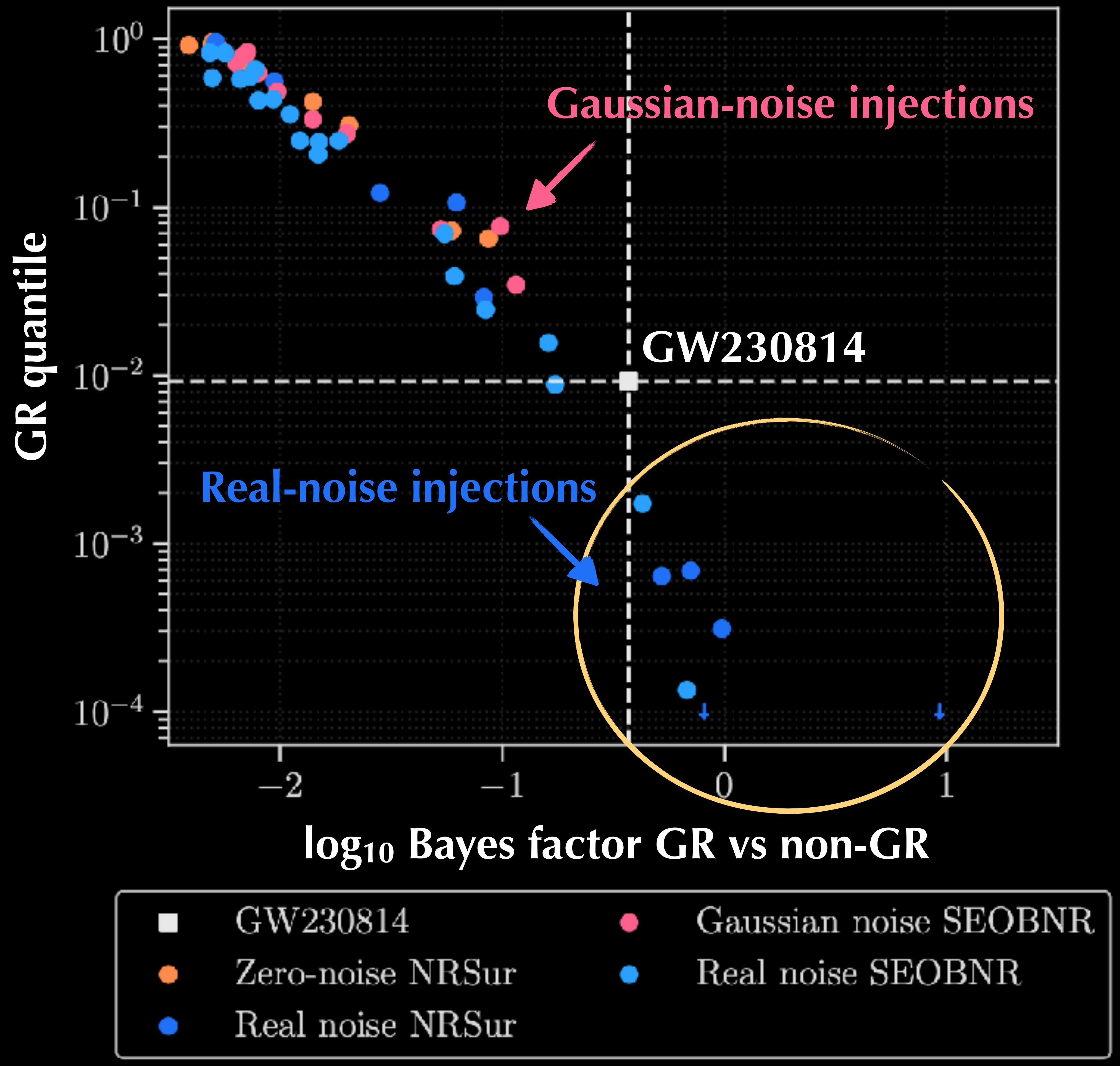


Statistical fluctuations in real detector noise can be responsible for apparent deviations from general relativity in the ringdown.

Abac et al., Astrophys.J.Lett. **1004** (2026) 2, L23

What have we learnt?

- GW230814 highlights the need for a network of gravitational-wave observatories for robust tests of fundamental physics.

- We need to perform accurate studies of waveform and noise systematics.

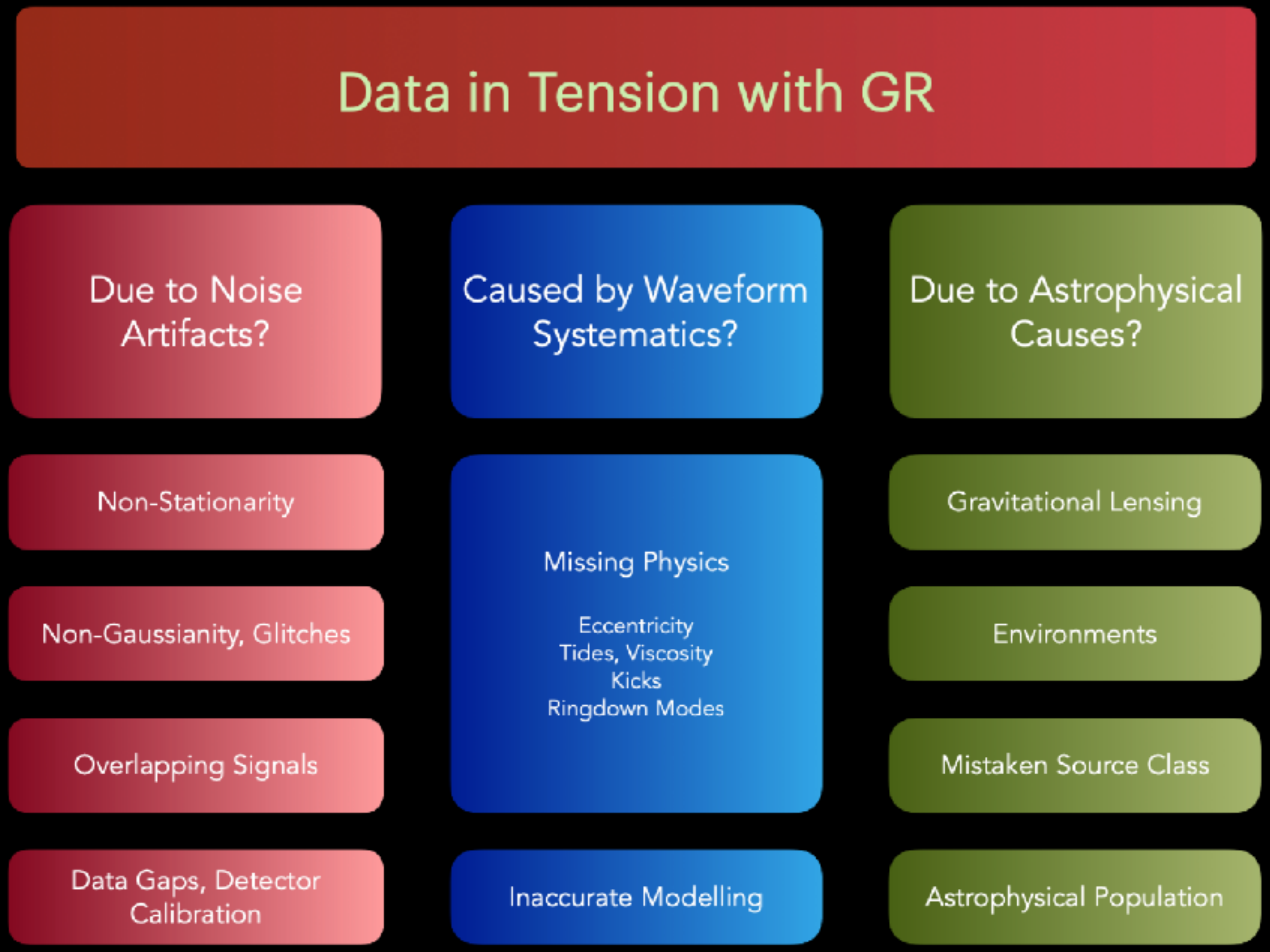
Prospects in O4

- A $(30+30)M_\odot$ binary at the luminosity distance of GW150914 has $\mathrm{SNR} \sim 50$ with the predicted sensitivity for O4 and a 3-detector network. Abbott+, LRR **23**, 3 (2020)

- The ringdown parameters are constrained with higher precision.

- Tests of GR could show false GR deviations.

Gupta+, SciPost Phys. Comm. Rep. 5 (2025)



Open questions

- Which causes of false violations of GR are more impactful?
- Which effects should be accounted for in priority order?

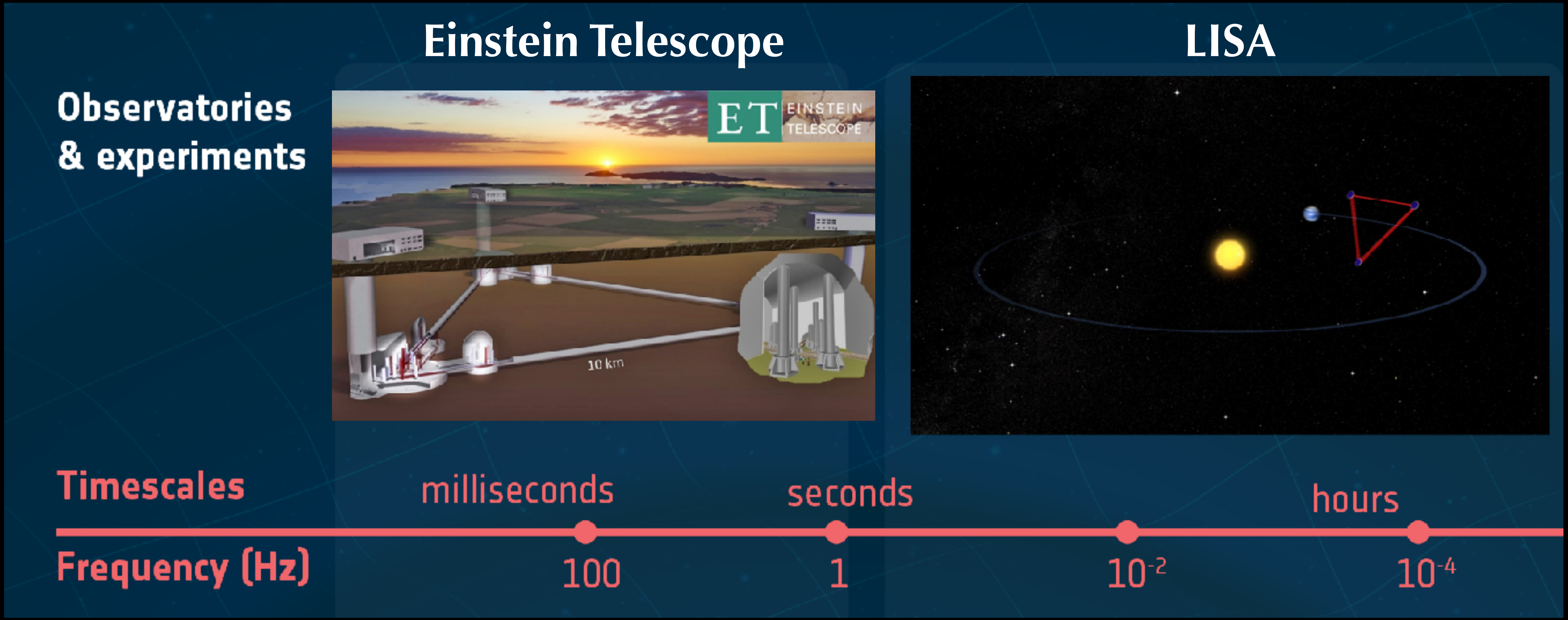
Cause	O4	A+	A#	XG
Non-Stationary Noise	✓	✓	✓	✓
Non-Gaussian Noise/Glitches	✓	✓	✓	✓
Overlapping Signals	✗	✗	✗	✓
Data Gaps	✗	✗	✗	✓
Detector Calibration	✗	✗	✗	✓
Eccentricity	✓	✓	✓	✓
Tidal Effects	✗	✓	✓	✓
Kick-induced Effects	✗	✗	✗	✓
Ringdown Modes	✓	✓	✓	✓
Precession and Higher-order Modes	✓	✓	✓	✓
Memory	✗	✗	✓	✓
Sub-optimal Waveform Calibration	✗	✗	✓	✓
Lensing	✗	✗	✗	✓
Environmental Effects	✗	✗	✗	✓
Source Misclassification	✓	✓	✓	✓
Astrophysical Population Assumptions	✓	✓	✓	✓

Gupta+, SciPost Phys. Comm. Rep. 5 (2025)

Future observatories

With next-generation detectors, thousands of gravitational-wave events are expected to be observed at large signal-to-noise ratios.

ratios.



Conclusions and future prospects

- Parametrized tests quantify how strongly gravitational-wave data agrees with GR.
- Recent GW observations probe the nature of merger remnants.
- Perform injection studies to evaluate how noise and systematics affect GR tests, and develop strategies to mitigate these effects.
- Construct links with modified gravity theories and alternative compact objects to place meaningful constraints on extensions of GR.