

Tests of General Relativity with ground-based detectors

A status report

Joachim Pomper

PhD Student, University of Pisa

Supervisor: Walter Del Pozzo

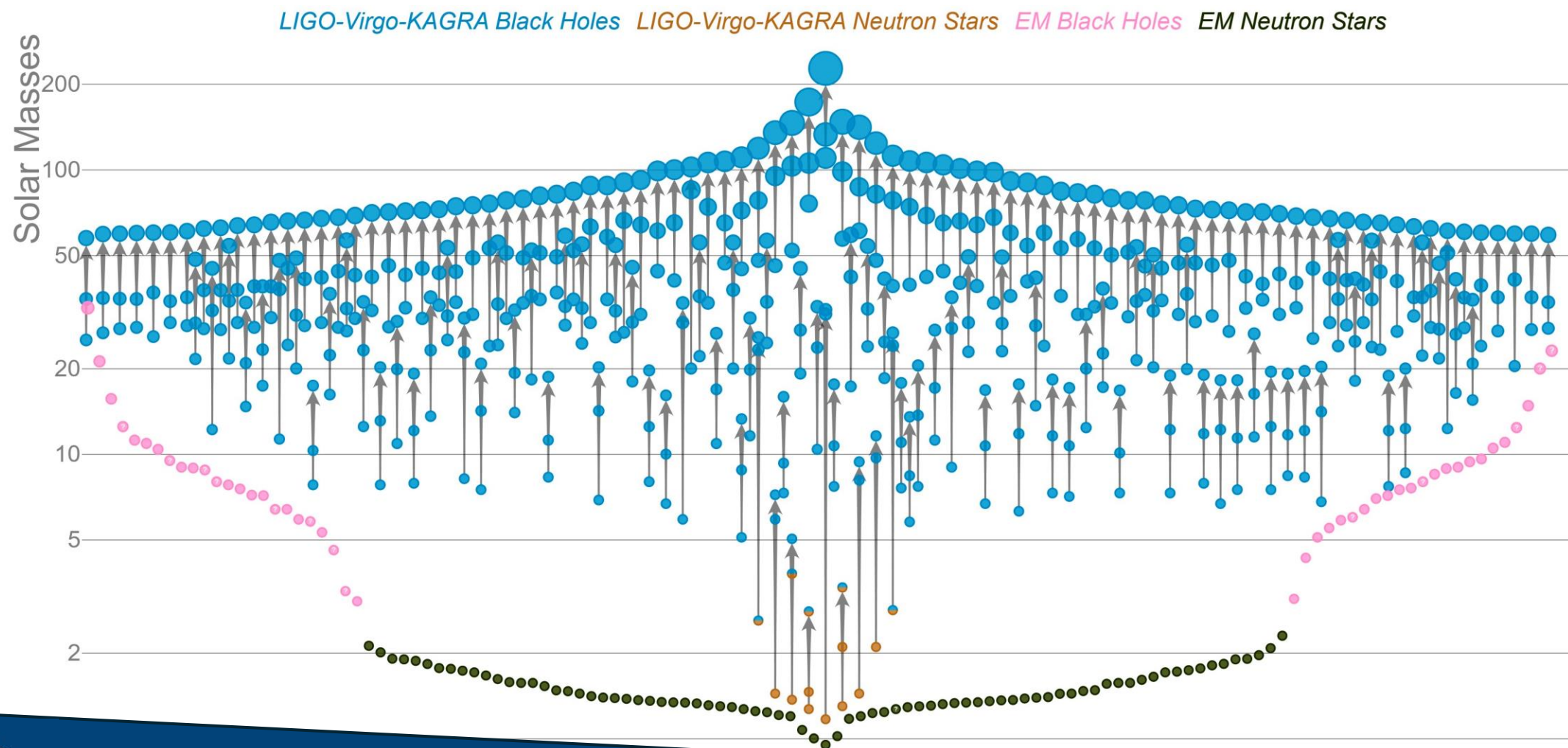
IFPU Focus Week: "Perspectives on Gravity: From Theory to Observation"

08/06/2026



UNIVERSITÀ DI PISA

Masses in the Stellar Graveyard – GWTC-4



References:

[1] Reference 1

[2] Reference 2, insert some citation text here

[3] Reference 3, insert some citation text here, Typically sort them such that they g

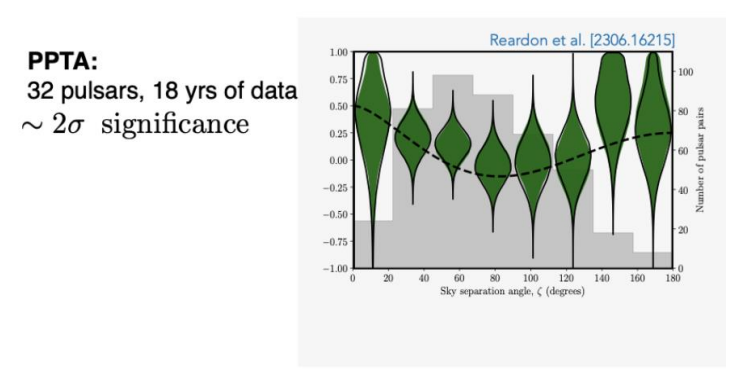
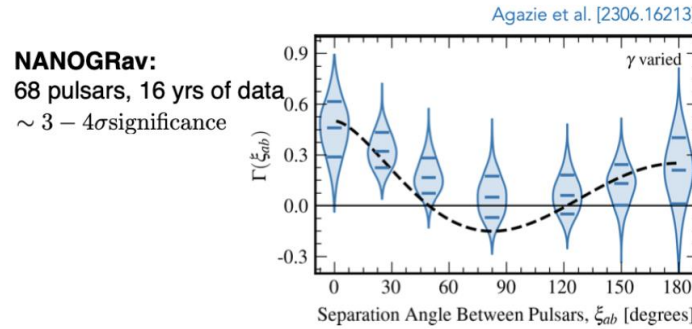
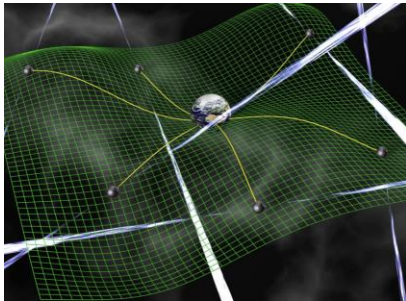
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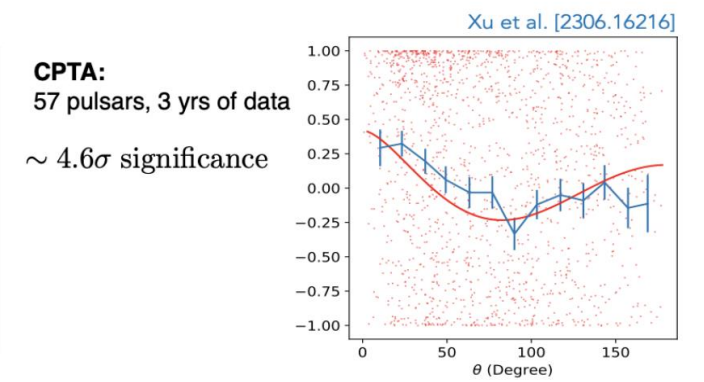
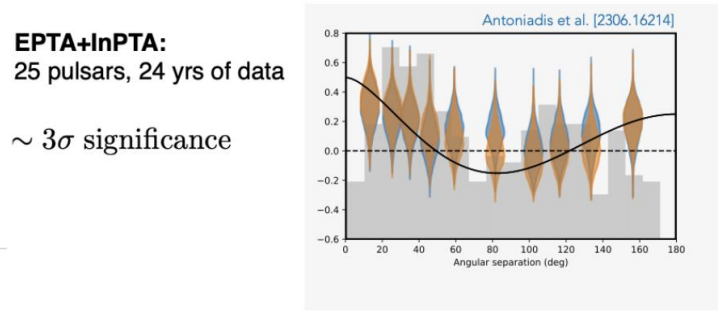
Stochastic background of gravitational waves

We see a SGWB from PTA

Pulsar timing arrays detect GW from correlations among different pulsars times of arrivals



First Detection of a SGWB



Gravitational wave astronomy

We are past the discovery era!
Enough sources to do astronomy

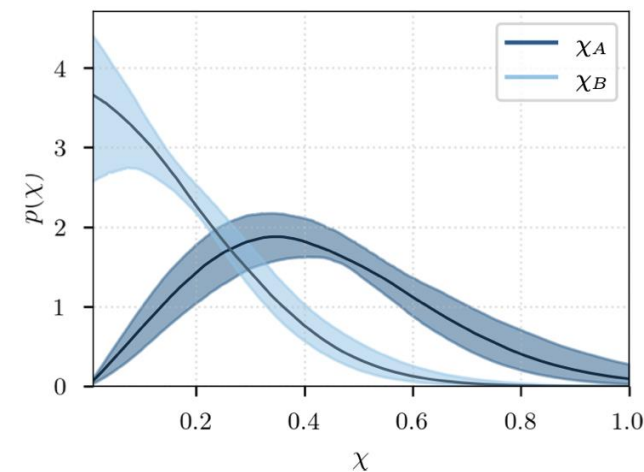
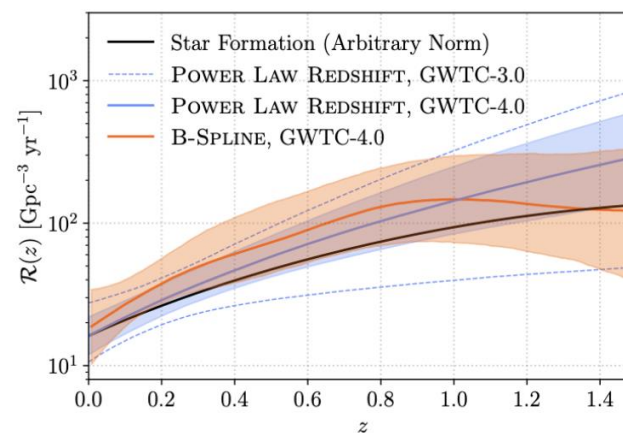
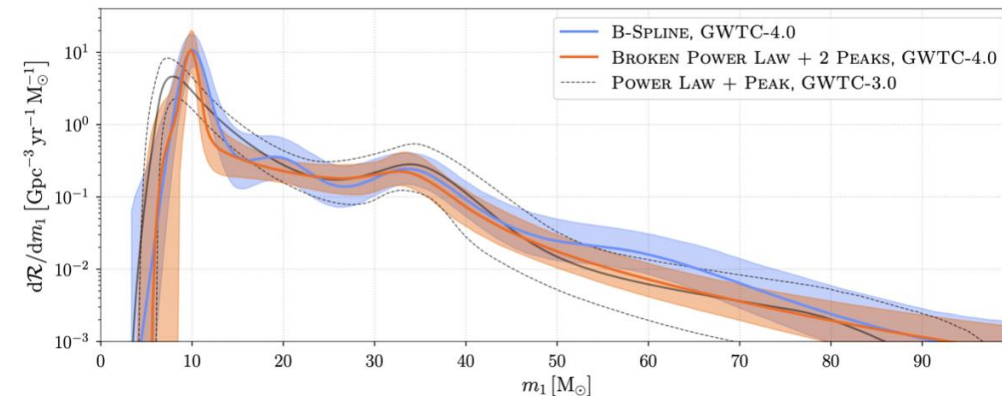
Current rates:

BNS : 7.6–250 $\text{Gpc}^{-3} \text{yr}^{-1}$

NSBH: 9.1–84 $\text{Gpc}^{-3} \text{yr}^{-1}$

BBH : 14–26 $\text{Gpc}^{-3} \text{yr}^{-1}$

GW astrophysics is feasible and
we see features in population inference.



Fundamental physics with Black Holes

Gravitational waves (GW) are wave solutions to Einstein's equations:

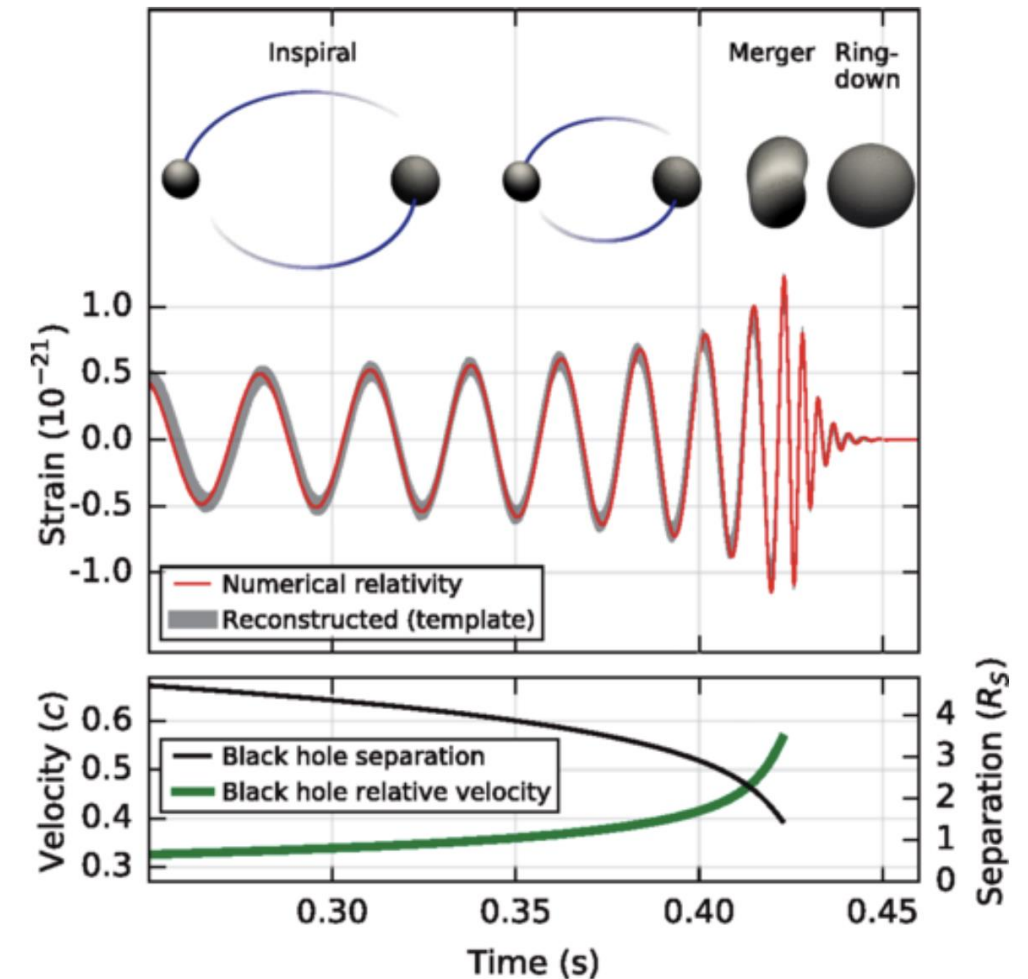
- Perturbations from accelerating masses
- Propagate as speed of light

Shape of GW signal carries information on:

- binary dynamics
- the nature of the binary components
- the non-linear dynamics of spacetime
- the nature of the final object nature

The best part: **We can look at BHs directly !**

Figure taken from [1]



References:

[1] LIGO-Virgo-KAGRA Scientific Collaboration, (2016); arXiv:1602.03837



CBC sources are probes of gravity

GR is very well tested but we know it is not the full answer:

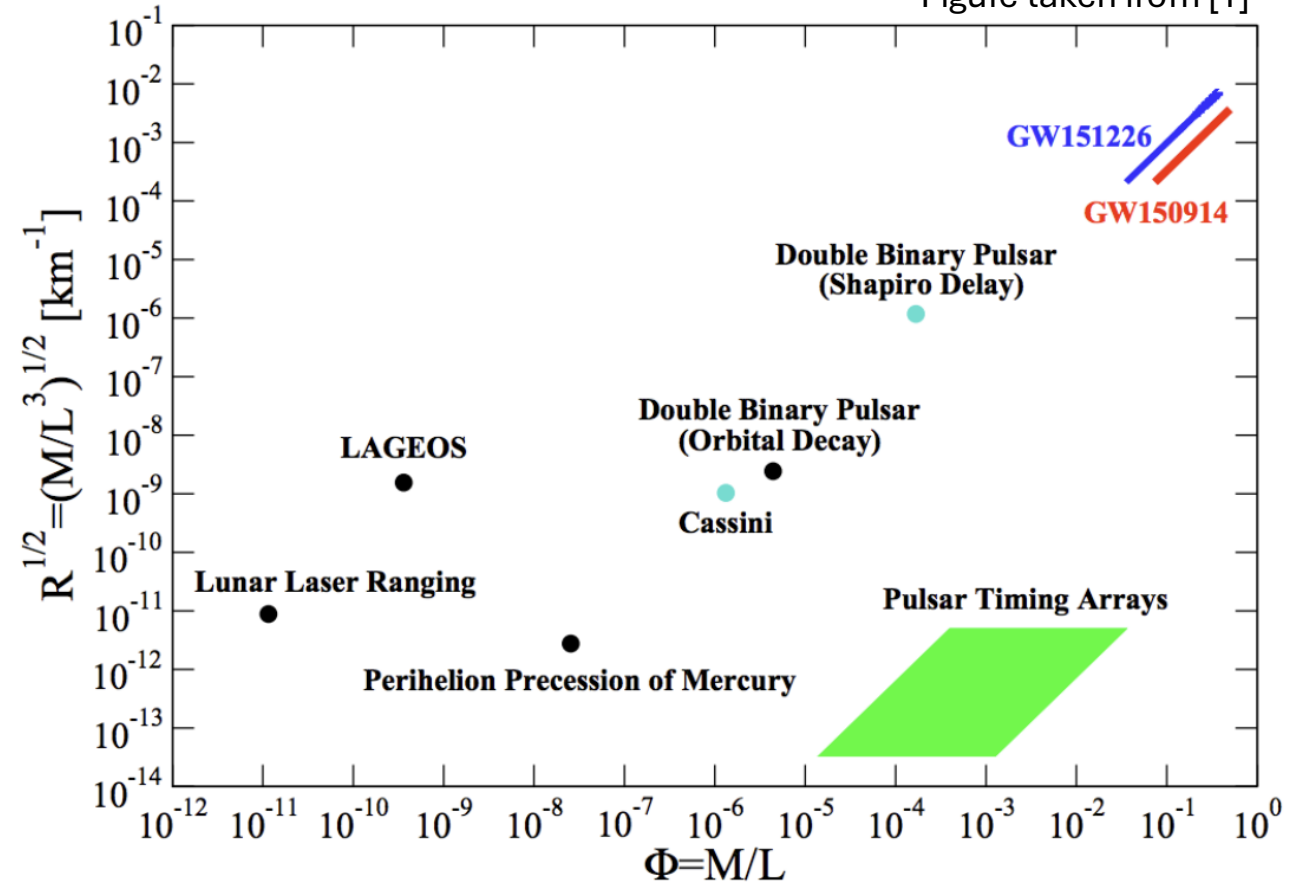
- GR is not renormalisable
- Dark energy
- Predicts singularities
- Horizons and information paradox

We might want to test

- high curvature regions
- Strong gravitational fields
- Dynamical regimes

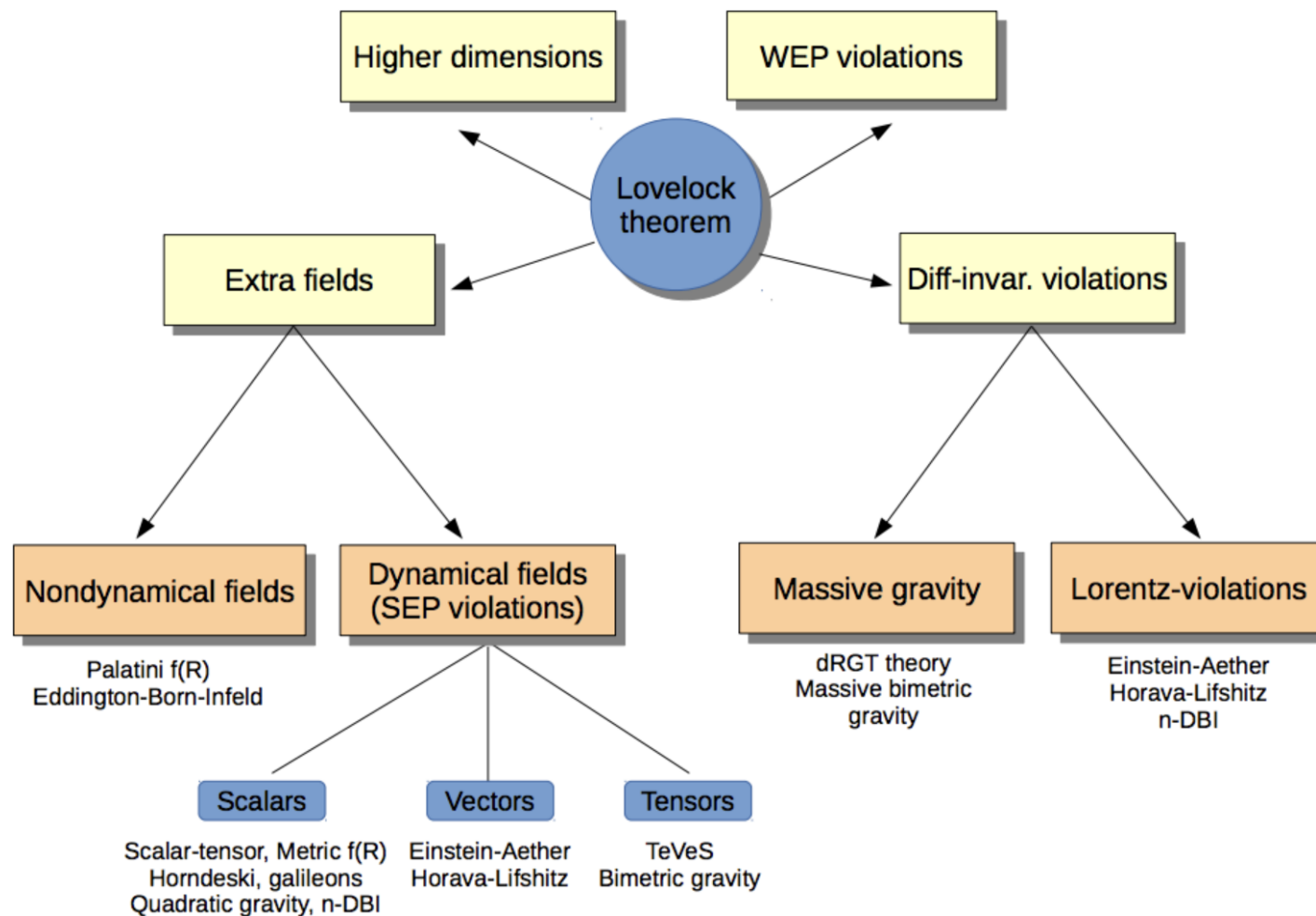
GWs from binary systems from LVK are **incredible probes** and they are **dynamical**.

Figure taken from [1]



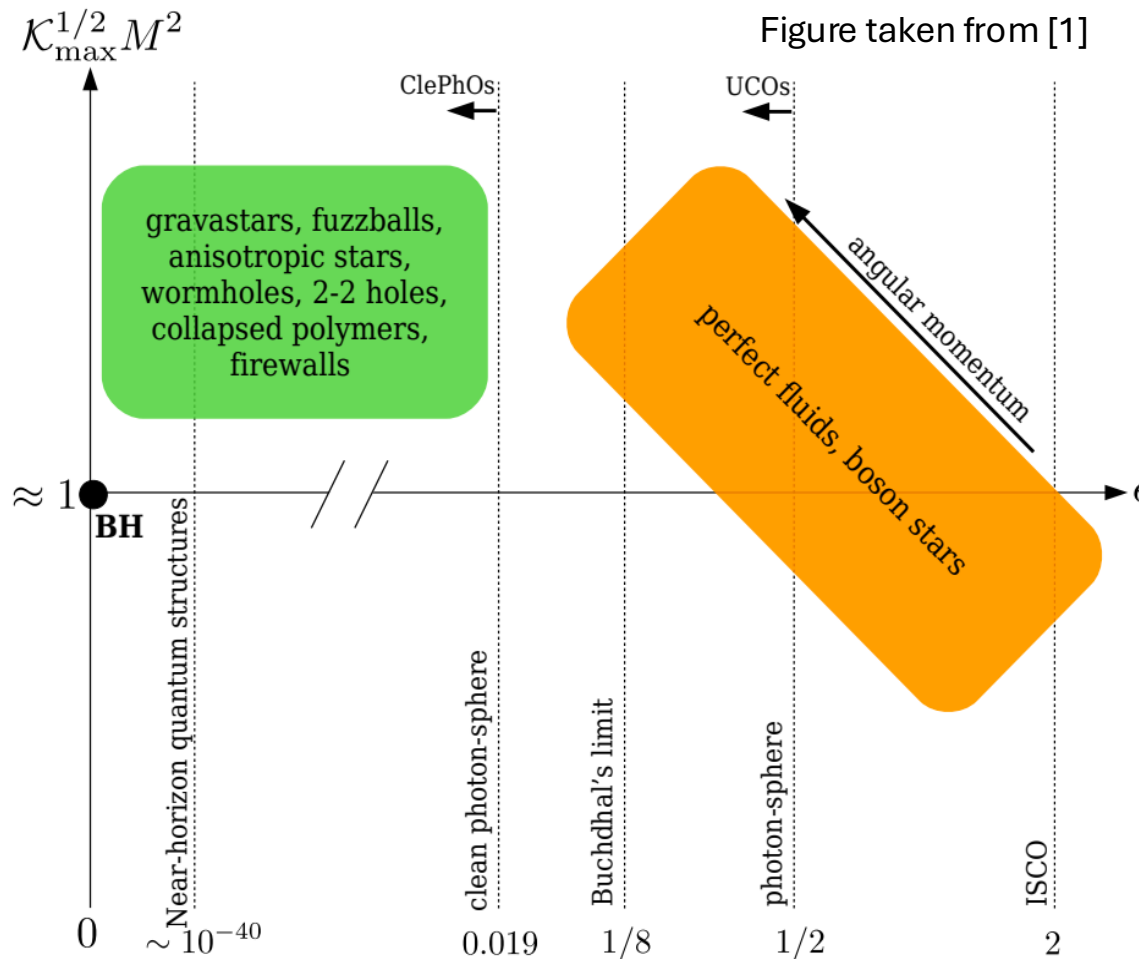
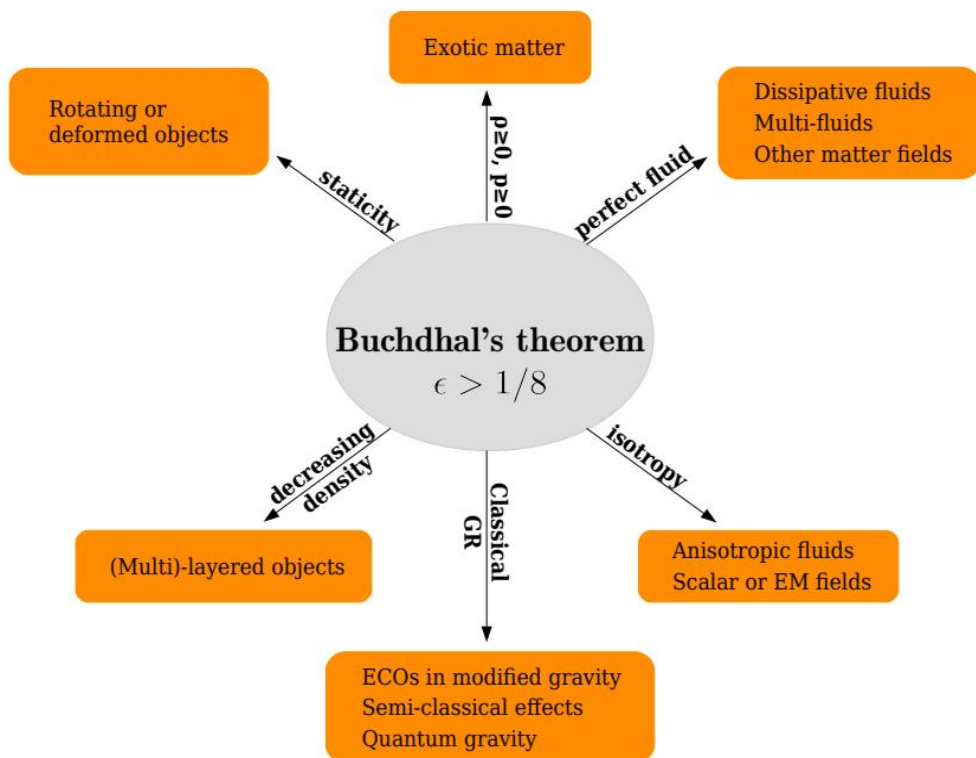
How to break GR

Figure taken from [1]

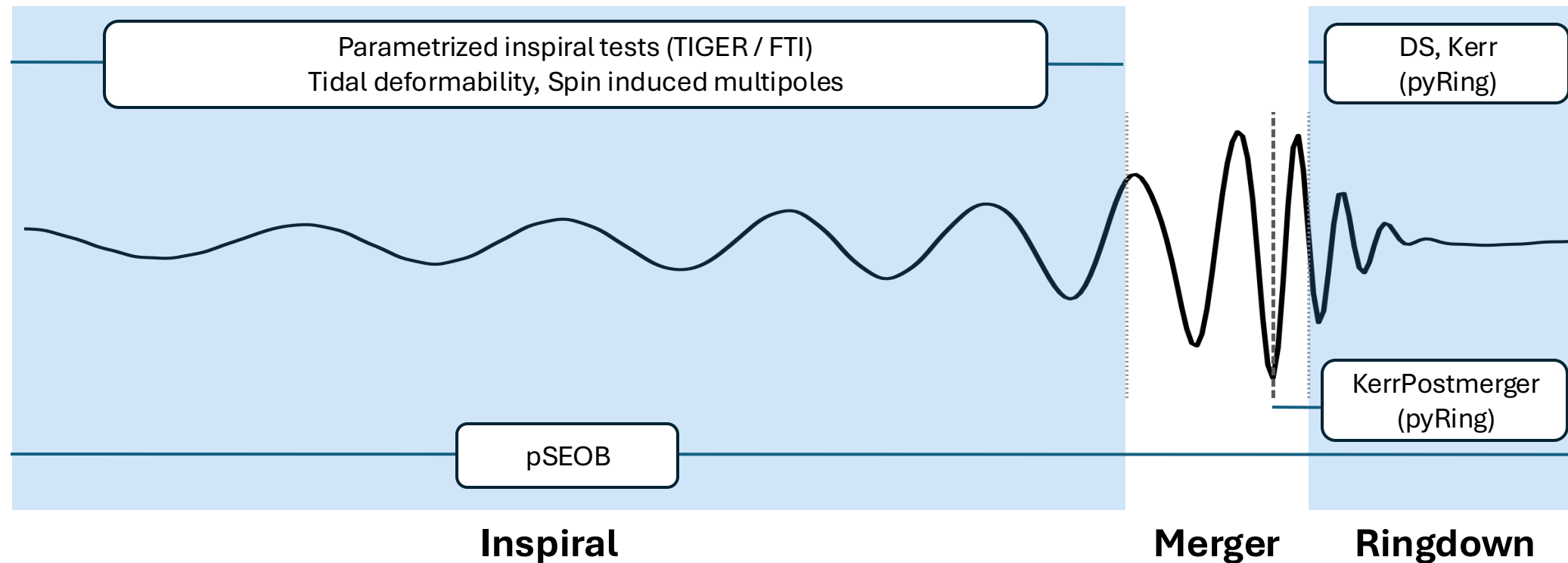


Exotic compact objects

Maybe what we see with GW signals are not Black Holes?



Overview of this talk



Resources:

Based on data from: <https://zenodo.org/records/16877102>

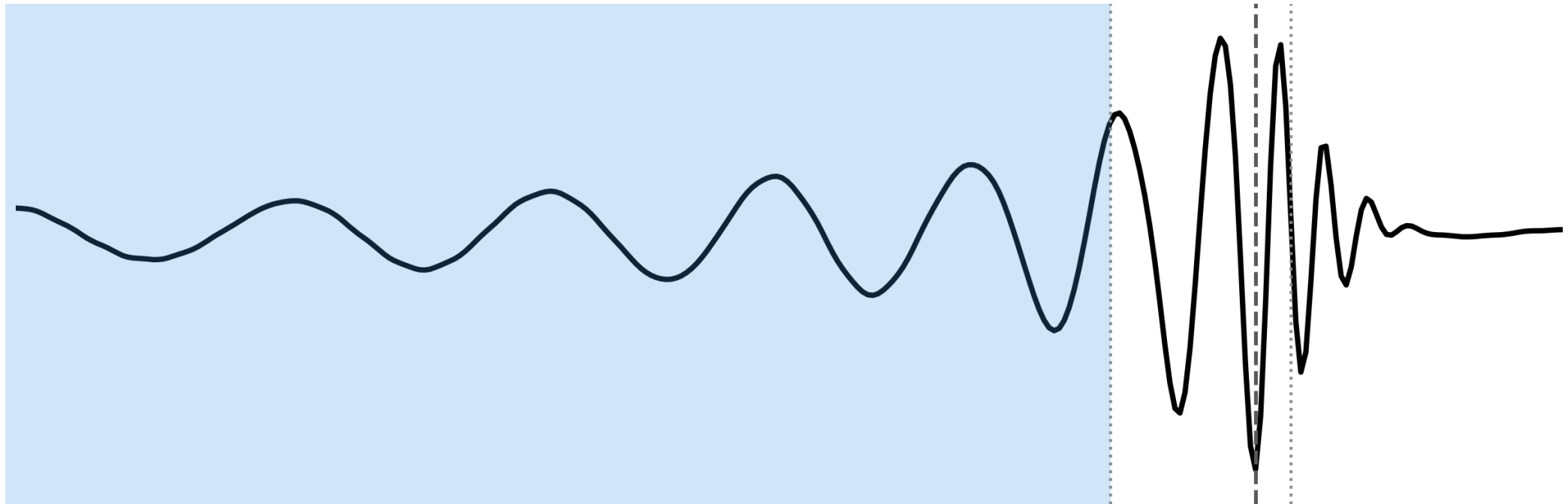
Inspired by Figure 6 in [1]

[1] LIGO-Virgo-KAGRA Scientific Collaboration, (2025), arXiv:2509.07348

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INSPIRAL TESTS



Parametrized Tests

Agnostic approach:

Alternatives to GR can introduce extra-fields, curvature terms, challenge GR pillars, etc ...

Search for specific alternative seldom feasible, we do not know an IMR waveform in alternative GR!

All putative violations change the phase in some way, let's try to look for departures from expectations!

Take an IMR waveform and modify PN coefficients from GR values [1,2]:

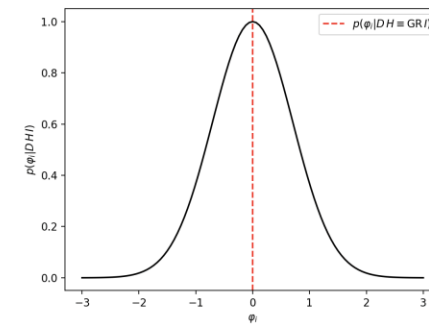
$$h(f; \theta) = A(f; \theta) e^{i\Phi(f; \theta)}$$

$$\Phi(f; \theta) = \sum_{k=0}^7 (\varphi_k + \varphi_k^{(l)}) f^{(k-5)/3} + \sum_{i \neq k} \varphi_i g(f)$$

post-Newtonian series
effective series

$$\varphi_j \equiv \varphi_j(m_1, m_2, \vec{s}_1, \vec{s}_2)$$

$$\hat{\varphi}_j \equiv \varphi_j^{GR} (1 + \delta\hat{\varphi}_j) \quad \delta\hat{\varphi}_j = 0 \iff \text{GR}$$



References:

- [1] Li et al. (2011); arXiv:1110.0530, Agathos et al. (2013); arXiv:1311.0420
- [2] Yunes & Pretorius (2009); arXiv:0909.3328, Cornish et al. (2011); arXiv:1105.2088



Hierarchical analysis: combining many events [1]

How do we combine knowledge of many observations?

We measure: $\Theta \equiv \delta\phi, M, \chi_{\text{eff}}, \dots$

Hyper parameter distribution:

- Must be inferred from data
- TGR: $\Lambda \equiv \mu_p, \Sigma_{pq}$

$$P(\Theta | D_{\text{obs}}^N) = \int d\Lambda P_{\text{pop}}(\Theta | \Lambda) P_{\text{hyp}}(\Lambda | D_{\text{obs}}^N, H_P)$$

Combined distribution:

- TGR: $\Theta \equiv \delta\phi_p$

Population Model:

- Must be modeled (Population hypothesis)
- Parametric vs. non-parametric ?
- TGR: minimal knowledge, multivariate gaussian

Hierarchical analysis: Inferring the population

How do we infer the hyper-parameter distribution?

Several Packages

- ICAROGW [3]
- FIGARO [4]
- Gaussian mixture [2]

Hyper parameter prior

$$P_{\text{hyp}}(\Lambda | D_{\text{obs}}^N, H_P) = \Pi(\Lambda) e^{\alpha(\Lambda)} \prod_{k=1}^{N_{\text{obs}}} \mathcal{L}_{\text{hyp}}(\Lambda | D_{\text{obs}}^k)$$

Selection function: [1]

- Corrects for biases through non-observation due to the detector.
- TGR: omitted i.e. $e^{\alpha(\Lambda)} = 1$

Reweighted single event posterior

$$\mathcal{L}_{\text{hyp}} = \int d\Theta P_{\text{pop}}(\Theta | \Lambda) \frac{P(\Theta | D_k)}{\Pi(\Theta)}$$

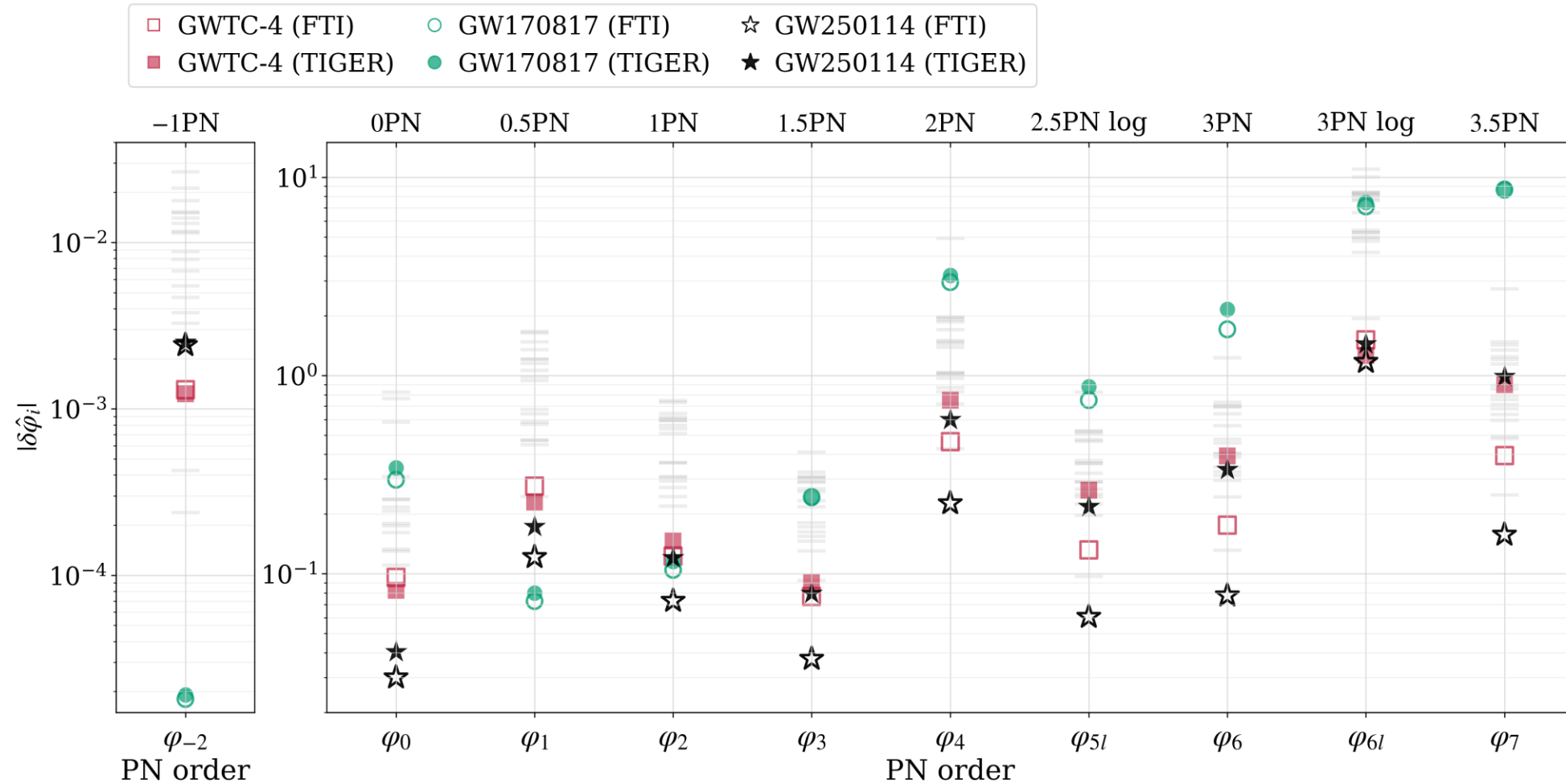
Resources:

- [1] Vitale, Gerosa, Farr & Taylor (2020); arXiv: 2007.05579
- [2] Zhong, Isi, Chatziioannou & Farr (2024); arXiv: 2405.19556
- [3] Mastrogiovanni et al. (2023); arXiv: 2305.17973
- [4] <https://figaro.readthedocs.io/en/latest/>

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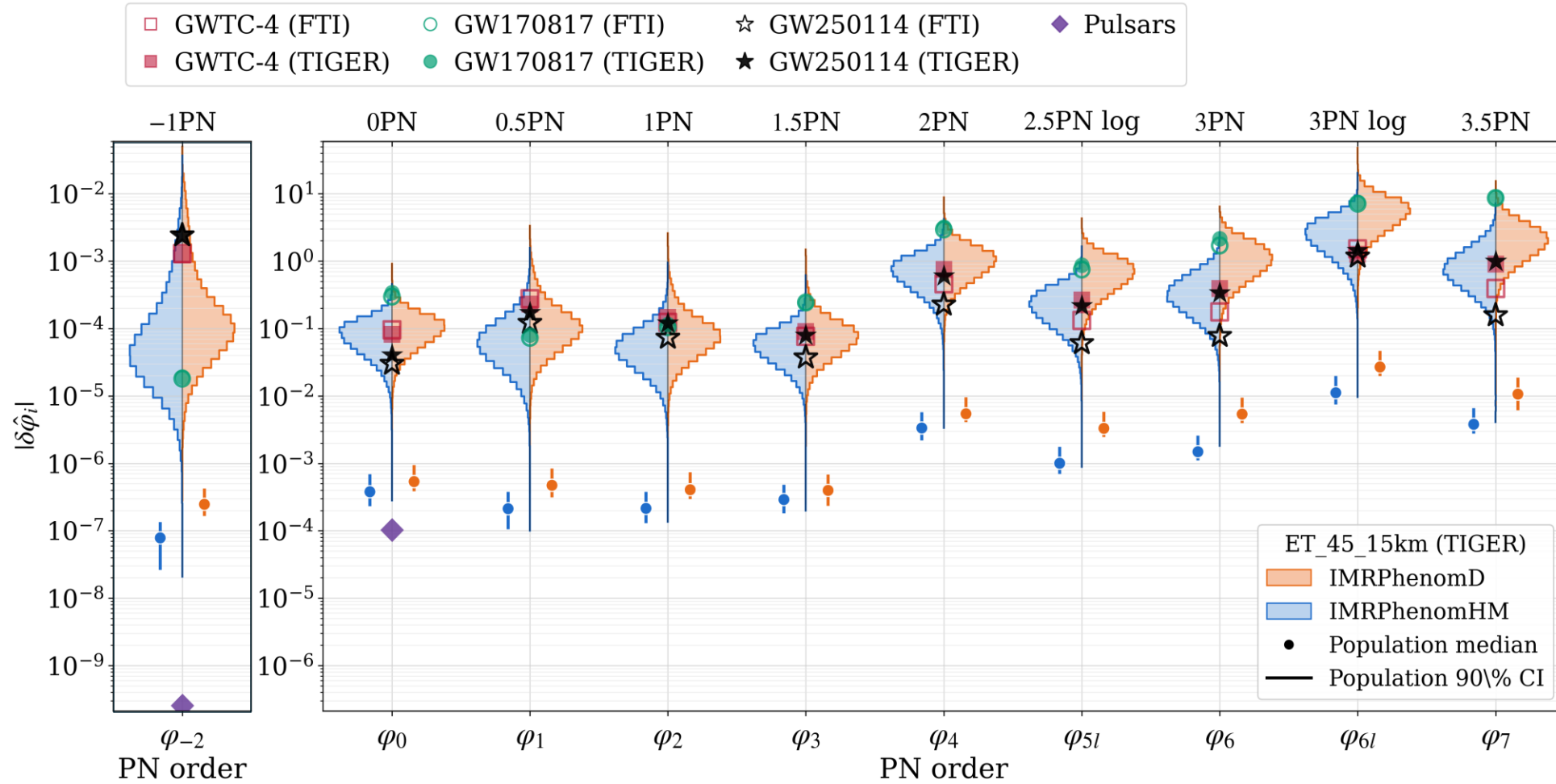
TIGER/FTI: Current constraints



References:

- [1] LIGO-Virgo-KAGRA Scientific Collaboration, (2025); arXiv:2509.08054
- [2] LIGO-Virgo-KAGRA Scientific Collaboration, (2026); arXiv:2603.19020

Future detectors: TIGER for ET



References:
 [1] Begnoni, Del Pozzo, Pegorin, Pomper, Ricciardone (2025); arXiv:2511.07520

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Black hole mimicker tests with the inspiral

Spin induced quadrupole Moment [1]

Quadrupole moment due to deformation by rotation.

$$Q = -\kappa\chi^2 m^2$$

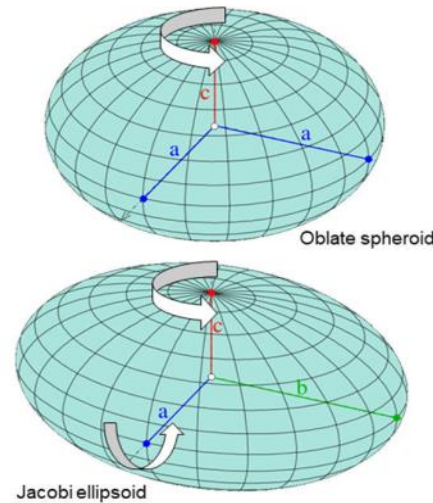
Black hole uniqueness

Kerr BH: $\kappa = 1$

Other objects

Neutron star: $\kappa \in [\sim 2, \sim 14]$

Boson star: $\kappa \in [\sim 10, \sim 150]$



Tidal deformability [2]

Induced quadrupole due

$$Q_{ij} = -\Lambda m^5 \mathcal{E}_{ij}, \quad \Lambda = \frac{2}{3} k_2$$

to an external tidal field.

Black holes are stiff

Tidal deformability $\Lambda = 0$

Other objects [3]

Neutron stars $\Lambda \sim 140$ ($C = 0.2$)

Boson stars $\Lambda > 27.6$ ($C = 0.2$)

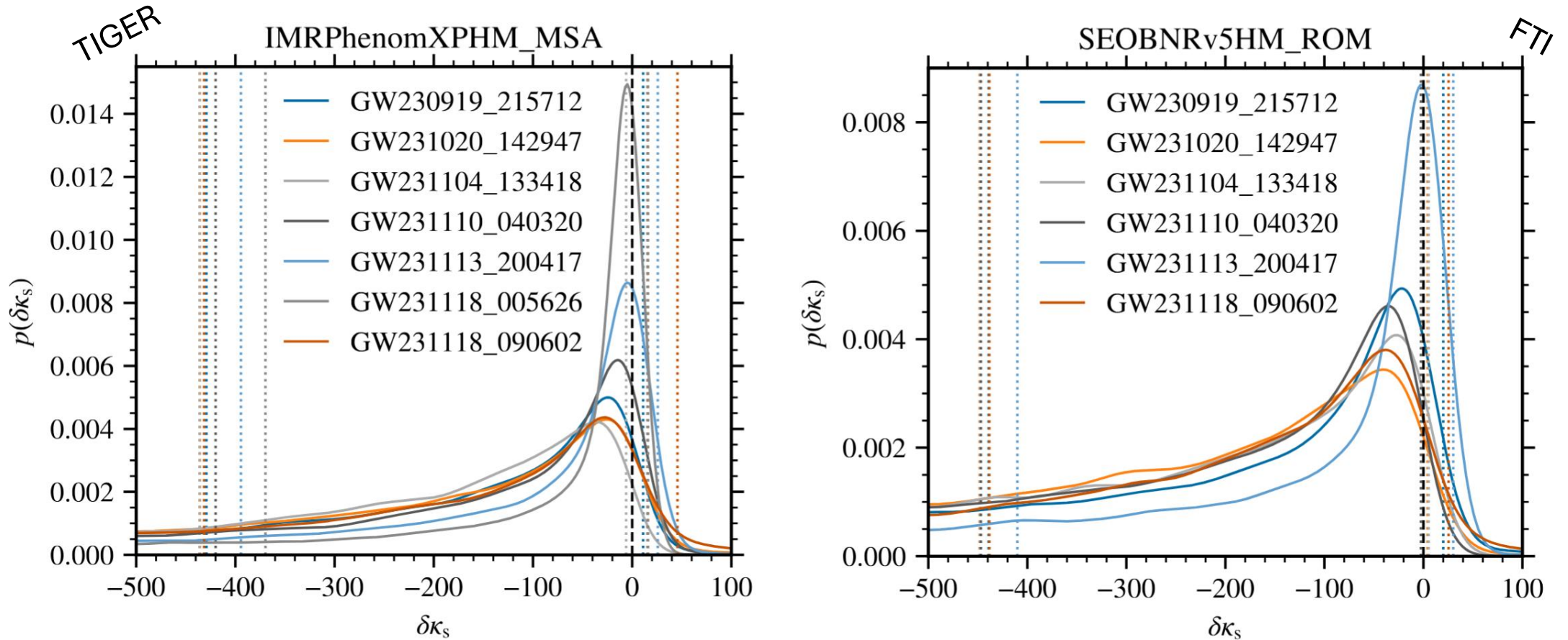
References

[1] Krishnendu et al. (2019); arXiv: 1908.02247, Saleem et al., arXiv:2111.04135,

[2] Johnson-McDaniel, Mukherjee, Kashyap, Ajith, Del Pozzo, Vitale (2018); arXiv:1804.08026

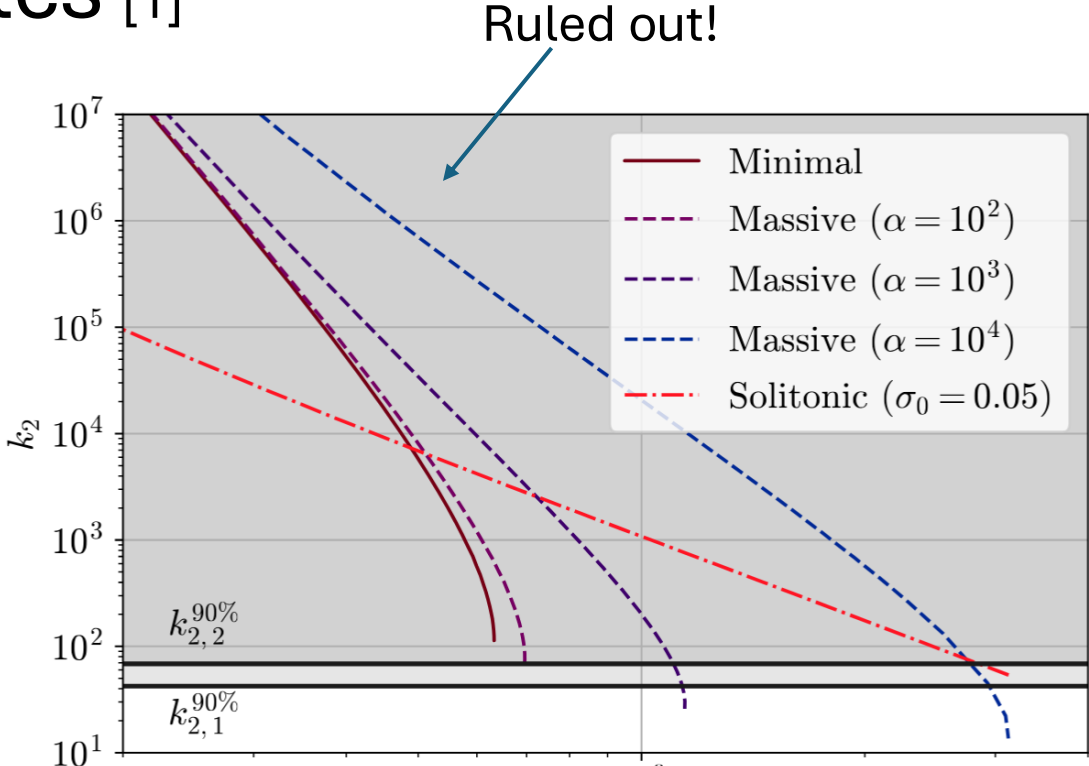
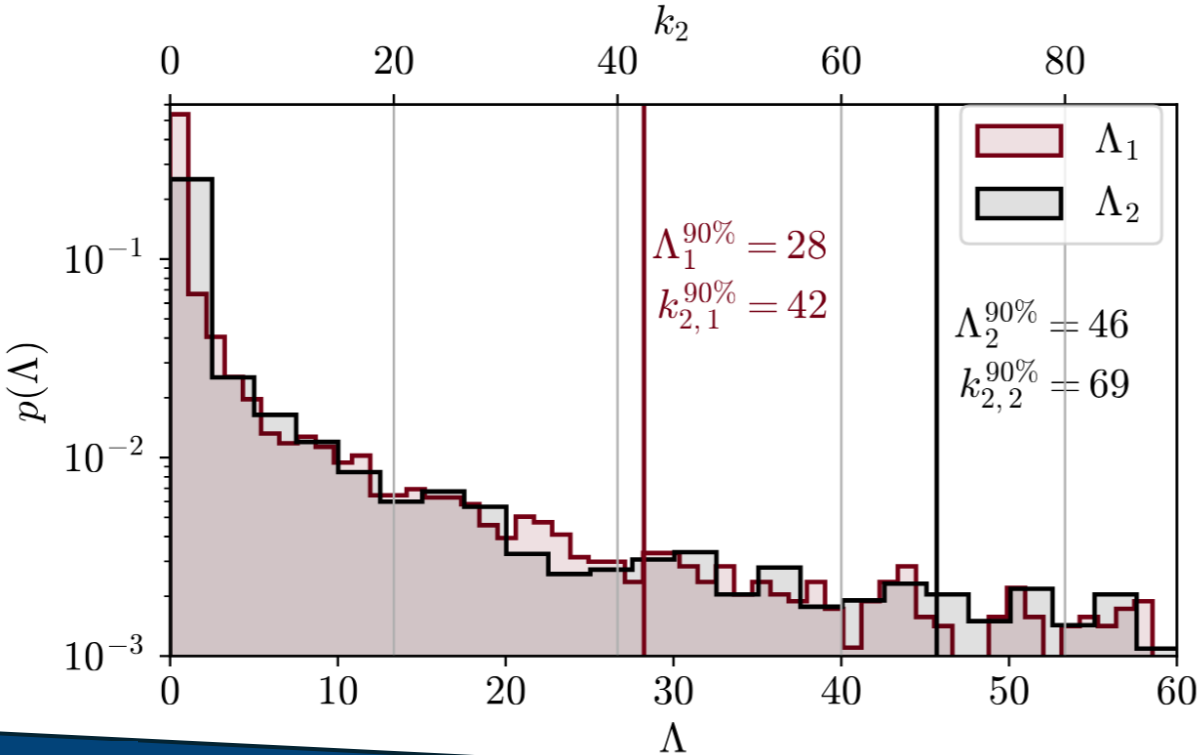
[3] Cardoso, Franzin, Maselli, Pani & Raposo (2017), arXiv:1701.01116

Tested spin induced quadrupole moments [1]



No love for black holes candidates [1]

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi} - g^{ab} \partial_a \Phi^* \partial_b \Phi - V(|\Phi|^2) \right]$$



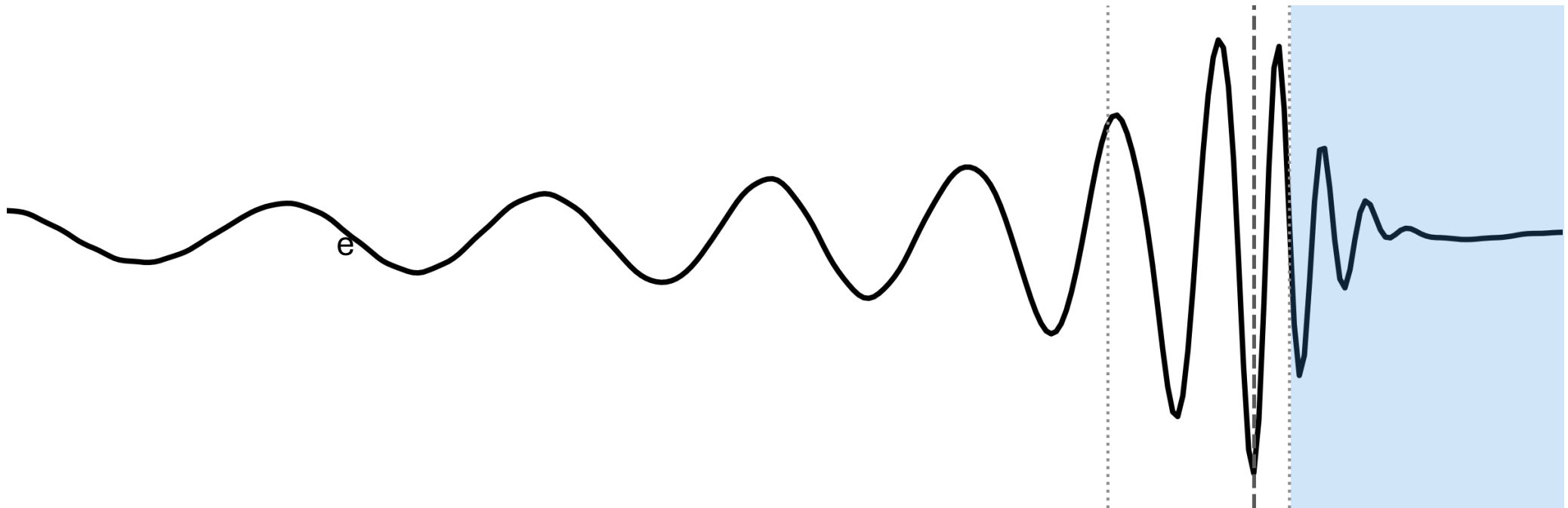
$$V(|\Phi|^2) = \mu^2 |\Phi|^2 \quad m\mu$$

$$\bar{V}(|\Phi|^2) = \mu^2 |\Phi|^2 + \frac{\alpha}{4} |\Phi|^4$$

$$V(|\Phi|^2) = \mu^2 |\Phi|^2 \left[1 - \frac{2|\Phi|^2}{\sigma_0^2} \right]^2$$



TESTS OF THE REMNANTS



Ringdown in the time domain

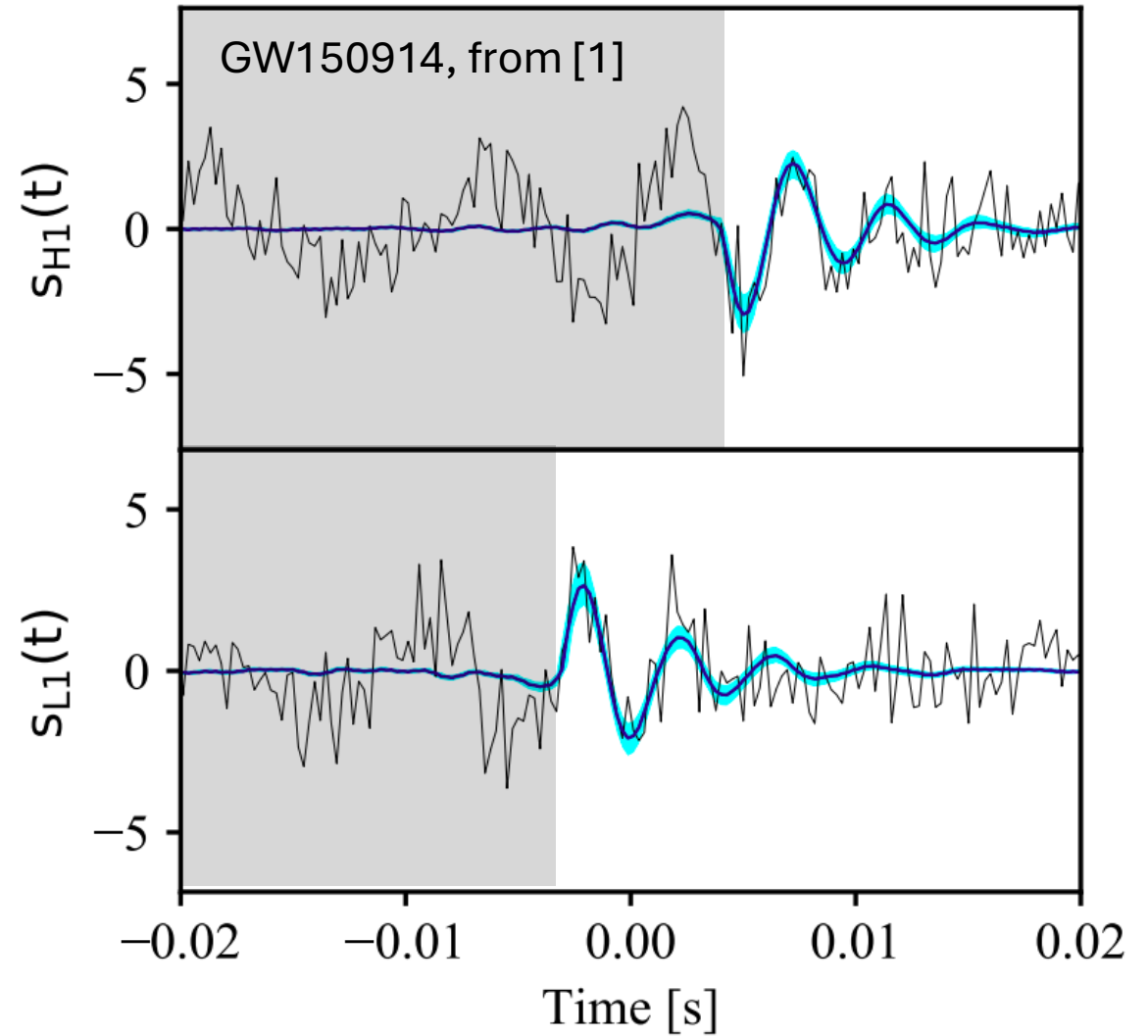
Signal model: [2]

$$h_+ - ih_\times = \sum_{\ell=2}^{+\infty} \sum_{m=-\ell}^{\ell} \sum_{n=0}^{+\infty} h_{\ell mn} -2S_{\ell mn}$$

$$h_{\ell mn} \equiv A_{\ell mn}(t) e^{-(t-t_0)/\tau_{\ell mn}} e^{-2\pi i f_{\ell mn}(t-t_0) + i\phi_{\ell mn}}$$

QNM frequencies are poles of the Teukolsky (FD) Greens function:

$$[\partial_{r_*}^2 + \omega^2 - V^T(\omega, r)] G(\omega, r_*, r'_*) = \delta(r_* - r'_*)$$



References:

[1] Carullo, Del Pozzo & Veitch (2019); arXiv:1902.07527

[2] Berti, Cardoso, Carullo, et al. (2025); arXiv:https://arxiv.org/pdf/2505.23895

Ringdown: Linear order vs. higher order [1,2]

$$g = \bar{g} + \epsilon h^{(1)} + \epsilon^2 h^{(2)} + \mathcal{O}(\epsilon^3)$$

$$G_{\mu\nu}[g] = G_{\mu\nu}^0[\bar{g}] + \underbrace{\epsilon G_{\mu\nu}^{(1)}[h^{(1)}]}_{=0} + \epsilon^2 \underbrace{\left(G_{\mu\nu}^{(2)}[h^{(2)}] + G_{\mu\nu}^{(1,1)}[h^{(1)}, h^{(1)}] \right)}_{=0} + \mathcal{O}(\epsilon^3) = 0$$

1st order:

$$\left(\partial_t^2 - \partial_{r_*}^2 - V_{\text{RWZ}} \right) \Psi^{(1)} = 0$$

2nd order:

$$\left(\partial_t^2 - \partial_{r_*}^2 - V_{\text{RWZ}} \right) \Psi^{(2)} = S^{(2)}[\Psi^{(1)}, \Psi^{(1)}]$$

Source of quadratic modes

Perturbation less decayed
= more excitation of non-lin mode

Effects expected closer to signal peak!

References:

[1] Macarena Lagos & Lam Hui (2022); arXiv: 2208.07379

[2] Bucciotti, Juliano, Kuntz, Trincherini (2024); arXiv: 2406.14611



Ringdown: The EOB picture

The idea [1,2]:

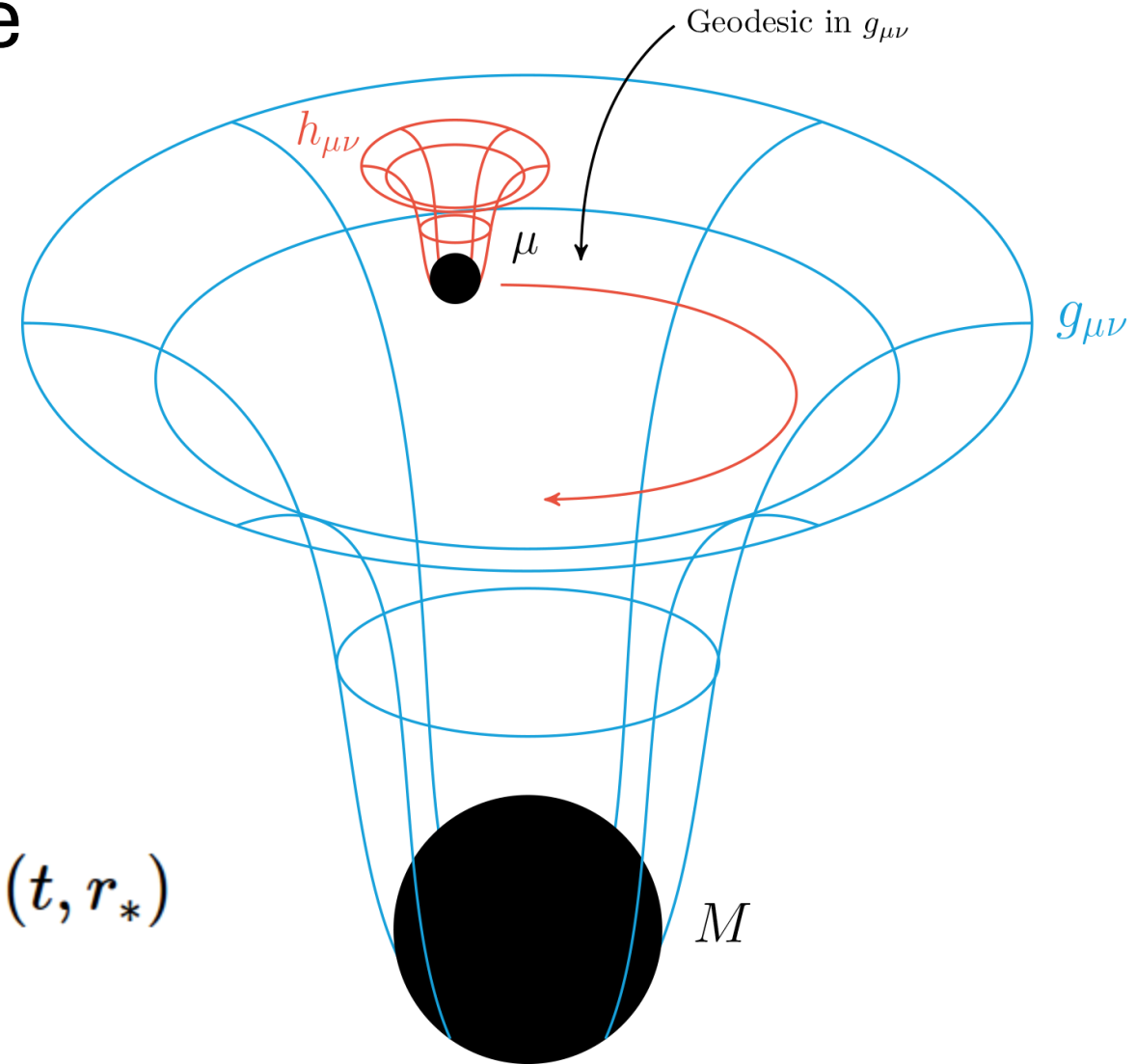
Relativistic two body problem



Point particle perturbation on effective Kerr background

Test mass limit - Schwarzschild BH with point particle Perturbation [3]:

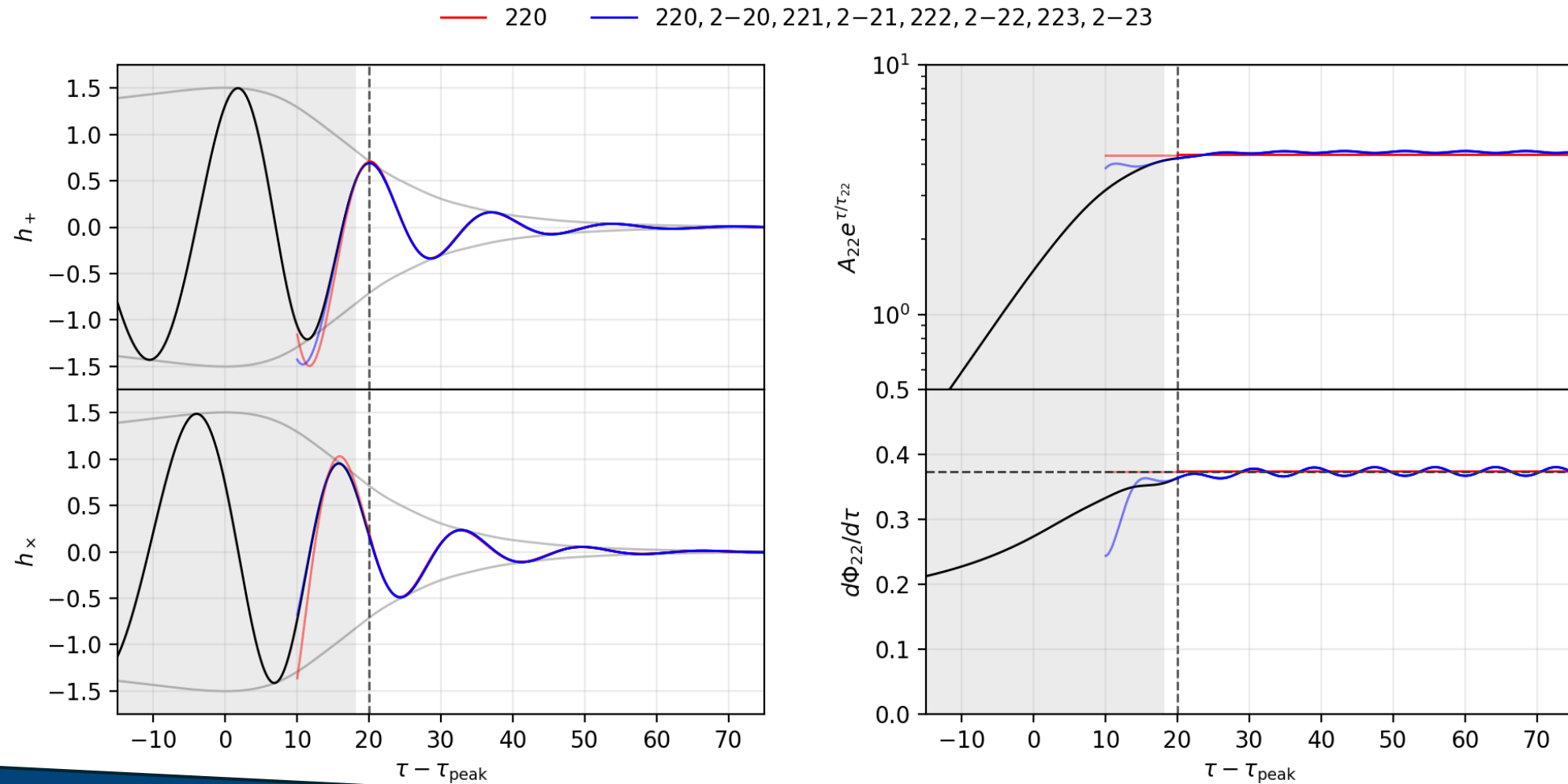
$$(\partial_t^2 - \partial_{r_*}^2 - V_{RWZ}) \Psi^{(1)} = S_{pp}(t, r_*)$$



References:

- [1] Buonanno & Damour, (1998); arXiv: 9811091
- [2] Damour & Nagar (2014); arXiv: 1406.6913
- [3] De Amicis et.al, (202); arXiv: 2506.21668

Dynamical vs. Stationary



Resources:

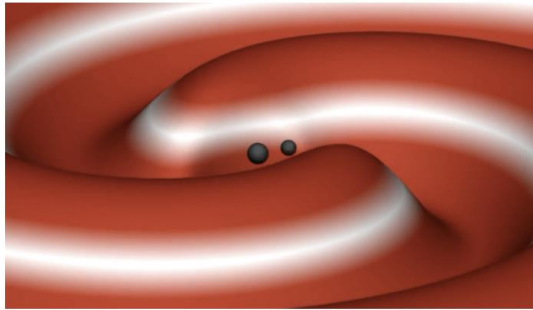
- [1] Inspiration from: De Amicis et.al, (202); arXiv: 2506.21668
- [2] RWZHyp solution: Bernuzzi, Nagar & Zenginoglu, (2011), arXiv:1107.5402
- [3] Fits produced with bayRing: <https://github.com/GCArullo/bayRing>

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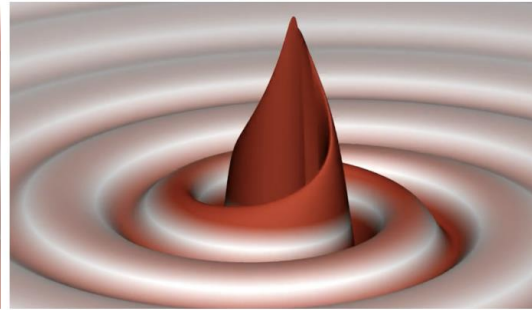


Driven harmonic oscillator analogy

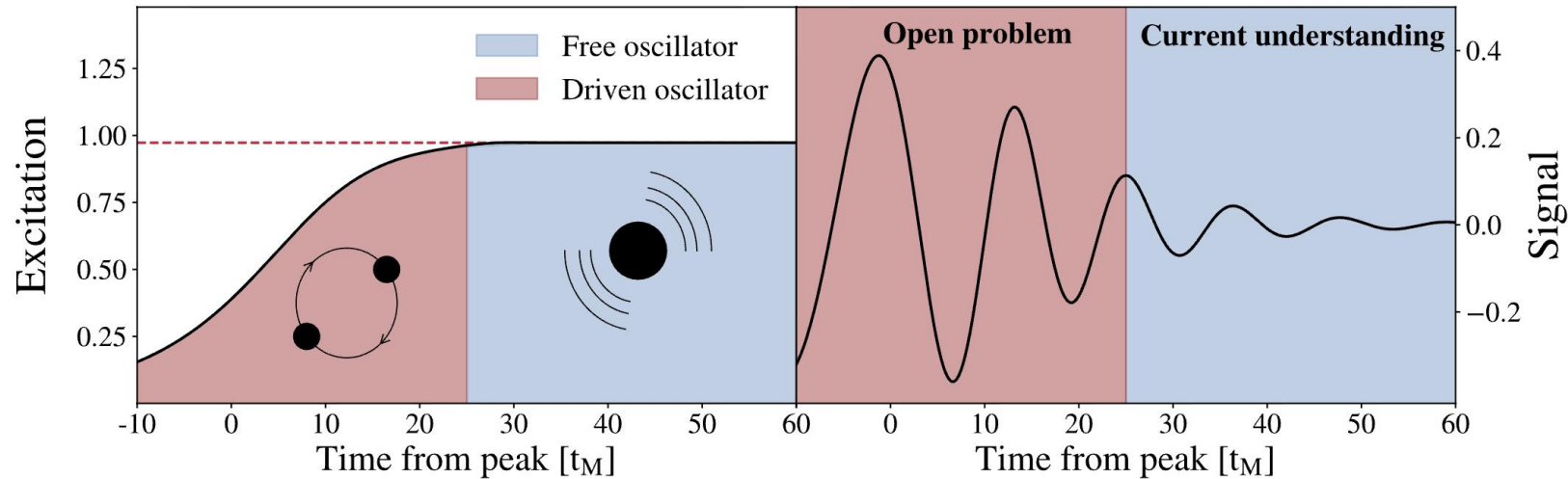
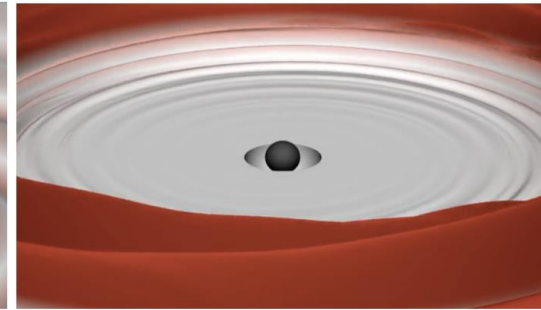
Current knowledge: Inspiral



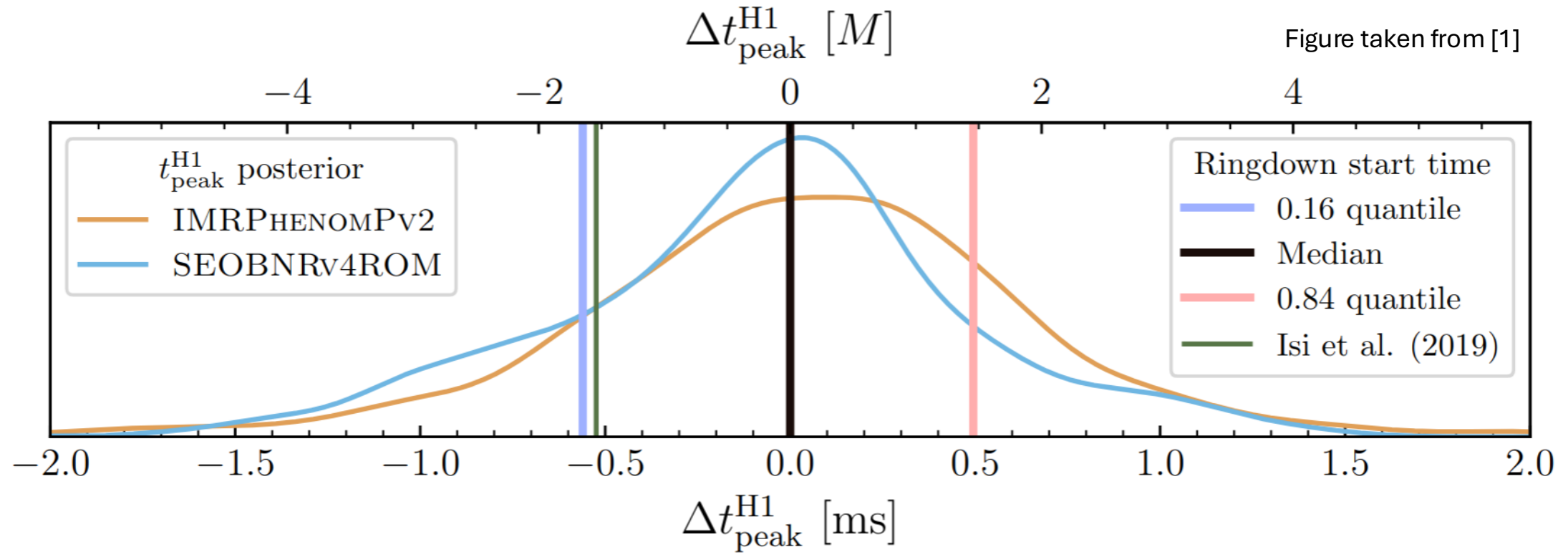
Open problem



Current knowledge: Ringdown



Systematics: We don't know the peak time



Higher mode detection

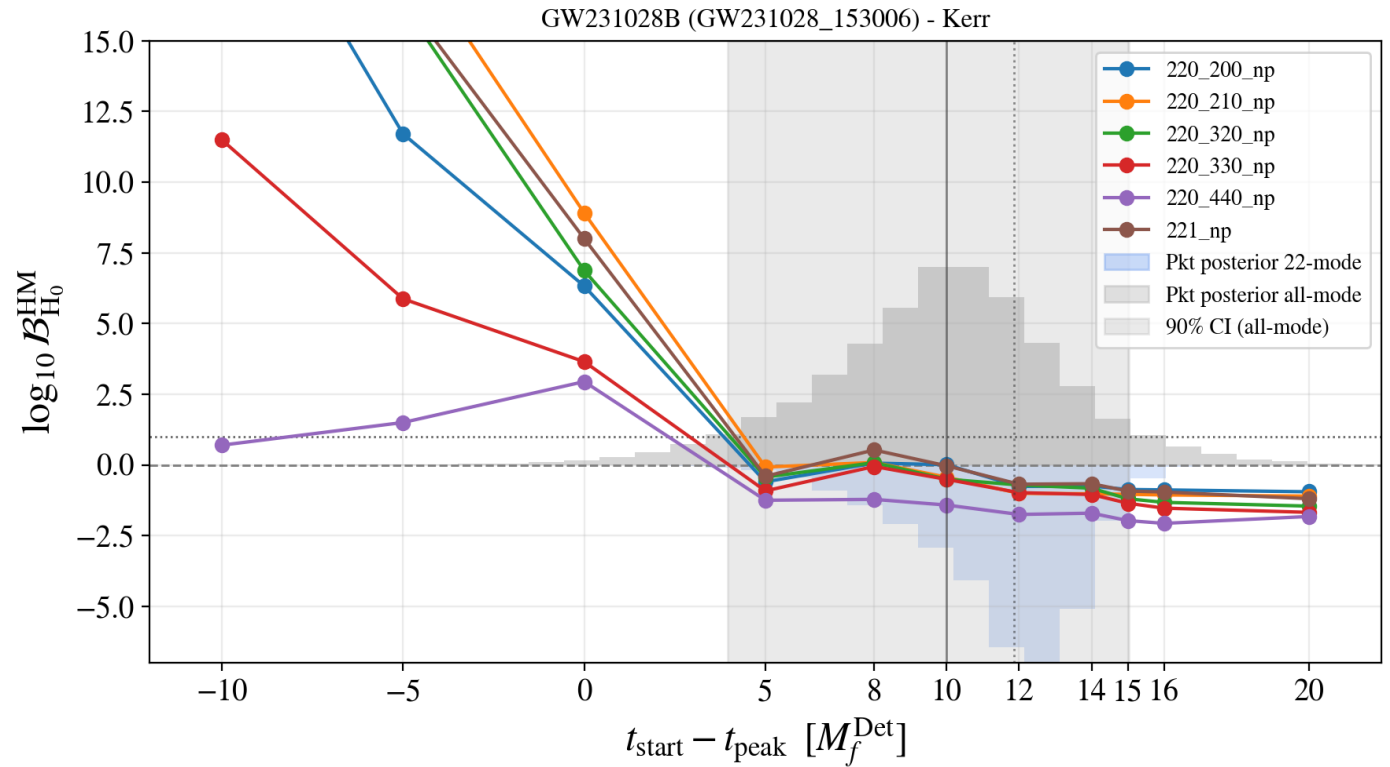
Model selection via Bayes factors

$$\frac{P(\text{HM}|D)}{P(\text{H}_0|D)} = \frac{P(\text{HM})}{P(\text{H}_0)} \underbrace{\frac{P(D|\text{HM})}{P(D|\text{H}_0)}}_{=: \mathcal{B}_{\text{H}_0}^{\text{HM}}(t_M^{\text{start}})} = \mathcal{O}_{\text{H}_0}^{\text{HM}}(t_M^{\text{start}})$$

- BF support on 90% CI of start-time

Amplitude posterior support

- Less dependent on prior ranges.
- Allows to investigate mode evolution with time.



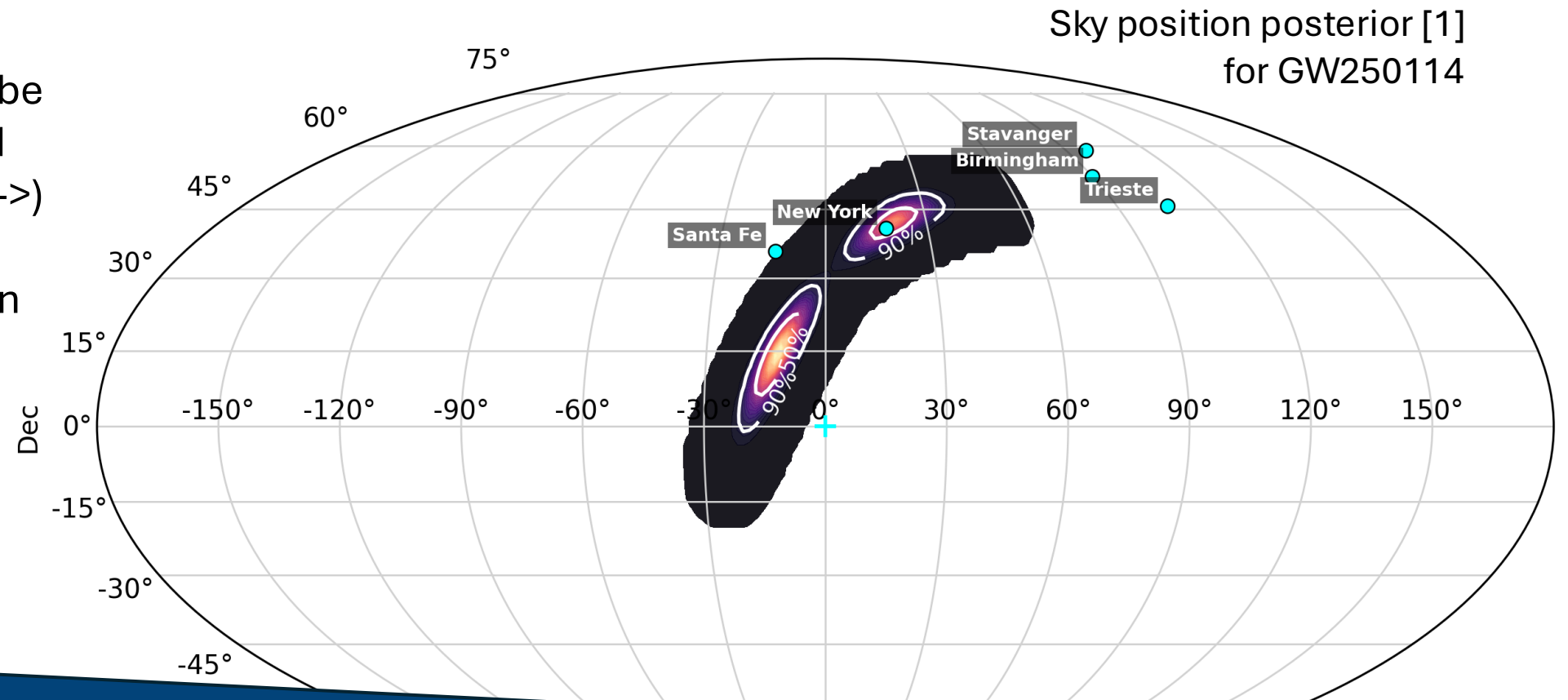
Sky-location systematics

In current LVK analysis, the sky-position is fixed due to similar issues as with the start time

Sky position can be
 1) badly localized
 2) bi-modal (see ->)

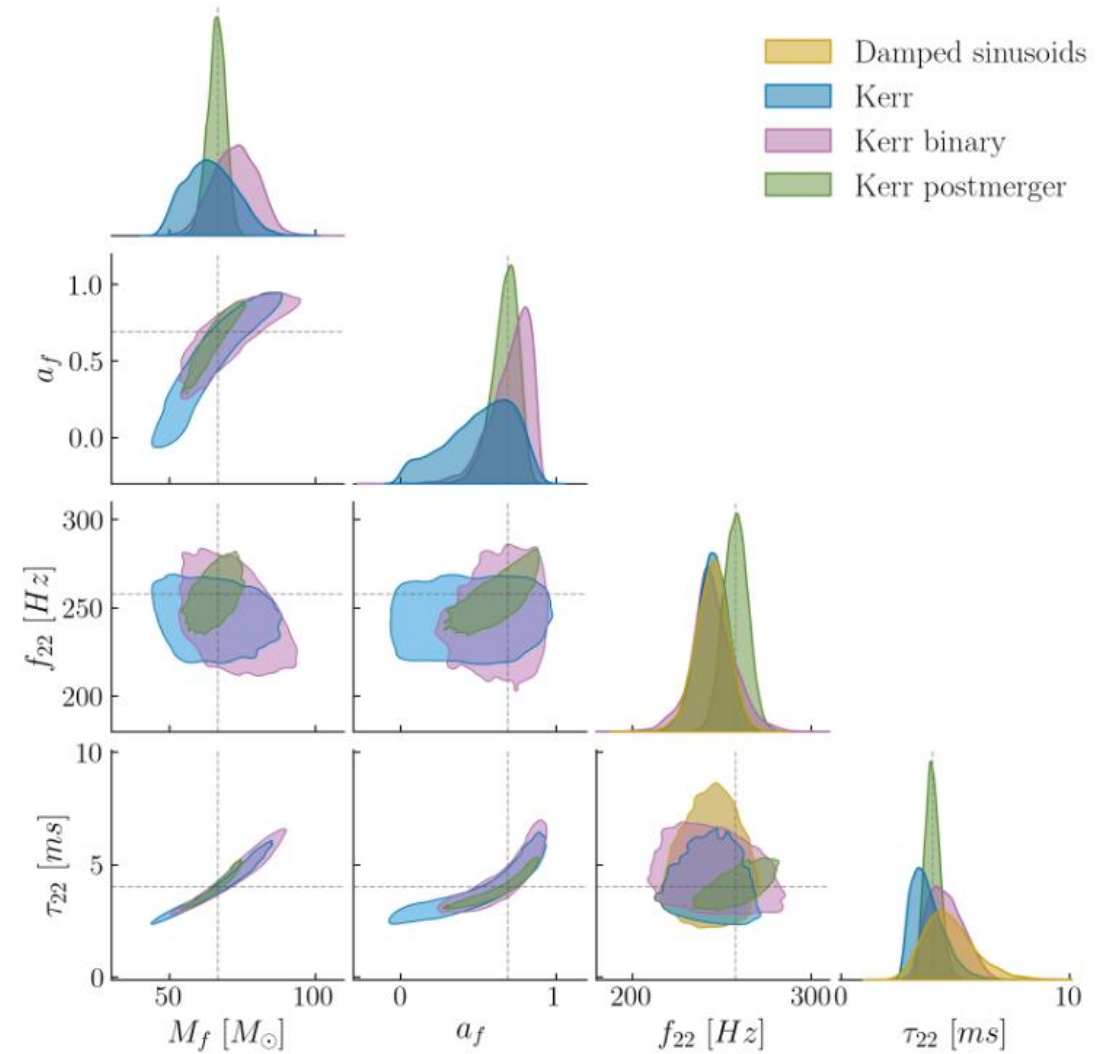
Fixing sky position can introduce a bias.

Improve this with new proposal [2]



Ringdown templates

Models	Free intrinsic parameters	Assumptions
Damped sinusoids	f_j, τ_j, A_j, ϕ_j	
Kerr (Kerr-informed f, τ)	$M_f, a_f, A_{\ell mn}, \phi_{\ell mn}$	$f_{\ell mn}(M_f, a_f),$ $\tau_{\ell mn}(M_f, a_f)$
KerrBinary (NR-informed f, τ, A, ϕ)	$m_{1,2}, \chi_{1,2}$	$f_{\ell mn}(M_f, a_f),$ $\tau_{\ell mn}(M_f, a_f),$ $A_{\ell mn}(m_{1,2}, \chi_{1,2}),$ $\phi_{\ell mn}(m_{1,2}, \chi_{1,2})$
KerrPostmerger (NR-informed $f, \tau, A(t), \phi(t)$)	$m_{1,2}, \chi_{1,2}$	$f_{\ell mn}(M_f, a_f),$ $\tau_{\ell mn}(M_f, a_f),$ $A_{\ell mn}(t; m_{1,2}, \chi_{1,2}),$ $\phi_{\ell mn}(t; m_{1,2}, \chi_{1,2})$



Resources:

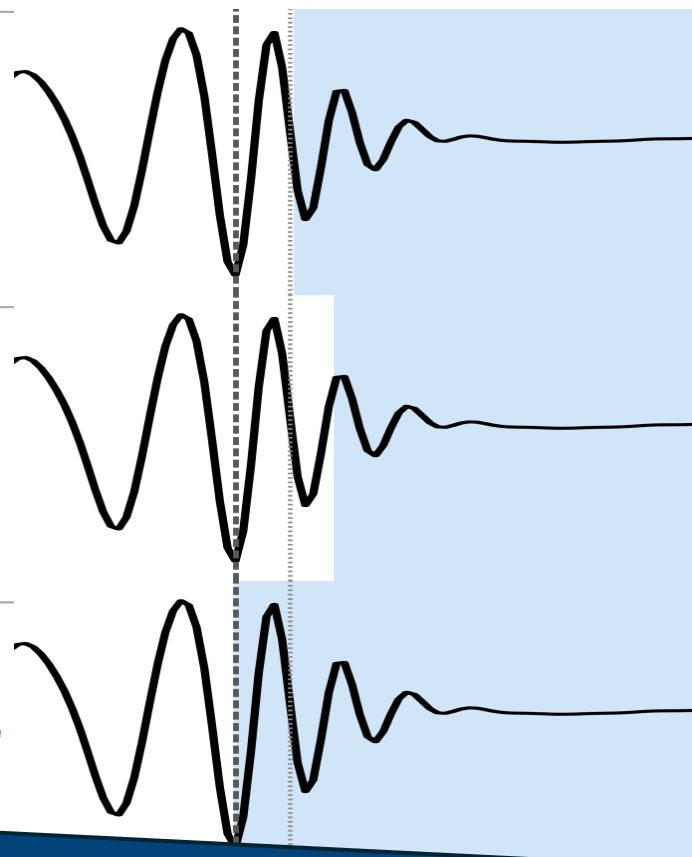
Table taken from Section 6, Table 7 in [1]

Pot taken from Section 6, Figure 6.1 in [1]

[1] Berti, Cardoso, Carullo, et al. (2025); arXiv:https://arxiv.org/pdf/2505.23895

Ringdown templates

Models	Free intrinsic parameters	Assumptions
Damped sinusoids	f_j, τ_j, A_j, ϕ_j	
Kerr (Kerr-informed f, τ)	$M_f, a_f, A_{\ell mn}, \phi_{\ell mn}$	$f_{\ell mn}(M_f, a_f),$ $\tau_{\ell mn}(M_f, a_f)$
KerrBinary (NR-informed f, τ, A, ϕ)	$m_{1,2}, \chi_{1,2}$	$f_{\ell mn}(M_f, a_f),$ $\tau_{\ell mn}(M_f, a_f),$ $A_{\ell mn}(m_{1,2}, \chi_{1,2}),$ $\phi_{\ell mn}(m_{1,2}, \chi_{1,2})$
KerrPostmerger (NR-informed $f, \tau, A(t), \phi(t)$)	$m_{1,2}, \chi_{1,2}$	$f_{\ell mn}(M_f, a_f),$ $\tau_{\ell mn}(M_f, a_f),$ $A_{\ell mn}(t; m_{1,2}, \chi_{1,2}),$ $\phi_{\ell mn}(t; m_{1,2}, \chi_{1,2})$



Resources:

[1] Table taken from Section 6, Table 7 in [1]

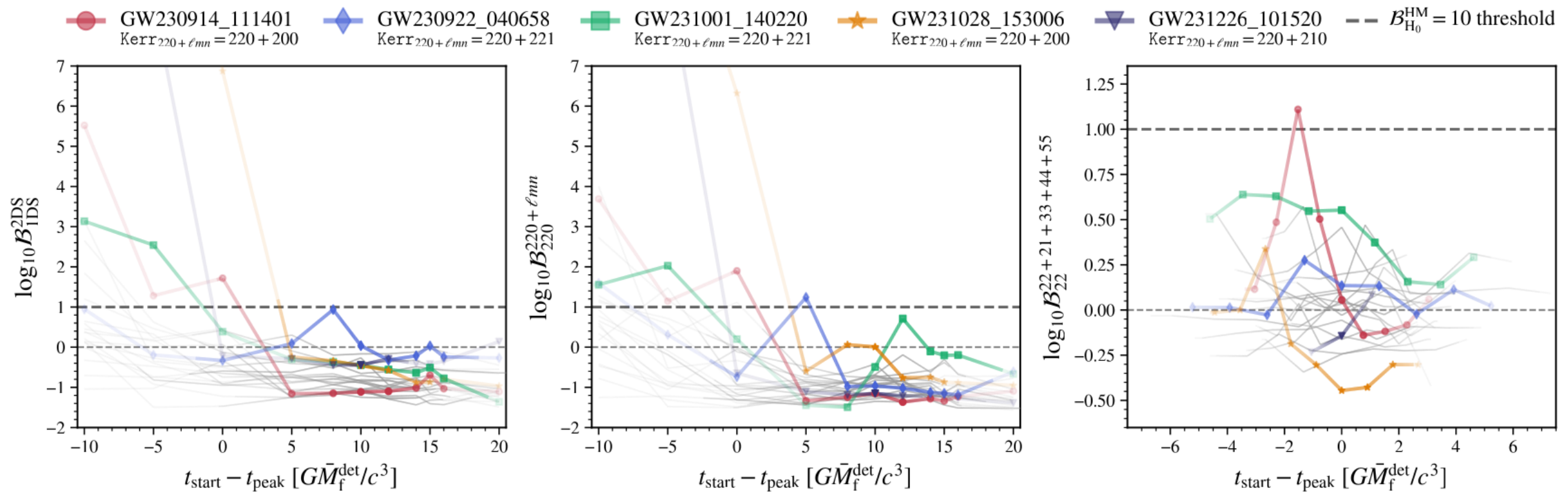
[2] Pot taken from Section 6, Figure 6.1 in [1]

[1] Berti, Cardoso, Carullo, et al. (2025); arXiv:<https://arxiv.org/pdf/2505.23895>

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Searches for higher modes with pyRing in O4a



(a) DampedSinusoids

(b) Kerr

(c) KerrPostmerger

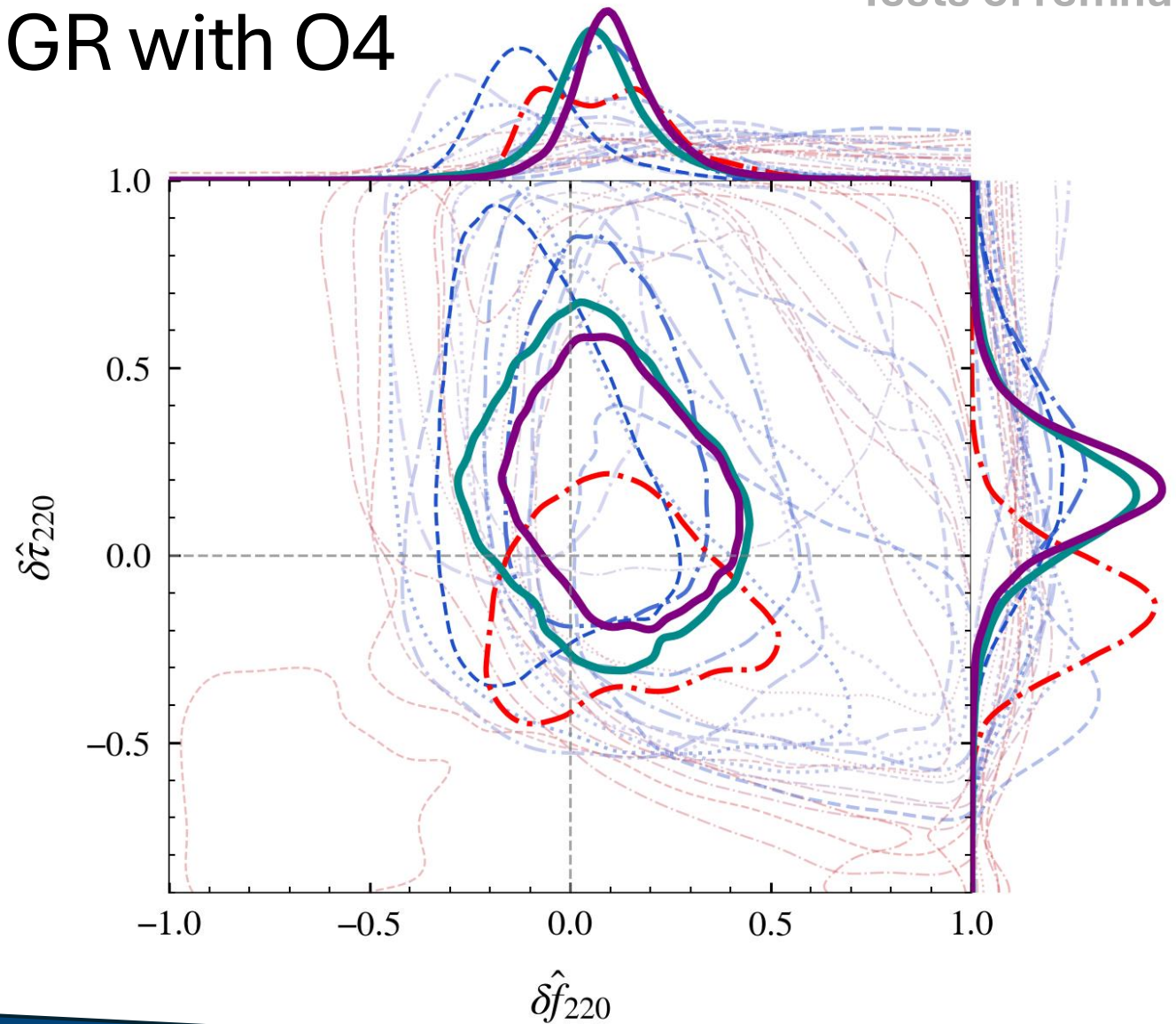


Parametrized RD tests of GR with O4

- Hierarchical combination
- Hierarchical combination ($\log_{10} \mathcal{B}_{\text{Noise}}^{22} > 8$)
- - - GW250114
- - - GW231226_101520
- · - · GW231028_153006

$$f_{220} = f_{220}^{\text{GR}} (1 + \delta \hat{f}_{220})$$

$$\tau_{220} = \tau_{220}^{\text{GR}} (1 + \delta \hat{\tau}_{220})$$



Resources for plot:

[1] GW250114 data: <https://zenodo.org/records/17018009>

[2] GWTC-4 data: <https://dcc-llo.ligo.org/LIGO-P2600130/public>

[3] Values taken from the related papers/the data from the releases.

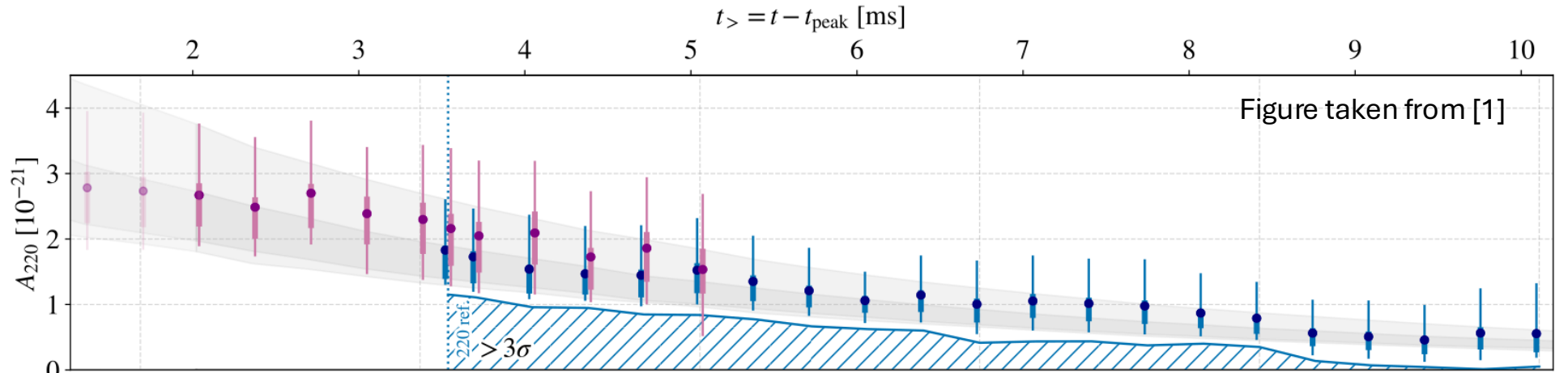
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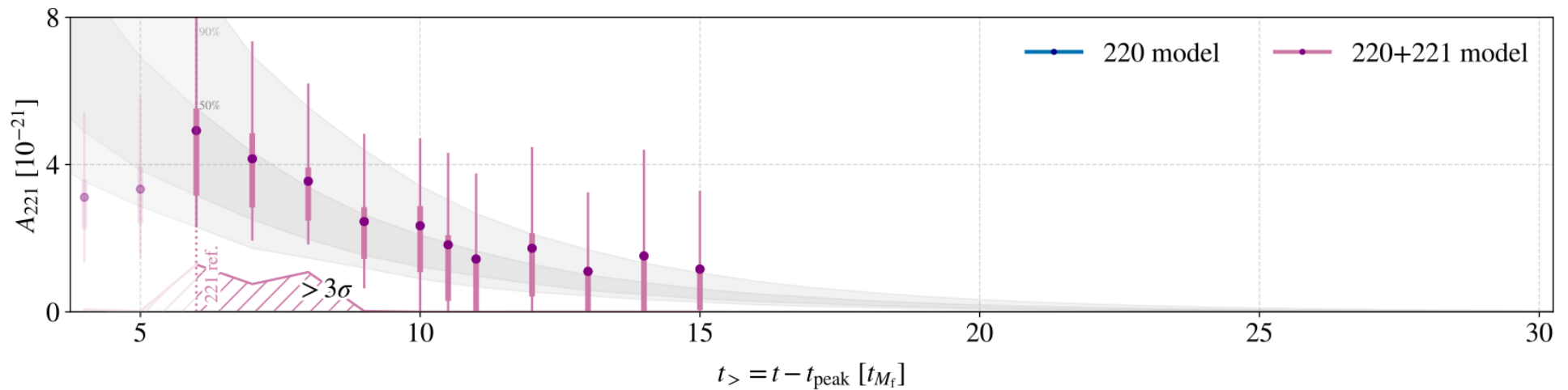
First robust detection of an overtone

Kerr-Template

Amplitudes of fundamental mode 220

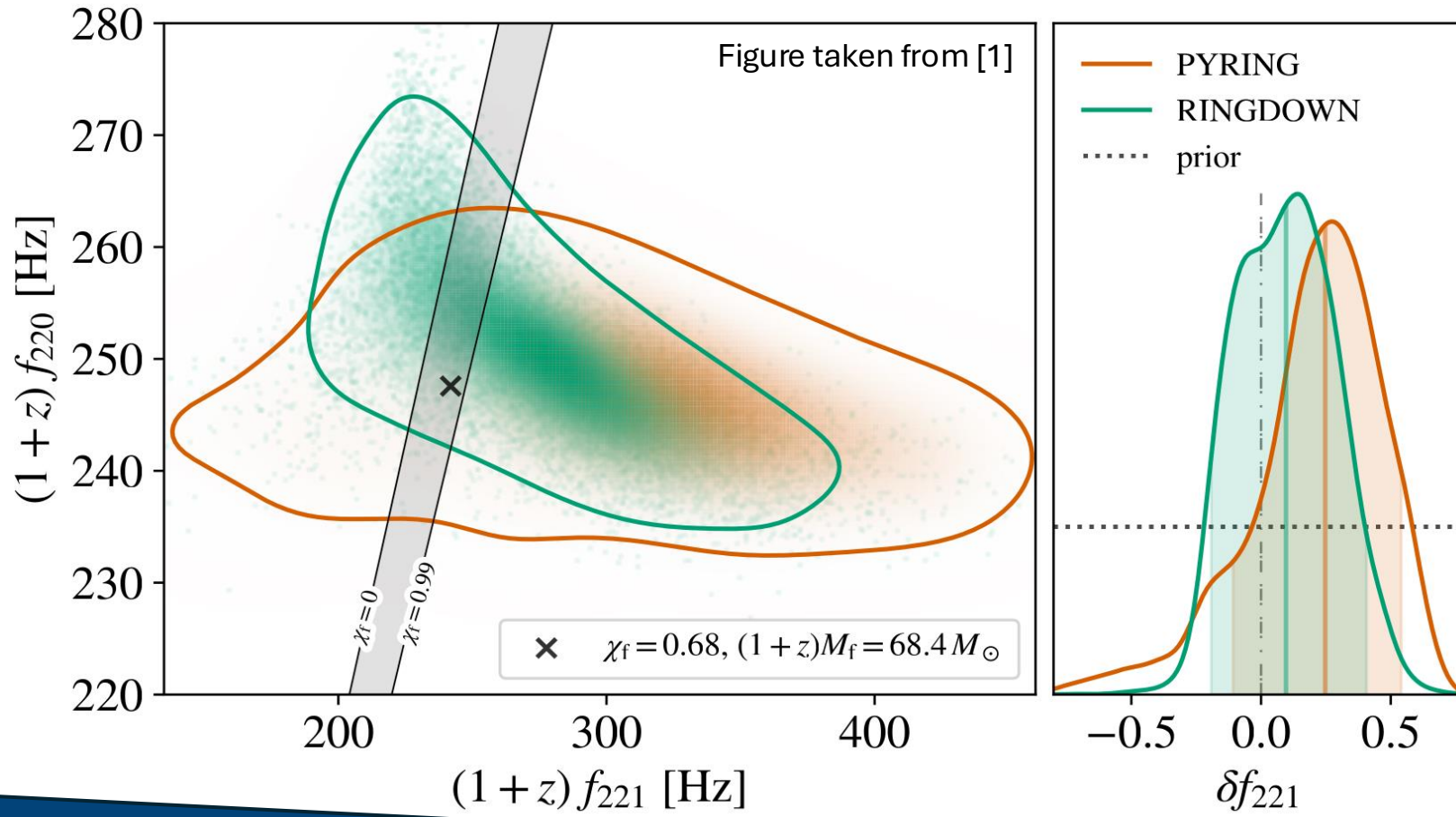


Amplitudes of First overtone 221



No-Hair tests – Testing the Kerr nature

$$f_{221} = f_{221}^{(\text{Kerr})}(M_f, \chi_f) \exp(\delta f_{221}) \quad \gamma_{221} = \gamma_{221}^{(\text{Kerr})}(M_f, \chi_f) \exp(\delta \gamma_{221})$$



Hawking's Area Law

The **second law** of black hole mechanics states that the black hole horizon area cannot decrease in time.

$$\frac{dA}{dt} \geq 0$$

The Theorem is based on three axioms

- 1) General relativity
- 2) Null-energy condition
- 3) Object is a Black Hole

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

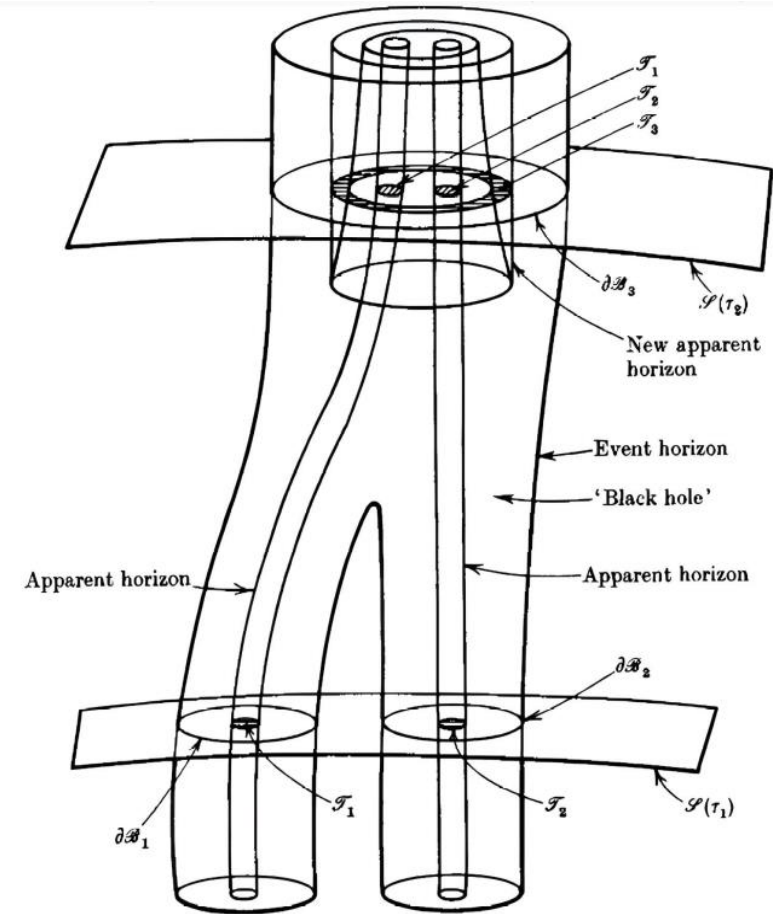


FIGURE 60. The collision and merging of two black holes. At time τ_1 , there are apparent horizons $\partial\mathcal{F}_1, \partial\mathcal{F}_2$ inside the event horizons $\partial\mathcal{B}_1, \partial\mathcal{B}_2$ respectively. By time τ_2 , the event horizons have merged to form a single event horizon; a third apparent horizon has now formed surrounding both the previous apparent horizons.

Figure taken from [1]

References:

[1] Hawking & Ellis (2010); DOI:<https://doi.org/10.1017/CBO9780511524646>

Observational test of the Area Law

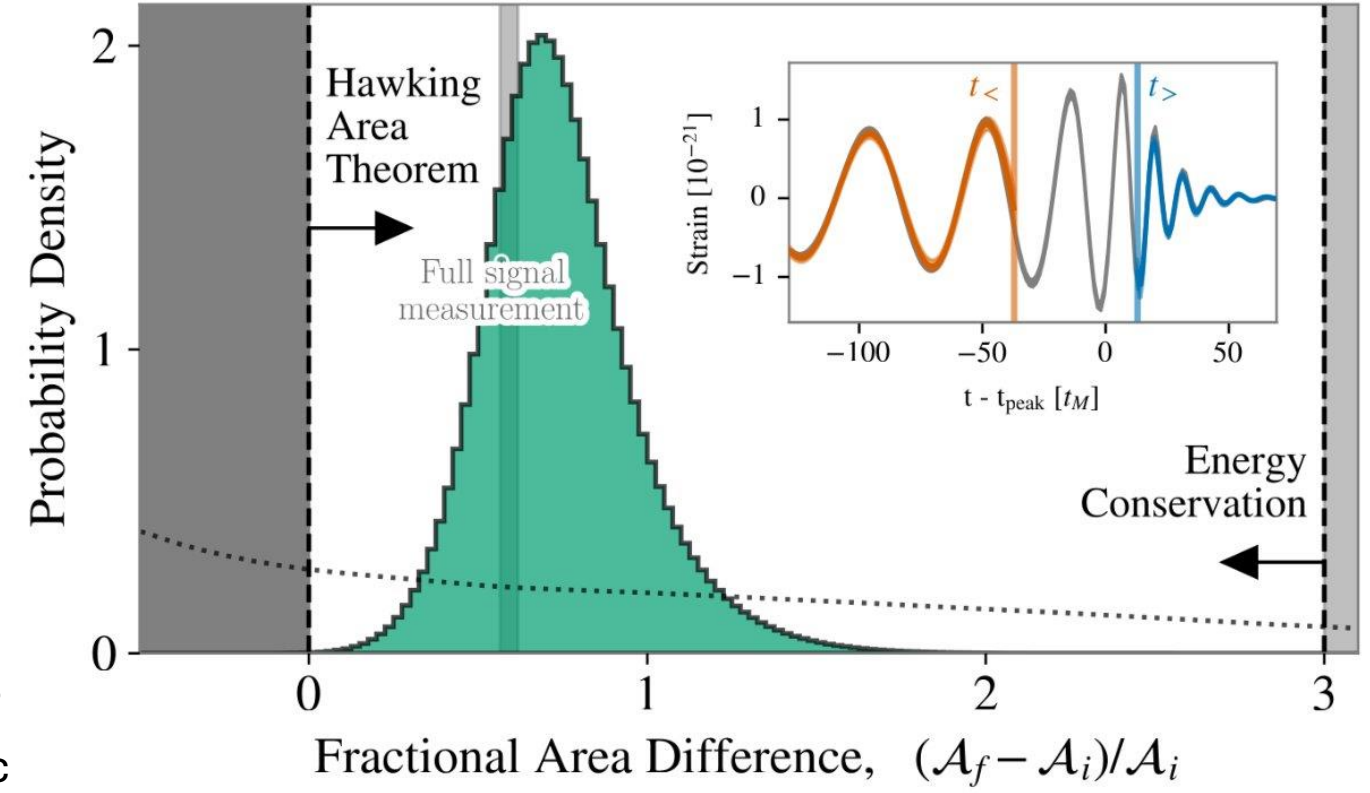
Calculate area in the inspiral and Ringdown independently from masses and spin.

$$\mathcal{A}_i = \mathcal{A}_1 + \mathcal{A}_2 < \mathcal{A}_f$$

The test is based on three assumption:

- 1) Signal originates from a quasi-circular merging binary
- 2) GR is valid away in highly dynamical regions
- 3) Black holes are described by the Kerr metric

Figure taken from [1]



An alternative approach: pSEOBS

pSEOBS analysis [1]:

$$h(t; \theta, \delta\omega, \delta\tau) = h^{\text{Insp-plunge}}(t)\Theta(t - t_{\text{match}}^{\text{lm}}) + h^{\text{merger-RD}}(t)\Theta(t_{\text{match}}^{\text{lm}} - t)$$

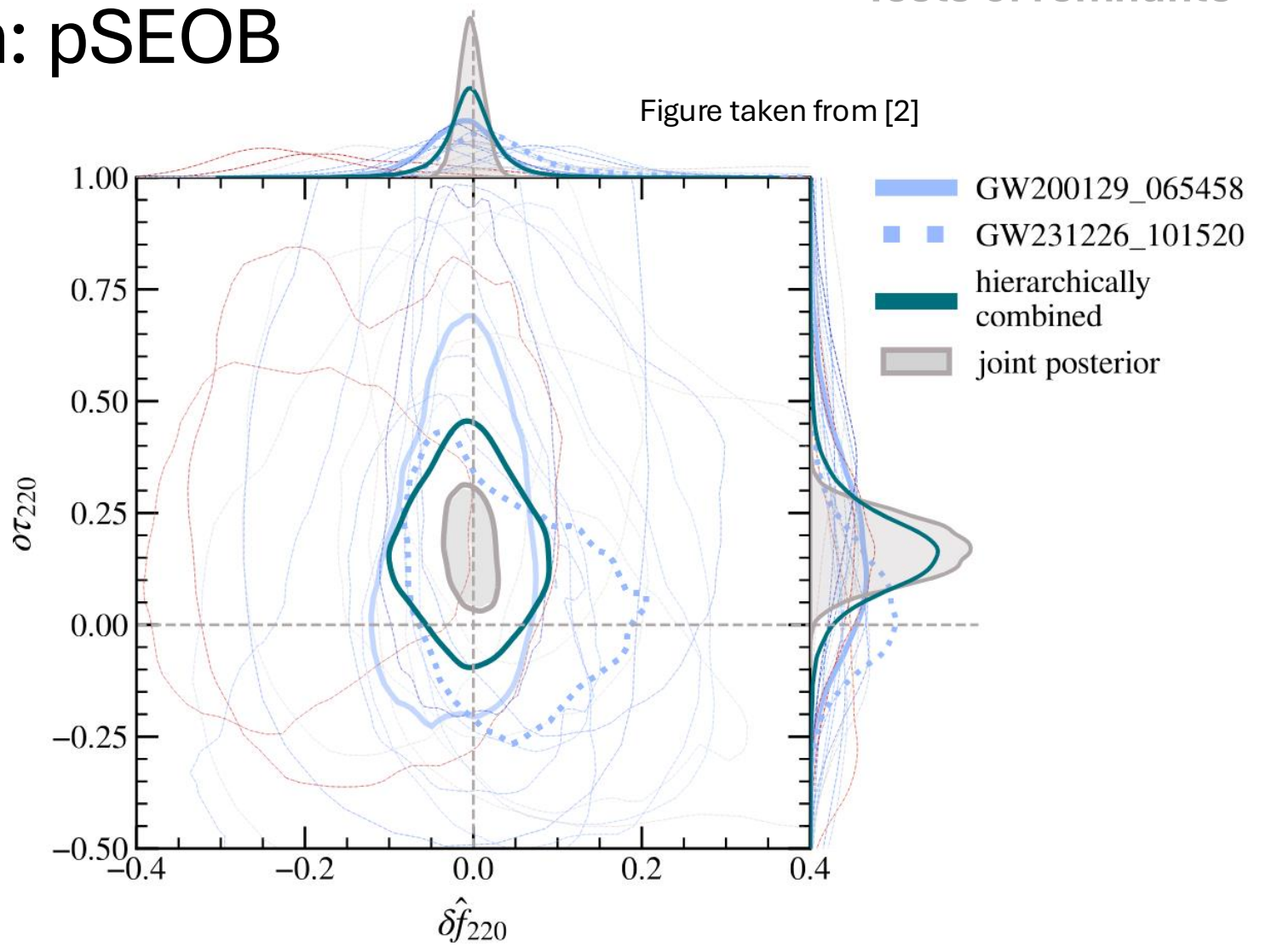
$$h_{\text{lm}}^{\text{merger-RD}}(t) = \eta M A_{\text{lm}}(t) e^{-i\phi_{\text{lm}}(t)} e^{-i\sigma_{\text{lm}0}(t - t_{\text{match}}^{\text{lm}})}$$

$$\sigma_{\text{lm}0} = f_{\text{lm}0} - \frac{i}{\tau_{\text{lm}0}}$$

$$\tau_{\text{lm}0} = \tau_{\text{lm}0}^{\text{GR}} (1 + \delta\hat{\tau}_{\text{lm}0})$$

$$f_{\text{lm}0} = f_{\text{lm}0}^{\text{GR}} (1 + \delta\hat{f}_{\text{lm}0})$$

Figure taken from [2]



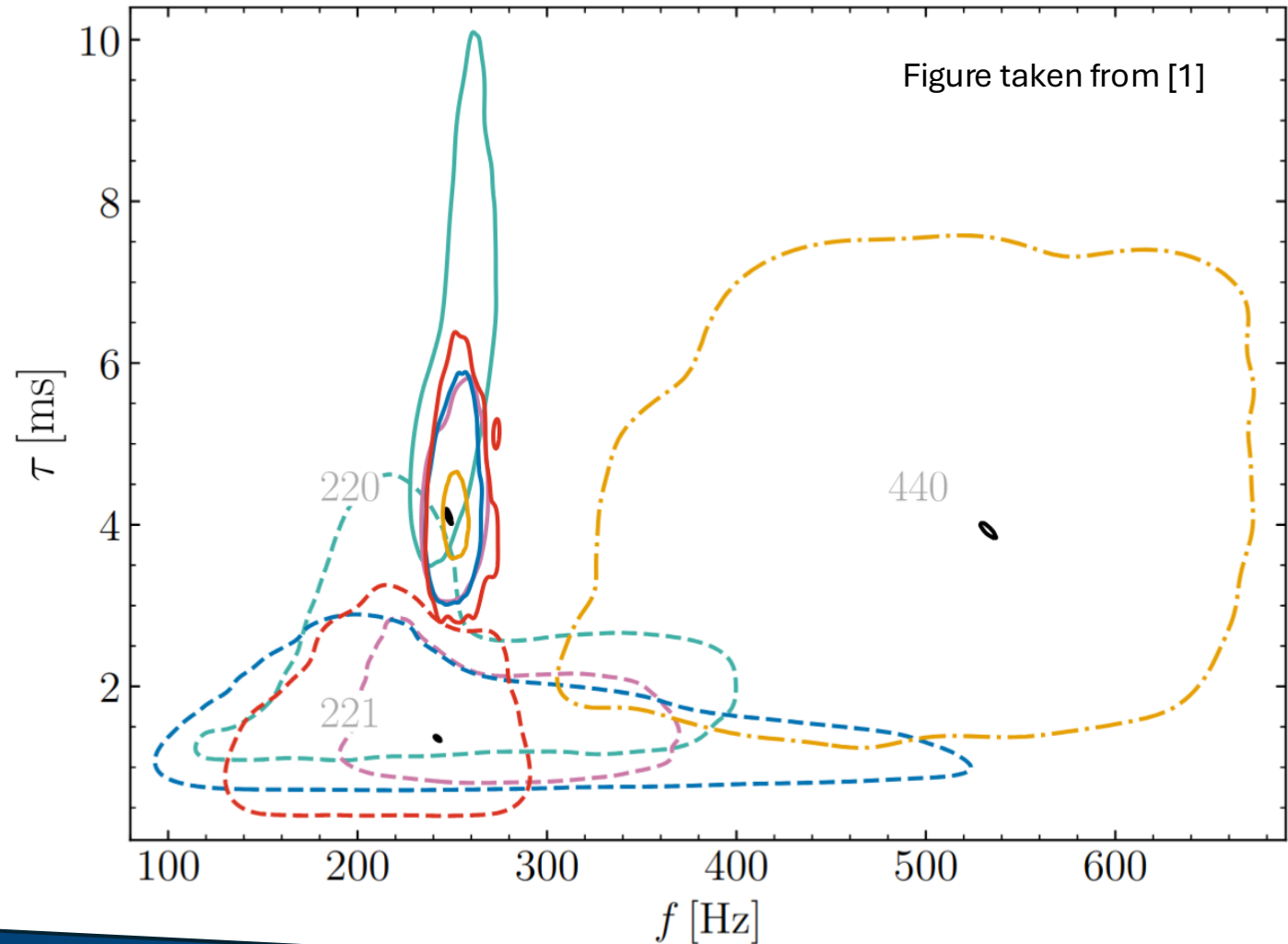
References:

- [1] Grimaldi, Maggio, Pompili & Buonanno, (2026); 2601.13173
- [2] LIGO-Virgo-KAGRA Scientific Collaboration, (2026); arXiv:12603.19021

Status on higher multipoles: (4,4) in GW250114

Models:

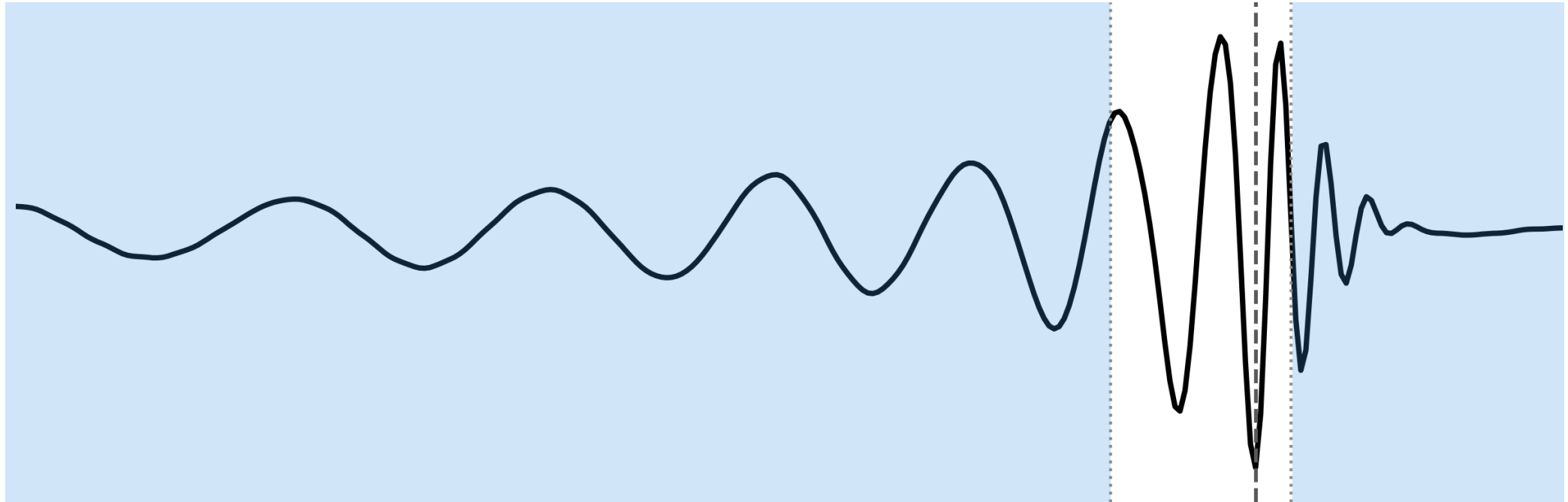
- 220+ δ 221, $t_{>} = 9 t_{M_f}$
- 220+ δ 221, $t_{>} = 6 t_{M_f}$
- 220+ δ 221, $t_{>} = 3 t_{M_f}$
- 2DS, $t_{>} = 9 t_{M_f}$
- pSEOBNR
- IMR



References:

[1] LIGO-Virgo-KAGRA Scientific Collaboration, (2025); arXiv:2509.08099

SUMMARY & OUTLOOK

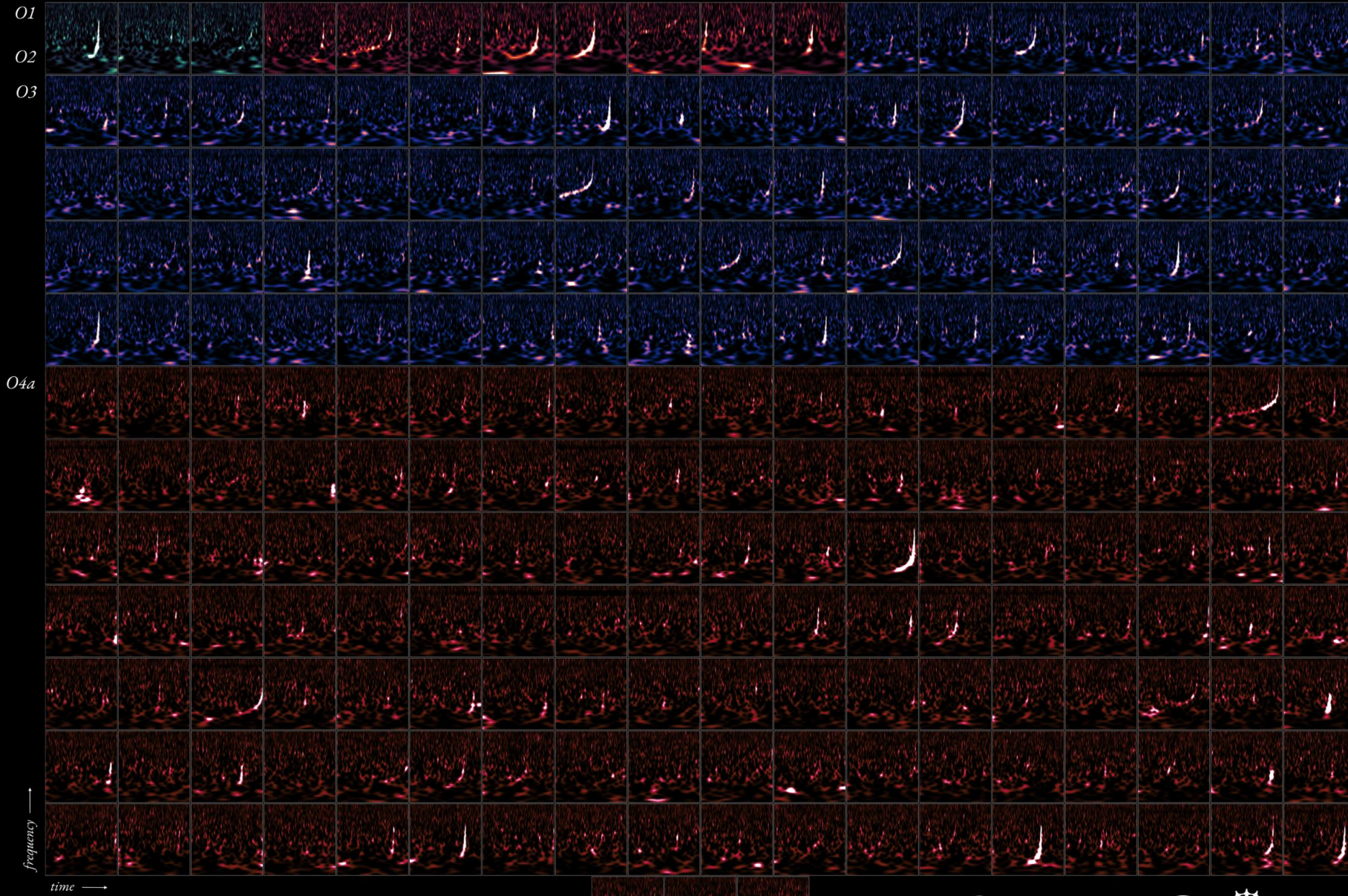


Summary and outlook

- **We will see louder events:**
 - These will dominate TGR constraints.
 - Waveform systematics will become increasingly important.
- **More events and GW-Astronomie :**
 - We will learn about the (sub)-population(s) of black holes (mimickers)
 - We need to **improve hierarchical methods** for test of GR
- **Ringdown :**
 - Great observational tool with independent systematics
 - Community is converging and first robust overtone detection.
 - The future of Ringdown are the **dynamical** aspects!

Gravitational-Wave Transient Catalog

10 Years of Detections (2015-2024) of Compact Binary Coalescences with Black Holes and Neutron Stars

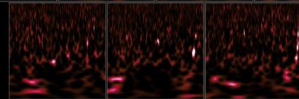


Thank
you for
your
attention.

I am glad to
to take further
Questions!

Also, I am
up for hire ;)

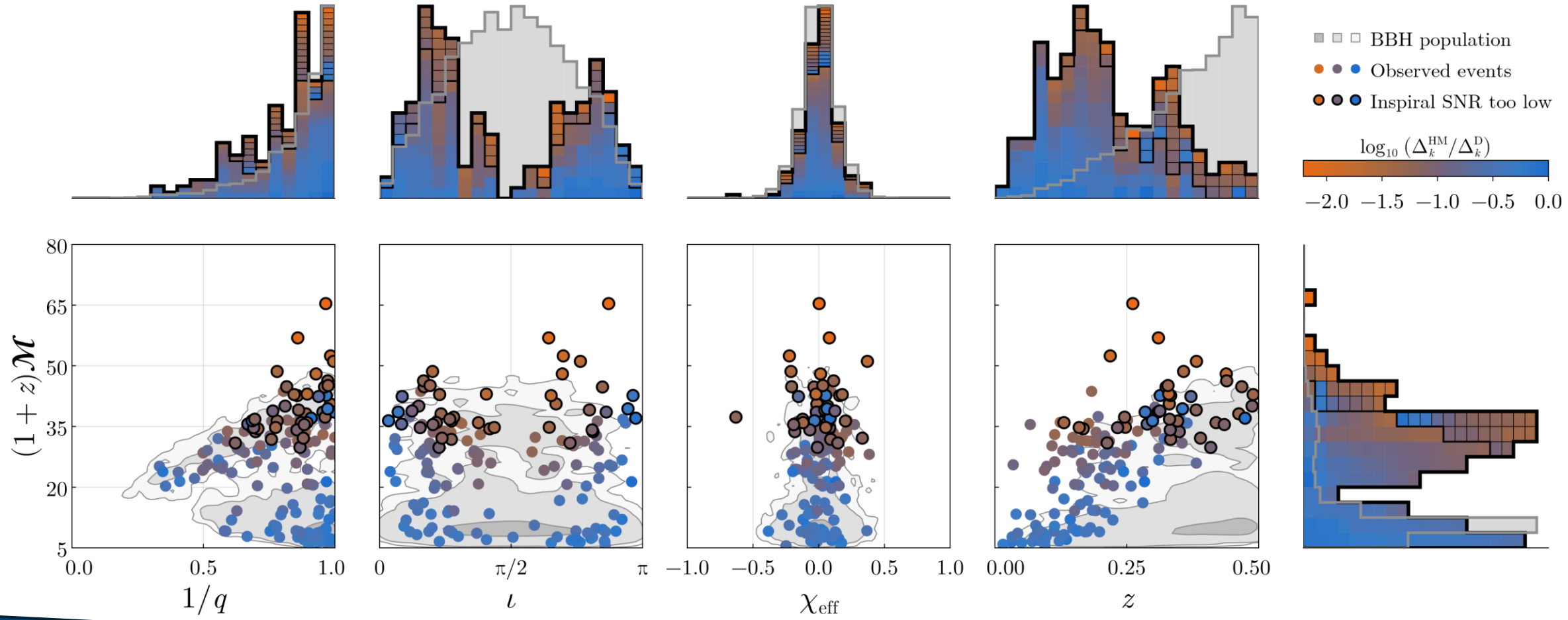
Ryan Nowicki | Bill Smith | Karan Jani



Bonus Material



Systematics of parametrized deviations



References:
 [1] Begnoni, Del Pozzo, Pegorin, Pomper, Ricciardone (2025); arXiv:2511.07520

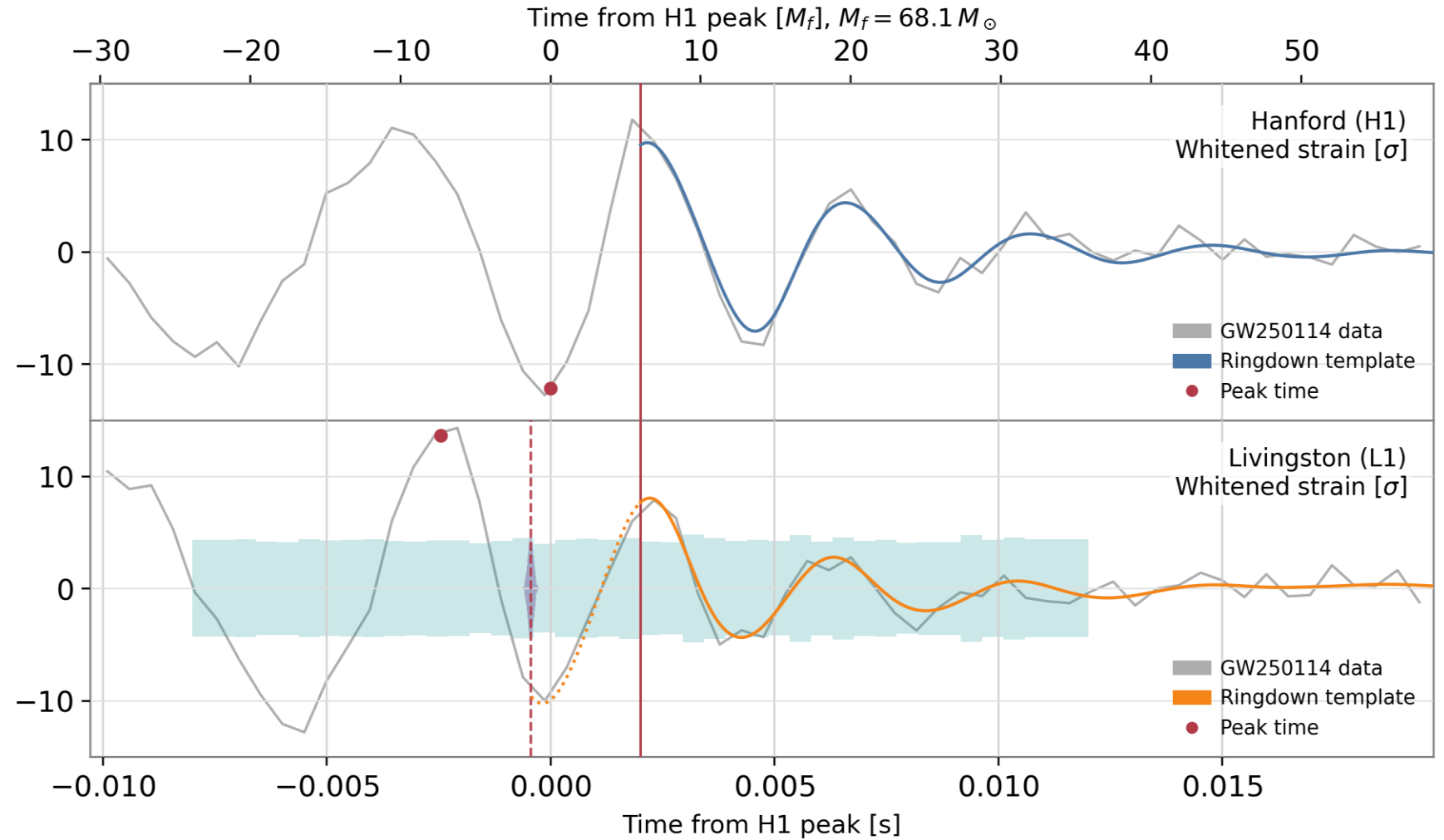
Joachim Pomper

Sky location: Marginalization [2]

Time delay between Detectors a function Of sky location.

State-of-the-art:
Fix sky location with maxL estimator.

New proposal [2]:
by Dey, Barausse, Crisostomi and Trotta



Data take from:

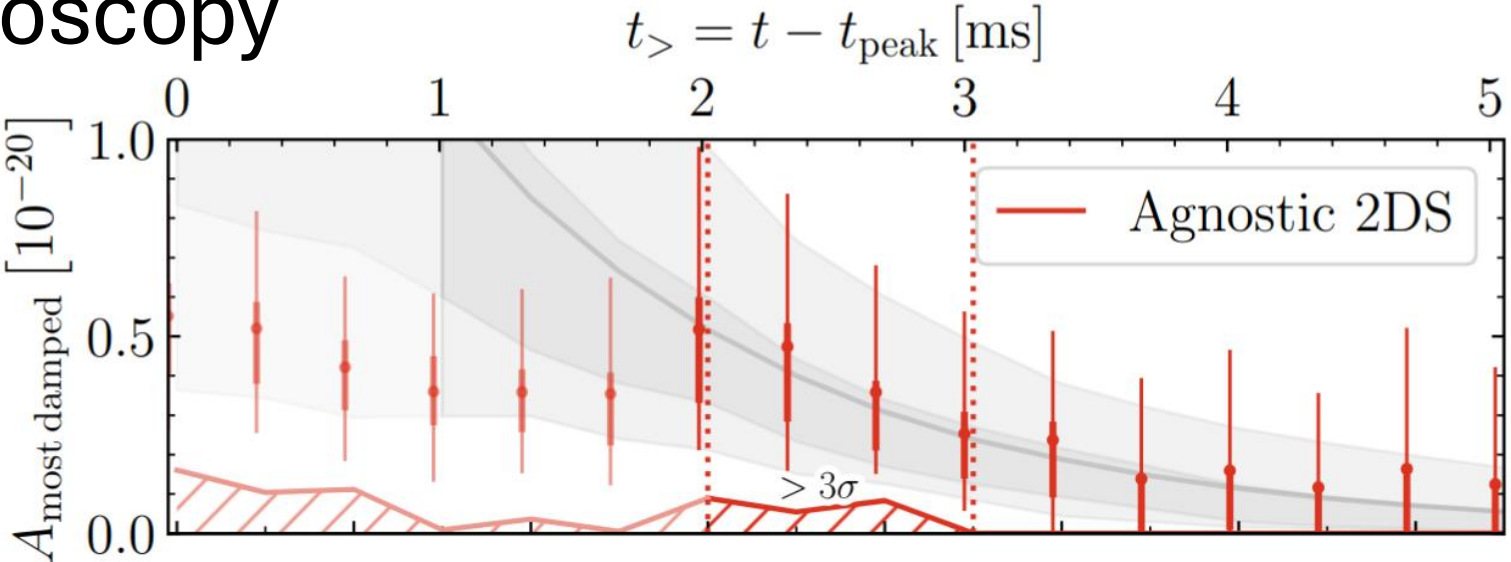
[1] <https://zenodo.org/records/16877102>

References:

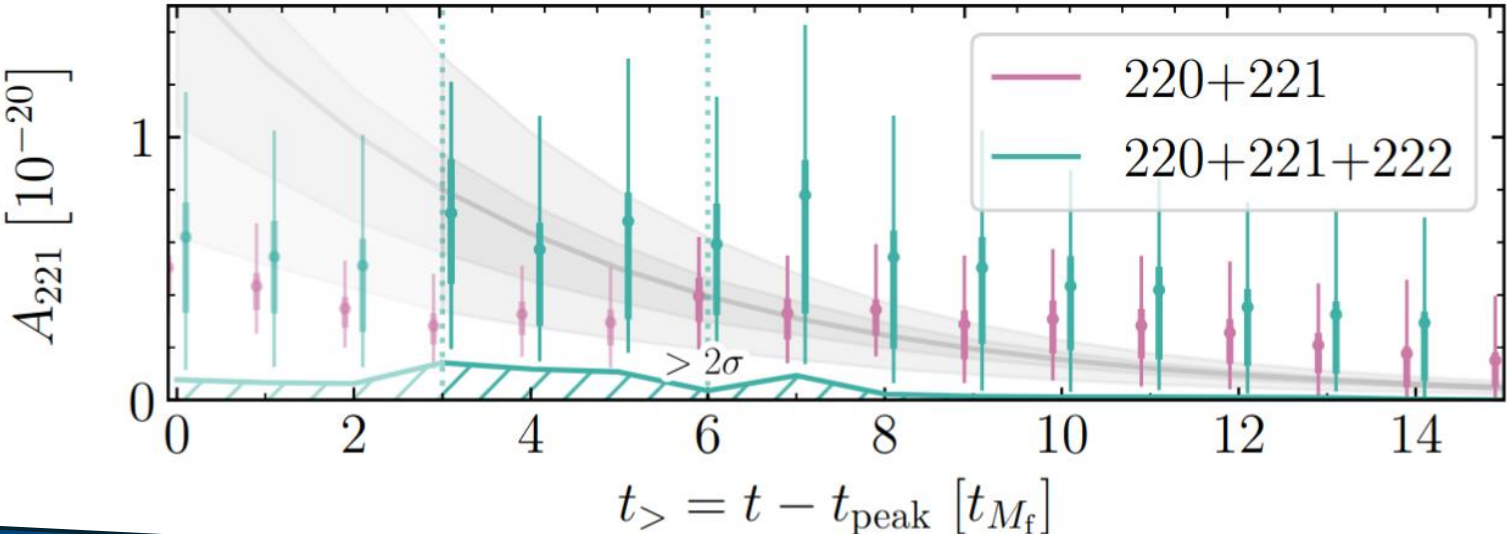
[2] Dey, Barausse, Crisostomi, Trotta (2026) arXiv:2605.18595

GW250114 - Spectroscopy

Damped Sinusoids with 2 modes

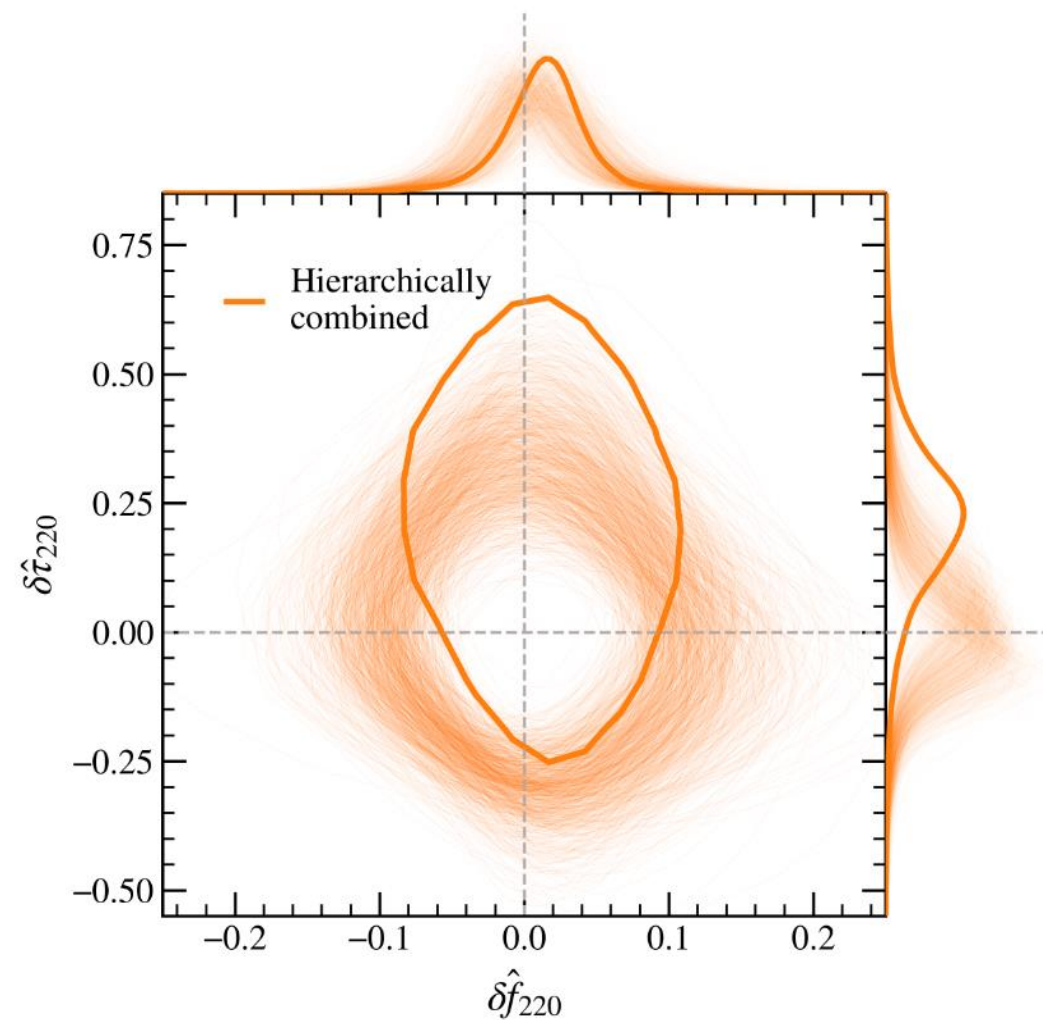
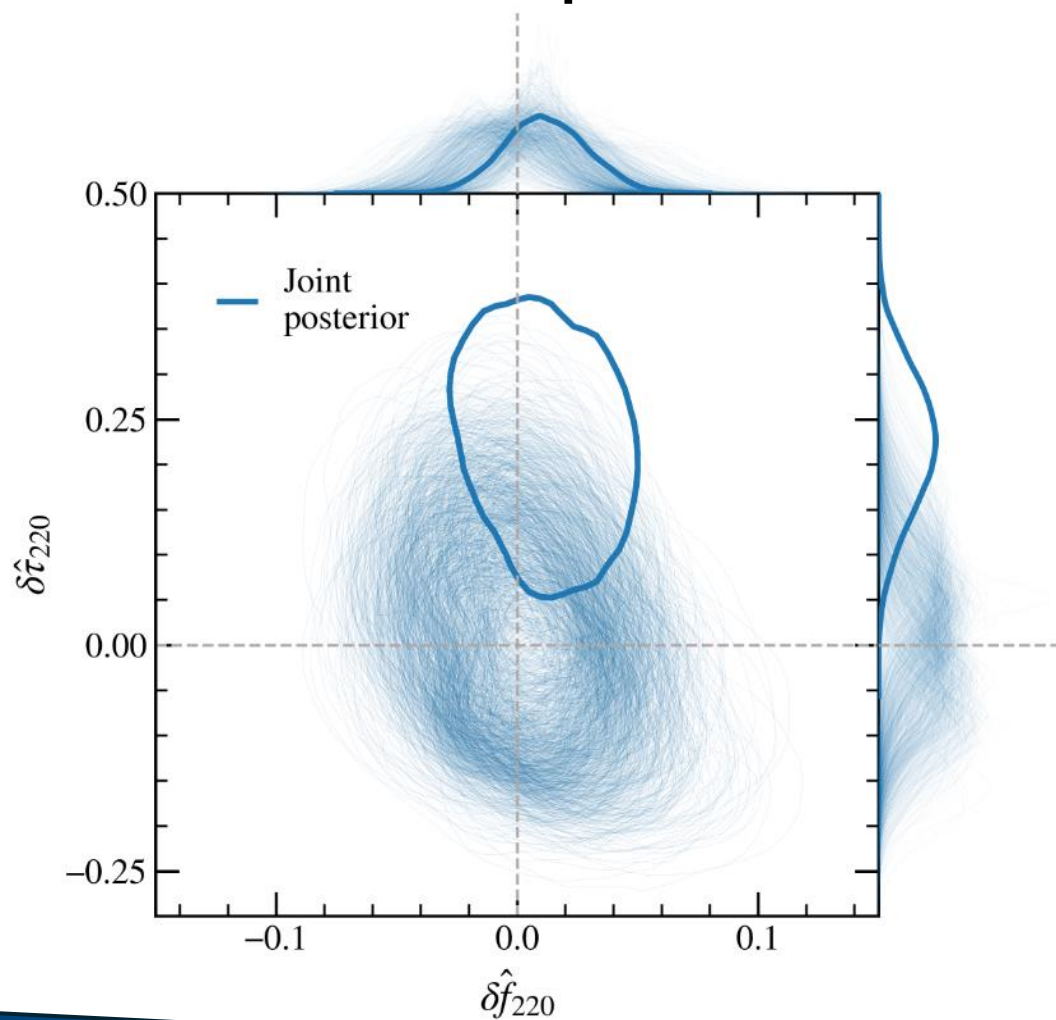


Kerr (full) up to 3 modes



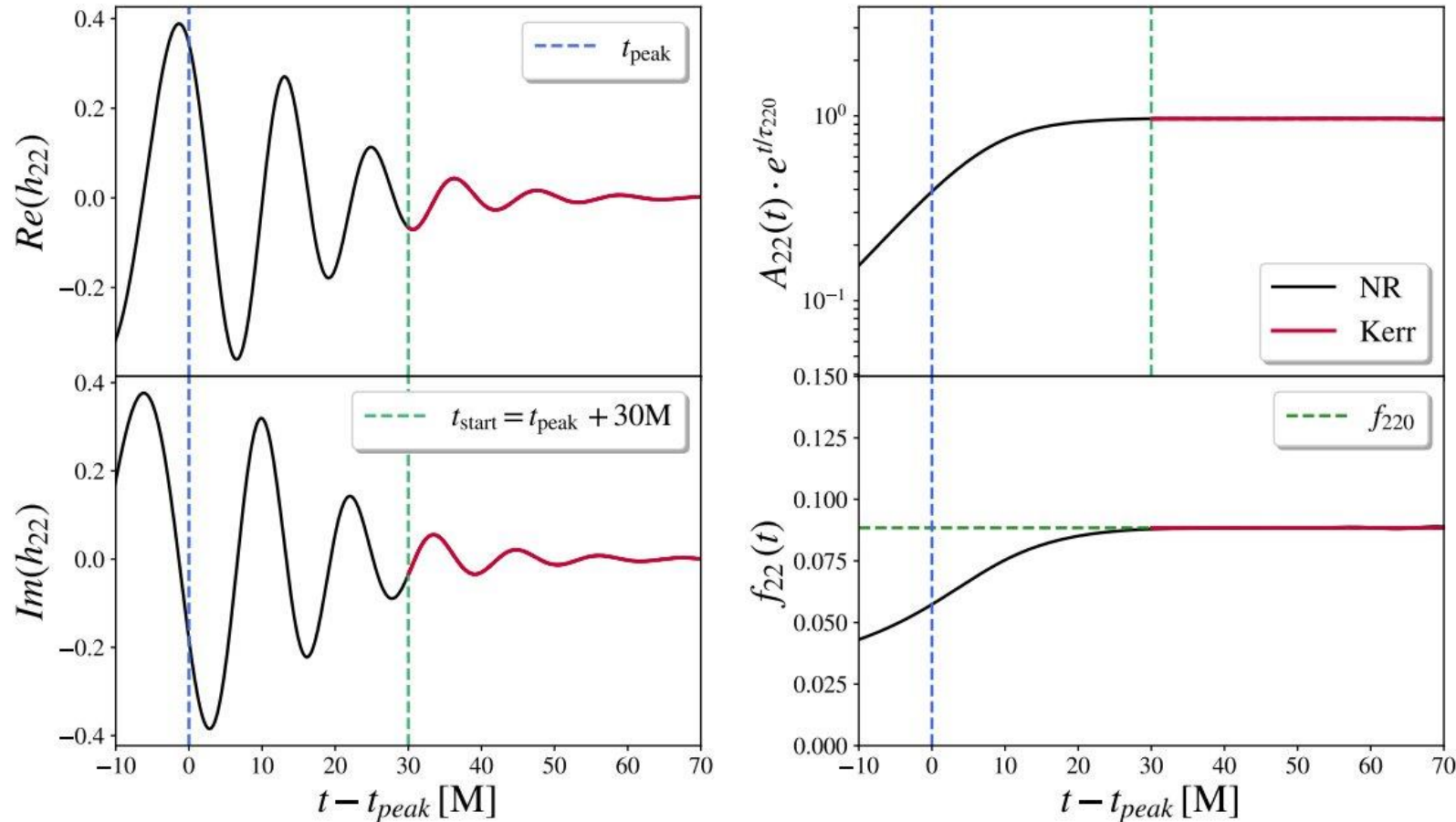
References:
[1] LIGO-Virgo-KAGRA Scientific Collaboration, (2025); arXiv:2509.08099

Injection studies: pSEOB



Dynamical regime SXS

SXS-0305



Resources:

[1] Fits produced with bayRing: <https://github.com/GCArullo/bayRing>

Joachim Pomper



Spin induced quadrupole moments: impact of spin

