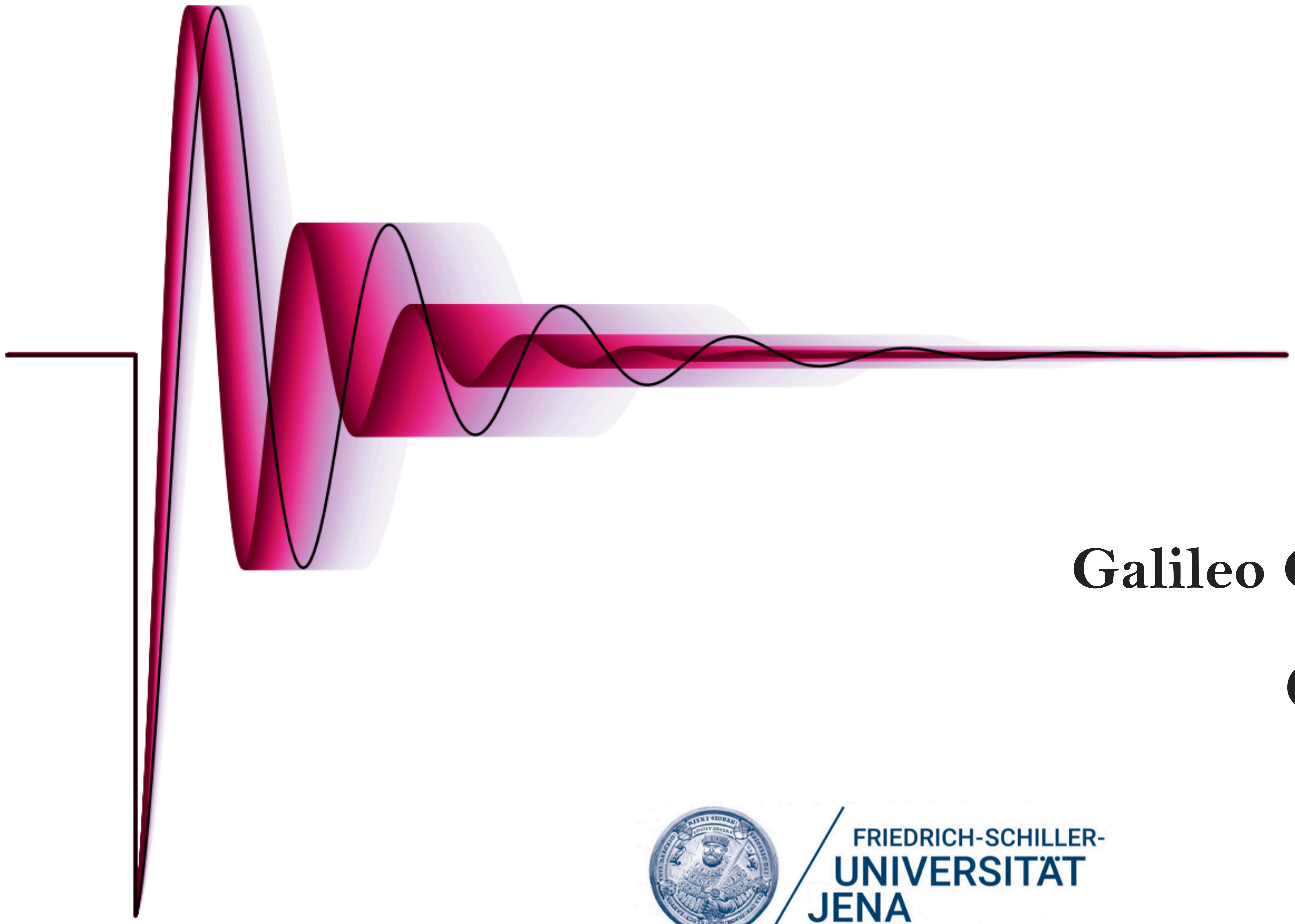
FROM BLACK HOLE SPECTROSCOPY TO NEAR-HORIZON MICROSCOPY: AN OBSERVATIONAL PERSPECTIVE



Galileo Galilei Institute, April 2022

Gregorio Carullo

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

CONTENT

- What have we observed?

CONTENT

- What have we observed?

  - Gravitational wave **ringdown** from **black holes coalescences**

CONTENT

- What have we observed?

  - Gravitational wave **ringdown** from **black holes coalescences**

  - The day we saw a **black hole ringing** and subsequent **LVK catalogues**

CONTENT

- What have we observed?
  - Gravitational wave **ringdown** from **black holes coalescences**
  - The day we saw a **black hole ringing** and subsequent **LVK catalogues**
- **Fundamental physics** implications from ringdown observations

CONTENT

- What have we observed?
    - Gravitational wave **ringdown** from **black holes coalescences**
    - The day we saw a **black hole ringing** and subsequent **LVK catalogues**
- **Fundamental physics** implications from ringdown observations
- Have we **tested** the "*no-hair theorem*" (in the "standard" sense)?

CONTENT

- What have we observed?
  - Gravitational wave **ringdown** from **black holes coalescences**
  - The day we saw a **black hole ringing** and subsequent **LVK catalogues**
- **Fundamental physics** implications from ringdown observations
- Have we **tested** the "*no-hair theorem*" (in the "standard" sense)?
- Avenues to constrain **horizon properties** through ringdown

What have we observed?

Masses in the Stellar Graveyard

GWTC-3

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

What have we observed that is of interest to us?

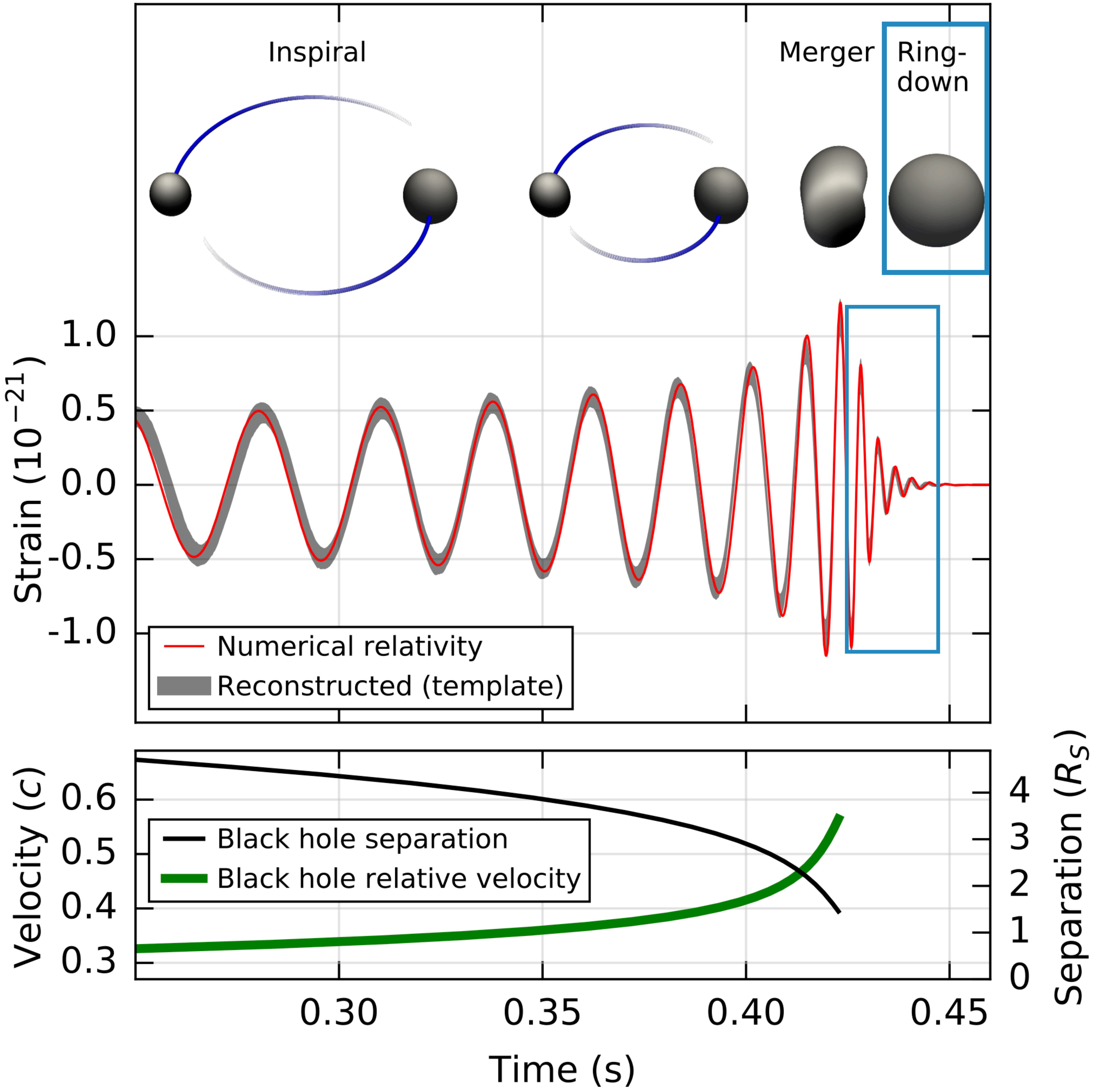
Masses in the Stellar Graveyard

GWTC-3

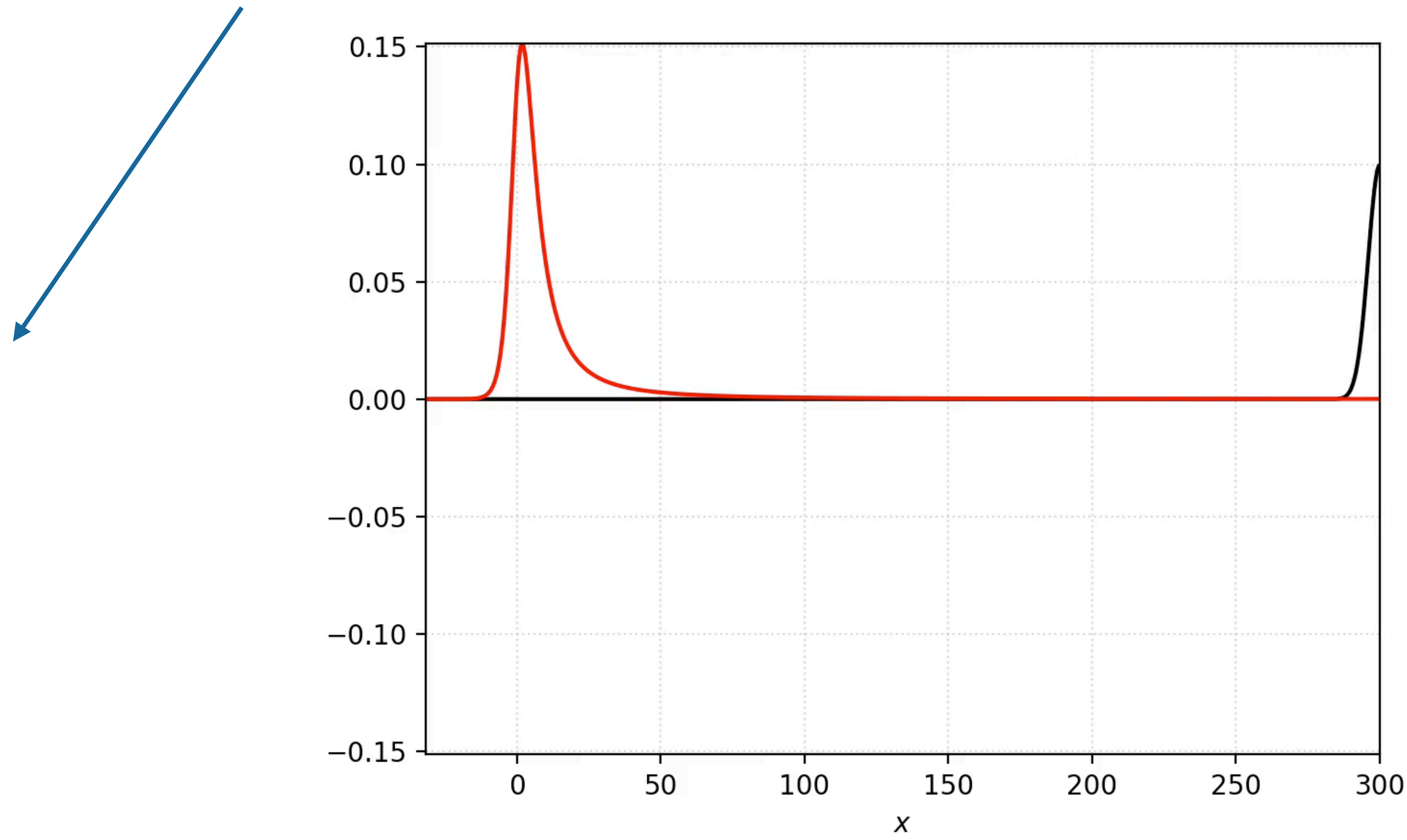
BINARY BLACK HOLES COALESCENCES

- Compact binary coalescence: a **distorted remnant** is formed.

- **Ringdown**: **remnant** approaches equilibrium. Damped **normal-modes** emission **(perturbation theory + NR)**

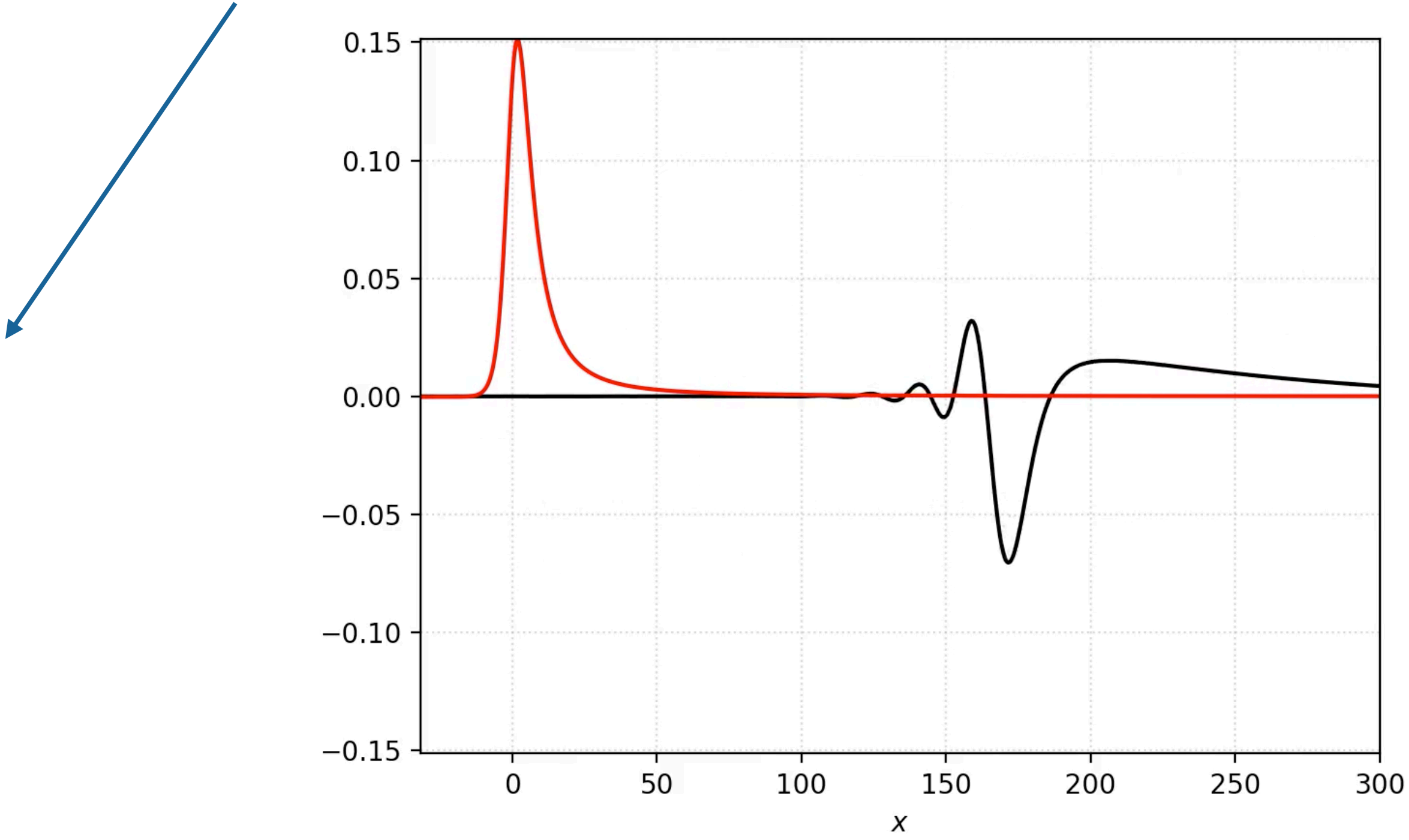


The event horizon is at -∞



Gregorio Carullo

The event horizon is at -∞



Gregorio Carullo

RINGDOWN: QUASI-NORMAL MODES SOLUTIONS

- In terms of gravitational wave multipoles:

$$h_+ - i\,h_\times = -\frac{M}{r}\sum_{l,m,n} \mathcal{A}_{lmn}\, S(\theta,\phi)\, e^{i\omega_{lmn}t}\, e^{-t/\tau_{lmn}}$$

Nollert, (CQG, 2000)

RINGDOWN: QUASI-NORMAL MODES SOLUTIONS

- In terms of gravitational wave multipoles:

$$h_+ - i\, h_\times = -\frac{M}{r} \sum_{l,m,n} \mathcal{A}_{lmn}\, S(\theta, \phi)\, e^{i\omega_{lmn} t}\, e^{-t/\tau_{lmn}}$$

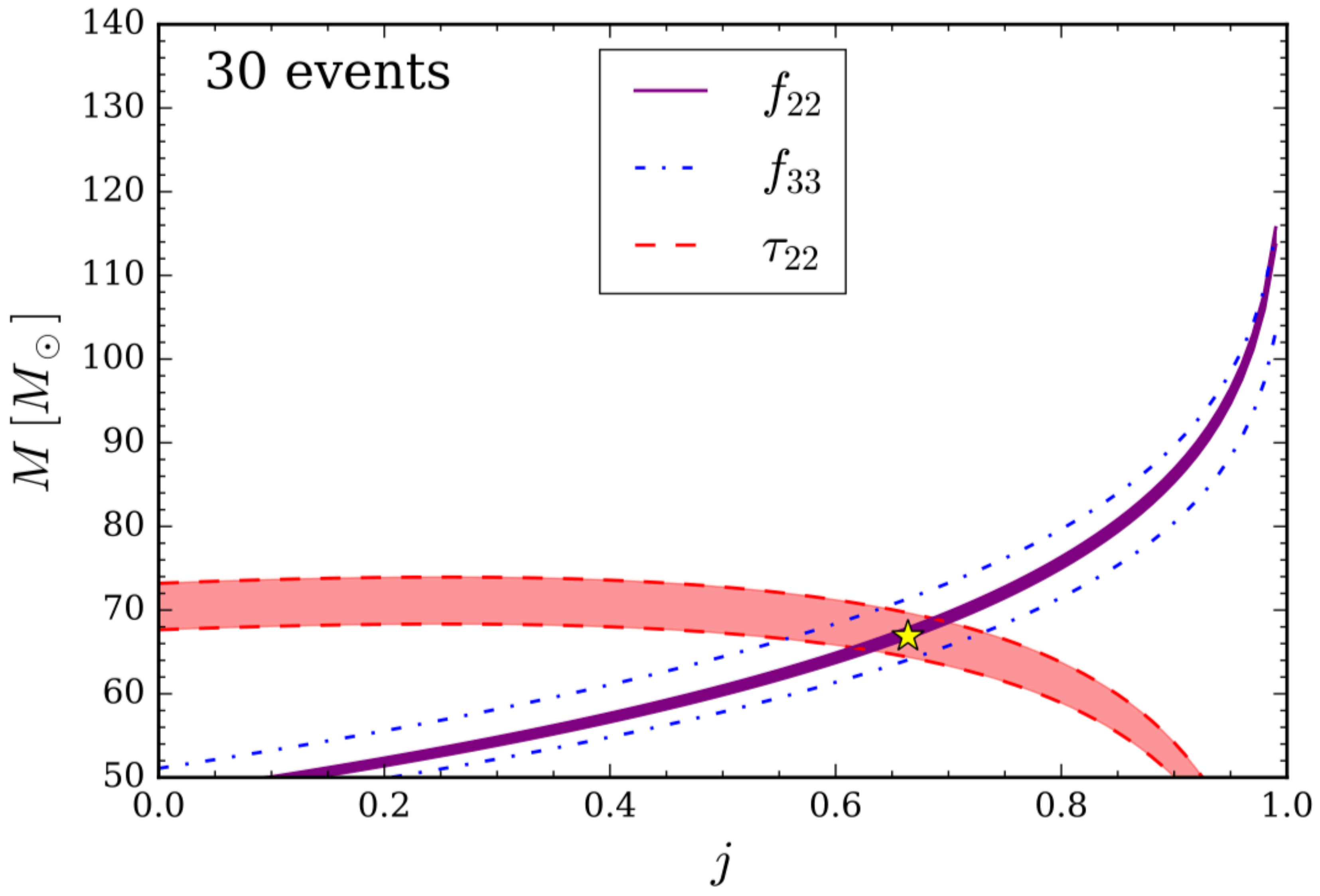
- Frequencies and damping times spectrum predicted by perturbation theory, fixed only by **mass** and **spin** of the black hole (“*no-hair theorem*”)

RINGDOWN: QUASI-NORMAL MODES SOLUTIONS

- In terms of gravitational wave multipoles:

$$h_+ - i\,h_\times = -\frac{M}{r}\sum_{l,m,n} \mathcal{A}_{lmn}\, S(\theta,\phi)\, e^{i\omega_{lmn}t}\, e^{-t/\tau_{lmn}}$$

Brito, Buonanno, Reymond, PRD (2018)



- Frequencies and damping times spectrum predicted by perturbation theory, fixed only by **mass** and **spin** of the black hole ("*no-hair theorem*")

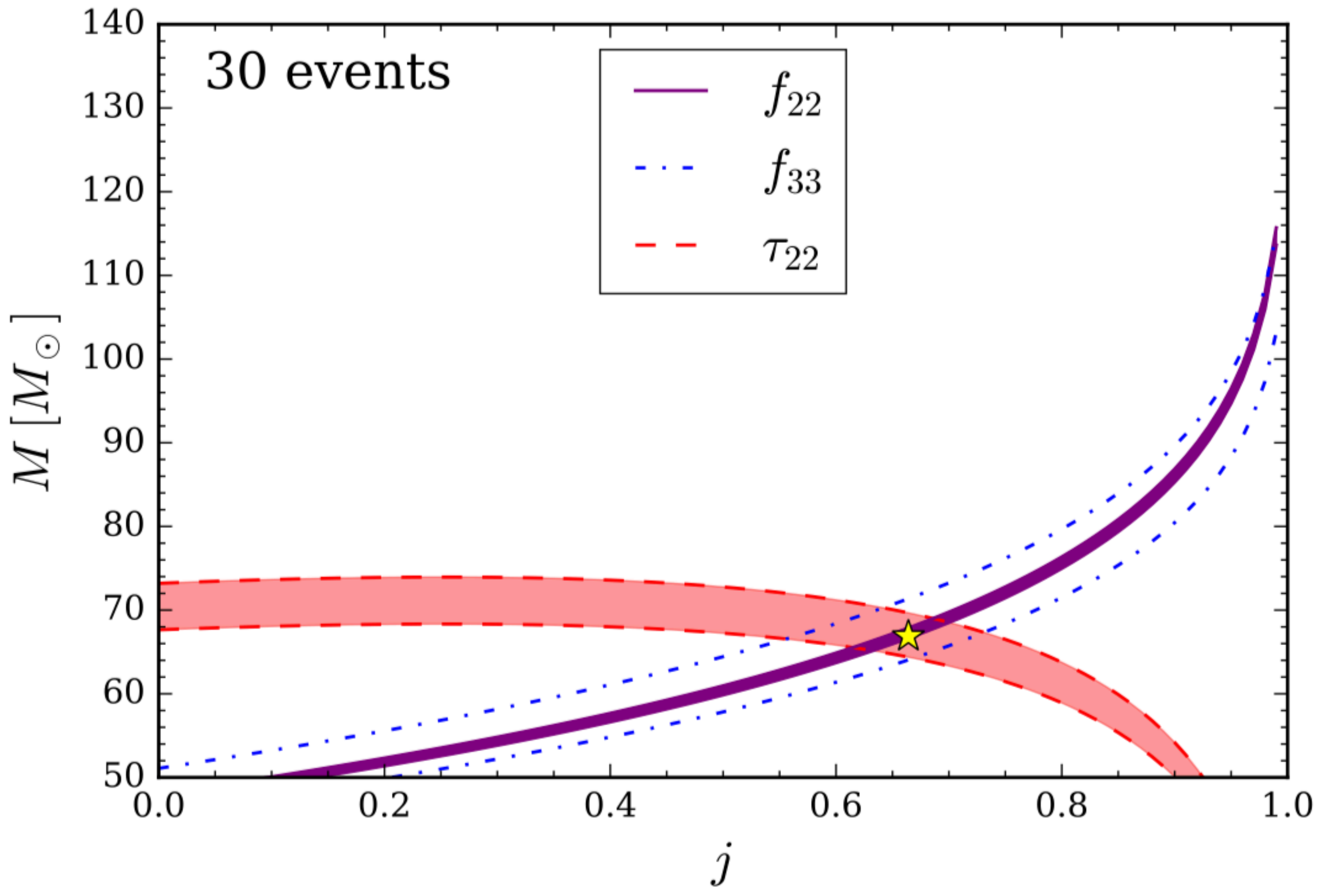
- Measure two frequencies and one damping time: test of General Relativity

RINGDOWN: QUASI-NORMAL MODES SOLUTIONS

- In terms of gravitational wave multipoles:

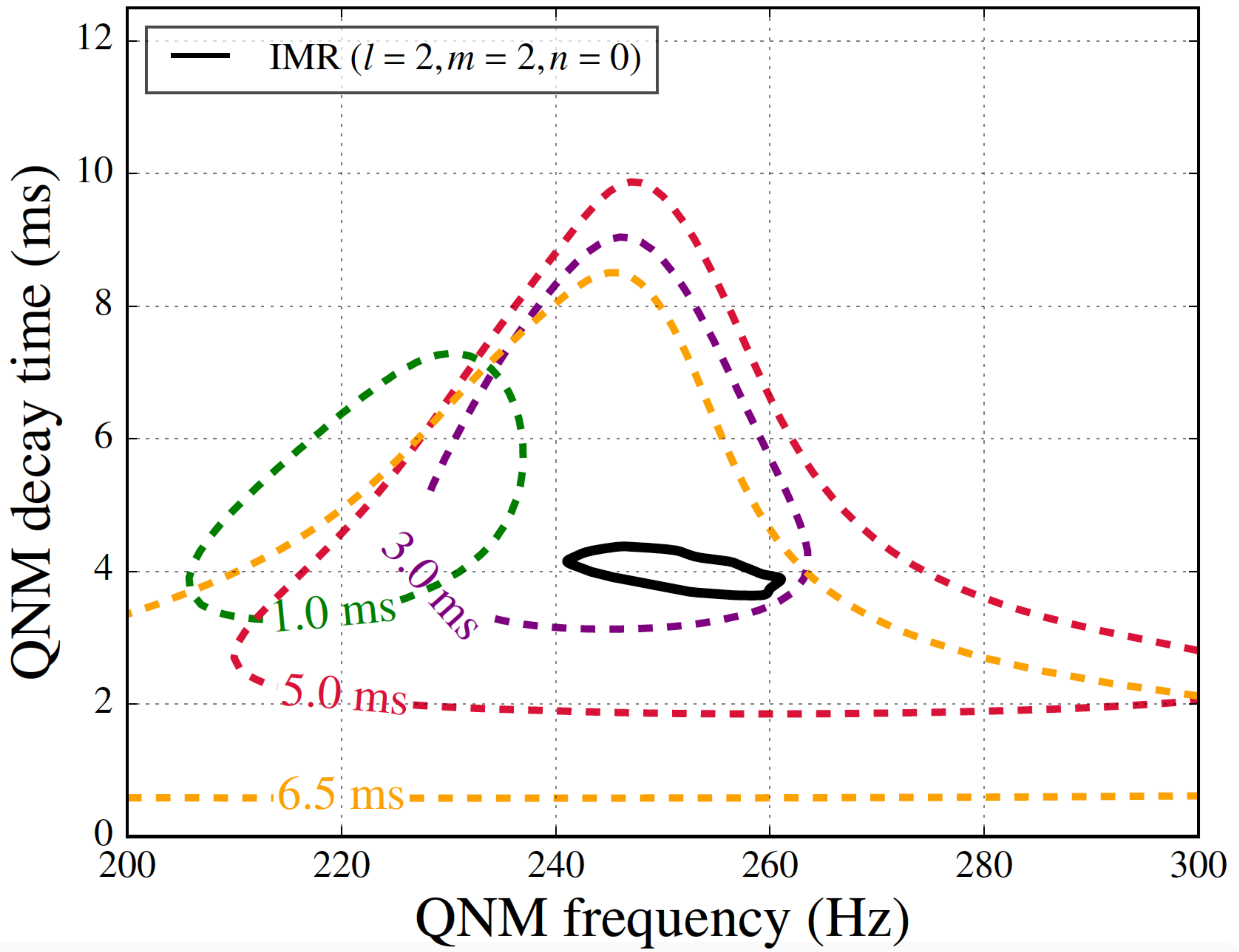
$$h_+ - i\,h_\times = -\frac{M}{r}\sum_{l,m,n} \mathcal{A}_{lmn}\,S(\theta,\phi)\,e^{i\omega_{lmn}t}\,e^{-t/\tau_{lmn}}$$

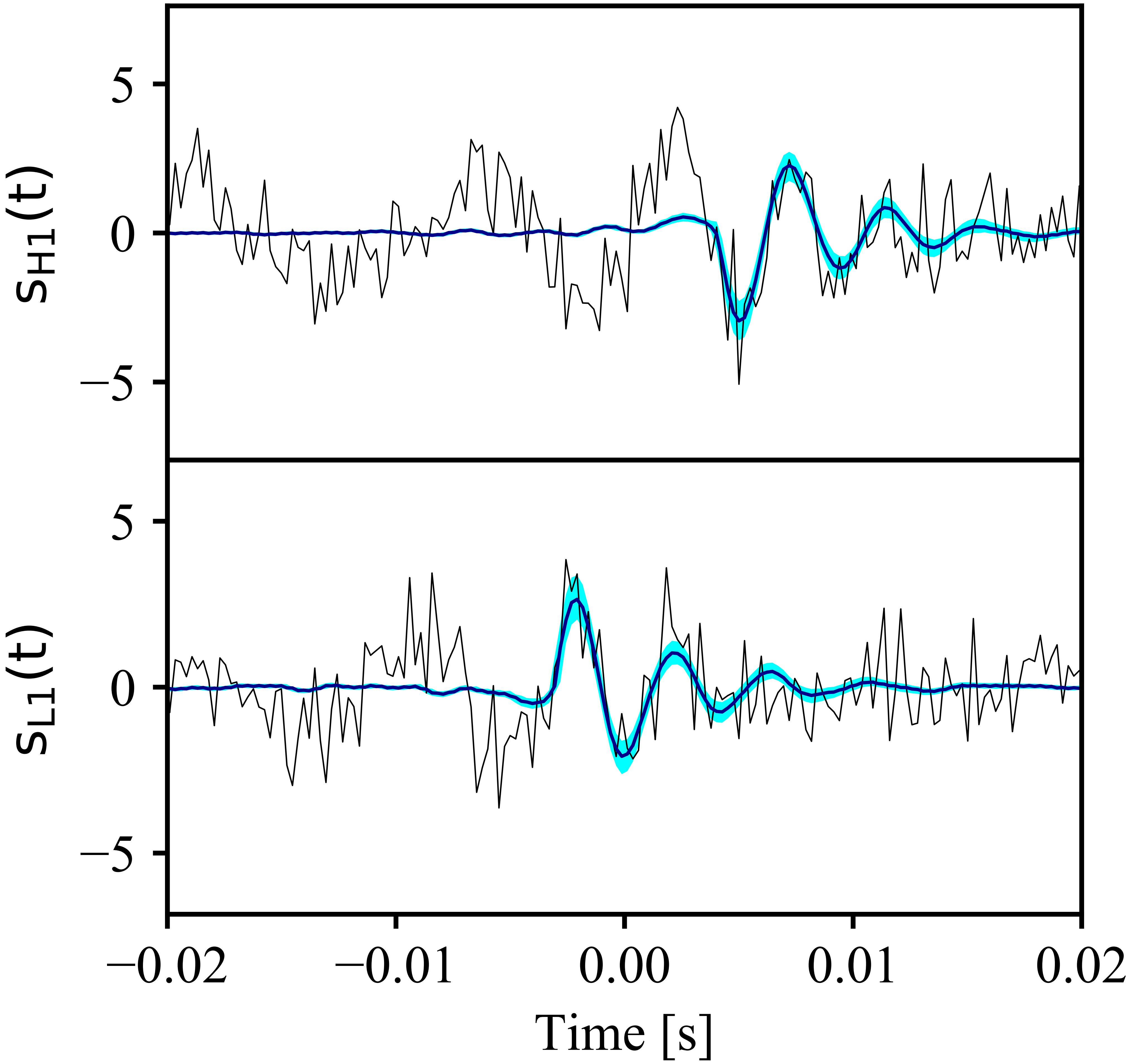
Brito, Buonanno, Reymond, PRD (2018)



- Frequencies and damping times spectrum predicted by perturbation theory, fixed only by **mass** and **spin** of the black hole (“*no-hair theorem*”)
- Measure two frequencies and one damping time: test of General Relativity
- “Universal” prediction: “know” how to incorporate **beyond-GR** effects

GW150914: THE DAY WE SAW A BLACK HOLE RINGING





BLACK HOLE SPECTROSCOPY

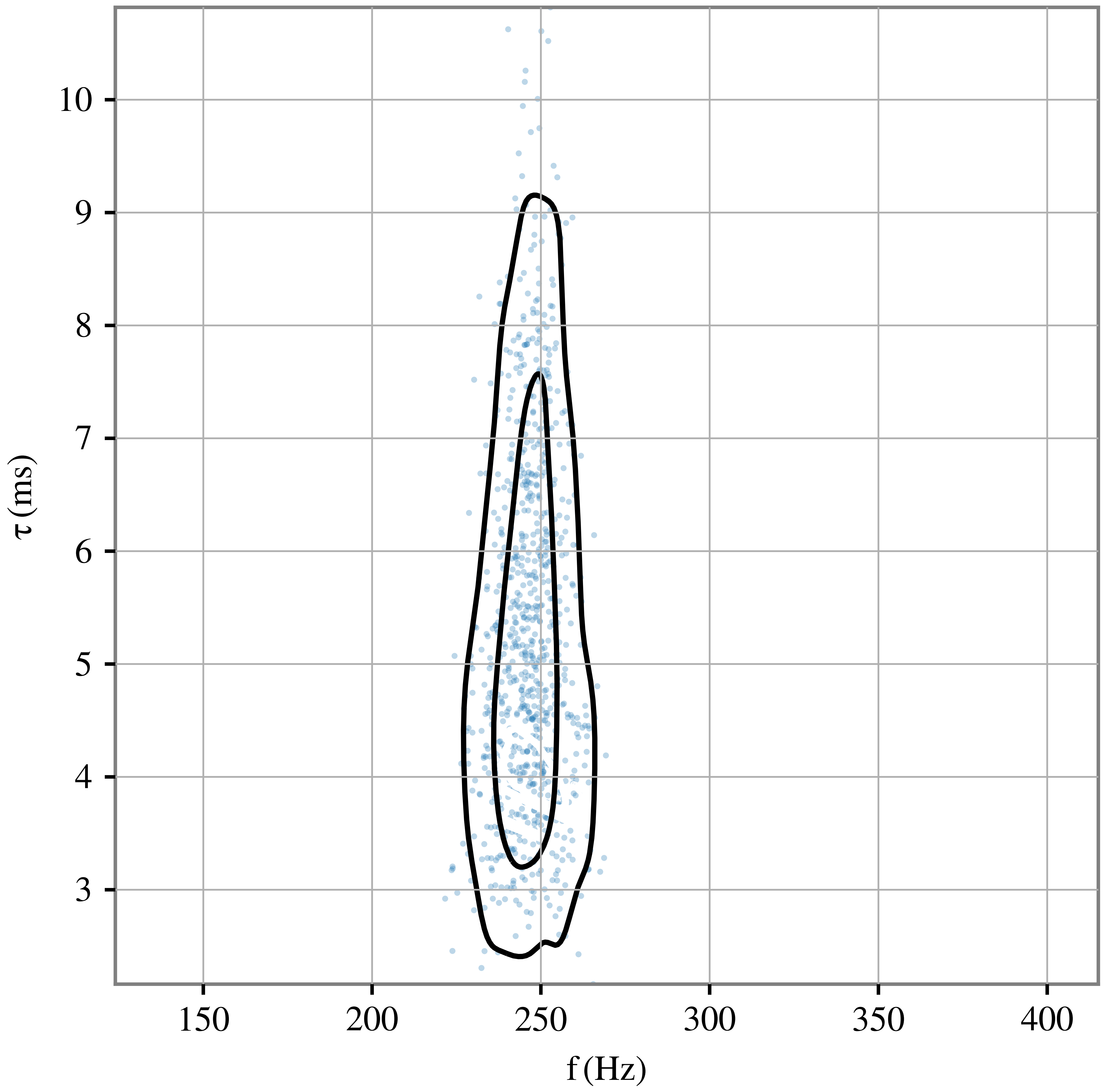
- Time-domain approach

Carullo, Del Pozzo, Veitch,
PRD 99, 123029 (2019)

See also: Isi, Farr arXiv:2107.05609

BLACK HOLE SPECTROSCOPY

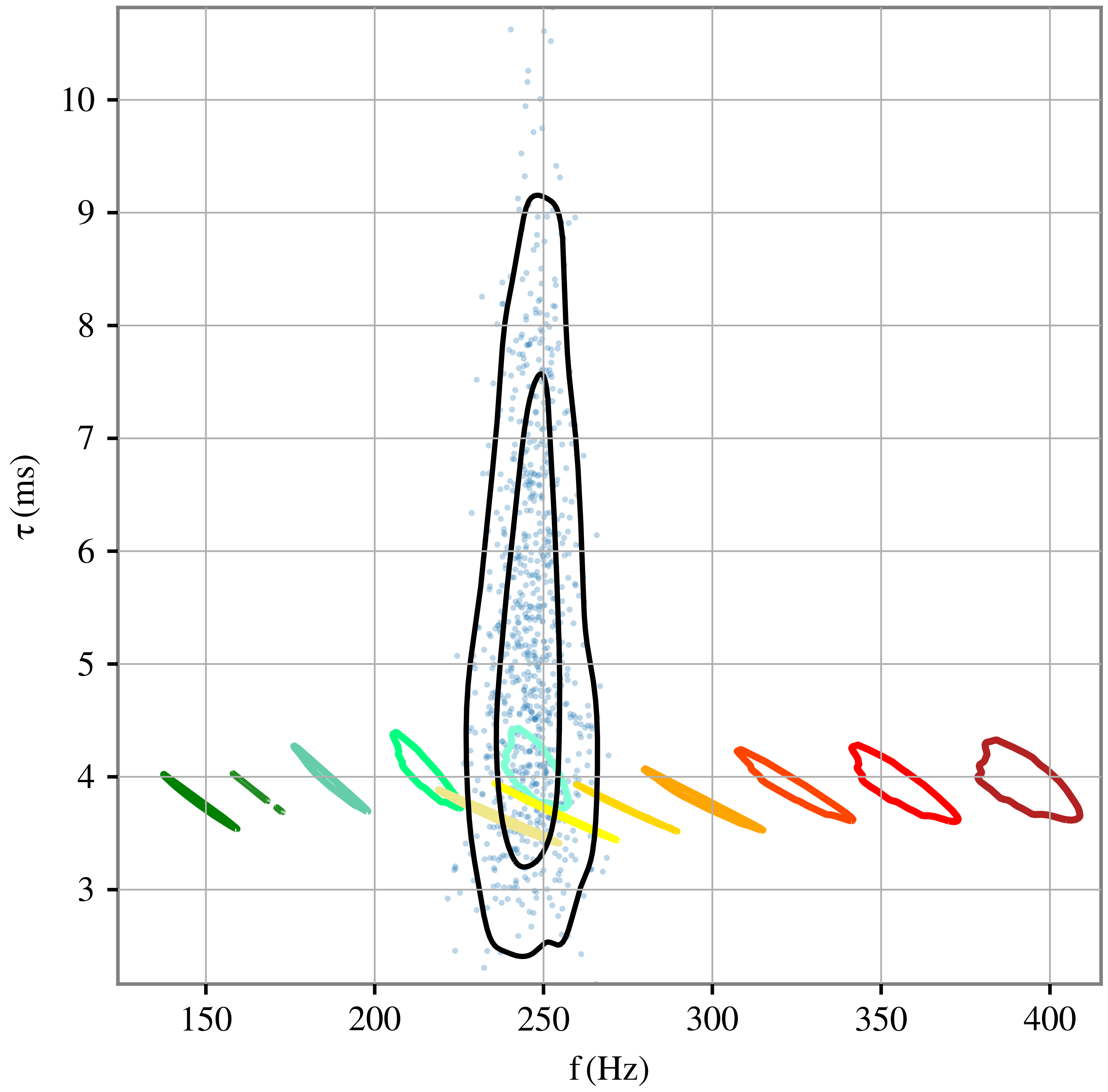
- Time-domain approach
- Compute **agnostic frequency reconstruction**



Carullo, Del Pozzo, Veitch, PRD 99, 123029 (2019)

BLACK HOLE SPECTROSCOPY

- Time-domain approach
- Compute **agnostic** frequency **reconstruction**
- Predict GR **spectrum**

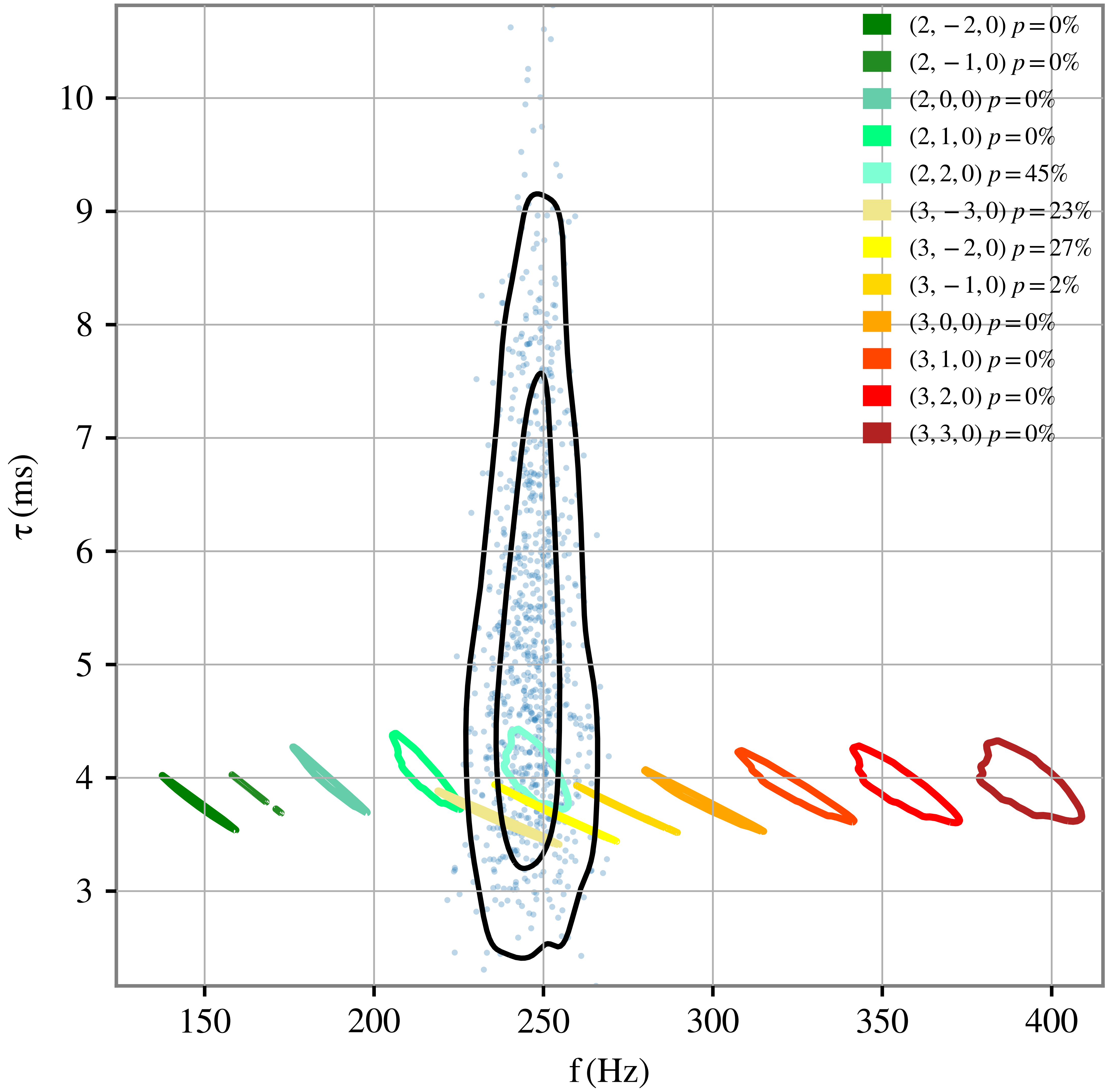


Carullo, Del Pozzo, Veitch,
PRD 99, 123029 (2019)

BLACK HOLE SPECTROSCOPY

- Time-domain approach
- Compute **agnostic** frequency **reconstruction**
- Predict GR **spectrum**
- Compute the **probability** that recovered agnostic mode corresponds to **given predicted mode**

Carullo, Del Pozzo, Veitch, PRD 99, 123029 (2019)



See also: Isi, Farr arXiv:2107.05609

PYRING

- Previous formalism implemented in a dedicated python package: **pyRing**
  - Source code: https://git.ligo.org/lscsoft/pyring
  - Documentation: https://lscsoft.docs.ligo.org/pyring
  - pypi release: https://pypi.org/project/pyRingGW

PYRING

- Previous formalism implemented in a dedicated python package: **pyRing**
    - Source code: https://git.ligo.org/lscsoft/pyring
    - Documentation: https://lscsoft.docs.ligo.org/pyring
    - pypi release: https://pypi.org/project/pyRingGW
- Routinely used to produce catalogs of BH ringdown properties and related tests of GR by the LVK collaboration.

PYRING

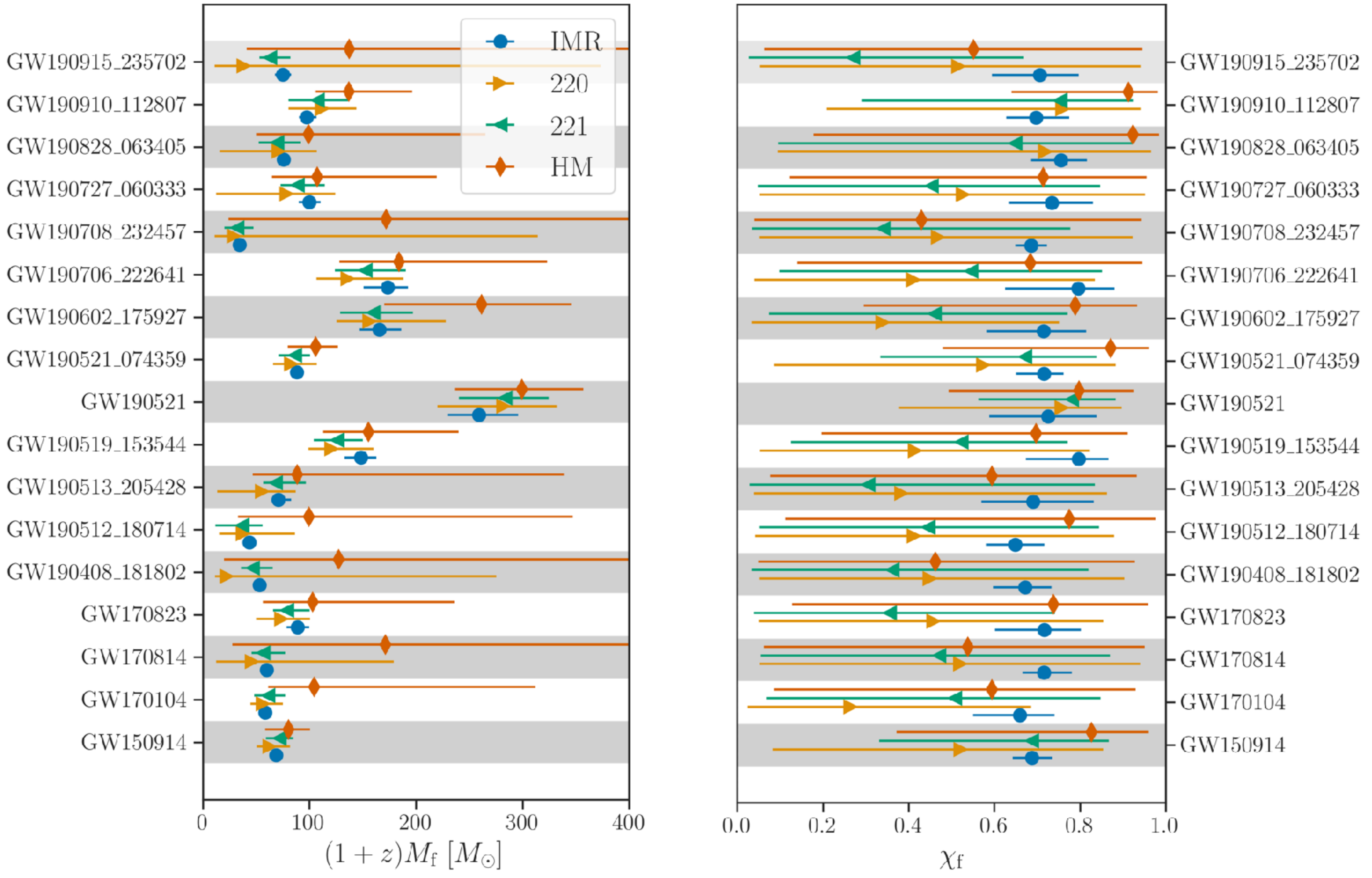
- Previous formalism implemented in a dedicated python package: **pyRing**
  - Source code: **https://git.ligo.org/lscsoft/pyring**
  - Documentation: **https://lscsoft.docs.ligo.org/pyring**
  - pypi release: **https://pypi.org/project/pyRingGW**
- Routinely used to produce catalogs of BH ringdown properties and related tests of GR by the LVK collaboration.
- You can measure a BH vibrational frequency in ~3 mins on your laptop!

Tutorial link

BLACK HOLE RINGDOWN CATALOG

- First **catalog** of ringdown-only observations:

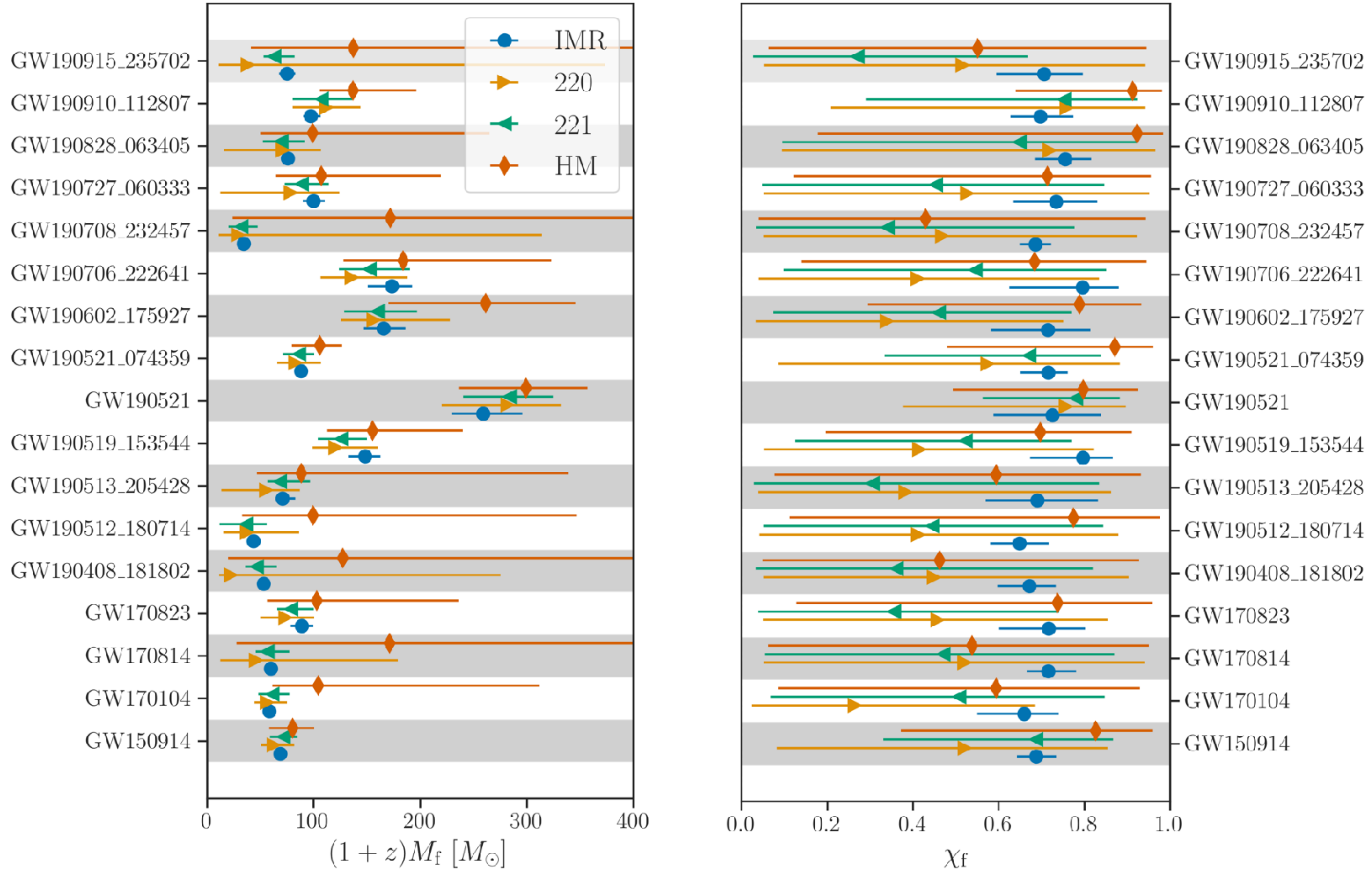
Image credit: LIGO-Virgo/Rico Lo



BLACK HOLE RINGDOWN CATALOG

- First **catalog** of ringdown-only observations:

Image credit: LIGO-Virgo/Rico Lo



Higher modes	Overtones	
$\log_{10} \mathcal{B}^{HM}_{220}$	$\log_{10} \mathcal{B}^{221}_{220}$	$\log_{10} O^{modGR}_{GR}$
0.03	0.63	−0.34
0.26	−0.20	−0.23
0.04	−0.19	−0.11
0.02	−0.98	−0.07
−0.05	−1.02	−0.02
0.09	−0.42	0.03
0.09	−0.54	−0.05
0.21	−0.00	−0.11
0.12	−0.86	−0.50
−0.04	1.29	−0.27
0.61	−1.56	0.32
−0.06	−0.64	−0.45
−0.11	−0.17	−0.02
−0.02	−1.65	−0.40
0.05	−0.72	−0.05
−0.10	−0.64	−0.40
0.06	−0.37	−0.04

- **Bounds on deviations** from the GR spectrum.

- **Deviations** parameterized as:

$$\omega = \omega^{Kerr} \cdot (1 + \delta\omega)$$
$$\tau = \tau^{Kerr} \cdot (1 + \delta\tau) \,.$$

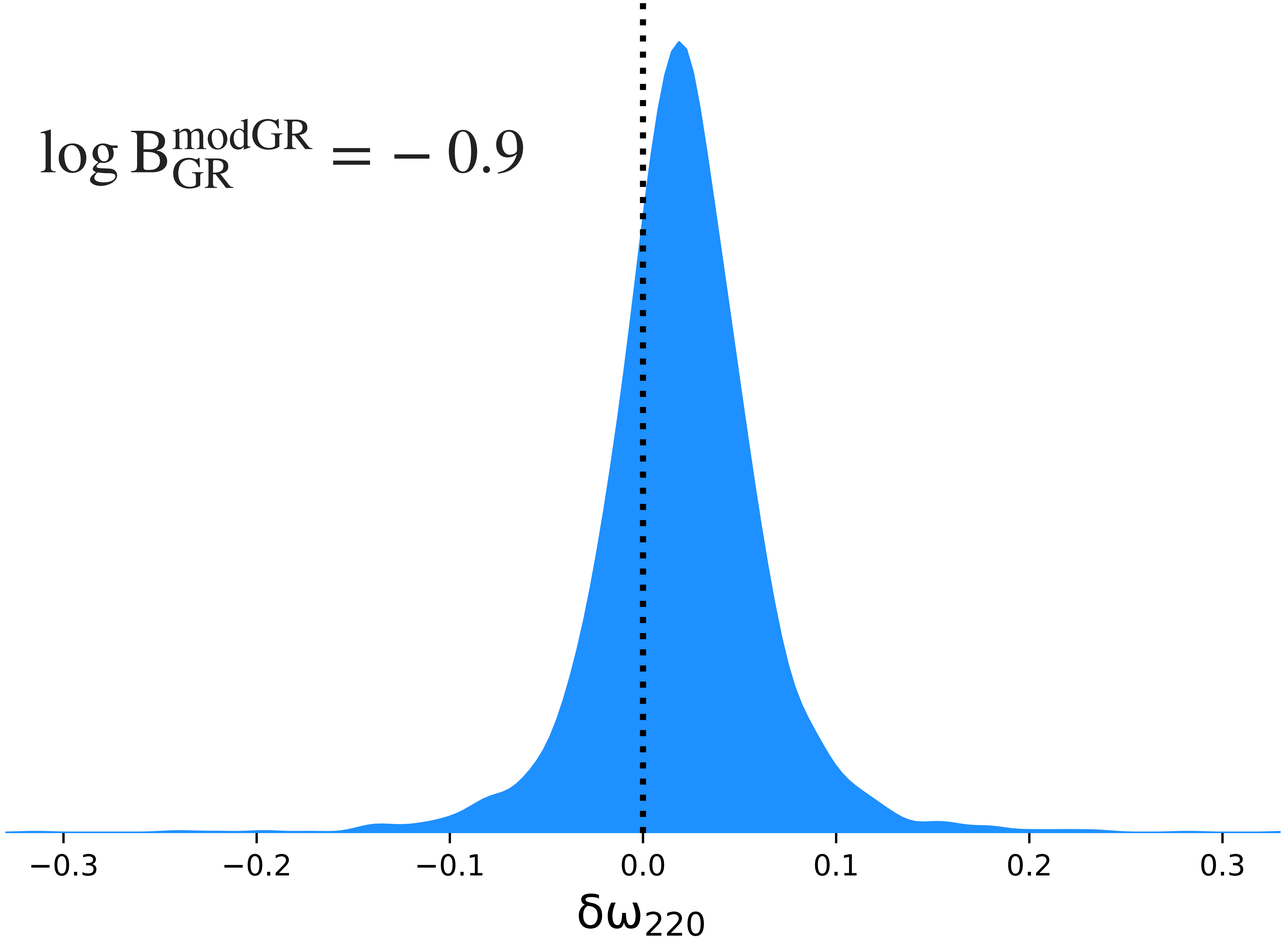
TESTS OF GENERAL RELATIVITY WITH GWTC-3

- **Bounds on deviations** from the GR spectrum.

- **Deviations** parameterized as:

$$\omega = \omega^{Kerr} \cdot (1 + \delta\omega)$$
$$\tau = \tau^{Kerr} \cdot (1 + \delta\tau) \, .$$

$$\delta\omega_{220} = 0.02^{+0.07}_{-0.07}$$
$$\delta\tau_{220} = 0.13^{+0.21}_{-0.22}$$



Fundamental physics implications

LOST IN TRANSLATION

- **Implications** of **LVC** results to specific **alternative theories** of gravity?

LOST IN TRANSLATION

- **Implications** of **LVC** results to specific **alternative theories** of gravity?
- **Large amount of possibilities** and of effects to take into account (isospectrality breaking, modes induced by extra-fields dynamics…)

LOST IN TRANSLATION

- **Implications** of **LVC** results to specific **alternative theories** of gravity?
- **Large amount of possibilities** and of effects to take into account (isospectrality breaking, modes induced by extra-fields dynamics…)
- Previous (global) parametrisation not very suited:
  - Event-dependent (requires hierarchical analysis)
  - No dependence on spin
  - No dependence on extra-couplings

CONSTRAINTS ON MODIFIED GRAVITY

Enhancing modified gravity detection from gravitational-wave observations using the Parametrized ringdown spin expansion coefficients formalism

Gregorio Carullo[1,2]

[1] *Dipartimento di Fisica "Enrico Fermi", Università di Pisa, Pisa I-56127, Italy*
[2] *INFN sezione di Pisa, Pisa I-56127, Italy*

(Dated: May 13, 2021)

Harvesting the full potential of black hole spectroscopy demands realising the importance of casting constraints on modified theories of gravity in a framework as general and robust as possible. Requiring more stringent – yet well-motivated – beyond General Relativity (GR) parametrizations improves the inference drawn from available GW data, substantially decreasing the errors on deviation parameters. This implies a reduction in the number of signals needed to detect a deviation from GR predictions and an increase of the number of GR-violating coefficients that can be meaningfully constrained with a given number of signals. To this end, we apply to LIGO-Virgo observations a high-spin version of the Parametrized ringdown spin expansion coefficients (ParSpec) formalism, encompassing large classes of modified theories of gravity. We constrain the lowest-order perturbative deviation of the fundamental ringdown frequency to be $\delta\omega^0_{220} = -0.05^{+0.05}_{-0.05}$, when assuming adimensional beyond-GR couplings, substantially improving upon previously published results. We also establish upper bounds $\ell_{p=2} < 23\,\mathrm{km}$, $\ell_{p=4} < 35\,\mathrm{km}$, $\ell_{p=6} < 42\,\mathrm{km}$ on the scale ℓ_p at which the appearance of new physics is disfavoured, depending on the mass dimension p of the ringdown coupling. These bounds exceed the ones obtained by previous analyses or are competitive with existing ones, depending on the specific alternative theory considered, and promise to quickly improve as the number of detectors, sensitivity and duty-cycle of the gravitational-wave network steadily increases.

PARSPEC

- **Consistent framework** for perturbative **constraints** valid on **specific modified theories** of gravity:

$$\omega_K = \frac{1}{M} \sum_{j=0}^{N_{max}} \chi^j \, \omega_K^{(j)}$$

Expand each QNM parameter in a polynomial expansion in the remnant spin.

$$\tau_K = M \sum_{j=0}^{N_{max}} \chi^j \, \tau_K^{(j)}$$

Extract the mass and spin structure in polynomial form.

PARSPEC

- **Consistent framework** for perturbative **constraints** valid on **specific modified theories** of gravity:

$$\omega_K = \frac{1}{M} \sum_{j=0}^{N_{max}} \chi^j \boxed{\omega_K^{(j)}}$$

$$\tau_K = M \sum_{j=0}^{N_{max}} \chi^j \boxed{\tau_K^{(j)}}$$

Expand each QNM parameter in a polynomial expansion in the remnant spin.

Extract the mass and spin structure in polynomial form.

Numerical constants

PARSPEC

- **Consistent framework** for perturbative **constraints** valid on **specific modified theories** of gravity:

$$\omega_K = \frac{1}{M} \sum_{j=0}^{N_{max}} \chi^j \, \omega_K^{(j)} \left(1 + \gamma \, \delta\omega_K^{(j)}\right),$$

$$\tau_K = M \sum_{j=0}^{N_{max}} \chi^j \, \tau_K^{(j)} \left(1 + \gamma \, \delta\tau_K^{(j)}\right).$$

Proportional to action coupling(s):

$$\gamma := \left(\frac{\ell \, c^2 \, (1+z)}{G \, M} \right)^p$$

Add deviations at each given order.

PARSPEC

- **Consistent framework** for perturbative **constraints** valid on **specific modified theories** of gravity:

$$\omega_K = \frac{1}{M} \sum_{j=0}^{N_{max}} \chi^j \, \omega_K^{(j)} \left(1 + \gamma \, \boxed{\delta\omega_K^{(j)}}\right),$$

$$\tau_K = M \sum_{j=0}^{N_{max}} \chi^j \, \tau_K^{(j)} \left(1 + \gamma \, \boxed{\delta\tau_K^{(j)}}\right).$$

Proportional to action coupling(s):

$$\gamma := \left(\frac{\ell \, c^2 \, (1+z)}{G \, M}\right)^p$$

Add deviations at each given order.

Also numerical constants!
Independent of specific signal.

PARSPEC

- **Consistent framework** for perturbative **constraints** valid on **specific modified theories** of gravity:

$$\omega_K = \frac{1}{\boxed{M}} \sum_{j=0}^{N_{max}} \boxed{\chi^j} \omega_K^{(j)} \left(1 + \gamma\, \delta\omega_K^{(j)}\right),$$

$$\tau_K = \boxed{M} \sum_{j=0}^{N_{max}} \boxed{\chi^j} \tau_K^{(j)} \left(1 + \gamma\, \delta\tau_K^{(j)}\right).$$

GR values!

Proportional to action coupling(s):

$$\gamma := \left(\frac{\ell\, c^2\, (1+z)}{G\, M}\right)^p$$

 Maselli+, PRD 101, 024043 (2020)

PARSPEC

- **Consistent framework** for perturbative **constraints** valid on **specific modified theories** of gravity:

$$\omega_K = \frac{1}{M} \sum_{j=0}^{N_{max}} \chi^j \, \omega_K^{(j)} \left(1 + \gamma \, \delta\omega_K^{(j)}\right),$$

$$\tau_K = M \sum_{j=0}^{N_{max}} \chi^j \, \tau_K^{(j)} \left(1 + \gamma \, \delta\tau_K^{(j)}\right).$$

Proportional to action coupling(s):

$$\gamma := \left(\frac{\ell \, c^2 \, (1+z)}{G \, M}\right)^p$$

Much **smaller number** of signals to **detect** modifications to GR predictions!

THEORY PARAMETER SPACE

- **p=0** (e.g. certain **scalar-tensor** or **Lorentz-violating**)

$$S_{Æ} = \frac{1}{16\pi G_{Æ}} \int \sqrt{-g}\ \left(R - M^{\alpha\beta}{}_{\mu\nu} \nabla_\alpha u^\mu \nabla_\beta u^\nu\right)\ d^4x$$

THEORY PARAMETER SPACE

- **p=0** (e.g. certain **scalar-tensor** or **Lorentz-violating**)

$$S_{Æ} = \frac{1}{16\pi G_{Æ}} \int \sqrt{-g}\, \left(R - M^{\alpha\beta}{}_{\mu\nu} \nabla_\alpha u^\mu \nabla_\beta u^\nu\right)\, d^4x$$

- **p=2** (e.g. **Kerr-Newman** or charged dark matter)

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + 4\pi e j^\mu_{\rm em} A_\mu + 4\pi e_h j^\mu_h B_\mu + 4\pi \epsilon e j^\mu_h A_\mu\right)$$

Cardoso+, arXiv:1604.07845 Berti+, arXiv:1501.07274

THEORY PARAMETER SPACE

- **p=0** (e.g. certain **scalar-tensor** or **Lorentz-violating**)

$$S_{Æ} = \frac{1}{16\pi G_{Æ}} \int \sqrt{-g}\, \left(R - M^{\alpha\beta}{}_{\mu\nu} \nabla_\alpha u^\mu \nabla_\beta u^\nu\right)\, d^4x$$

- **p=2** (e.g. **Kerr-Newman** or charged dark matter)

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + 4\pi e j^\mu_{\rm em} A_\mu + 4\pi e_h j^\mu_h B_\mu + 4\pi\epsilon e j^\mu_h A_\mu\right)$$

- **p=4** (e.g. **Einstein-scalar-Gauss-Bonnet** or **dynamical Chern-Simons**)

$$S \equiv \int \frac{m_{\rm pl}^2}{2} d^4x \sqrt{-g}\left[R - \frac{1}{2}(\partial\vartheta)^2 + 2\alpha_{\rm GB} f(\vartheta)\mathcal{R}_{\rm GB}\right], \quad S \equiv \int d^4x \sqrt{-g}\left(\frac{m_{\rm pl}^2}{2} R - \frac{1}{2}(\partial\vartheta)^2 - \frac{m_{\rm pl}}{8}\ell^2 \vartheta\, {}^*RR\right)$$

Cardoso+, arXiv:1604.07845 Berti+, arXiv:1501.07274

THEORY PARAMETER SPACE

- **p=0** (e.g. certain **scalar-tensor** or **Lorentz-violating**)

$$S_{Æ} = \frac{1}{16\pi G_{Æ}} \int \sqrt{-g}\, \left(R - M^{\alpha\beta}{}_{\mu\nu} \nabla_\alpha u^\mu \nabla_\beta u^\nu\right) d^4x$$

- **p=2** (e.g. **Kerr-Newman** or charged dark matter)

$$\mathcal{L} = \sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + 4\pi e j^\mu_{\rm em} A_\mu + 4\pi e_h j^\mu_h B_\mu + 4\pi \epsilon e j^\mu_h A_\mu\right)$$

- **p=4** (e.g. **Einstein-scalar-Gauss-Bonnet** or **dynamical Chern-Simons**)

$$S \equiv \int \frac{m_{\rm pl}^2}{2} d^4x \sqrt{-g}\left[R - \frac{1}{2}(\partial\vartheta)^2 + 2\alpha_{\rm GB} f(\vartheta)\mathcal{R}_{\rm GB}\right], \quad S \equiv \int d^4x \sqrt{-g}\left(\frac{m_{\rm pl}^2}{2}R - \frac{1}{2}(\partial\vartheta)^2 - \frac{m_{\rm pl}}{8}\ell^2\vartheta\, {}^*RR\right)$$

- **p=6** (e.g. **Effective Field Theories**)

Symmetries + short distance experiments (assuming causality, locality, diff. inv., unitarity)

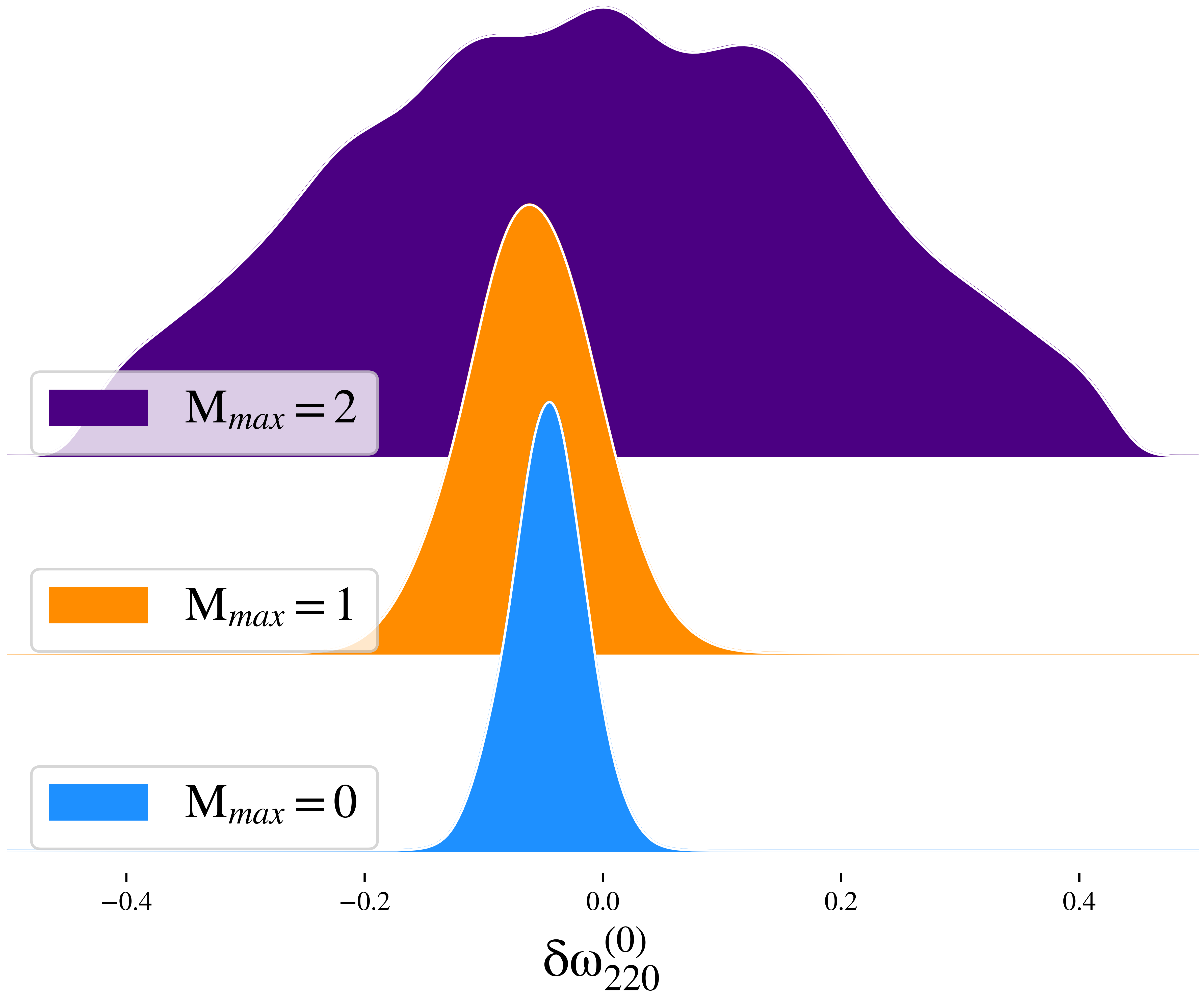
$$S_{\rm eff} = \int d^4x \sqrt{-g}\, 2M_{\rm pl}^2\left(R - \frac{\mathcal{C}^2}{\Lambda^6} - \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} - \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6}\right)$$

$$\mathcal{C} \equiv R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}, \qquad \tilde{\mathcal{C}} \equiv R_{\alpha\beta\gamma\delta}\tilde{R}^{\alpha\beta\gamma\delta}$$

 Endlich+, arXiv:1704.01590 Cardoso+, arXiv:1604.07845 Berti+, arXiv:1501.07274

RESULTS FOR SCALAR DEVIATIONS

- Constraints on theories with scalar coupling in the action:



$$\delta\omega_{220}^{0} = -0.05^{+0.05}_{-0.05}$$

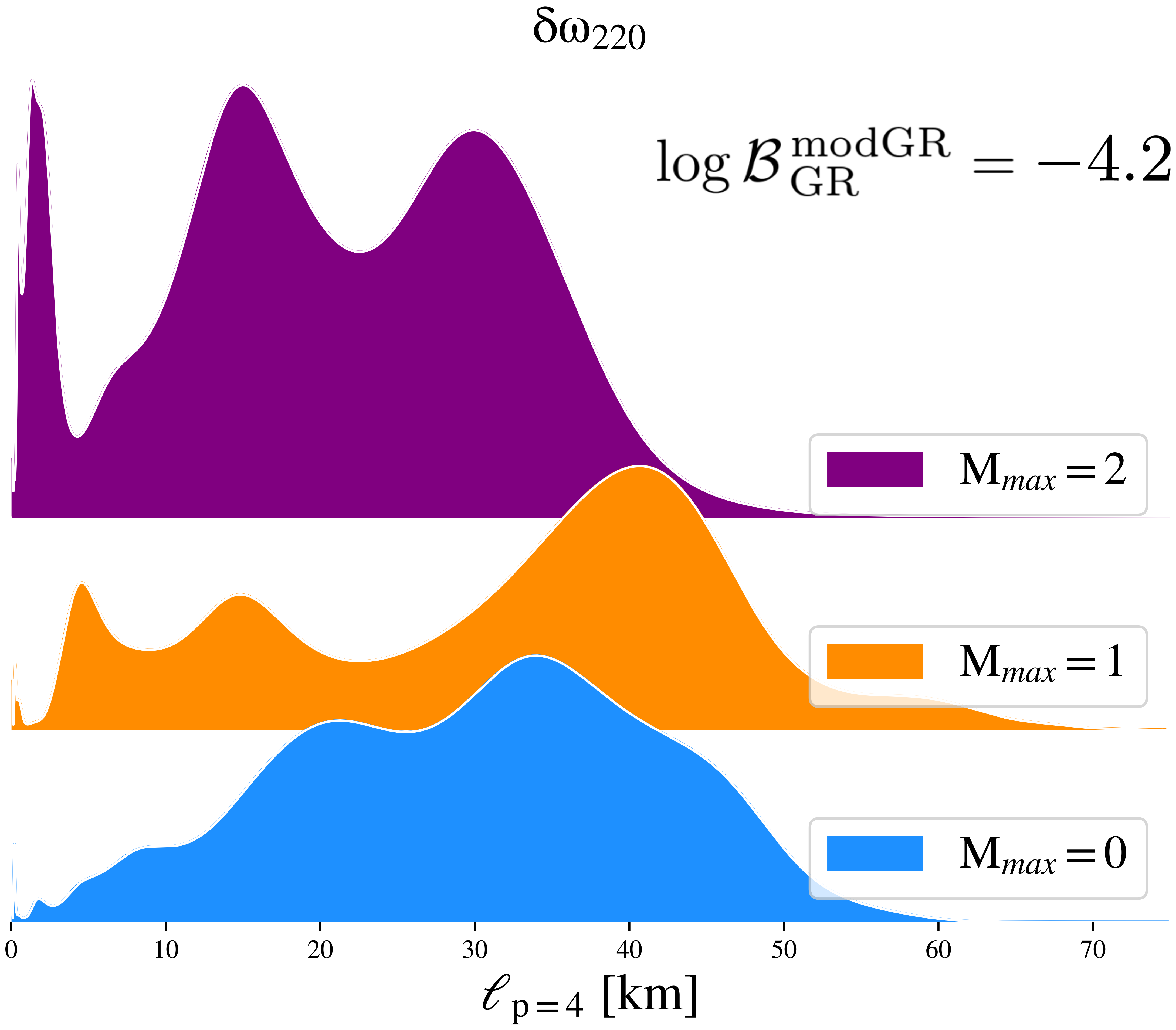
$$\log \mathcal{B}^{\mathrm{modGR}}_{\mathrm{GR}} = -14.55$$

Reduction **factor of $\sim$4** in N_{events} to detect a violation wrt LVC parametrisation.

M_{max} = spin-expansion order.

RESULTS FOR QUADRATIC GRAVITY

- Constraints on theories introducing quadratic curvature terms in the action:



$$\ell_{\mathrm{p}=4} \lesssim 35 \ \mathrm{km}$$

dCS: (NICER+LVC) $\ell \lesssim 30 - 50\,\mathrm{km}$

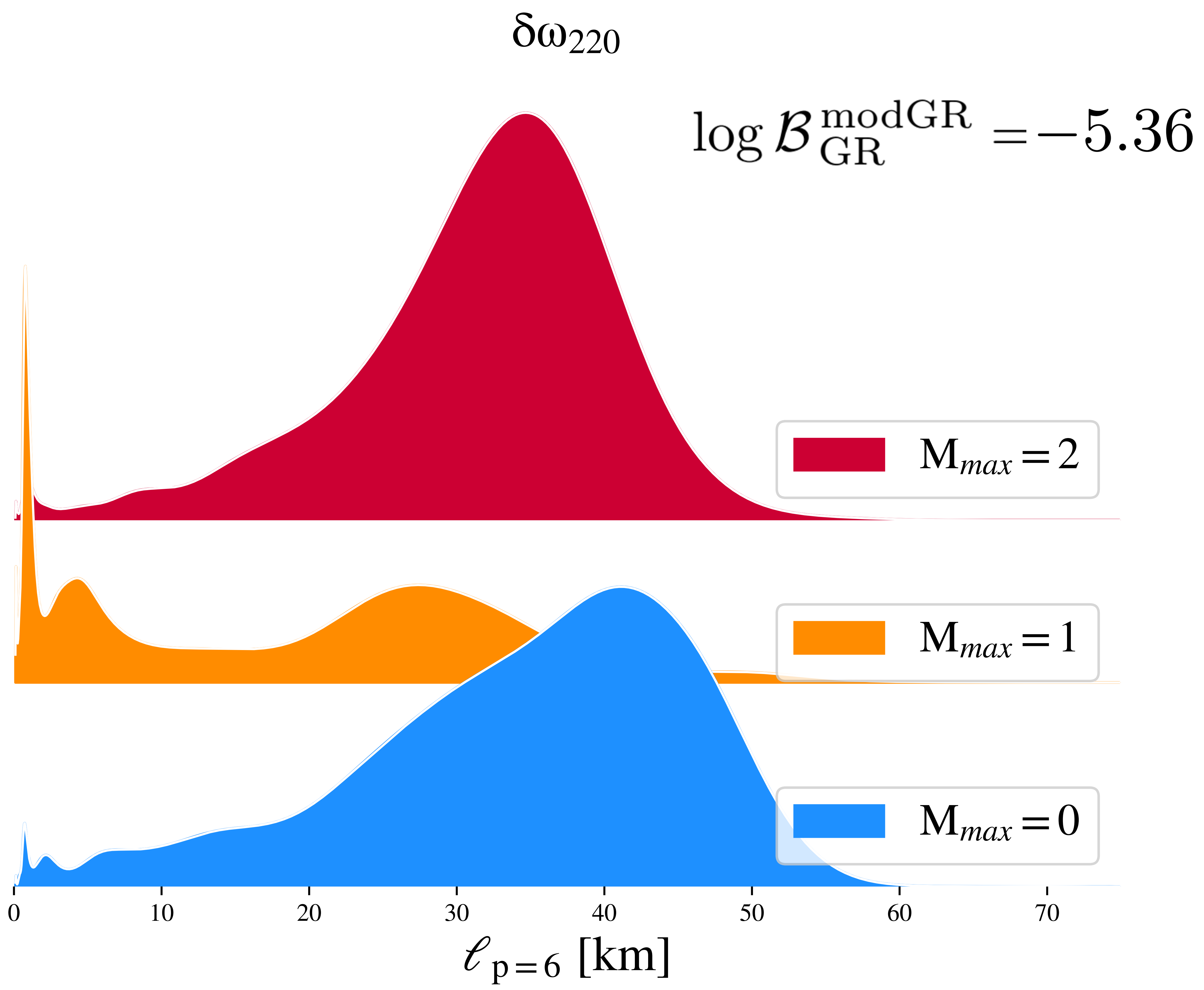
EsGB: (X-rays) $\ell \lesssim 6 - 10\,\mathrm{km}$

Competitive! Also, will rapidly improve with next observing runs.

Yagi, PRD 86, 081504 (2012) Silva et al. 2004.01253 (2020)

RESULTS FOR EFFECTIVE FIELD THEORIES

- Constraints on viable Effective Field Theories of beyond-GR gravity:



$$\ell_{p=6} \lesssim 42 \text{ km}$$

Previous best bound from GW inspiral:

$$\ell \lesssim 150 \, \text{km}$$

(Now probing finite-size effects)

FUTURE DEVELOPMENTS

- Incorporates **predictions** available up to a **given order**, **marginalising** over unknown terms. No *direct* **non-gravitational branches**, but could.

$$\omega_K = \frac{1}{M} \sum_{j=0}^{N_{max}} \chi^j \, \omega_K^{(j)} \left(1 + \gamma \, \boxed{\delta\omega_K^{(j)}}\right),$$

$$\tau_K = M \sum_{j=0}^{N_{max}} \chi^j \, \tau_K^{(j)} \left(1 + \gamma \, \boxed{\delta\tau_K^{(j)}}\right).$$

Can include, e.g.:

Wagle+, arXiv:2103.09913

Pierini+, Phys. Rev. D 103, 124017 (2021)

Srivastava+, Phys. Rev. D 104, 064034 (2021)

Cano+, Phys. Rev. D 102, 044047 (2020)

KERR-NEWMAN RINGDOWN

Splitting the third hair: constraints on Kerr-Newman black holes from merger-ringdown gravitational waves observations

Gregorio Carullo,[1,2] Walter Del Pozzo,[1,2] Óscar J. C. Dias,[3] Mahdi Godazgar,[4] Nathan K. Johnson-McDaniel,[5] Danny Laghi,[1,2] Jorge E. Santos,[5] and John Veitch[6]

[1] *Dipartimento di Fisica "Enrico Fermi", Università di Pisa, Pisa I-56127, Italy*
[2] *INFN sezione di Pisa, Pisa I-56127, Italy*
[3] *STAG research centre and Mathematical Sciences, University of Southampton, UK*
[4] *School of Mathematical Sciences, Queen Mary University of London, Mile End Road, London E1 4NS, UK.*
[5] *DAMTP, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, United Kingdom*
[6] *Institute for Gravitational Research, University of Glasgow, Glasgow, G12 8QQ, United Kingdom*

(Dated: May 16, 2021)

MOTIVATIONS FOR KERR-NEWMAN GW STUDIES

- Final state conjecture (*No-hair* conjecture+): Kerr-Newman family, determined by mass, spin and **charge**

MOTIVATIONS FOR KERR-NEWMAN GW STUDIES

- Final state conjecture (*No-hair* conjecture+): Kerr-Newman family, determined by mass, spin and **charge**
  - **Astrophysical charge** expected to be **negligible (polarised vacuum**, **neutralisation,** …). Can it be observationally confirmed?

MOTIVATIONS FOR KERR-NEWMAN GW STUDIES

- Final state conjecture (*No-hair* conjecture+): Kerr-Newman family, determined by mass, spin and **charge**
    - **Astrophysical charge** expected to be **negligible (polarised vacuum**, **neutralisation,** …). Can it be observationally confirmed?
- Fundamental physics motivations:

MOTIVATIONS FOR KERR-NEWMAN GW STUDIES

- Final state conjecture (*No-hair* conjecture+): Kerr-Newman family, determined by mass, spin and **charge**
  - **Astrophysical charge** expected to be **negligible (polarised vacuum, neutralisation,** …). Can it be observationally confirmed?
- Fundamental physics motivations:
  - Minicharged **dark matter, magnetic charge** (primordial magnetic monopoles)

MOTIVATIONS FOR KERR-NEWMAN GW STUDIES

- Final state conjecture (*No-hair* conjecture+): Kerr-Newman family, determined by mass, spin and **charge**
  - **Astrophysical charge** expected to be **negligible (polarised vacuum**, **neutralisation,** …). Can it be observationally confirmed?
- Fundamental physics motivations:
  - Minicharged **dark matter, magnetic charge** (primordial magnetic monopoles)
  - Scalar-**vector**-tensor gravity, **topologically** induced charge

 Cardoso+, arXiv:1604.07845

MOTIVATIONS FOR KERR-NEWMAN GW STUDIES

- Final state conjecture (*No-hair* conjecture+): Kerr-Newman family, determined by mass, spin and **charge**
  - **Astrophysical charge** expected to be **negligible (polarised vacuum**, **neutralisation,** …). Can it be observationally confirmed?
- Fundamental physics motivations:
  - Minicharged **dark matter, magnetic charge** (primordial magnetic monopoles)
  - Scalar-**vector**-tensor gravity, **topologically** induced charge
  - Valuable **test-bed** for **beyond-Kerr** effects.

QNM SPECTRUM PREDICTIONS

- Long-standing problem (Einstein-Maxwell equations **non-separable**)

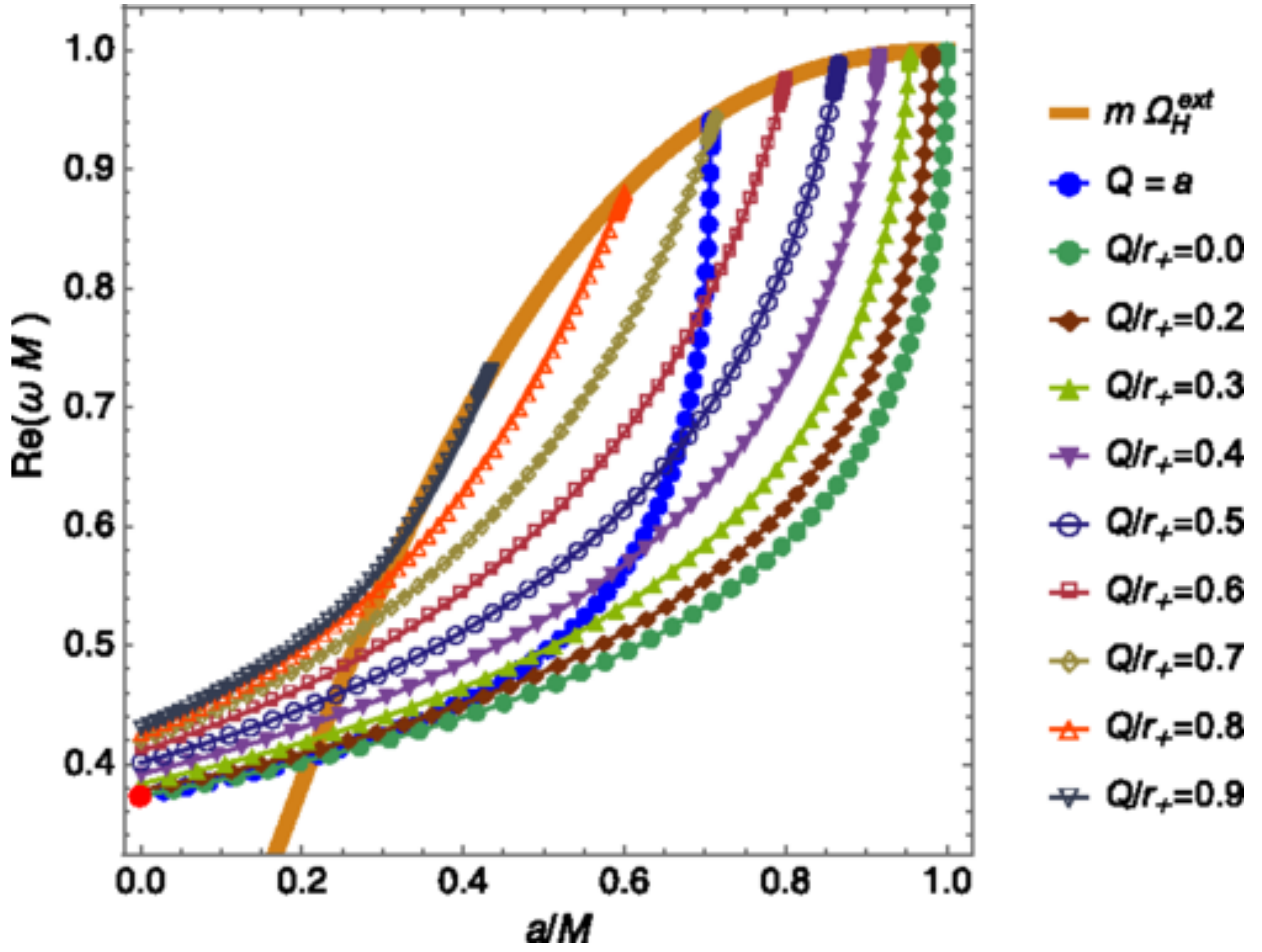
QNM SPECTRUM PREDICTIONS

- Long-standing problem (Einstein-Maxwell equations **non-separable**)
- **Dias, Godazgar, Santos: Linear stability** of Kerr-Newman up to 99.999% of extemality

Berti+. arXiv:gr-qc/0502065
Pani+, arXiv:1304.1160
Mark+, arXiv:1409.5800
Zimmerman+, arXiv:1512.02247

QNM SPECTRUM PREDICTIONS

- Long-standing problem (Einstein-Maxwell equations **non-separable**)
- **Dias, Godazgar, Santos: Linear stability** of Kerr-Newman up to 99.999% of extemality
- Modes **connected to Schwarzschild** dominate the spectrum



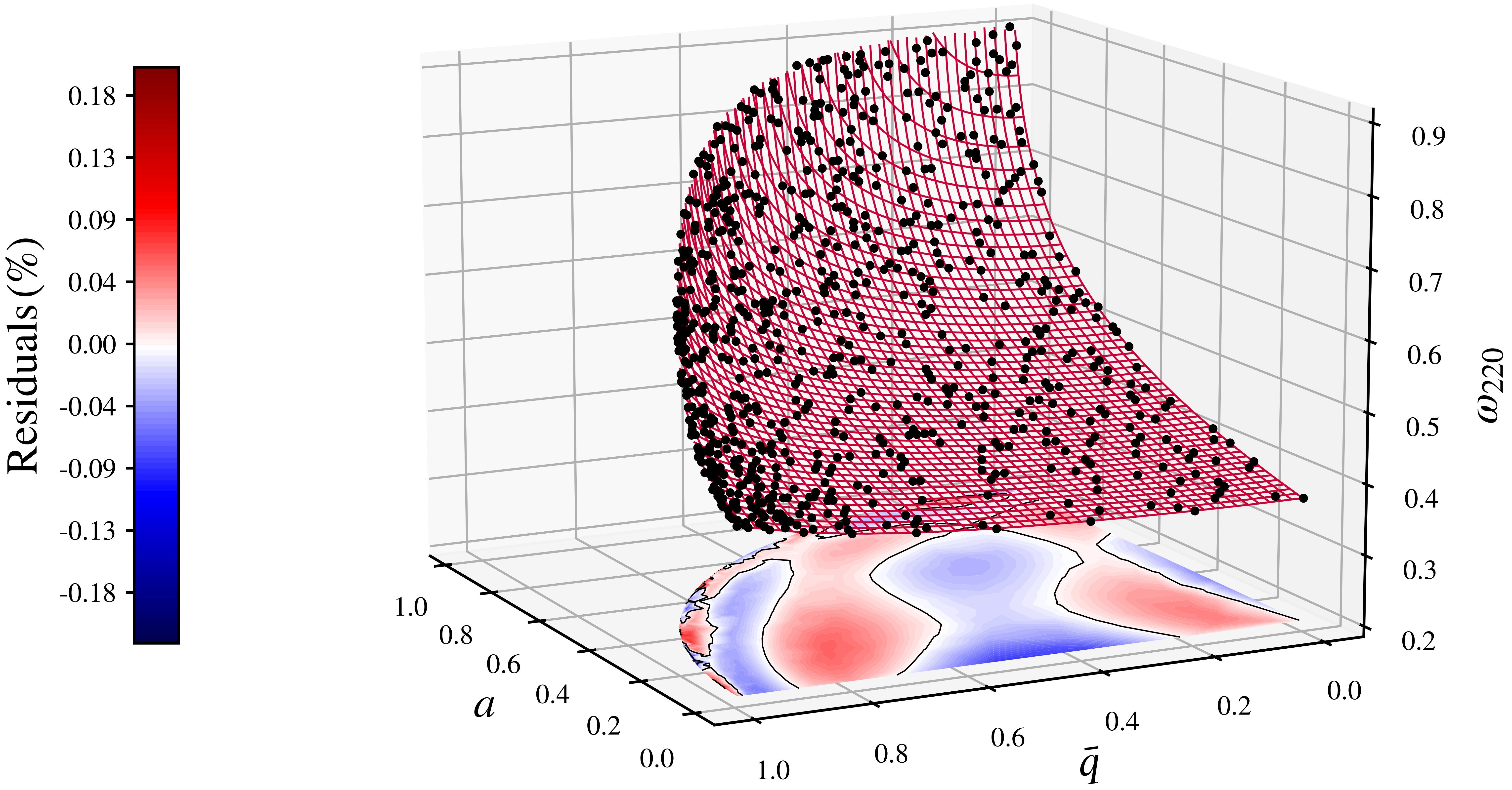
Berti+. arXiv:gr-qc/0502065
Pani+, arXiv:1304.1160
Mark+, arXiv:1409.5800
Zimmerman+, arXiv:1512.02247

KERR-NEWMAN SPECTRUM

- **Tabulate QNM** numerical solutions for: $(l, m, n) = [(2,2,0), (2,2,1), (3,3,0)]$
- Build an **analytical** effective **representation**
- **Bayesian** fit
- Exclude **extremal limit**

↓

Near-horizon modes, eigeinvalues repulsion, see arXiv:2109.13949



KERR-NEWMAN TEMPLATE

- Build a **template** by using KN complex frequencies
- Free complex amplitudes, ignore **EM modes**

$$h_+ - i h_\times = \frac{M_f}{D_L} \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{+\ell} \sum_{n=0}^{\infty} (h^+_{\ell mn} + h^-_{\ell mn}) \tag{7}$$

with:

$$h^+_{\ell mn} = \mathcal{A}^+_{\ell mn} \, S_{\ell mn}(\iota, \varphi) \, e^{-i(t - t_{\ell mn})\tilde{\omega}_{\ell mn} + i\phi^+_{\ell mn}} \tag{8a}$$

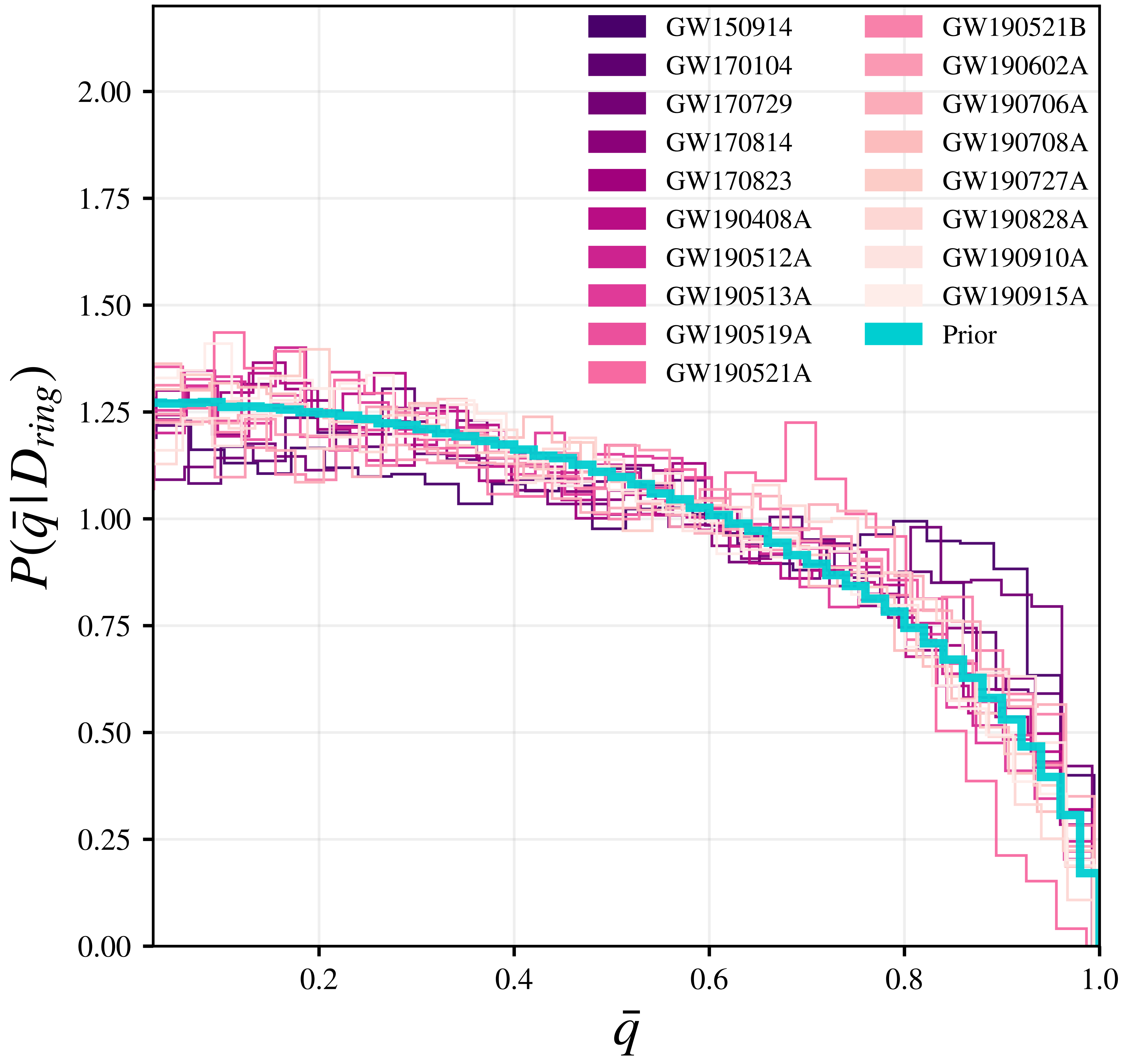
$$h^-_{\ell mn} = \mathcal{A}^-_{\ell mn} \, S^*_{\ell mn}(\pi - \iota, \varphi) \, e^{+i(t - t_{\ell mn})\tilde{\omega}^*_{\ell mn} + i\phi^-_{\ell mn}} \tag{8b}$$

KERR-NEWMAN CONSTRAINTS

- Plug previous results into pyRing and apply to all **LIGO-Virgo detections**

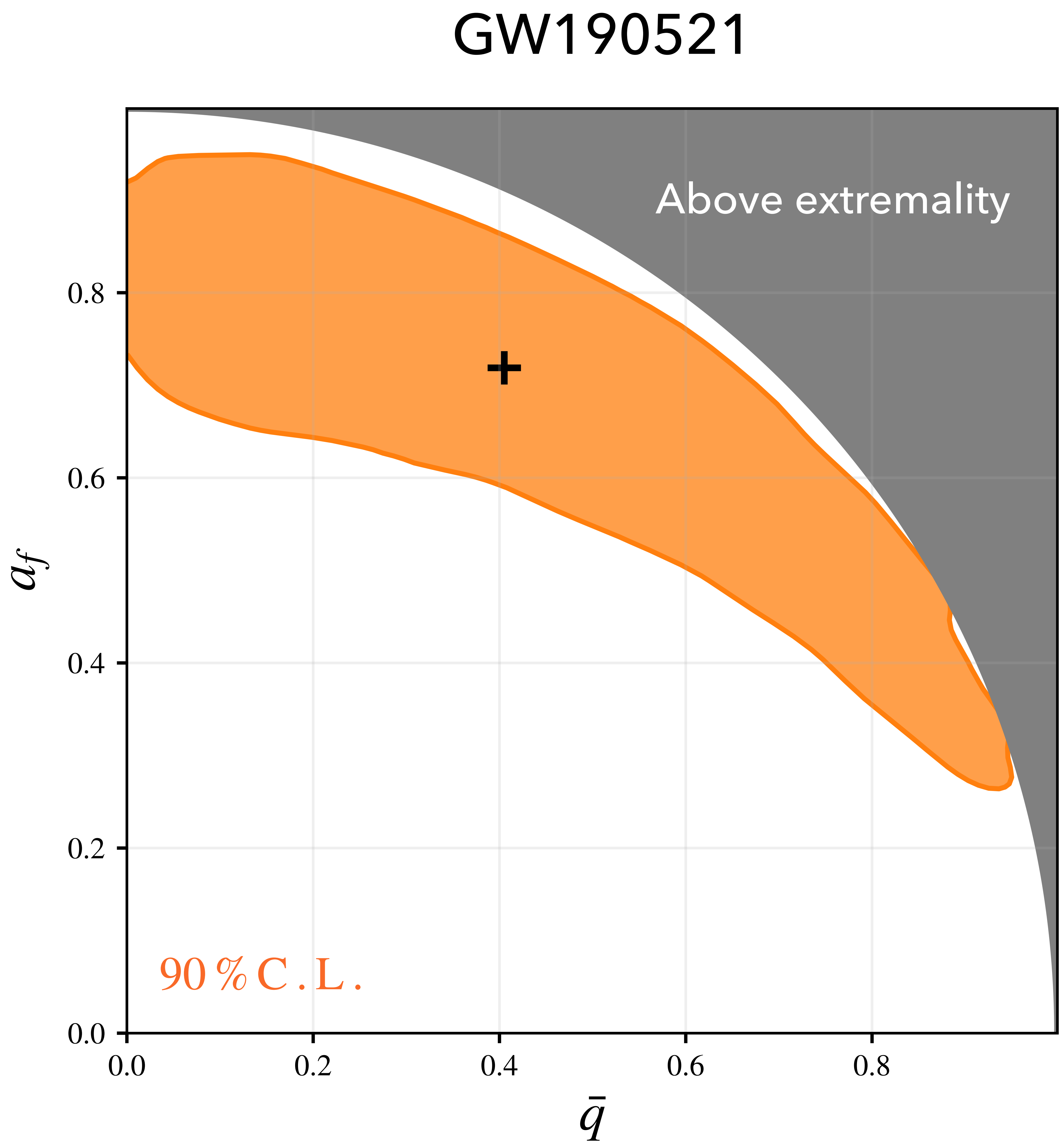
KERR-NEWMAN CONSTRAINTS

- Plug previous results into pyRing and apply to all **LIGO-Virgo detections**
- **No direct measurement** possible: posterior is equal to the prior for $\bar{q}$ (conditioned on $\bar{q}^2 + a^2 < 1$)



KERR-NEWMAN CONSTRAINTS

- Plug previous results into pyRing and apply to all **LIGO-Virgo detections**
- **No direct measurement** possible: posterior is equal to the prior for $\bar{q}$ (conditioned on $\bar{q}^2 + a^2 < 1$)
- **Strong** spin-charge correlation

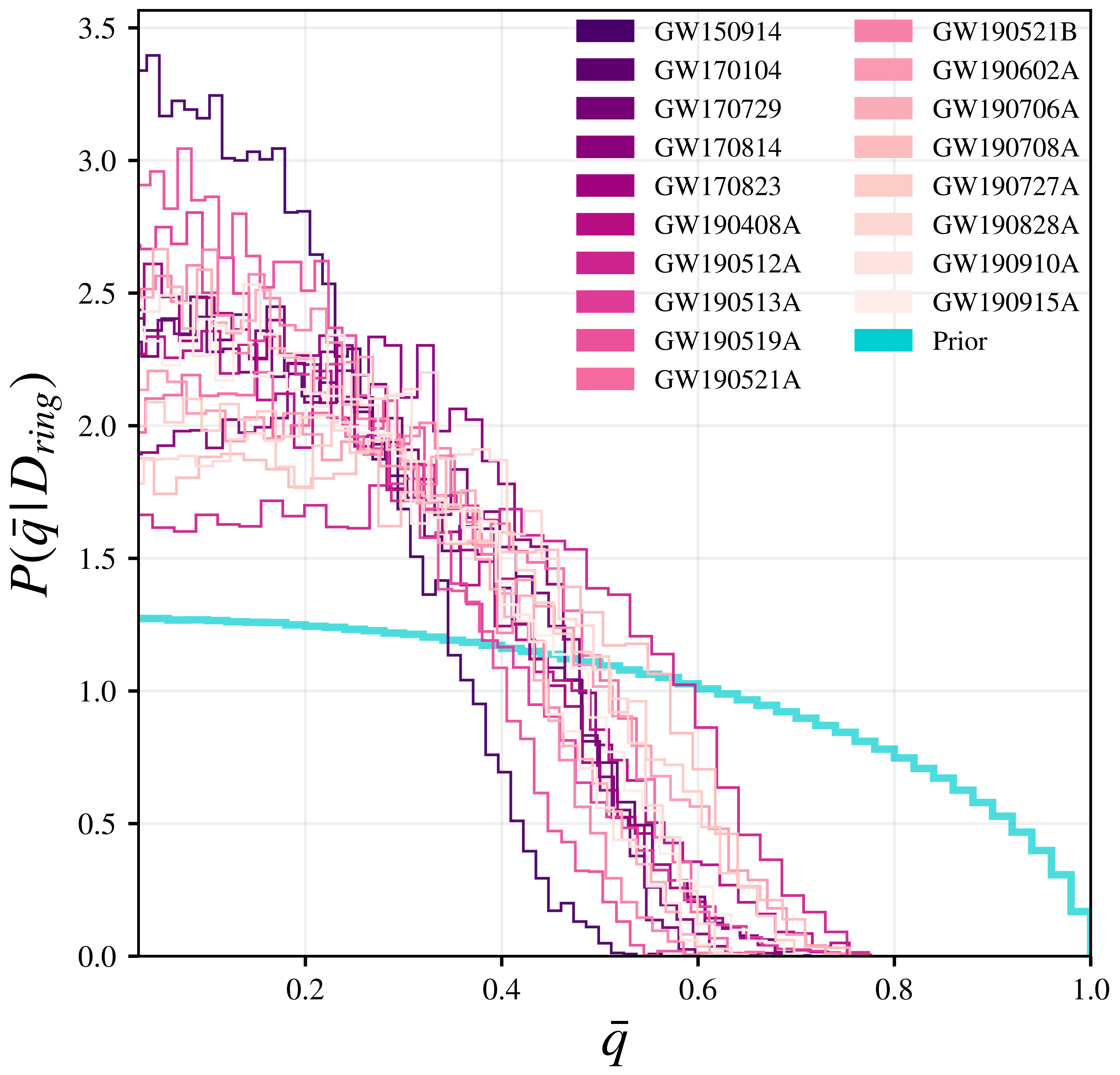


KERR-NEWMAN OBSERVATIONAL CONSTRAINTS

- **Restrict mass-spin** around LIGO-Virgo values: "mimick" information from inspiral-merger
- **Null** test: maximum amount of charge compatible with current observations

KERR-NEWMAN OBSERVATIONAL CONSTRAINTS

- **Restrict mass-spin** around LIGO-Virgo values: "mimick" information from inspiral-merger
- **Null** test: maximum amount of charge compatible with current observations
- Best event (GW150914) gives: $\bar{q} < 0.33$

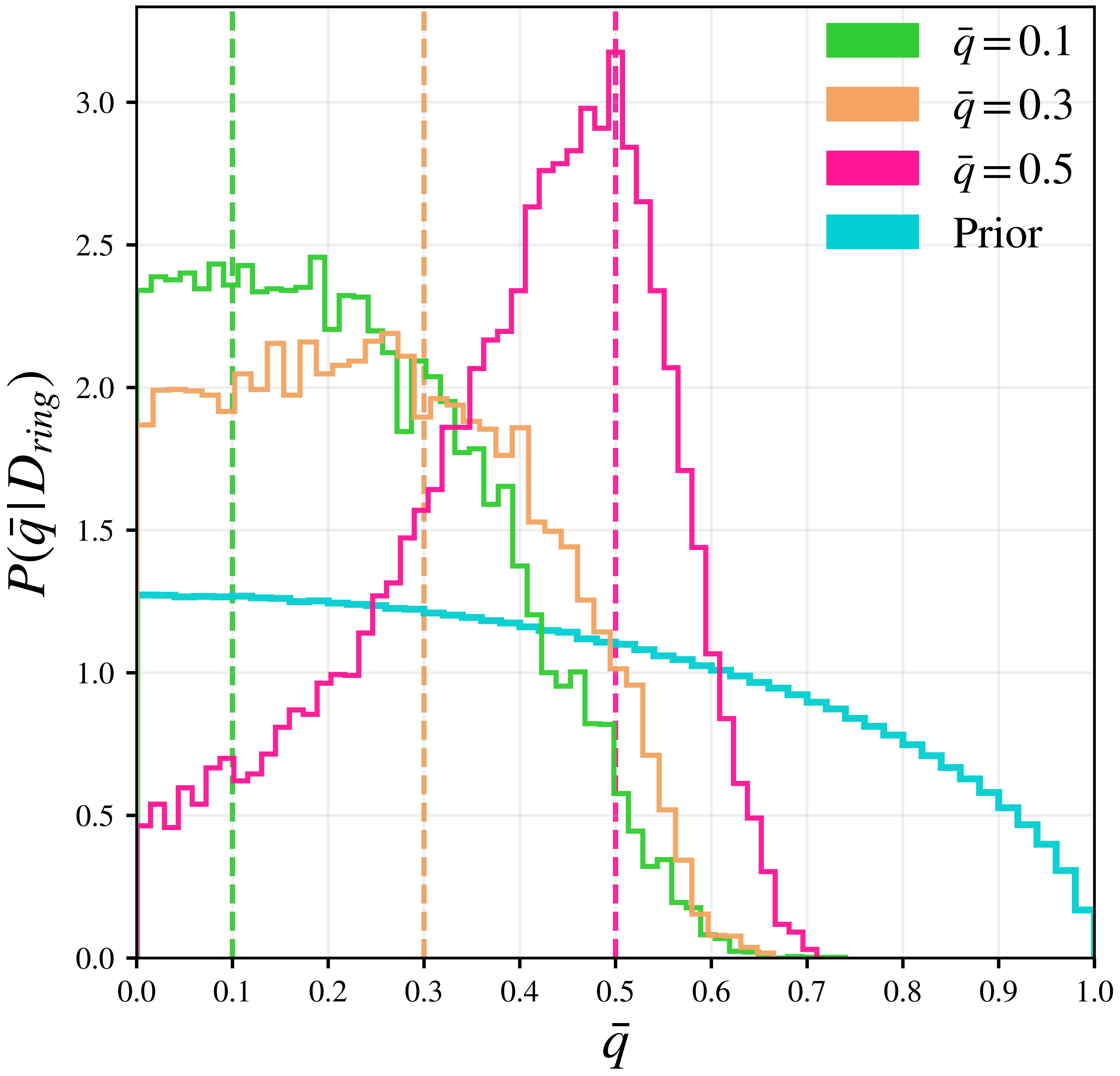


KERR-NEWMAN FUTURE CONSTRAINTS

- Can future observations from current detector network **discriminate** the presence of a **charge**?
- Simulate observations of KN signals with LIGO-Virgo at design sensitivity

KERR-NEWMAN FUTURE CONSTRAINTS

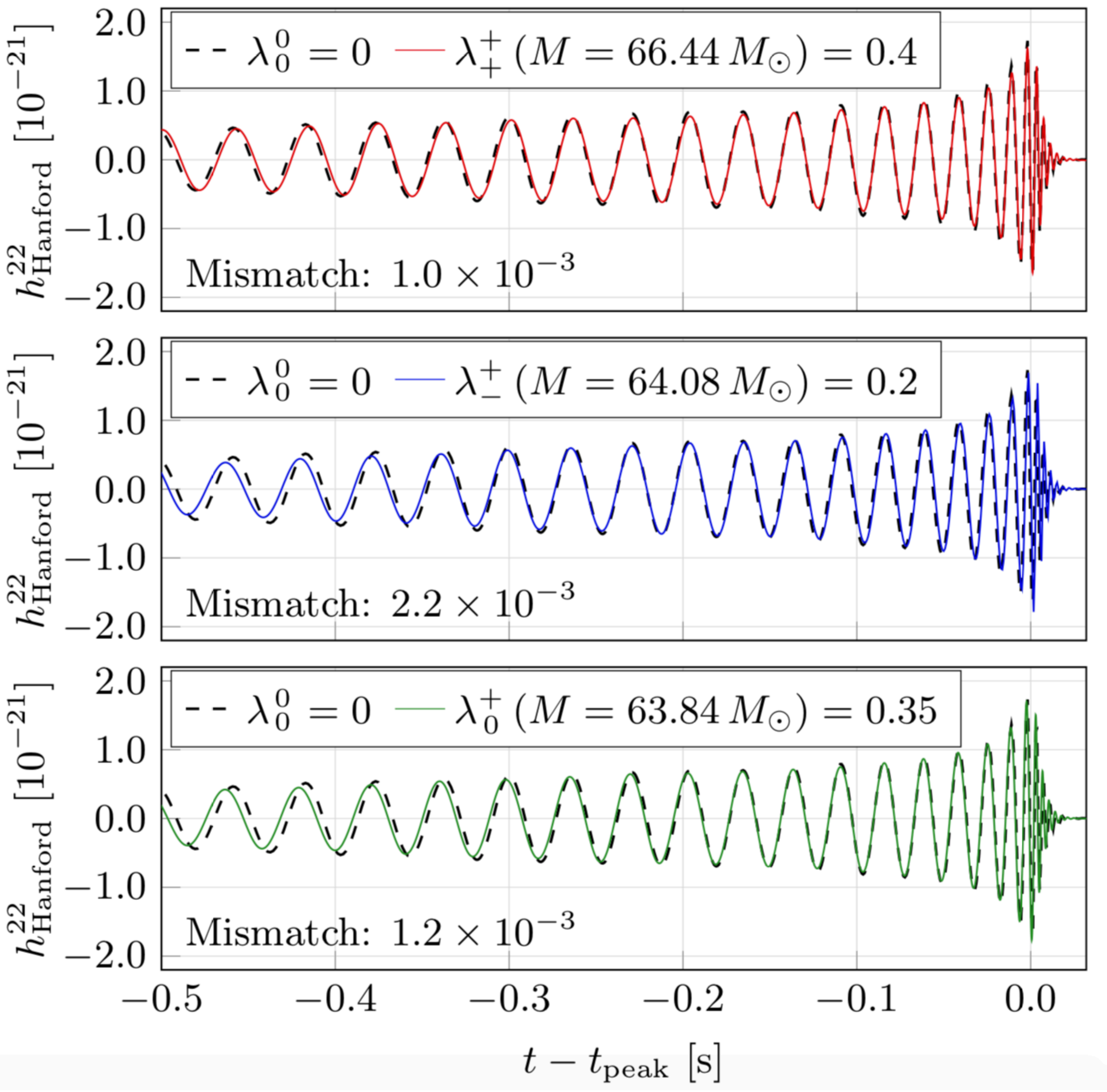
- Can future observations from current detector network **discriminate** the presence of a **charge**?
- Simulate observations of KN signals with LIGO-Virgo at design sensitivity
- Charge confidently measured **only** for **high values**
- Need more info to break **spin-charge correlations**



KERR-NEWMAN TEMPLATE

Bozzola, Paschalidis, arXiv:2006.15764

- In the future:
  - Compare against **NR**
  - Predict amplitudes
  - Additional modes?



Khalil+, arXiv:1809.03109 Gupta+, arXiv:2107.12111

 Zilhao+, arXiv:1410.0694 Mukherjee+, arXiv:2202.12133

WRAP-UP OF CURRENT OBSERVATIONS

- **Deviations** in the fundamental mode **~5-10%** LVK, arXiv:2112.06861

WRAP-UP OF CURRENT OBSERVATIONS

- **Deviations** in the fundamental mode **~5-10%** LVK, arXiv:2112.06861

- Can bound new **lenght scales** $<$ 40 kms Carullo, arXiv:2102.05939

WRAP-UP OF CURRENT OBSERVATIONS

- **Deviations** in the fundamental mode **~5-10%** — LVK, arXiv:2112.06861
- Can bound new **lenght scales** < 40 kms — Carullo, arXiv:2102.05939
- Can't really tell if observed BHs are **charged** or not — Carullo+, arXiv:2109.13949

WRAP-UP OF CURRENT OBSERVATIONS

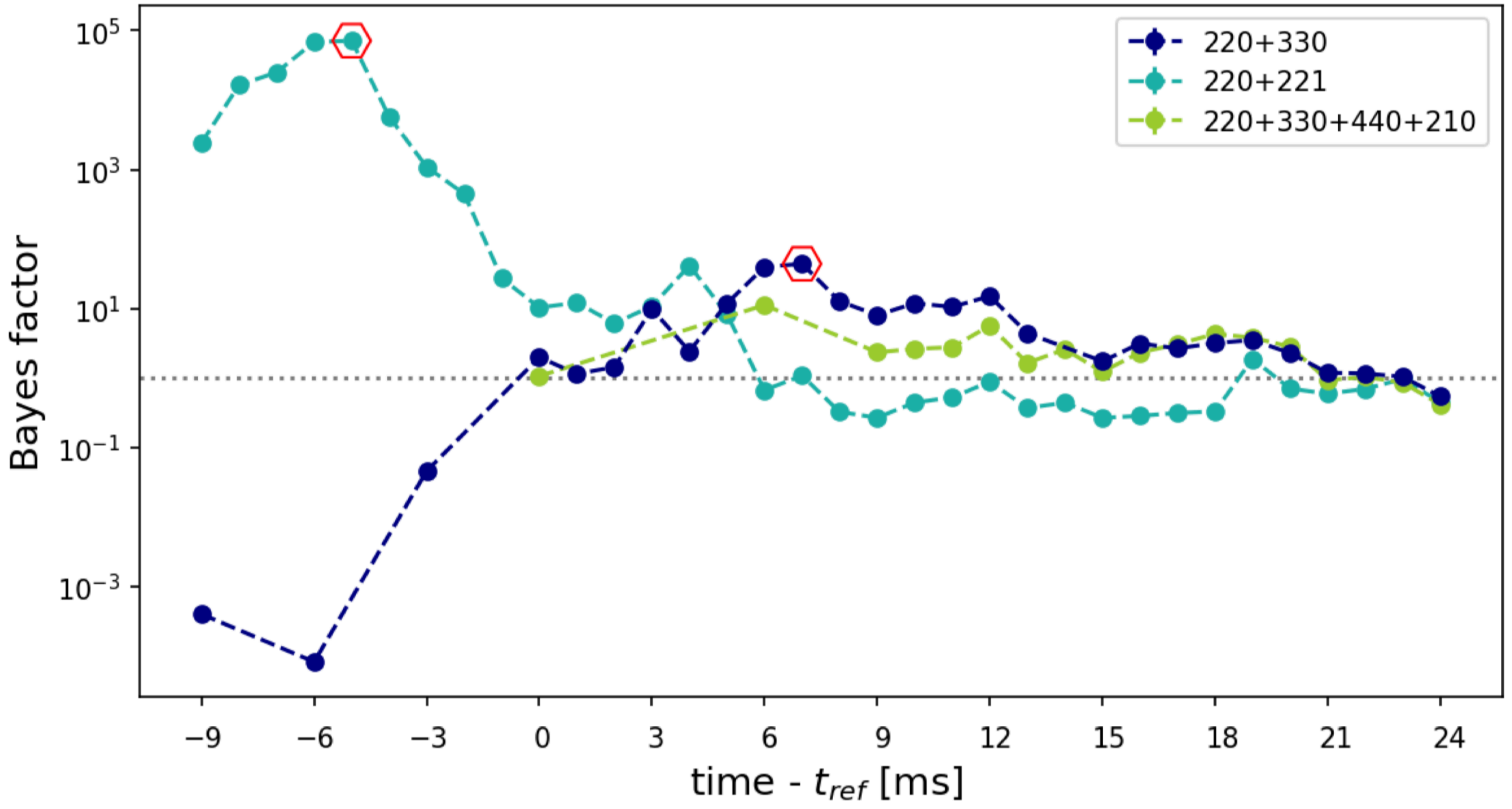
- **Deviations** in the fundamental mode **~5-10%** — LVK, arXiv:2112.06861
- Can bound new **lenght scales** < 40 kms — Carullo, arXiv:2102.05939
- Can't really tell if observed BHs are **charged** or not — Carullo+, arXiv:2109.13949
- Can't exclude **naive area quantisation** (see later) — Laghi+, arXiv:2011.03816

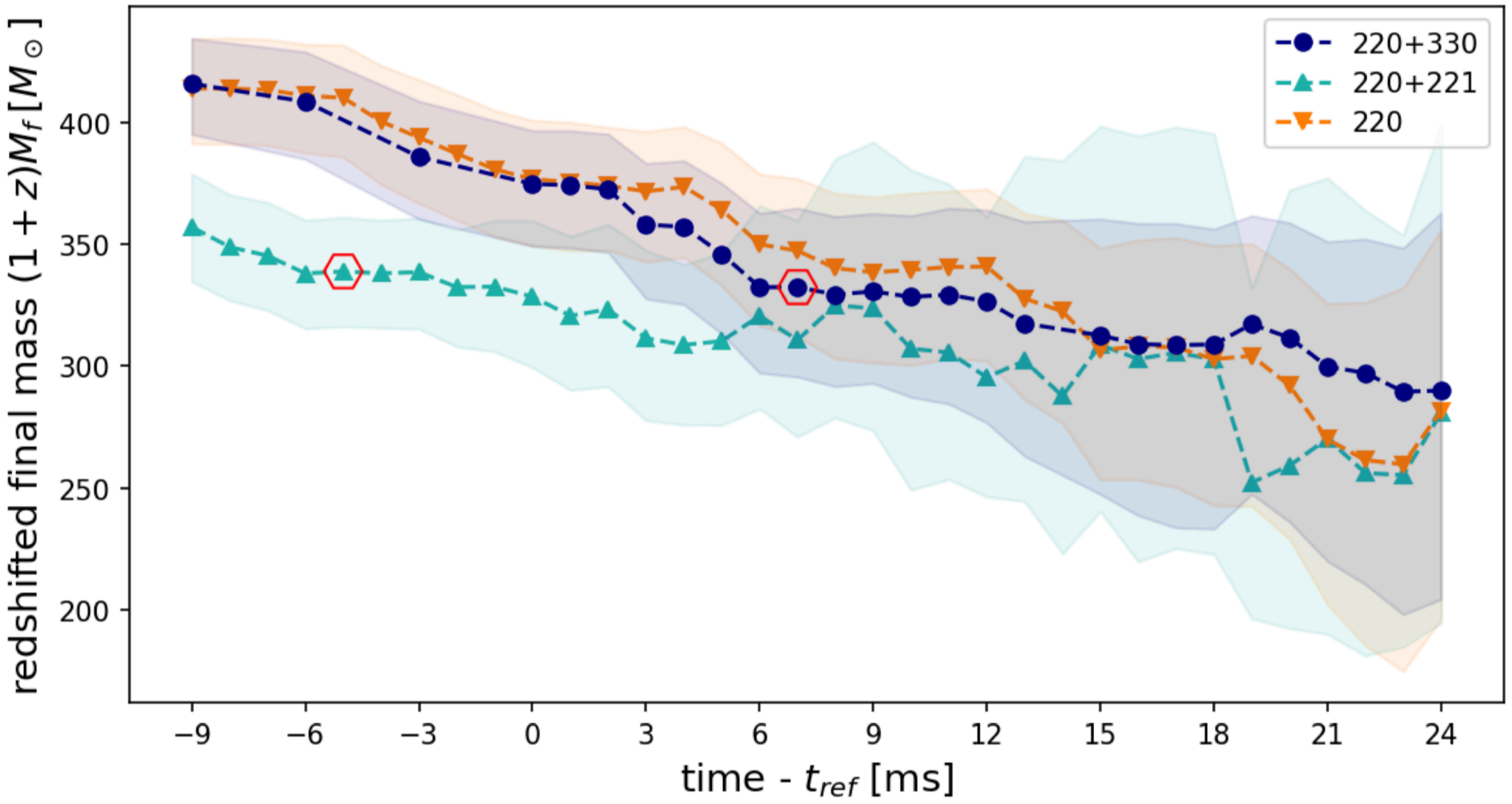
So, have we tested the “no-hair theorem” (in the “standard” sense)?

Concerning overtones, see: Cotesta+, arXiv:2201.00822

HIGHER MODES IN GW190521

- Capano+, arXiv:2105.05238 claimed the detection of the $(\ell, m, n) = (3,3,0)$ mode in GW190521, allowing for the first standard "no-hair test".





HIGHER MODES IN GW190521

- Large overestimation of the mass. Incompatible with all existing estimates

HIGHER MODES IN GW190521

- Large overestimation of the mass. Incompatible with all existing estimates
- Peaktime reconstruction uncertainty: $\pm 7ms$

HIGHER MODES IN GW190521

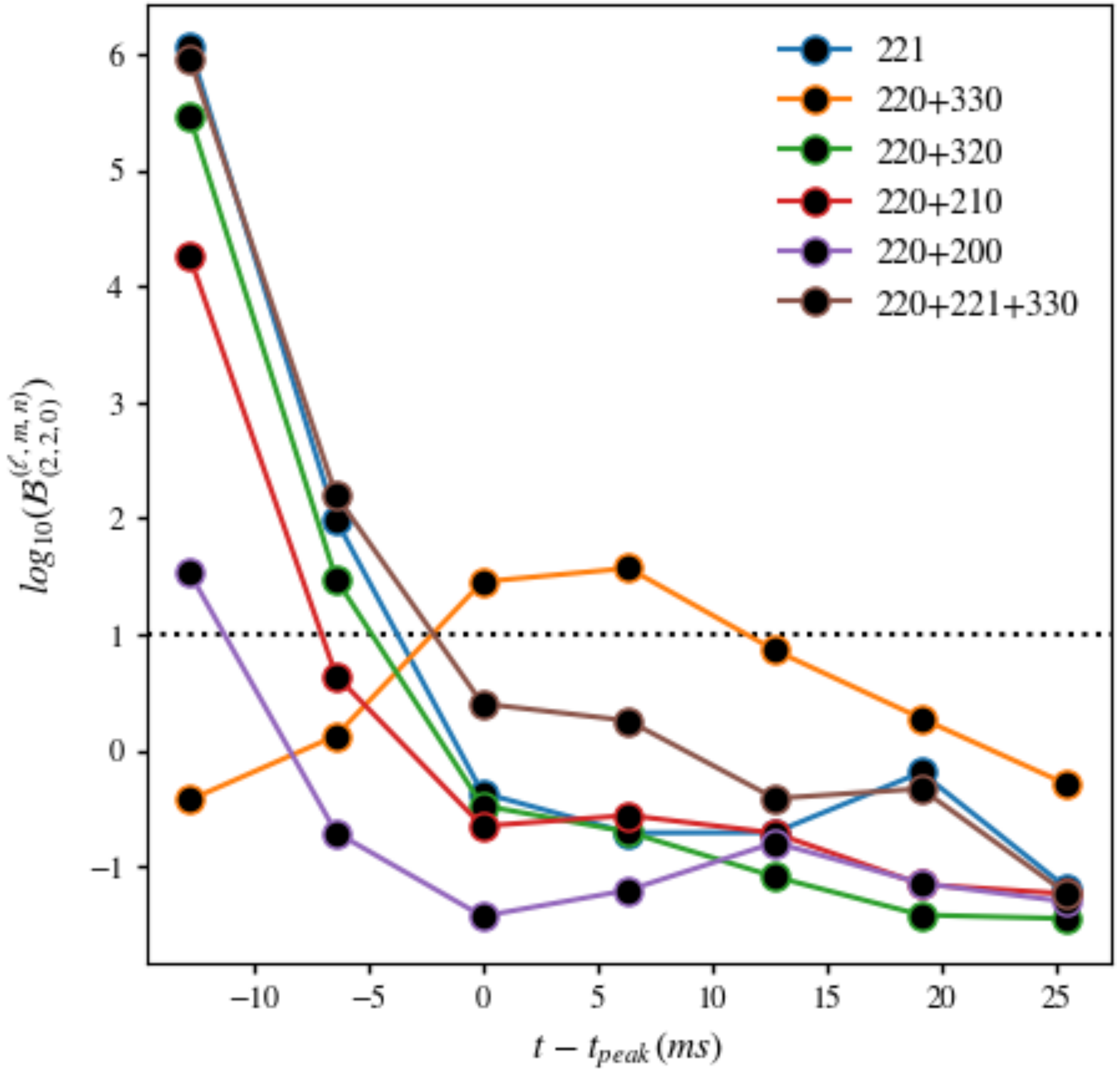
- Large overestimation of the mass. Incompatible with all existing estimates
- Peaktime reconstruction uncertainty: $\pm 7ms$
- Quote results **4ms** ($2.5M_f$, **with** $M_f = 330M_\odot$) after the peak of $h_+^2 + h_\times^2$ extracted from NRSur.

HIGHER MODES IN GW190521

- Large overestimation of the mass. Incompatible with all existing estimates
- Peaktime reconstruction uncertainty: $\pm 7ms$
- Quote results **4ms** ($2.5M_f$ **, with** $M_f = 330M_{\odot}$) after the peak of $h_+^2 + h_\times^2$ extracted from NRSur.
- Fundamental modes expected to dominate the signal $10 - 15$ M after the peak

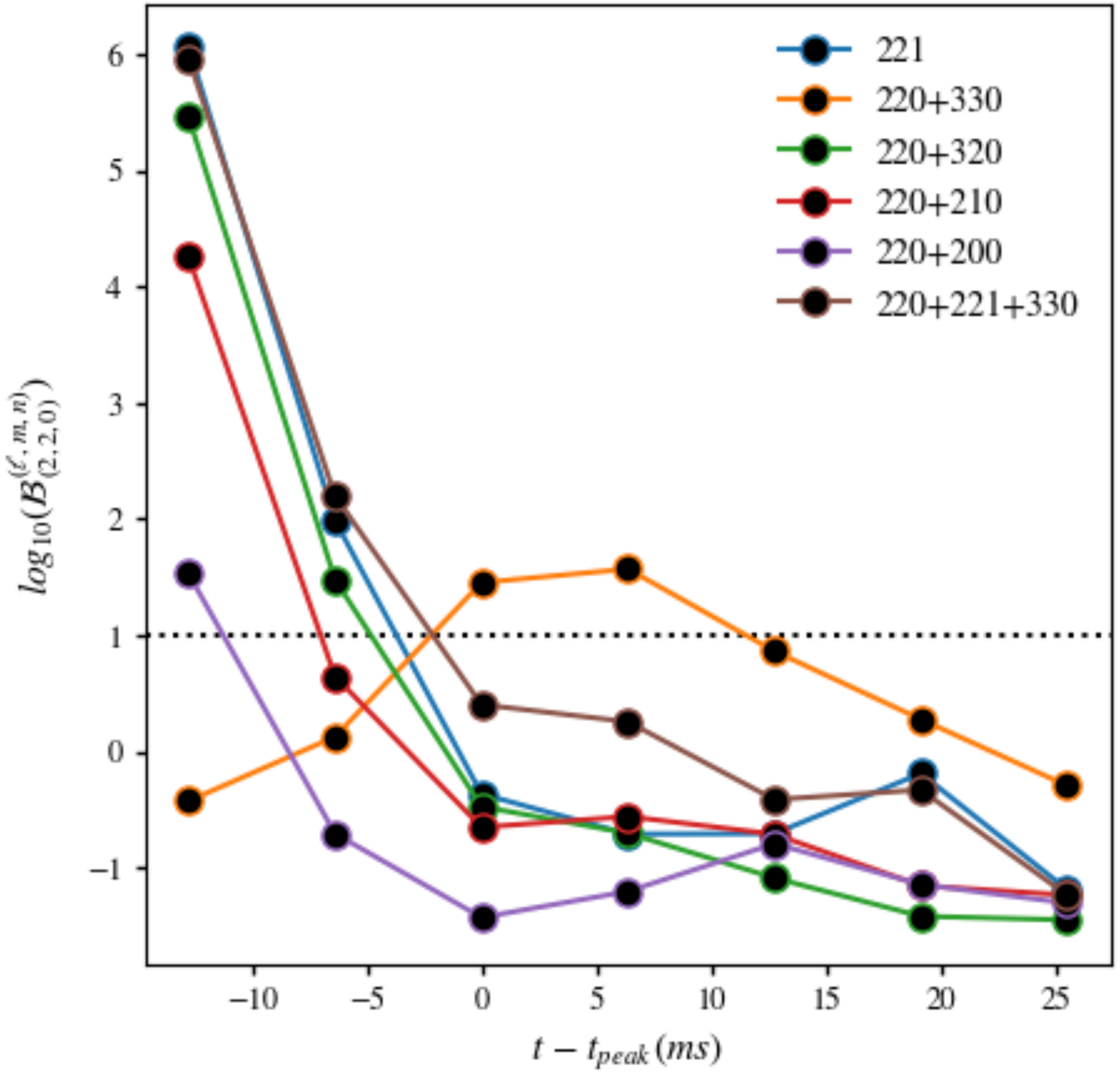
HIGHER MODES IN GW190521

- Can reproduce their results. The peak is there:



HIGHER MODES IN GW190521

- Can reproduce their results. The peak is there:
- But quite a few assumptions (validity?) in addition to LVC. Main ones:



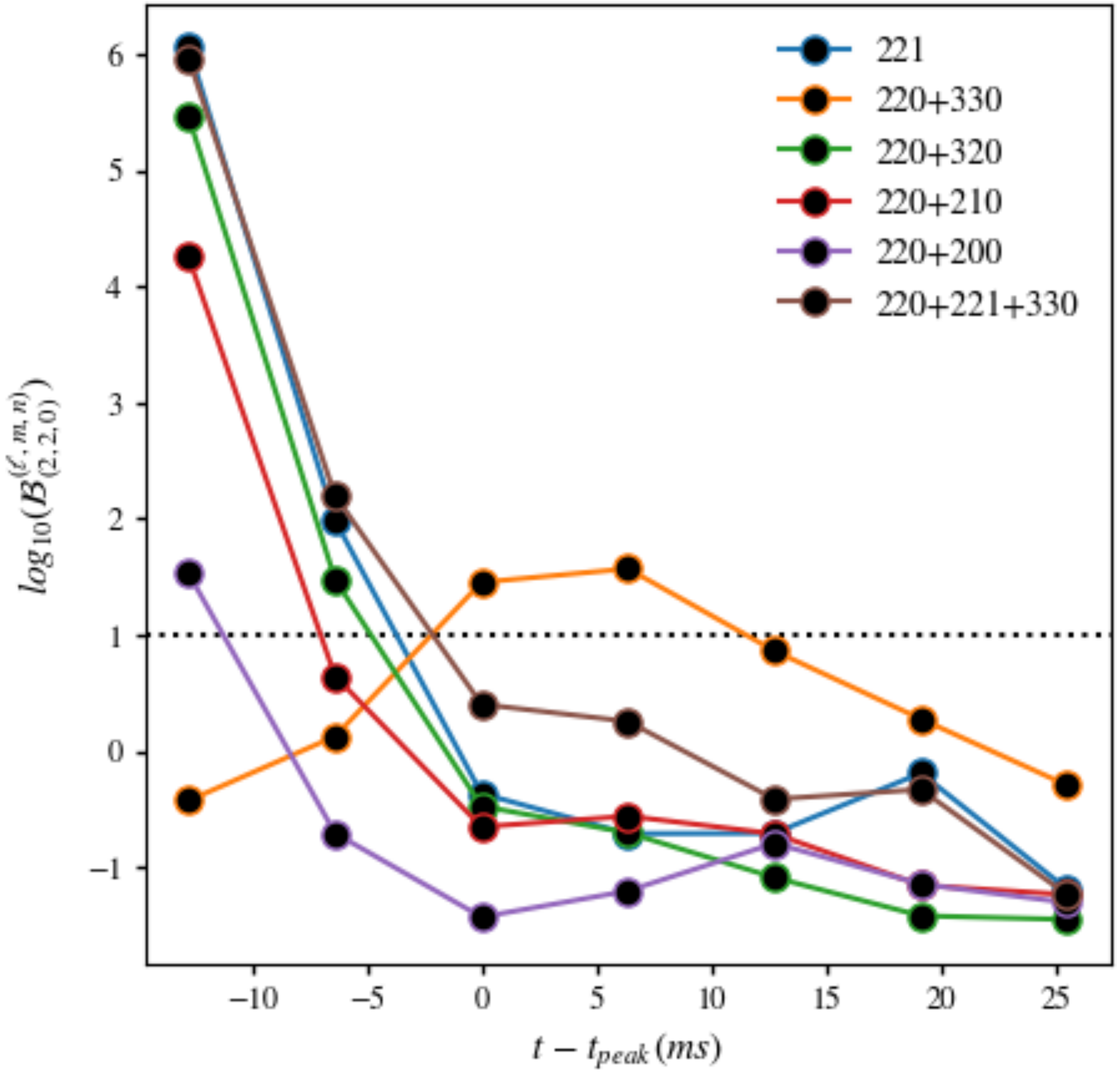
HIGHER MODES IN GW190521

- Can reproduce their results. The peak is there:

- But quite a few assumptions (validity?) in addition to LVC. Main ones:

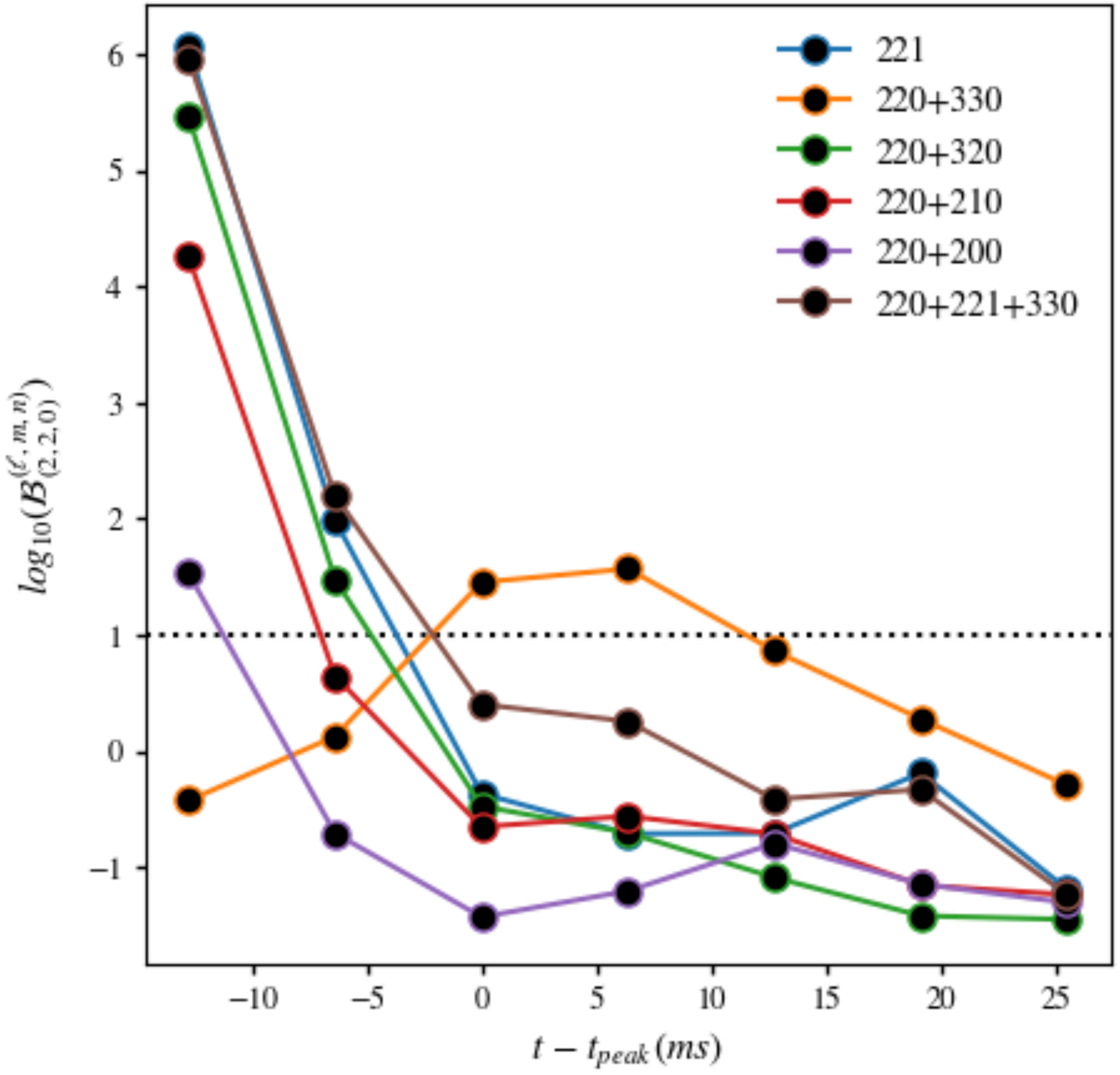
  - Amplitude hierarchy:

$$\mathcal{A}_{330} < 0.9 \cdot \mathcal{A}_{220}$$



HIGHER MODES IN GW190521

- Can reproduce their results. The peak is there:



- But quite a few assumptions (validity?) in addition to LVC. Main ones:
  - Amplitude hierarchy:

$$\mathcal{A}_{330} < 0.9 \cdot \mathcal{A}_{220}$$

  - Non-precessing symmetry:

$$\mathcal{A}^-_{\ell mn} = (-1)^l \mathcal{A}^+_{\ell mn}, \phi^-_{\ell mn} = -\phi^+_{\ell mn}.$$

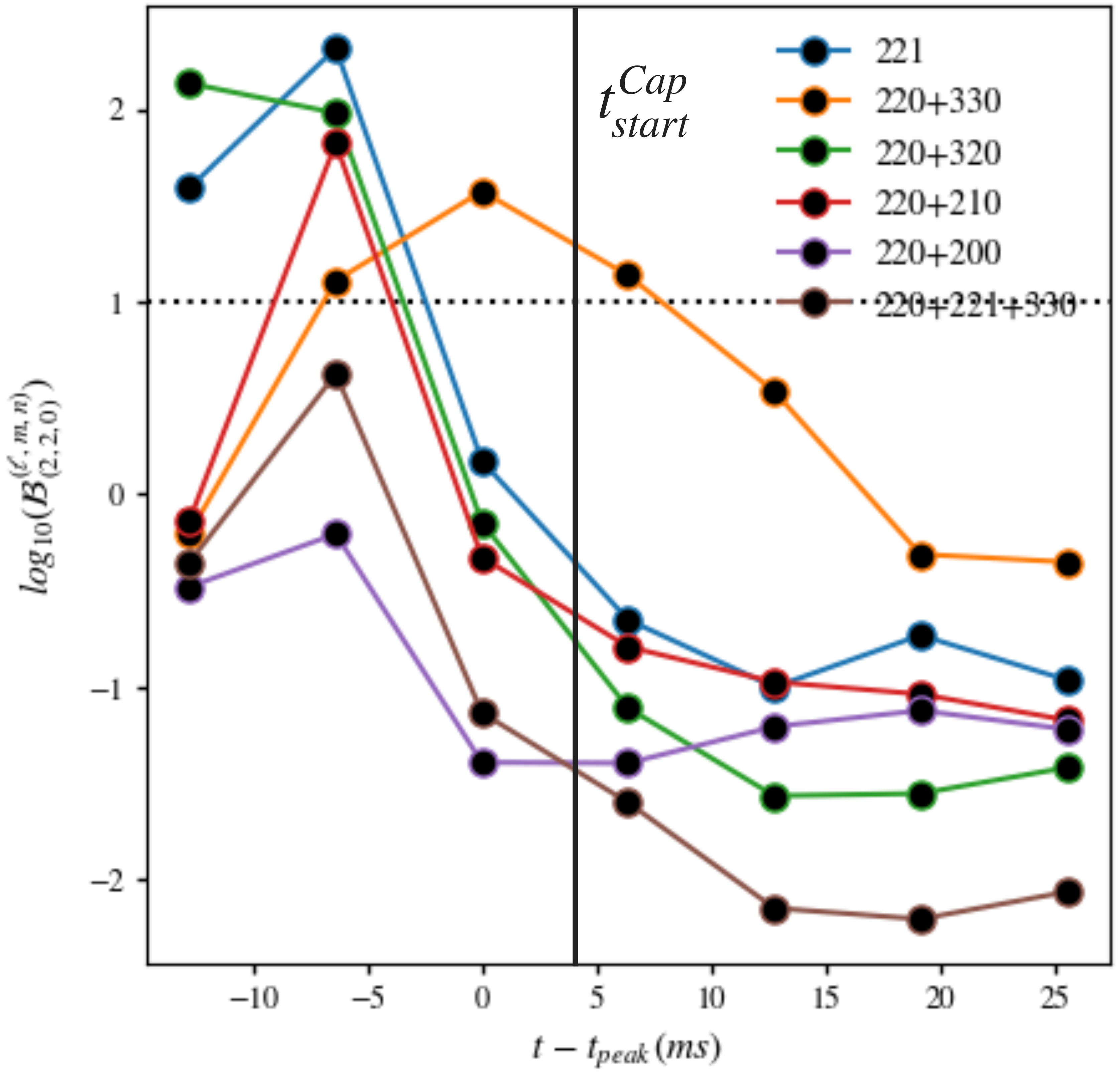
ASSUMPTIONS IMPACT

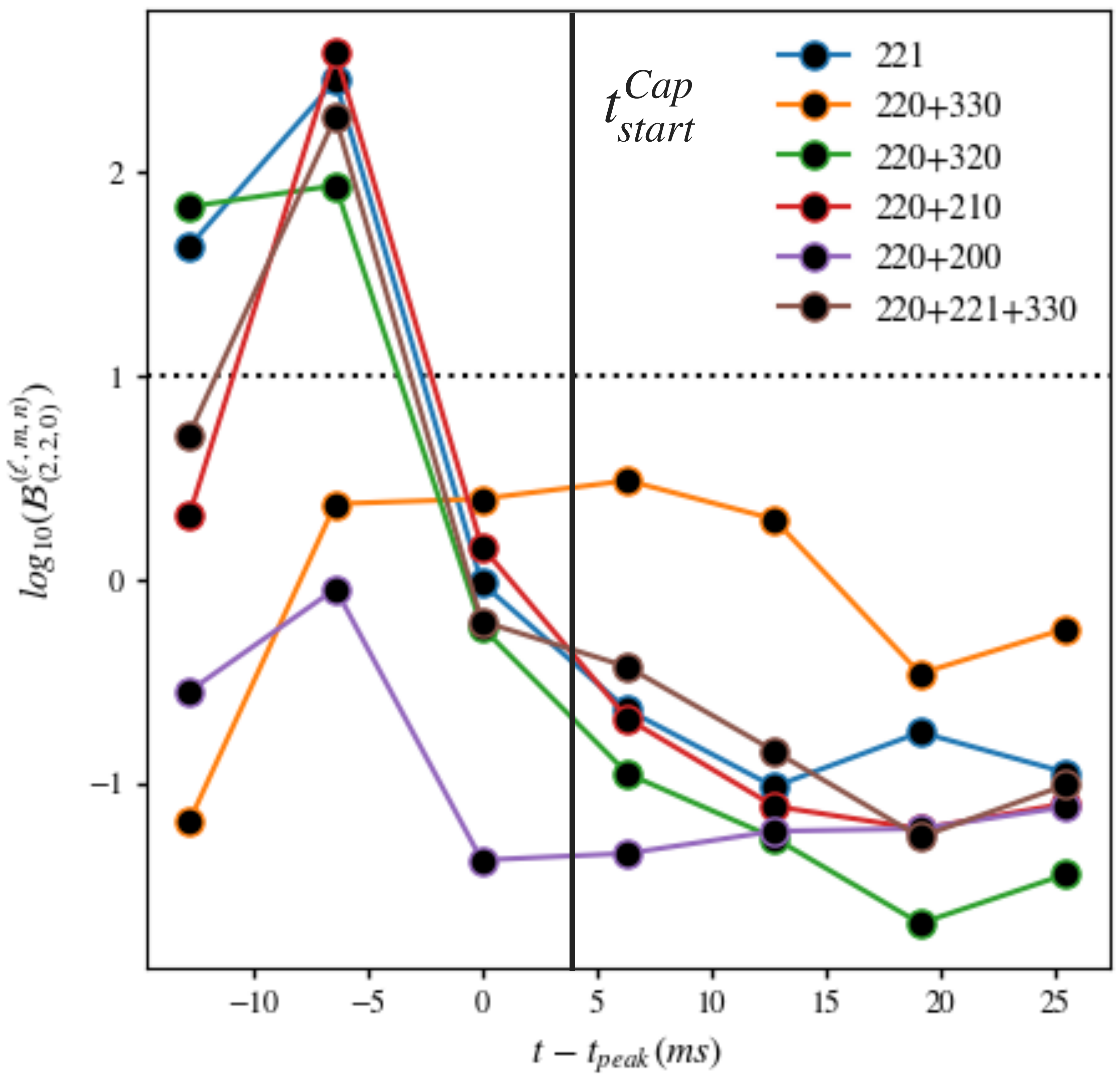
- Impact of the amplitude hierarchy: $\mathcal{A}_{330} < 0.9 \cdot \mathcal{A}_{220}$
- This assumption significantly restricts the parameter space.

ASSUMPTIONS IMPACT

- Impact of the amplitude hierarchy: $\mathcal{A}_{330} < 0.9 \cdot \mathcal{A}_{220}$

- This assumption significantly restricts the parameter space.





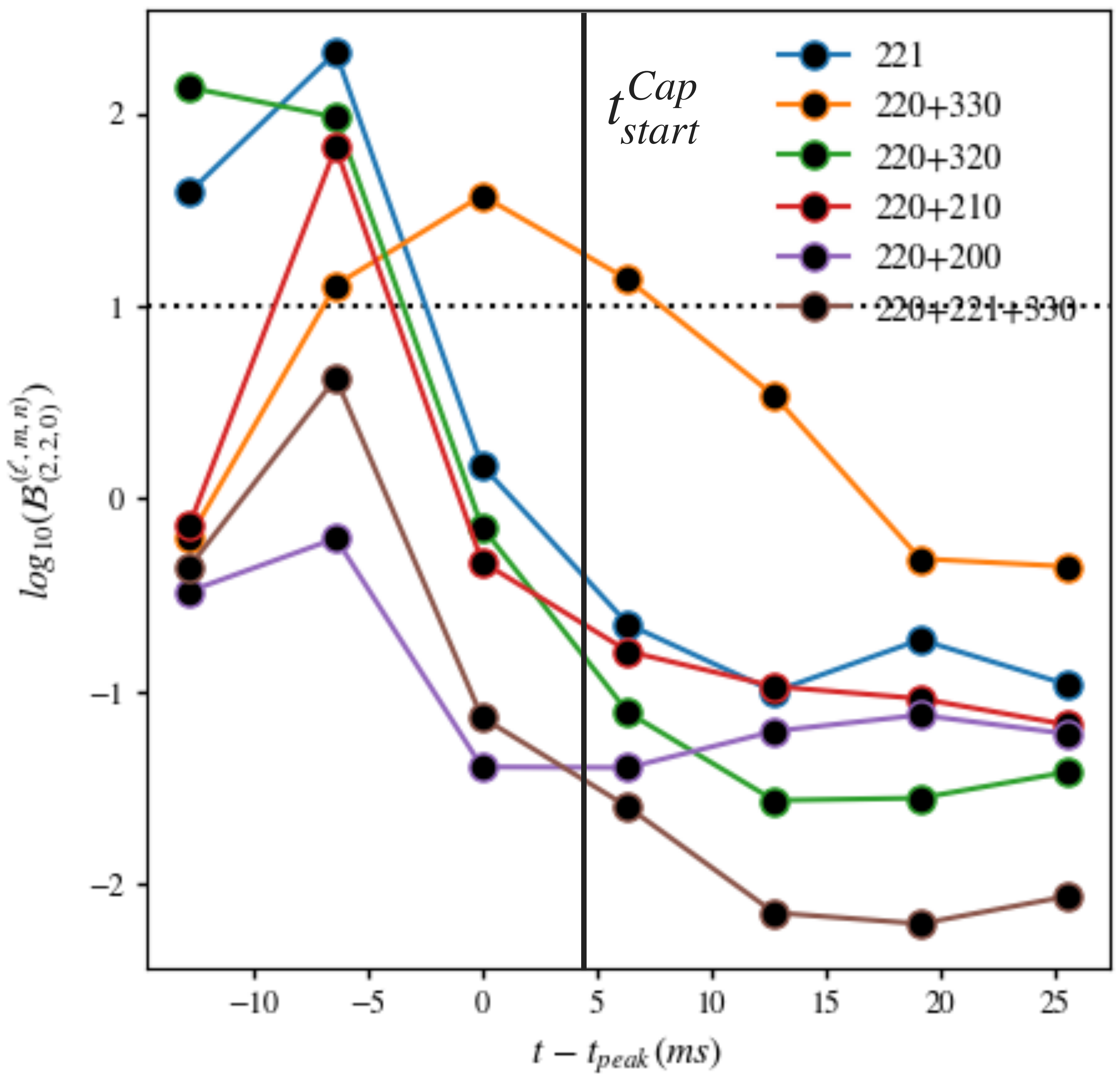
- Without the hierarchy, the result goes away.

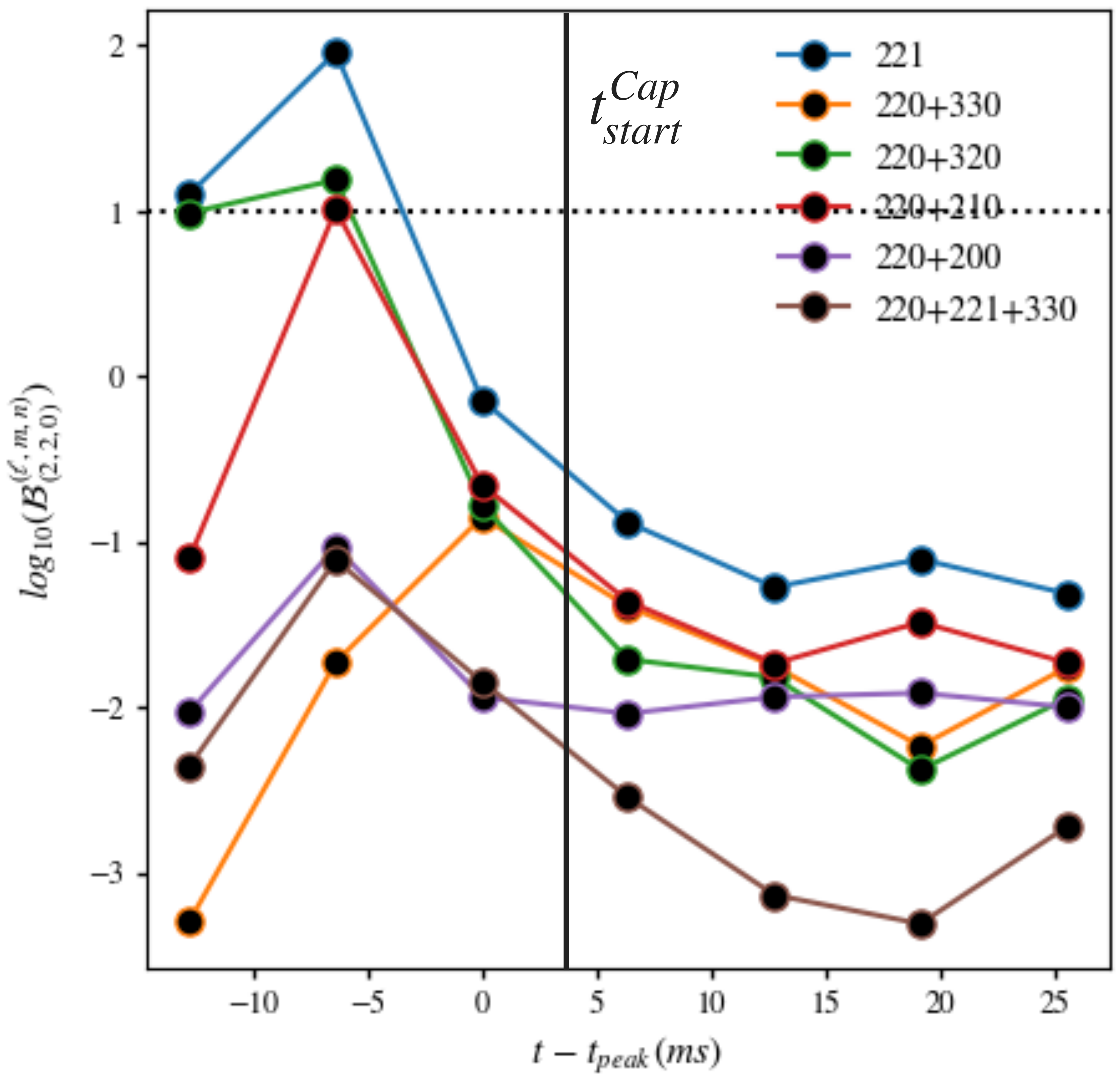
ASSUMPTIONS IMPACT

- Impact of the non-precessing symmetry: $\mathcal{A}^{-}_{\ell mn} = (-1)^{l} \mathcal{A}^{+}_{\ell mn}, \phi^{-}_{\ell mn} = -\phi^{+}_{\ell mn}.$
- This assumption cuts by half the number of amplitudes parameters.

ASSUMPTIONS IMPACT

- Impact of the non-precessing symmetry: $\mathcal{A}^{-}_{\ell mn} = (-1)^{l} \mathcal{A}^{+}_{\ell mn}, \phi^{-}_{\ell mn} = -\phi^{+}_{\ell mn}.$
- This assumption cuts by half the number of amplitudes parameters.





- Without the symmetry, the result goes away.

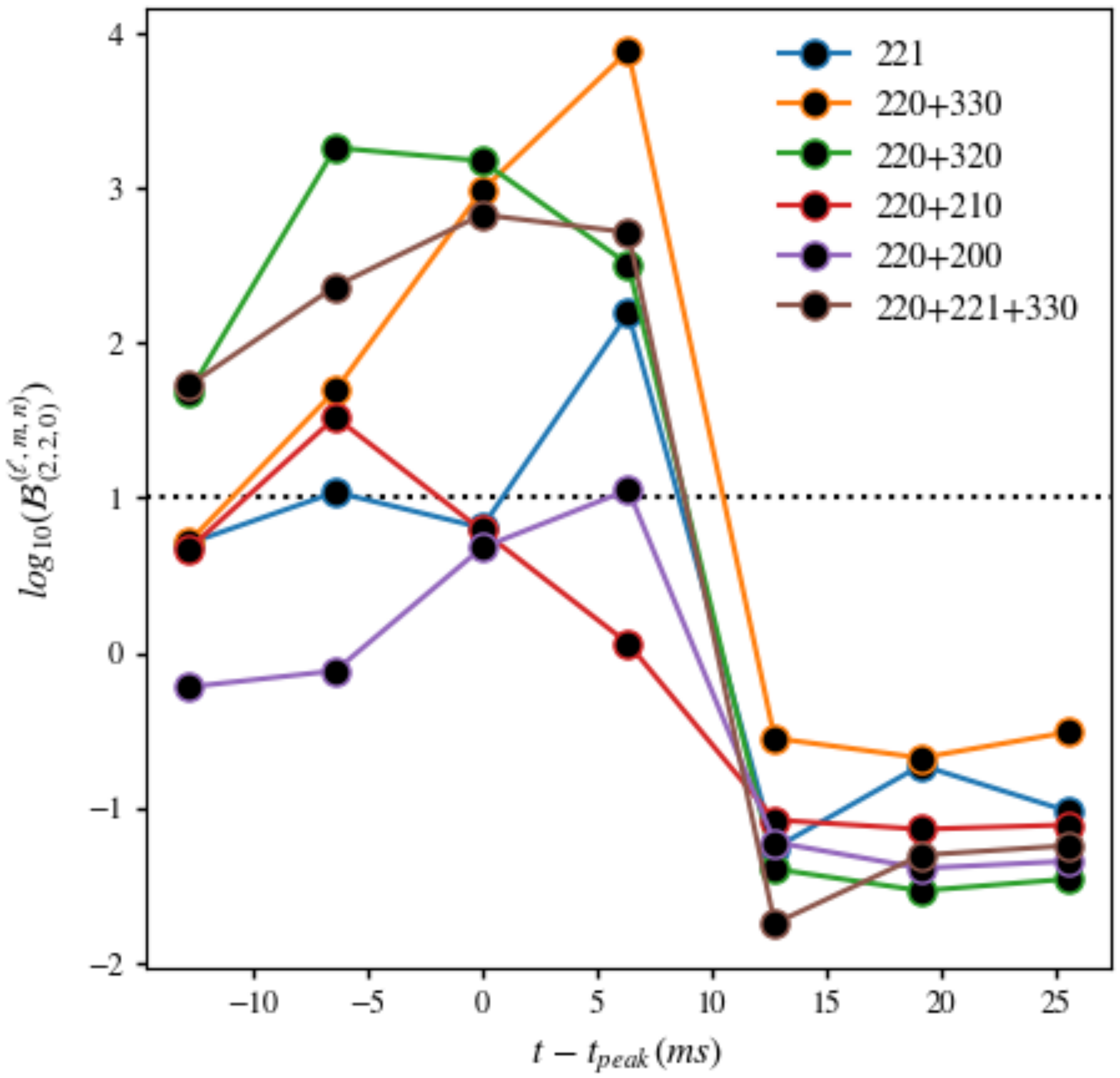
Left Capano | Right Capano with one assumption less

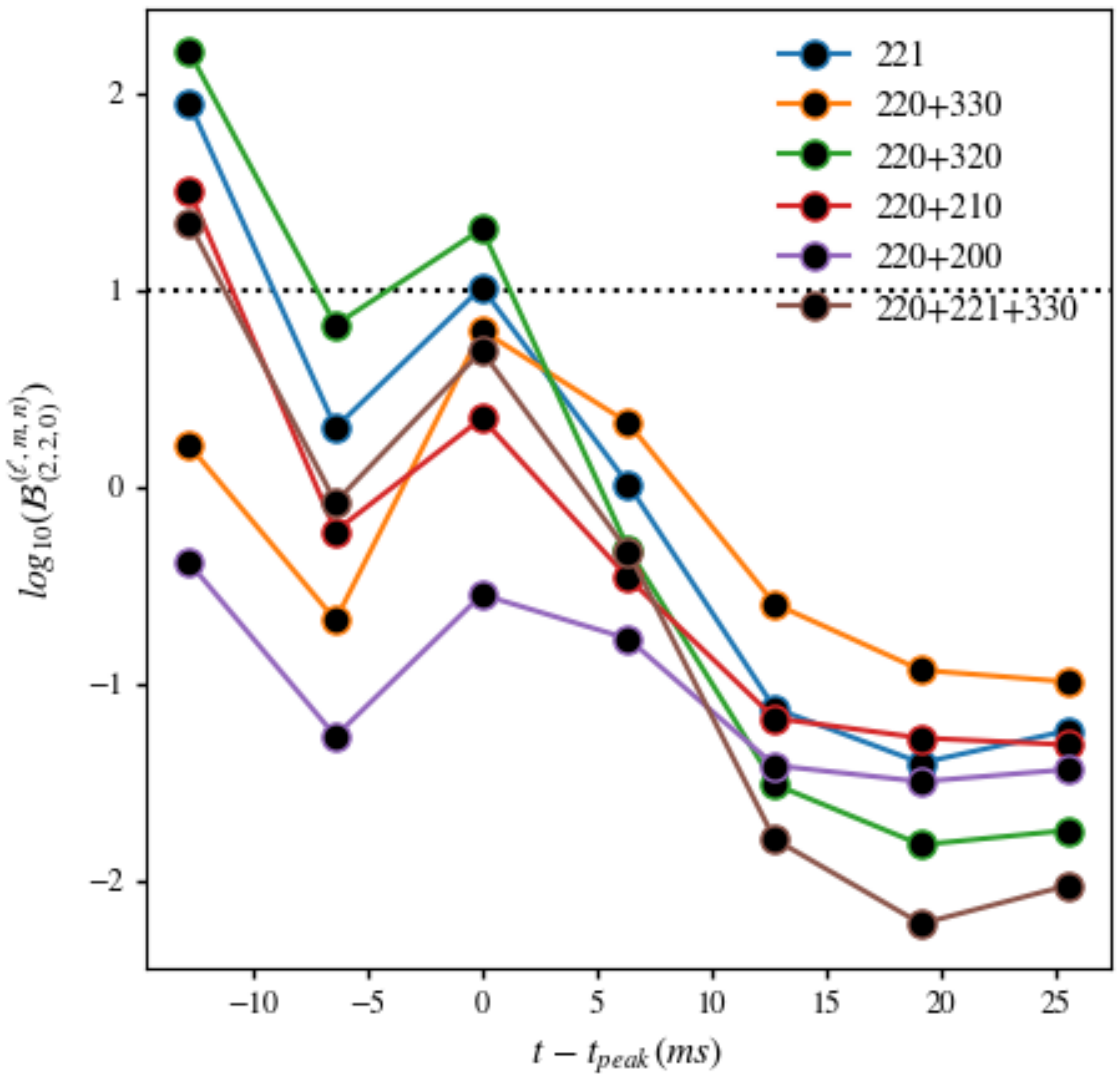
NOISE BACKGROUND EFFECT

- Example of posterior draws from NRSur waveform (w/wo noise on top of signal):

NOISE BACKGROUND EFFECT

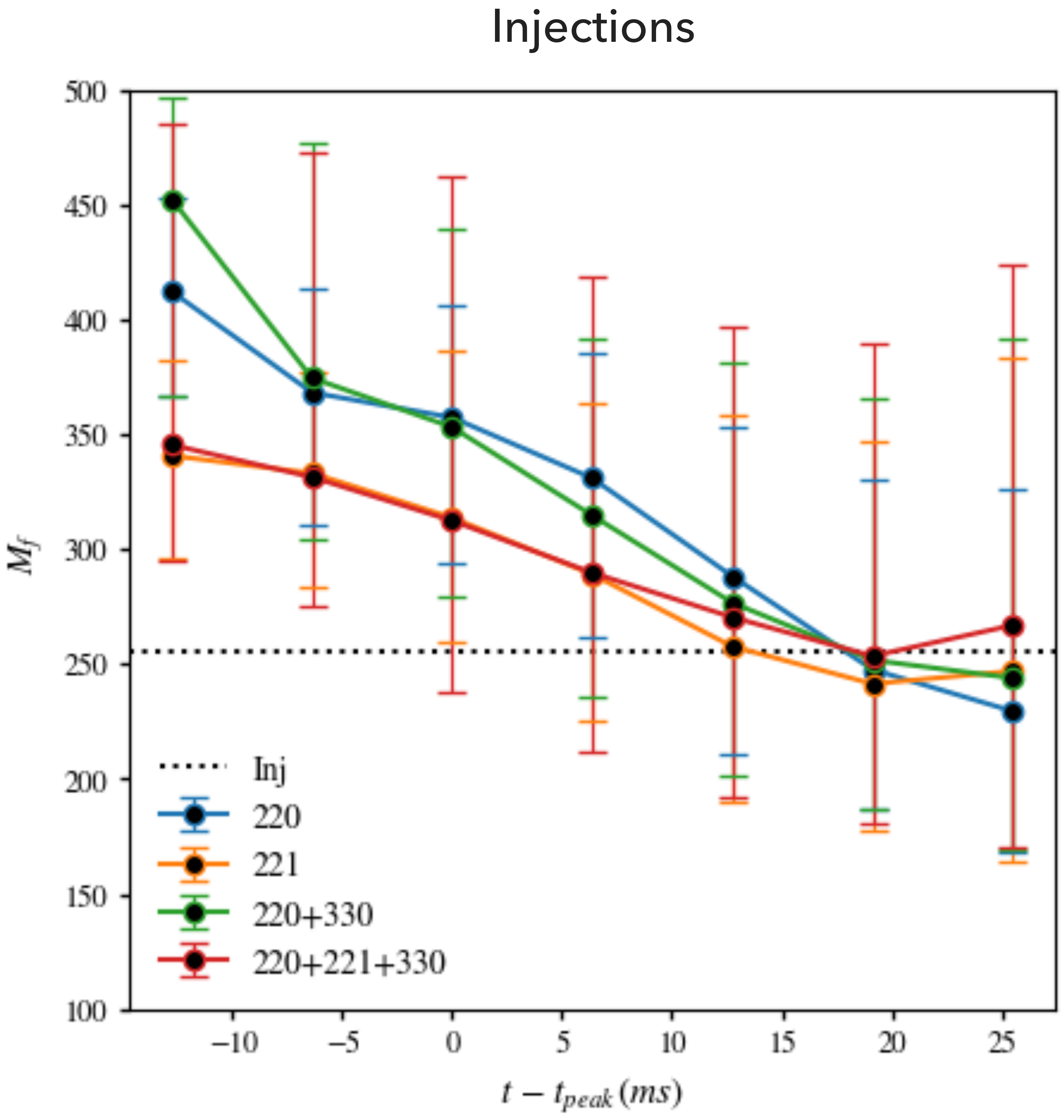
- Example of posterior draws from NRSur waveform (w/wo noise on top of signal):

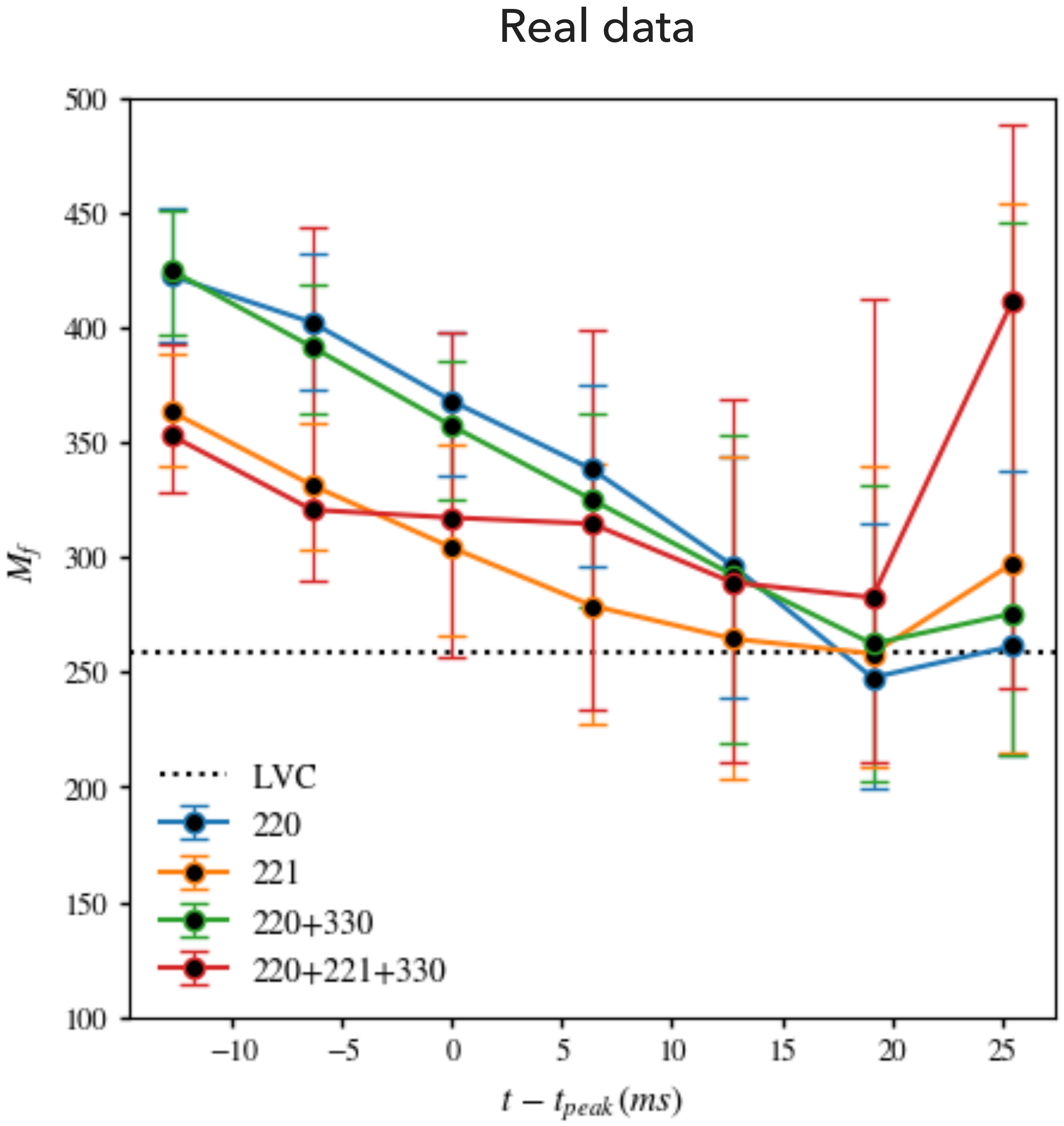




REAL DATA VS INJECTIONS

- Injection of NRSurrogate with parameters consistent with the real signal





Left detector noise | Right zero detector noise

HIGHER MODES IN GW190521

- The "peak" is there at early times, but strongly assumption dependent

HIGHER MODES IN GW190521

- The "peak" is there at early times, but strongly assumption dependent
- Nothing in the region where we trust fundamental modes ($t_{start} \sim 10 - 15\,\mathrm{M_f}$)

HIGHER MODES IN GW190521

- The "peak" is there at early times, but strongly assumption dependent
- Nothing in the region where we trust fundamental modes ($t_{start} \sim 10 - 15\,\mathrm{M_f}$)
- Not robust to detector noise, **but** might depend on injection assumptions

HIGHER MODES IN GW190521

- The "peak" is there at early times, but strongly assumption dependent
- Nothing in the region where we trust fundamental modes ($t_{start} \sim 10 - 15\,\mathrm{M_f}$)
- Not robust to detector noise, **but** might depend on injection assumptions
- Overestimation of the mass strongly indicates an early start time

HIGHER MODES IN GW190521

- The "peak" is there at early times, but strongly assumption dependent
- Nothing in the region where we trust fundamental modes ($t_{start} \sim 10 - 15\,\mathrm{M_f}$)
- Not robust to detector noise, **but** might depend on injection assumptions
- Overestimation of the mass strongly indicates an early start time
- Wise to test GR on events with unknown nature?

LVC, arXiv:2009.01075, Bustillo+, arXiv:2009.01066
Bustillo+, arXiv:2009.05376, Romero-Shaw+, arXiv:2009.04771
Nitz+, arXiv:2010.12558, Gayatry+, arXiv:2009.05461
Gamba+, arXiv:2106.05575 Olsen+, arXiv:2106.13821

Can we say something on horizon physics from ringdown?

HORIZON FROM RINGDOWN

- Standard ringdown emission dominated by light-ring physics.

Cardoso+, arXiv:1602.07309

HORIZON FROM RINGDOWN

- Standard ringdown emission dominated by light-ring physics.
- Might probe the horizon through some exotic or not-fully understood mechanism (not including echoes):

HORIZON FROM RINGDOWN

- Standard ringdown emission dominated by light-ring physics.
- Might probe the horizon through some exotic or not-fully understood mechanism (not including echoes):
  - QNM-horizon multipoles correlations
    - Also shear modes, and during inspiral
    - Measurements at infinity as indicators of horizon dynamics?

Prasad+, arXiv:2003.06215
Gupta+, arXiv:1801.07048
Mourier+, arXiv:2010.15186

HORIZON FROM RINGDOWN

- Standard ringdown emission dominated by light-ring physics.
- Might probe the horizon through some exotic or not-fully understood mechanism (not including echoes):
  - QNM-horizon multipoles correlations
  - Quantum horizon modifications
    - Horizon area quantisation

$$A_H^Q = \alpha l_P^2 N$$

$$\omega = \frac{|\Delta M|}{\hbar} = \frac{\alpha\, \Delta N}{32\pi M}$$

Bekenstein, Lett. Nuovo Cim. (1974)
Mukhanov, JETP Lett. (1986)

HORIZON FROM RINGDOWN

- Standard ringdown emission dominated by light-ring physics.
- Might probe the horizon through some exotic or not-fully understood mechanism (not including echoes):
  - QNM-horizon multipoles correlations
  - Quantum horizon modifications
    - Horizon area quantisation
      - Ringdown (long-range) modifications — Foit, Kleban, CQG (2019)
      - Echoes and tidal heating — Cardoso+, CQG (2019) Coates+, arXiv:2201.03245 Agullo+ PRL (2021)

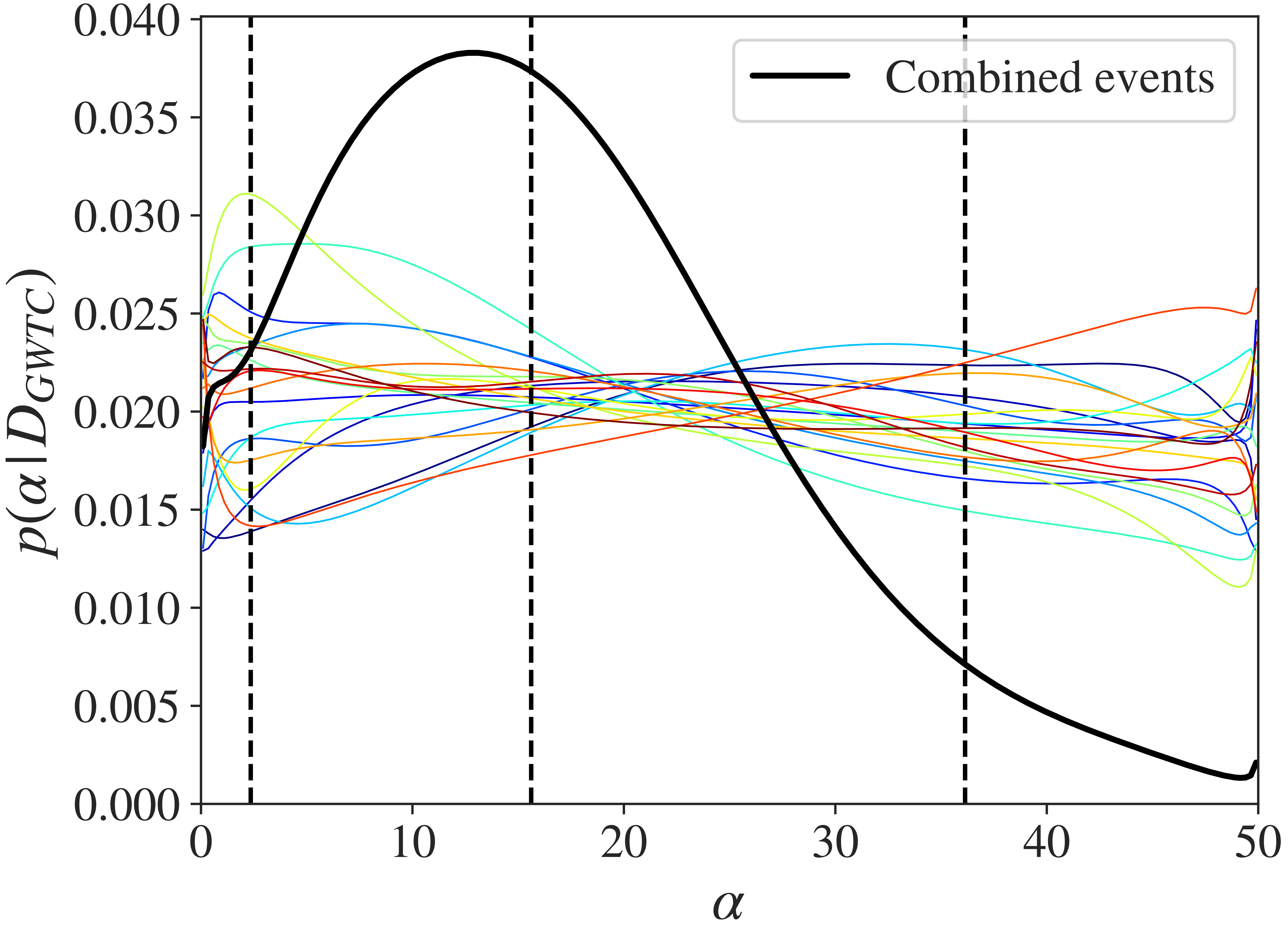
HORIZON FROM RINGDOWN

- Standard ringdown emission dominated by light-ring physics.
- Might probe the horizon through some exotic or not-fully understood mechanism (not including echoes):
  - QNM-horizon multipoles correlations
  - Quantum horizon modifications
    - Horizon area quantisation
      - Ringdown (long-range) modifications — Testable by LIGO-Virgo-Kagra — Foit, Kleban, CQG (2019)
      - Echoes and tidal heating — Cardoso+, CQG (2019) Coates+, arXiv:2201.03245 Agullo+ PRL (2021)

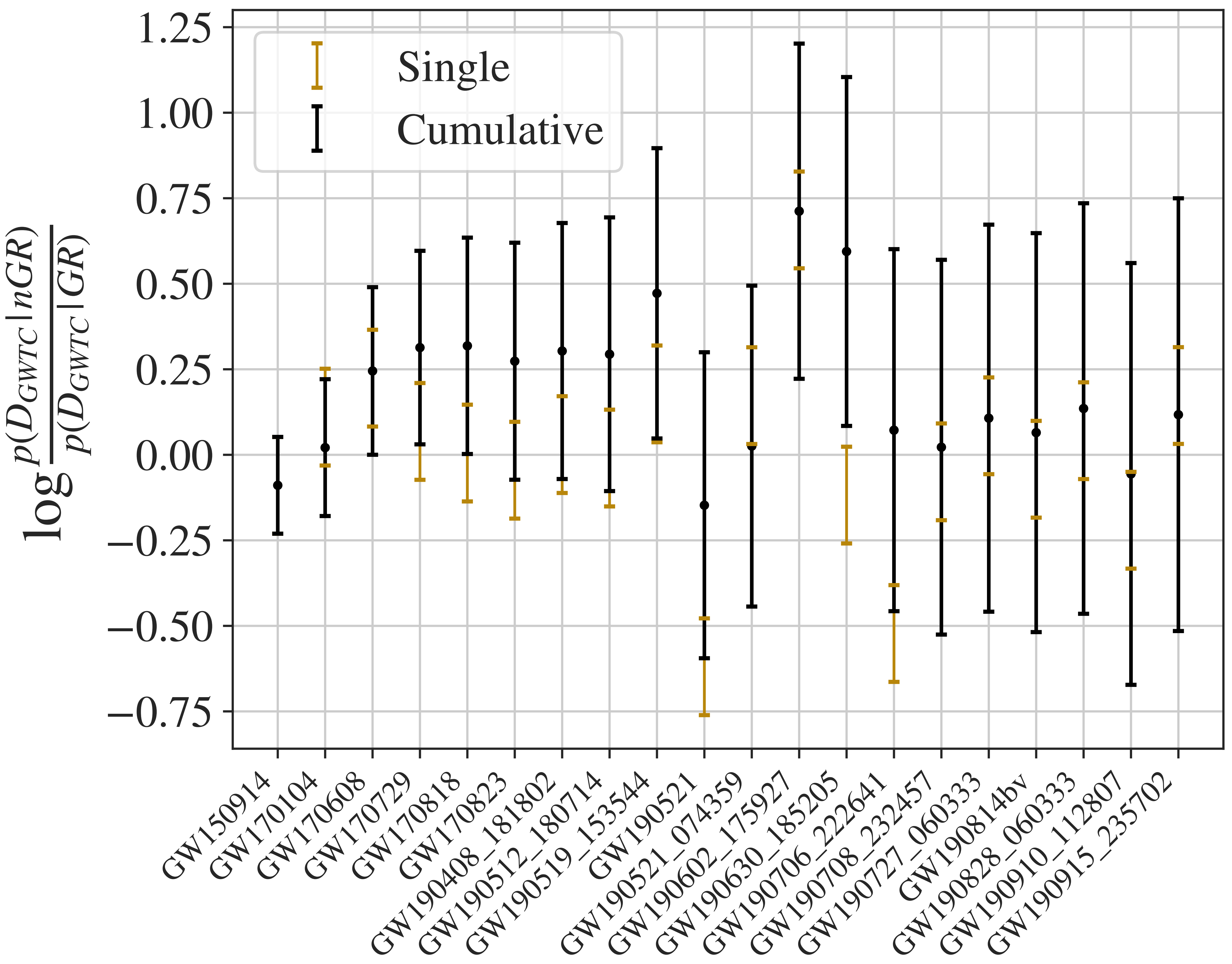
GWTC-2 ANALYSIS

- No evidence for (or against) area quantisation signatures.

$15.6^{+20.5}_{-13.3}$



$\log B^{nGR}_{GR} = 0.1 \pm 0.6$

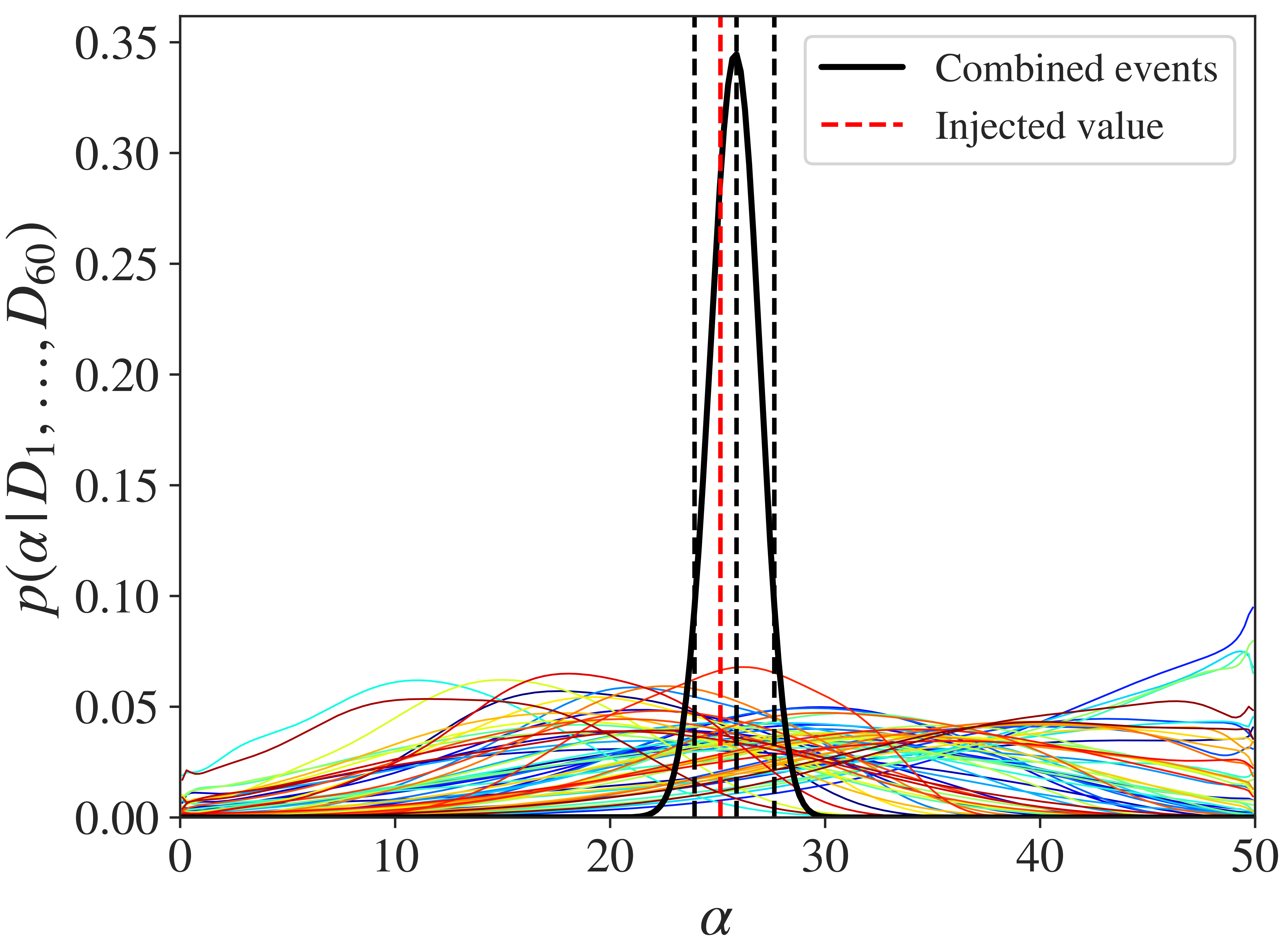


QUANTUM BLACK HOLES POPULATION

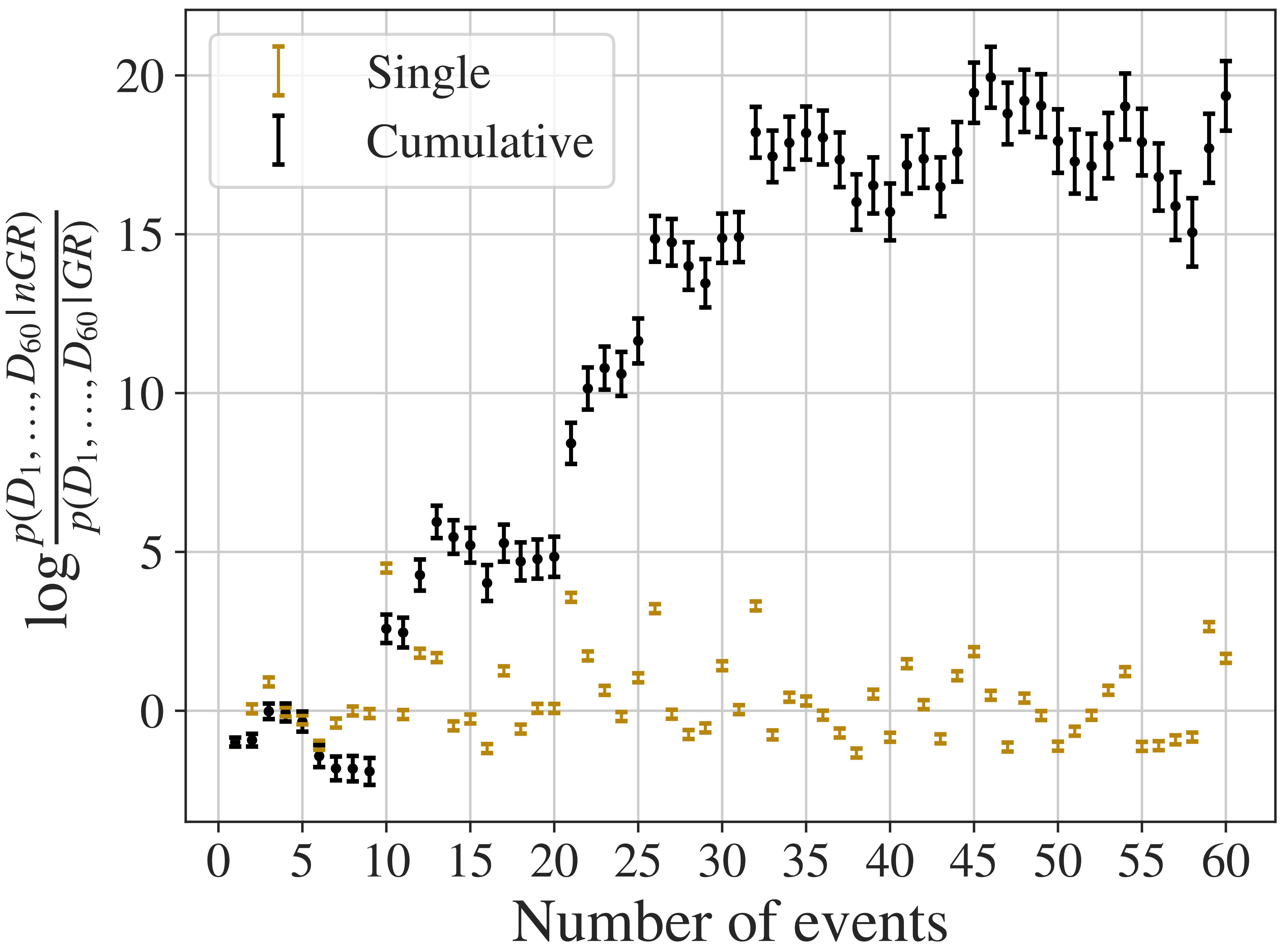
Bekenstein value

≈ 25.1

$25.7^{+2.0}_{-1.8}$



$\log B^{nGR}_{GR} = 19.4 \pm 1.1$



HORIZON FROM RINGDOWN

- Standard ringdown emission dominated by light-ring physics.
- Might probe the horizon through some exotic or not-fully understood mechanism (not including echoes):
    - QNM-horizon multipoles correlations
    - Quantum horizon modifications
        - Horizon area quantisation
        - Membrane paradigm/braneworld

Maggio+, arXiv:2006.14628
Mishra+, arXiv:2106.05558
Chakraborty+, arXiv:2202.09111

HORIZON FROM RINGDOWN

- Standard ringdown emission dominated by light-ring physics.
- Might probe the horizon through some exotic or not-fully understood mechanism (not including echoes):
  - QNM-horizon multipoles correlations
  - Quantum horizon modifications
  - Near-extremal BHs

Rates in GW?

HORIZON FROM RINGDOWN

- Standard ringdown emission dominated by light-ring physics.
- Might probe the horizon through some exotic or not-fully understood mechanism (not including echoes):
  - QNM-horizon multipoles correlations
  - Quantum horizon modifications
  - Near-extremal BHs
  - Spectral instabilities?

HORIZON FROM RINGDOWN

- Jaramillo et al.:

Jaramillo+, arXiv:2004.06434

HORIZON FROM RINGDOWN

- Jaramillo et al.:
  - Hyperboloidal approach to QNM computations

HORIZON FROM RINGDOWN

- Jaramillo et al.:
  - Hyperboloidal approach to QNM computations
  - Eigenvalue problem of a non-selfadjoint operator

HORIZON FROM RINGDOWN

- Jaramillo et al.:
  - Hyperboloidal approach to QNM computations
  - Eigenvalue problem of a non-selfadjoint operator
  - Pseudo-spectrum of the QNM operator (eigenvalues of the perturbed operator)

$$V_{(\epsilon)} = V_{BH} + \epsilon \cdot \delta V$$

$$\omega_{(\epsilon)} \neq \omega_{BH} + \epsilon \cdot \delta\omega$$

See also:

Jaramillo+, arXiv:2105.03451
Destounis+, arXiv:2107.09673
Gasperin+, arXiv:2107.12865
Cheung+, arXiv:2111.05415

Nollert, PRD 53, 8 (1996)
Barausse, Cardoso, Pani, arXiv:1404.7149

HORIZON FROM RINGDOWN

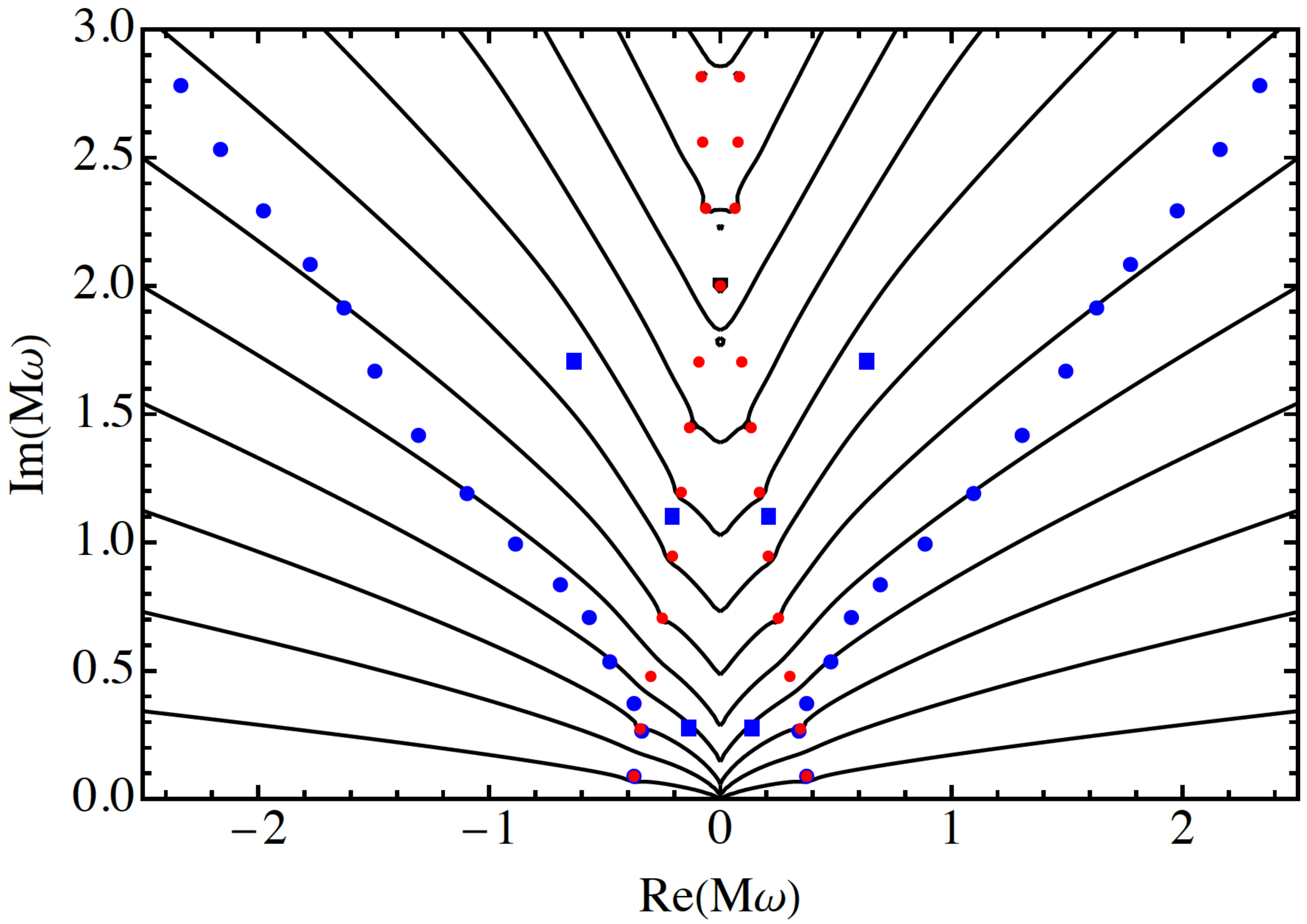
High-freq. perturbations imply a migration of overtones away from unperturbed values

BH

ϵ−BH

$$\delta V = cos(2\pi k)$$

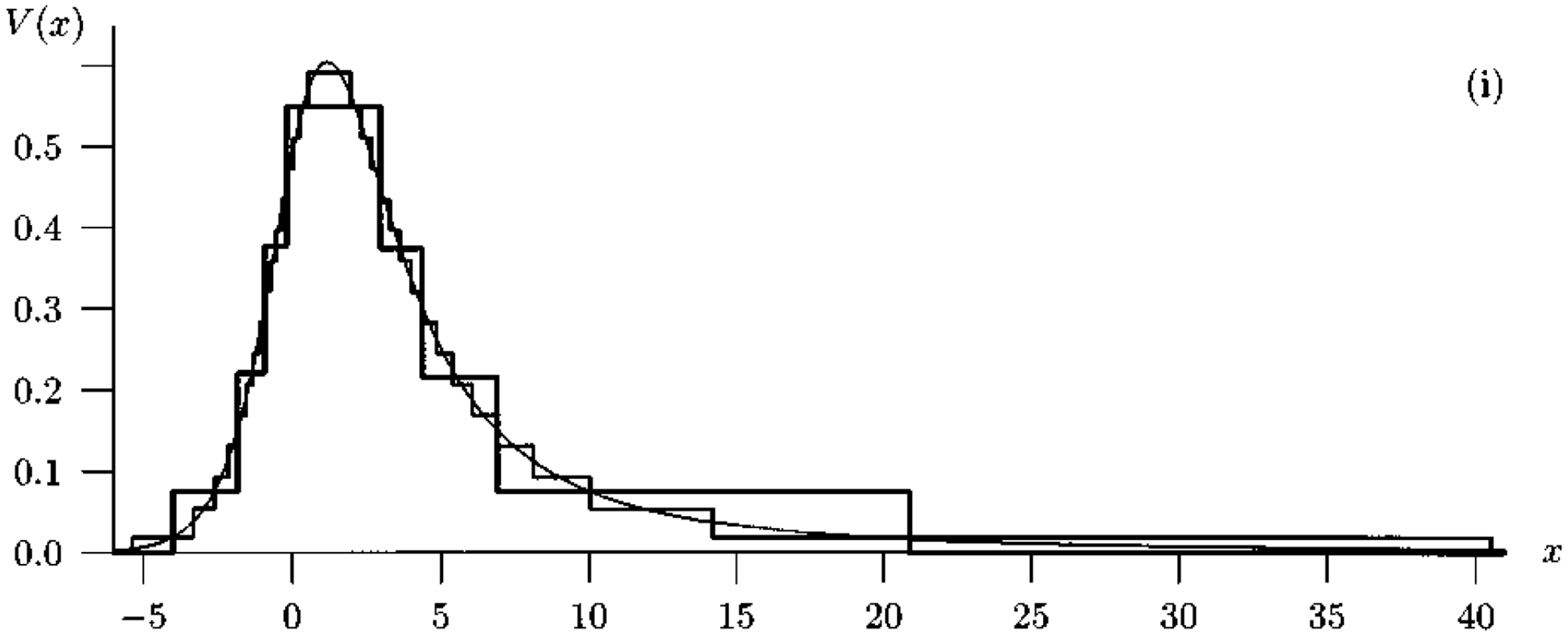
$$\epsilon = 10^{-3}\,,\ k = 10$$



Jaramillo+, arXiv:2004.06434

HORIZON FROM RINGDOWN

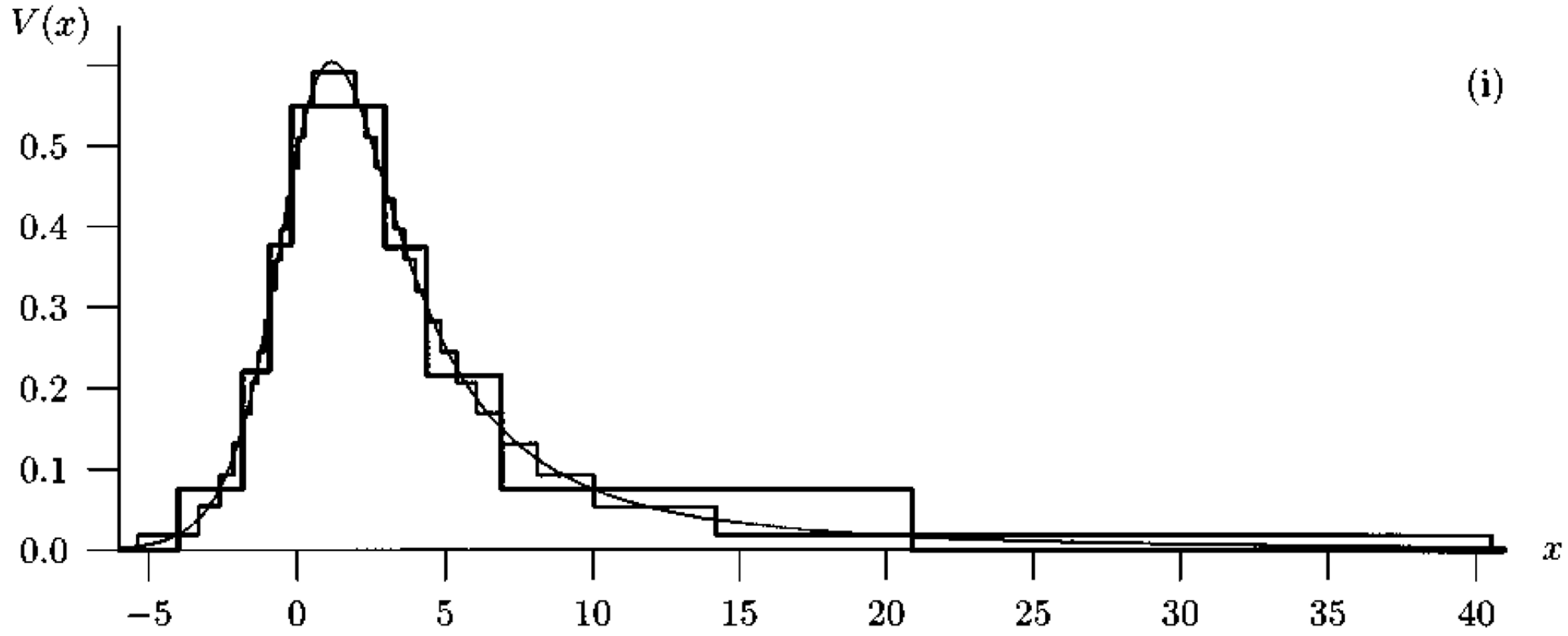
- Not new (but much better understood now):
    - Nollert showed that discretisation of the potential leads to the same phenomenon.



Nollert, PRD 53, 8 (1996)

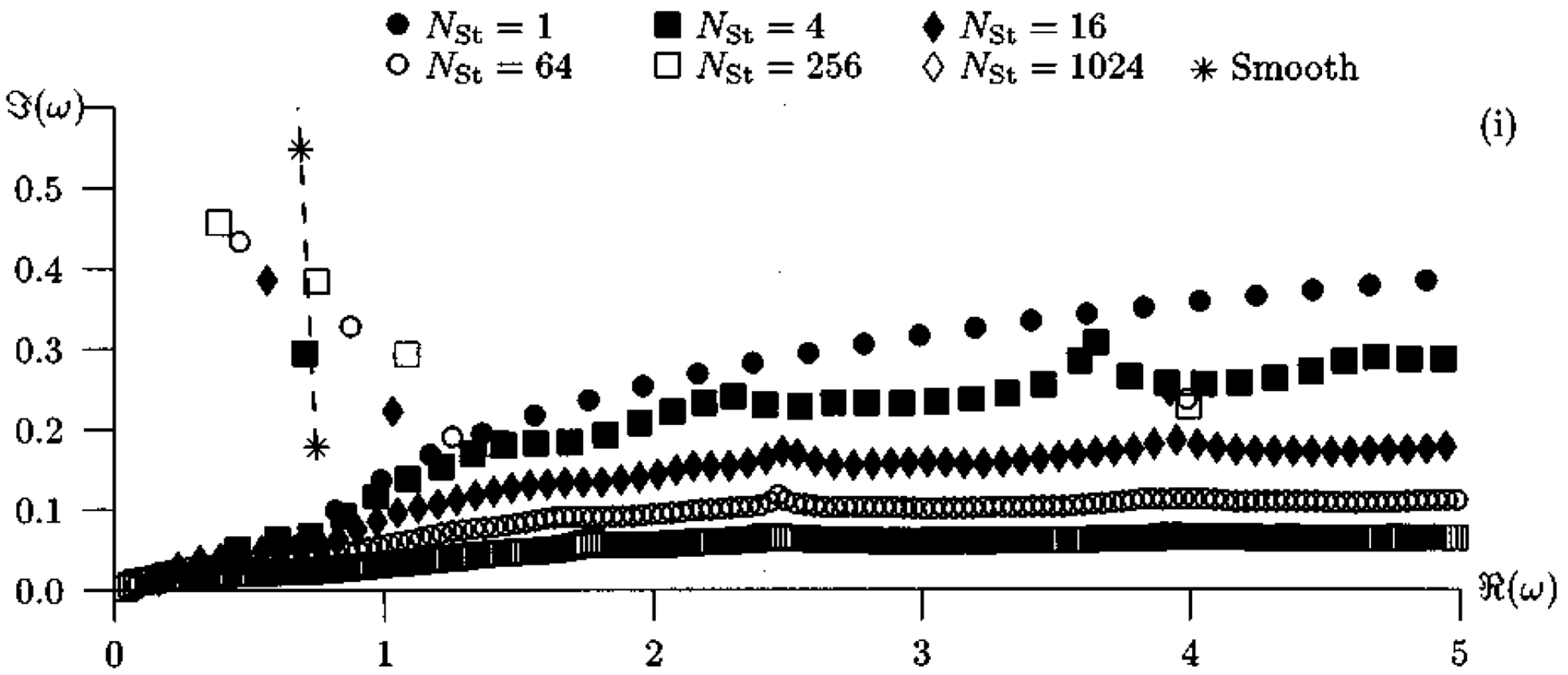
HORIZON FROM RINGDOWN

- Not new (but much better understood now):
  - Nollert showed that discretisation of the potential leads to the same phenomenon.
  - Does not go smoothly to Sch. with increasing N



HORIZON FROM RINGDOWN

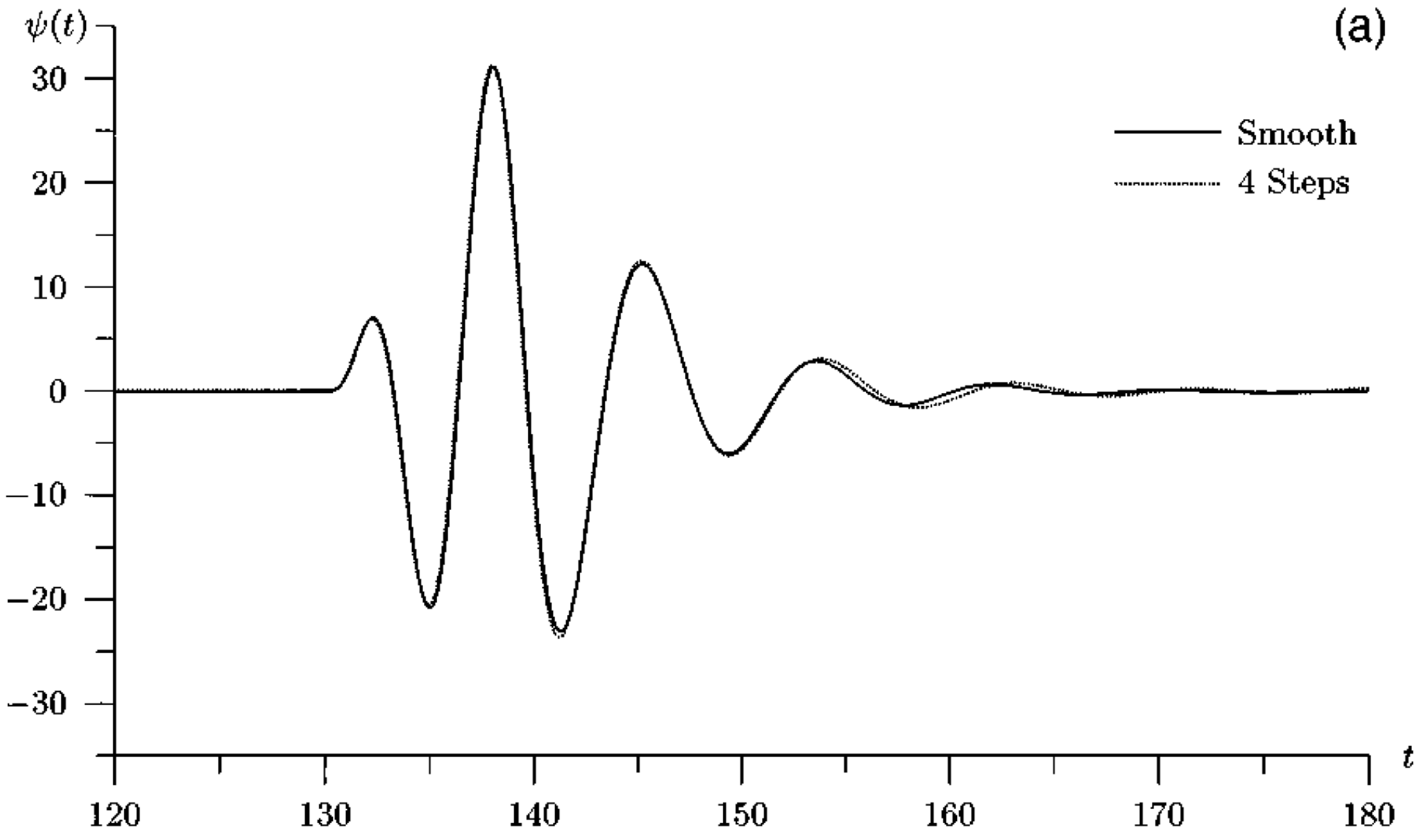
- Not new (but much better understood now):
  - Nollert showed that discretisation of the potential leads to the same phenomenon.
  - Does not go smoothly to Sch. with increasing N
  - Spectrum unstable



 Nollert, PRD 53, 8 (1996)

HORIZON FROM RINGDOWN

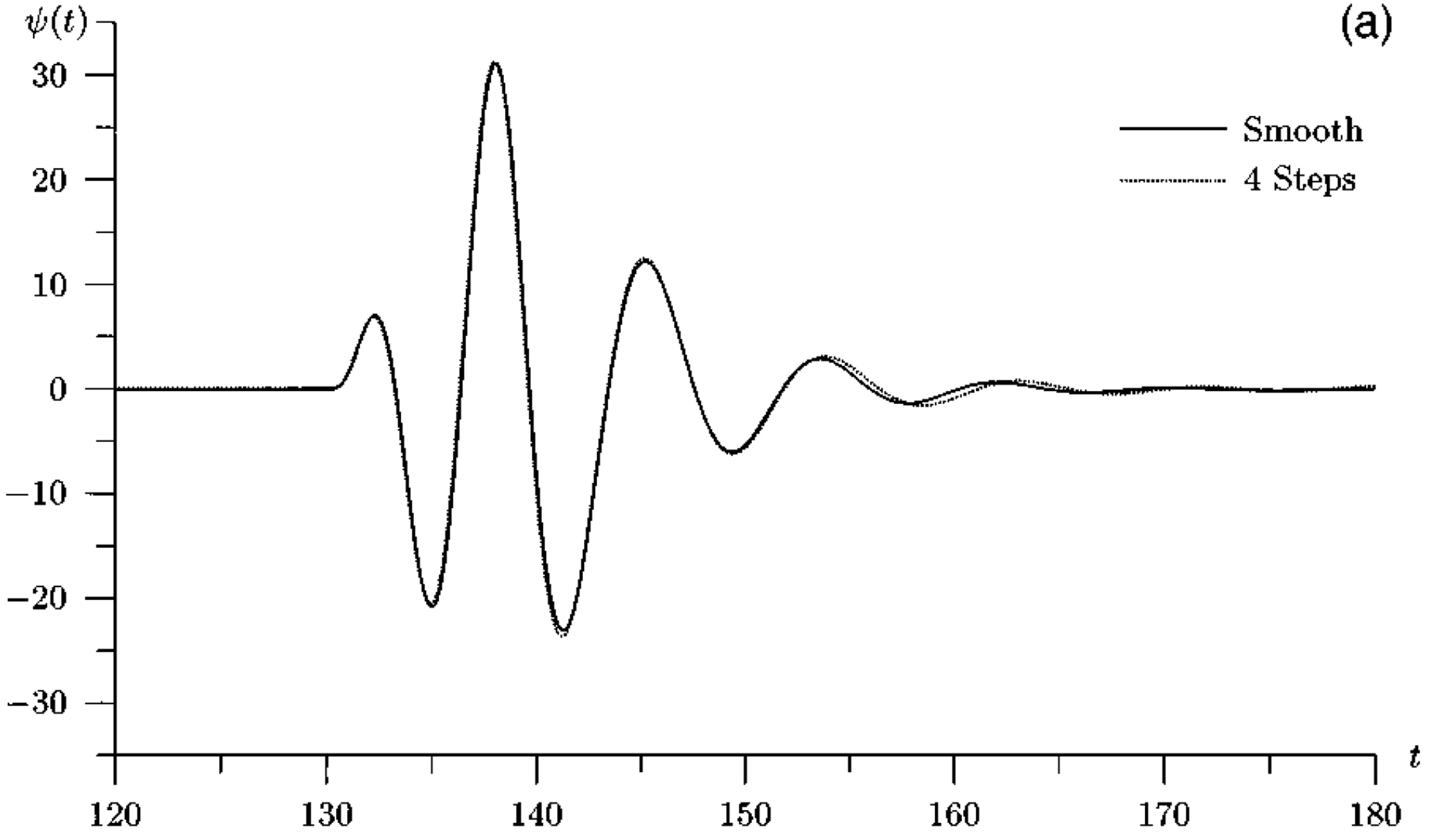
- But does not imply a change in the time-evolution!



 Nollert, PRD 53, 8 (1996)

HORIZON FROM RINGDOWN

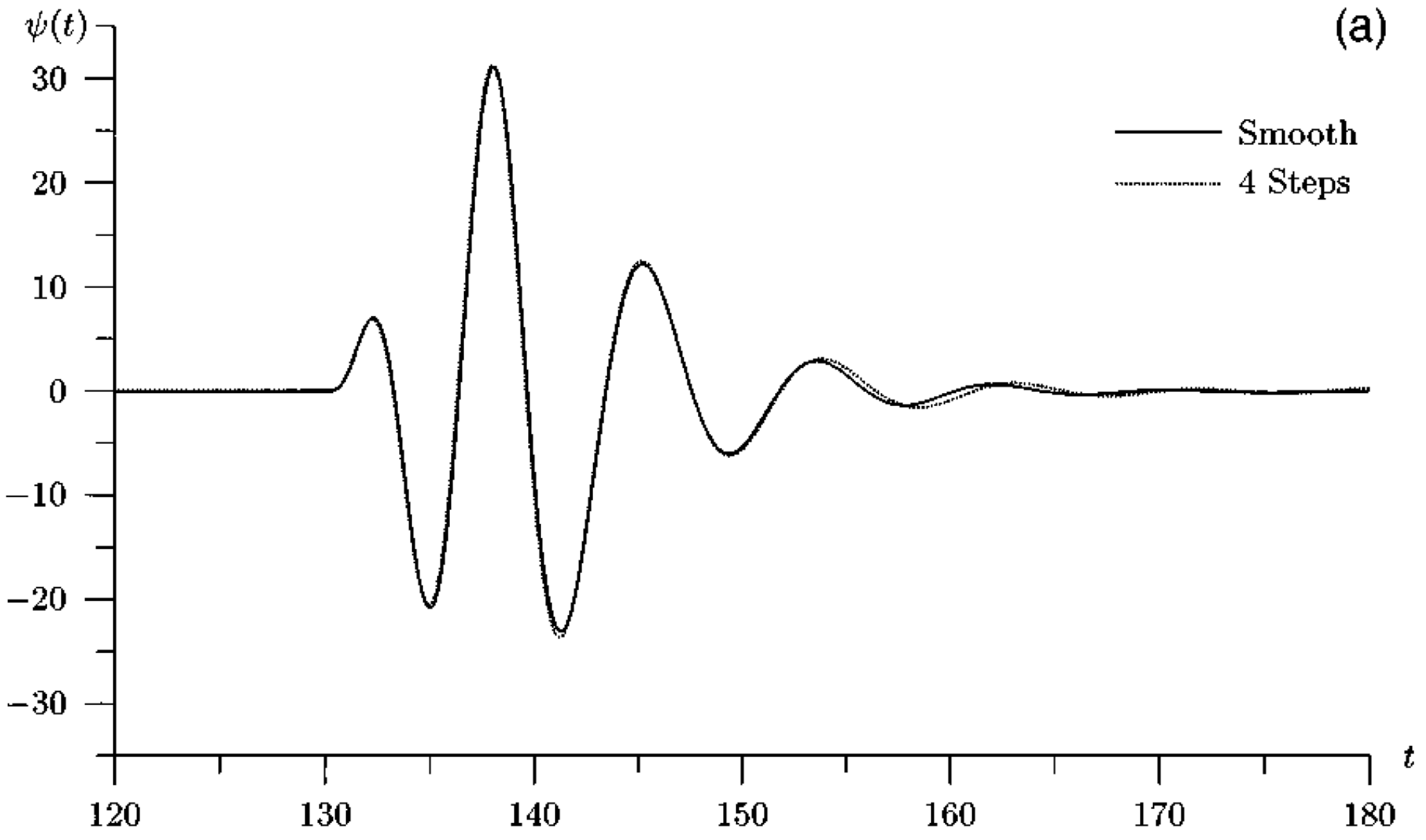
- But does not imply a change in the time-evolution!
- "Memory" effect: time-evolution dominated by unperturbed BH QNMs



 Barausse+, PRD 89 (2014) 104059 Nollert, PRD 53, 8 (1996)

HORIZON FROM RINGDOWN

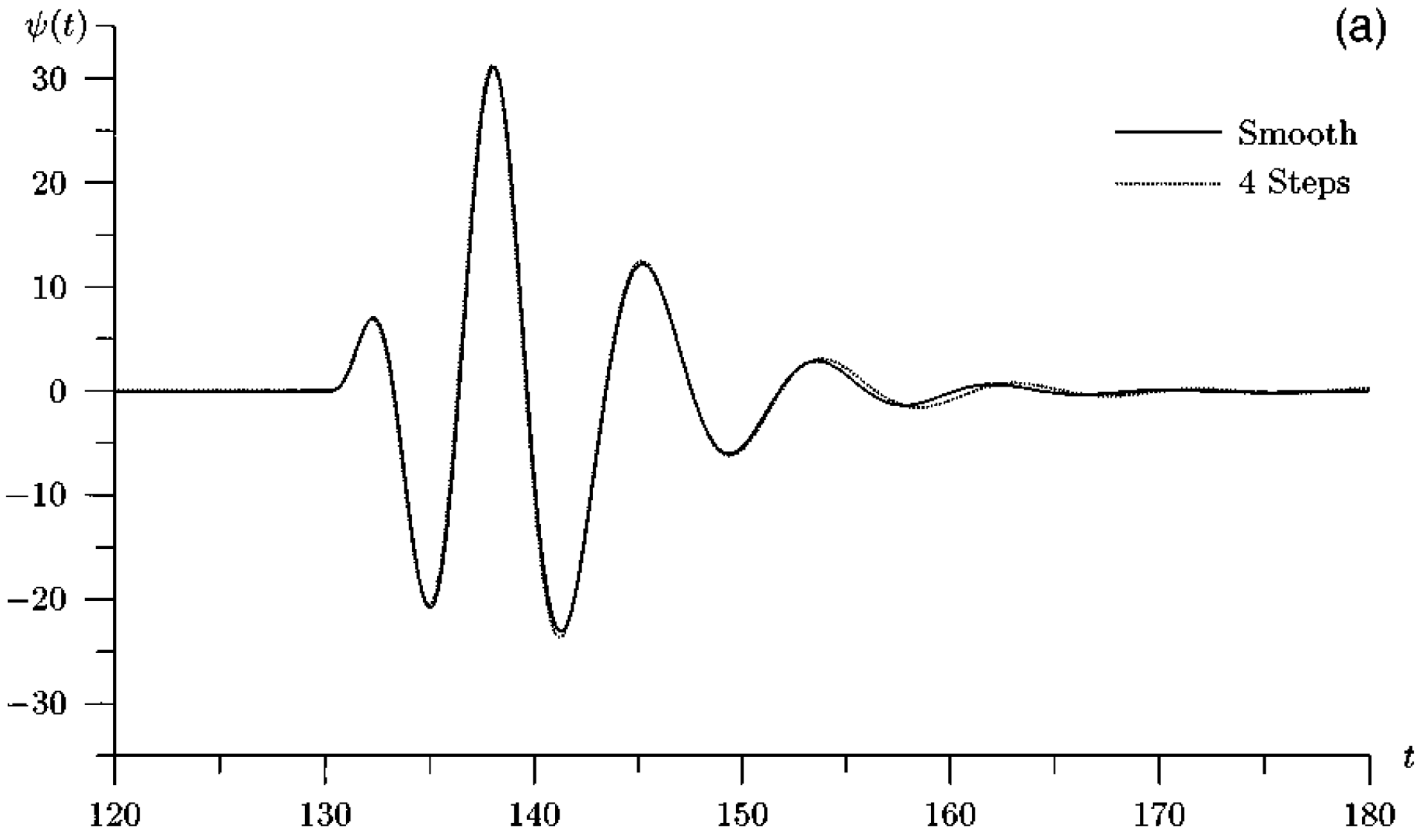
- But does not imply a change in the time-evolution!
- "Memory" effect: time-evolution dominated by unperturbed BH QNMs
- ϵ-BH QNMs dominate only at late times. Contribute $\sim 10^{-3}$ to E_{tot}



 Barausse+, PRD 89 (2014) 104059 Nollert, PRD 53, 8 (1996)

HORIZON FROM RINGDOWN

- But does not imply a change in the time-evolution!
- "Memory" effect: time-evolution dominated by unperturbed BH QNMs
- ϵ-BH QNMs dominate only at late times. Contribute $\sim 10^{-3}$ to E_{tot}
- QNMS exponentially sensitive to far-away bumps in V, while time-evolution is not.



 Barausse+, PRD 89 (2014) 104059 Nollert, PRD 53, 8 (1996)

HORIZON FROM RINGDOWN

- Might be a *"probe into fundamental high-frequency spacetime fluctuations at the Planck scale"* or in general to high-freq contributions (incl. horizon)

HORIZON FROM RINGDOWN

- Might be a *"probe into fundamental high-frequency spacetime fluctuations at the Planck scale"* or in general to high-freq contributions (incl. horizon)

- Need to quantify the contributed energy under physical perturbations

 Jaramillo+, arXiv:2004.06434

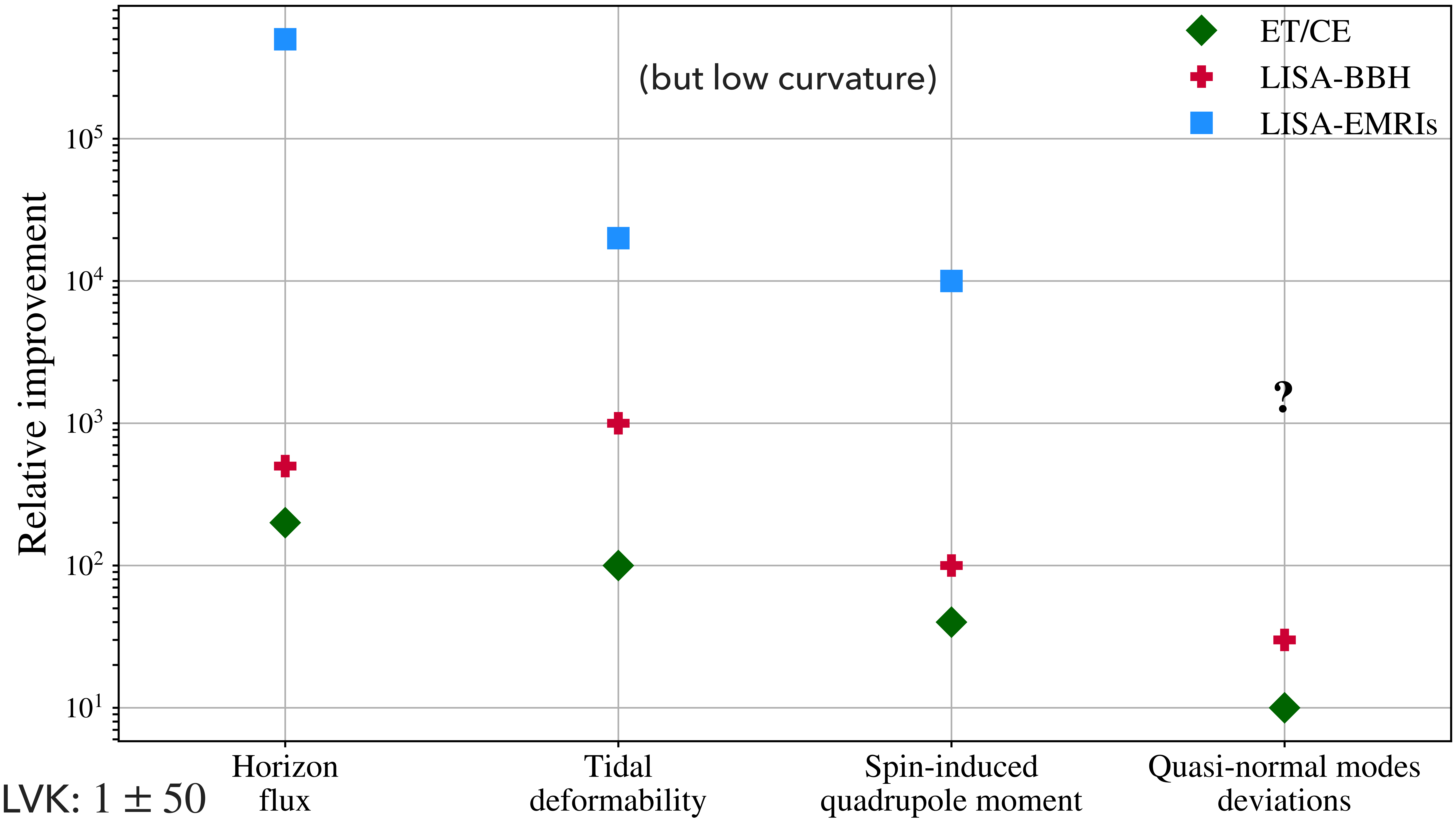
HORIZON FROM RINGDOWN

- Might be a *"probe into fundamental high-frequency spacetime fluctuations at the Planck scale"* or in general to high-freq contributions (incl. horizon)
- Need to quantify the contributed energy under physical perturbations
- Need to account for realistic data-analysis settings (unknown mass, spin, amplitudes, …)

HORIZON FROM RINGDOWN

- Might be a "*probe into fundamental high-frequency spacetime fluctuations at the Planck scale*" or in general to high-freq contributions (incl. horizon)
- Need to quantify the contributed energy under physical perturbations
- Need to account for realistic data-analysis settings (unknown mass, spin, amplitudes, …)
- Disentangle from not-exactly-Kerr potential for realistic observations?

SPACE SUPREMACY



LVK: 1 ± 50

Babak+, arXiv:1703.09722 Cardoso-Pani, arXiv:1904.05363 Datta+, arXiv:1910.0784 Maselli+, arXiv:1910.12893

CONCLUSIONS AND PROSPECTS

- **Black hole perturbations** have unquestionably transitioned from a mathematical problem to an **observational reality**
- The analysis of **gravitational** black holes **spectra** is a powerful tool to:
  - Test our current **gravity paradigm**
  - Investigate the **nature** of dark **compact objects**
  - Constrain **black holes** charges
  - Search for signs of **new physics**
  - … infer **horizon** properties?

Credits to: Jani, Ghonge