CONSTRAINTS ON MODIFIED THEORIES OF GRAVITY FROM THE LATEST LIGO-VIRGO RINGDOWN OBSERVATIONS

Phys. Rev. D 103, 124043 (2021)

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Lomonosov Conference

August 2021

INFN

IN SUPREMÆ DIGNITATIS 1343

UNIVERSITÀ DI PISA

CONTENTS

- Current status of **Observational black hole spectroscopy**;
- The "**So what?**" test
- Beyond the LVC parametrisation: **ParSpec**
- ParSpec constraints on **modified gravity** from black holes spectra
- **Comparison** to other **experimental bounds**
- A **non-perturbative** beyond-Kerr case: Kerr-Newman black holes

BLACK HOLE RINGDOWN

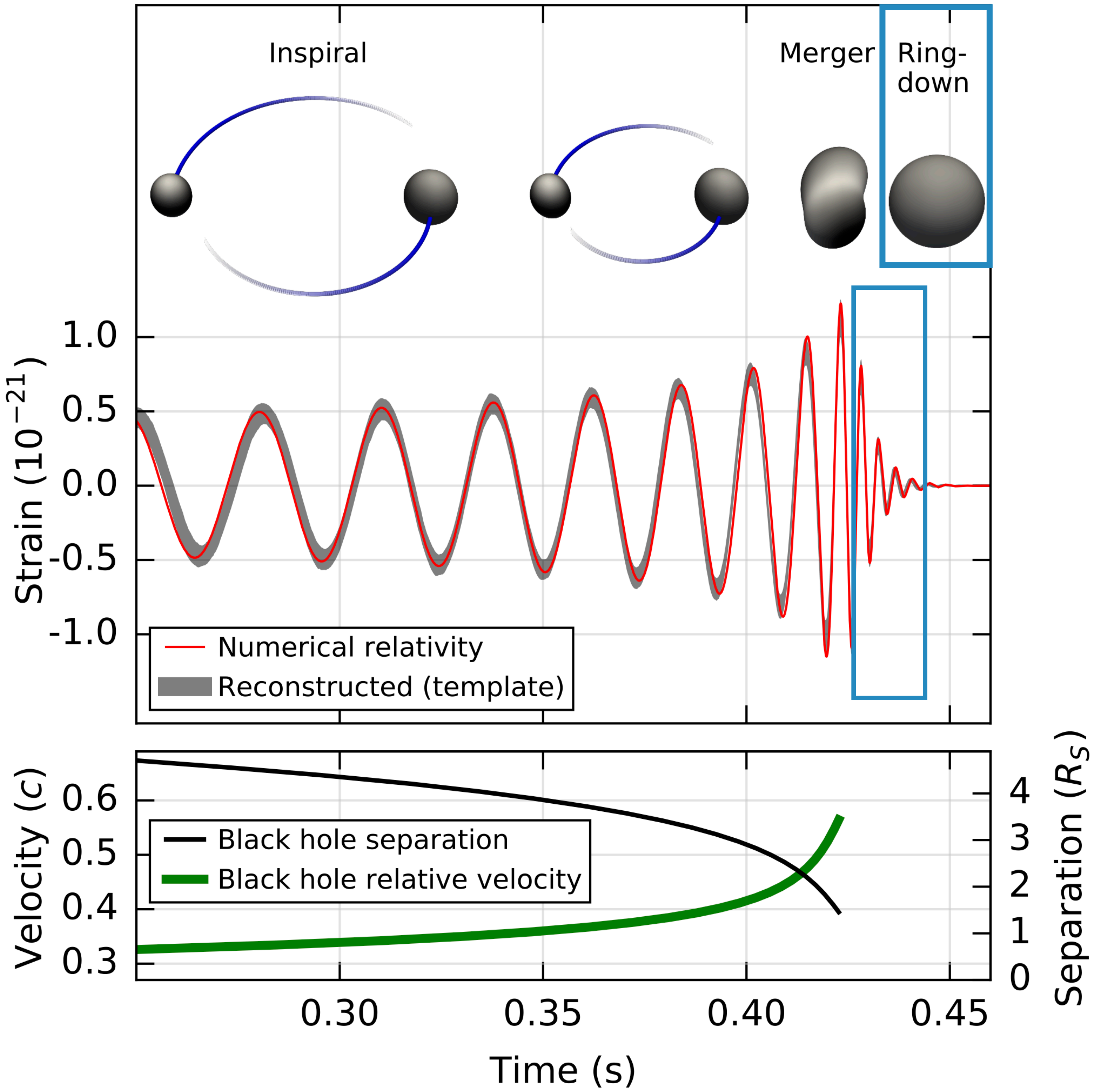
- Binary black holes **remnant** approaches equilibrium emitting damped **normal-modes** ("*spacetime signature*").

- **Spectrum** predicted by **perturbation theory**:

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

  - "Simple" prediction ("easy" to incorporate *beyond-GR* effects)

  - Sensitive to ~ *light ring* physics.



 LVC (2016) PRL 116, 061102

SCIENCE GOALS

- **Testing** the emission:
    - Remnant compact object **nature**;
      Are we really observing black holes?
    - General Relativity predictions for **spectral emission**;
      Is General Relativity a correct description of gravity at high curvatures?
    - Black Hole **Uniqueness Theorems**;
      Do non-extremal black holes have additional hairs?
    - Possible **quantum horizon** effects and classical **BH thermodynamics**.
      Is our classical description of black holes valid?

MISSING PHYSICS?

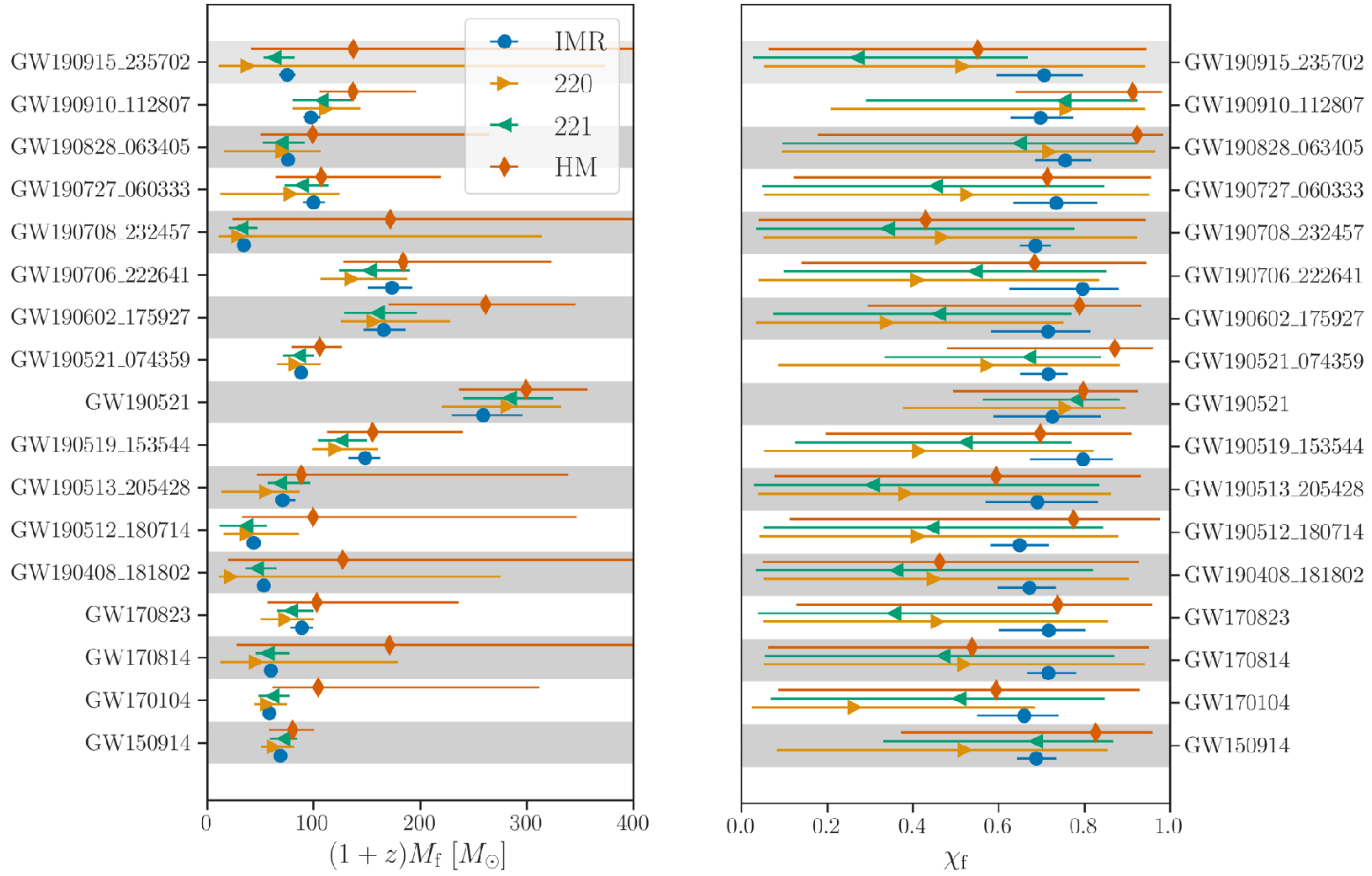
- Why GW merger-ringdown observations compared to **other experiments?** (Solar System, Binary Pulsars, X-ray binaries)
  - **Largest curvature** regime experimentally accessible;
  - **Gauge** the contribution of **missing physics** for precision tests:
    - ~~**Cosmological expansion**~~
    - ~~**Dark matter**~~
    - ~~**Accretion, magnetic fields, electric charge**~~
- GW ringdown tests are **clean**!

 Barausse, Cardoso, Pani, PRD 89 (2014) 104059

BLACK HOLE RINGDOWN CATALOG

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

Image credit: LIGO-Virgo/Rico Lo



Higher modes	Overtones	
$\log_{10} \mathcal{B}^{\rm HM}_{220}$	$\log_{10} \mathcal{B}^{221}_{220}$	$\log_{10} O^{\rm modGR}_{\rm GR}$
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
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Much more than just GW150914!

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

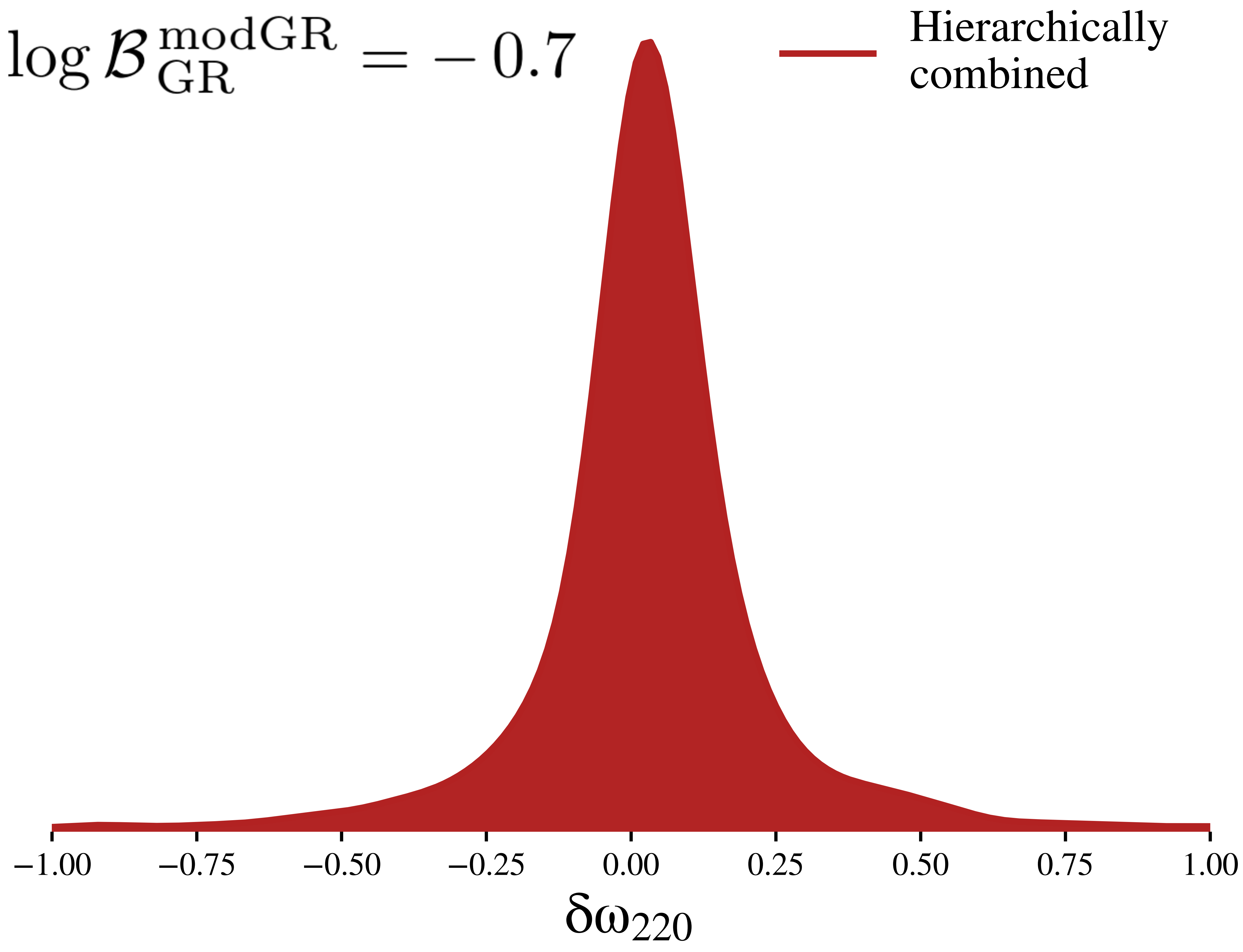
  Data consistent with GR.

- **Deviations** parameterized as:

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

$$\delta\omega_{220} = 0.03^{+0.38}_{-0.35}$$

See also: Ghosh+, arXiv:2104.01906



THE "SO WHAT?" TEST

- Do these results pass the "**So what?**" test?
    - Take an **urn** full of a gaussian mixture of **theoretical particle physicists** and **general relativists**, with a possibly non-null intersection.
    - Draw them at random and have **them look** separately at **these results**.
    - **Count** how many people say: "So what?"
    - If it's more than **42%** of them, the test is **failed**.

LOST IN TRANSLATION

- **Implications** of **LVK** results to specific **alternative theories** of gravity **not immediate** (unlike, e.g. graviton mass);
- Why doesn't the **LVK constrain** specific and well-motivated **beyond-GR theories**?
  - Most theories are **not proven to be well-posed**.
    Difficult to rigorously justify certain approximations or understand merger-ringdown in a specified theory.
  - **Huge amount of possibilities** and of effects to take into account (isospectrality breaking, parity violations, additional modes, scalar-fields dynamics…)
- **Policy** of the Testing GR group: **do not consider** specific theories for which a **rigorous framework** has **not** been **established**.

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.

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Numerical constants

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

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Proportional to action coupling(s):

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

Add deviations at each given order.

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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:

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GR values!

Proportional to action coupling(s):

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

PARSPEC

- **Advantages**:
  - Applicable to large classes of **beyond-GR** theories;
  - **Source-independent** parameters: optimal constraints when combining events;
  - Perturbative expansion: can retain **GR remnant mass and spin** parameters;
  - Direct connection with **parameters** appearing in the **action**.
- Consequence: much **smaller number** of signals (or smaller SNR) to **detect** modifications from GR predictions.

THEORY PARAMETER SPACE

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

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

- **p=2** (e.g. **Kerr-Newman** or Dark photon)

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

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

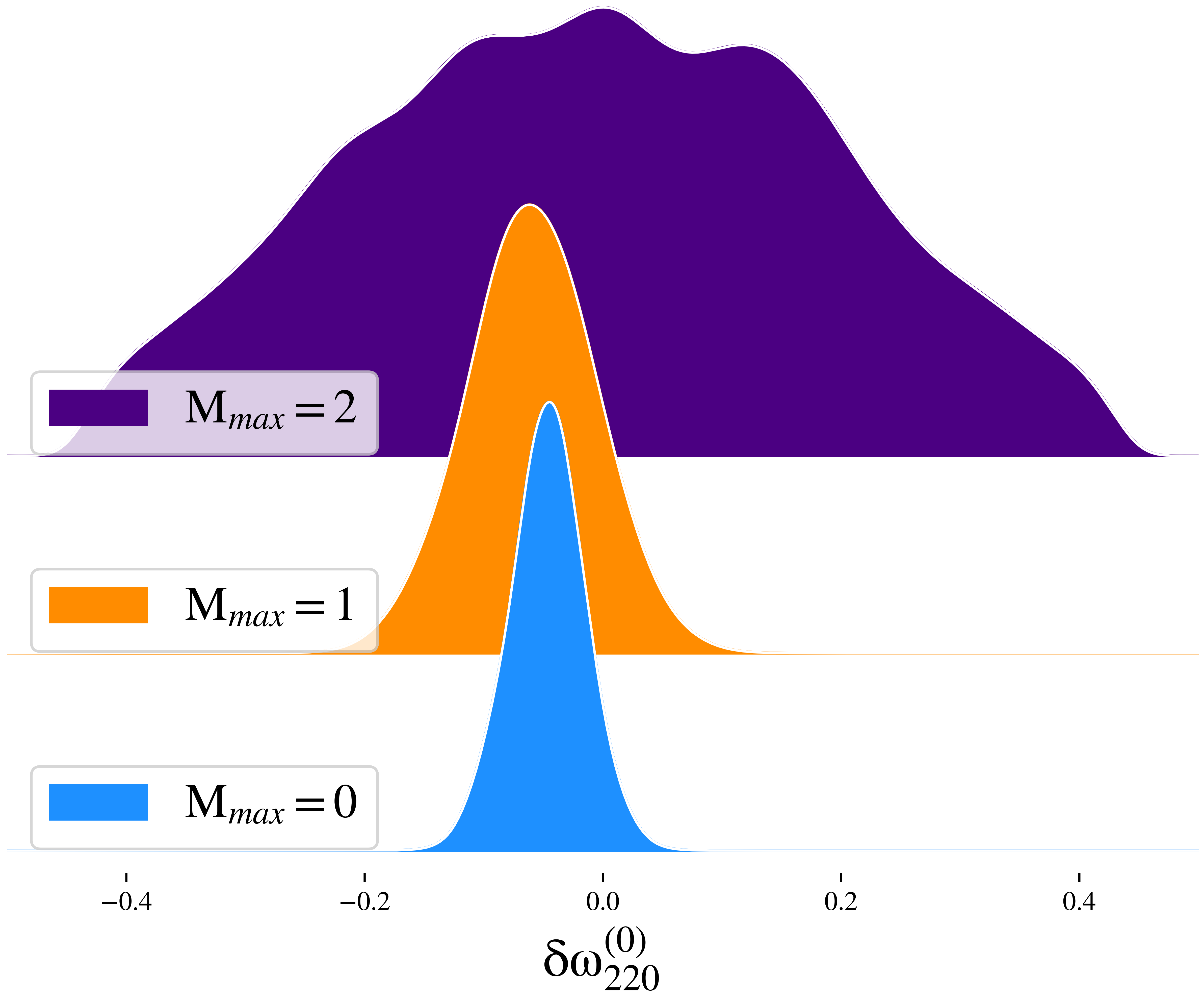
$$S \equiv \int \frac{m_{\text{pl}}^2}{2} d^4x \sqrt{-g}\left[R - \frac{1}{2}(\partial\vartheta)^2 + 2\alpha_{\text{GB}} f(\vartheta)\mathcal{R}_{\text{GB}}\right], \quad S \equiv \int d^4x \sqrt{-g}\left(\frac{m_{\text{pl}}^2}{2}R - \frac{1}{2}(\partial\vartheta)^2 - \frac{m_{\text{pl}}}{8}\ell^2 \vartheta\,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

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

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

RESULTS FOR SCALAR DEVIATIONS

- Constraints on theories with scalar coupling in the action:



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

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

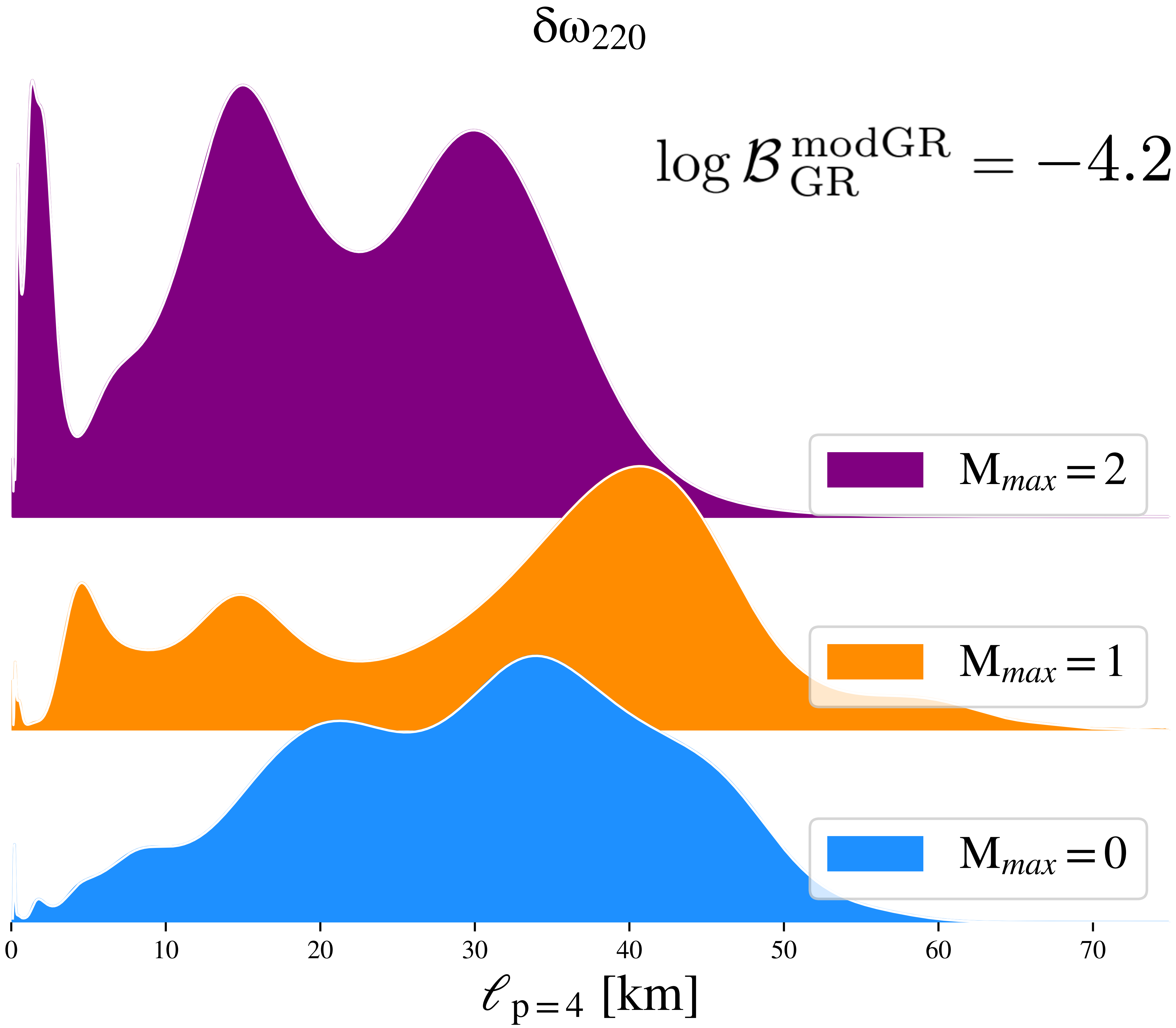
Improvement of a **factor of ~2** wrt LVC parametrization.

Reduction **factor of ~4** in N_{events} to detect a violation.

M_{max} = spin-expansion order.

RESULTS FOR QUADRATIC GRAVITY

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



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

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

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

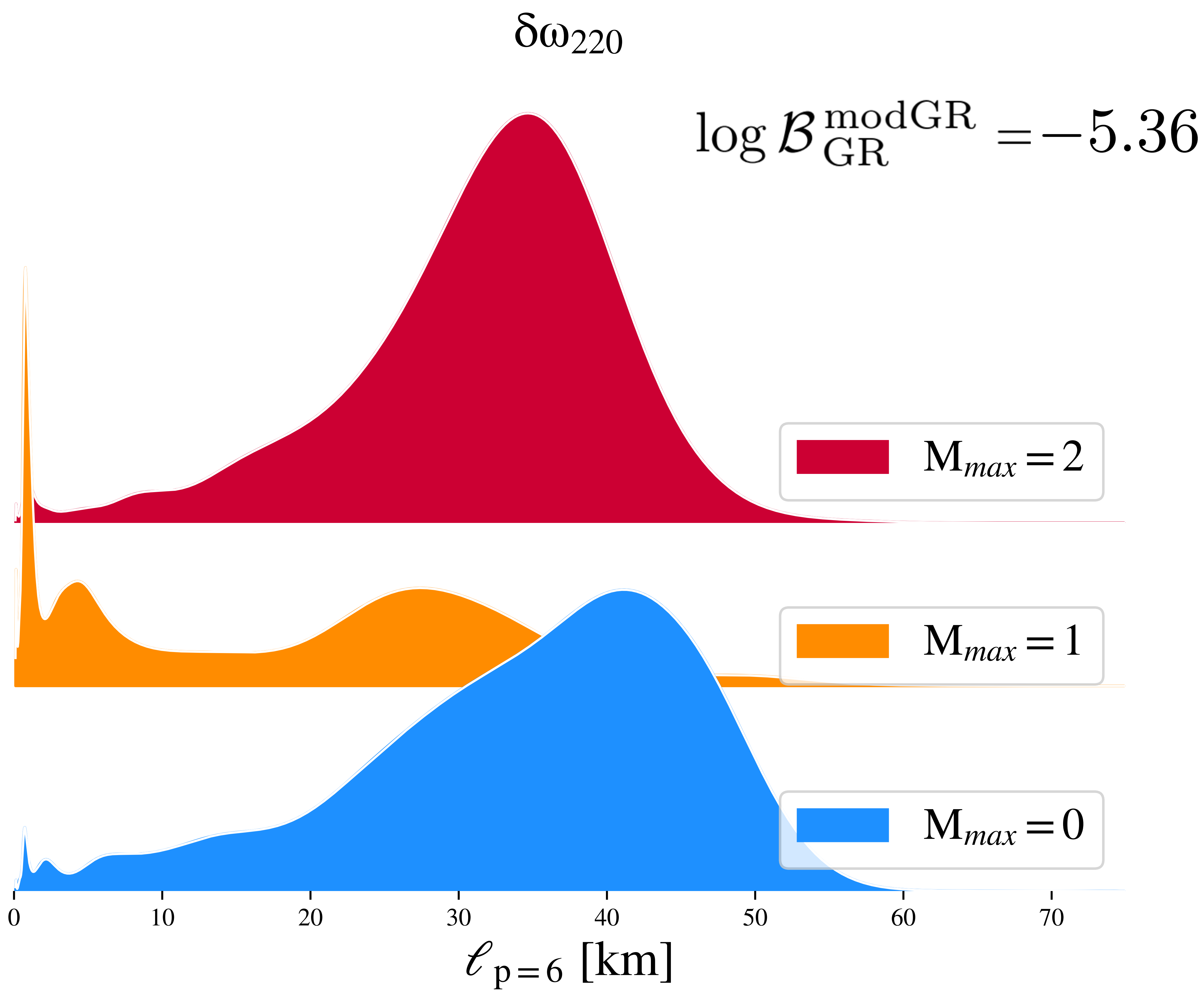
New best non-perturbative constraint:

GW190814: (if BBH) $\ell \lesssim 3.3 \text{ km}$

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:



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

Previous best bound from GW inspiral:

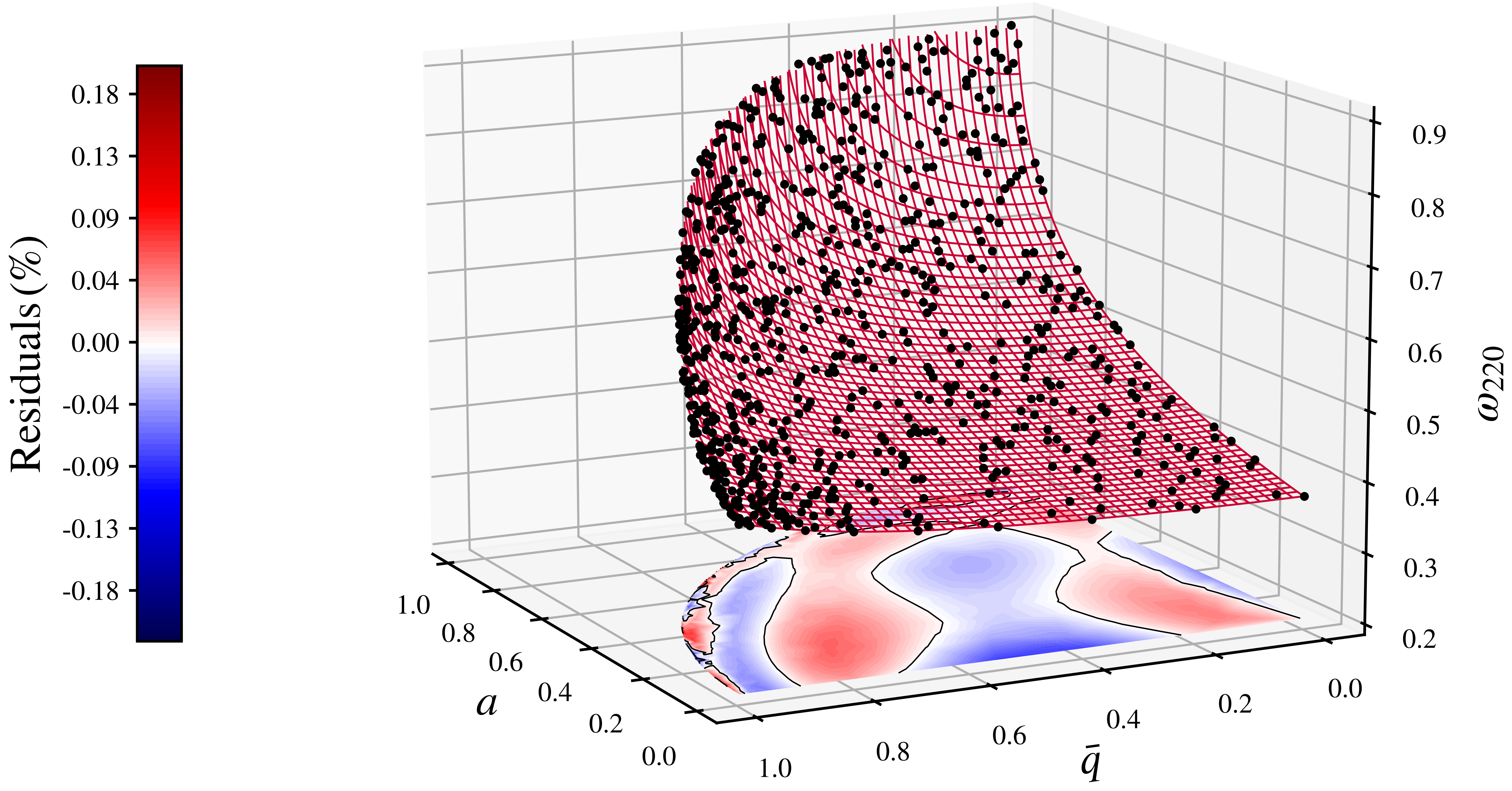
$$\ell \lesssim 150\,\mathrm{km}$$

(Now probing finite-size effects)

Sennett et al. PRD 102, 044056 (2020)

KERR-NEWMAN SPECTRUM

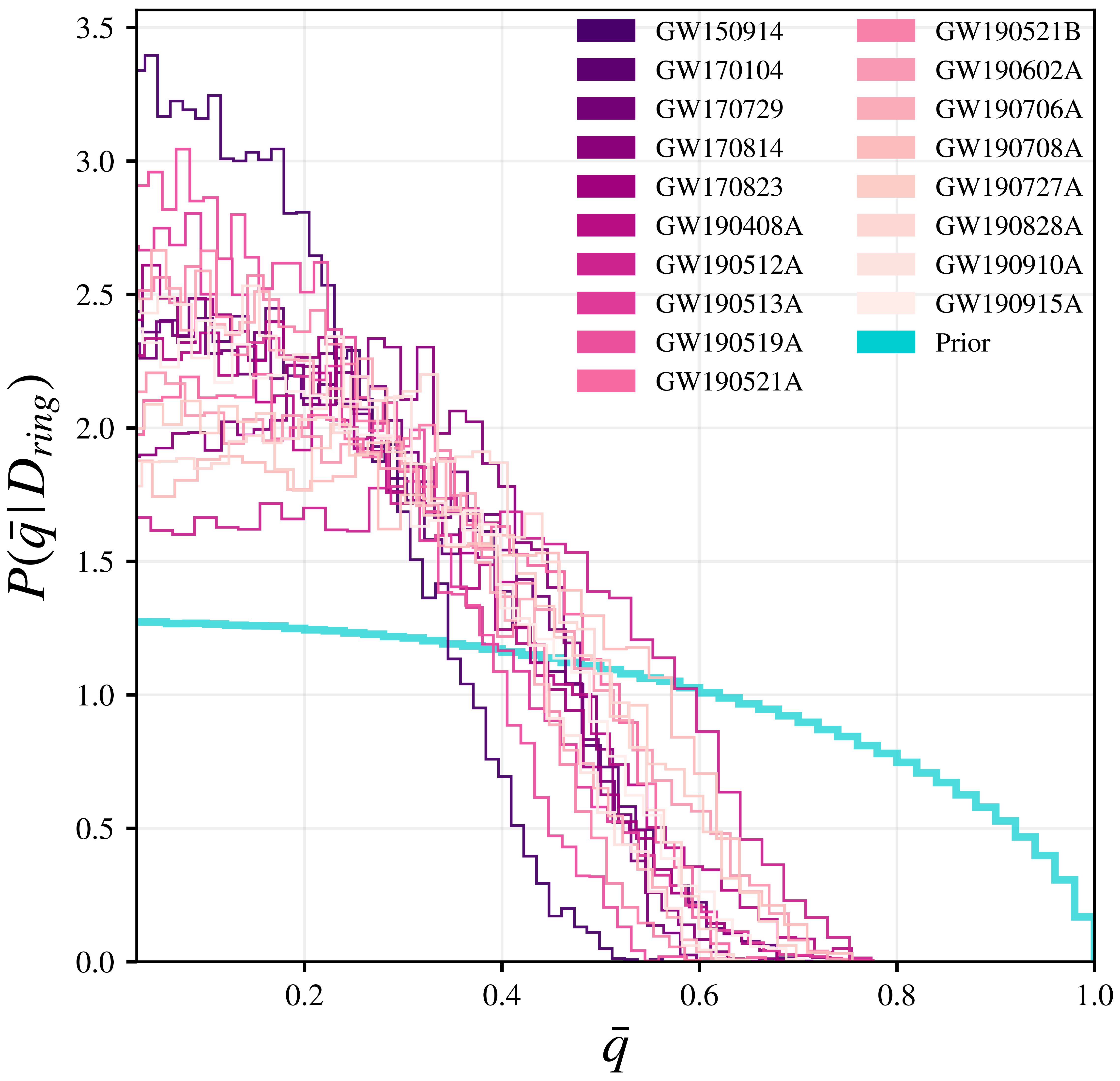
- Application to **charged BHs**: the **Kerr-Newman (KN)** case.
- Kerr spectrum deviations known for arbitrary spin: valuable **test-bed** for **beyond-GR** effects.
- Non-standard scenarios: minicharged **dark matter**, **magnetic monopoles**, scalar-tensor-vector gravity, …



Carullo, Del Pozzo, Dias, Godazgar, Johnson-McDaniel, Laghi, Santos, Veitch (In prep.)

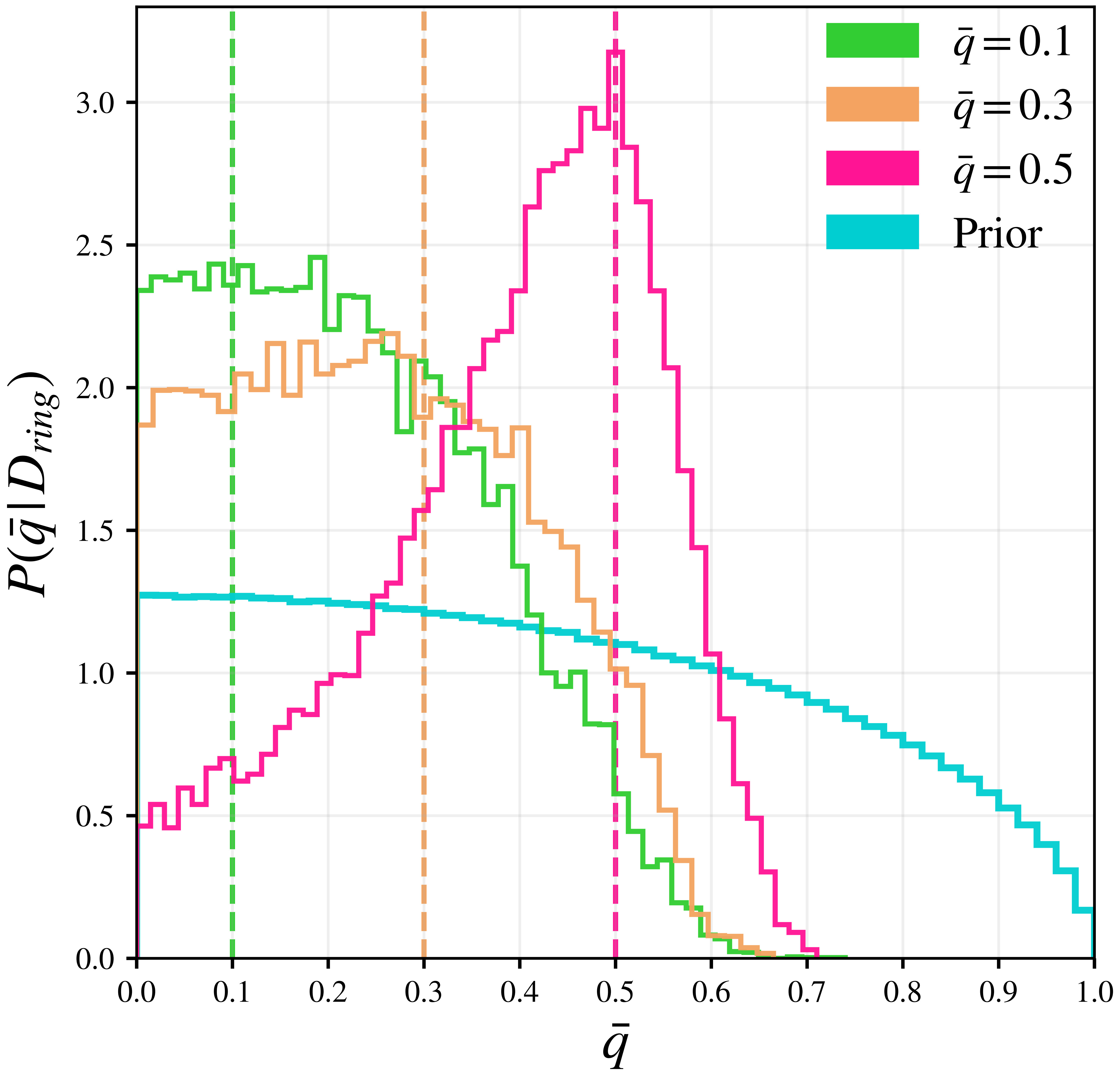
KERR-NEWMAN CONSTRAINTS

- "Standard" parameter estimation **uninformative**, due to **strong correlation** between spin and charge.
- **Null** test: maximum amount of charge compatible with current observations
- Best event (GW150914) gives: $\bar{q} < 0.33$
- **No evidence** for/against the presence of charge from Bayes' Factors



KERR-NEWMAN FUTURE CONSTRAINTS

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



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** and search for signs of **new physics.**
- LIGO-Virgo ringdown observations can already probe high-curvature **unexplored regimes** of beyond-GR theories or place **competitive bounds** on beyond-GR extensions.
- Future detections promise to quickly overcome other experimental bounds.

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation and by the European Gravitational Observatory, composed by CNRS, INFN and Nikhef.

Credits to: Jani, Ghonge