TESTING THE AREA QUANTISATION HYPOTHESIS FROM BLACK HOLE RINGDOWN SIGNALS

Danny Laghi

in collaboration with

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PISA, 24 October '19

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The gentleman who is speaking for me

Istituto Nazionale di Fisica Nucleare

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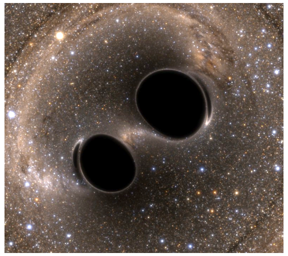
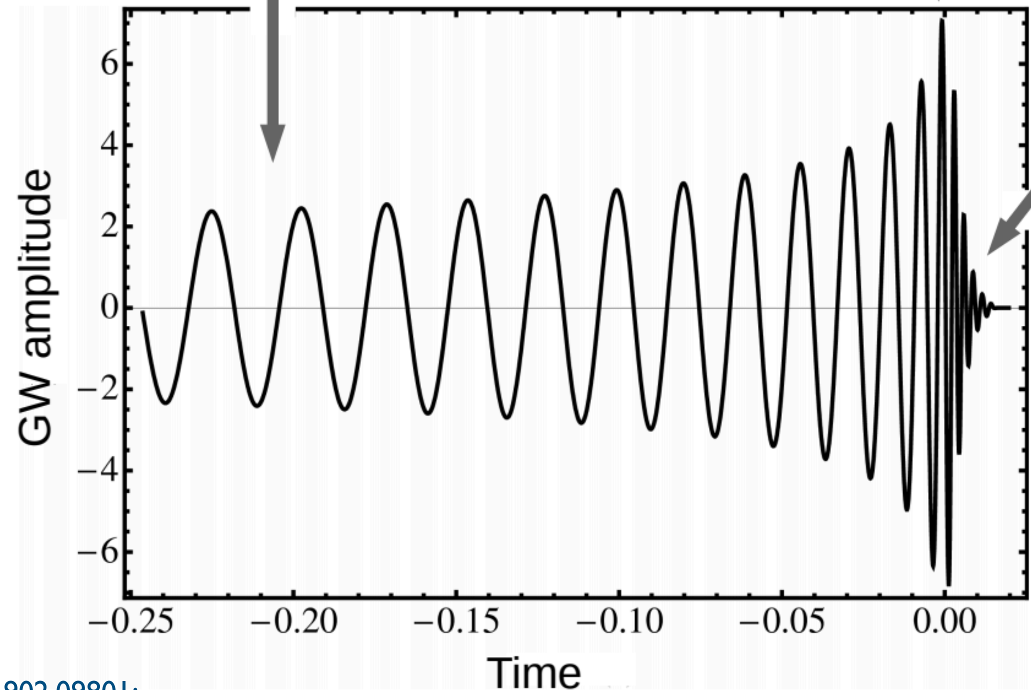
INTRODUCTION (I): THEORY

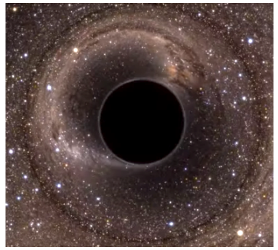


inspiralling phase
post-Newtonian theory

merger phase
numerical relativity



ringdown phase
BH perturbation theory



The remnant BH
is a
perturbed Kerr BH

[Sources: Blanchet, arXiv:1902.09801;
SXS Project: http://www.black-holes.org]

INTRODUCTION (I): THEORY

- Perturbation theory is governed by Teukolsky's equation (TE)

[Teukolsky, *Phys. Rev. Lett.* 29, 1114 (1972)]
[Teukolsky, *Astrophys. J.* 185, 635 (1973)]

- TE solution can be expressed through the complex strain:

$$h_+ - ih_\times = \frac{M_f}{D_L} \sum_{lmn} \left\{ \tilde{\mathcal{A}}_{lmn} \; {}_{-2}S_{lmn}(a_f \, \tilde{\omega}_{lmn}, \iota, \Phi) e^{i(t-t_{lmn})\tilde{\omega}_{lmn}} + \text{c.c.} \right\}$$

where:

$$\tilde{\mathcal{A}}_{lmn} = \mathcal{A}_{lmn} e^{i\phi_{lmn}}$$

$${}_{-2}S_{lmn}(a_f \, \tilde{\omega}_{lmn}, \iota, \Phi) = \{\text{spin-weighted spheroidal harmonics}\}$$

$$\tilde{\omega}_{lmn}(M_f, a_f) = \omega_{lmn}(M_f, a_f) + i/\tau_{lmn}(M_f, a_f)$$

- $\tilde{\omega}_{lmn}(M_f, a_f)$ are called quasinormal modes (QNMs)

- The signal is a superposition of damped sinusoids

INTRODUCTION (II): TOOLS

- Bayes' theorem:

Posterior — Prior — Likelihood

$$p(\vec{\theta}|d,\mathcal{H}_i,I) = \frac{p(\vec{\theta}|\mathcal{H}_i,I)\,p(d|\vec{\theta},\mathcal{H}_i,I)}{p(d|\mathcal{H}_i,I)}$$

Evidence

$$\vec{\theta} = \{M_f, a_f, D_L, \ldots\}$$
$$d(t) = n(t) + h(t)$$
$$\mathcal{H}_i = \{\text{our assumed model}\}$$
$$I = \{\text{our prior information}\}$$

We can use this probability density function to determine estimators (e.g. median value) and credible intervals (e.g. 90% CI) for any of the waveform parameters (e.g. mass, spin, distance, etc.)

$$p(d|\mathcal{H}_i,I) = \int d\theta_1 \cdots d\theta_N \, p(d|\vec{\theta},\mathcal{H}_i,I)\,p(\vec{\theta}|\mathcal{H}_i,I).$$

- Odds' ratio:

$$O^i_j = \frac{p(\mathcal{H}_i|d,I)}{p(\mathcal{H}_j|d,I)} = \frac{p(\mathcal{H}_i|I)}{p(\mathcal{H}_j|I)}\frac{p(d|\mathcal{H}_i,I)}{p(d|\mathcal{H}_j,I)} = \frac{p(\mathcal{H}_i|I)}{p(\mathcal{H}_j|I)} B^i_j$$

B^i_j → Bayes' Factor

A LONG-STANDING PROPOSAL

- Bekenstein & Mukhanov (for nonextremal black holes):

[Bekenstein, *PRD* 7, 2333 (1973)]
[Bekenstein, *Lett. Nuovo Cimento* 11, 467 (1974)]
[Mukhanov, *JETP Letters* 44, 63 (1986)]
[Kogan, *JETP Letters* 44, 267 (1986)]
[Garcia-Bellido, arXiv:hep-th/9302127 (1993)]
[Danielson, Schiffer, *PRD* 48, 4779 (1993)]
[Maggiore, *Nucl. Phys. B* 429, 205 (1994)]
[Bekenstein, Mukhanov, *Phys. Lett. B* 360, 7 (1995)]
[Lousto, *PRD* 51, 1733 (1995)]
[Bekenstein, *8th Marcel Grossmann Meeting, Pts. A*, pp. 92-111 (1997)]
[Hod, *PRL* 81, 4293 (1998)]
[Maggiore, *PRL* 100, 141301 (2008)]
[Davidson, *Int. J. Mod. Phys. D* 23, 1450041 (2014)]
[Bekenstein, *PRD* 91, 124052 (2015)]
[Völkel, Kokkotas, arXiv:1908.00252 (2019)]
[Hod, arXiv:1909.04057 (2019)]

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

where:

$$N \in \mathbb{Z}^+$$

$$l_P \approx 1.6 \times 10^{-35}\mathrm{m}$$

$$\alpha = \mathcal{O}(1)$$

- Some "popular" proposals for α:
  - $\alpha = 8\pi$ (Bekenstein '74, Maggiore '08)
  - $\alpha = 8\ln 2$ (Davidson, '05)
  - $\alpha = 4\ln 3$ (Hod, '98)
  - $\alpha = 4\ln 2$ (Mukhanov '86, Bekenstein & Mukhanov '95)

"QUANTUM BLACK HOLES AS ATOMS"

[Bekenstein, *Brazilian National Meeting on Particles and Fields, Braz. Phys. Society*, pp. 59-69 (1996)]
[Bekenstein, *PRD* 91, 124052 (2015)]

- Central claim:

$$A_H^Q = A_H^{Kerr}$$

where $(c = 1)$:

$$A_H^Q = \alpha \hbar G N \qquad A_H^{Kerr} = 8\pi G^2 \left(M^2 + \sqrt{M^2 - J^2/G^2}\right)$$

- Differentiate both sides and use QM:

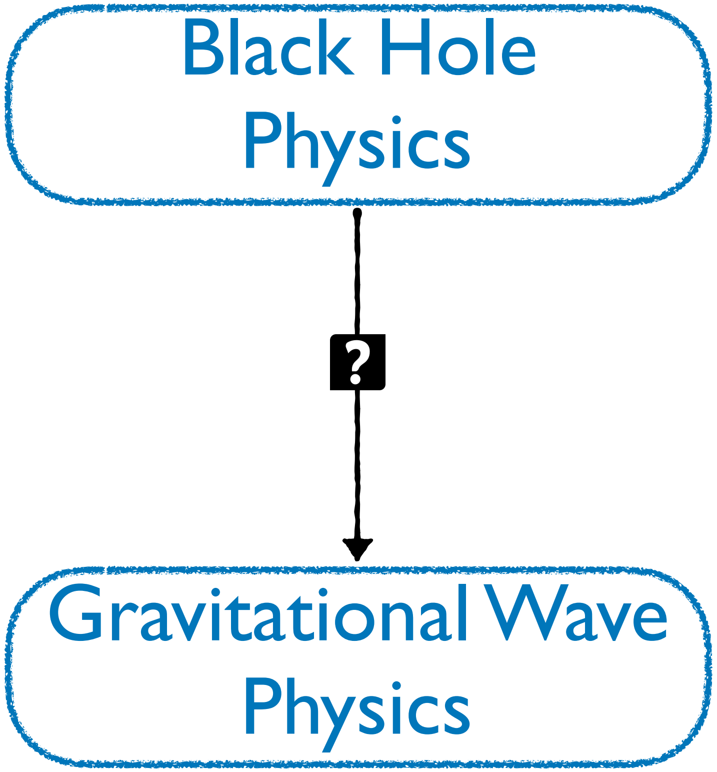
$$\Delta N = -n$$
$$\Delta M = -\hbar \omega_n$$
$$\Delta J = -\hbar m$$

- Get the quanta spectrum $(a \equiv J/GM^2)$:

$$\omega_n = \frac{1}{MG} \frac{n\alpha\sqrt{1-a^2} + 8\pi a m}{16\pi(1 + \sqrt{1-a^2})}$$

"IS A GRAVITON DETECTABLE?"

[Dyson, *Int. J. Mod. Phys. A* Vol. 28, No. 25, 1330041 (2013)]



A HEURISTIC RINGDOWN MODEL

- Foit & Kleban: heuristic interpretation of the Bekenstein-Mukhanov conjecture

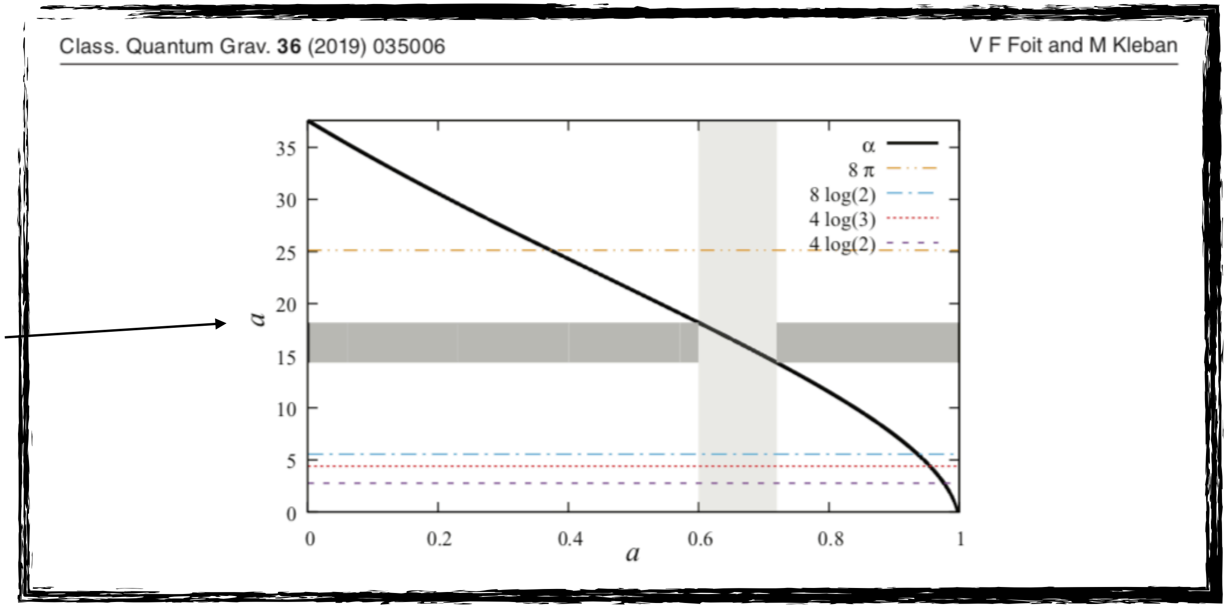
[Foit, Kleban, *CQG* 36 035006 (2019)]
[Cardoso, Foit, Kleban, *JCAP* 2019 006 (2019)]

- MAIN CONSEQUENCE: the remnant BH settles down according to the "nGR" quantised QNM frequency:

$$\omega_1(M_f, a_f, \alpha) = \frac{1}{M_f G} \frac{\alpha\sqrt{1-a_f^2} + 16\pi a_f}{16\pi(1+\sqrt{1-a_f^2})}$$

A (PARTIAL) CLAIM WITH GW150914

This label should be α



[Foit, Kleban, *CQG* 36 035006 (2019)]

Can we make
a more thorough analysis
on real data?

OUR FRAMEWORK

[DL, Carullo, Veitch, Del Pozzo, in preparation]

- Full time-domain analysis: pyRing [Carullo, Del Pozzo, Veitch, *PRD* 99, 123029 (2019)]
- Sampler: CPNest [Del Pozzo, Veitch, https://github.com/johnveitch/cpnest] [Skilling, *AIP Conference Proceedings*, 2004]
  - → Bayes' factors
  - → Posterior distributions of intrinsic and extrinsic parameters
    $\{M_f, a_f, \alpha, \mathcal{A}_{220}, \phi_{220}, \iota, \Phi, t_0\}$ $\{\alpha', \delta', D_L, \psi\}$
- Priors: uniform + $\alpha \in [0, 50]$
- Ringdown start time prior: $t_0 \in [10, 20] M_f$ after a fiducial GPS merger time t_M
  $\simeq [3.5, 7.0]\mathrm{ms}$ peak strain amplitude of $(h_+^2 + h_\times^2)(t)$
  [Abbott et al. (LVC), PRL 116, 221101 (2016)]

OUR nGR QUANTISED RINGDOWN MODEL

[DL, Carullo, Veitch, Del Pozzo, in preparation]

- Kerr-like ringdown waveform:

$$h_{220} = h_+ - ih_\times = \frac{M_f}{D_L}\tilde{\mathcal{A}}_{220\ -2}Y^{22}(\iota, \Phi)e^{i(t-t_0)(\omega_1 + i/\tau_1)} + \text{c.c.}, \qquad t \geq t_0$$

"nGR" quantised QNM frequency:

$$\omega_1(M_f, a_f, \alpha) = \frac{1}{M_f G}\frac{\alpha\sqrt{1-a_f^2} + 16\pi a_f}{16\pi(1+\sqrt{1-a_f^2})}$$

"nGR" quantised QNM damping time:

No ansatz:

$$\tau_1 \in [0.5, 20]\ \text{ms}$$

Ansatz from GR quality factor Q_{220}^{GR}:

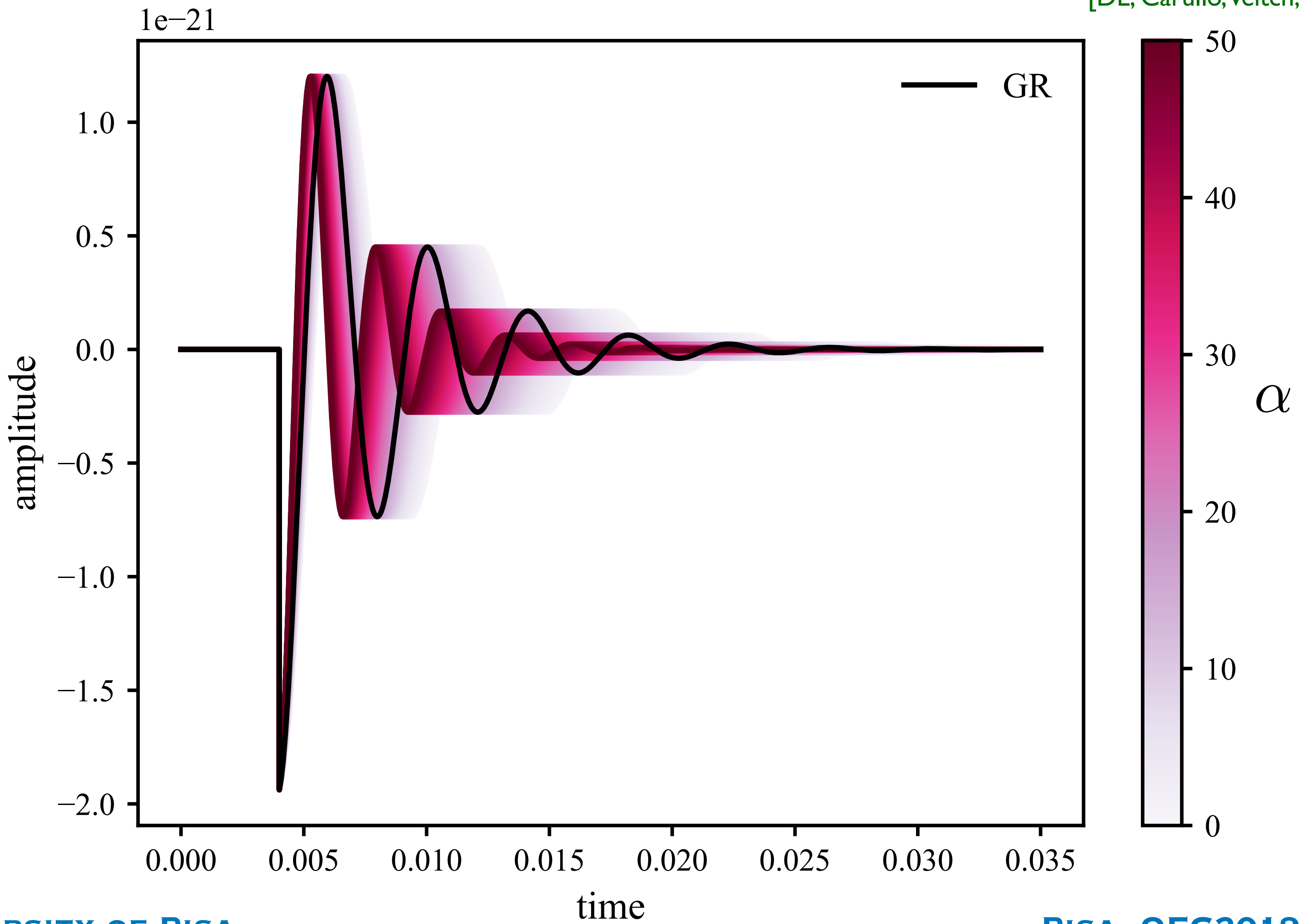
$$\tau_1(M_f, a_f, \alpha) = 2\frac{Q_{220}^{GR}(M_f, a_f)}{\omega_1(M_f, a_f, \alpha)}$$

- Conclusions are very similar, so a posteriori we assume the functional ansatz

GR vs nGR WAVEFORMS

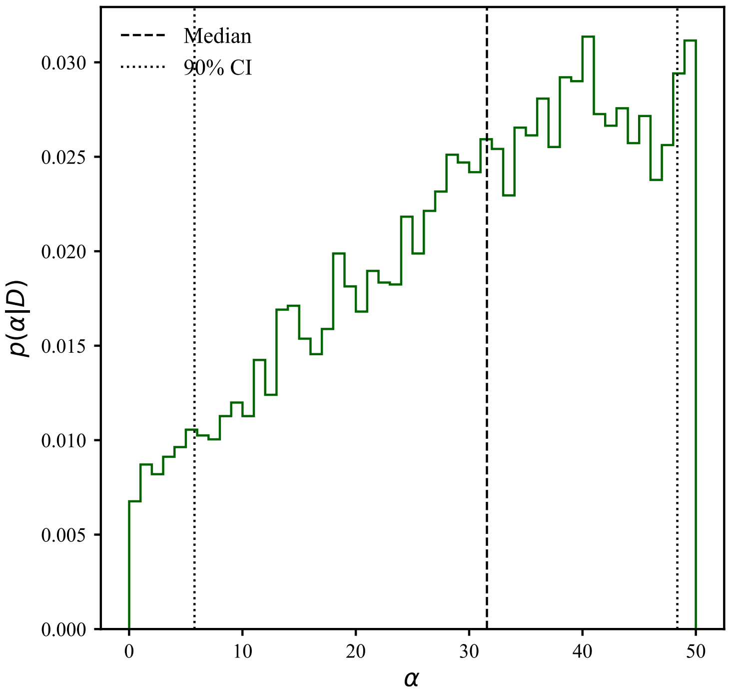
[DL, Carullo, Veitch, Del Pozzo, in preparation]

GR
is NOT
a subset of
nGR

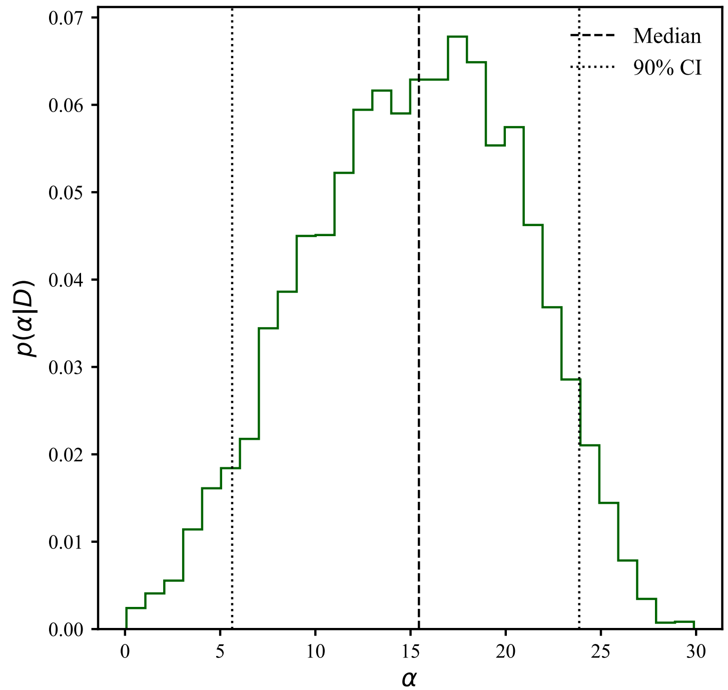


MEASURING α FROM GW150914

[DL, Carullo, Veitch, Del Pozzo, in preparation]



Compare with:
[Foit, Kleban, *CQG* 36, 035006 (2019)]



Uniform priors:

$$M_f \in [10, 250] M_\odot$$

$$a_f \in [0.0, 0.99]$$

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

LVC priors:

$$M_f \in [62, 75] M_\odot$$

$$a_f \in [0.55, 0.75]$$

$$\log B^{nGR}_{GR} = -1.6 \pm 0.1$$

SIMULATIONS

[DL, Carullo, Veitch, Del Pozzo, in preparation]

- Single events in general do not provide much information about α

What about a population of GW150914-like events?

- Generate $\{\mathcal{A}_{220}, \phi_{220}\}$ using a non-precessing BBH ringdown model [London, arXiv: 1801.08208]
    - Injection: GR signal vs nGR signal

$$\omega_{220} = \omega_{220}(M_f, a_f) \qquad \omega_1 = \omega_1(M_f, a_f, \alpha)$$
$$\tau_{220} = \tau_{220}(M_f, a_f) \qquad \tau_1 = \tau_1(M_f, a_f, \alpha)$$

[Berti, Cardoso, Will, *PRD* 73, 064030 (2006)]

- Recovery: GR template vs nGR template

$$\omega_{220} = \omega_{220}(M_f, a_f) \qquad \omega_1 = \omega_1(M_f, a_f, \alpha)$$
$$\tau_{220} = \tau_{220}(M_f, a_f) \qquad \tau_1 = \tau_1(M_f, a_f, \alpha)$$

- We can make model selection: e.g. $\log B^{nGR}_{GR} = \log \dfrac{P(D|nGR)}{P(D|GR)}$

SIMULATIONS (GR)

[DL, Carullo, Veitch, Del Pozzo, in preparation]

- Injection: GR signal vs nGR signal

$$\omega_{220} = \omega_{220}(M_f, a_f)$$
$$\tau_{220} = \tau_{220}(M_f, a_f)$$

[Berti, Cardoso, Will, *PRD* 73, 064030 (2006)]

- Recovery: GR template vs nGR template

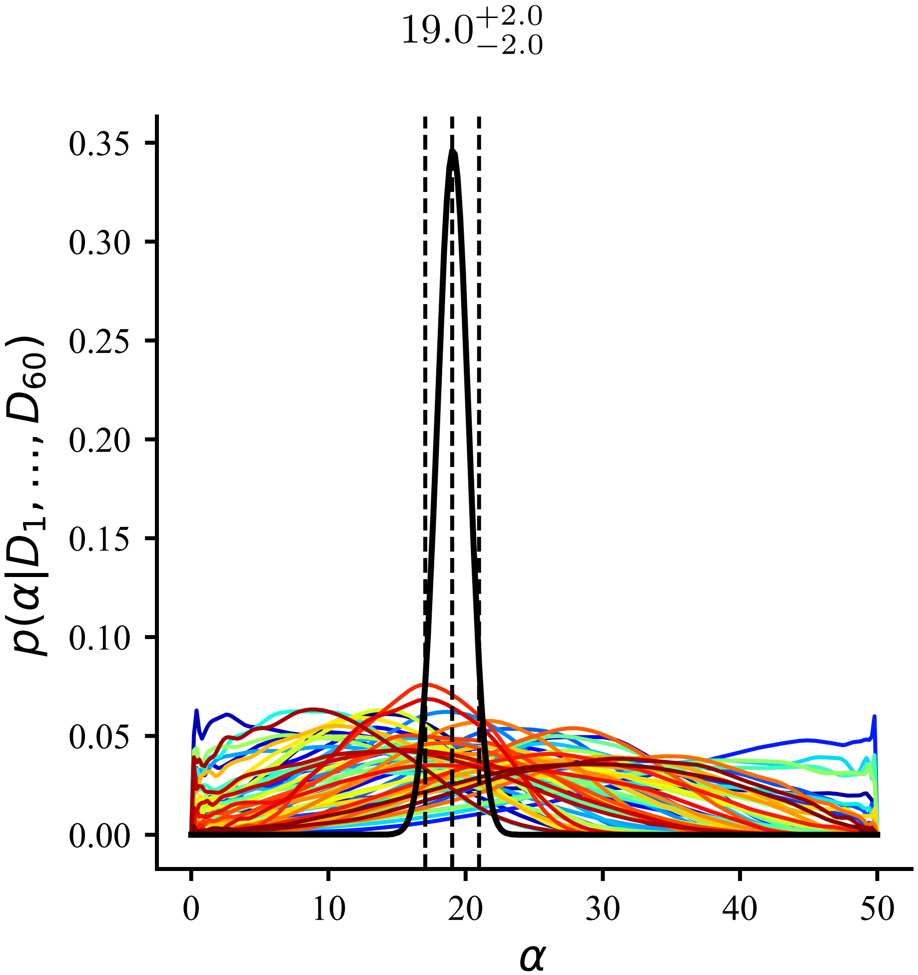
$$\omega_{220} = \omega_{220}(M_f, a_f)$$
$$\tau_{220} = \tau_{220}(M_f, a_f)$$

$$\omega_1 = \omega_1(M_f, a_f, \alpha)$$
$$\tau_1 = \tau_1(M_f, a_f, \alpha)$$

- We can make model selection: e.g. $\log B^{nGR}_{GR} = \log \dfrac{P(D|nGR)}{P(D|GR)}$

SIMULATIONS: GR POPULATION

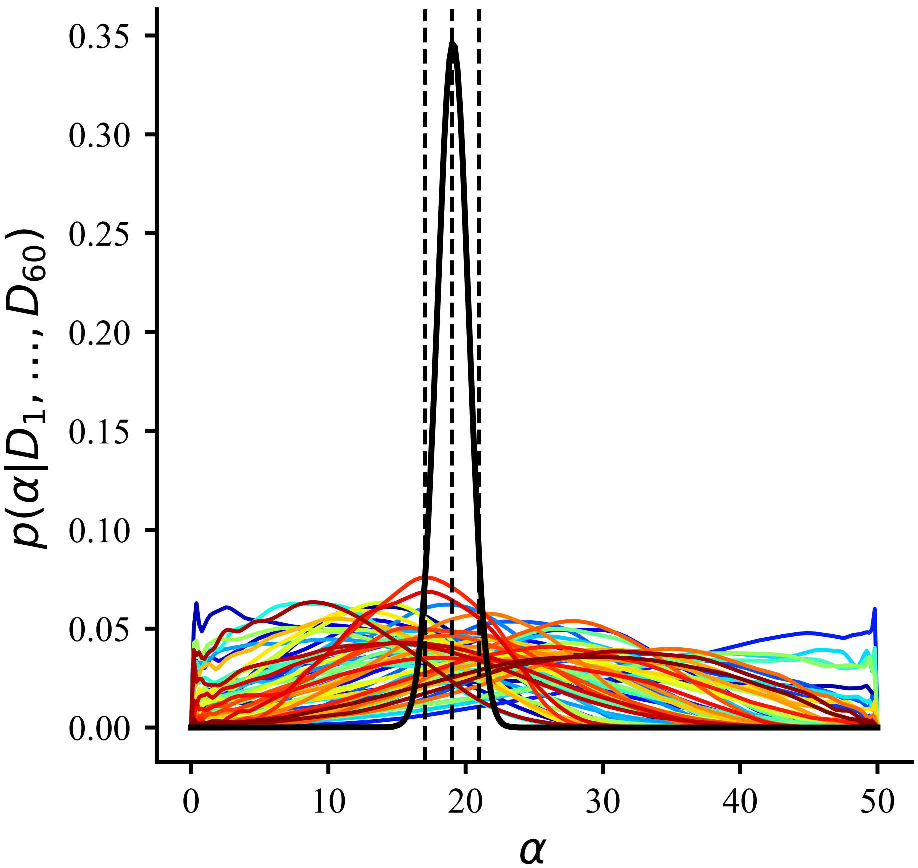
[DL, Carullo, Veitch, Del Pozzo, in preparation]

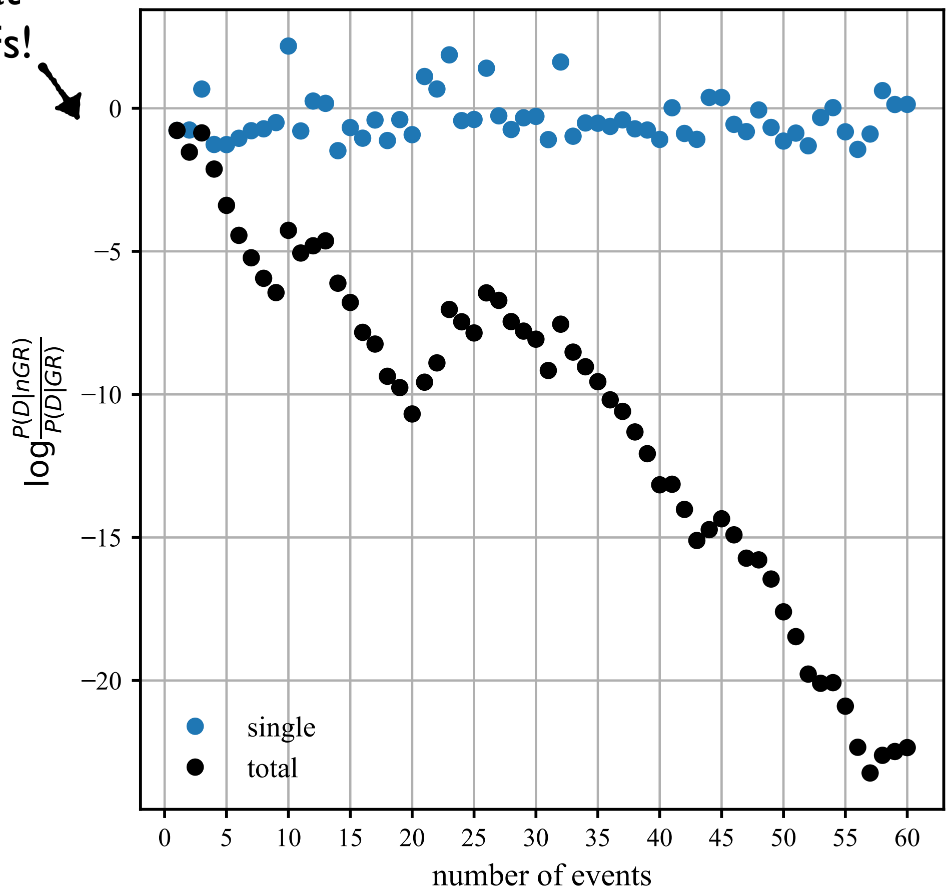


SIMULATIONS: GR POPULATION

$19.0^{+2.0}_{-2.0}$ BUT → Look at the BFs!

[DL, Carullo, Veitch, Del Pozzo, in preparation]





SIMULATIONS (nGR)

[DL, Carullo, Veitch, Del Pozzo, in preparation]

- Injection: GR signal vs nGR signal

$$\omega_1 = \omega_1(M_f, a_f, \alpha)$$
$$\tau_1 = \tau_1(M_f, a_f, \alpha)$$

- Recovery: GR template vs nGR template

GR template:

$$\omega_{220} = \omega_{220}(M_f, a_f)$$
$$\tau_{220} = \tau_{220}(M_f, a_f)$$

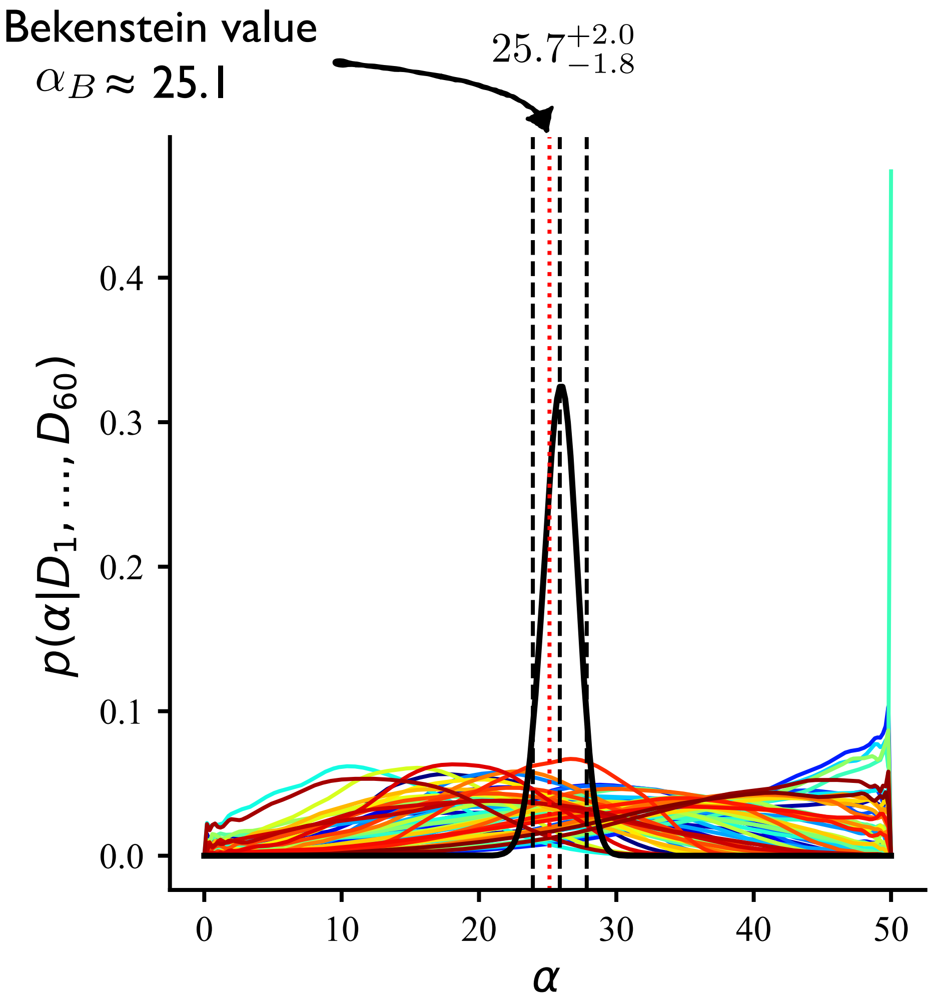
nGR template:

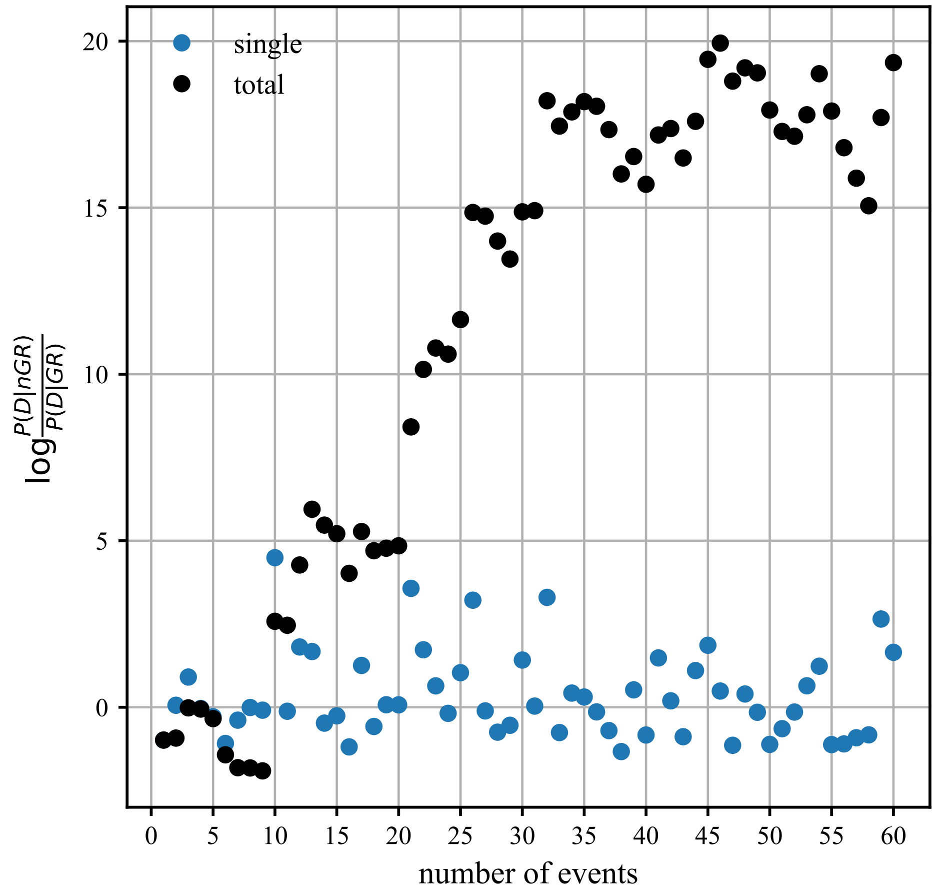
$$\omega_1 = \omega_1(M_f, a_f, \alpha)$$
$$\tau_1 = \tau_1(M_f, a_f, \alpha)$$

- We can make model selection: e.g. $\log B_{GR}^{nGR} = \log \dfrac{P(D|nGR)}{P(D|GR)}$

SIMULATIONS: nGR BEKENSTEIN BHs

[DL, Carullo, Veitch, Del Pozzo, in preparation]



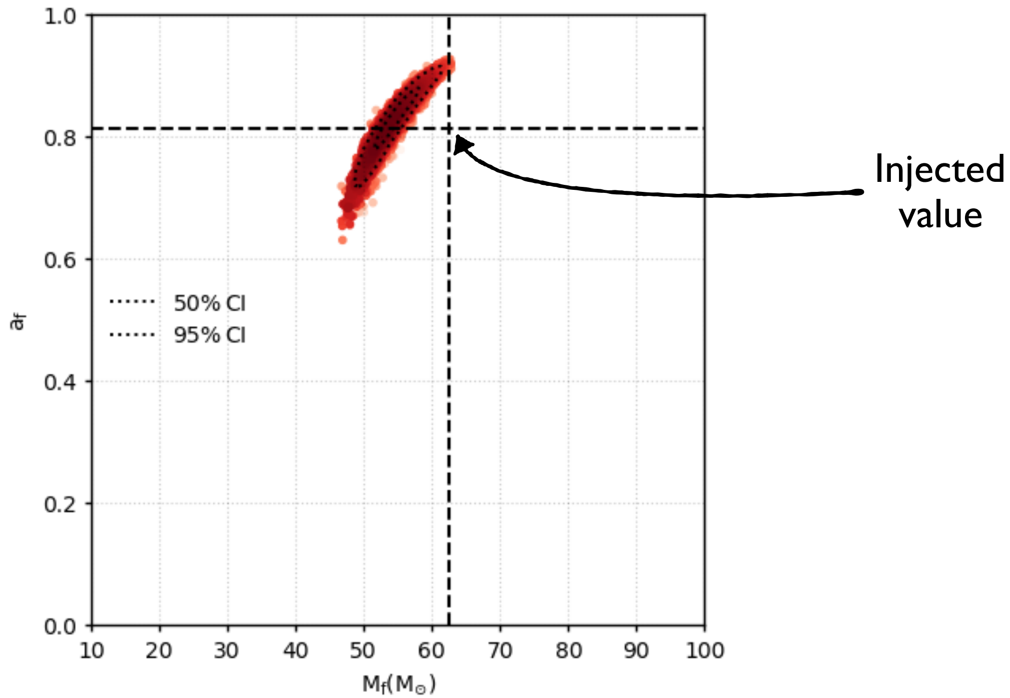


STEALTH BIASES: (I)

[DL, Carullo, Veitch, Del Pozzo, in preparation]

- Simulate the signal of a Bekenstein QBH

$$\omega_1 = \omega_1(a_f, M_f, \alpha = \alpha_B)$$
$$\tau_1 = \tau_1(a_f, M_f, \alpha = \alpha_B)$$



- Recover the signal assuming a GR template

$$\omega_{220} = \omega_{220}(a_f, M_f)$$
$$\tau_{220} = \tau_{220}(a_f, M_f)$$

CONCLUSIONS AND PROSPECTS

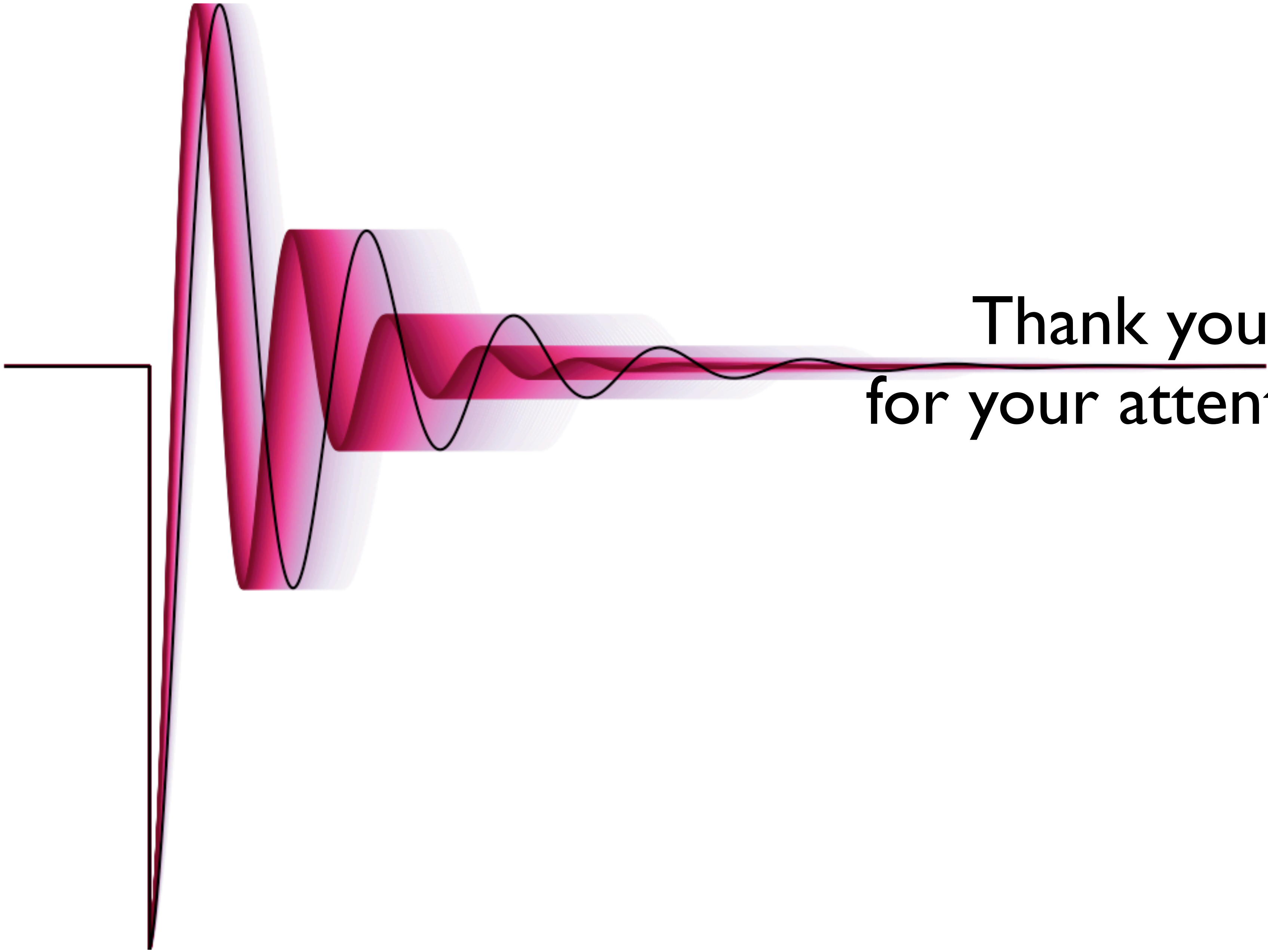
- We developed an infrastructure to measure possible GR deviations analysing the ringdown
- We have shown how it could be used, e.g. to test the area quantisation conjecture
- If a theory predicts nGR QNMS:

$$\omega_{nGR} = \omega_{nGR}(M_f, a_f, \vec{\theta})$$
$$\tau_{nGR} = \tau_{nGR}(M_f, a_f, \vec{\theta})$$

we can test it on real data and explore its observational effects through simulated events

OUTLOOK

- Applying the method to all the GWTC-1 events
- Article with detailed results in preparation



Thank you
for your attention