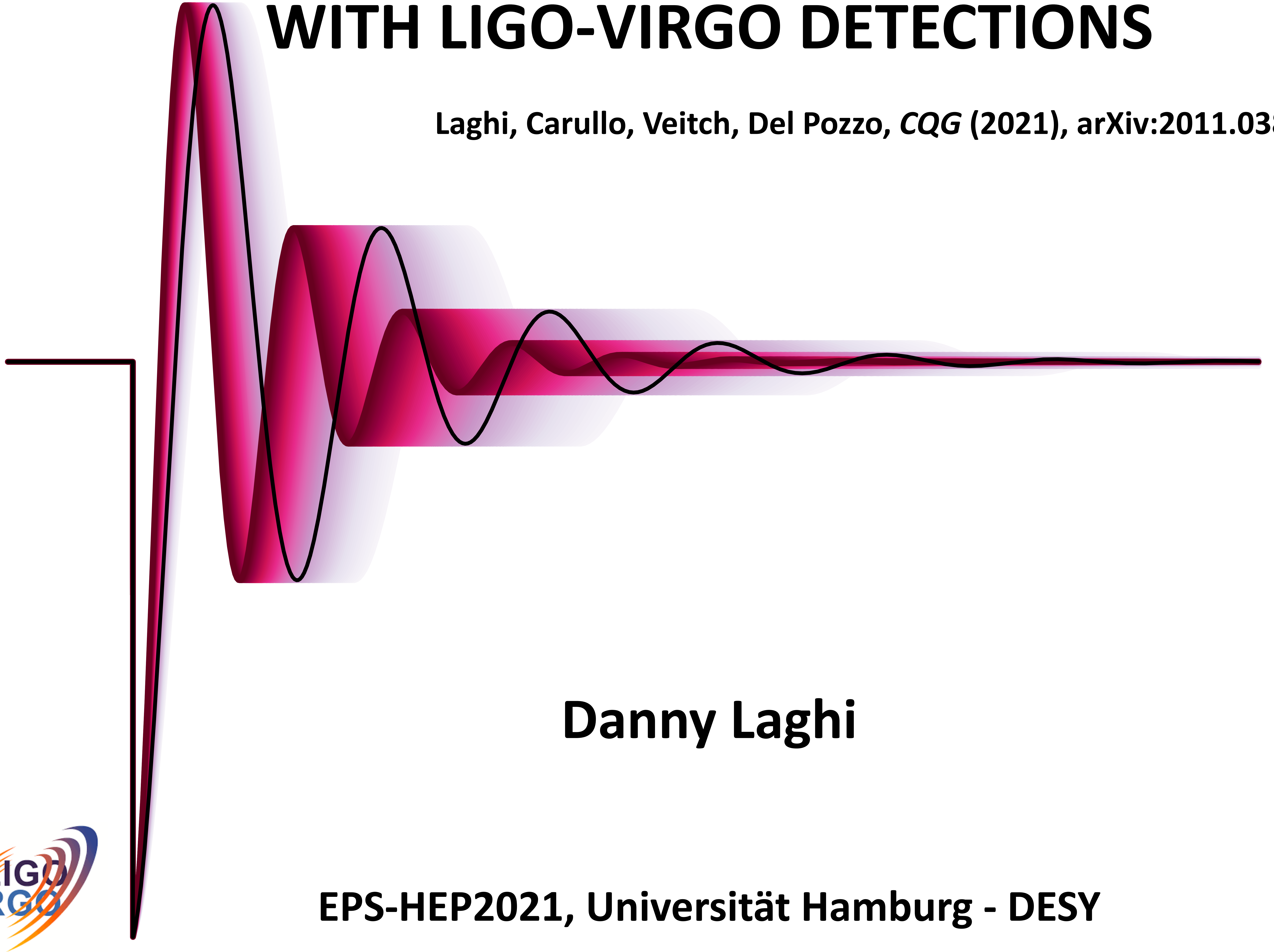
QUANTUM BLACK HOLES AND RINGDOWN PHYSICS WITH LIGO-VIRGO DETECTIONS

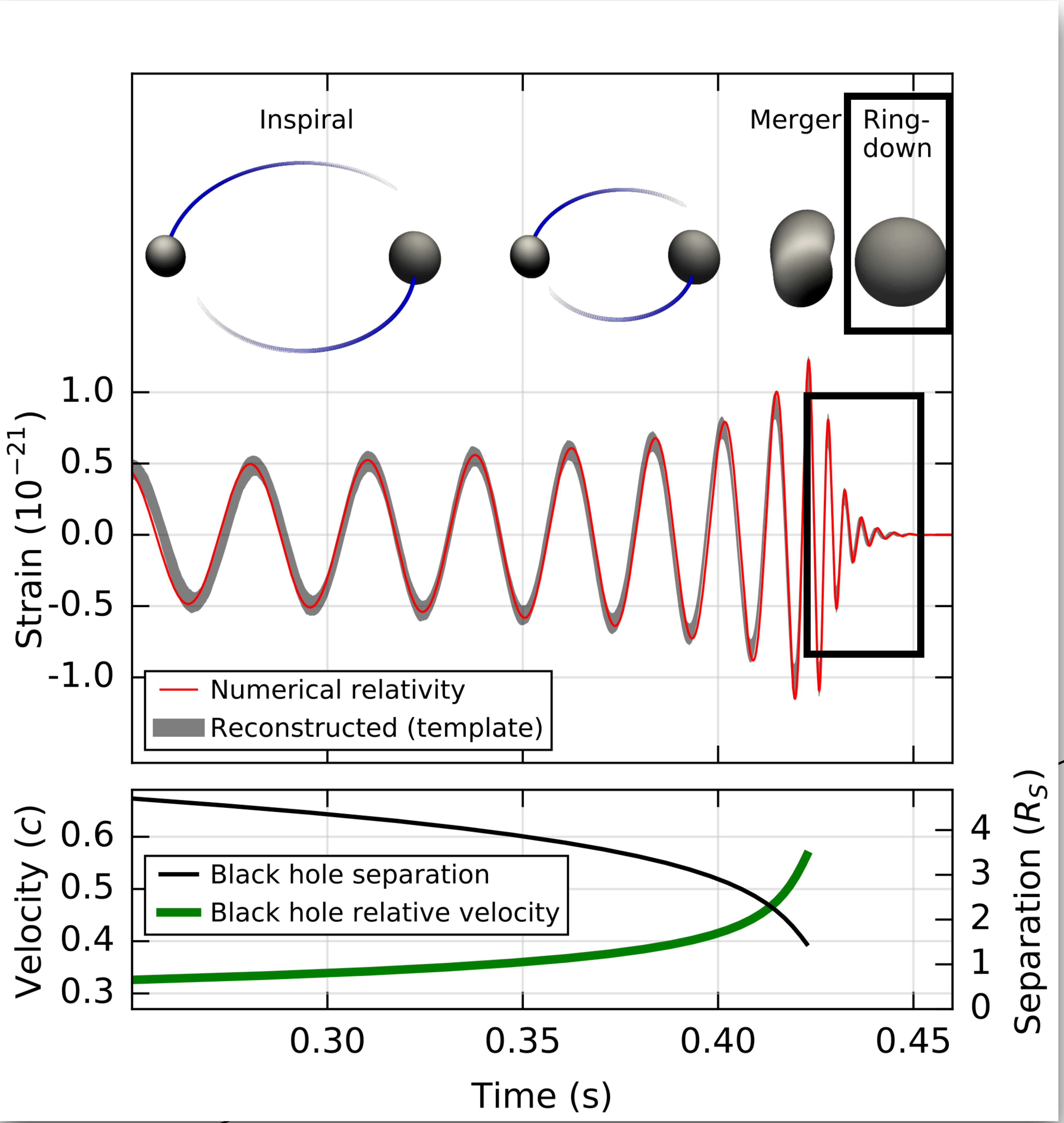


Laghi, Carullo, Veitch, Del Pozzo, *CQG* (2021), arXiv:2011.03816

Danny Laghi

EPS-HEP2021, Universität Hamburg - DESY

BLACK HOLE RINGDOWN



Credits: LVC - GW150914 [*PRL* **116**, 061102 (2016)]

- The last stage of a binary BH merger observed by LIGO and Virgo GW interferometers is the **ringdown**
- The BH remnant relaxes to its stationary state, vibrating according to its **"normal-mode" frequencies**
- GR predicts the oscillatory behaviour as a sum of **exponentially damped sinusoids**
  - **Frequencies** and **damping rates** are fixed only by the BH **mass** and **spin**

A LONG-STANDING PROPOSAL

- **Bekenstein & Mukhanov** (for nonextremal BH):

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

where:

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

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

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

Bekenstein, *Lett. Nuovo Cim.* (1974)
Mukhanov, *JETP Lett.* (1986)
Maggiore, *Nucl. Phys. B* (1994)
Bekenstein, Mukhanov, *Phys. Lett. B* (1995)
Bekenstein, arXiv:gr-qc/9710076
Hod, *PRL* (1998)
Maggiore, *PRL* (2008)
Bekenstein, *PRD* (2015)

- Quantum BHs have a discrete spectrum ("quantum black holes as atoms"):

$$(a \equiv J/M^2) \qquad \omega_k^{BM} = \frac{1}{M}\frac{(k+1)\alpha\sqrt{1-a^2}+8\pi a m}{16\pi(1+\sqrt{1-a^2})}\,, \qquad k \geq 0$$

TESTING BEKENSTEIN-MUKHANOV WITH GWs

Foit, Kleban, *CQG* (2019)

- **Foit & Kleban**: heuristic interpretation of the quantised frequency formula

- **Main assumption**: area quantisation affects the light ring structure

- **Light ring frequency** ≈ prompt ringdown frequency

Goebel, *Astroph. J.* (1972)
Ferrari, Mashhoon, *PRD* (1984)
Cardoso, Franzin, Pani, *PRL* (2016)
Cardoso, Pani, *Liv Rev. Rel.* (2019)

- **Main consequence**: the remnant BH (initially) settles down according to:

$$\omega_0(M_f, a_f, \alpha) = \frac{1}{M_f} \frac{\alpha\sqrt{1-a_f^2} + 16\pi a_f}{16\pi(1+\sqrt{1-a_f^2})}$$

INVESTIGATING THE FOIT-KLEBAN MODEL

- **Working hypothesis**: Foit-Kleban model
  - Single-mode template, ringdown complex amplitudes inferred from the data (not predicted by the model)
- Use the GW events detected so far to **infer** α

$$p(\alpha) = \mathcal{U}(0{,}50)$$

- Do **model selection** between GR and the Foit-Kleban model

GR

$$\omega = \omega_{GR}(M_f, a_f)$$
$$\tau = \tau_{GR}(M_f, a_f)$$

nGR

$$\omega = \omega_0(M_f, a_f, \alpha)$$
$$\tau = \tau_0(M_f, a_f, \alpha) = 2\frac{Q_{\rm GR}(a_f)}{\omega_0(M_f, a_f, \alpha)}$$

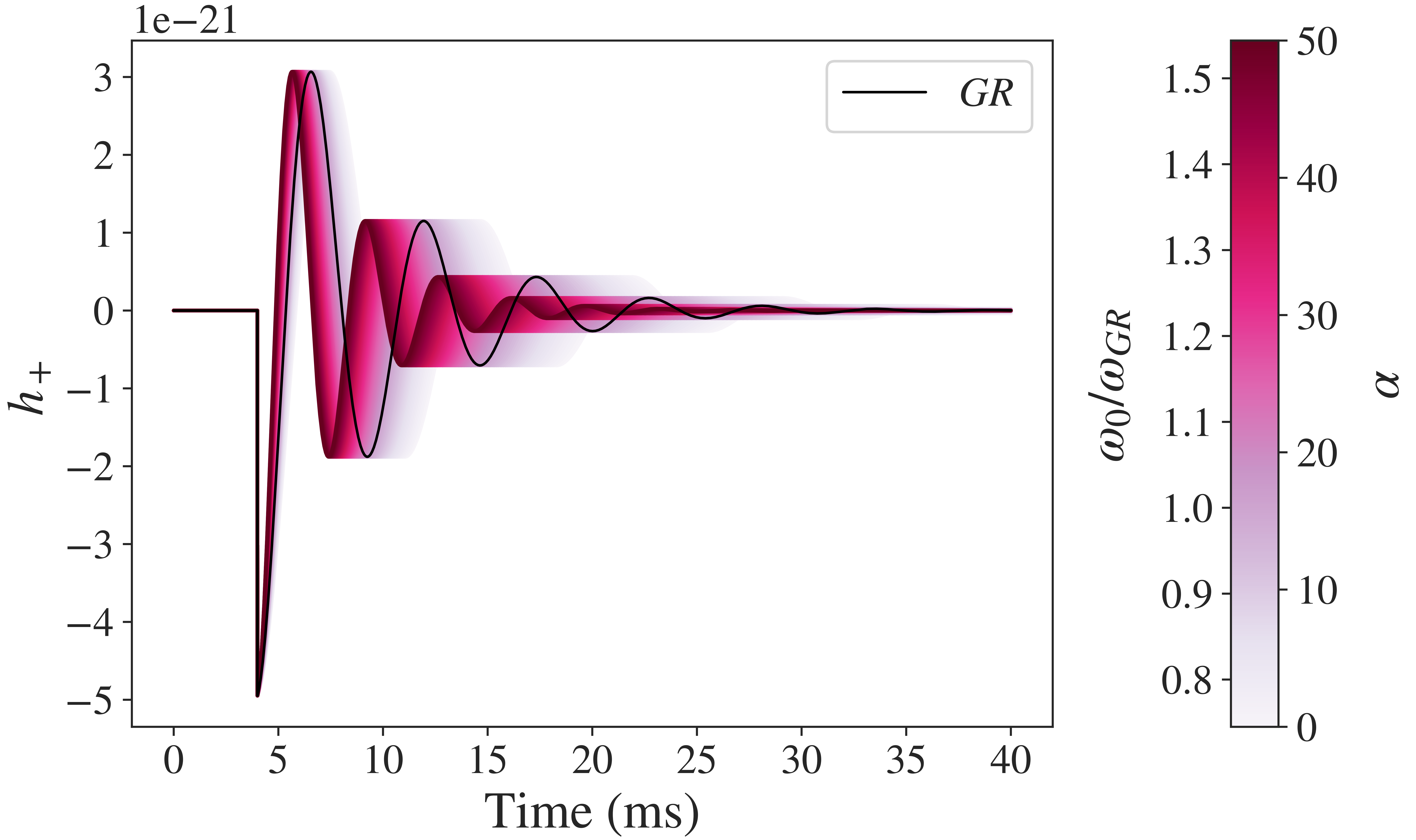
Prompt ringdown **frequency** set by the model

damping time set by an ansatz

↓

can also be inferred from the data

GR vs nGR WAVEFORMS



MEASURING RINGDOWN: PYRING

- **pyRing** is a **time-domain** (both likelihood and waveforms) parameter estimation infrastructure, currently targeting ringdown-only signals
  - Fully **python** based
  - Fully integrated with LVK code (GWpy, PESummary, LALSimulation, LALInference) and **streamlined for use in LVK publications**

LVC, O3a TGR paper - *PRD* (2021)

Tests of General Relativity with Binary Black Holes from the second LIGO–Virgo Gravitational-Wave Transient Catalog

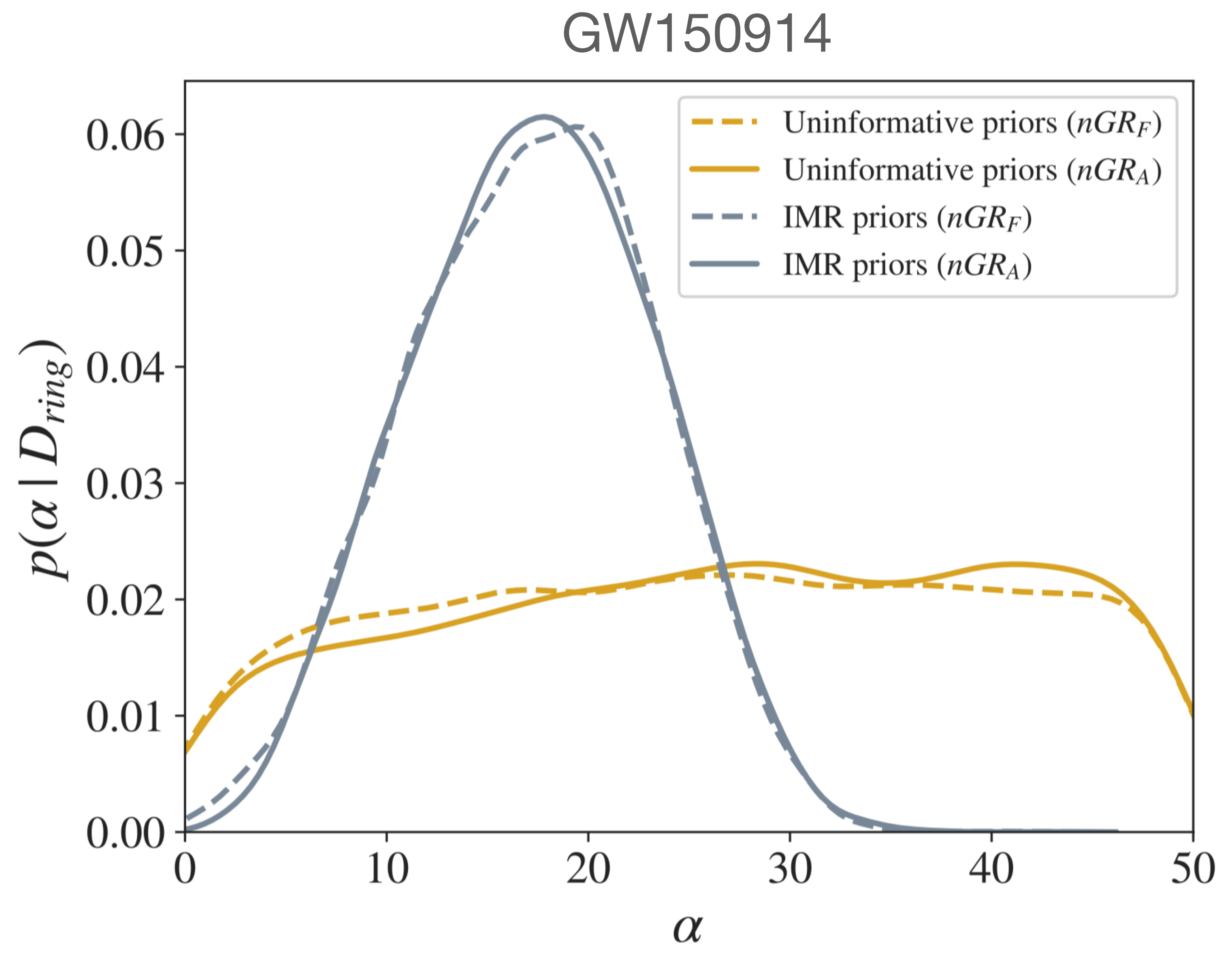
The LIGO Scientific Collaboration and the Virgo Collaboration

  - Fully **public**! Repository: **https://git.ligo.org/lscsoft/pyring**

See also talk by Carullo on Friday @ 09:30

Carullo et al., *PRD* (2019)
Isi et al., *PRL* (2019)
pyRing - [https://git.ligo.org/lscsoft/pyring]

BEYOND SINGLE-EVENT INFERENCE



- At current sensitivity, single events do not provide much information on α

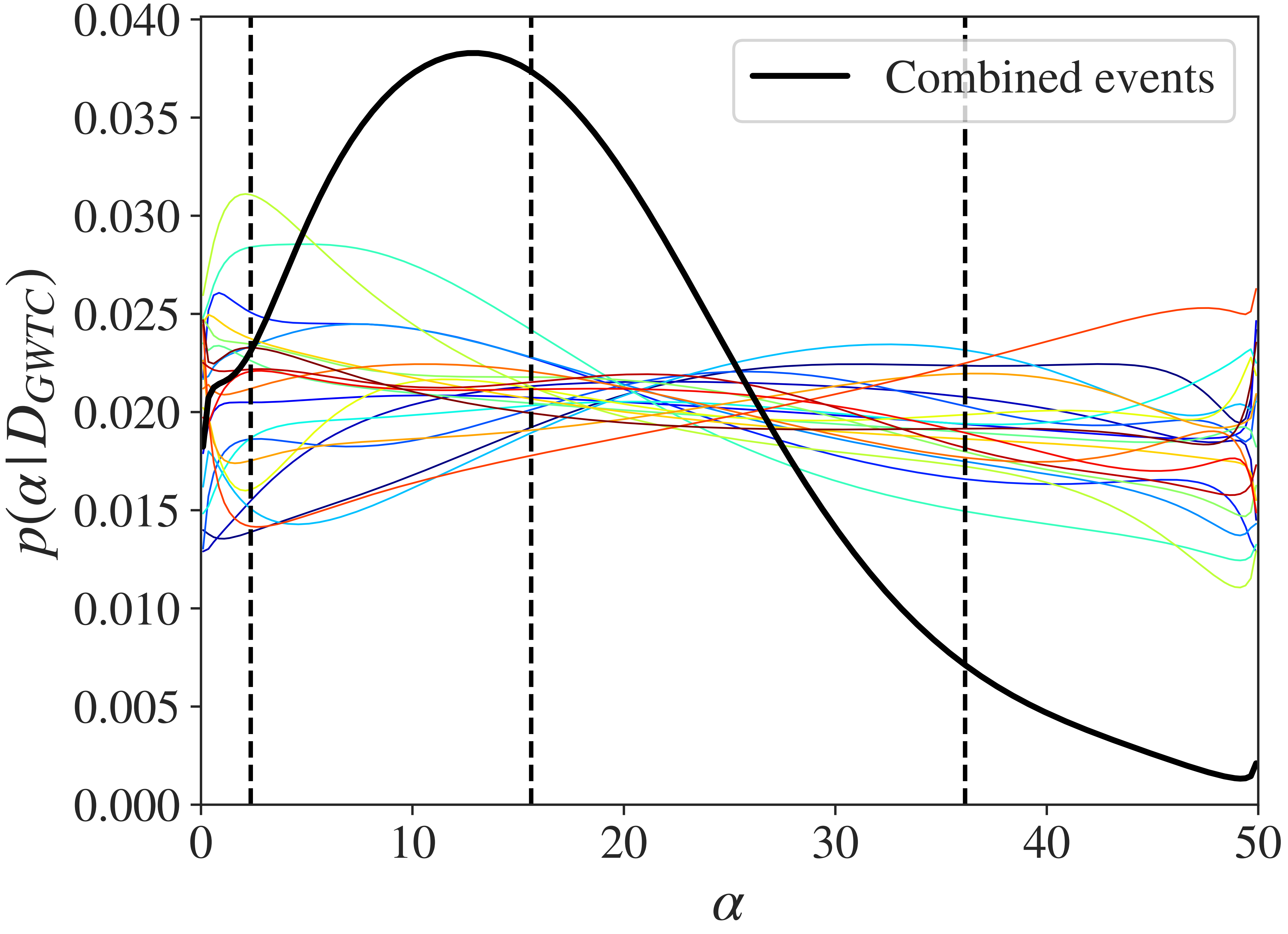
- What about the full observed population?
  Combine GWTC-2 (O1+O2+O3a) events to obtain a **joint** posterior

- Population-based model selection: $\log B_{GR}^{nGR} = \log \dfrac{P(D|nGR)}{P(D|GR)}$

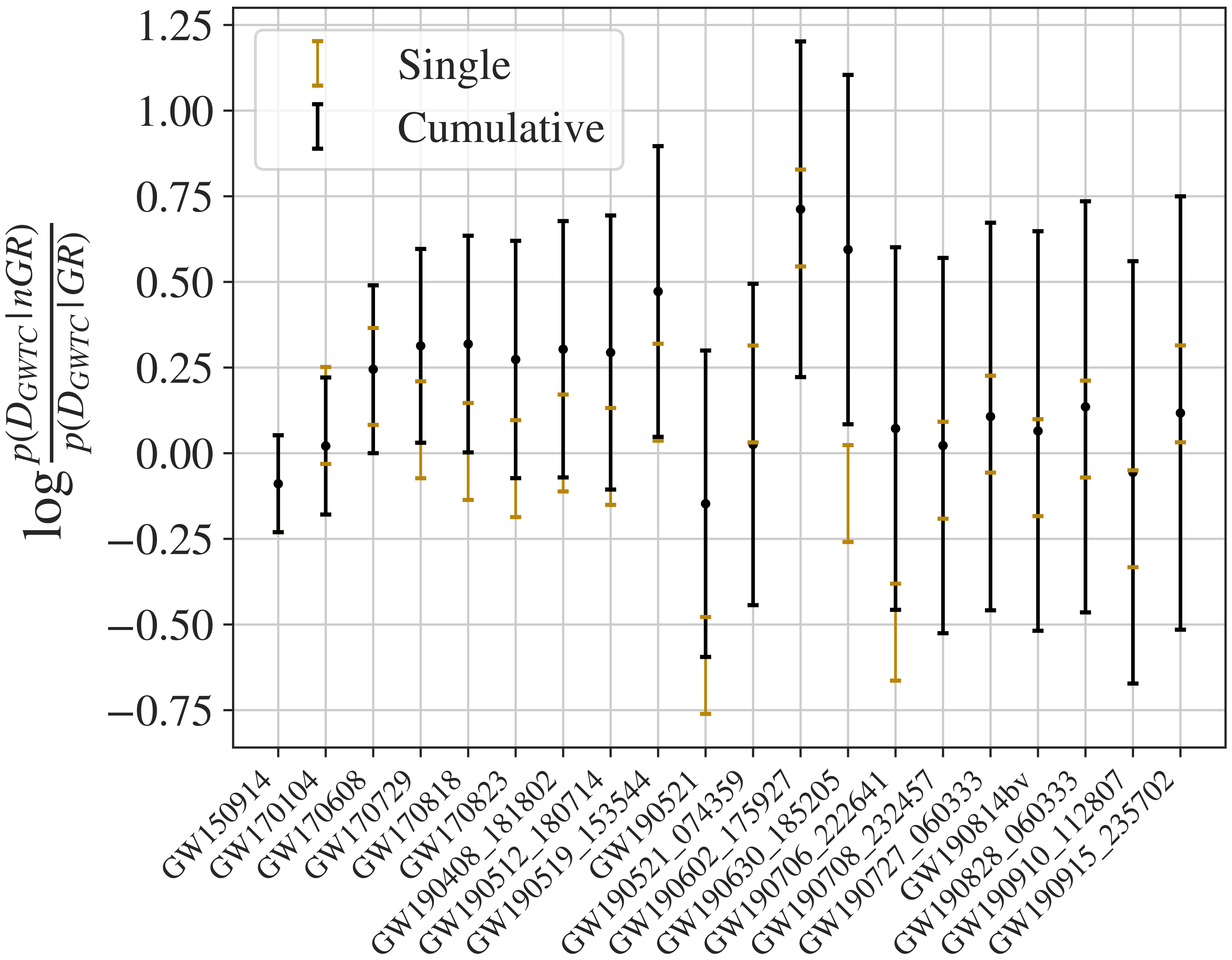
GWTC-2 EVENTS

- From the full GWTC-2 population:
  No evidence for (or against) area quantisation signatures.

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



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



SIMULATIONS

- No information from current data: will 2G ground-based detectors **ever** be able to test the area-quantisation conjecture?

- **Simulation campaign** with LIGO-Virgo detectors at design sensitivity

- Generate two BH populations: **GR BHs** and **Quantum BHs** *(GR* or *nGR)*

- Recover each population assuming either *GR* or *nGR*

GR POPULATION

- Injection: *GR* signal vs *nGR* signal

$$\omega = \omega_{GR}(M_f, a_f) \qquad \omega = \omega_0(M_f, a_f, \alpha^*)$$
$$\tau = \tau_{GR}(M_f, a_f) \qquad \tau = \tau_0(M_f, a_f, \alpha^*)$$

- Recovery: *GR* template vs *nGR* template

$$\omega = \omega_{GR}(M_f, a_f) \qquad \omega = \omega_0(M_f, a_f, \alpha)$$
$$\tau = \tau_{GR}(M_f, a_f) \qquad \tau = \tau_0(M_f, a_f, \alpha)$$

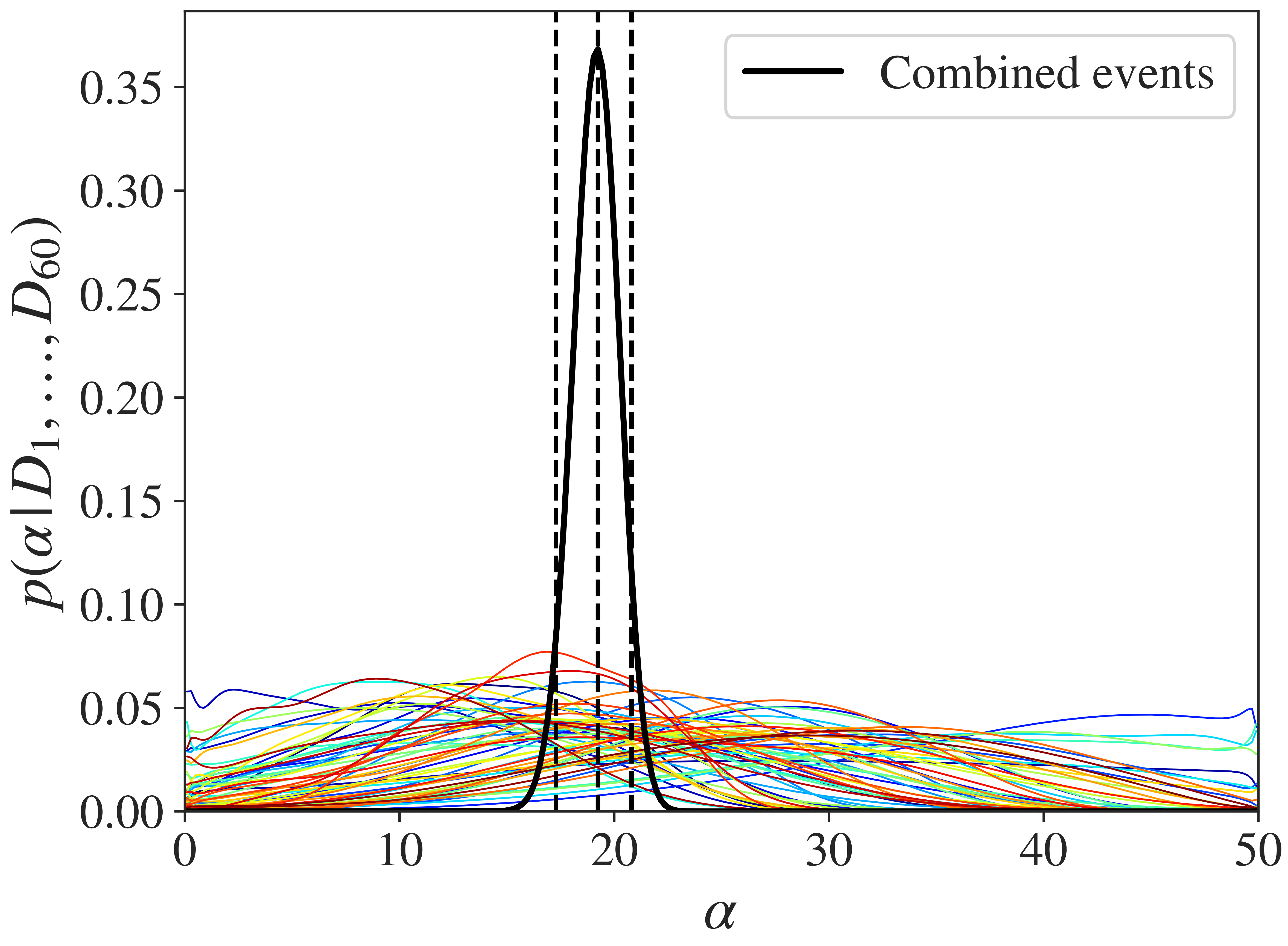
SIMULATIONS: GR POPULATION

Posteriors can deceive you!

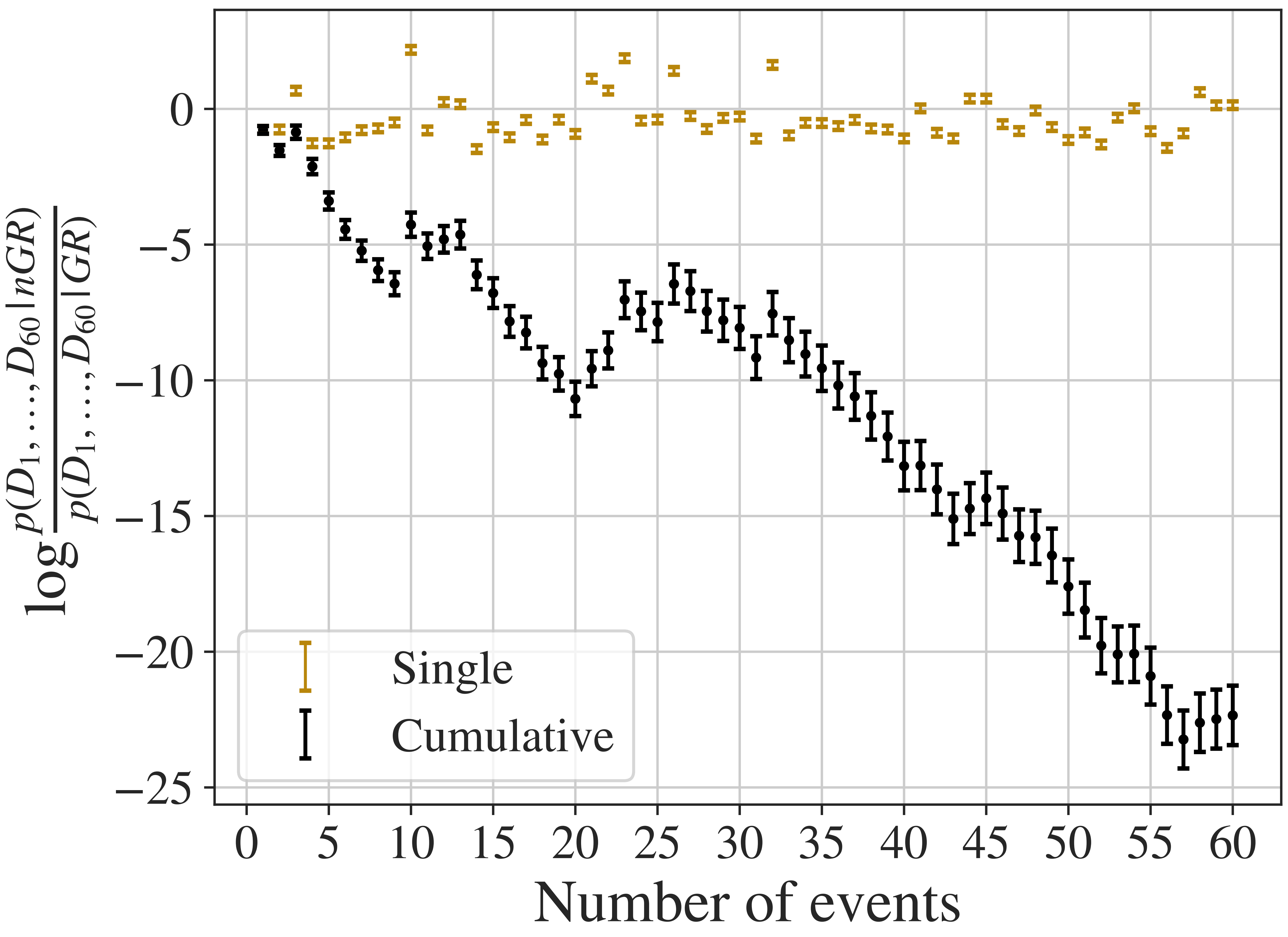
BUT

Bayes' Factors don't!

$19.0^{+2.0}_{-2.0}$



$\log B^{nGR}_{GR} = -22.3 \pm 1.1$



No GR limit in this model

nGR POPULATION

- Injection: *GR* signal vs *nGR* signal

$$\omega = \omega_{GR}(M_f, a_f) \qquad \omega = \omega_0(M_f, a_f, \alpha^*)$$
$$\tau = \tau_{GR}(M_f, a_f) \qquad \tau = \tau_0(M_f, a_f, \alpha^*)$$

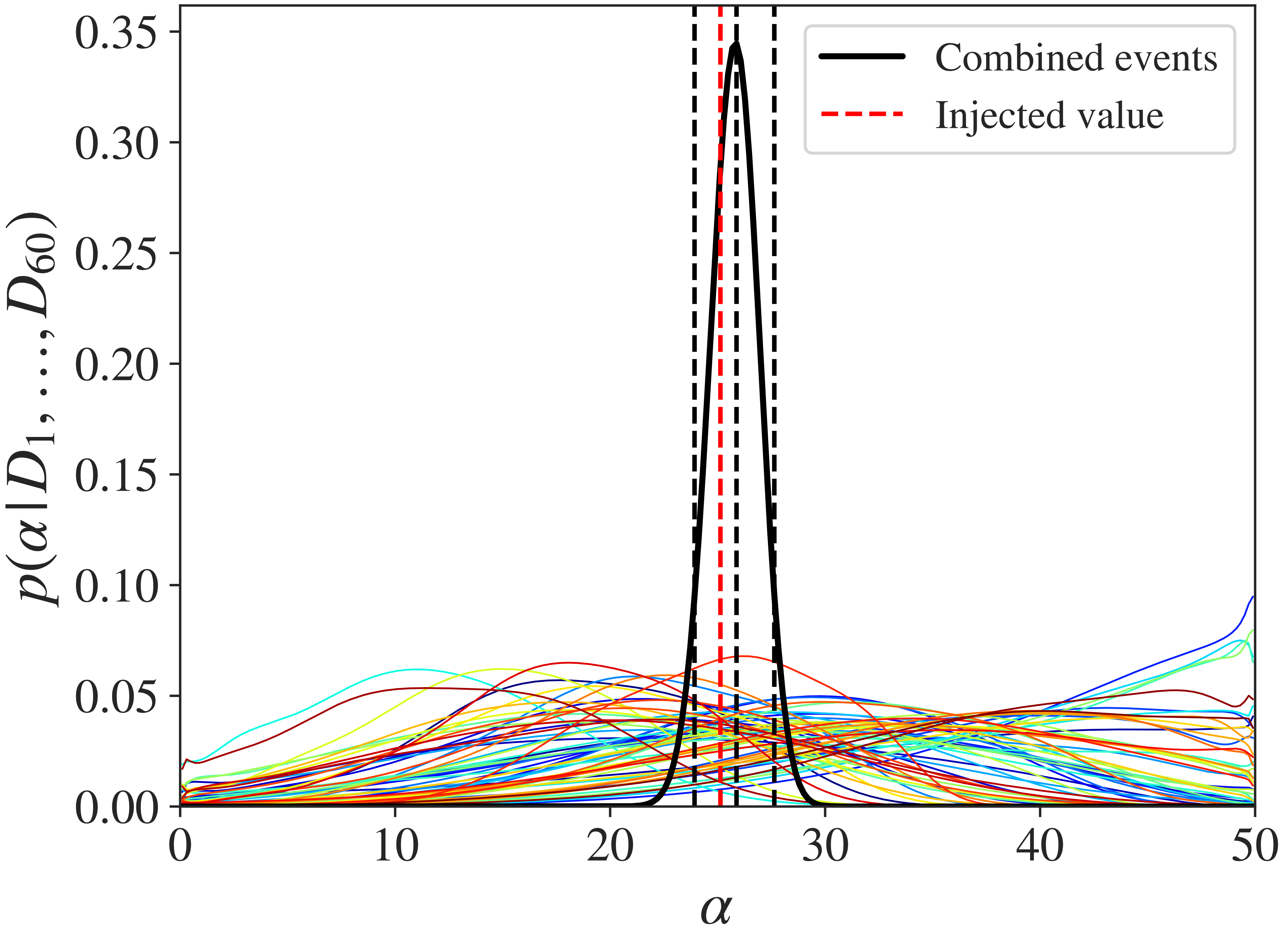
- Recovery: *GR* template vs *nGR* template

$$\omega = \omega_{GR}(M_f, a_f) \qquad \omega = \omega_0(M_f, a_f, \alpha)$$
$$\tau = \tau_{GR}(M_f, a_f) \qquad \tau = \tau_0(M_f, a_f, \alpha)$$

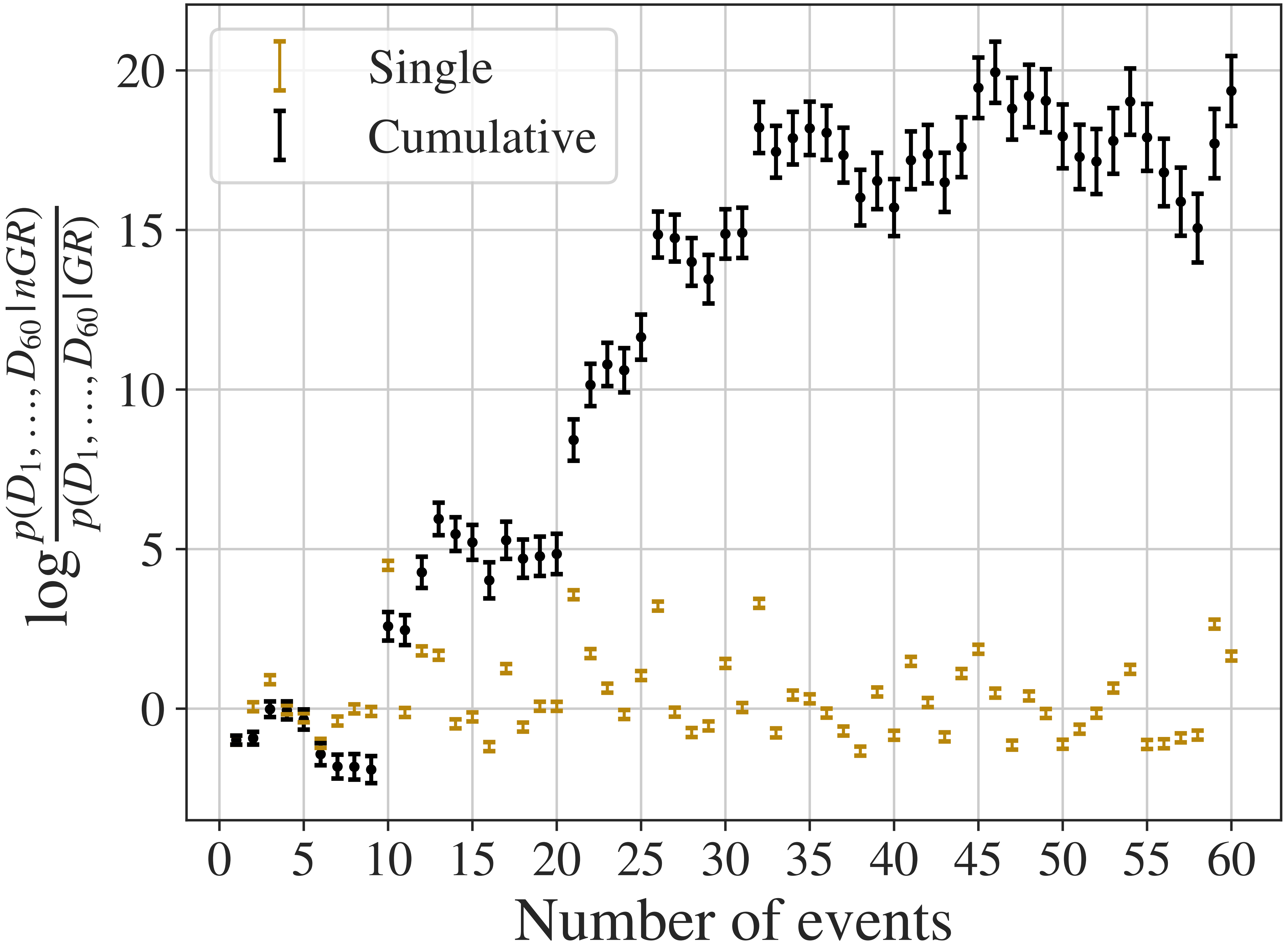
SIMULATIONS: nGR POPULATION

Bekenstein value
$\alpha_B \approx 25.1$

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



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



CONCLUSIONS AND PERSPECTIVES

Laghi et al., *CQG* (2021)

- The Bekenstein-Mukhanov **area quantisation** conjecture in the Foit-Kleban formulation:
  - Is **not incompatible** with current ringdown GW observations
  - **Can be tested** with ringdown signals detected by **current** (upgraded) ground-based **GW detectors**
- **Bayes' Factors** are **crucial** to correctly interpret results

OUTLOOK

- **Complete** the **Foit-Kleban model** with a theoretically-motivated τ_0
- Repeat the analysis adding an horizon reflective coefficient to test other observational signatures of this conjecture (**echoes**)

Cardoso, Foit, Kleban, *JCAP* (2019)
Agullo et al., *PRL* (2021)

Thank you for your attention