Adventures in gravitational-wave astronomy: Testing for hair, memory, and eccentricity

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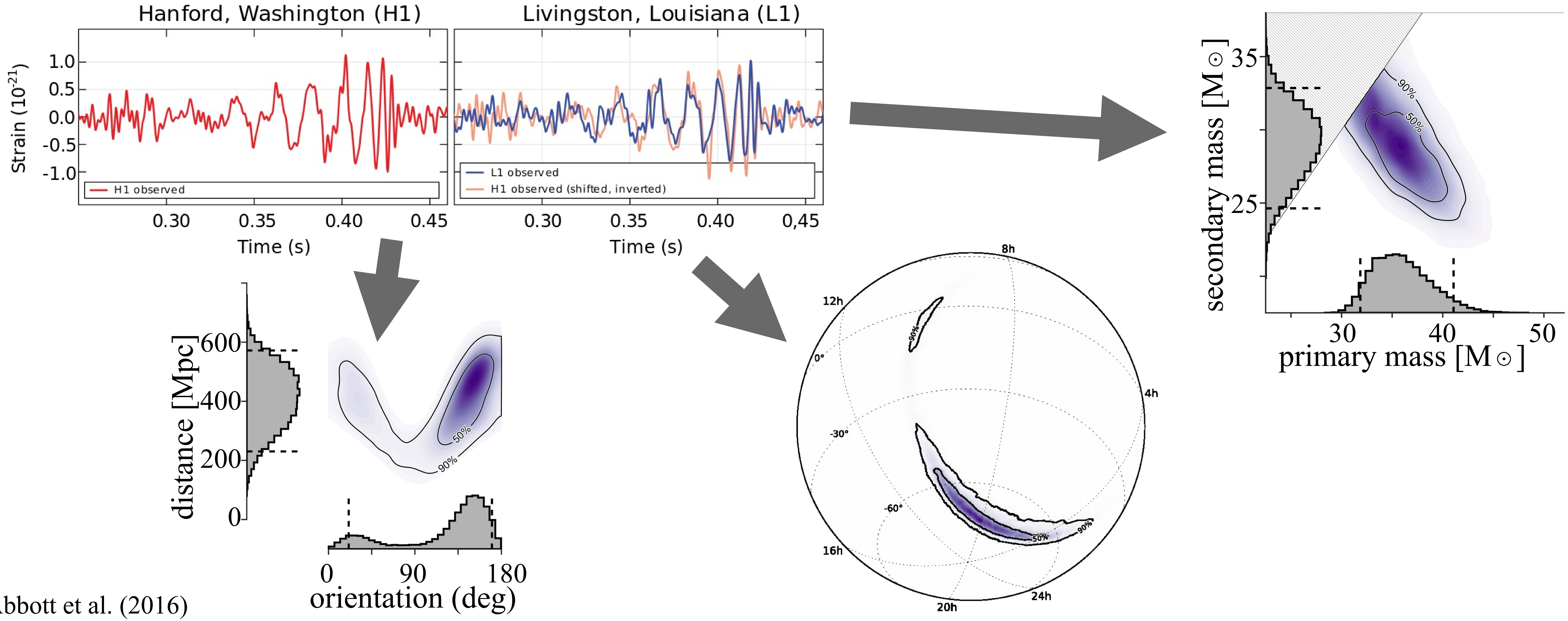
MONASH University

OzGrav

CONTENTS

- Determining gravitational-wave source physics
  - Black hole formation through eccentricity measurements
  - Gravitational-wave memory
  - Challenges testing of the no-hair theorem



Abbott et al. (2016)

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Masses in the Stellar Graveyard

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Masses in the Stellar Graveyard

Masses in the Stellar Graveyard

Masses in the Stellar Graveyard

- Most massive system measured to date!
- Eccentric orbit (Romero-Shaw, PL & Thrane 2020)
- How did it form? Dynamical merger / second generation!?

Masses in the Stellar Graveyard

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern


This waveform is just right.
I now know the right masses….
(with some posterior probability)
L1 observed
H1 observed (shifted, inverted)

The user-friendly Bayesian inference library

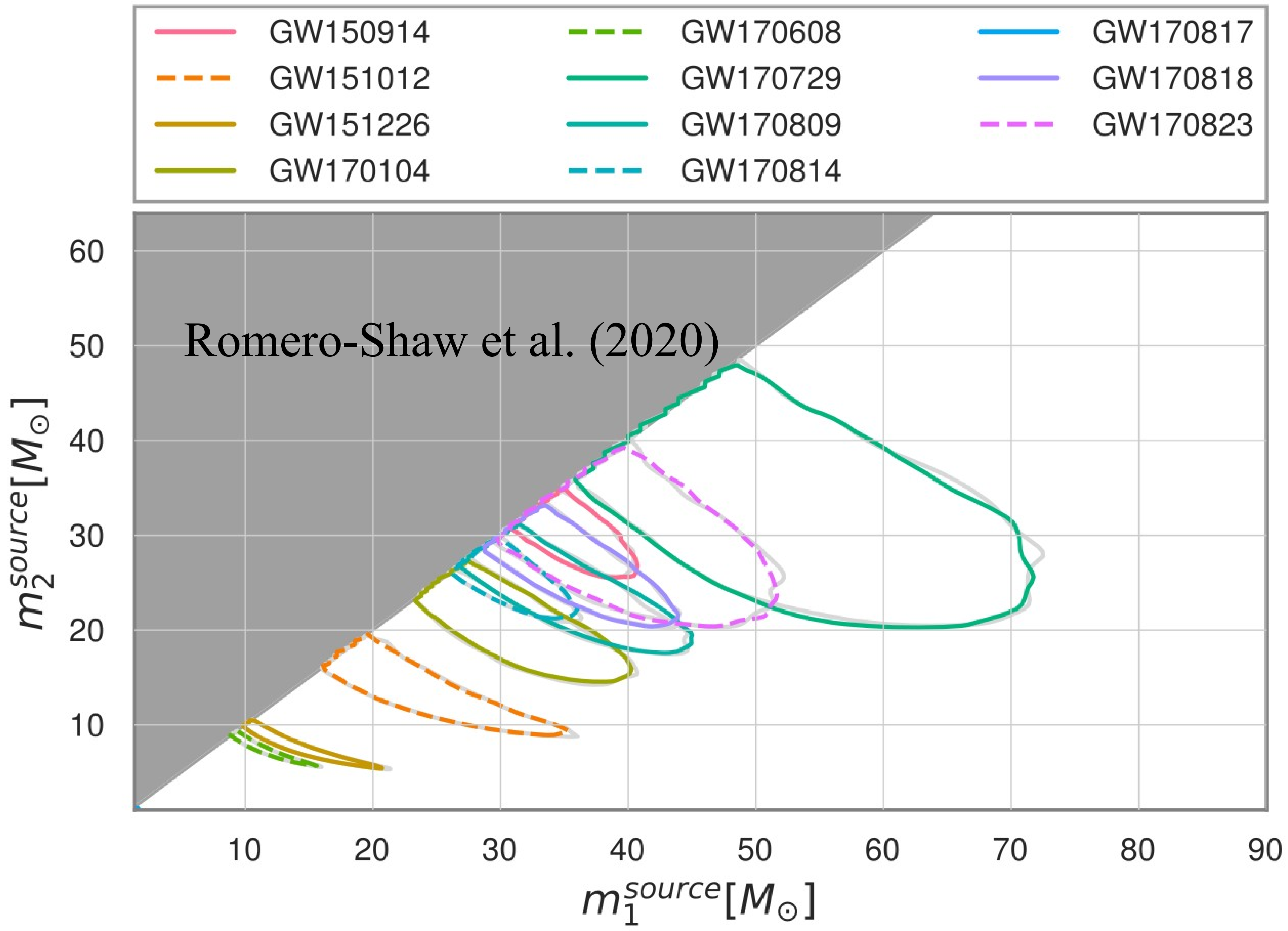
Ashton, Hübner, PL, Talbot + (2019)

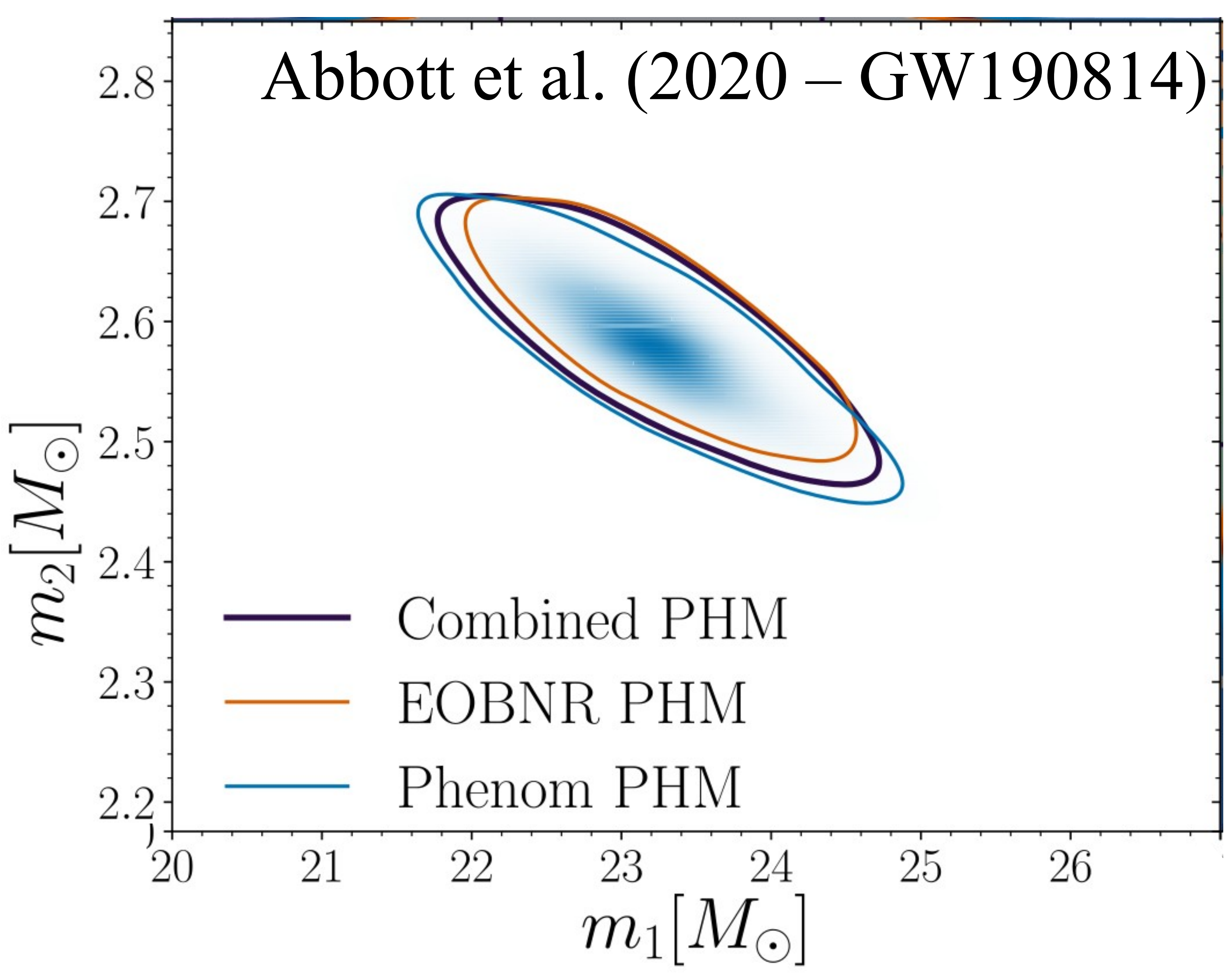
Romero-Shaw + (2020)

A versatile parameter-estimation code being used for production science by LIGO/Virgo collaboration

git.ligo.org/lscsoft/bilby/

pip install bilby





- User friendly, open source, modular, easily accessible
- LIGO production science
  - Special events (e.g., GW190412, GW190425, GW190814, GW190521, …)
  - Catalogues
  - Populations
  - Tests of GR, equation of state, ...
  - Synthetic and real data
- Many examples, user forum, help, etc.

Topics in Gravity

1. Orbital eccentricty and black hole formation
2. Gravitational-wave memory
3. The no-hair theorem

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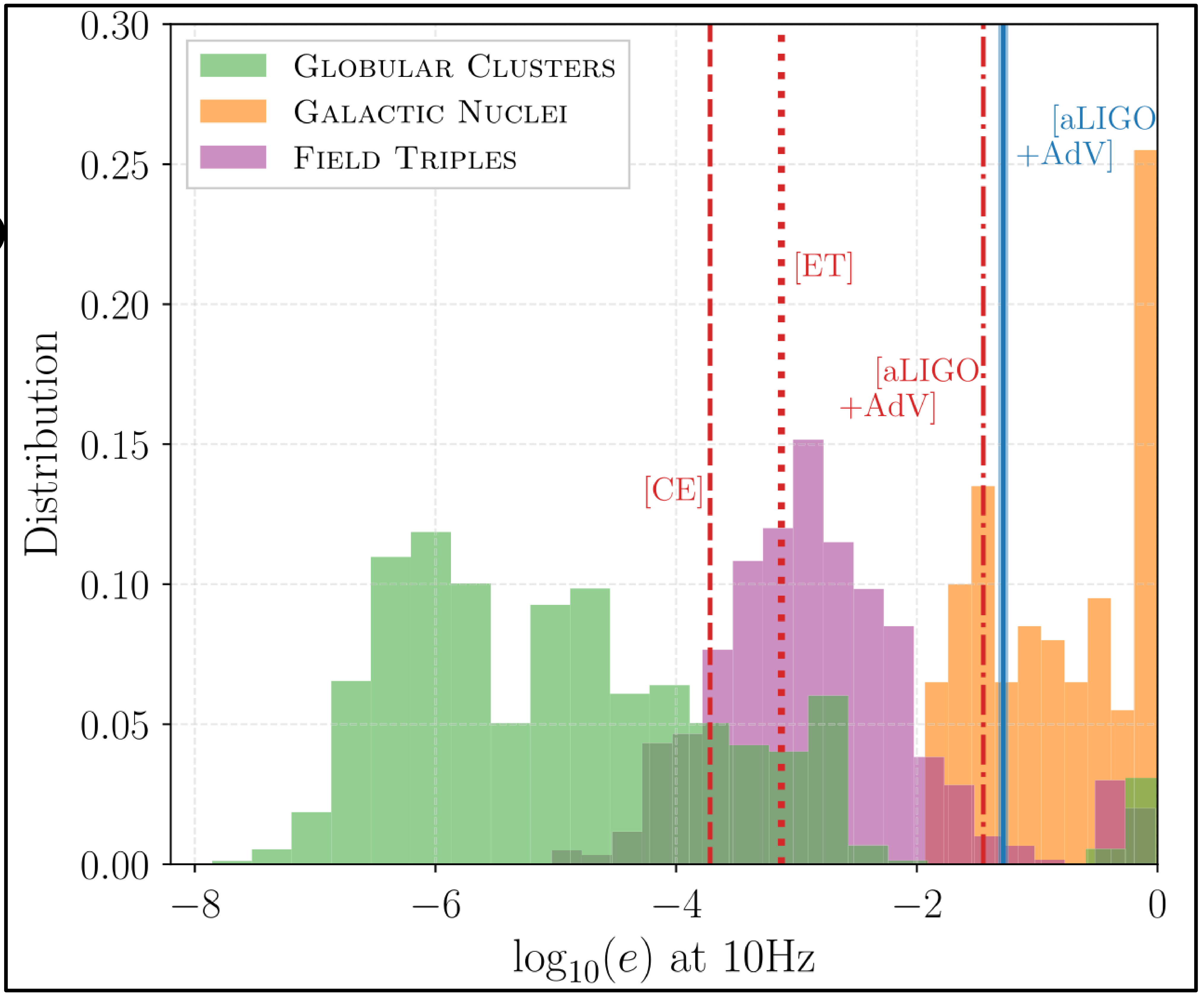
Measuring orbital eccentricity

How do LIGO/Virgo black hole binaries form?

binary stellar evolution

dynamical capture

Zero



Lower, Thrane, Lasky & Smith (2018)

isotropically-distributed spins

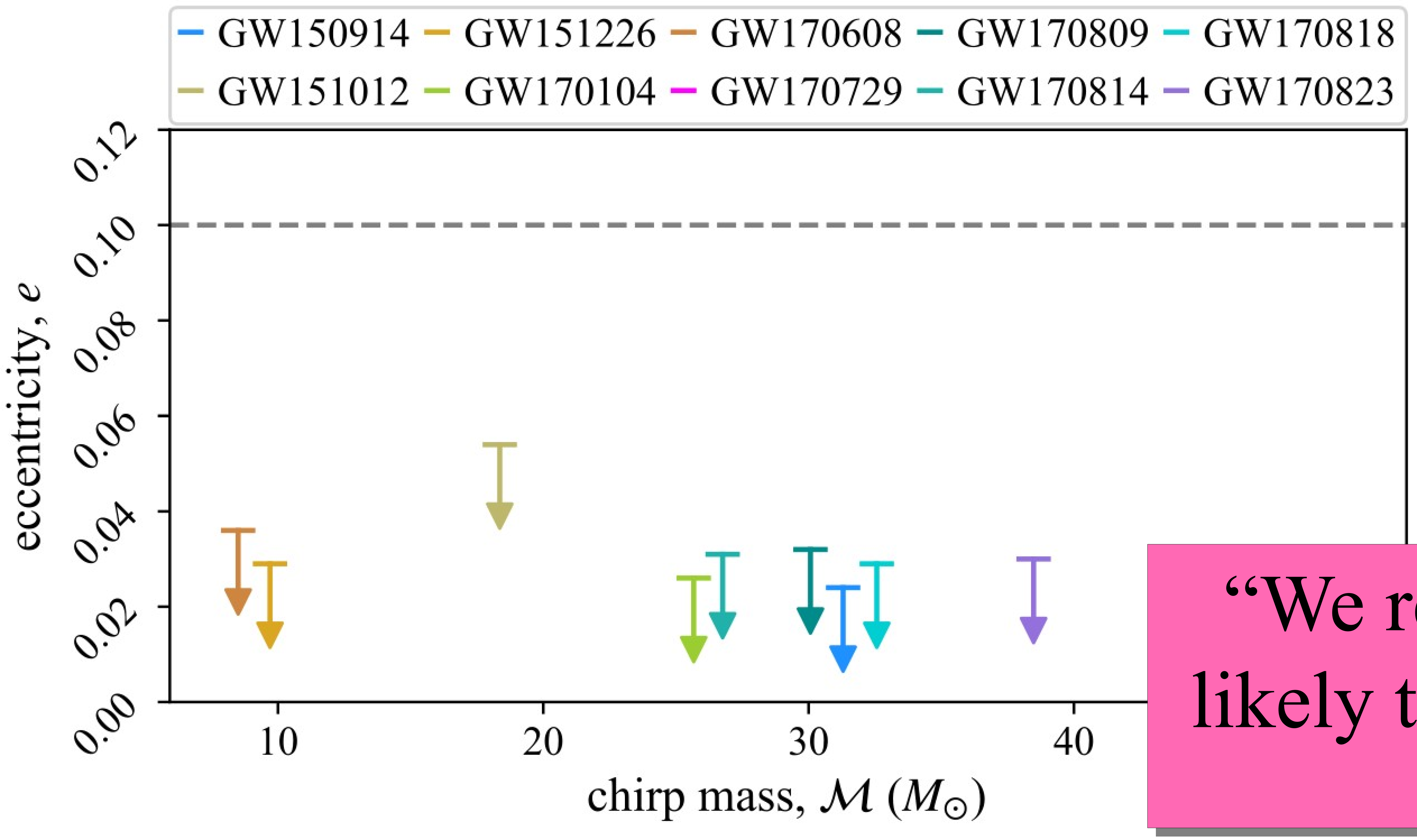
non-zero orbital eccentricity

Can we distinguish populations by measuring orbital eccentricity?

Measuring orbital eccentricity

GWTC1 (first ten discovered mergers)

Romero-Shaw, Lasky, Thrane (2019)



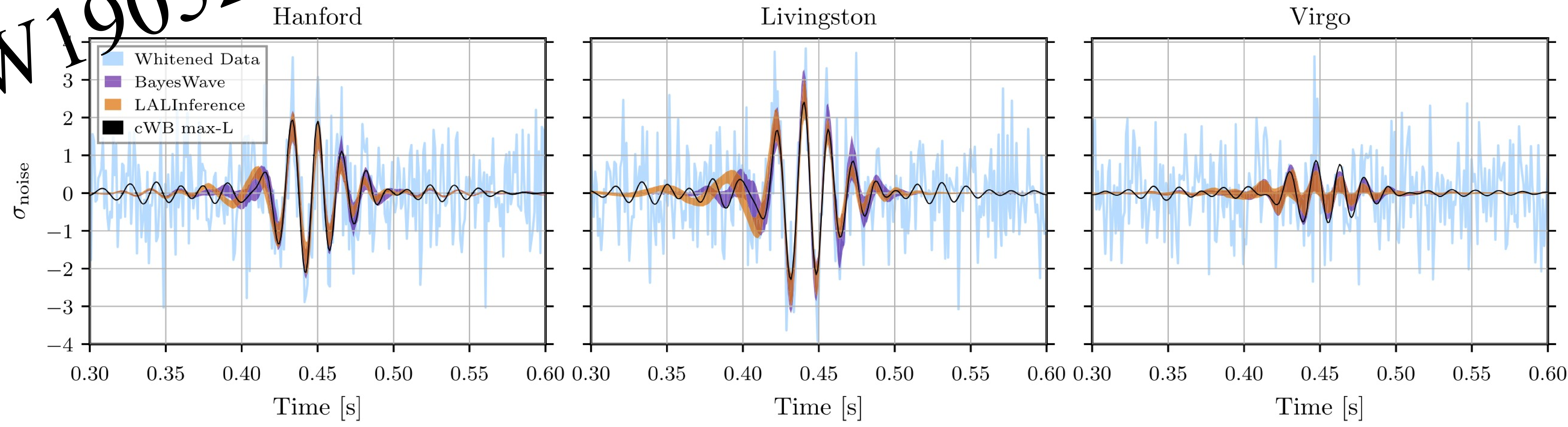
~5% of binaries formed in globular clusters should have non-zero eccentricity

(e.g. Samsing, 2018; Rodriguez et al 2018)

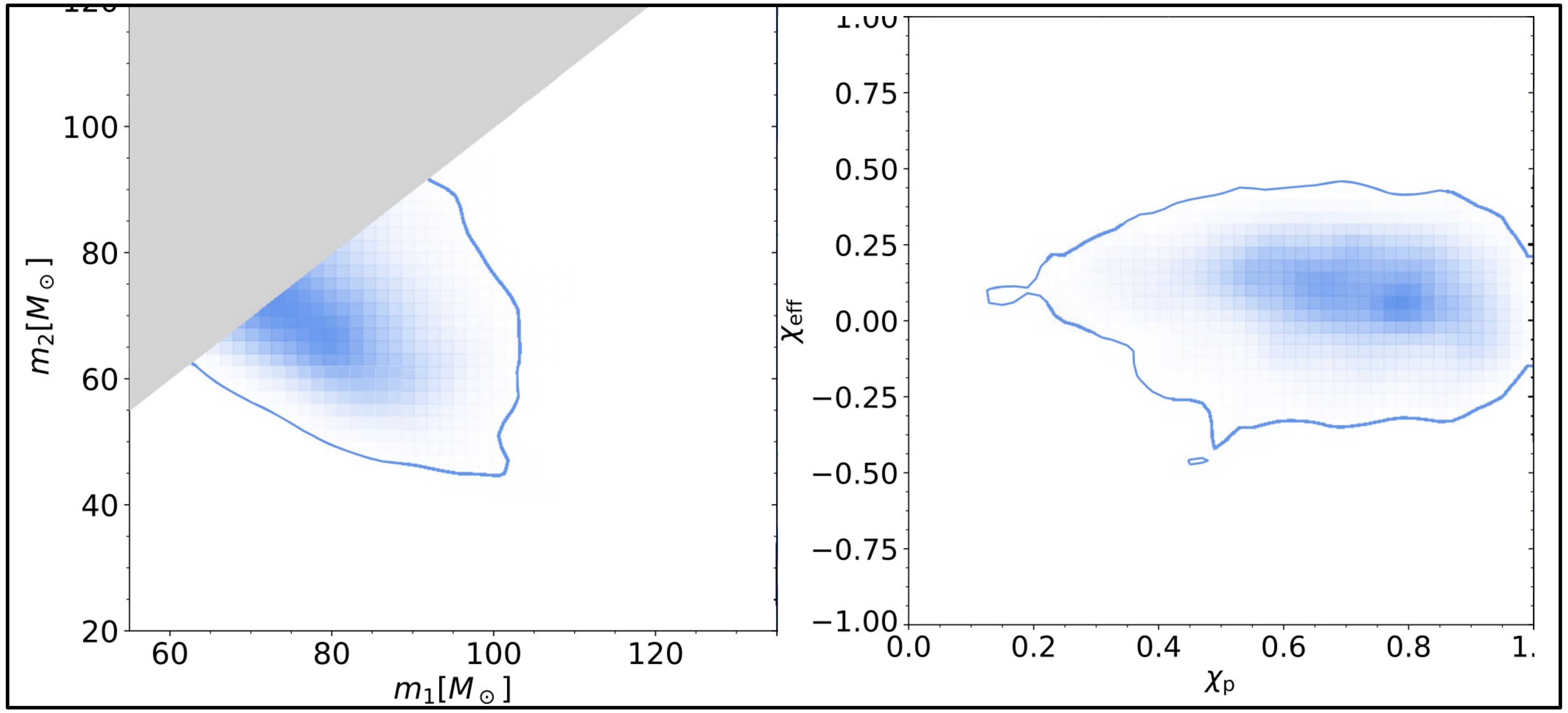
"We require ≈15 events before it becomes more likely than not to detect eccentricity if all mergers are produced in globular clusters"

Romero-Shaw, Lasky, Thrane (2019)

Introducing GW190521

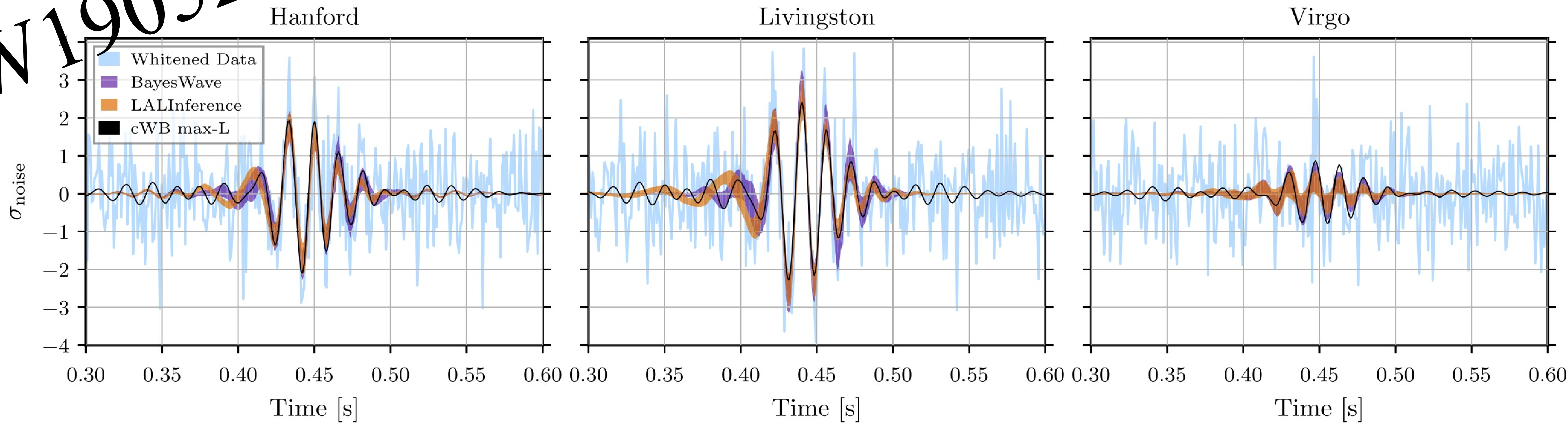


Abbott et al. (2020)

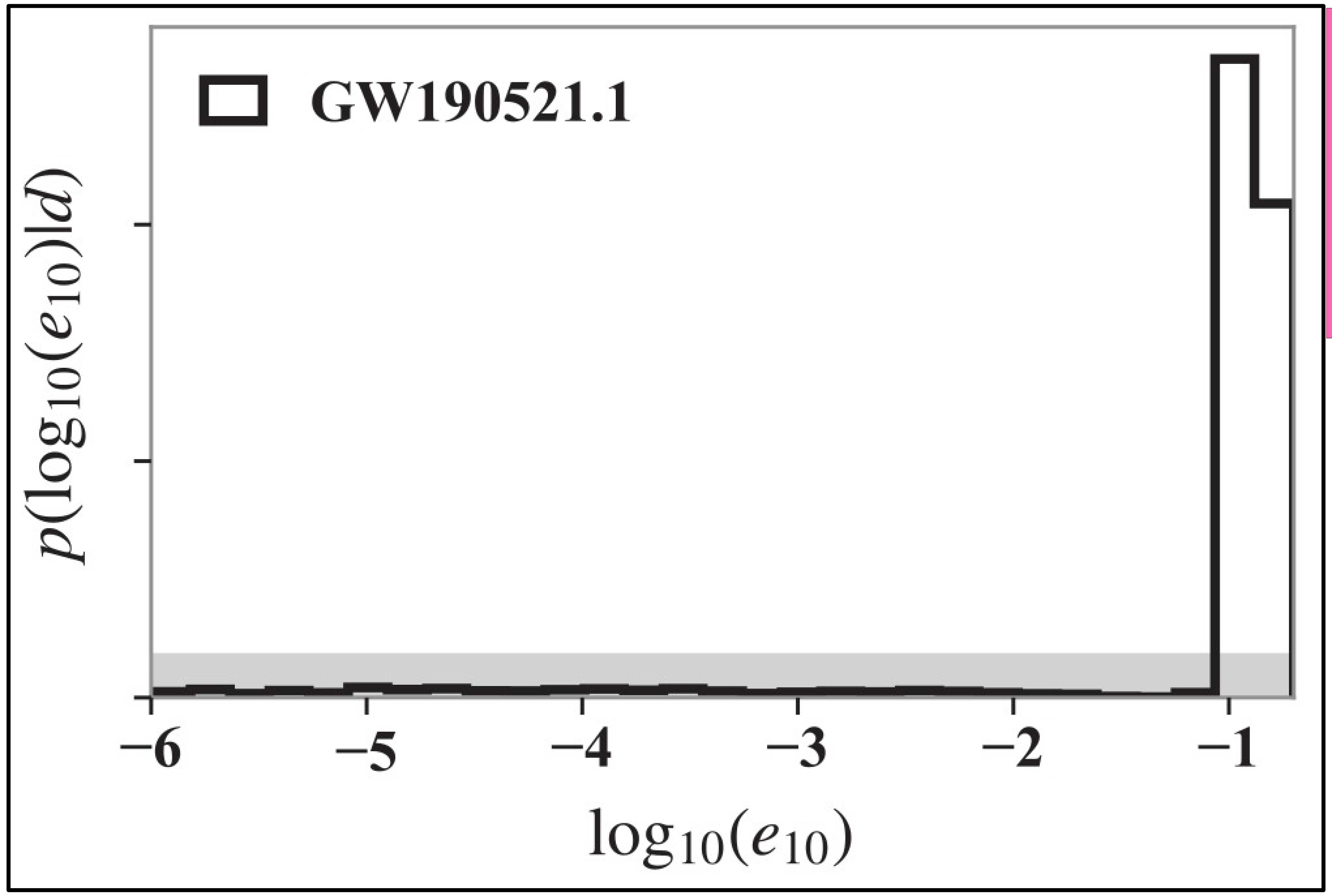


- Only analysed with quasi-circular templates
- Evidence of precession suggests dynamical formation
- Second-generation merger?

Introducing GW190521



Romero-Shaw, Lasky, Thrane & Calderon Bustillo (2020)



"… the data prefer a signal with eccentricity $e \geq 0.1$ at 10 Hz to a nonprecessing, quasi-circular signal, with a log Bayes factor ln B = 5.0"

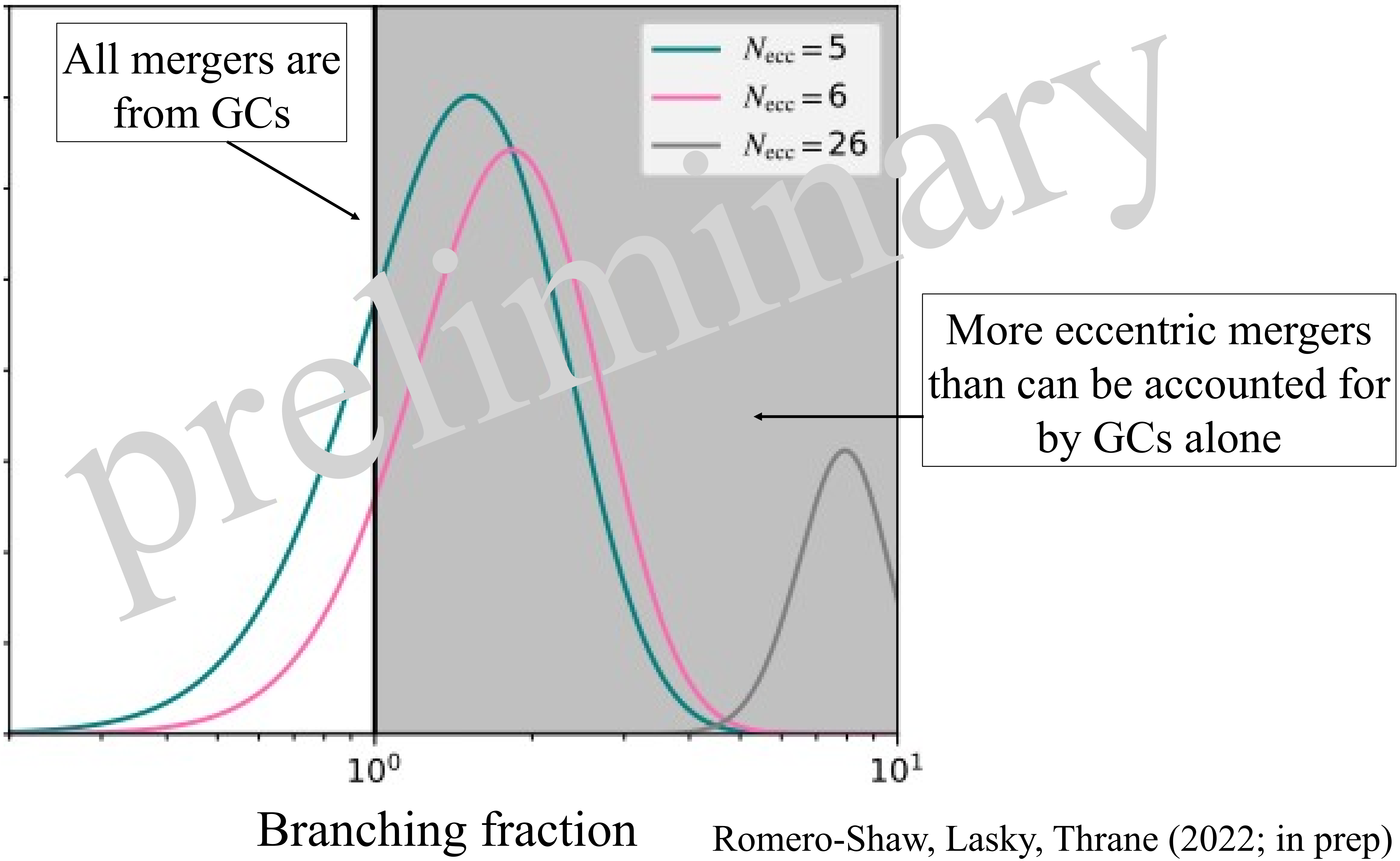
Words of caution:

- Our waveforms don't go above $e = 0.2$
- We find precession and eccentricity can be confused in GW190521-like signals
- Waveform models for parameter estimation with eccentricity and precession don't exist (see also Gayathri et al. 2022).

A catalogue of events

Romero-Shaw, Lasky, Thrane (2022; in prep)

A catalogue of events

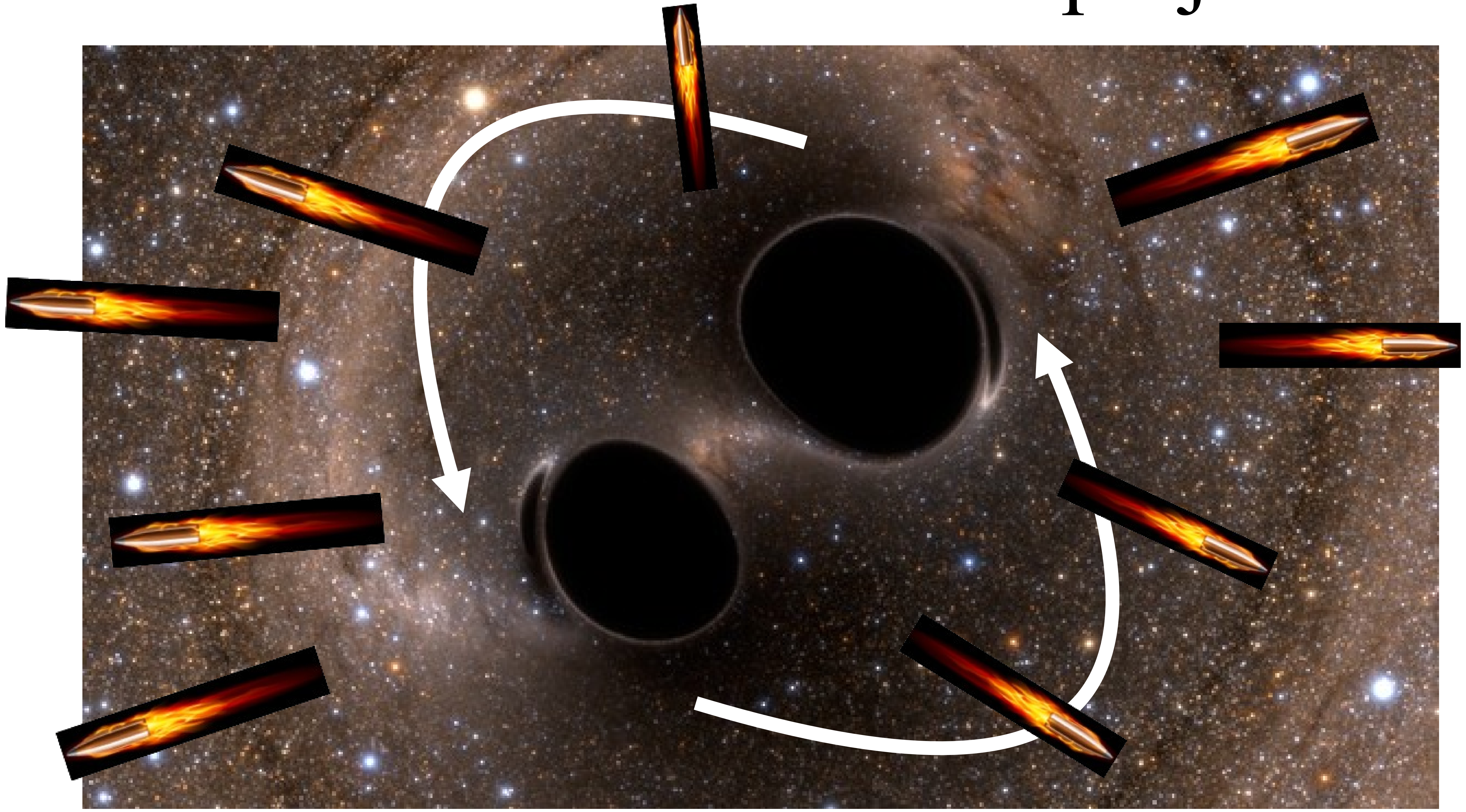


Romero-Shaw, Lasky, Thrane (2022; in prep)

Gravitational-wave memory

$$h \propto \ddot{Q}$$

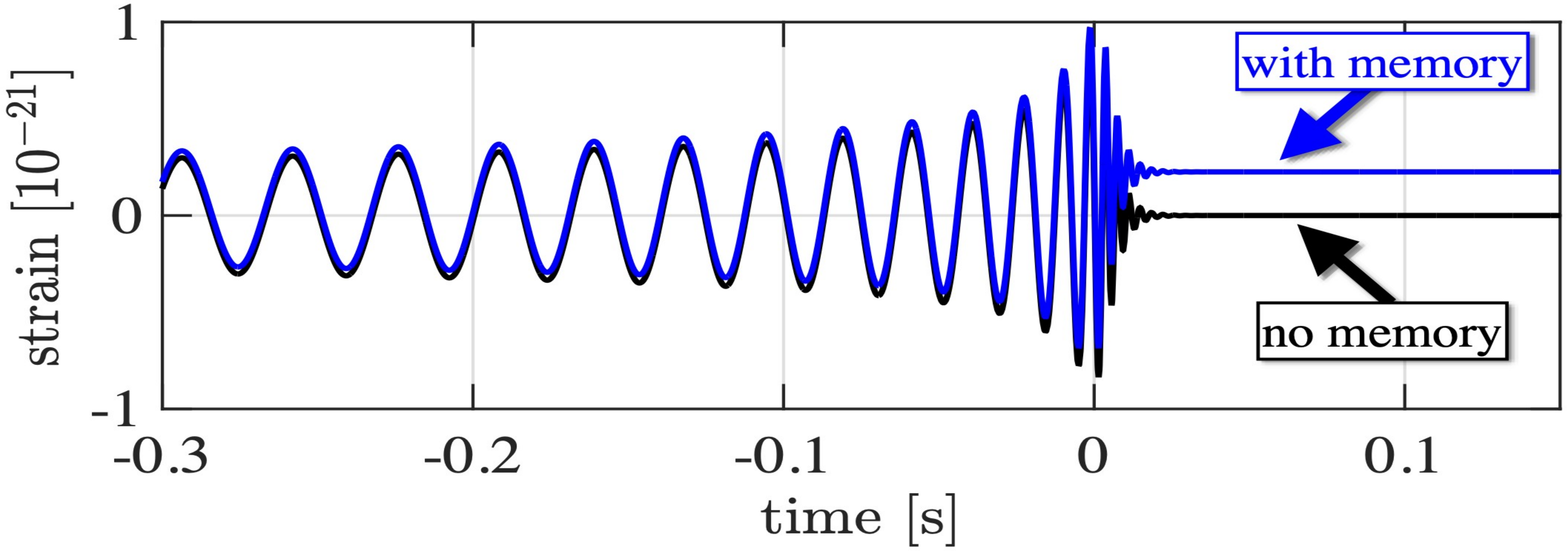
- Non-zero from inspiral of point masses
- Also from anisotropic distribution of projectiles (**gravitons**) leaving the source



Alternatively, think of gravitational waves providing extra source term

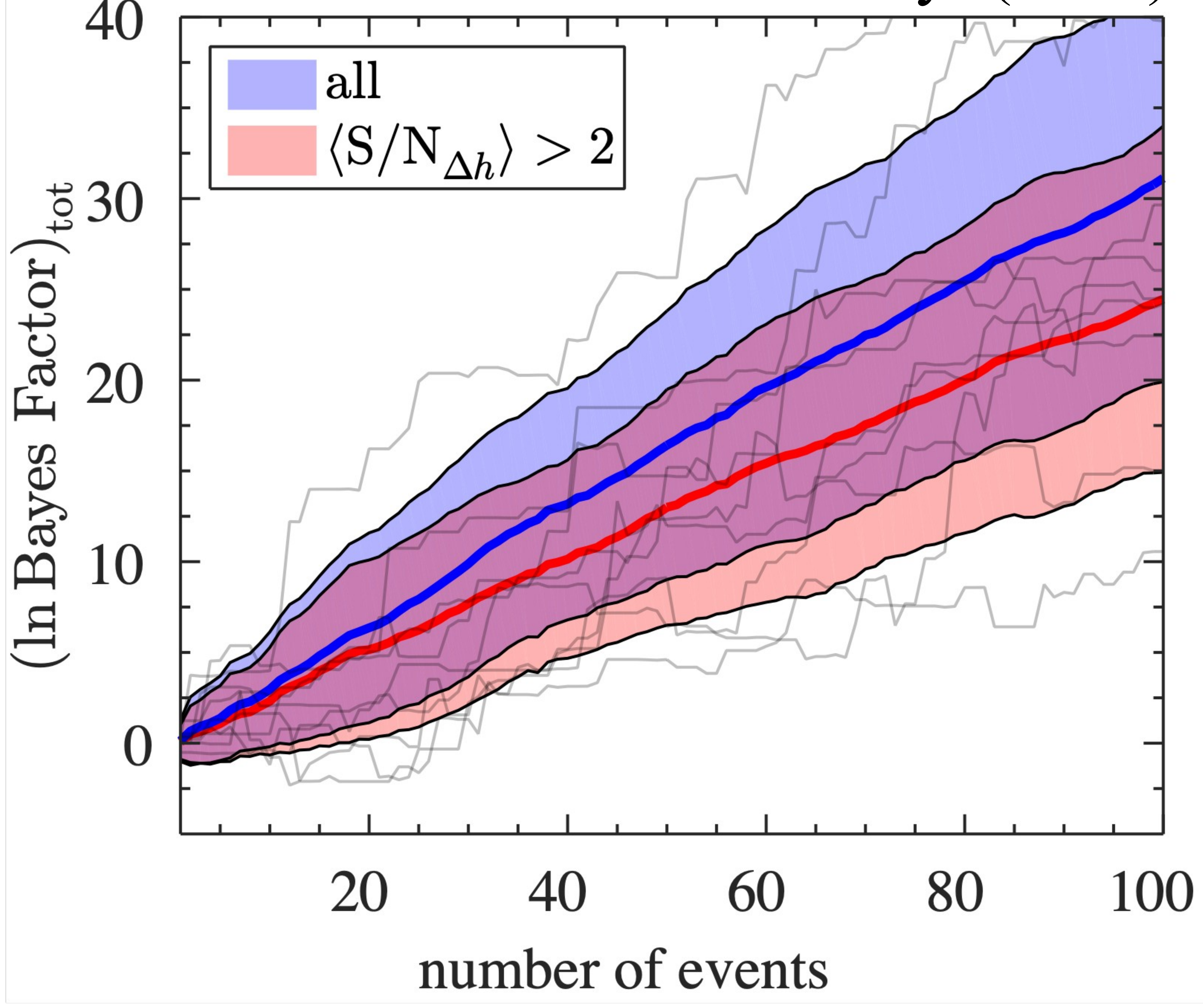
e.g., Braginsky & Thorne (1987), Christodoulou (1991), Thorne (1992)

Gravitational-wave memory



- Too small to measure in single LIGO/Virgo detection (~1/20 amplitude)
- Can detect statistical effect over many mergers (Lasky+2016)
- Require ~50 **loud** events

Lasky+(2016)

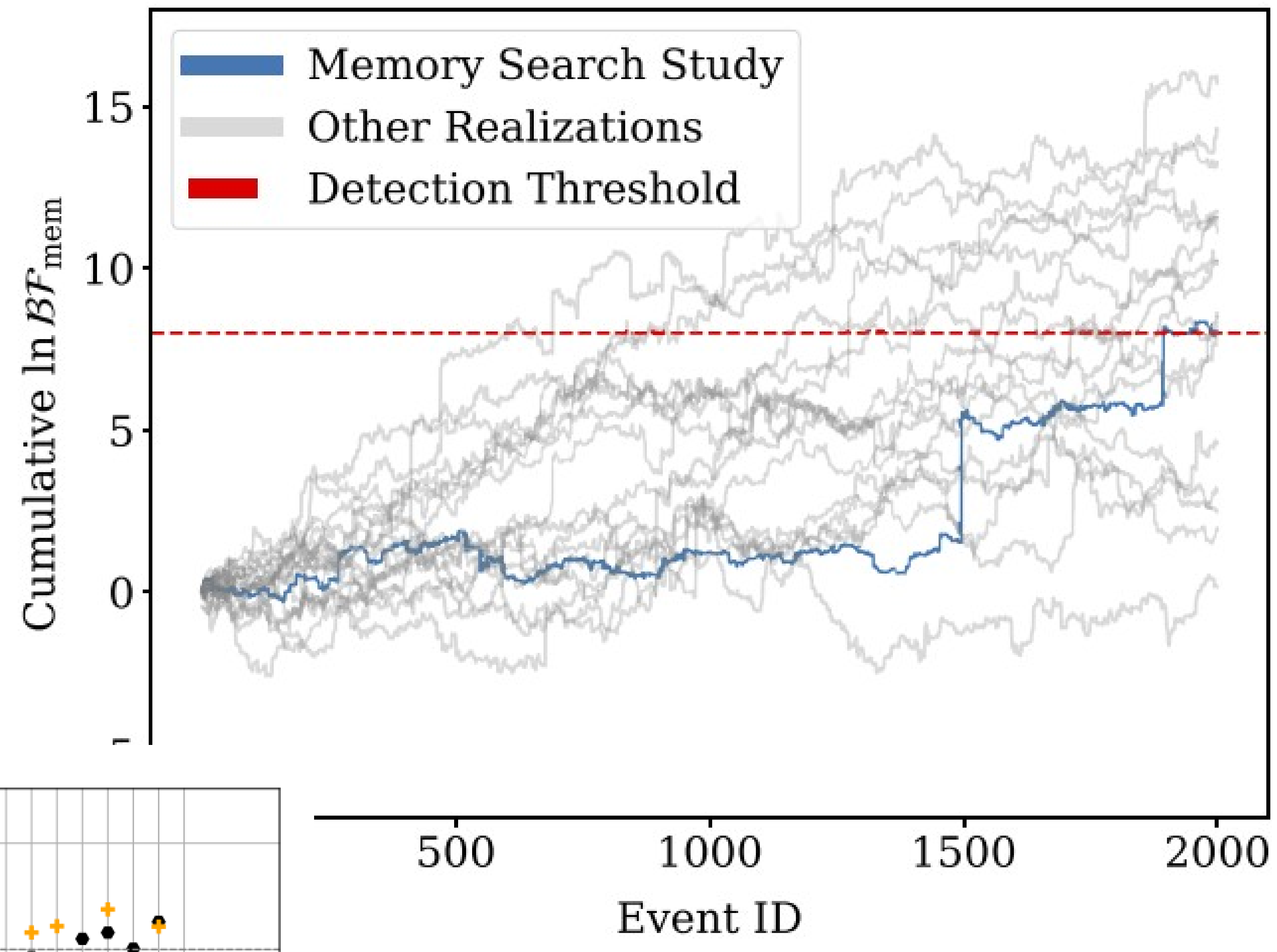


Gravitational-wave memory

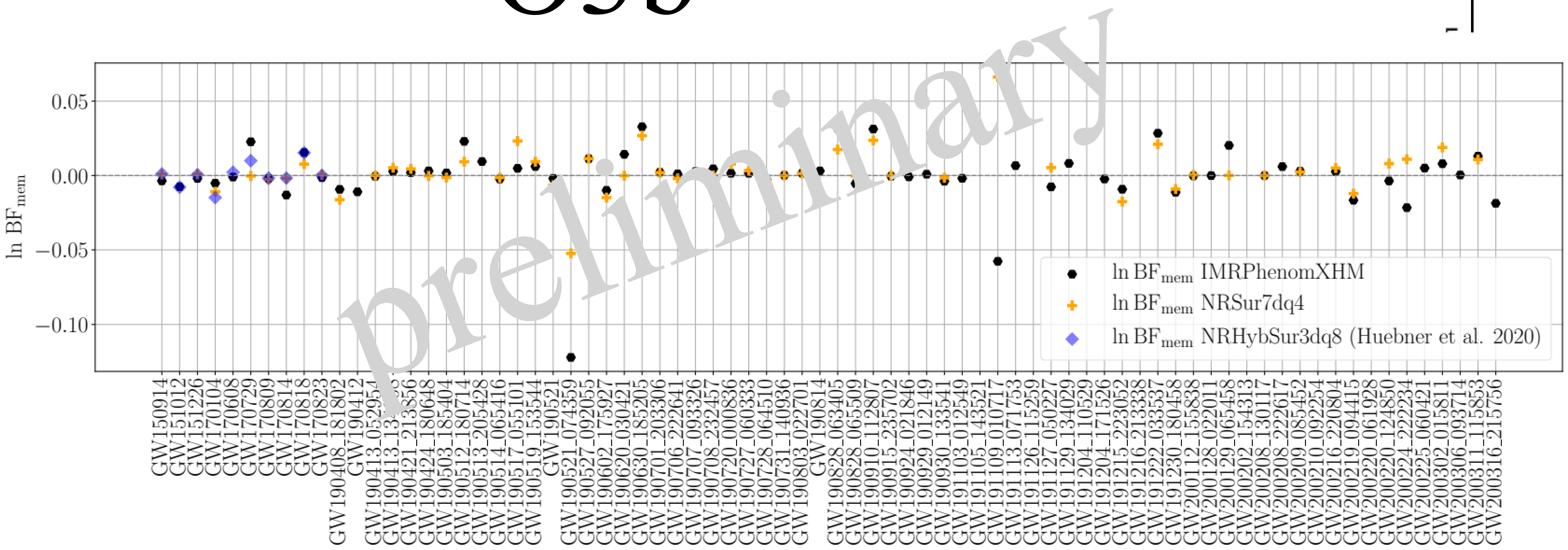
O3a

Huebner, Talbot, Lasky & Thrane (2021)

$$\ln \mathrm{BF}_{\mathrm{mem}} = 0.049$$



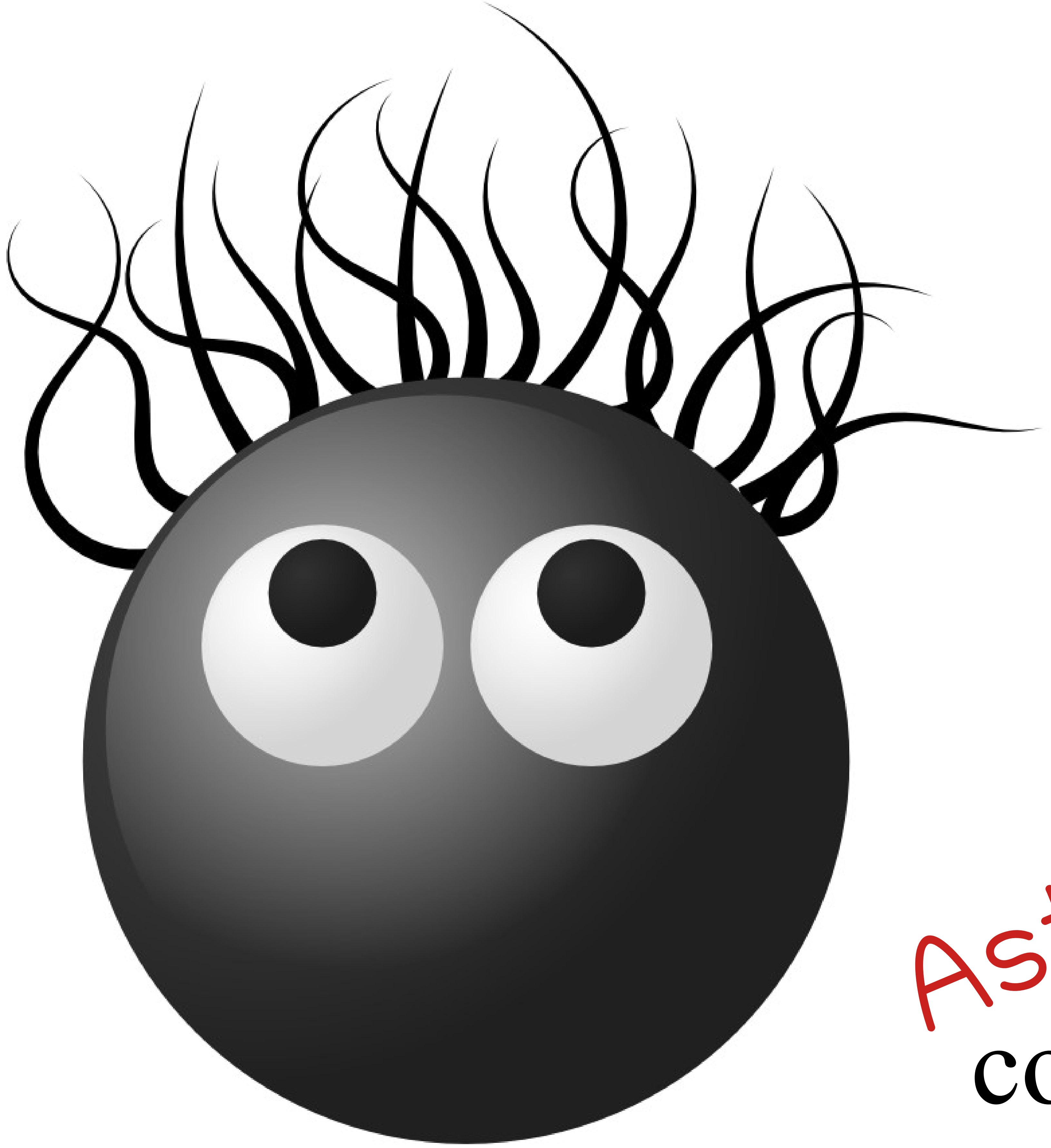
O3b

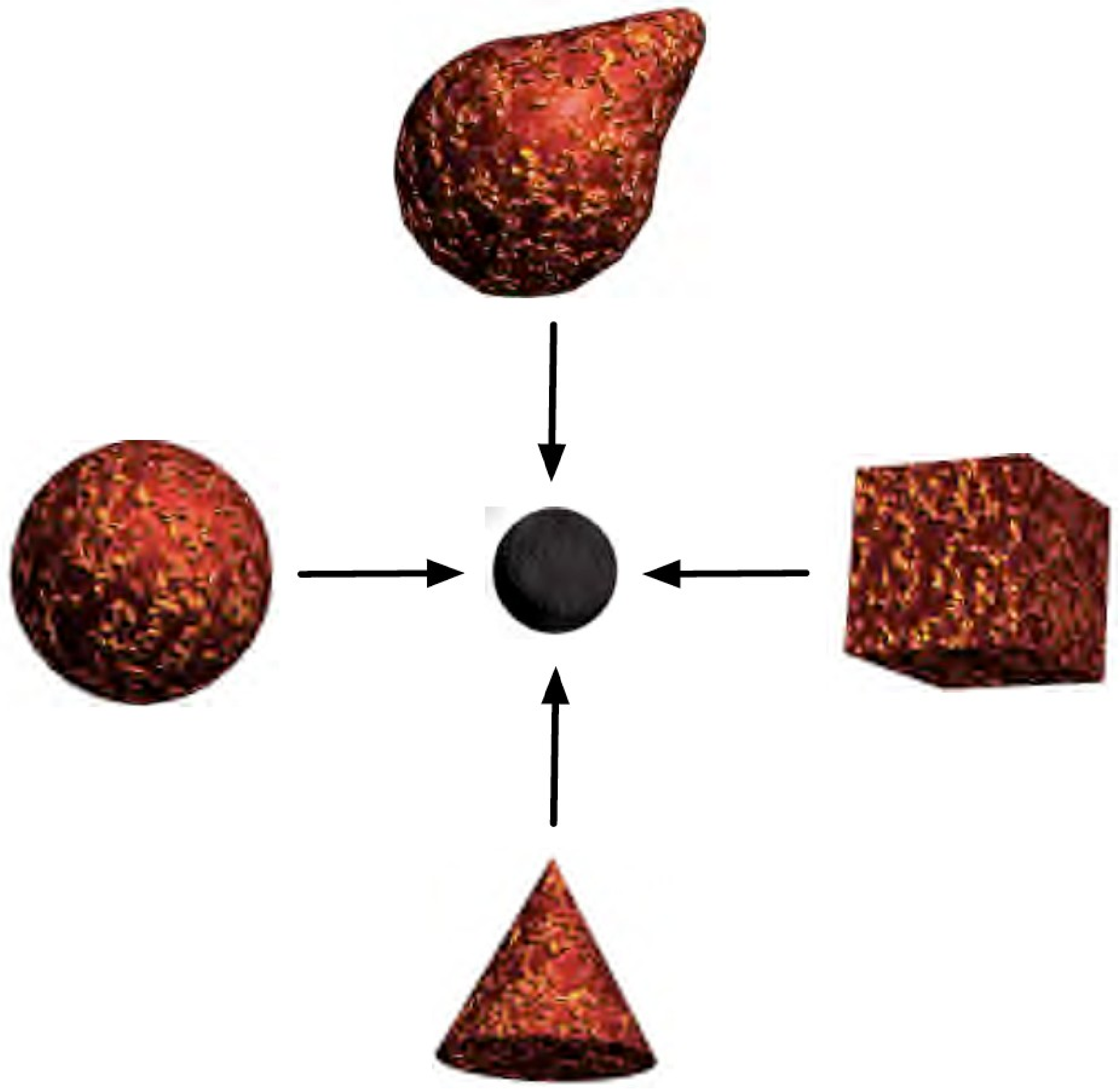


icting detection c. 2025
(large uncertainties)

The No-Hair Theorem

Challenges testing the no-hair theorem

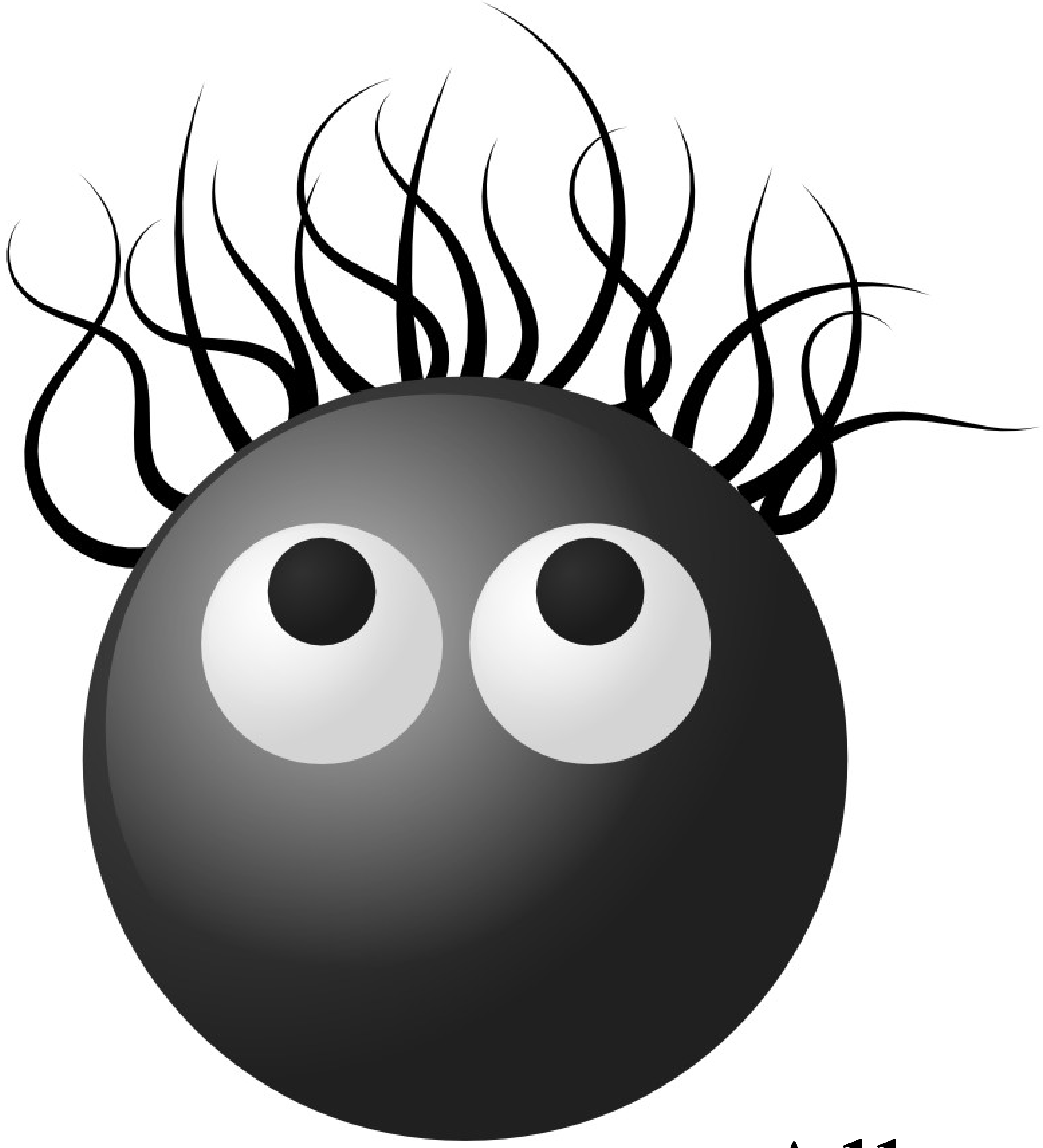


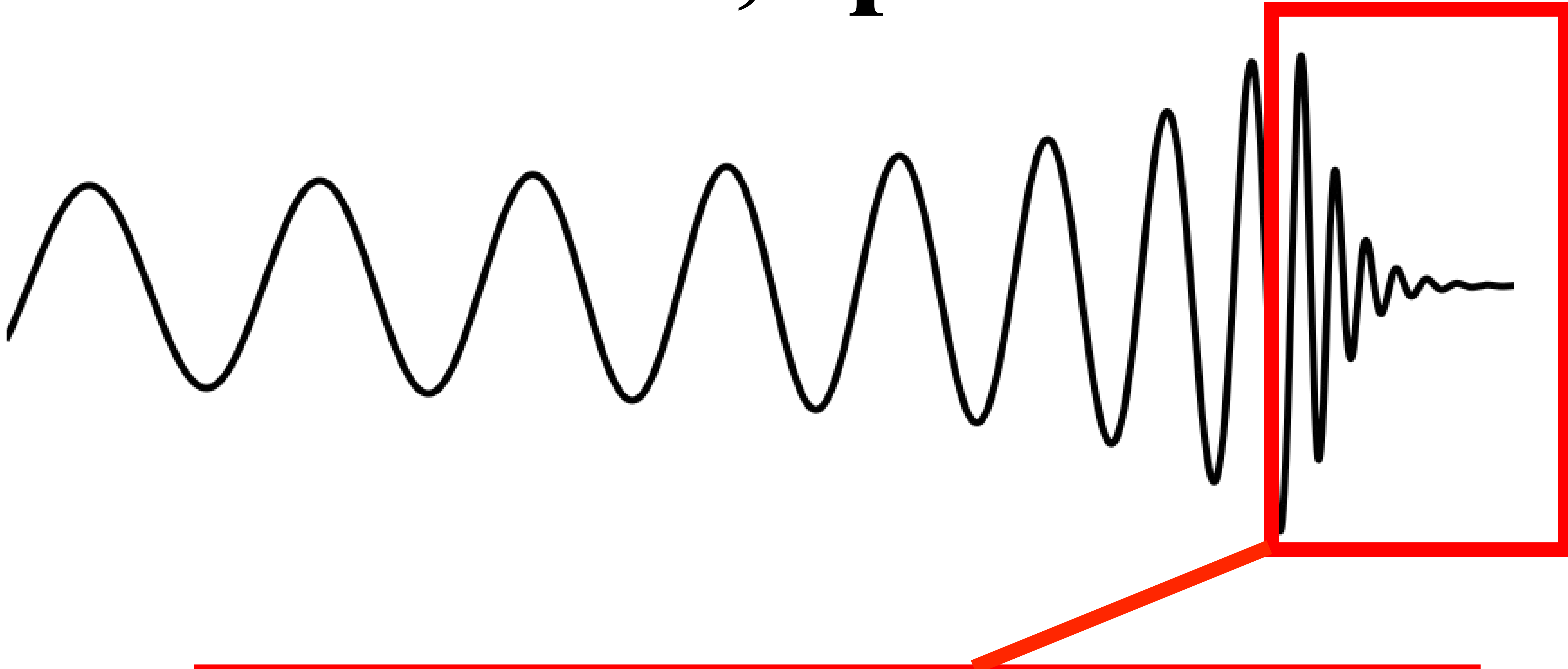


Astrophysical black holes in general relativity
completely characterized by ~~three~~ two parameters:
mass, spin, ~~charge~~

Challenges testing the no-hair theorem

mass, spin

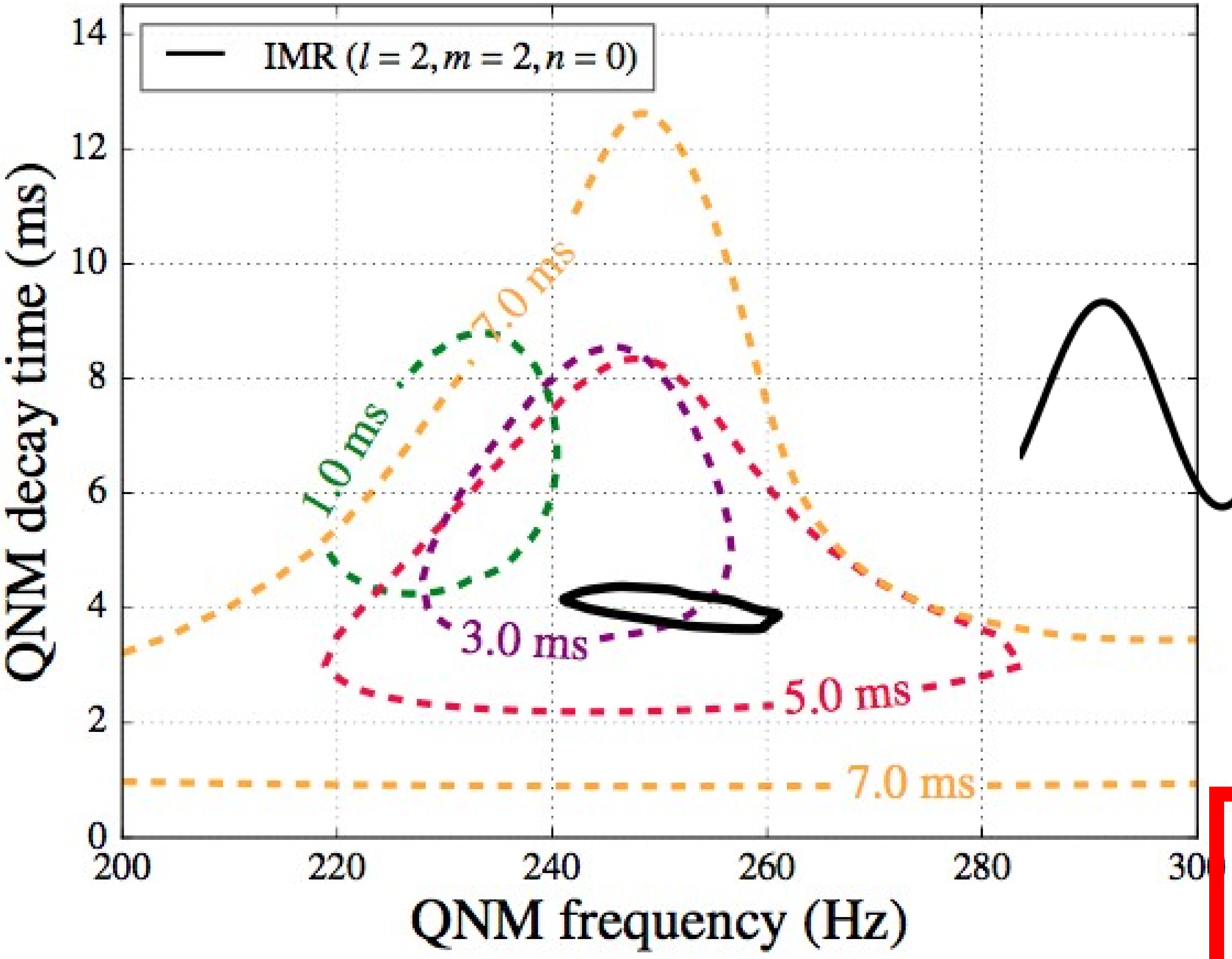




$$h(t) = \sum_{\ell m} c_{\ell m} \mathrm{e}^{-t/\tau_{\ell m}} \sin\left(2\pi f_{\ell m} t + \phi_{\ell m}\right)$$

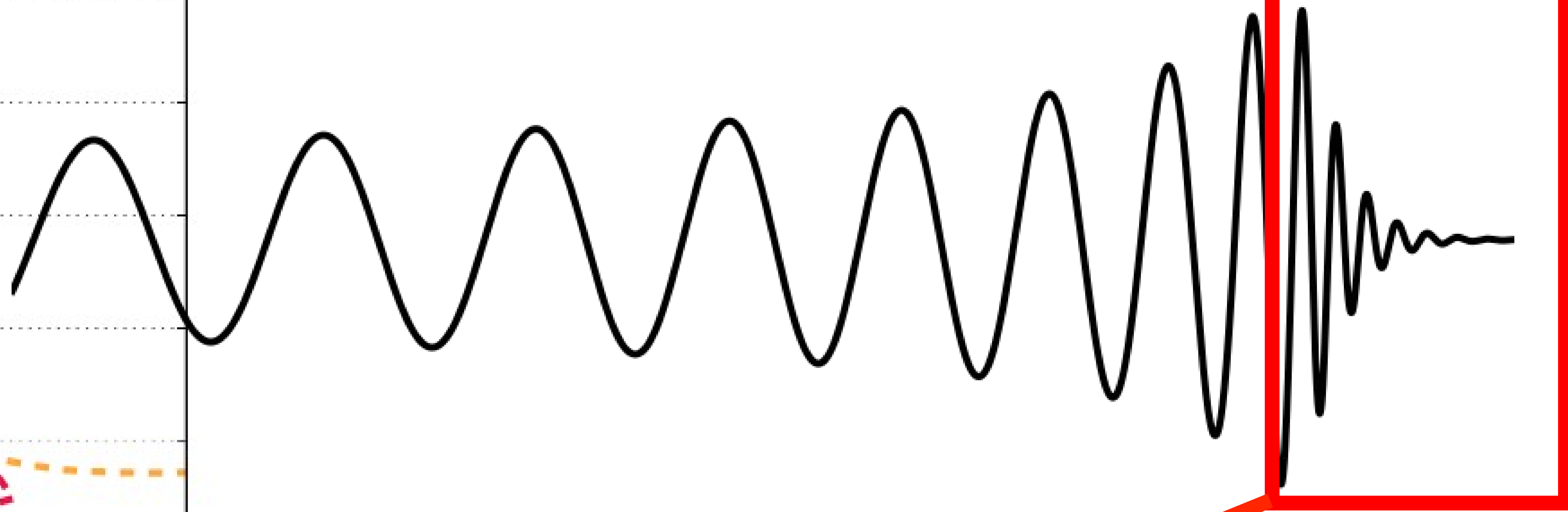
All values of τ_{lm} and f_{lm} are entirely determined by the final mass and spin of the black hole

Challenges testing the no-hair theorem



GW150914
Abbott et al. (2016)

mass, spin



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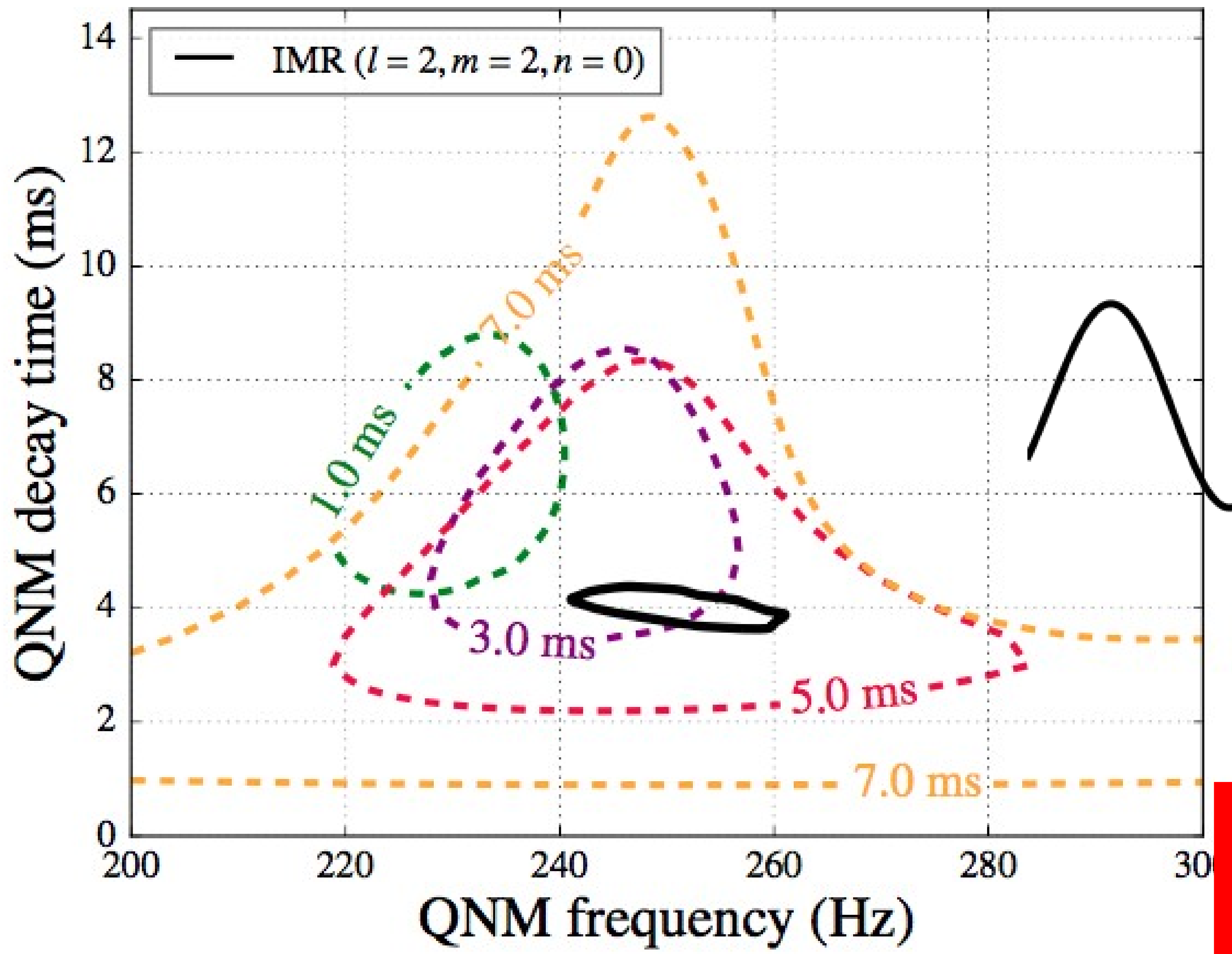
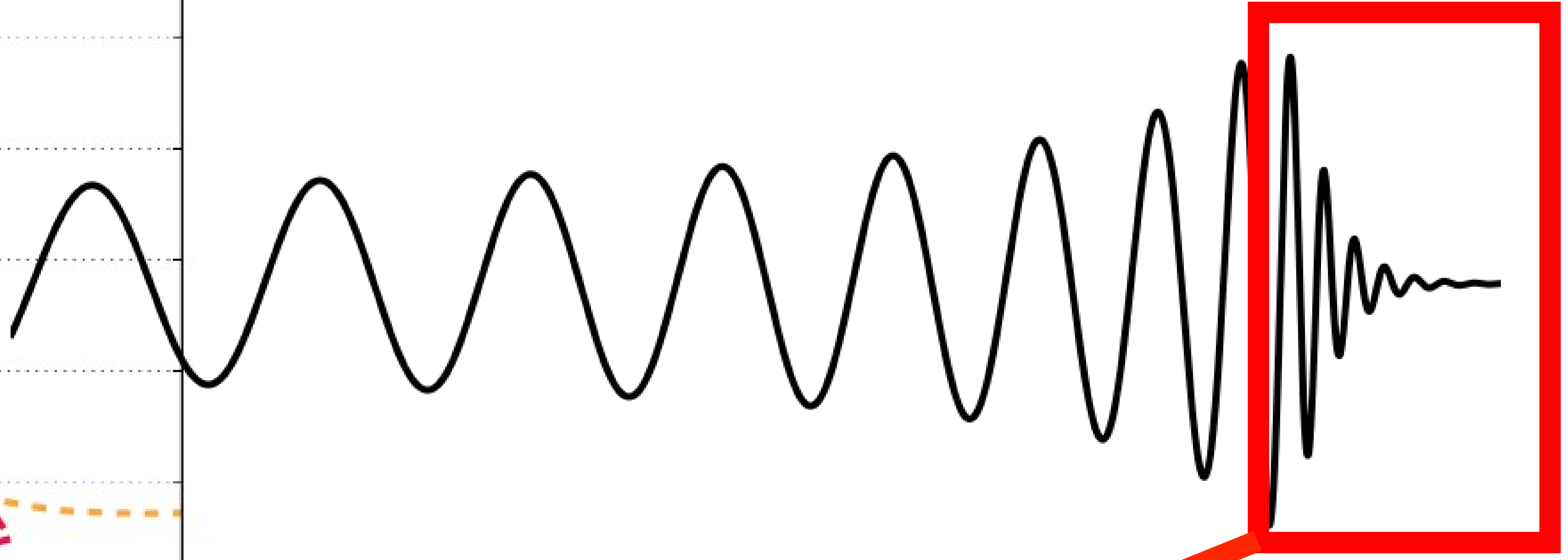
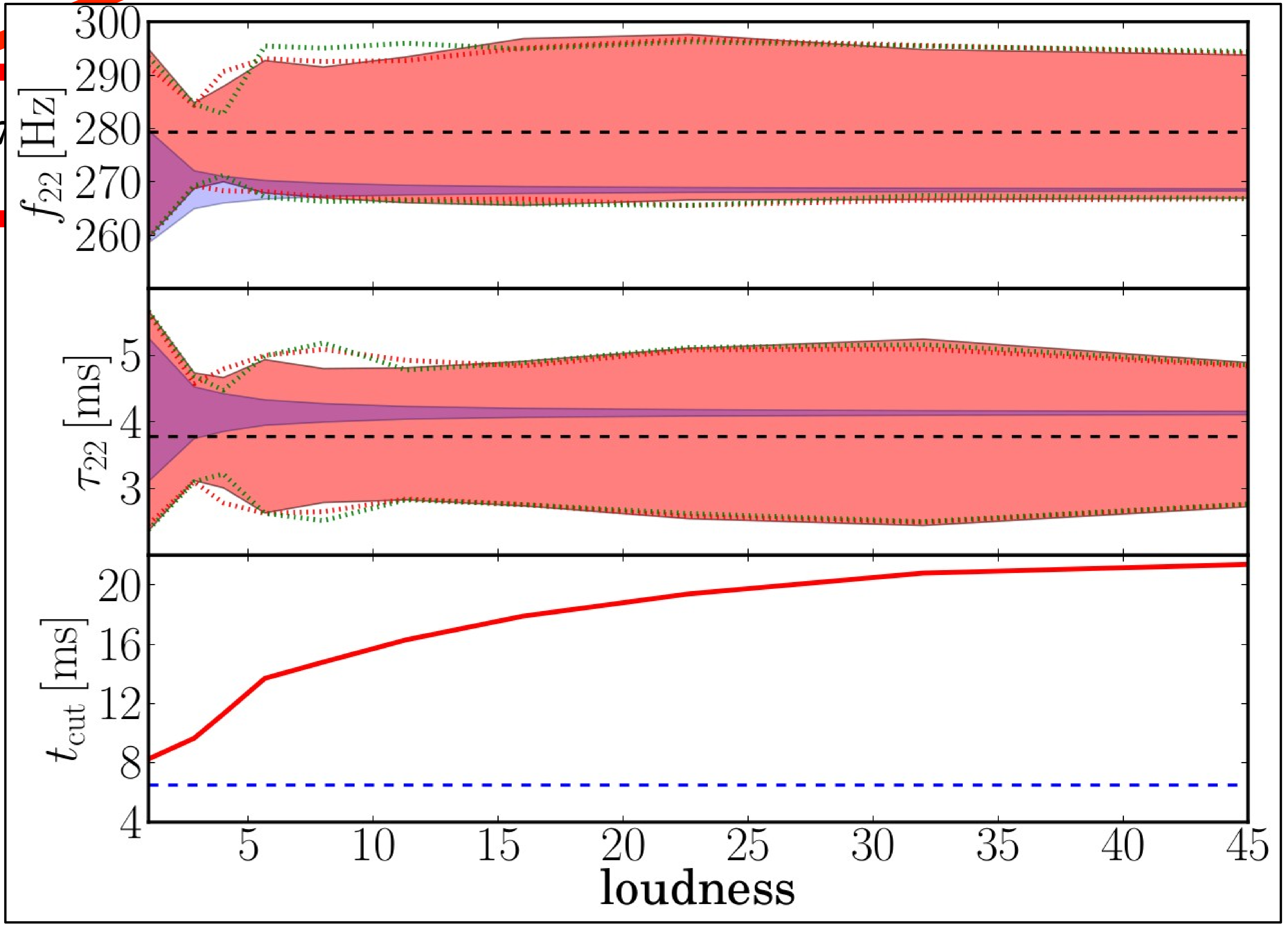
Challenges testing the no-hair theorem





$$h(t) = \sum_{\ell m} c_{\ell m} e^{-t/\tau_{\ell m}} \sin(2\pi$$



When is the ringdown linear?

- Mathematically: $t \to \infty$
- Astrophysically: ?? Never (sort of)

Thrane, Lasky & Levin 2018

Challenges testing the no-hair theorem

Overtones – a surprising, partial solution!

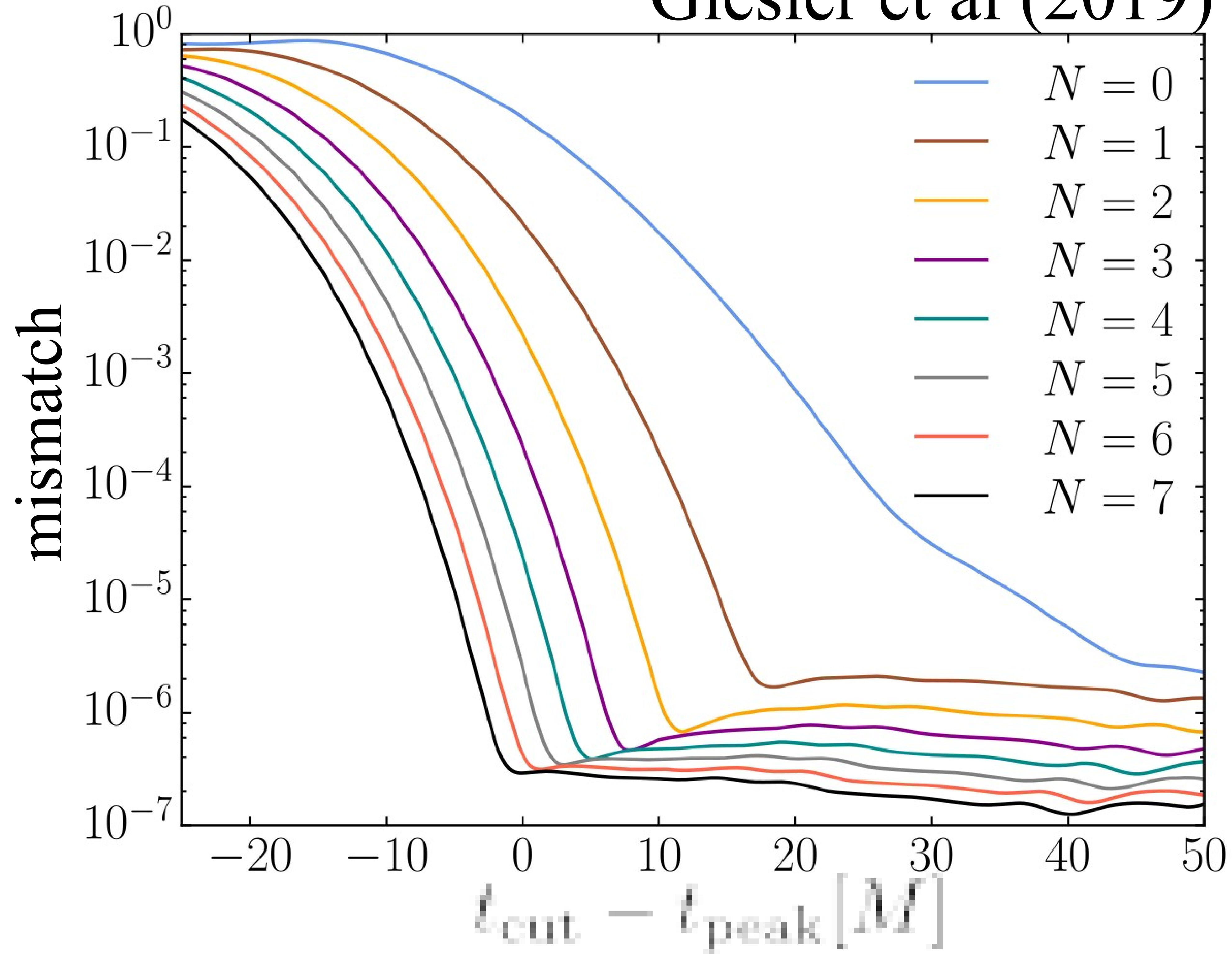
(Giesler et al, 2019; Isi et al, 2019)

$$(\tau_{lm}, f_{lm}) \longrightarrow (\tau_{lmn}, f_{lmn})$$

- More than one overtone of fundamental harmonic is enough to test no-hair theorem. i.e. τ_{22n}, f_{22n}

Punchline: post-merger waveform surprisingly well fit by sum of overtones with τ_{22n}, f_{22n}.

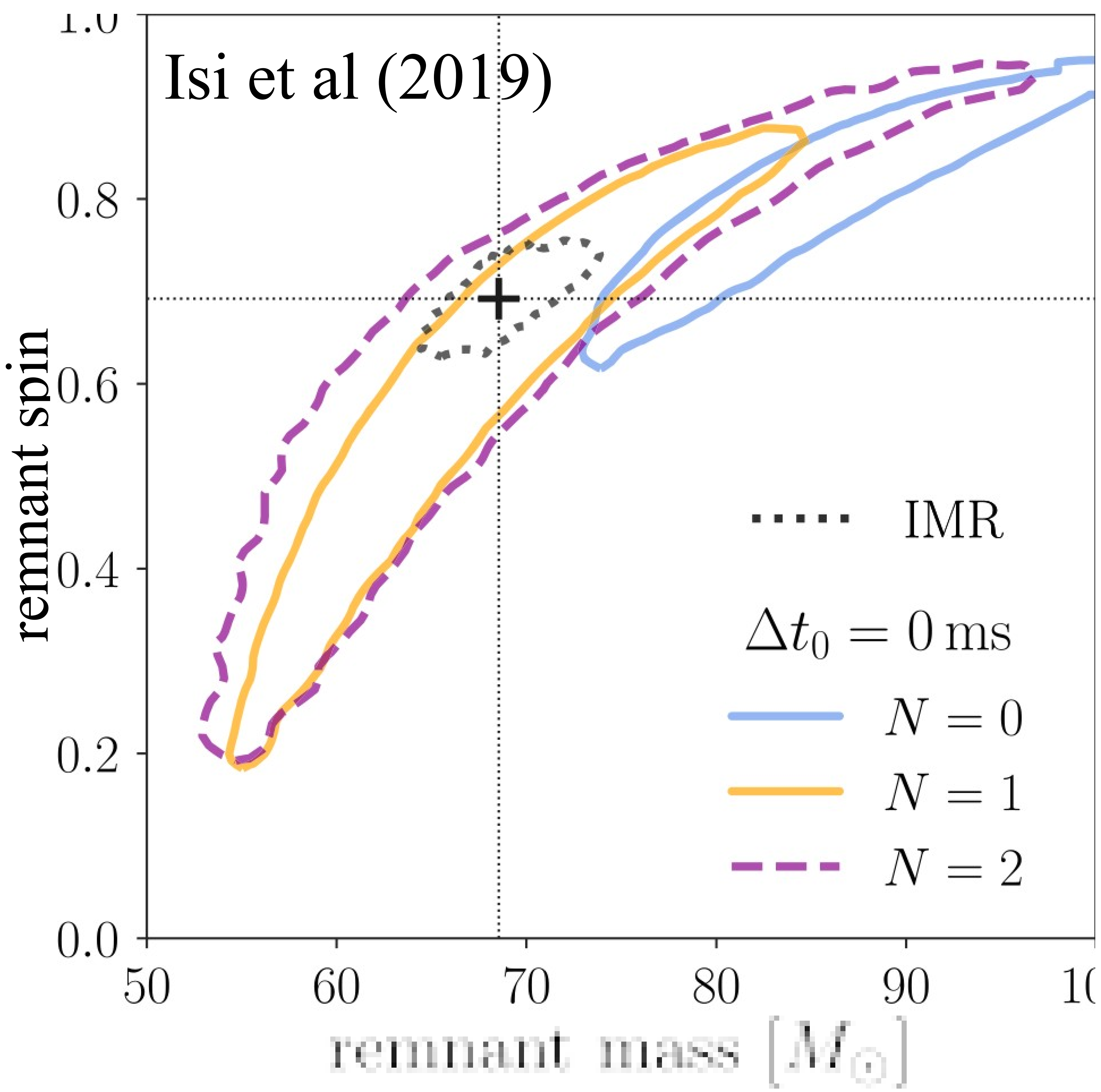
Giesler et al (2019)



Challenges testing the no-hair theorem

Overtones – a surprising, partial solution!

(Giesler et al, 2019; Isi et al, 2019)



GW150914

- Measure first overtone at 3.6σ
- "An independent measurement of the frequency of the first overtone yields agreement with the no-hair hypothesis at the ~20% level."

Challenges testing the no-hair theorem

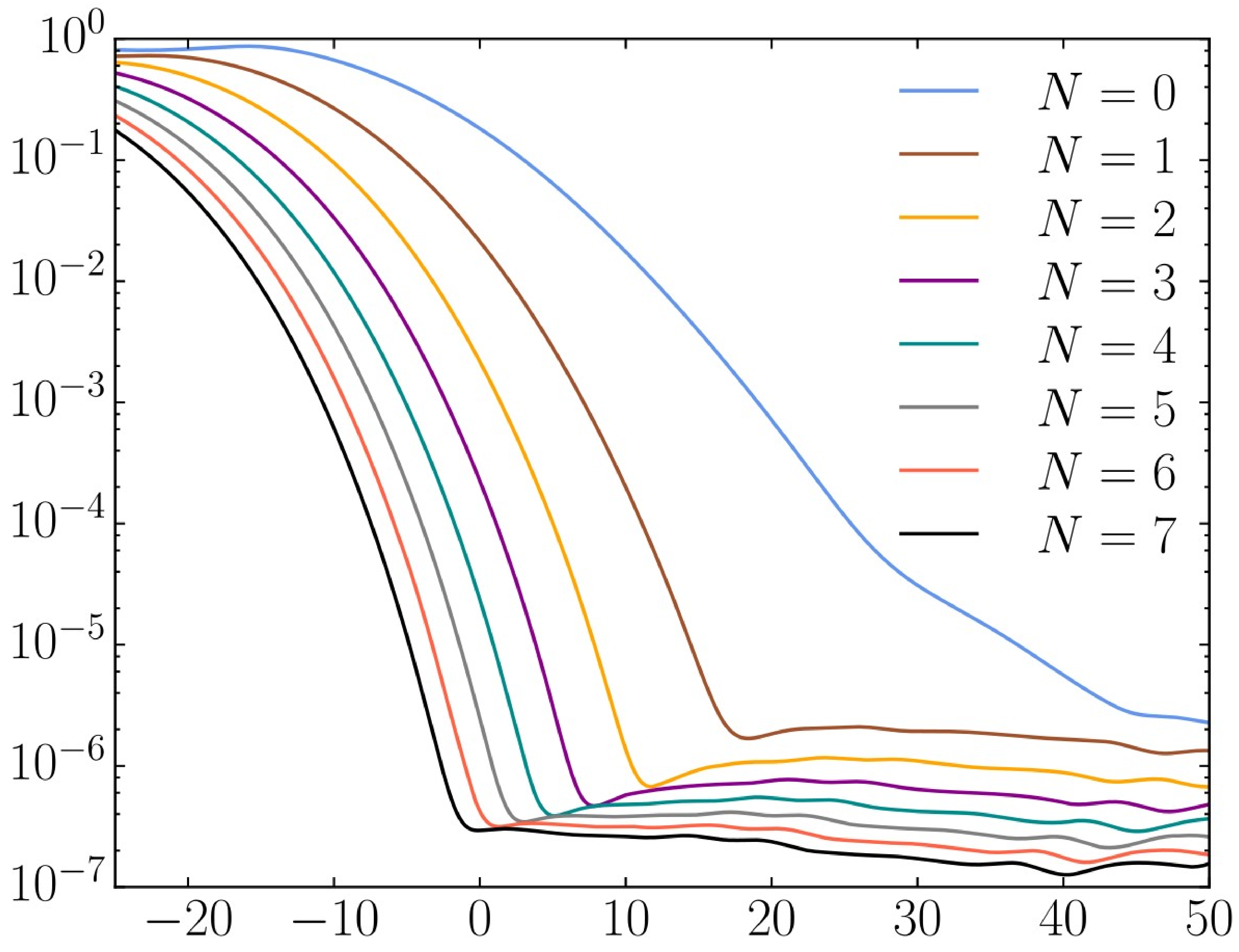
Aaah, but we're not done, yet!

What about model selection?

Challenges testing the no-hair theorem

What about model selection?

No-hair test ≡ test no hair (Kerr) vs. hairy (non-Kerr) hypothesis



- 2 + 2 x N parameters (amp/phase of each tone)
- For loud signals, require large N
- large Occam penalty

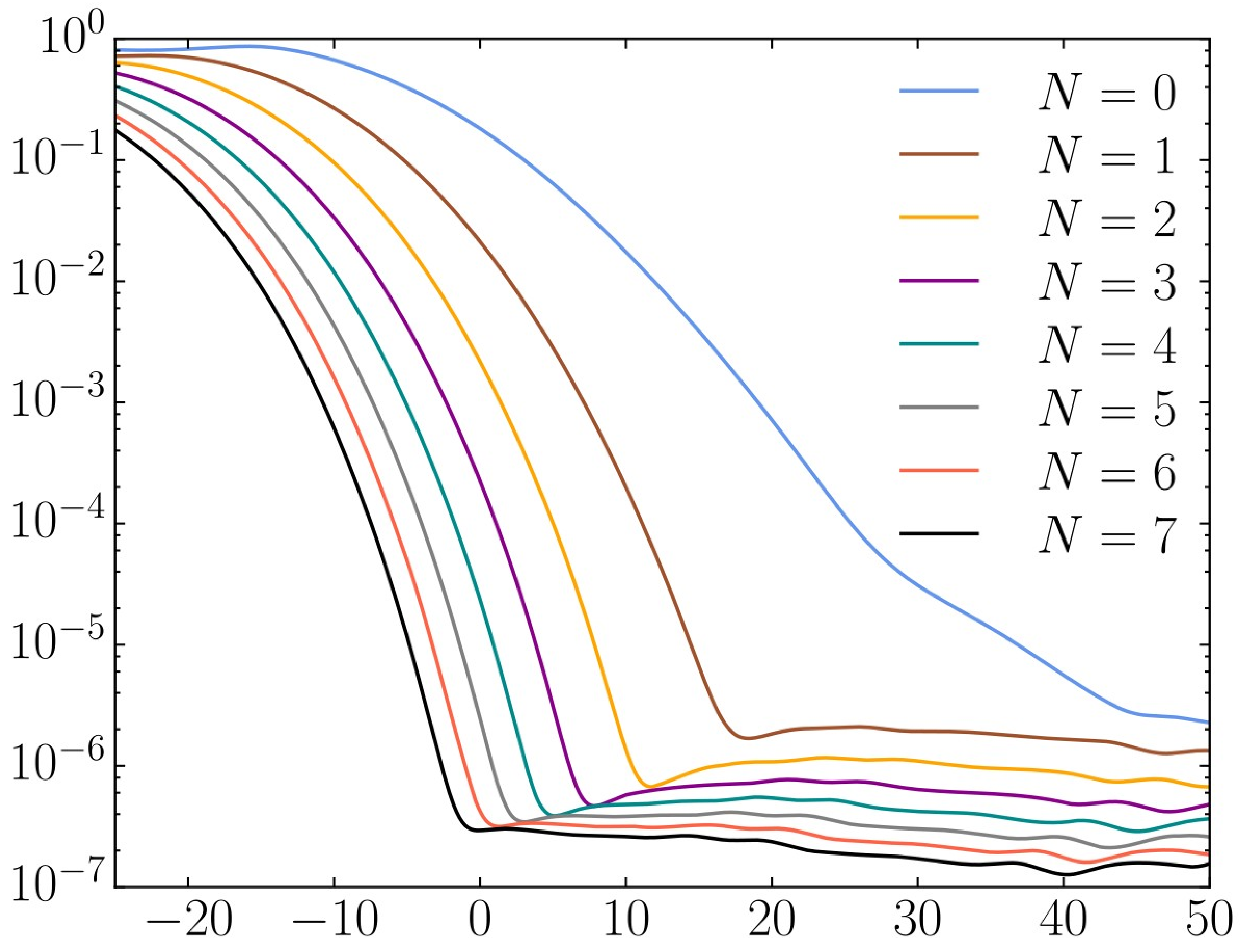
"It should give us all pause that this framework seeks to model the remnant of a binary black-hole merger using more physical degrees of freedom than those of the parent binary"

Calderon Bustillo, Lasky & Thrane (2021)

Challenges testing the no-hair theorem

What about model selection?

No-hair test ≡ test no hair (Kerr) vs. hairy (non-Kerr) hypothesis



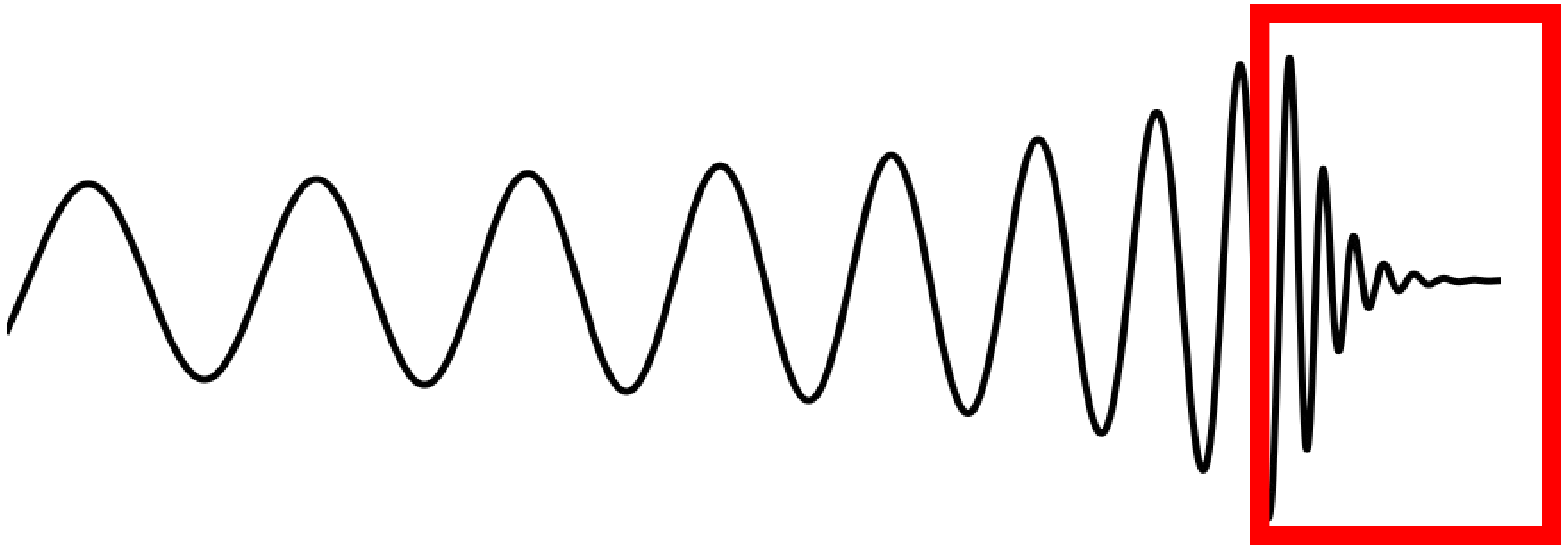
- Controlled test: inject SNR = 100
- Bayesian evidence increases with number of overtones, but so does prior volume.
- Prior volume increases faster than evidence → Bayes factor supports fewer overtones

Calderon Bustillo, Lasky & Thrane (2021)

Challenges testing the no-hair theorem

solution

Calderon Bustillo, Lasky & Thrane (2021)



GW150914

- Currently ignoring information: we know perturbed BHs form from binary merger
- Using that constrains parameter space v
- use waveform models to constrain possible phases and amplitudes of overtones.

ln BF = 6.5 for Kerr vs. non-Kerr
i.e. “hairy object hypothesis is disfavored with <1 : 600 with respect to the Kerr black-hole one.”

Gravitational-wave astronomy is in its infancy

- Formation mechanism of binaries: dynamical channel looking relevant
- Memory: detectable in a few years
- Testing no-hair: we finally (think we) understand this

Lot’s of interesting science to be done!

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“Bayesian parameter estimation is the future of gravitational-wave astronomy”
Matilda B. Bilby*
*not a real quote
(also not a her real name)

Gravitational-wave memory

Algorithm for detecting and distinguishing orphan memory and cosmic strings

McNeill, Thrane & Lasky (2017); Divakarla, Thrane, Lasky & Whiting (2020)