# Testing general relativity with black hole ringdown

Neil Lu (ANU) - ASGRG30


# Outline

- Background and motivation
- Current status of ringdown analysis
- Future prospects

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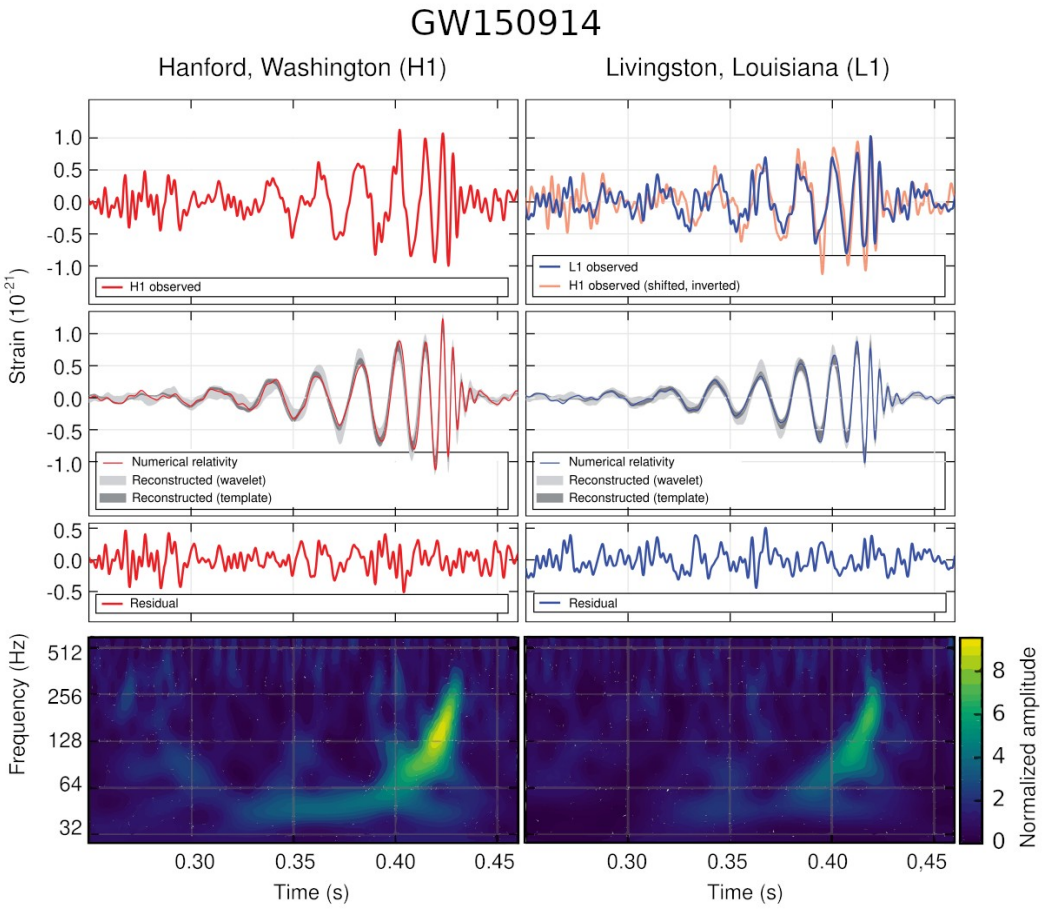
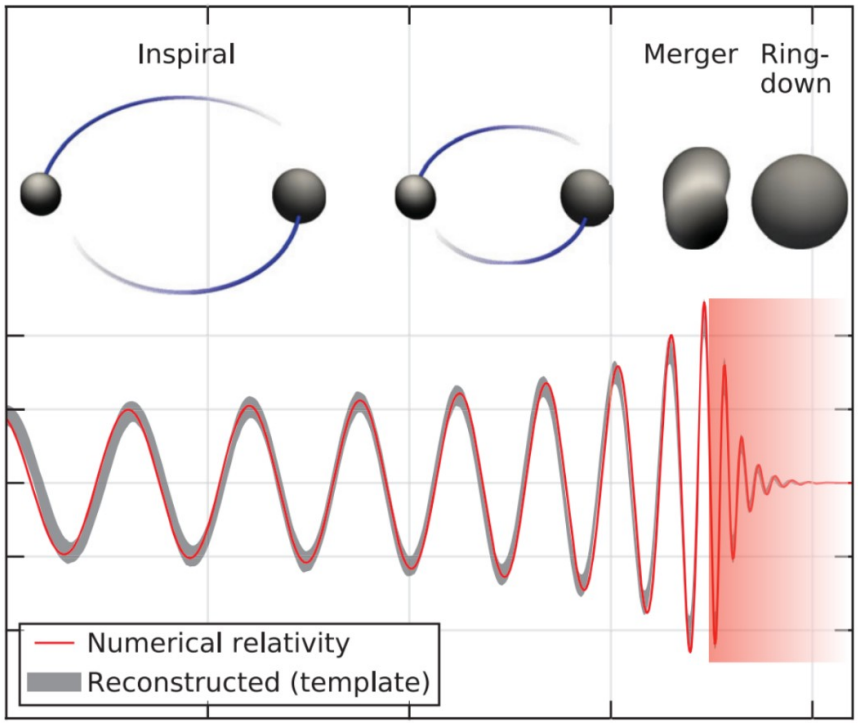
# Binary black hole coalescences

- Coalescence of binary black hole systems emit gravitational waves detectable on Earth



# What is ringdown?

- The **post-merger** phase of a binary black hole signal is known as **ringdown**




Abbott+ PRL, 2016

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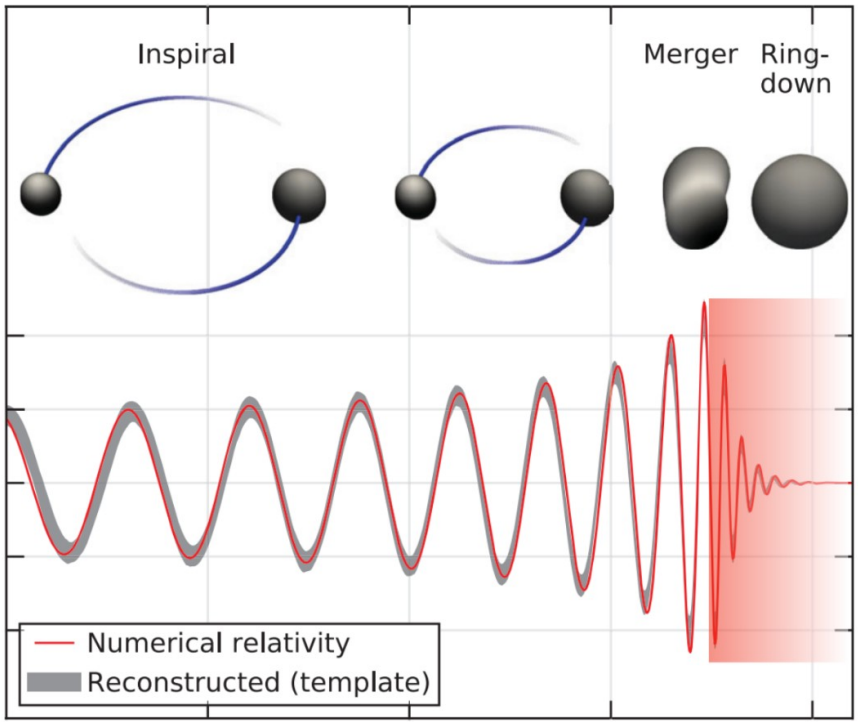
- In general relativity (GR), the ringdown signal consists of a superposition of **quasinormal modes** (**QNMs**)

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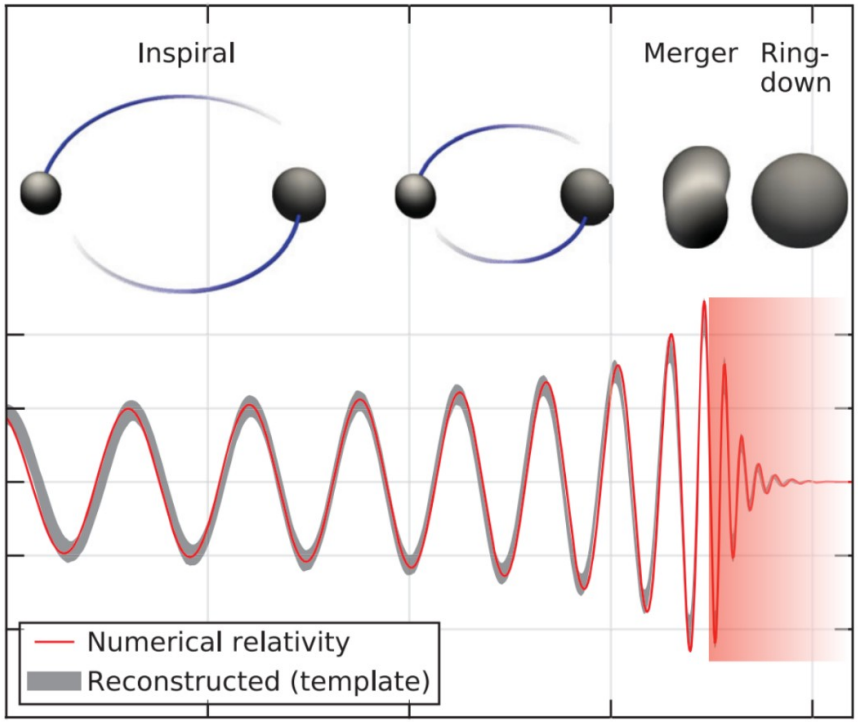
- Each are **exponentially damped sinusoids** – frequency and damping time

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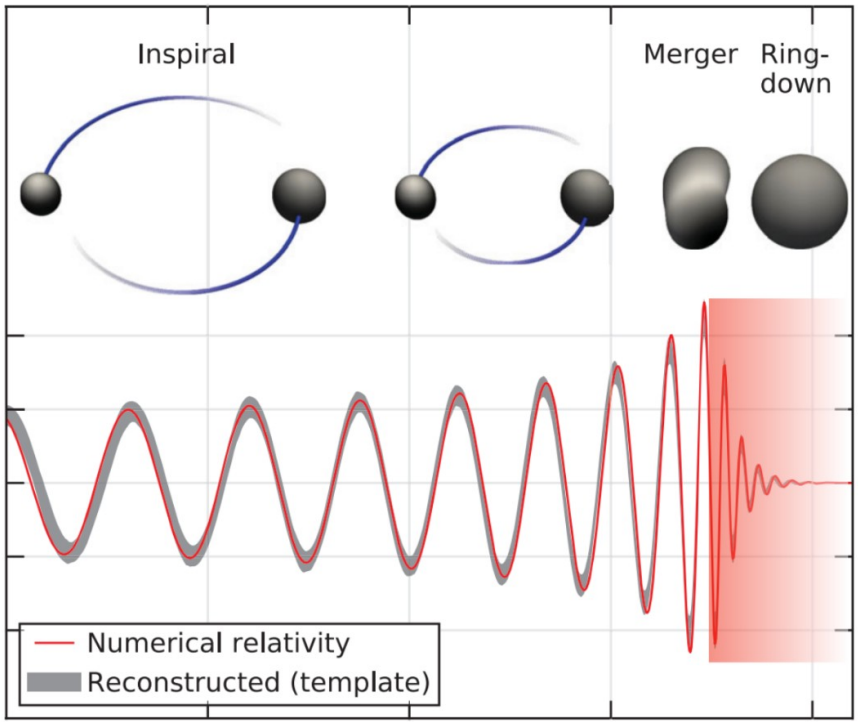
- Labelled by (*lmn*); **angular numbers** and **overtone number**. E.g. 220

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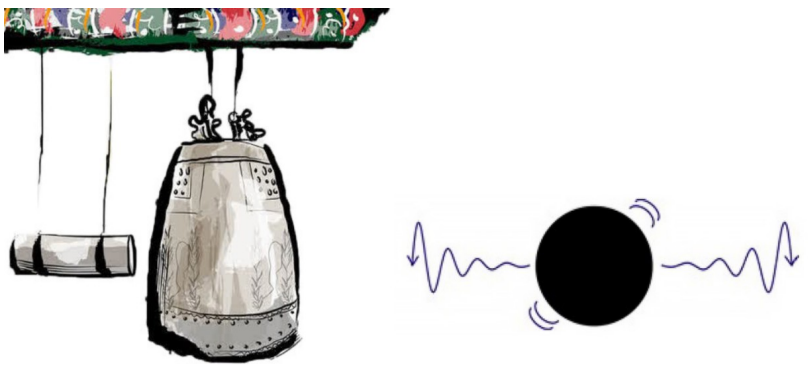
- The frequency and damping times of the QNMs depend only on the **mass** and **spin** of the remnant black hole – no hair theorem



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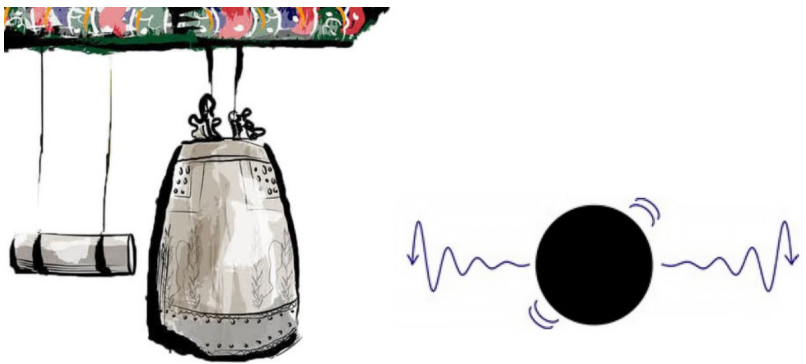
- Can use the ringdown signal to infer the mass and spin of the remnant black hole



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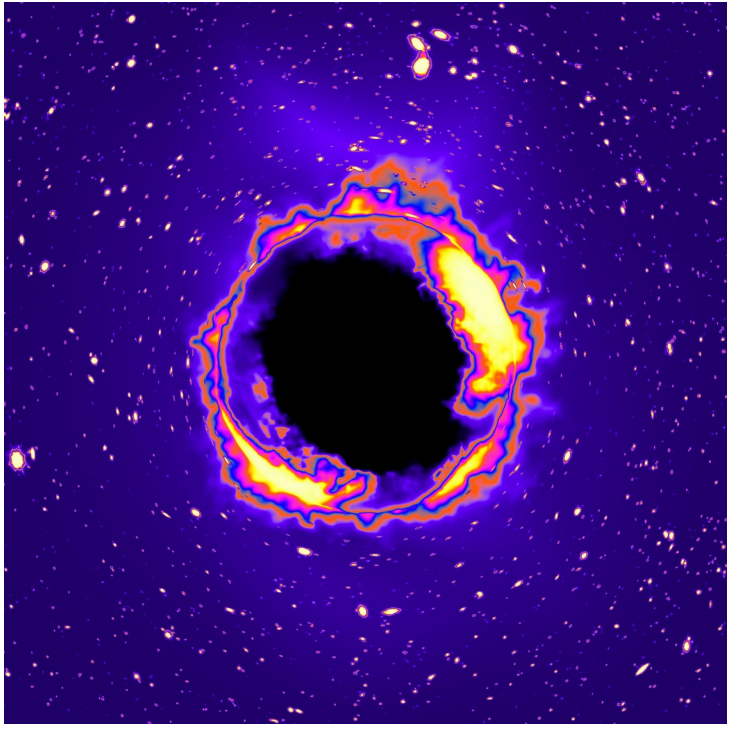

Credit: Carl Knox

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- Testing GR in the strong-field
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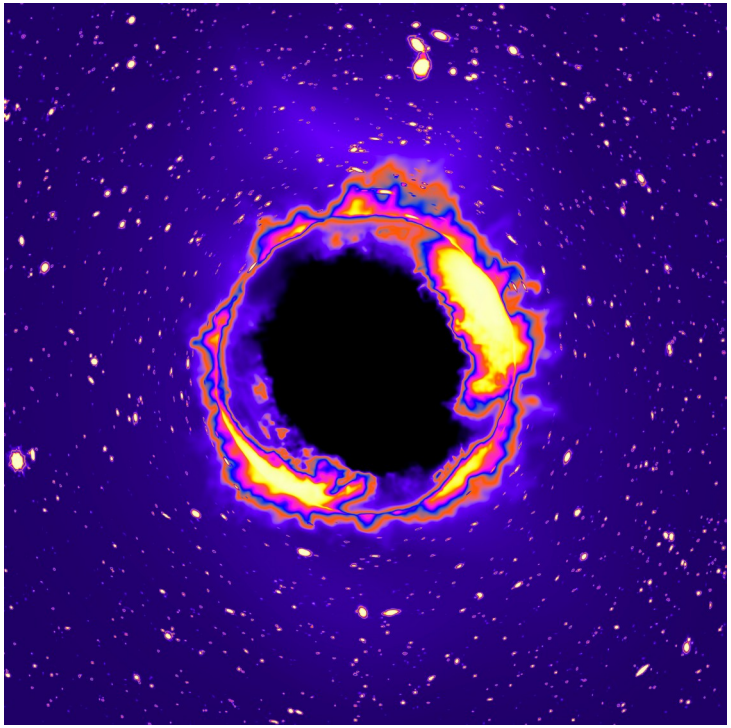
  - Consistency of ringdown with the full waveform



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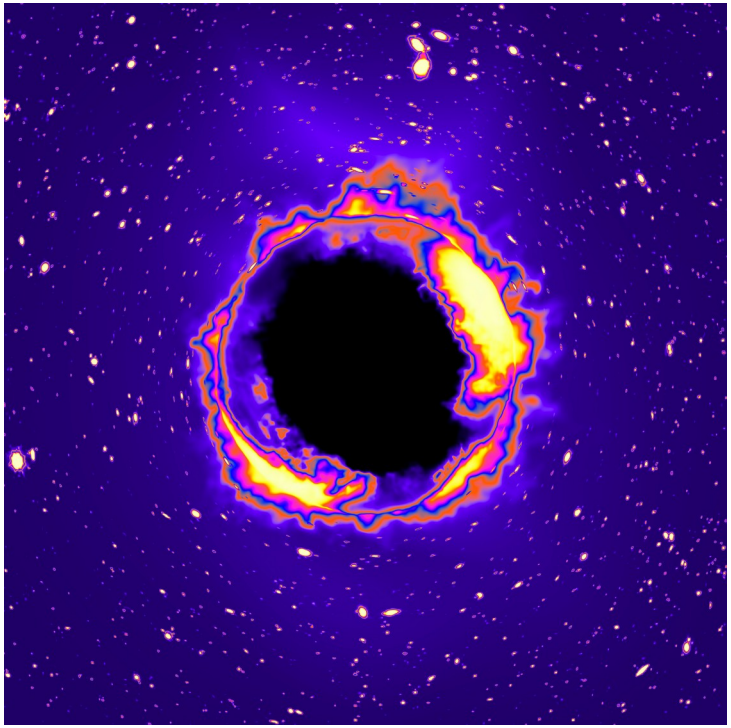

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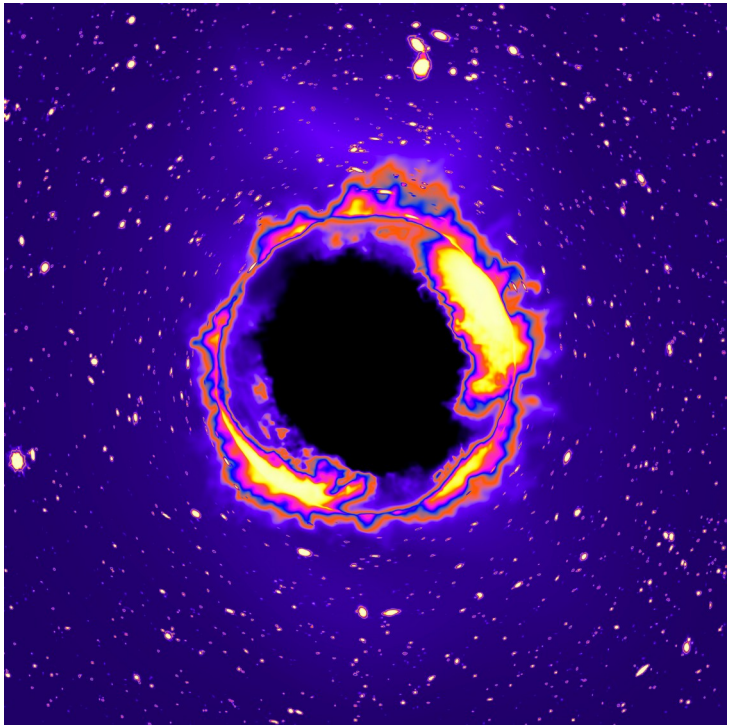
- Testing the nature of the remnant
  - Exotic compact objects would modify the ringdown spectrum – e.g. gravastars, firewalls, fuzzballs [5, 6]



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[5]:Cardoso+ PRL 2016
[6]: Maggio+ PRD 2020

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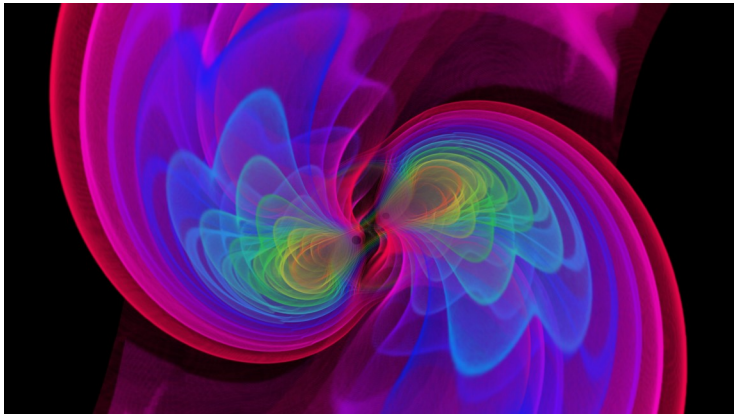
# Ringdown - present

- **Numerical relativity** simulations are important tools for studying ringdown



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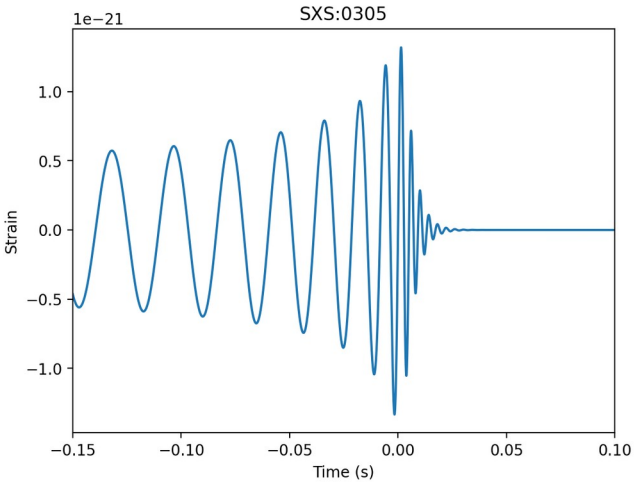
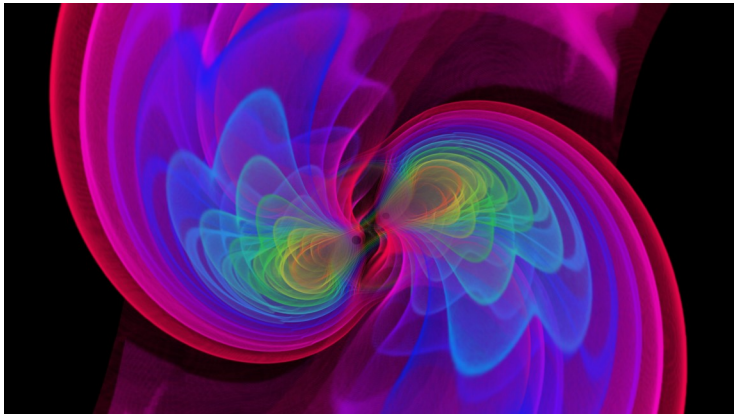


# Ringdown - present

- **Numerical relativity** simulations are important tools for studying ringdown
- Use it to understand how **initial conditions** of the binary affect the ringdown signal [1]
  - Precession
  - Eccentricity
  - Mass ratio



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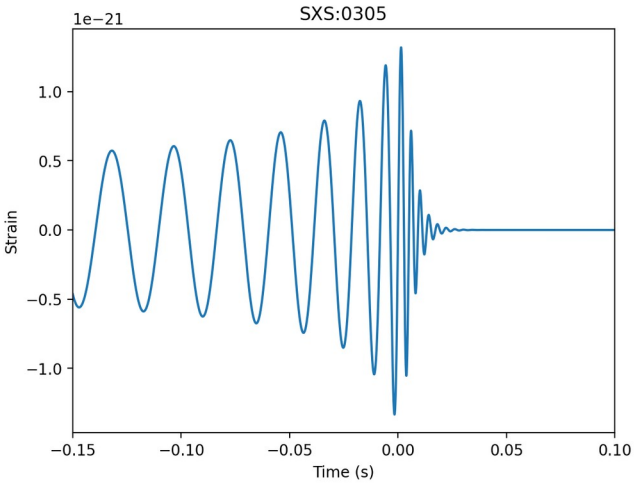


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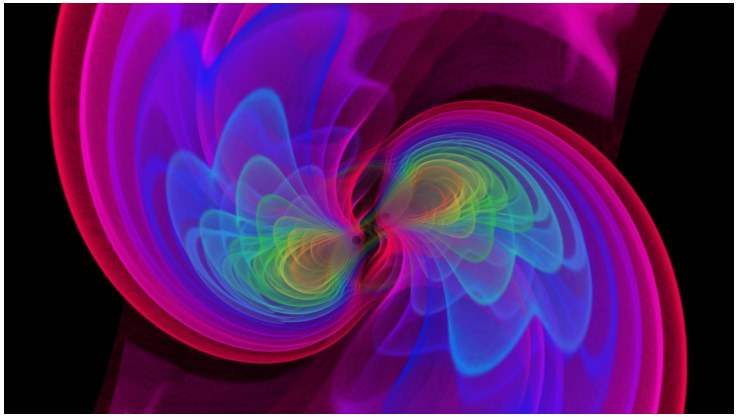
  - Mass ratio
- Despite having high SNRs, their mode contents are still **strongly debated**
  - GW150914-like waveform [2, 3, 4]



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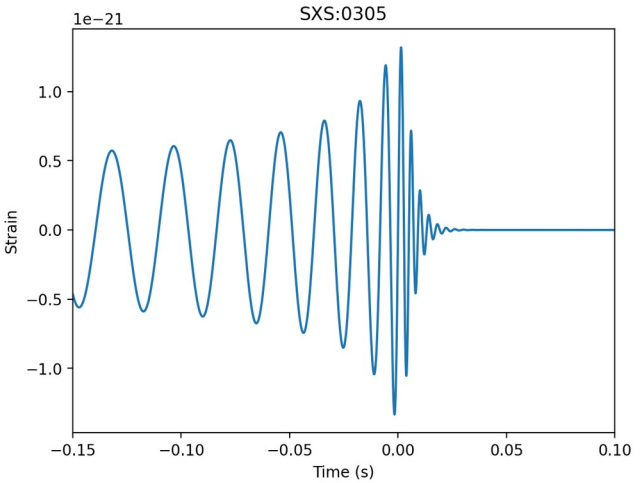


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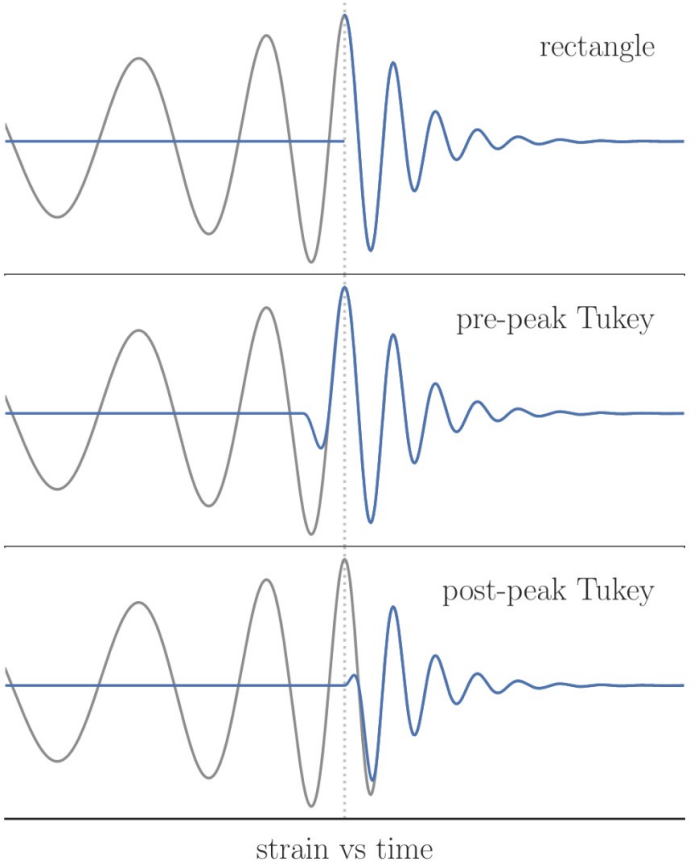
- This is a statistically and computationally difficult process




Isi+ arXiv 2019

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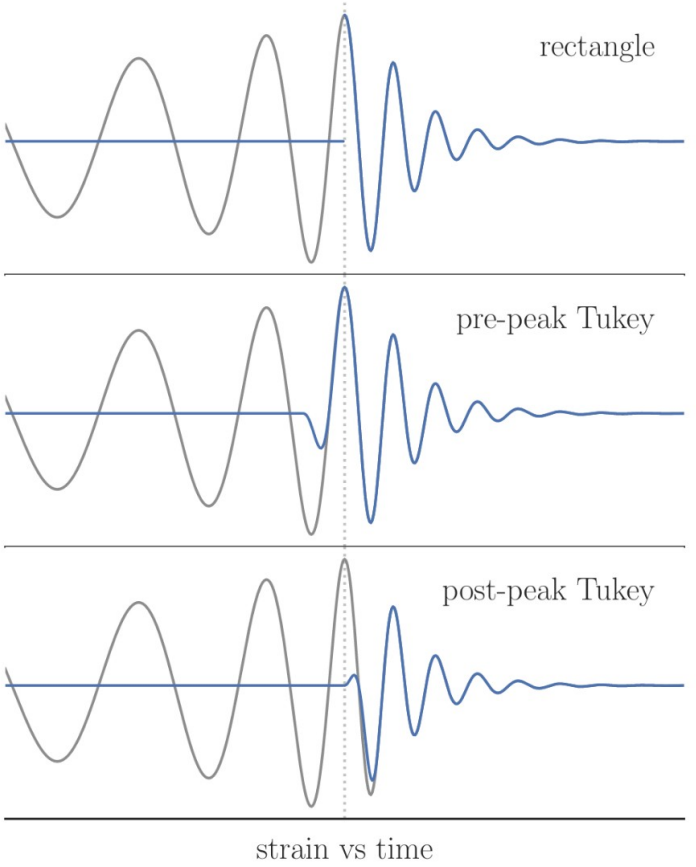
- This is a statistically and computationally difficult process
- Many different analysis techniques exist
  - PyRing [1]
  - Gating and in-painting [2]
  - Frequency domain [3]
  - QNM rational filter [4]
  - Many others

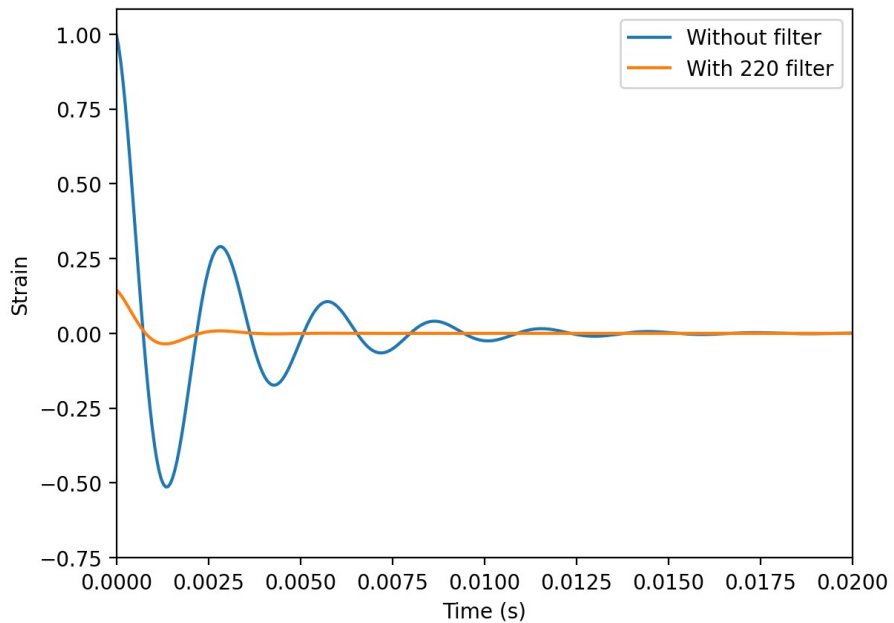


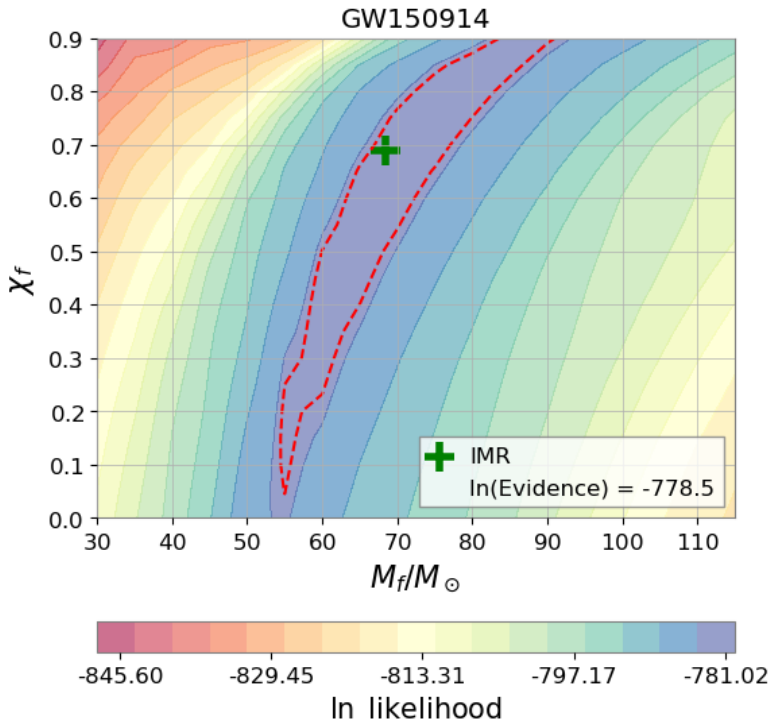

Isi+ arXiv 2019

[1]: Carullo+ PRD 2019
[2]: Capano+ PRL 2021
[3]: Finch+ PRD 2021
[4]: Ma+ PRD 2022

# Ringdown - present

- The QNM rational filter works by filtering out a specific mode to identify subdominant modes or leave only residual noise



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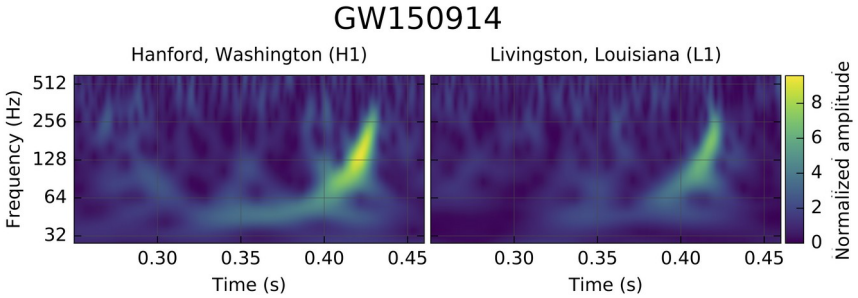
  - Confident detection of fundamental mode (220)
  - Disagreements about overtone (221) [1, 2, 3]

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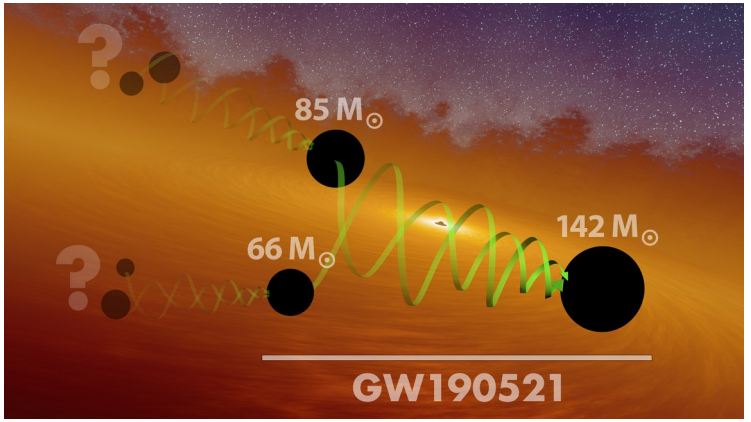


Credit: LIGO/Caltech/MIT/R. Hurt (IPAC).

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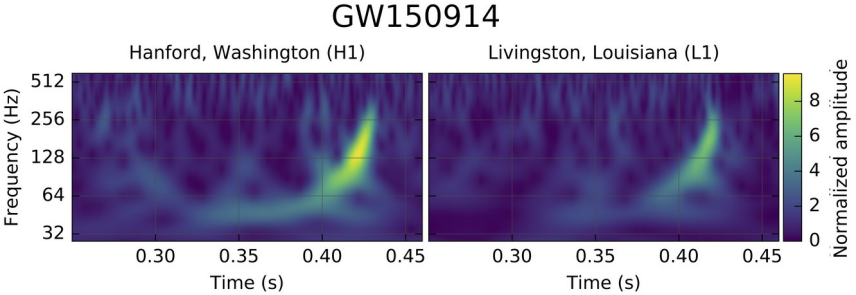
  - Marginal subdominant mode
  - Which one? [4, 5]

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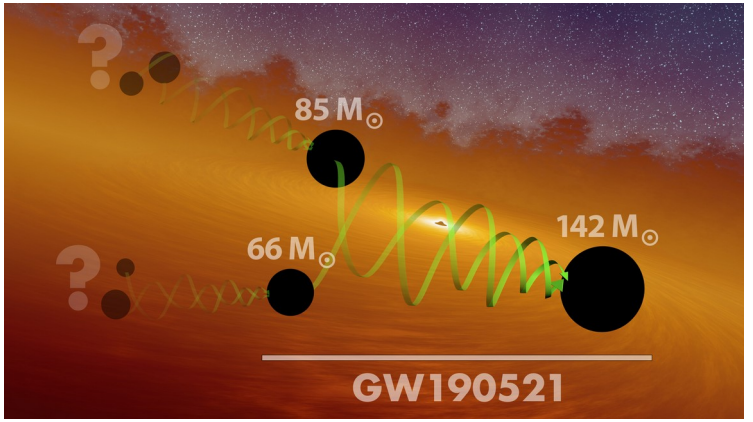


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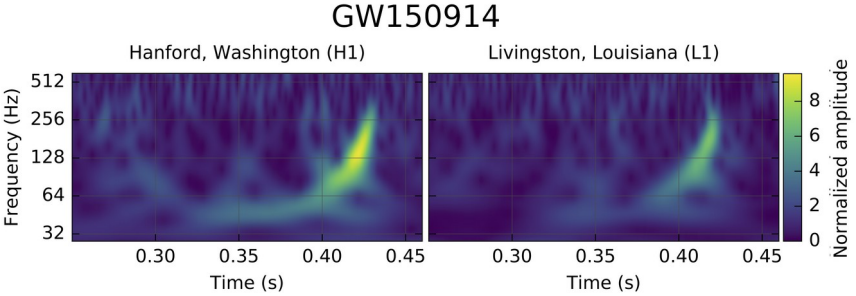
  - Which one? [4, 5]
- Ongoing work
  - O4 analysis
  - Statistical understanding [6, 7, 8, 9]

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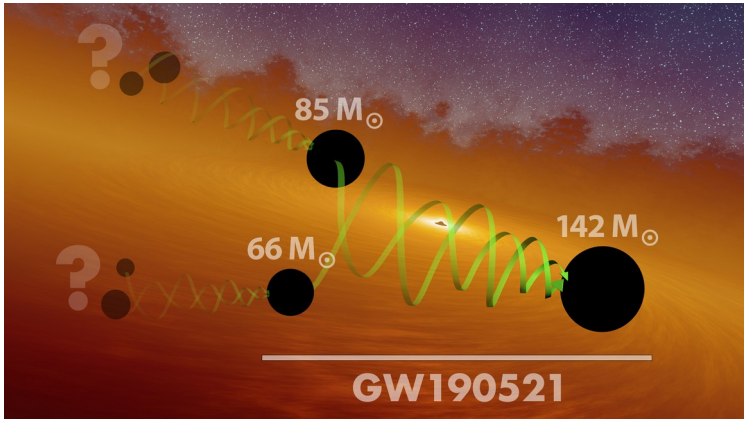


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[5]: Siegel+ PRD, 2023
[6]: May+ arXiv 2024
[7]: Baibhav+ PRD 2023
[8]: Nee+ PRD 2023
[9]: Lu+, in prep

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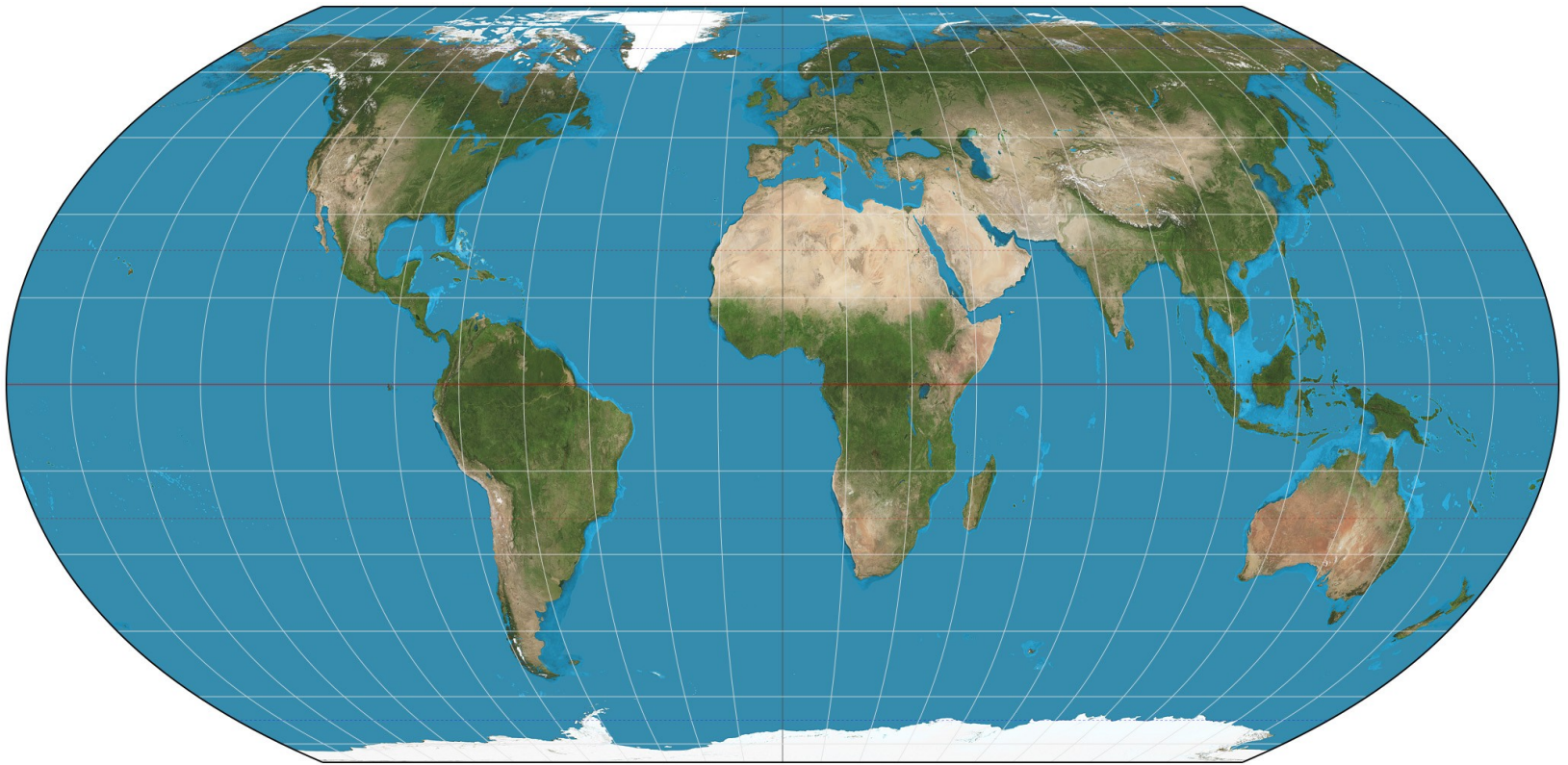
# Future ground-based detectors



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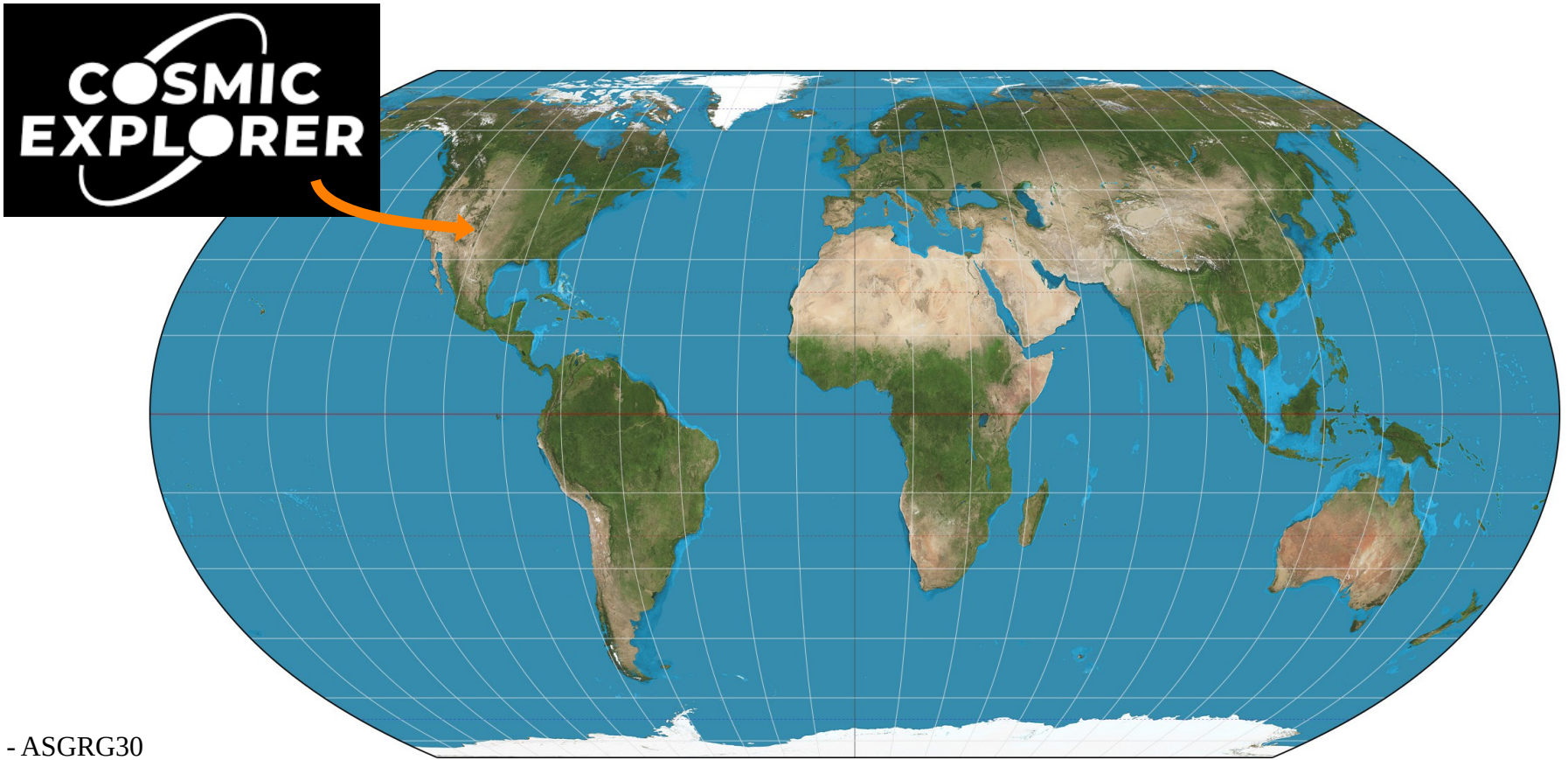

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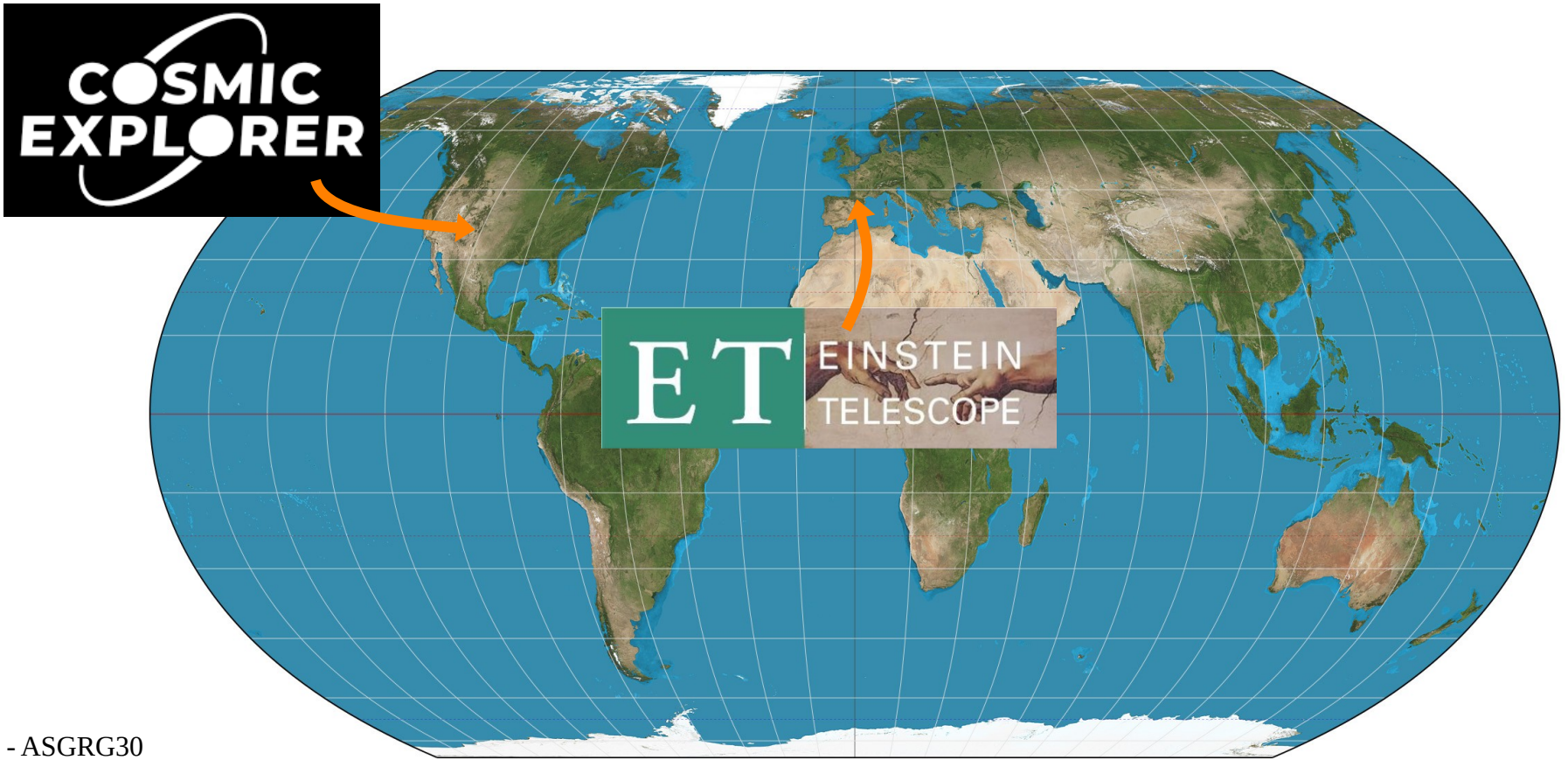

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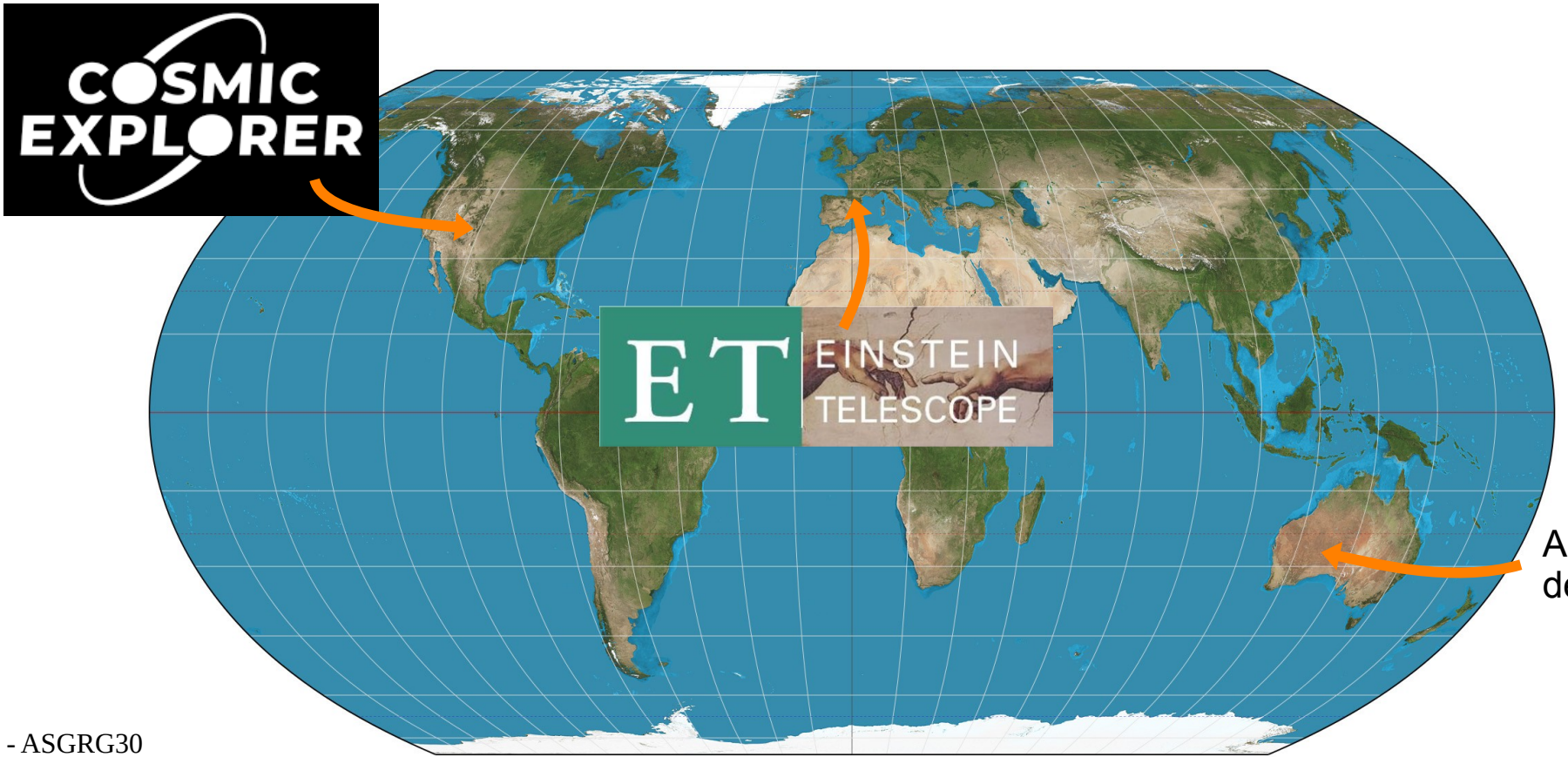

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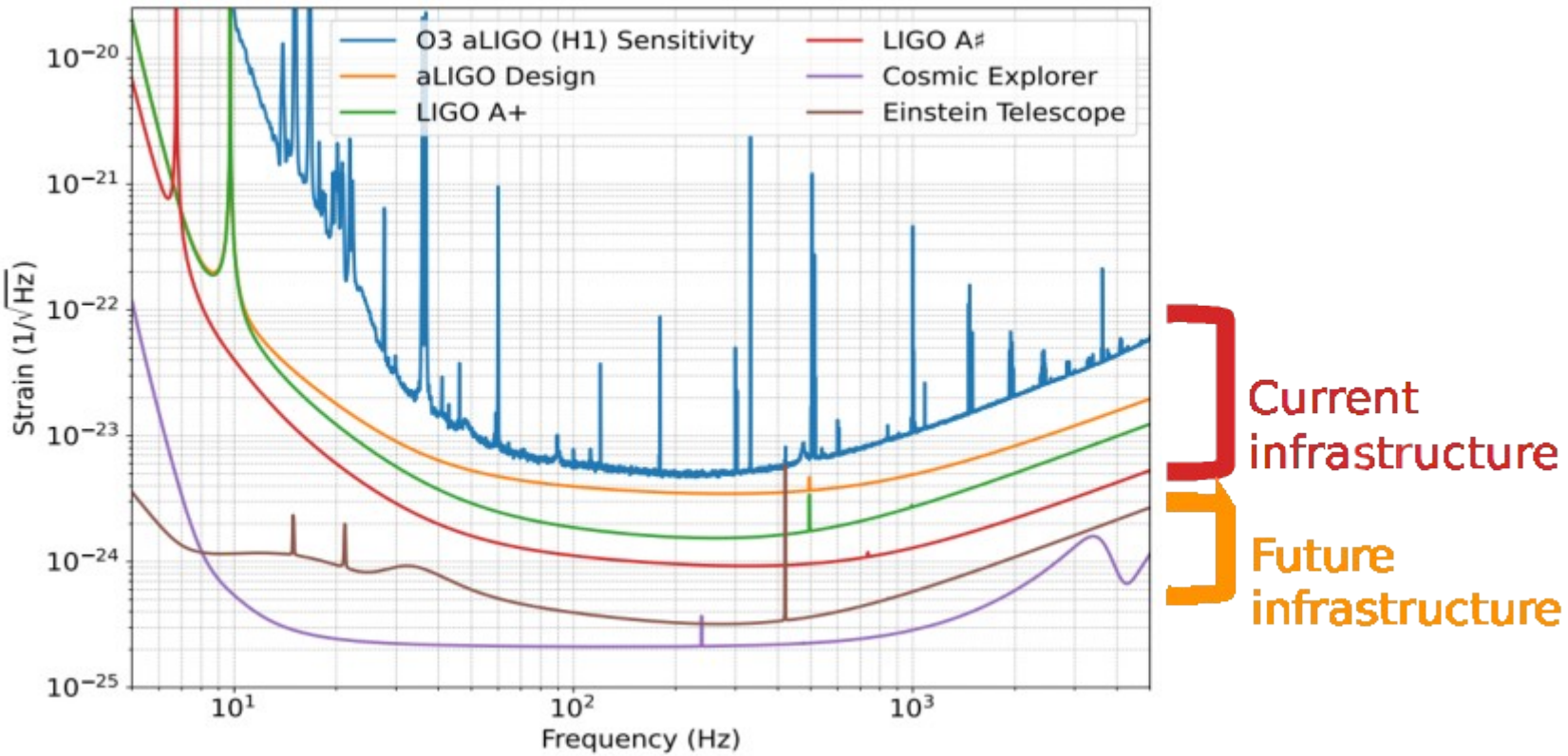
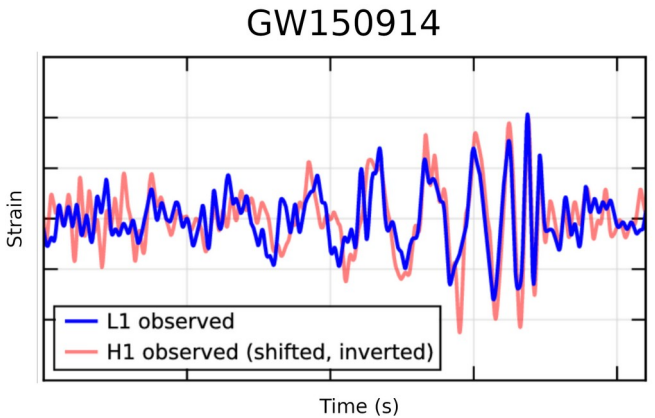
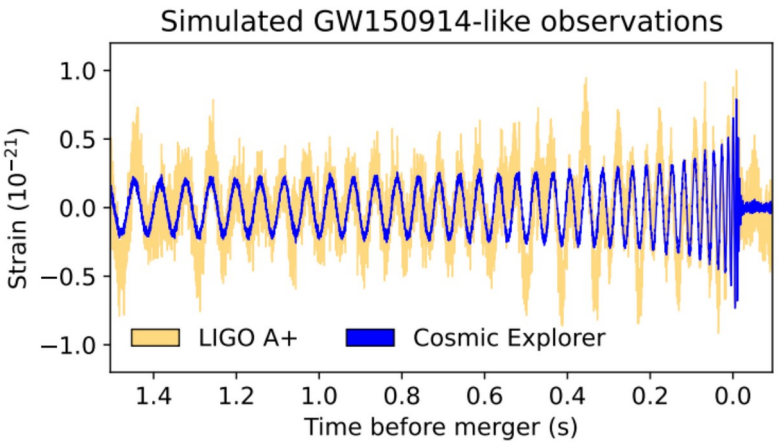


# “Golden” events




GWOSC data release

Evans+ CE horizon study, 2021

# “Golden” events

- ET or CE will see events with SNR ≈ 200 [1]
- Confident detection of multiple ringdown modes [2]
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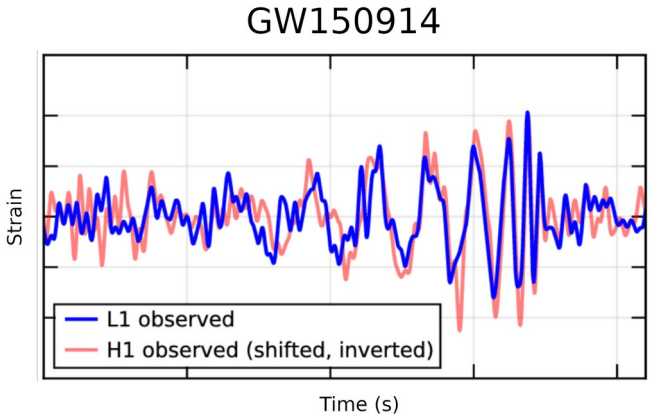


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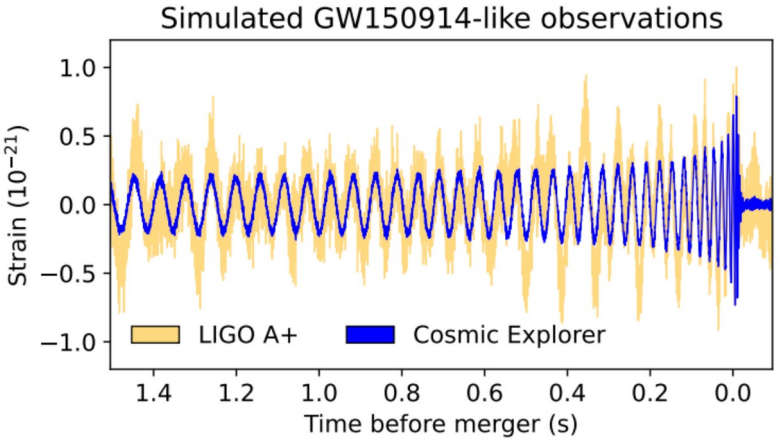


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[1]: Iacovelli+ ApJ 2022
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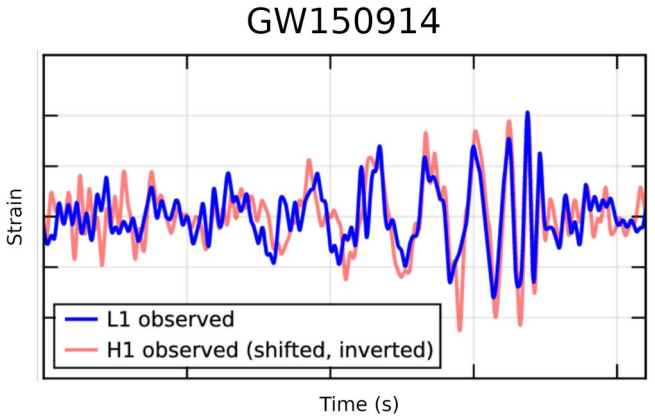


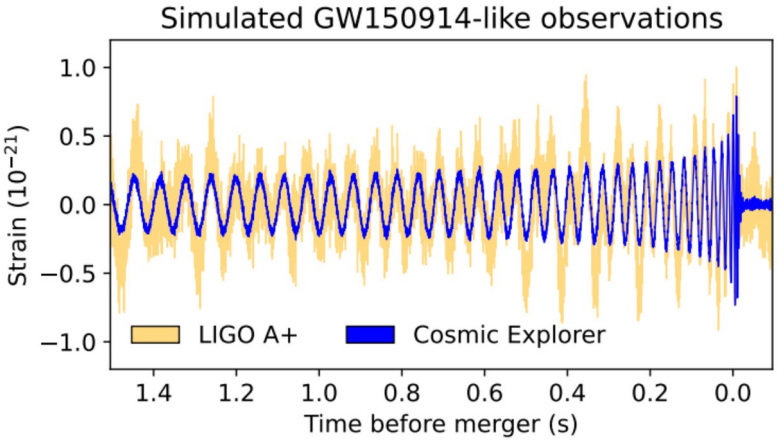


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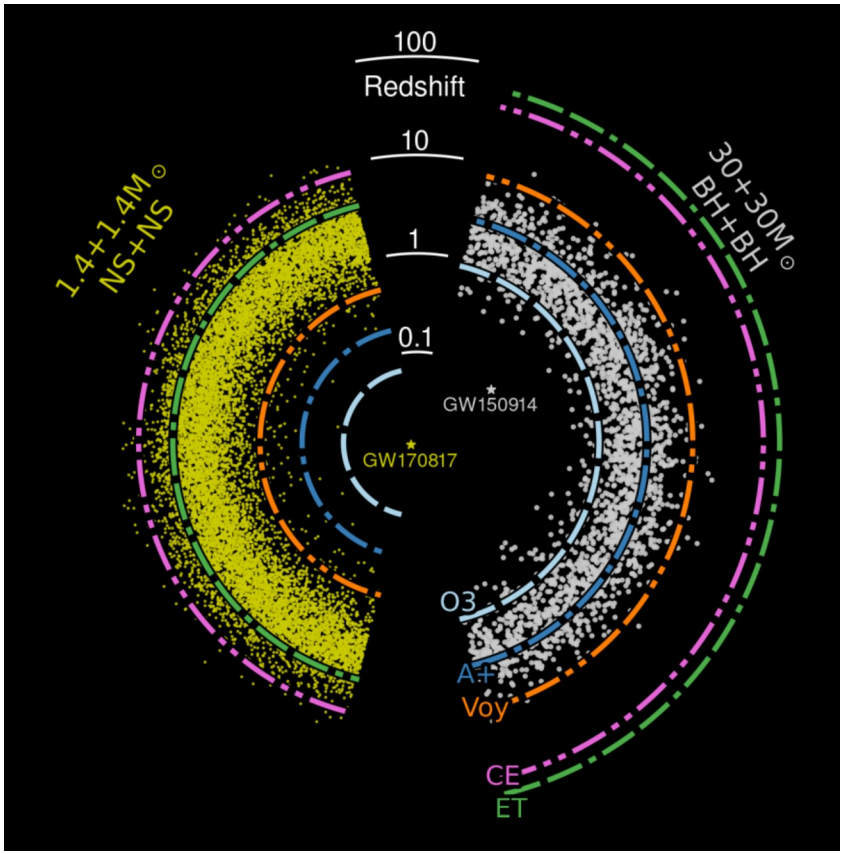


Credit: Cosmic Explorer Horizon Study

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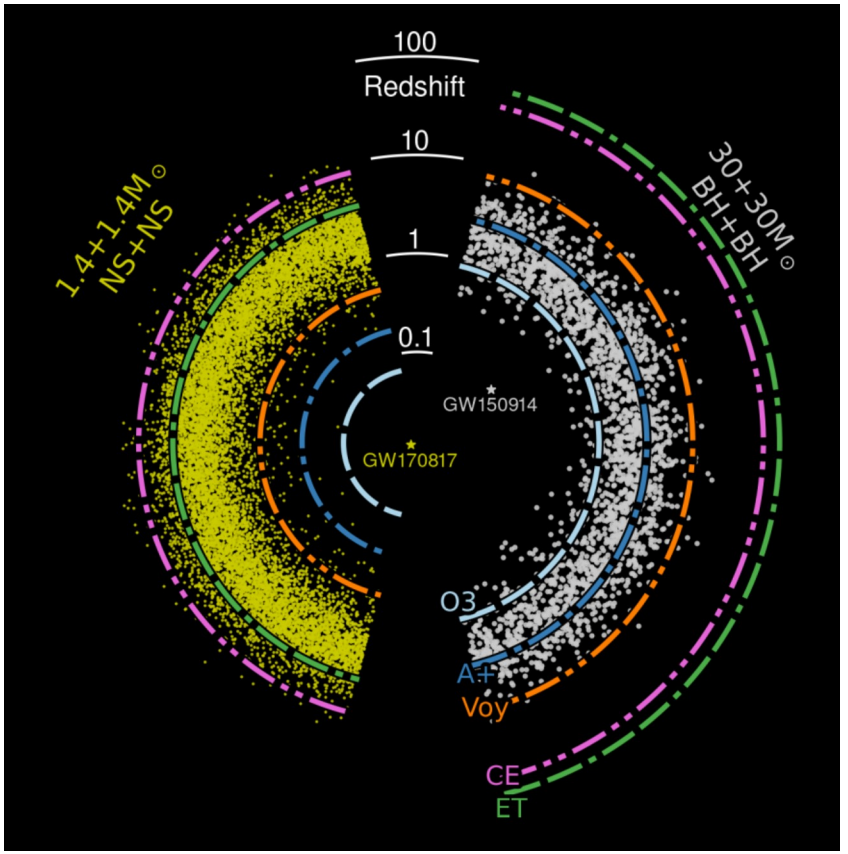


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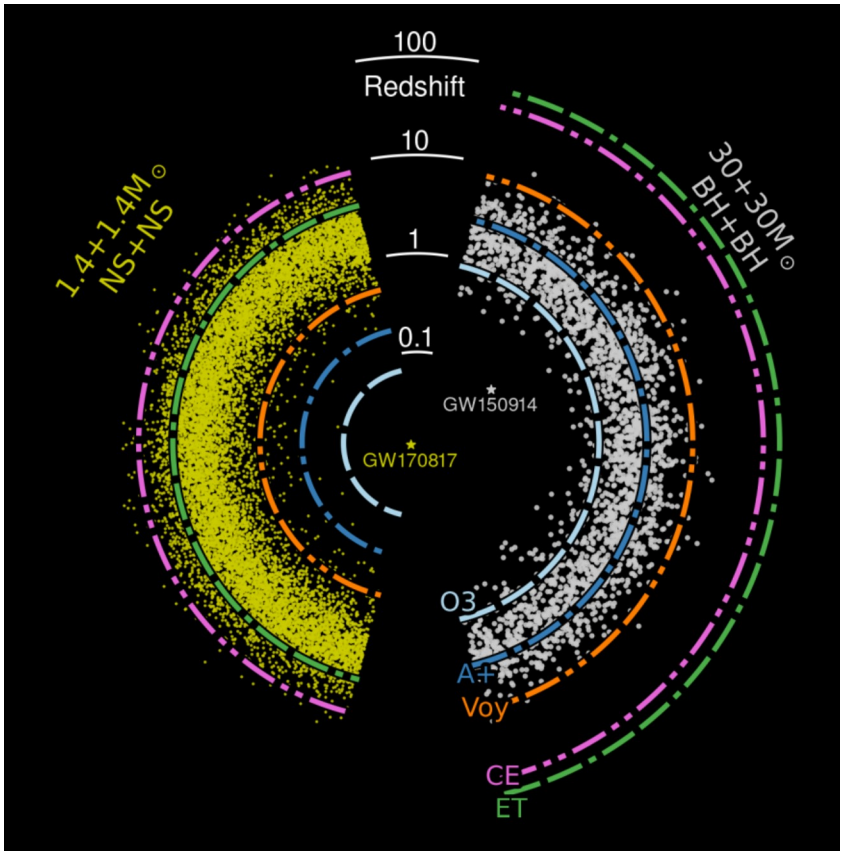


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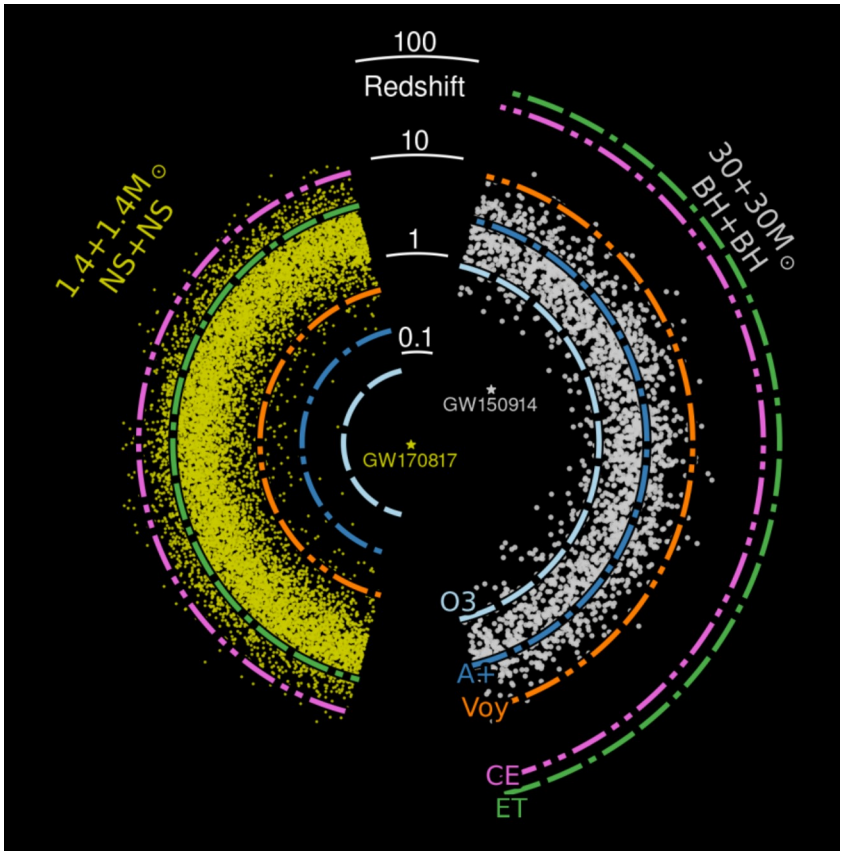


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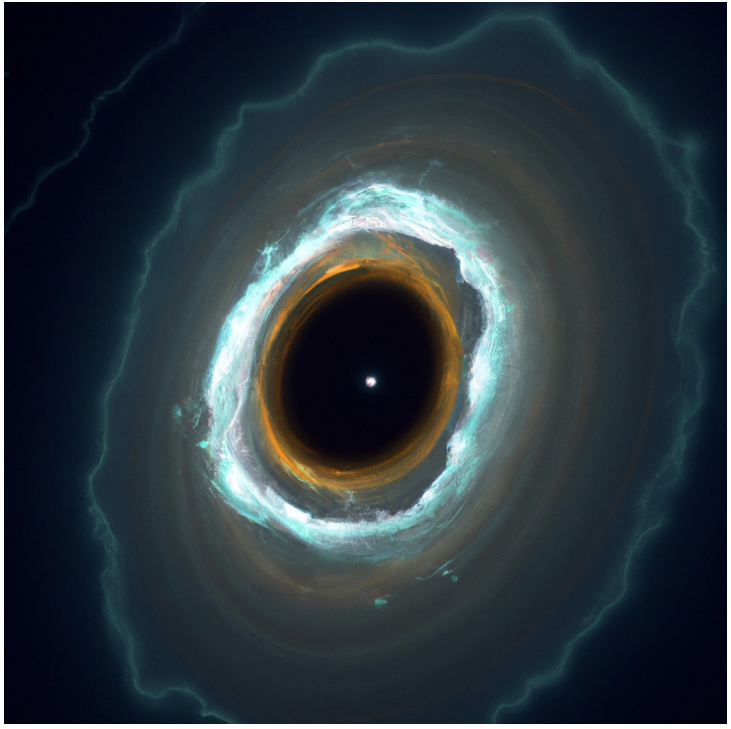
# Conclusion

- Ringdown analysis has the ability to probe GR and black holes in the strong-field regime
- The field has begun to progress through the study of NR and real data events
- Ringdown will become more important and more informative into the future



Credit: OpenAI