Detectability of Nonlinear Gravitational Wave Memory
(August 21, 2020)

LIGO SURF 2020

Darin C. Mumma

Departments of Physics and Philosophy, Grove City College

Mentors: Alan Weinstein, Colm Talbot, Alvin K. Y. Li

LIGO Laboratory, California Institute of Technology

Introduction

I. **Background:** gravitational wave (GW) memory form and types

II. **Problem:** can we detect GW memory?

III. **Approach:** Bayesian parameter estimation

IV. **Results:** posterior samples…and a lot of 'em!

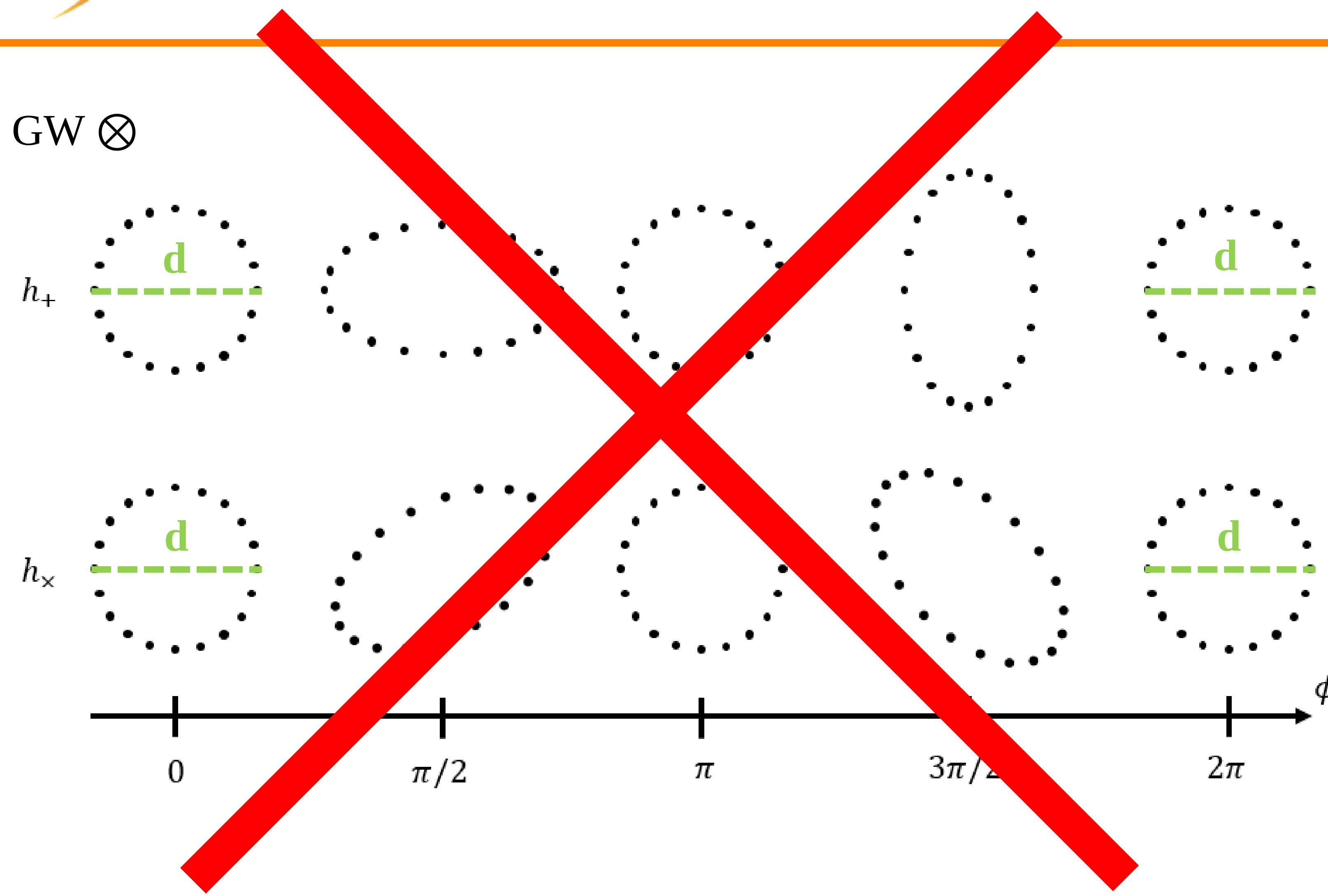
V. **Future work:** where can we go next?

Background

What is Memory?

What is GW Memory?

What is Memory?



Time Domain Waveform

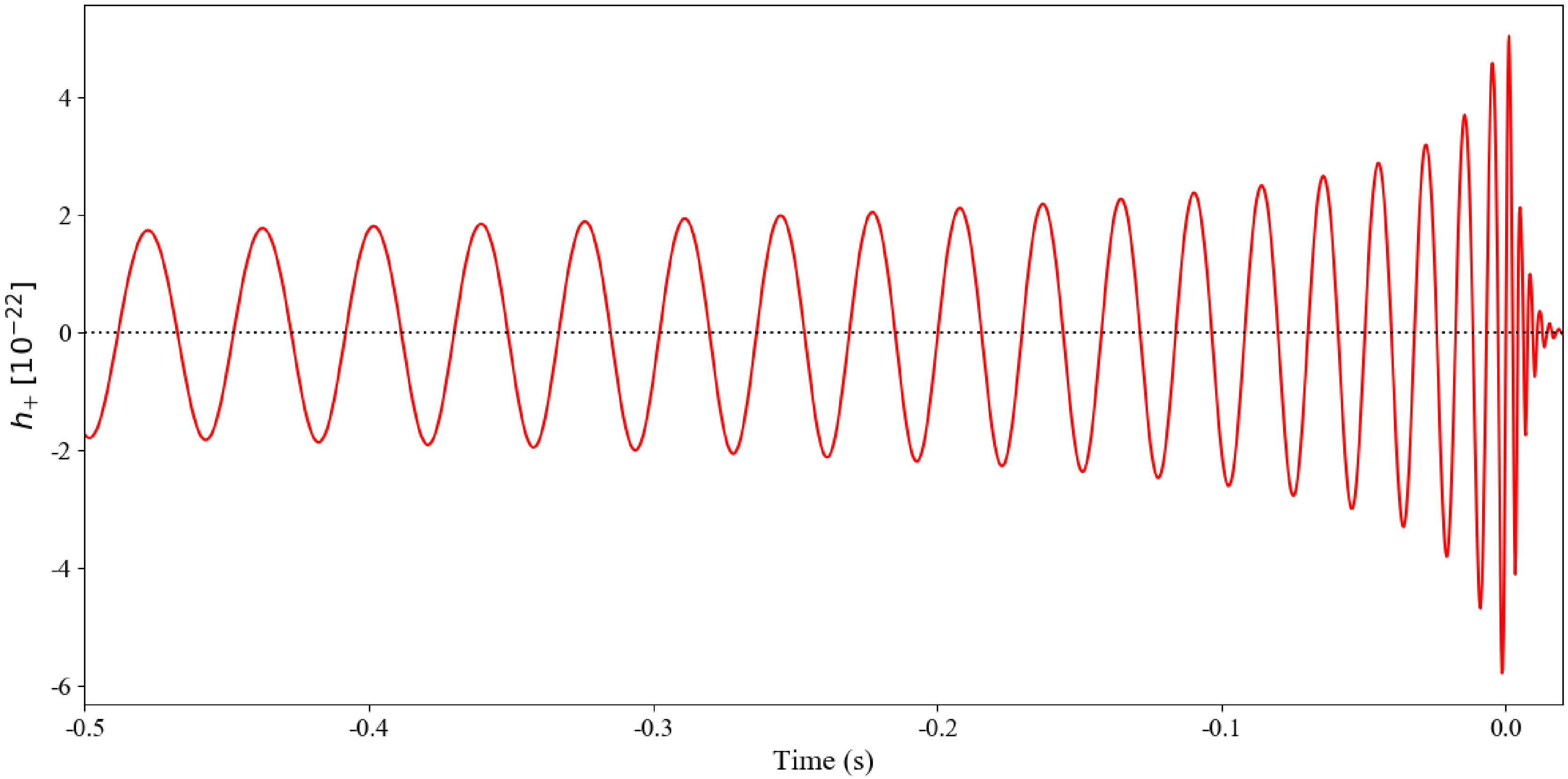


Figure 1. Sourced from a binary black hole (BBH) merger with non-spinning components, $M = 60\text{M}_\odot$, $q = 1$ and $d_\text{L} = 600\text{Mpc}$.

Time Domain Memory

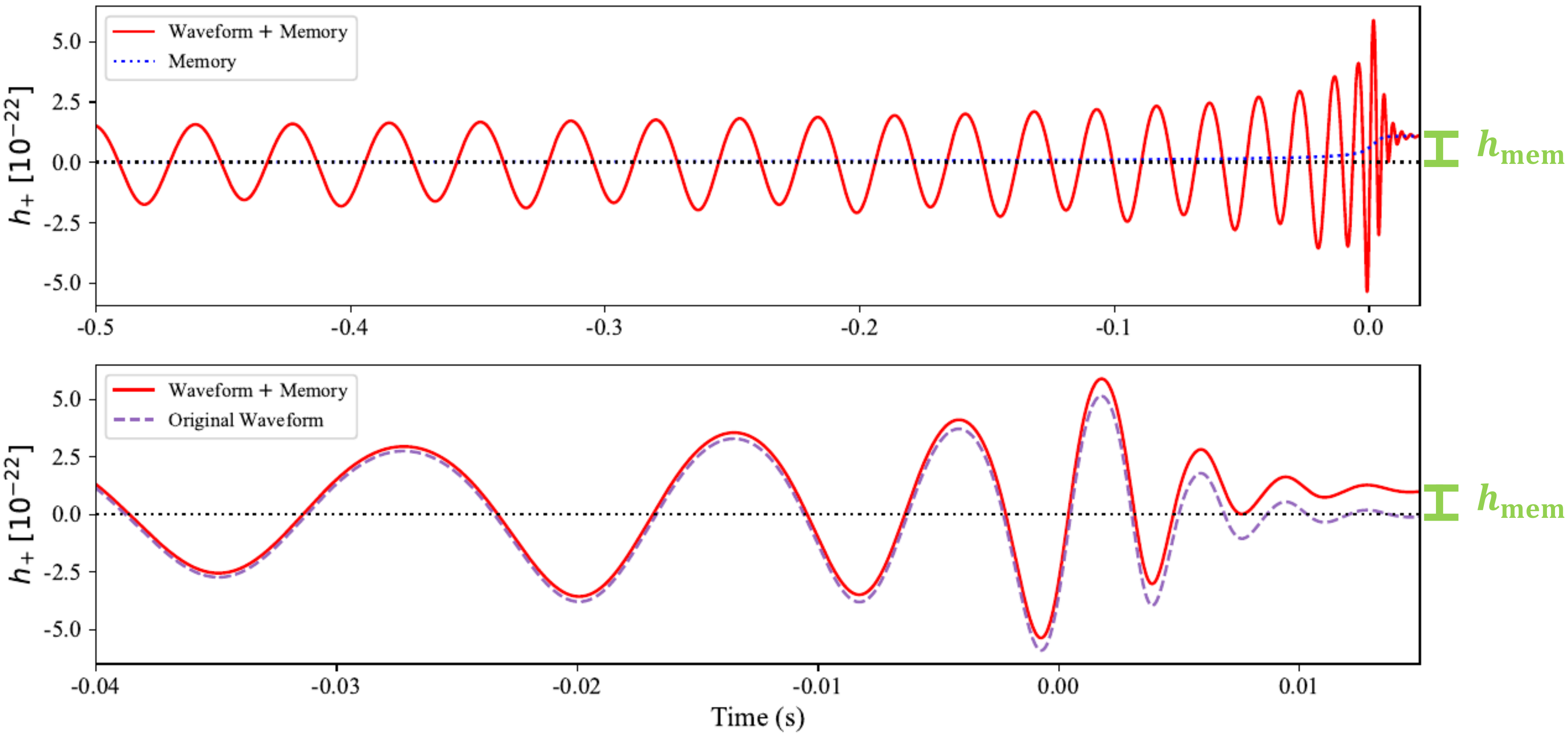
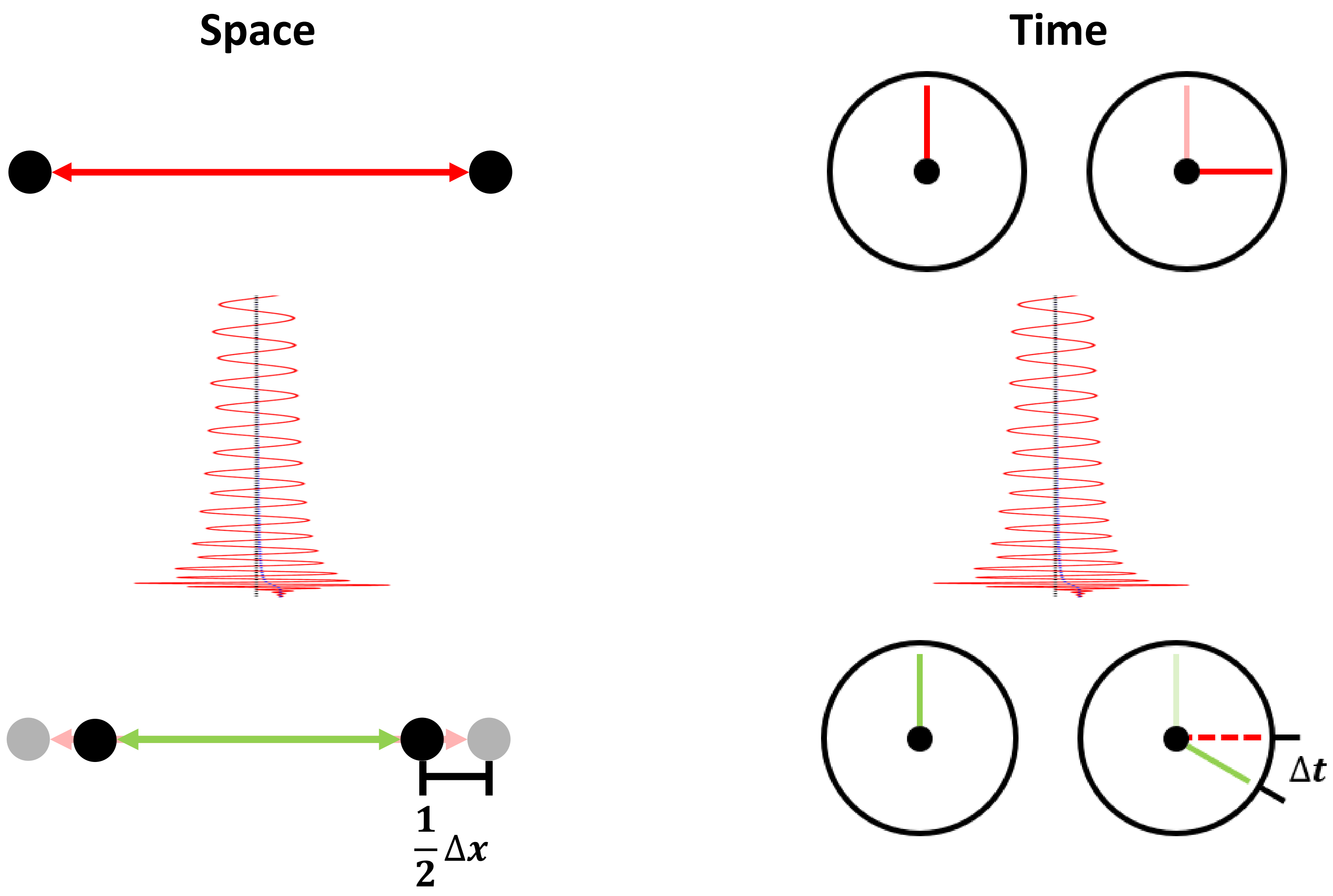


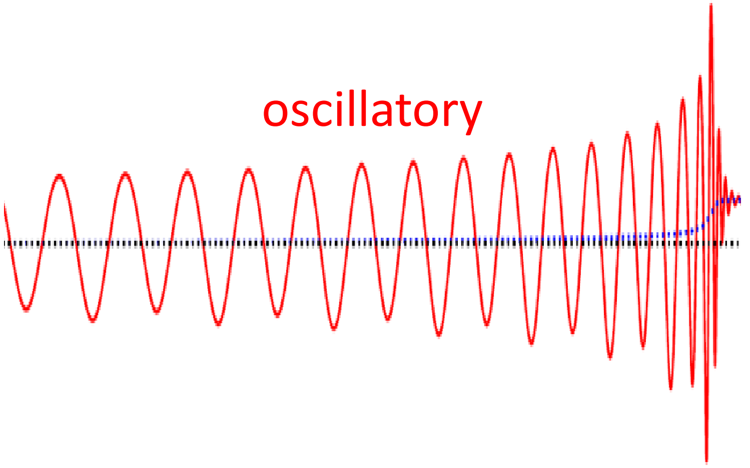
Figure 2. (*Top*) Superposed memory and full waveform. (*Bottom*) Superposed oscillatory and full waveform over the LIGO band only. All waveforms were sourced from a BBH merger with non-spinning components, $M = 60\mathrm{M}_{\odot}$, $q = 1$ and $d_{\mathrm{L}} = 600\mathrm{Mpc}$.

What is Memory?



What is Memory?

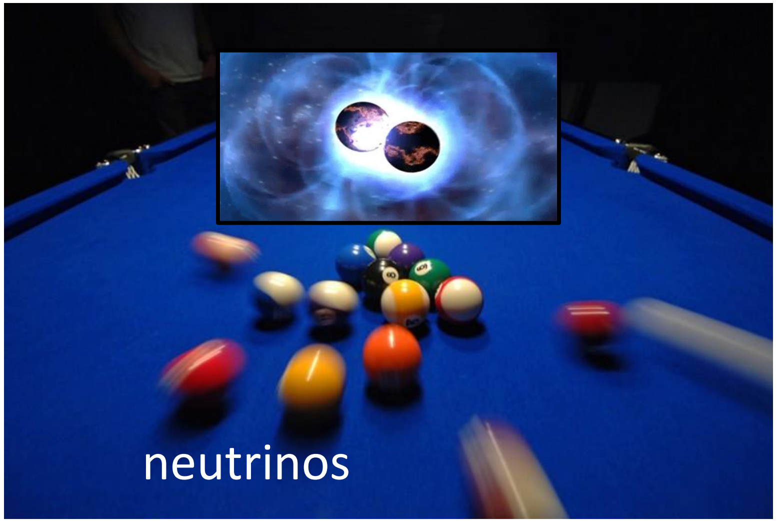
- ***<u>Every</u>*** gravitational waveform has two components: *oscillatory* and *secular* [1]



- Two kinds of secular components: *linear* and *nonlinear*

Linear Memory

- Independent of source's past motion (i.e. integrable or conservative)
- Only exists alongside mass emission (e.g. neutrinos)
- Too small to detect in BBH mergers [2, 3]



(*Courtesy of Lea* [4] and LIGO Caltech [5])

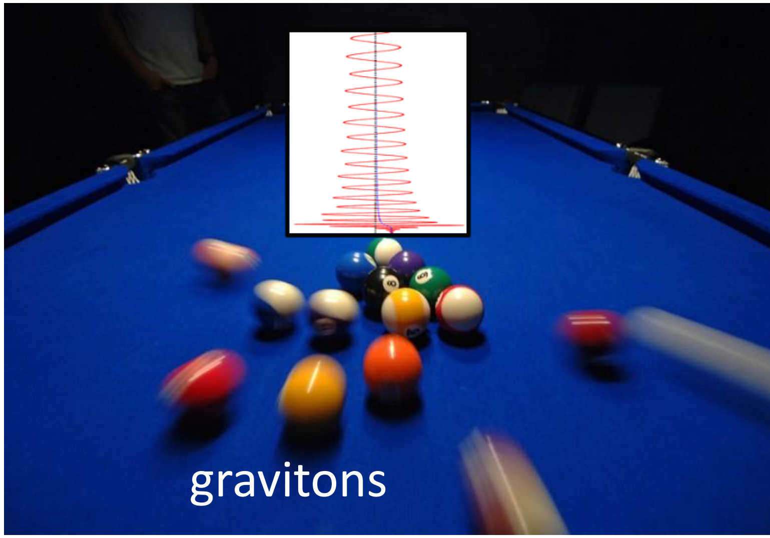
Nonlinear Memory

1. accelerating masses $\Longrightarrow$ GWs

2. mass $\propto$ energy

3. GWs = energy

$\therefore$ GWs $\Longrightarrow$ GWs!!! [3]



Nonlinear Memory

- Depends on entire past motion of source
  (i.e. hereditary, nonintegrable, or nonconservative)

- More prominent than linear memory in BBHs [1, 2]

- Typically 10 times weaker than oscillatory component [3]

Frequency Domain Memory

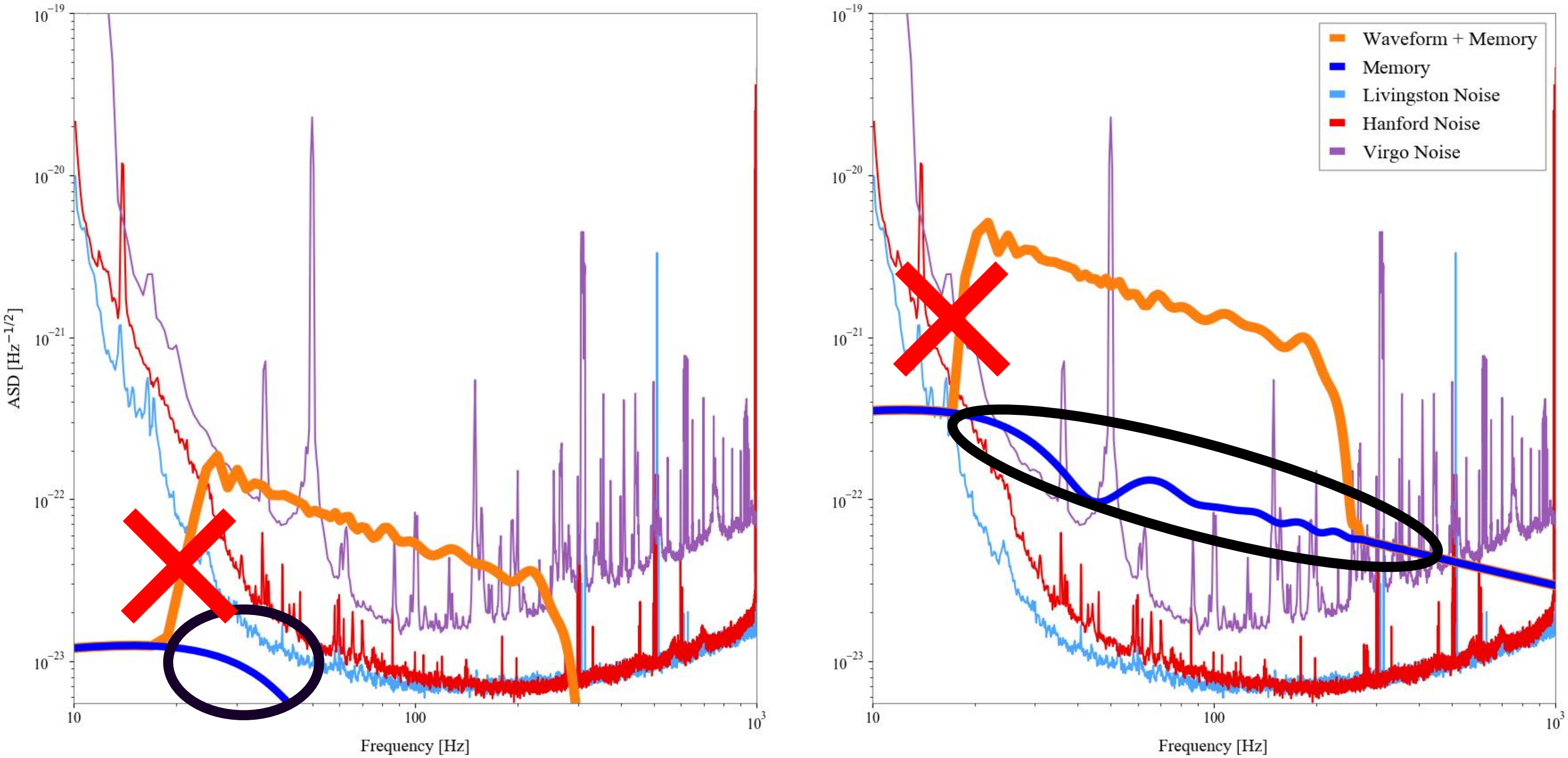


Figure 3. (*Left*) Undetectable memory: $M = 60\mathrm{M}_\odot,\ q = 1$ and $d_\mathrm{L} = 600\mathrm{Mpc}$. (*Right*) Detectable memory: $M = 80\mathrm{M}_\odot,\ q = 1$ and $d_\mathrm{L} = 20\mathrm{Mpc}$. All sub-20-Hz power from the total waveform is incorrect due to windowing.

Estimating Memory

- Nonlinear GW memory is given by:

$$h_{\text{mem}} \approx \frac{5}{14\text{c}^2}\frac{E}{r}\sin^2\iota \qquad (1)$$

where $E \equiv$ total radiated energy of GW source,
$\text{c} \equiv$ vacuum speed of light
$r \equiv$ distance between source and detector,
$\iota \equiv$ inclination angle $\equiv$ angle between $\vec{L}$ and $\vec{r}$.

- Let's use GW150914 as an example:

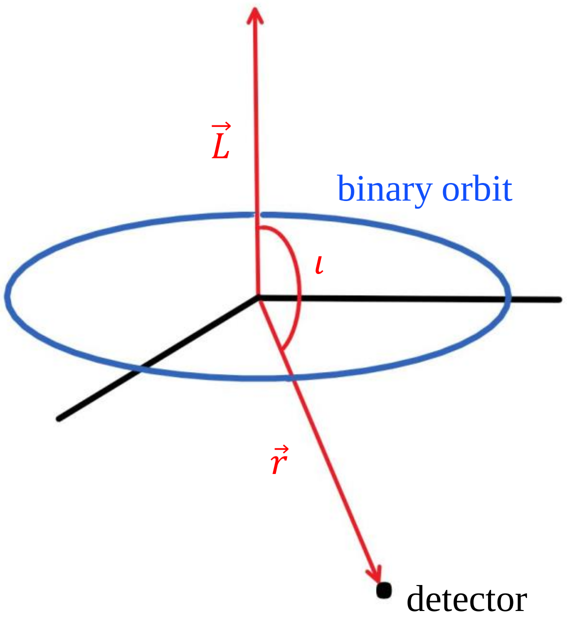
$$E = 3.0\text{M}_\odot \cdot \text{c}^2,\ r = 410\text{Mpc, and } \iota = 150^\circ.$$

Thus,

$$h_{\text{mem}} \approx 3.0 \times 10^{-23}. \qquad (2)$$

- For reference,

$$h_{\max} \approx 1.0 \times 10^{-21}.$$



(*Courtesy of Garfinkle* [6])

Problem

Can we detect memory?

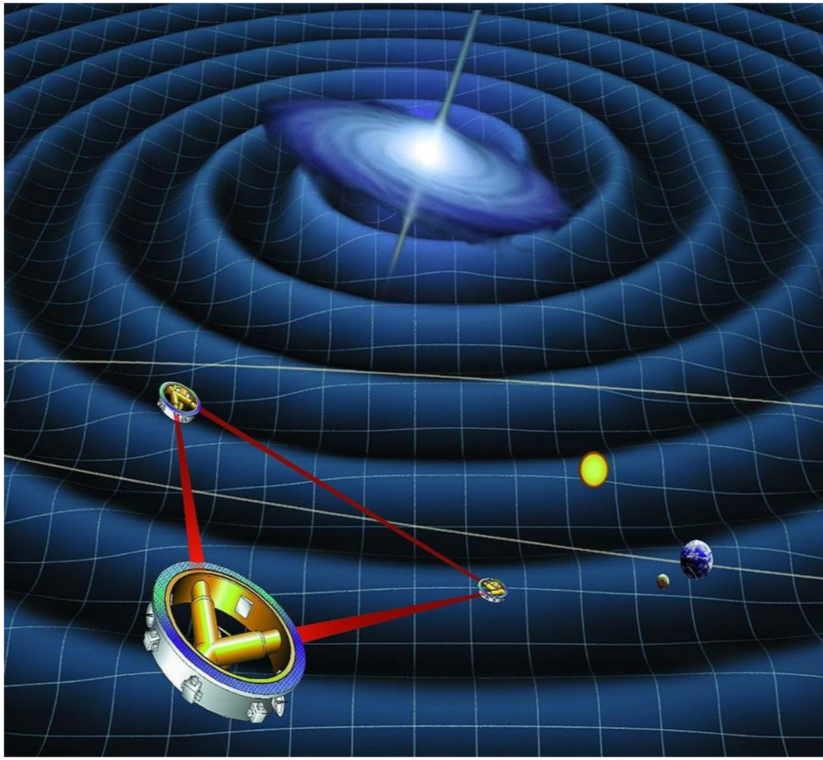
Under what circumstances can we detect memory?

Importance

- Verification of GR

But, why now?
- MANY new and exciting events [7]
- More detectors than ever
- Higher sensitivity per detector

Later…
- LISA [1]



(*Courtesy of NASA* [8])

Approach

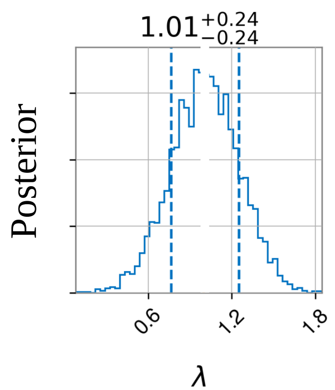
Model with Memory

memory constant

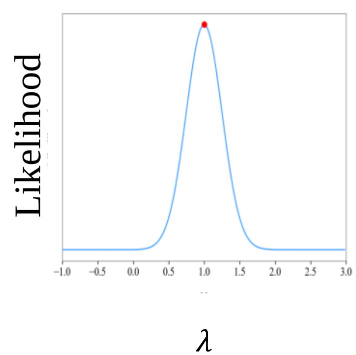
$$h_{\mathrm{tot}} = h + \lambda h_{\mathrm{mem}}$$

Bayes' Theorem

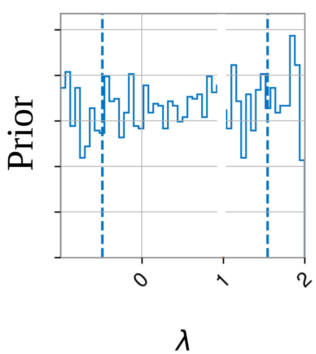
$$P(H \mid D) = \frac{P(D \mid H)\, P(H)}{P(D)} \qquad \text{or} \qquad \text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$



$=$



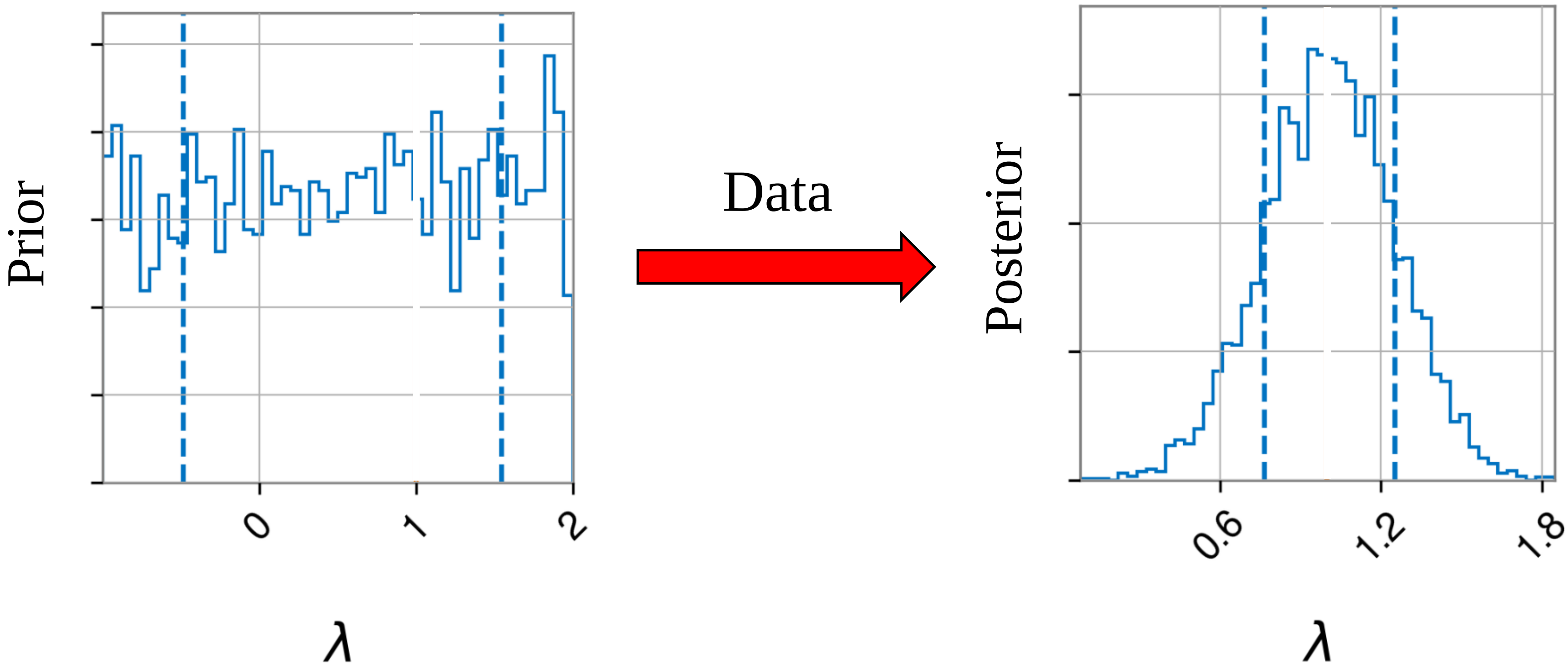
$\times$



―――――――――――――

constant

Bayes' Theorem



Results

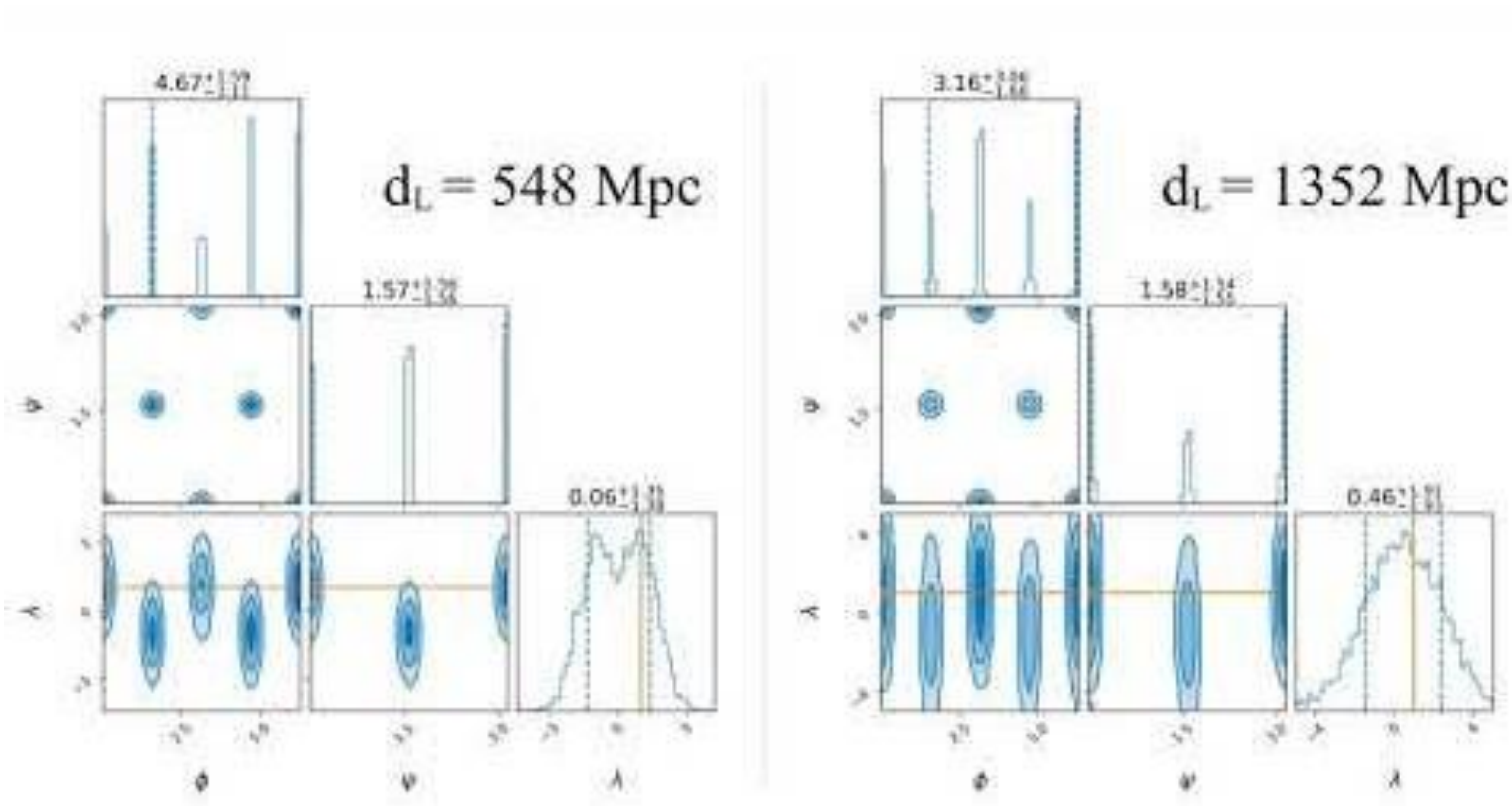


Figure 4. (*Left*) (2, 2) mode only and (*Right*) all modes included. The injected waveform used to generate these posterior distributions is sourced by non-spinning components with $M_{\mathrm{tot}} = 60$ solar masses, $q = 1$, $\iota = \pi/2$, $\alpha = 0$, $\delta = 0$.

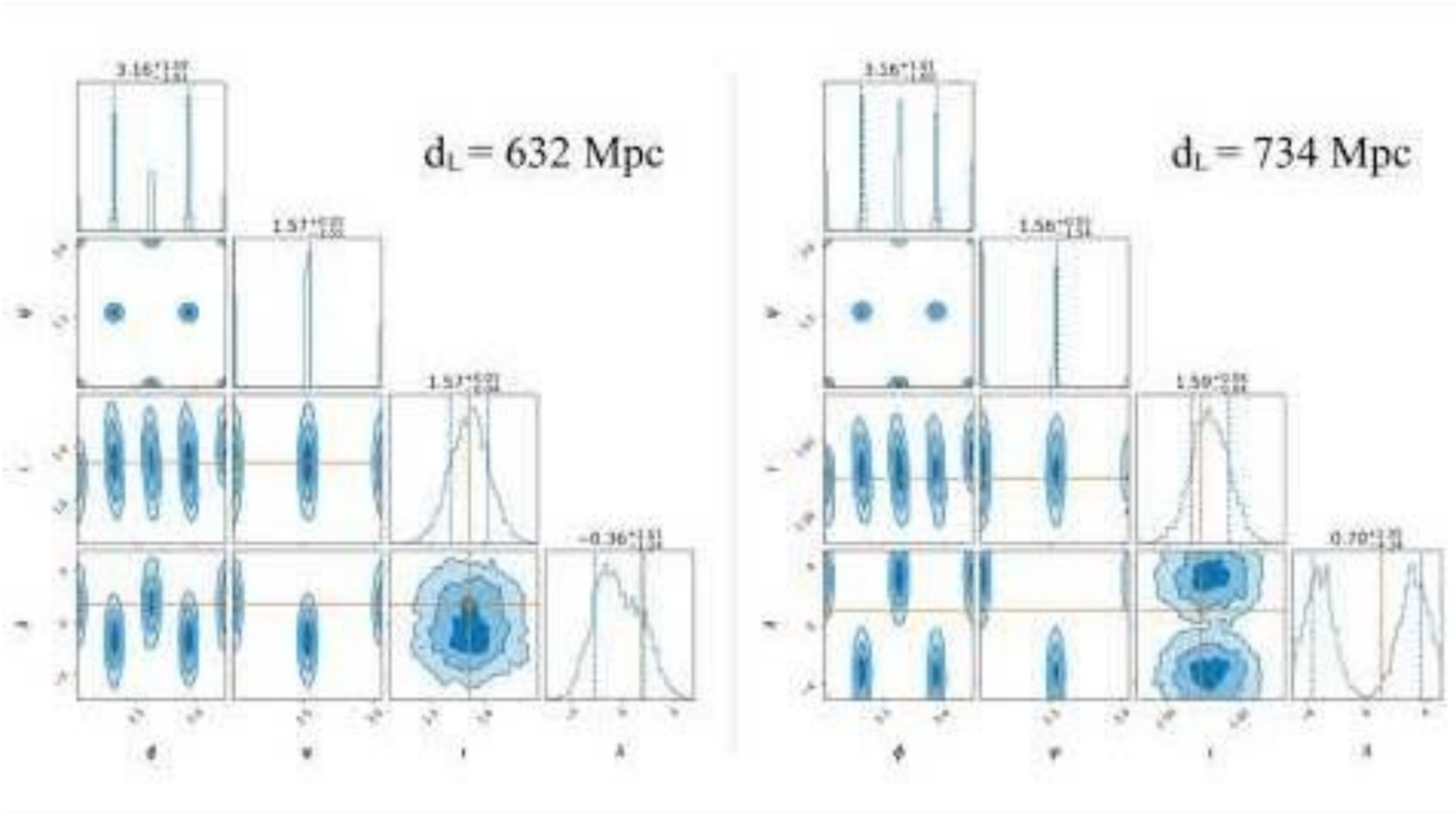


Figure 5. (2, 2)-mode degeneracy. (*Left*) noiseless and (*Right*) with noise. The injected waveform used to generate these posterior distributions is sourced by non-spinning components with $M_{\text{tot}} = 60$ solar masses, $q = 1$, $\iota = \pi/2$, $\alpha = 0$, $\delta = 0$.

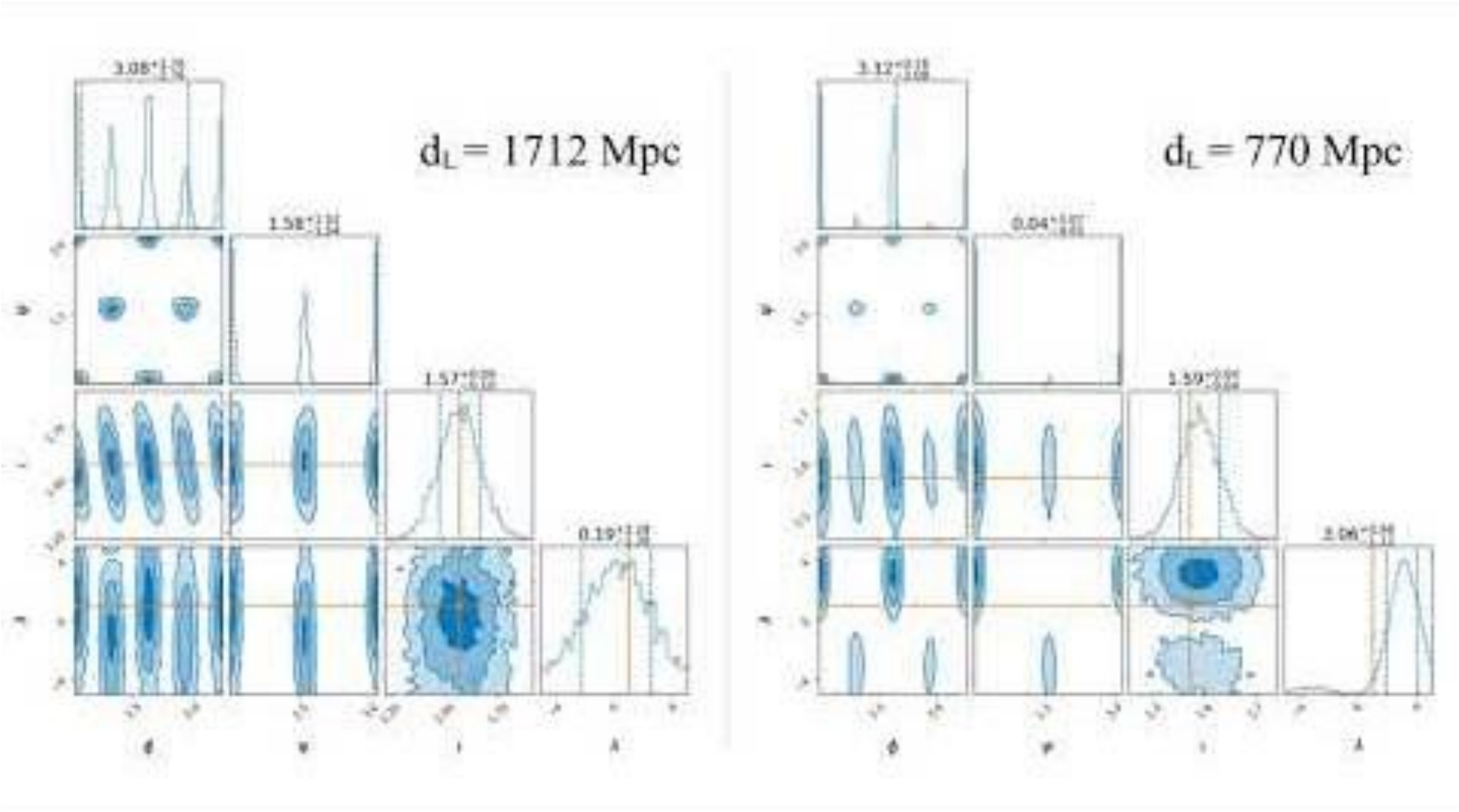


Figure 6. (*Left*) Noiseless signal with all modes included and (*Right*) noisy signal with all modes included. The injected waveform used to generate these posterior distributions is sourced by non-spinning components with $M_{\rm tot} = 60$ solar masses, $q = 1$, $\iota = \pi/2$, $\alpha = 0$, $\delta = 0$.

The Real Deal!!!

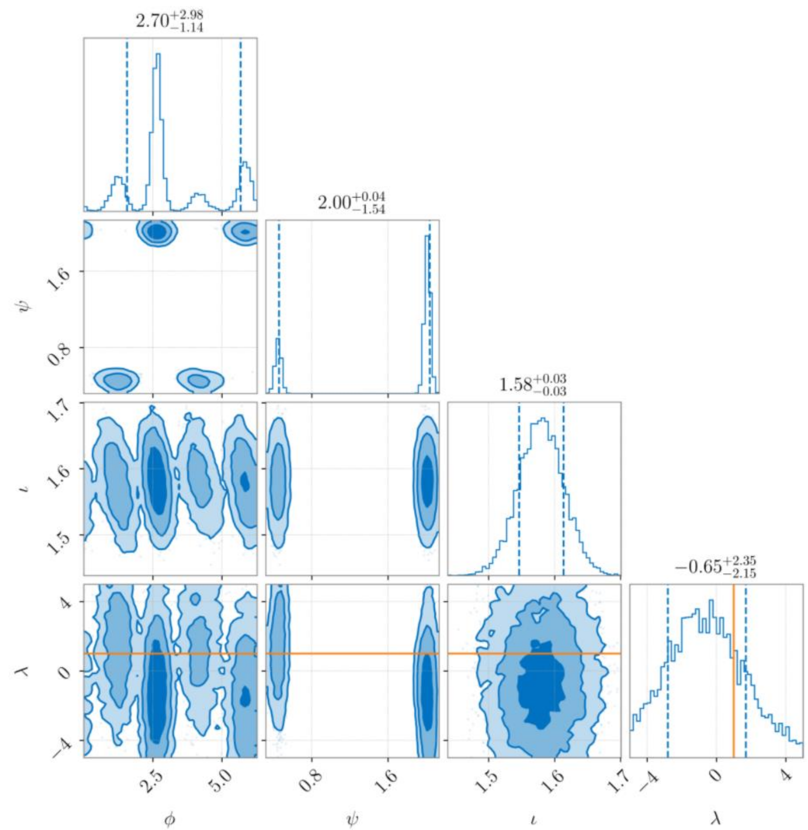
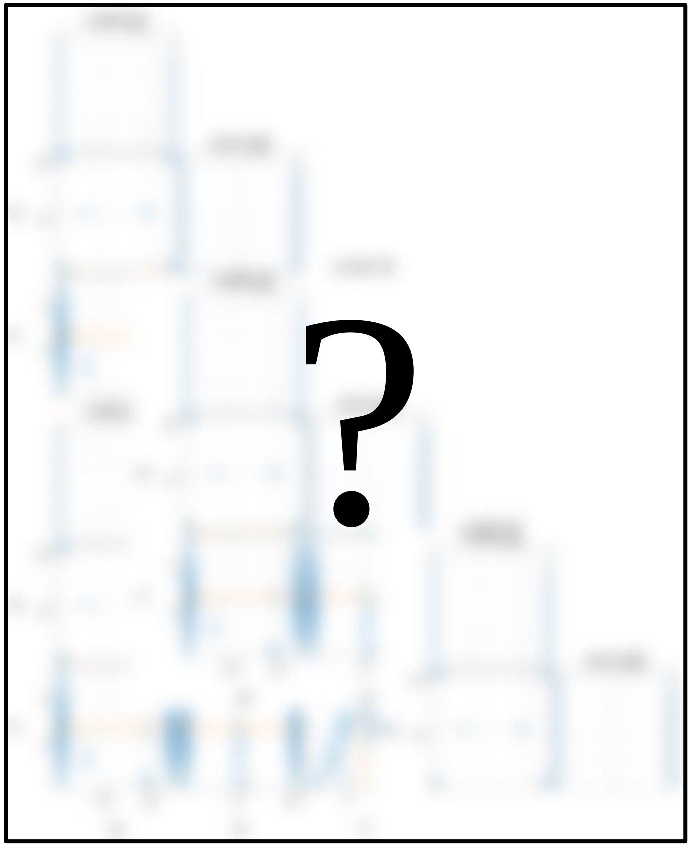


Figure 7. Strain data comes from GW150914. Non-inferred priors were retrieved from posterior samples obtained by memoryless parameter estimation. These values correspond to the maximum likelihood and are $M = 70.4$ solar masses, $q = 1.1$, $d_L = 342.2$Mpc, $\iota = 2.5$, $\alpha = \delta = 1.2$

Future Work

Future Work

- Analyze remaining events
- Explore higher dimensional parameter spaces
- Incorporate full posterior samples for physical events



Acknowledgements

Mentors

LIGO Laboratory

Caltech SURF

National Science Foundation (NSF)

References

[1] M. Favata. “The gravitational-wave memory effect.” *Classical Quantum Gravity*, 27(8), 2010.

[2] C. Talbot et al. *Phys. Rev. D*, 98(6), 2018.

[3] K. Thorne. *Phys. Rev. D*, 45(2): 520-24, 1992.

[4] R. Lea. DOI: https://sciscomedia.co.uk/reverse-time.

[5] LIGO Caltech. DOI: https://www.ligo.caltech.edu/video/BNS-merge.

[6] D. Garfinkle. “A Simple Estimate of Gravitational Wave Memory in Binary Black Hole Systems.” *Classical Quantum Gravity*, 33(17), 2016.

[7] B. P. Abbott et al. *Astrophys. J. Lett.*, 892(L3), 2020.

[8] NASA. DOI: lisa.jpl.nasa.gov/gallery/lisa-waves.

[9] C. M. Biwer et al. “PyCBC Inference: A Python-based parameter estimation toolkit for compact binary coalescence signals.” *PASP*, 131(996), 2019.

[10] C. Talbot. “GWMemory.” DOI: github.com/colmtalbot/gwmemory.

[11] G. Ashton. “BILBY.” DOI: lscsoft.docs.ligo.org/bilby/index.

Questions?