Detectability of Nonlinear Gravitational Wave Memory

(August 21, 2020)

LIGO SURF 2020

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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?

Time Domain Waveform

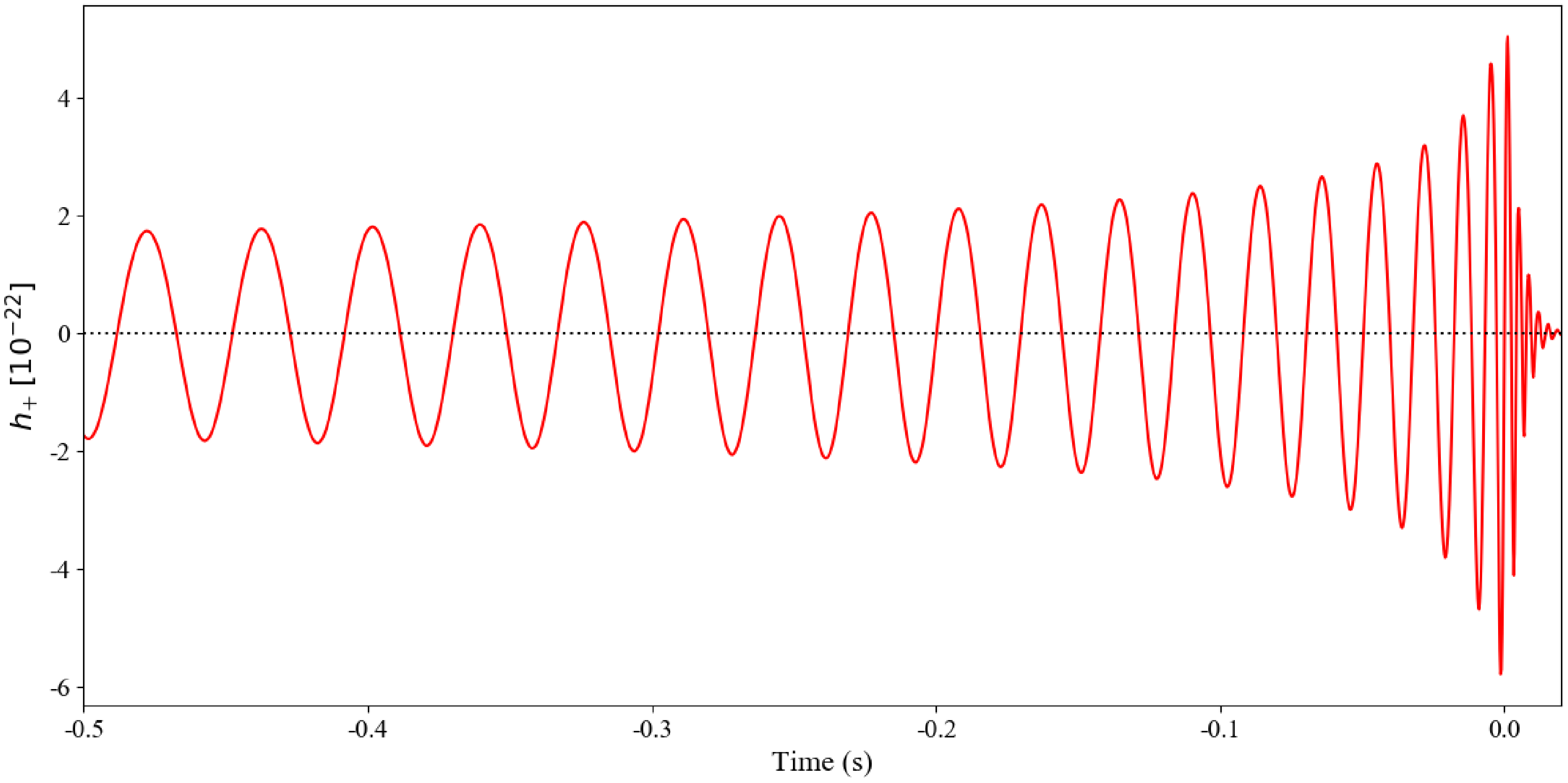
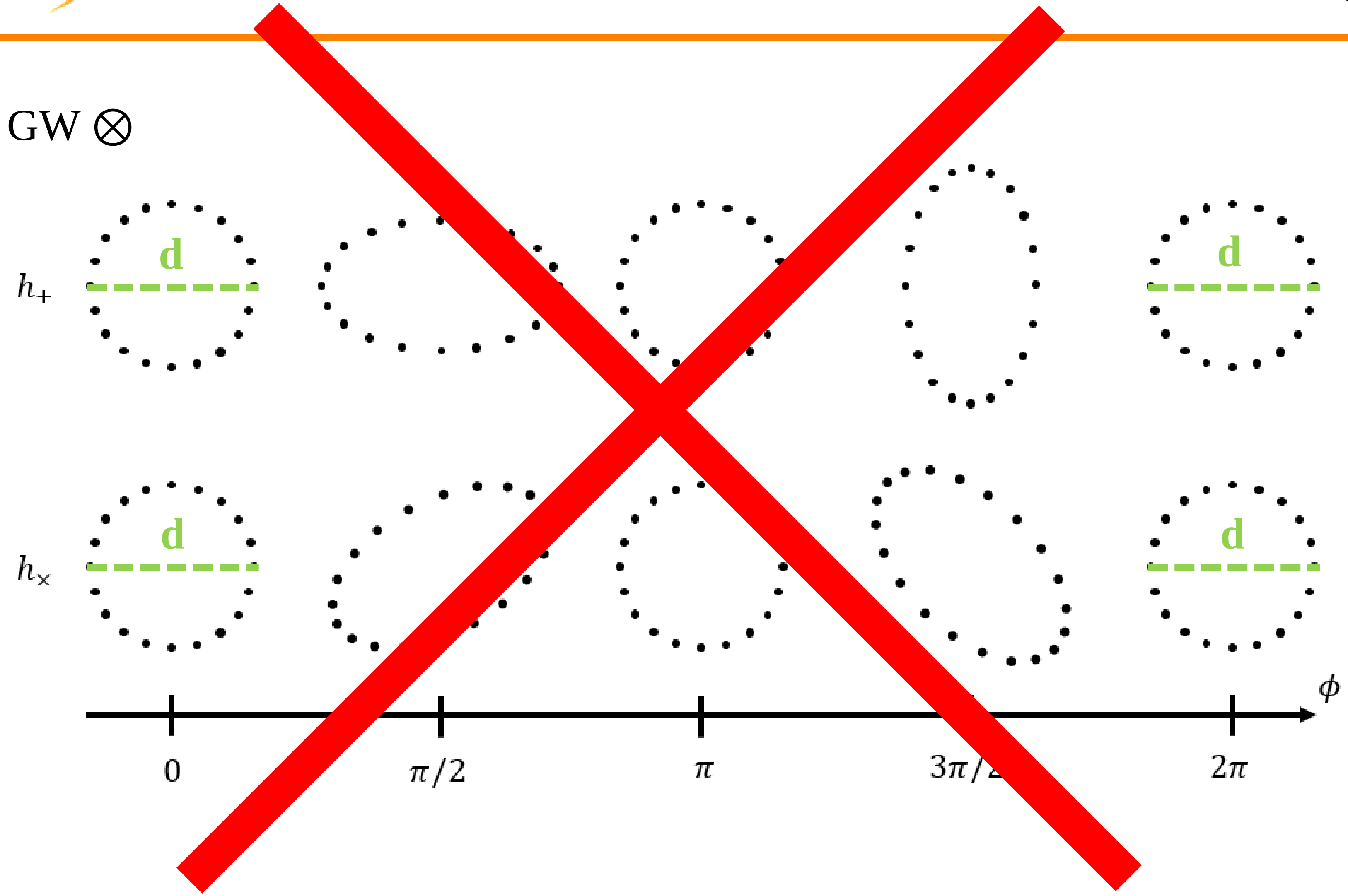


Figure 1. Sourced from a binary black hole (BBH) merger with non-spinning components, $M = 60\mathrm{M}_\odot$, $q = 1$ and $d_\mathrm{L} = 600\mathrm{Mpc}$.

What is Memory?



Time Domain Memory

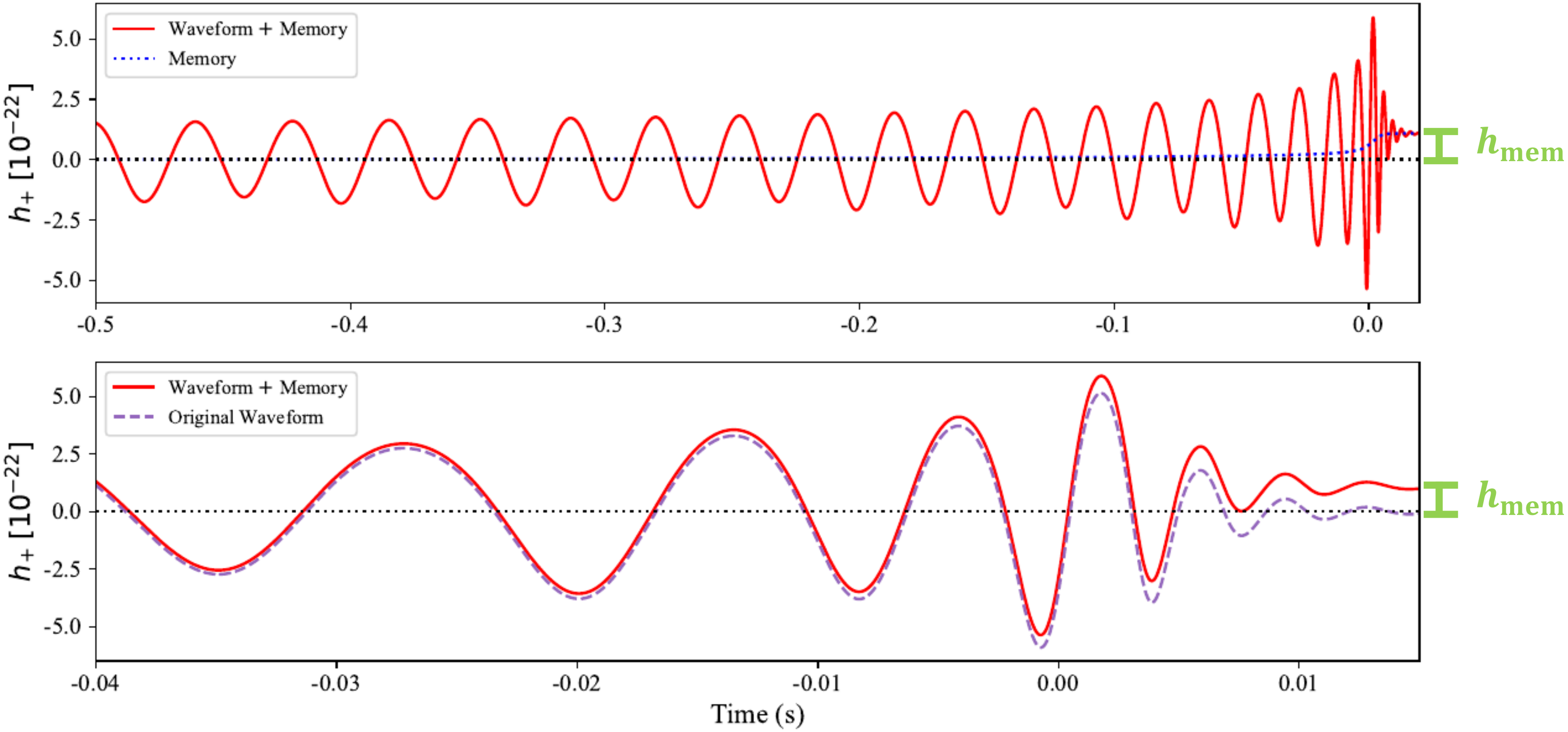
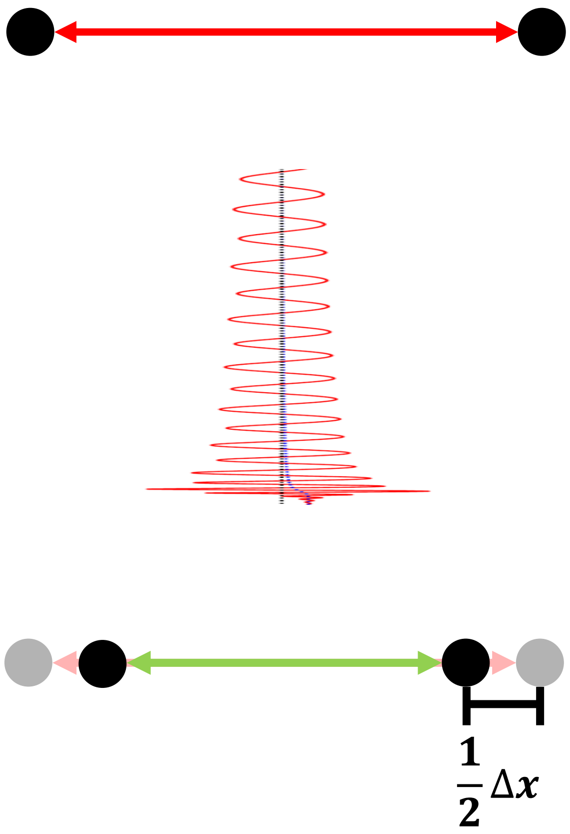


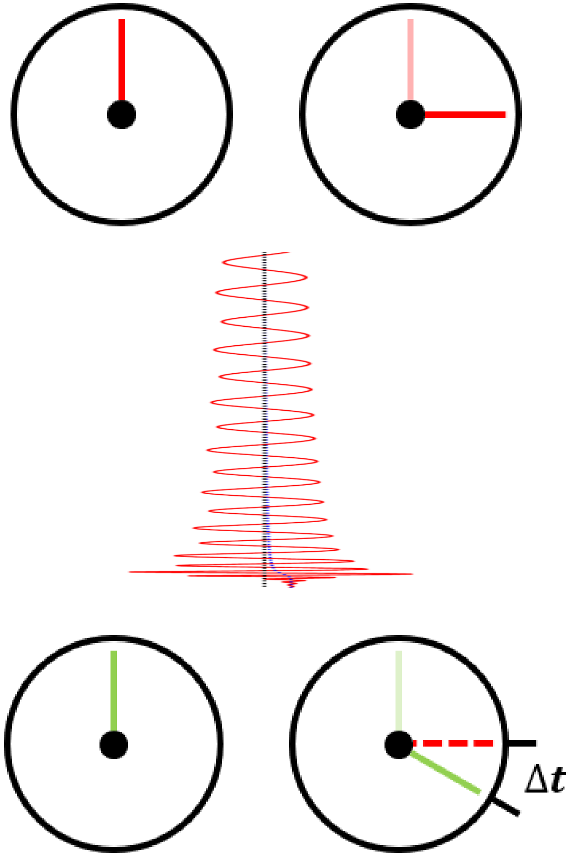
Figure 2. (*Top*) Superposed memory and full waveform. (*Bottom*) Superposed oscillatory and full waveform over the LIGO band only. All waveforms were sourced from a BBH merger with non-spinning components, $M = 60\mathrm{M}_\odot$, $q = 1$ and $d_\mathrm{L} = 600\mathrm{Mpc}$.

What is Memory?

Space

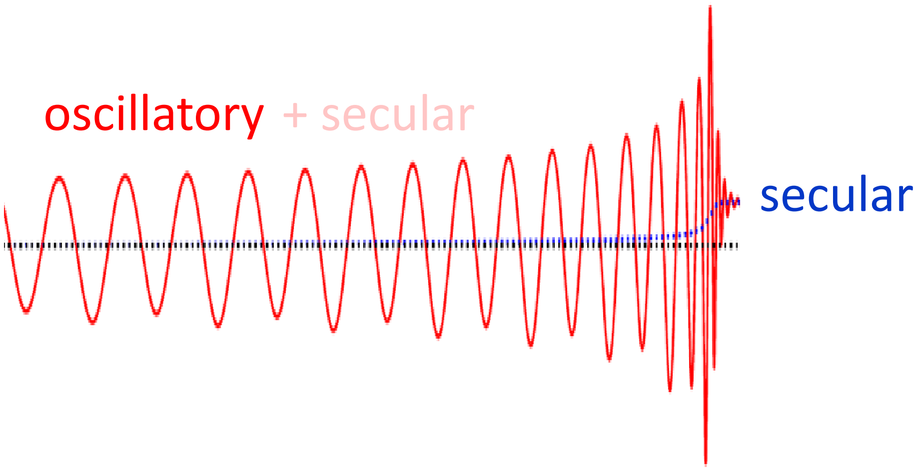


Time



What is Memory?

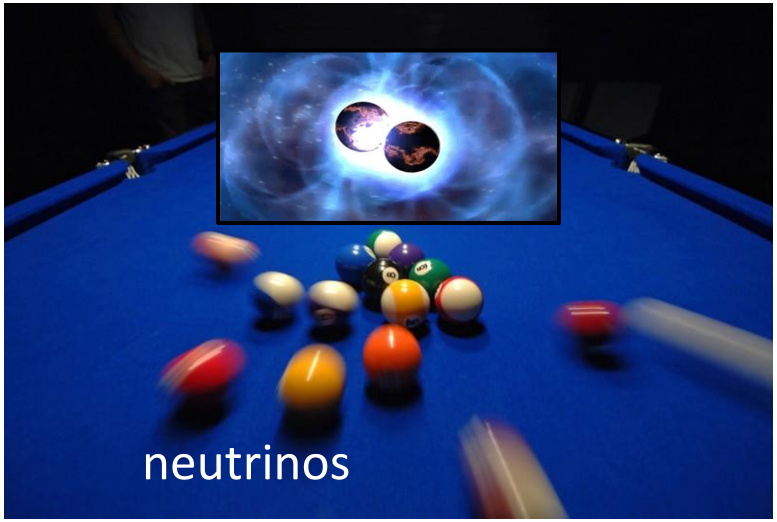
- ***Every*** gravitational waveform has two components: *oscillatory* and *secular* [1]



- 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])

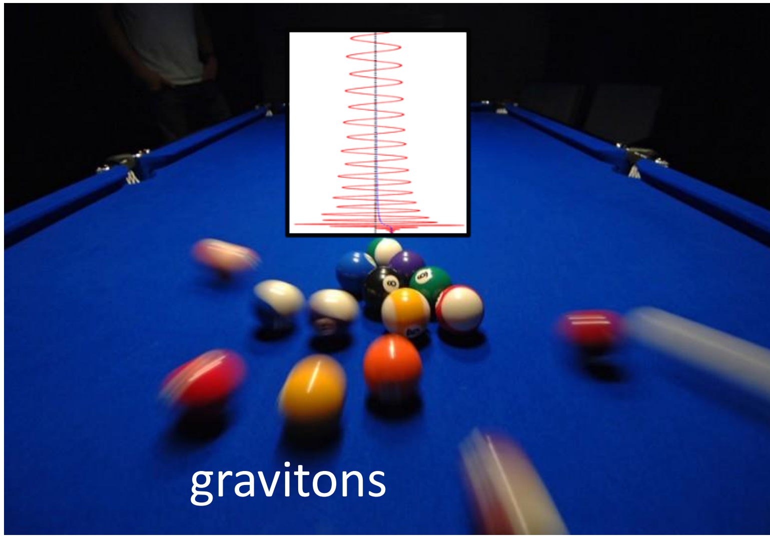
Nonlinear Memory

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

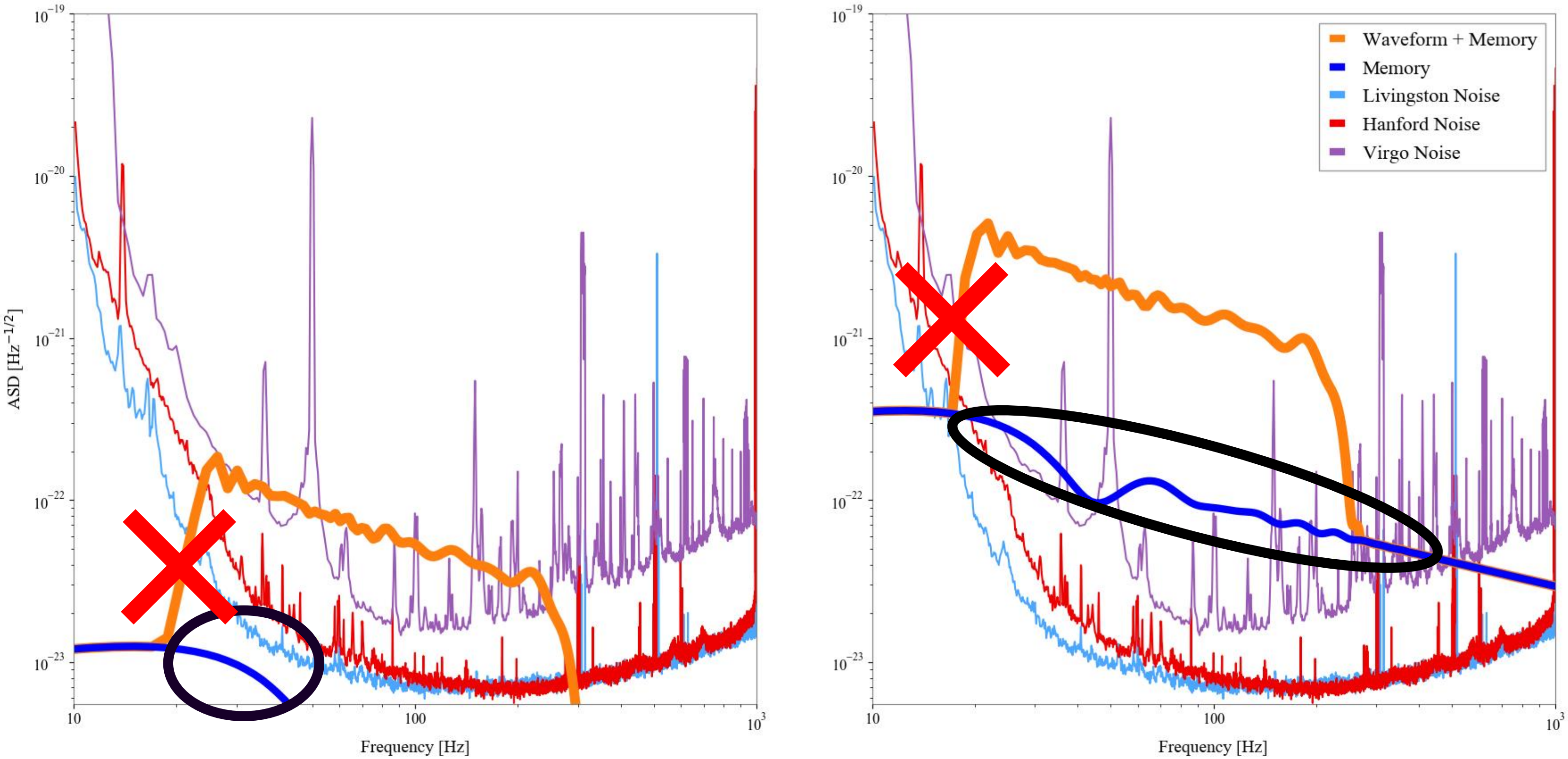


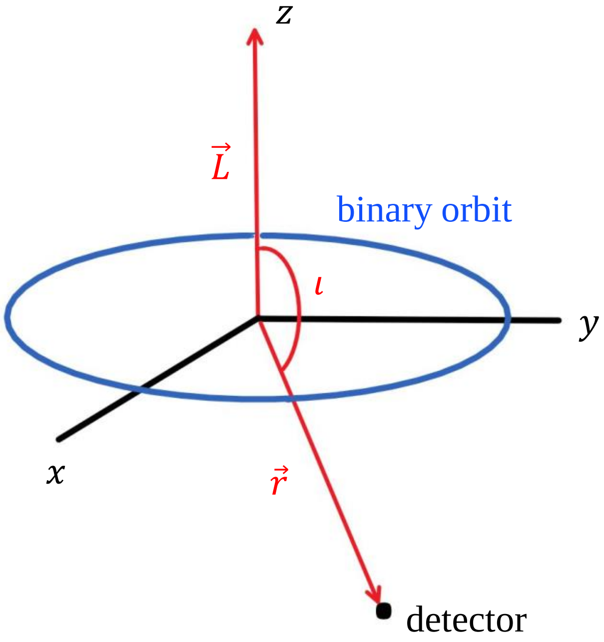
Figure 3. (*Left*) Undetectable memory: $M = 60\mathrm{M}_{\odot},\ q = 1$ and $d_\mathrm{L} = 600\mathrm{Mpc}$. (*Right*) Detectable memory: $M = 80\mathrm{M}_{\odot},\ q = 1$ and $d_\mathrm{L} = 20\mathrm{Mpc}$. All sub-20-Hz power from the total waveform is incorrect due to windowing.

Estimating Memory

- Nonlinear GW memory is given by:

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

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,

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

(*Courtesy of Garfinkle* [6])

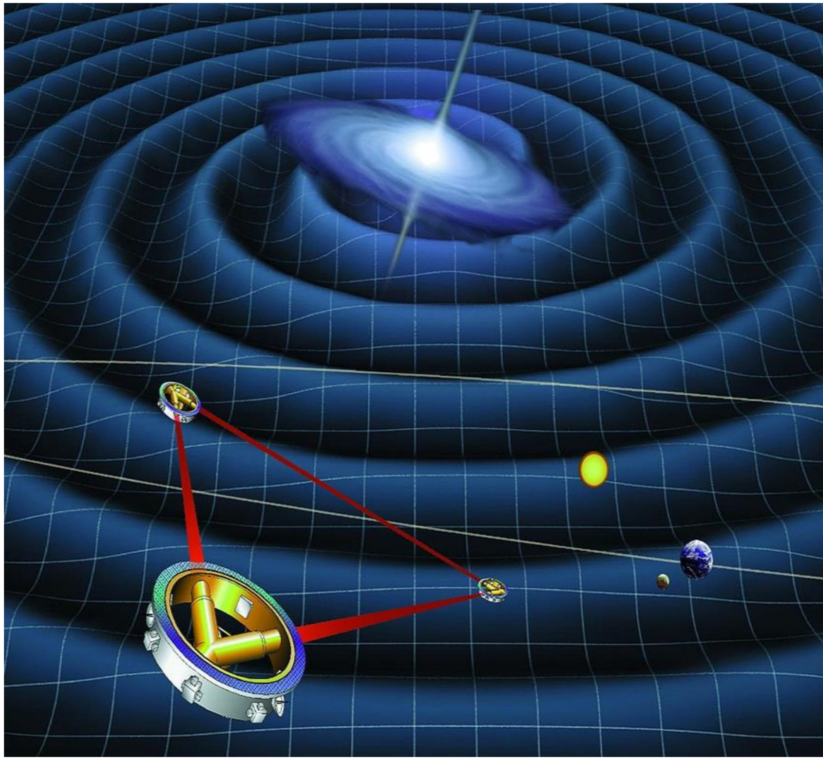
Problem

Can we detect memory?

<u>Under what circumstances</u> can we detect memory?

Importance

- Verification of General Relativity



(*Courtesy of NASA* [8])

<u>But, why now</u>?

- MANY new and exciting events [7]
- More detectors than ever
- Higher sensitivity per detector

<u>Later</u>…

- LISA [1]

Approach

Model with Memory

$$\boxed{h_{\text{tot}} = h + \overset{\text{memory constant}}{\lambda} h_{\text{mem}}}$$

Bayes' Theorem

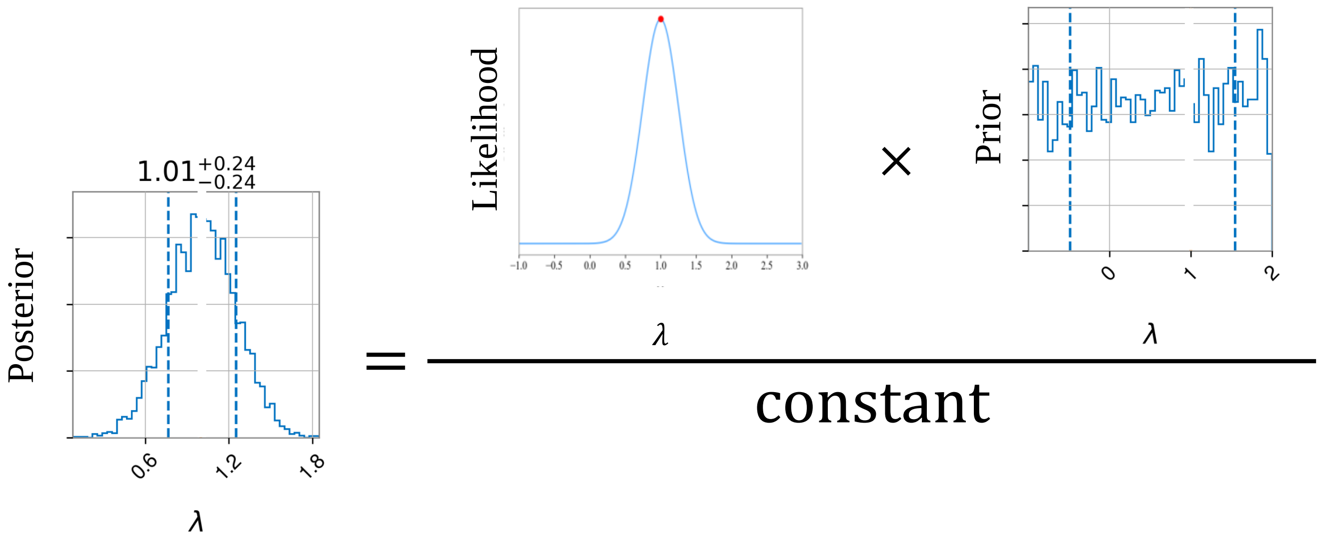
FOR MATHEMATICIANS

$$P(H\mid D) = \frac{P(D\mid H)\,P(H)}{P(D)}$$

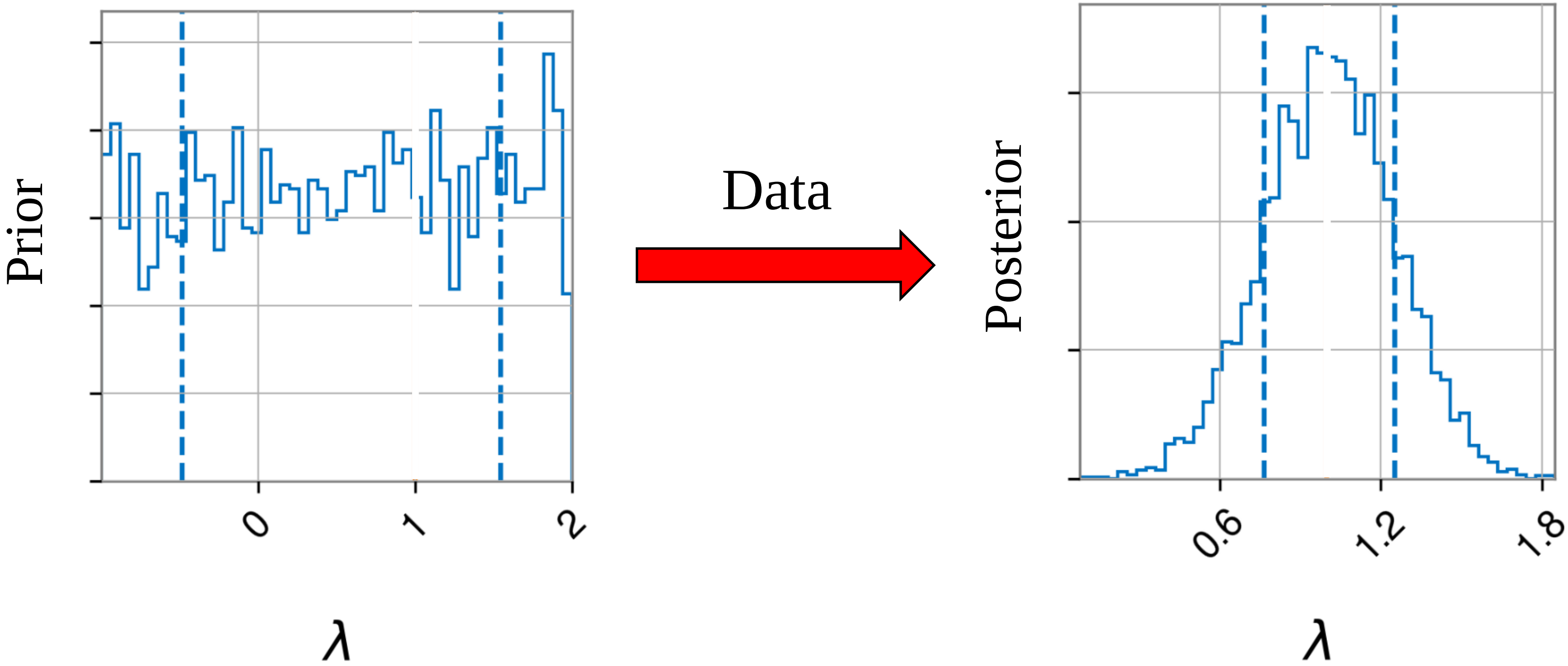
FOR THEORISTS

$$\text{posterior} = \frac{\text{likelihood} \times \text{prior}}{\text{evidence}}$$

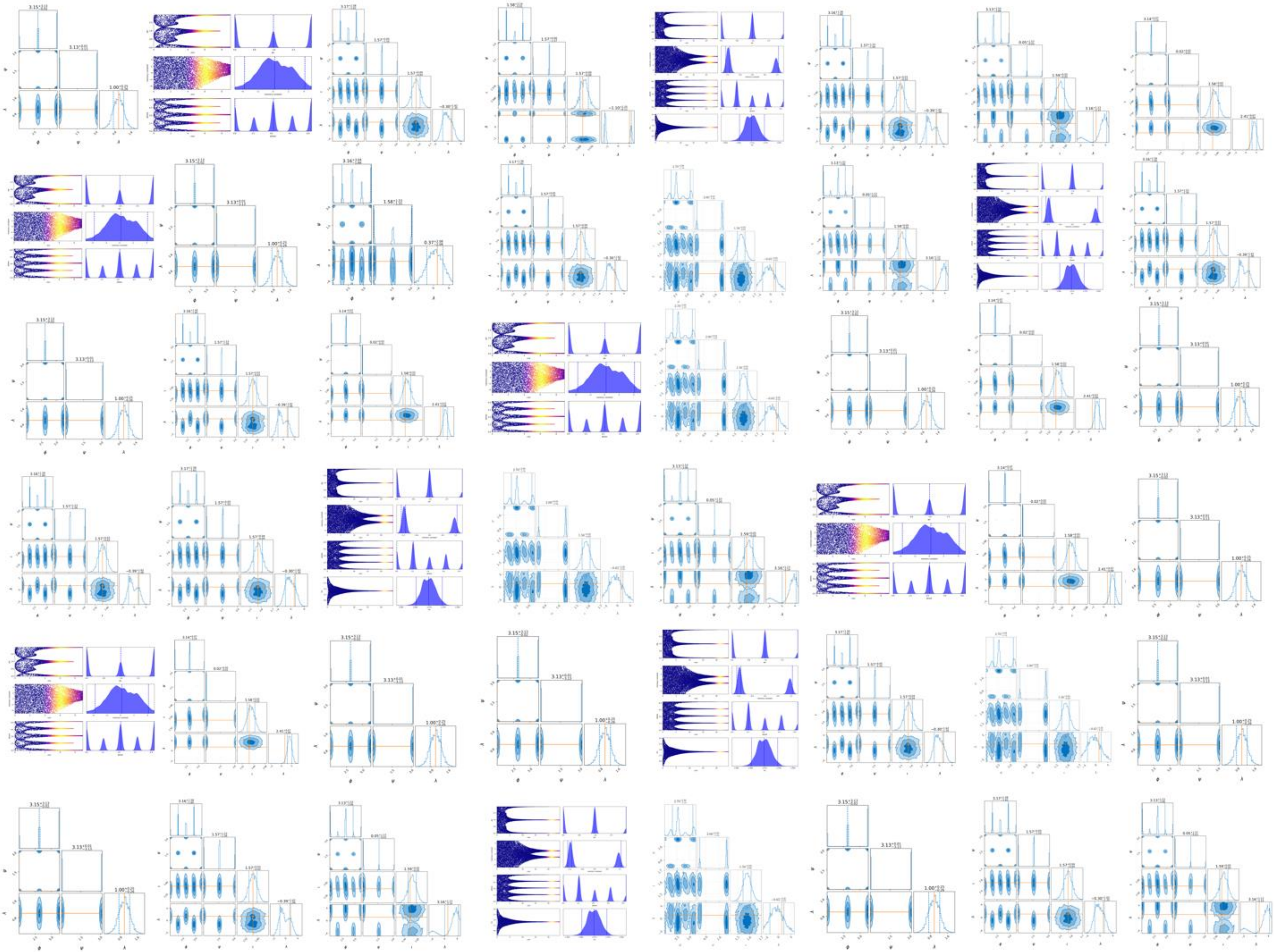
FOR LIGO SCIENTISTS



Bayes’ Theorem



Results


φ
ψ
λ

Questions?

Degeneracy

Under the transformation

$(\psi \to \psi + \pi/2, \phi_c \to \phi_c + \pi/2)$…

- Oscillatory part remains the same

- Memory swaps sign

…but <u>only</u> if we are looking at the (2, 2)-mode alone.

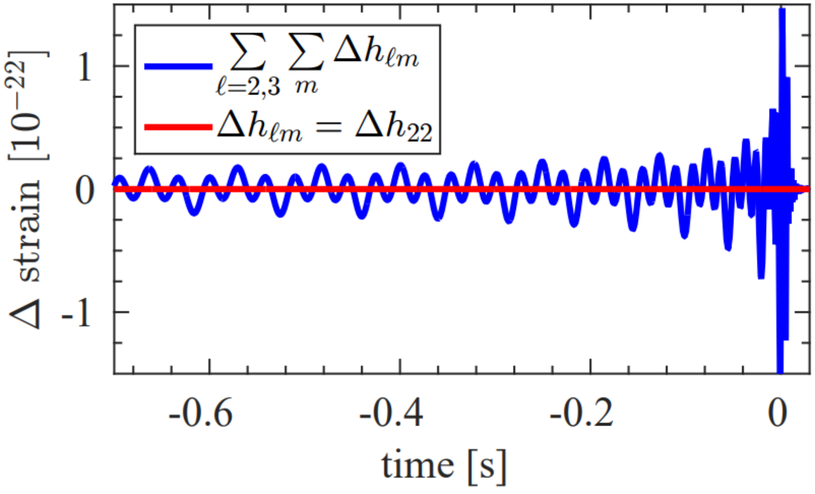
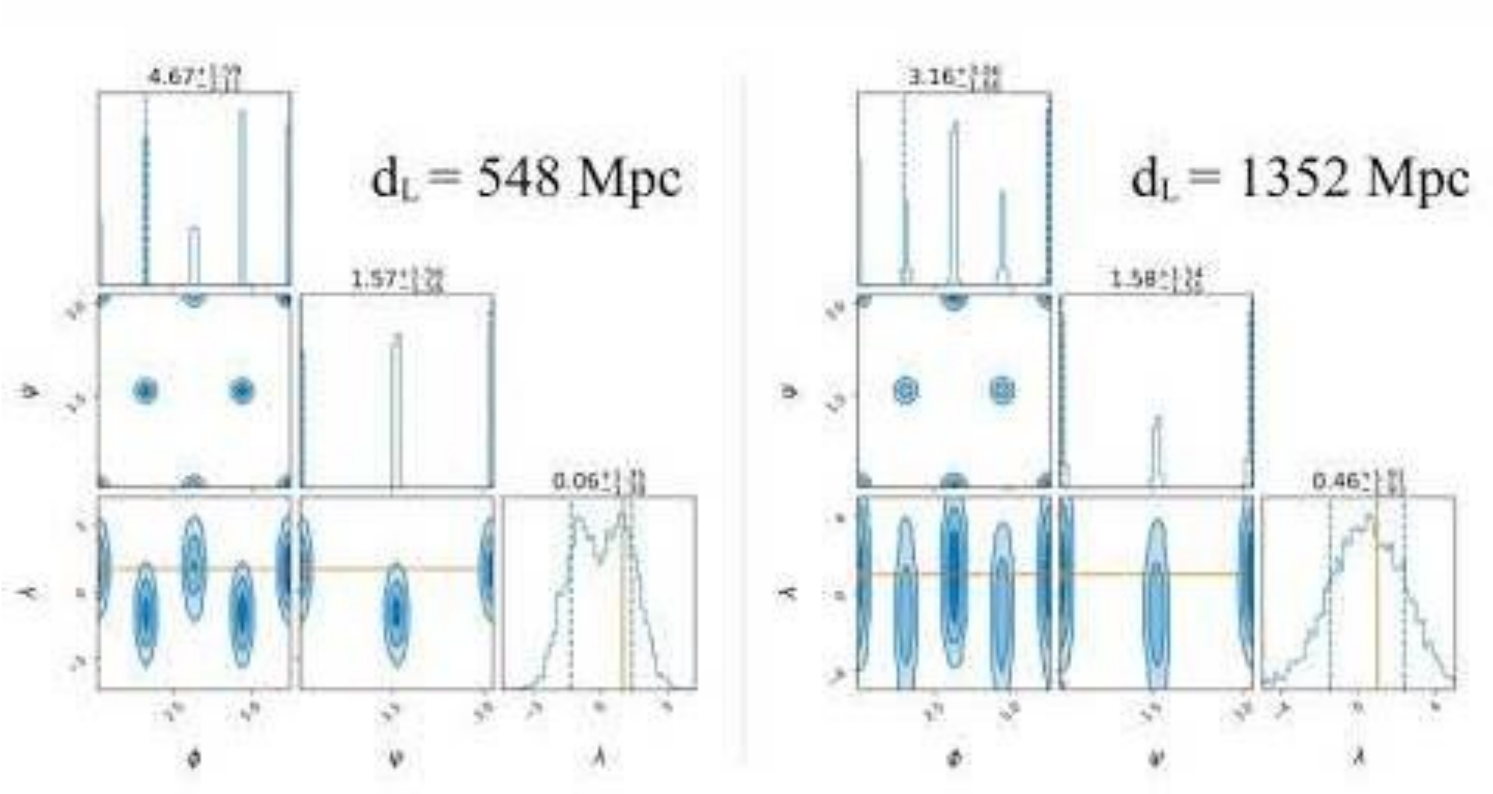


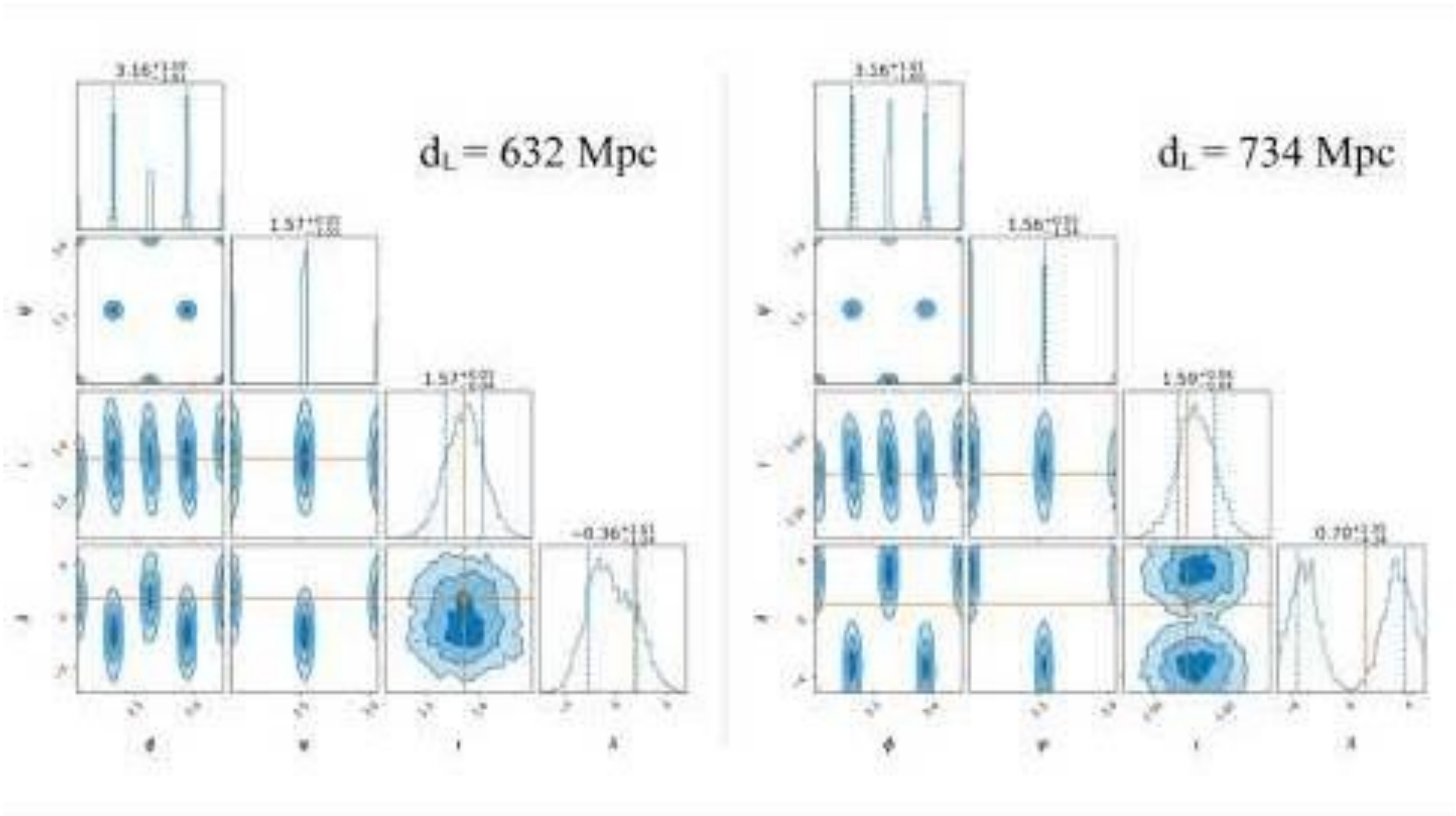
Figure 4. Time series plot of the difference between h_{lm} (ψ, ϕ_c) and $h_{lm}(\psi + \pi/2, \phi_c + \pi/2)$. (*Red*) (2, 2)-mode only and (*Blue*) higher-order modes only. The injected waveform used to generate these posterior distributions is sourced by a system with the following parameters: $M = 70.4$ solar masses, $q = 1.1$, $d_L = 342.2\,\mathrm{Mpc}$, $\iota = 2.5$, $\alpha = \delta = 1.2$ (*Courtesy of Lasky et al*. [])



(2, 2)-mode only

Higher-order modes

Figure 5. (*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, $q = 1$, $\iota = \pi/2$, $\psi = 0$, $\phi_c = 0$, $\alpha = 0$, $\delta = 0$.



Noiseless

Noisy

Figure 6. (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 $M_{\mathrm{tot}} = 60$ solar masses, $q = 1$, $\iota = \pi/2$, $\psi = 0$, $\phi_{\mathrm{c}} = 0$, $\alpha = 0$, $\delta = 0$.

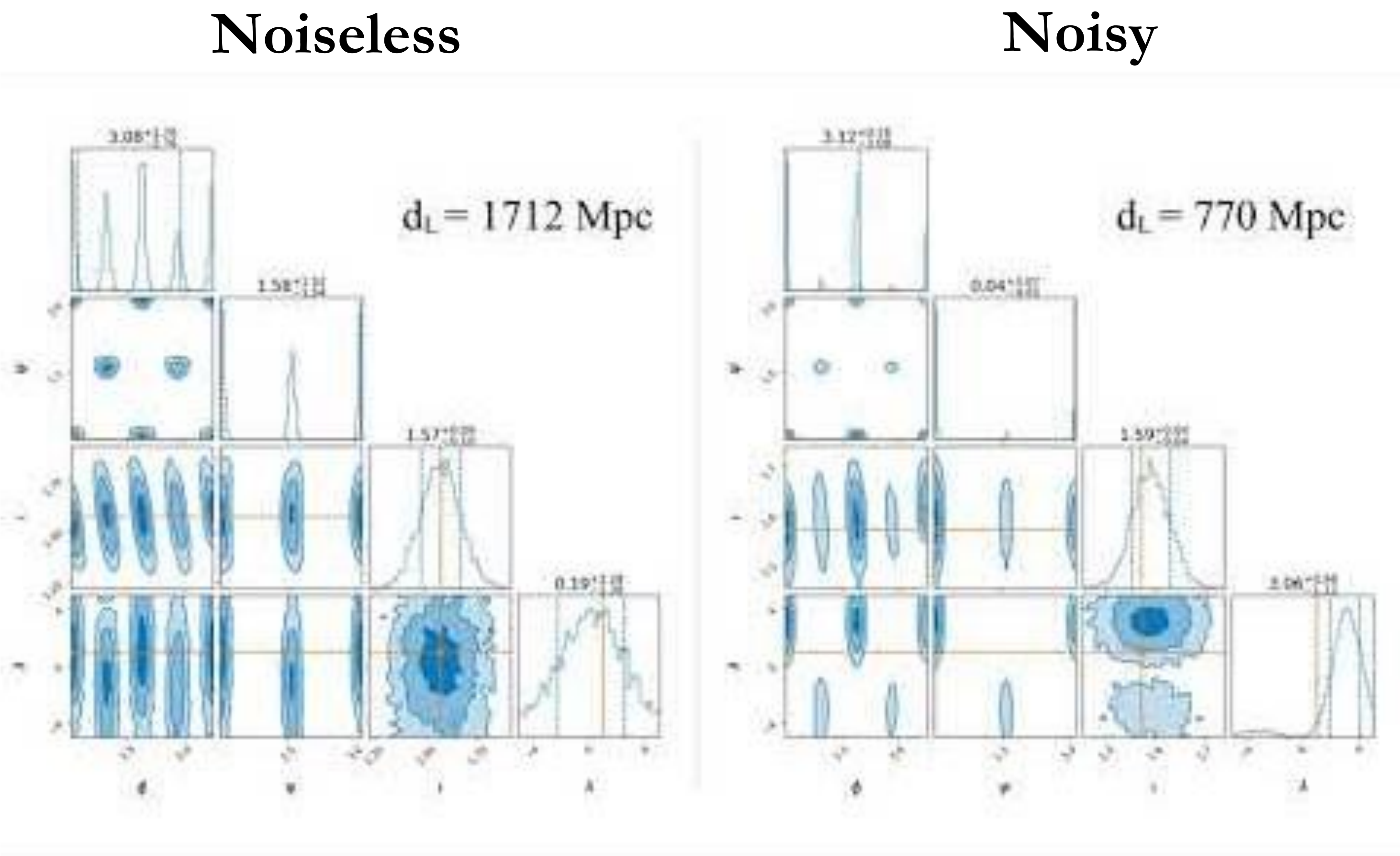


Figure 7. (*Left*) Noiseless signal with all modes included and (*Right*) noisy signal with all modes included. The injected waveform used to generate these posterior distributions is sourced by non-spinning components with $M_{\mathrm{tot}} = 60$ solar masses, $q = 1, \iota = \pi/2, \psi = 0,\ \phi_{\mathrm{c}} = 0, \alpha = 0, \delta = 0$.

The Real Deal!!!

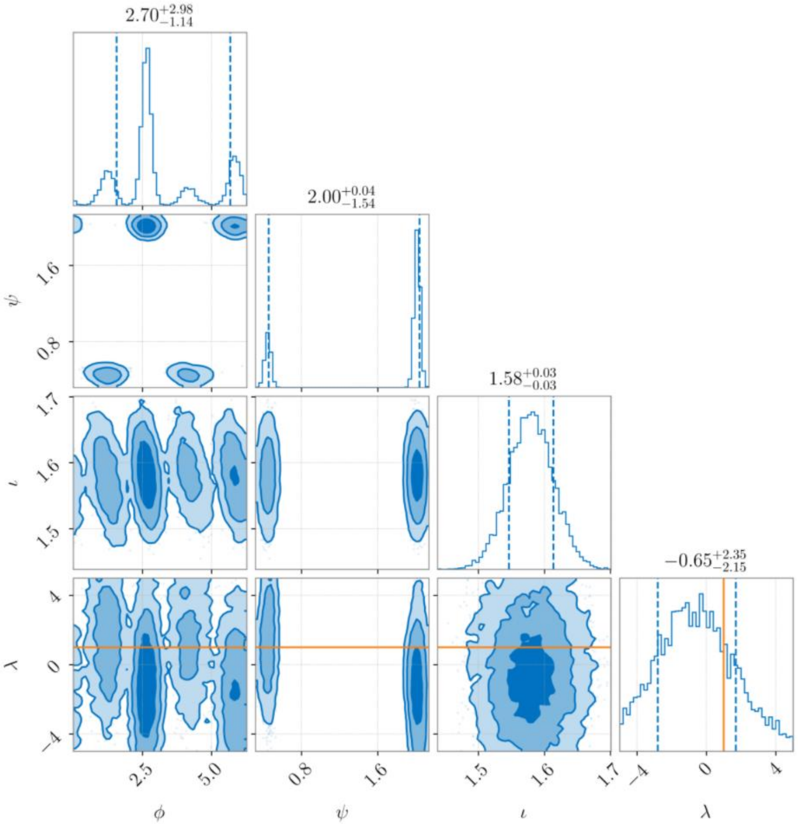
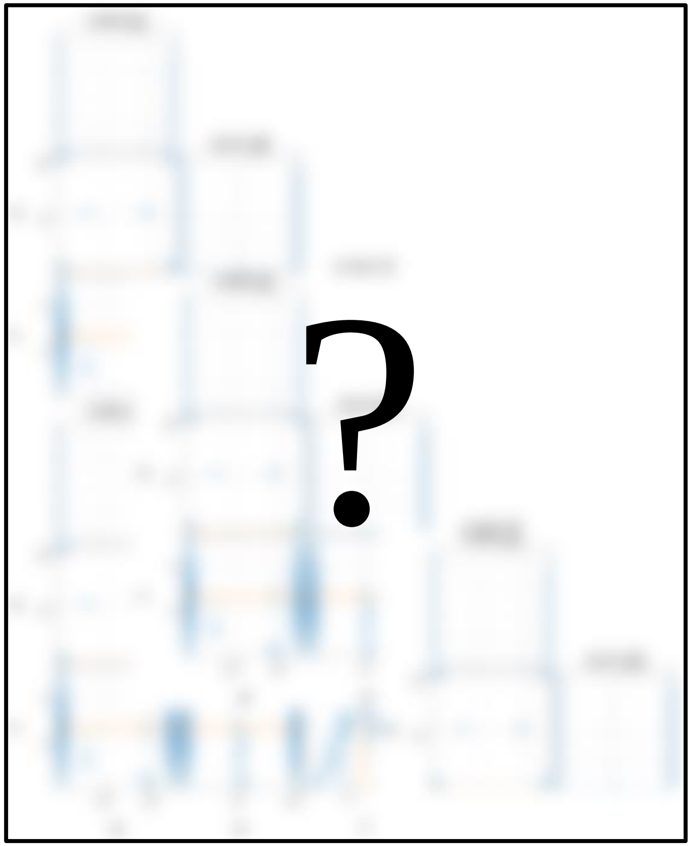


Figure 8. Strain data comes from GW150914. Non-inferred priors were retrieved from posterior samples obtained by memoryless parameter estimation. These values correspond to the maximum likelihood and are $M = 70.4$ solar masses, $q = 1.1$, $d_L = 342.2$Mpc, $\iota = 2.5$, $\psi = 0$, $\phi_c = 0$, $\alpha = \delta = 1.2$ (*Parameter values courtesy of Abbott et al*. [10])

Future Work

Future Work

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



Later…

- Event stacking

Acknowledgements

Mentors

LIGO Laboratory

Caltech SURF

National Science Foundation (NSF)

References

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Questions?