Inpainting for glitch mitigation in BILBY

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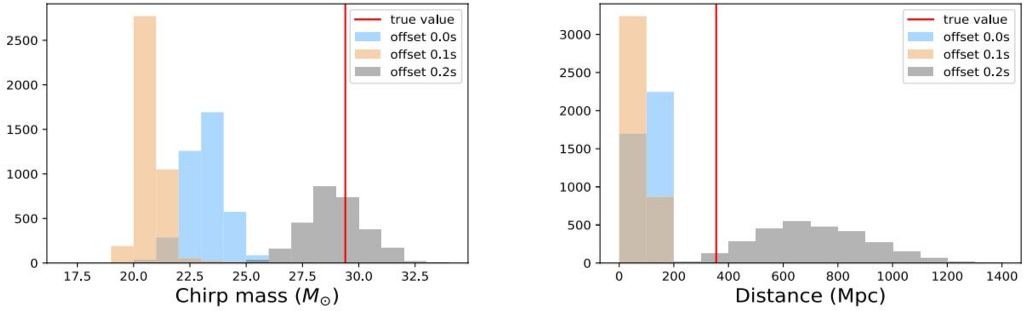
Caltech

Motivation

- Glitches create a bias in parameter estimation



Posterior distributions obtained for chirp mass and distance for a BBH signal at different glitch time offsets.

- Existing methods are complex and require a large amount of time

Powell 2018

Background

- Inpainting filter F is designed to satisfy

$$u^{(\alpha)T}\, C^{-1}\, F\, d = 0$$

$\longrightarrow$ overwhitened, inpainted data is zero inside the hole

- Samples inside hole will not contribute to noise-weighted inner products

$$\mathcal{L}(d_{inp}|\theta) \propto \exp\left[-\frac{1}{2}(d_{inp}|d_{inp}) + (d_{inp}|h_{inp}) - \frac{1}{2}(h_{inp}|h_{inp})\right]$$

Zackay+ 2021
Kwok+ 2022

Methods to obtain inpainted data

1. Calculate F and apply it to data and waveforms

$$F = 1 - A\, M^{-1}\, A^T\, C^{-1}$$

Example:

$$\begin{bmatrix}1&0&0&0&0\\0&1&0&0&0\\0&0&1&0&0\\0&0&0&1&0\\0&0&0&0&1\end{bmatrix} - \begin{bmatrix}0&0\\1&0\\0&1\\0&0\\0&0\end{bmatrix} \begin{bmatrix}a&b\\f&a\end{bmatrix}^{-1} \begin{bmatrix}0&1&0&0&0\\0&0&1&0&0\end{bmatrix} \begin{bmatrix}a&b&c&d&e\\f&a&b&c&d\\g&f&a&b&c\\h&g&f&a&b\\i&h&g&f&a\end{bmatrix}$$

Zackay+ 2021

Methods to obtain inpainted data

1. Calculate F and apply it to data and waveforms

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ \star & \star & \star & \star & \star \\ \star & \star & \star & \star & \star \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Methods to obtain inpainted data

2. Solve a Toeplitz system

    a. Inpainting removes the projection of the data into overwhitened data space, inside the hole:

$$Fd = d - d_{proj}$$

    b. Solve the Toeplitz system for d_{proj} in the hole

$$C^{-1} d_{proj} = C^{-1} d$$

Comparing the methods

F method

Pros:

- Can inpaint more than one segment without increasing cost

Cons:

- Slower $O(N_d^2)$
- Can take up a large amount of memory

Toeplitz method

Pros:

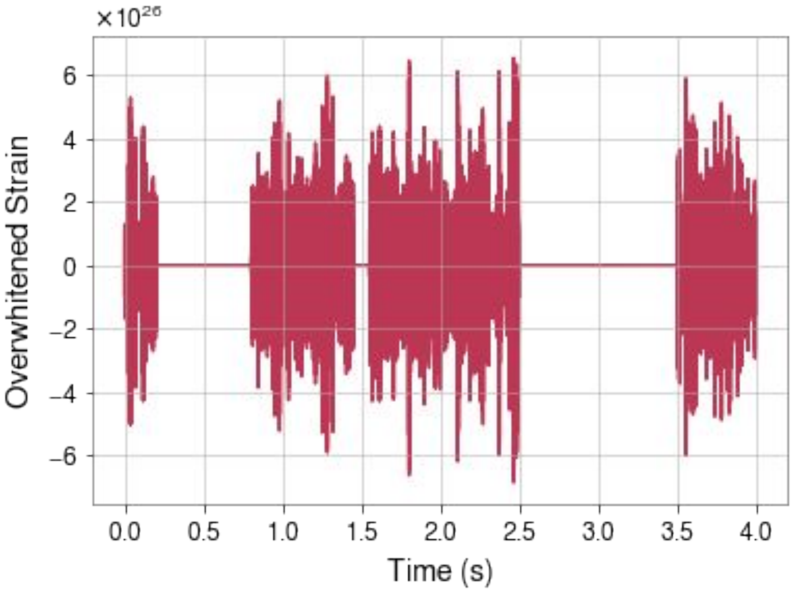
- Faster $O(N_h^2)$
- Low memory usage

Cons:

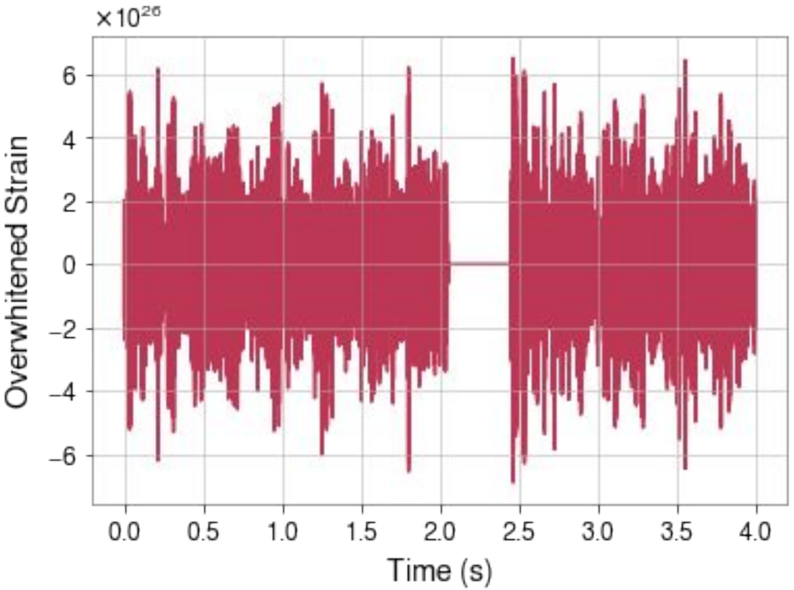
- Loses efficiency when used for more than one segment

Testing correct function performance

F method

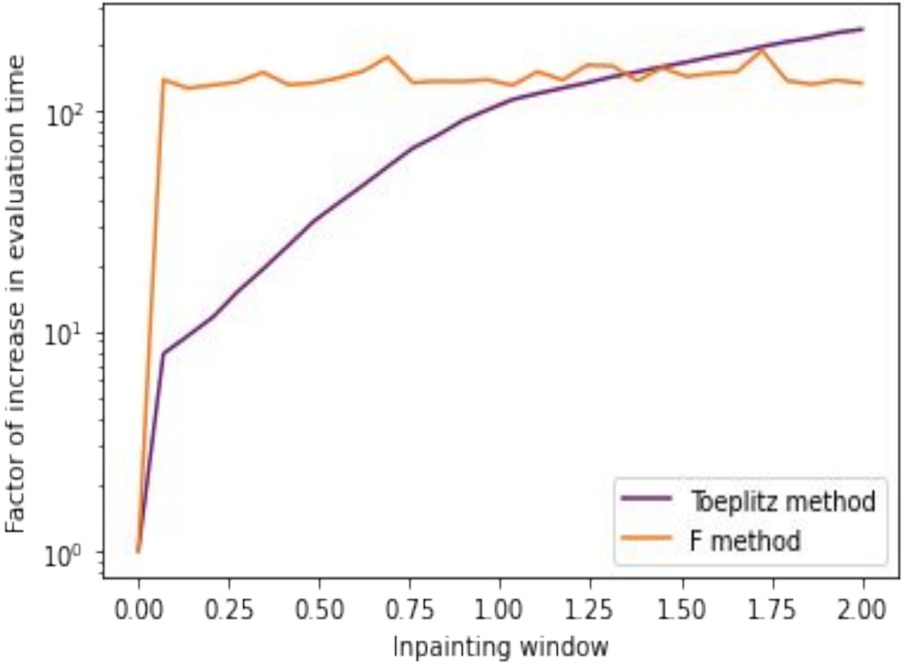


Toeplitz method



Efficiency

- Using 4s of data, 4096 Hz
- Single-likelihood evaluation times increased significantly
- F Method: $O(N_d^2)$
- Toeplitz Method: $O(N_h^2)$



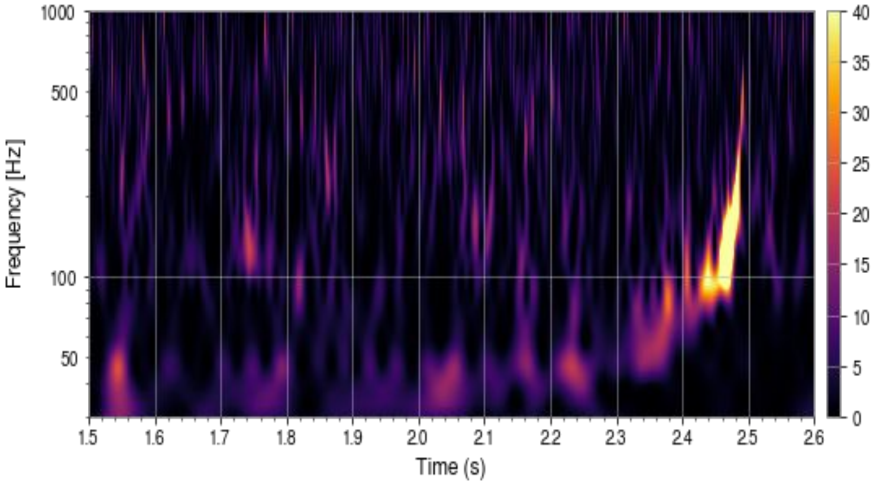
Inpainted injection PE runs

- Full analyses
  - Standard (no inpainting)
  - Inpainted 0.1 s before, 0.05 s window
  - Inpainted 0.25 s before, 0.2 s window
- Short analyses (chirp mass, mass ratio, phase, geocentric time)
  - Changing inpaint center in relation to merger time
  - Changing inpaint window

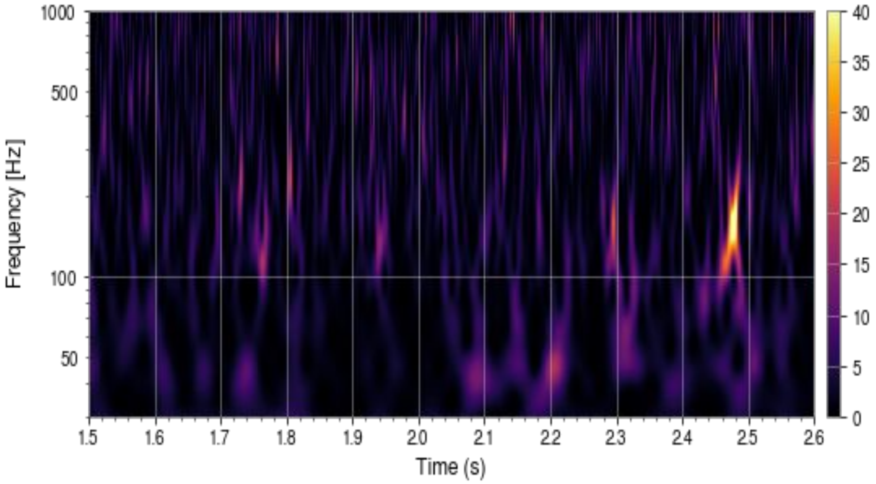
PE for injection with inpainting

- Injected BBH into Gaussian noise scaled to the PSD of LIGO detectors

H1

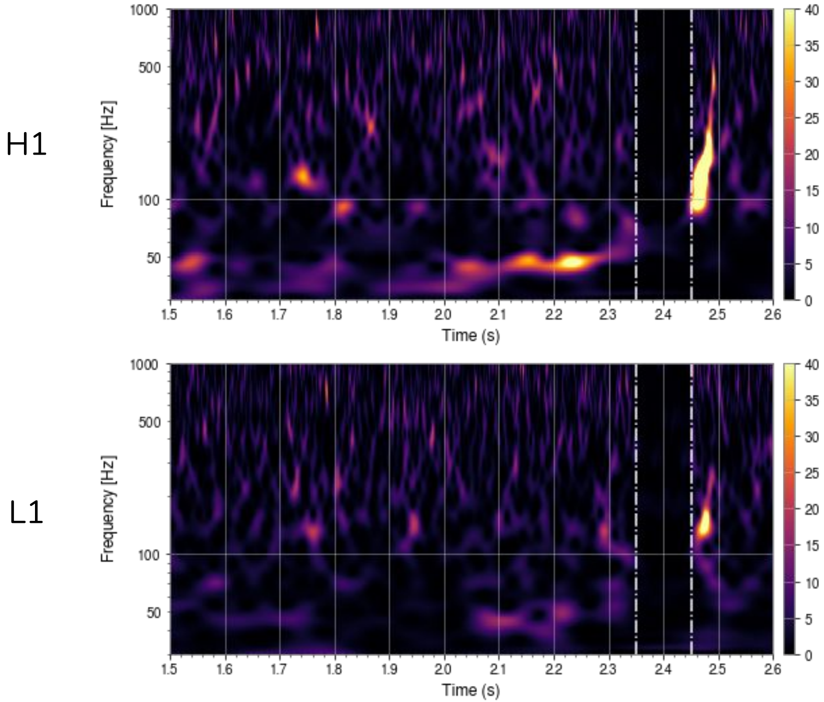


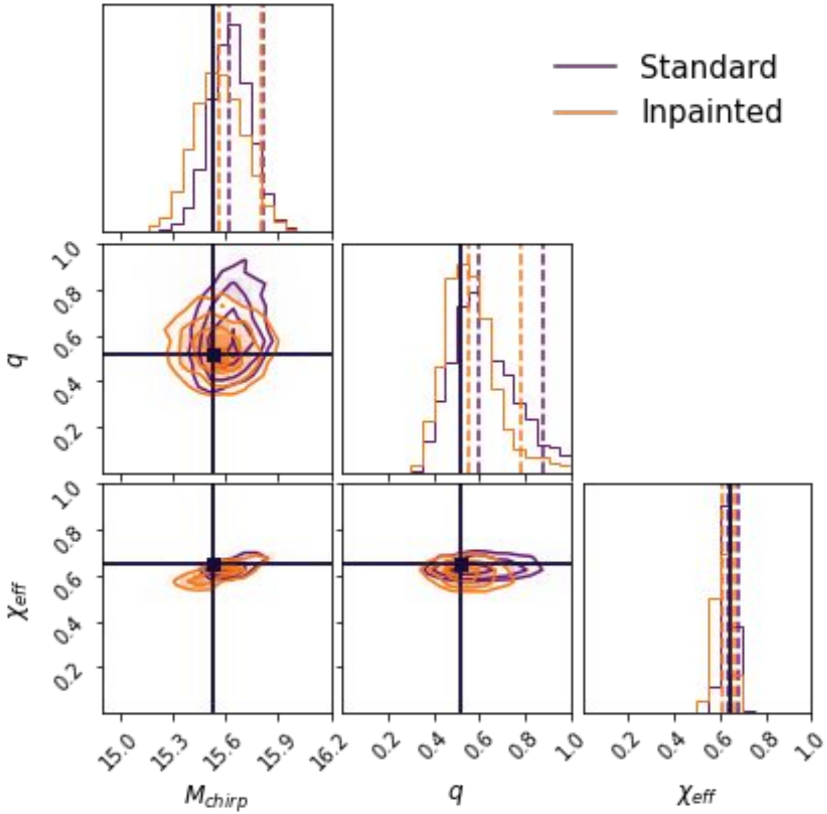
L1



PE results with inpainted data

Inpainted 0.1s before t_c with a 0.05s window

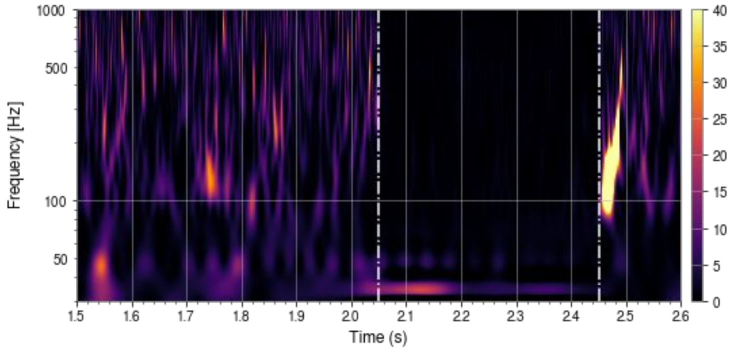




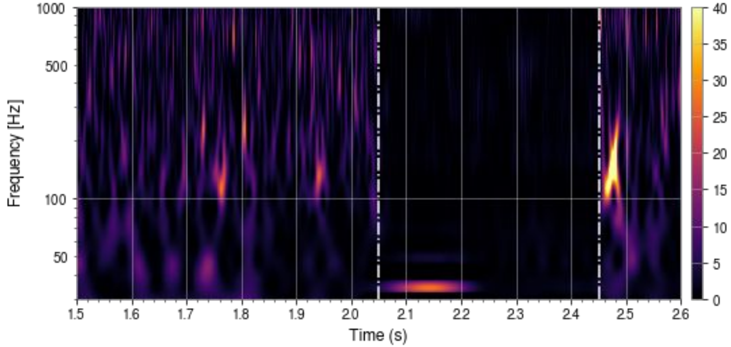
PE results with inpainted data

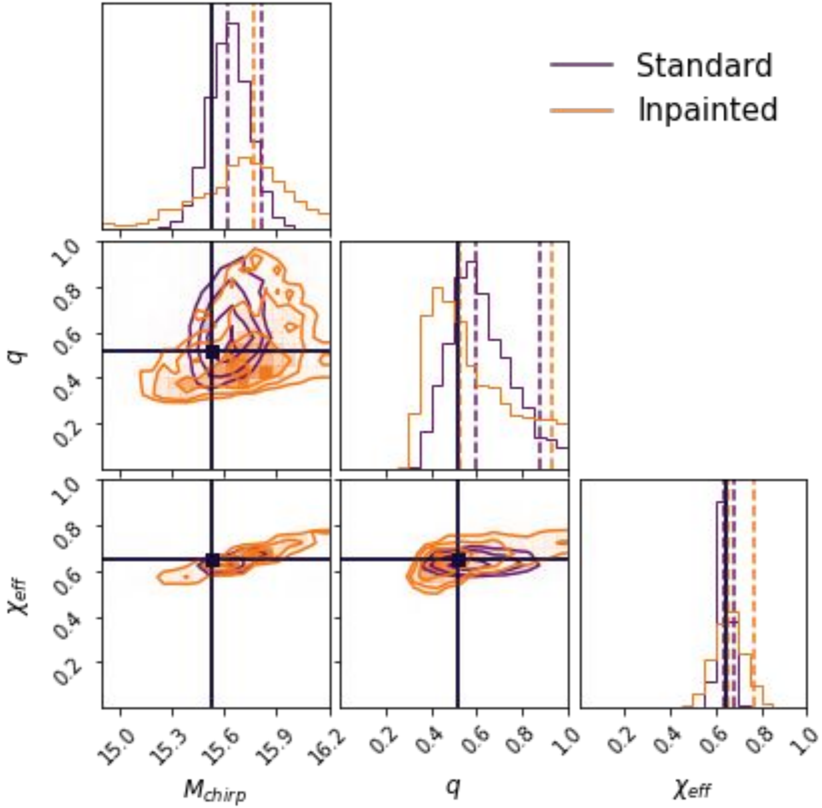
Inpainted 0.25s before t_c with a 0.2s window

H1

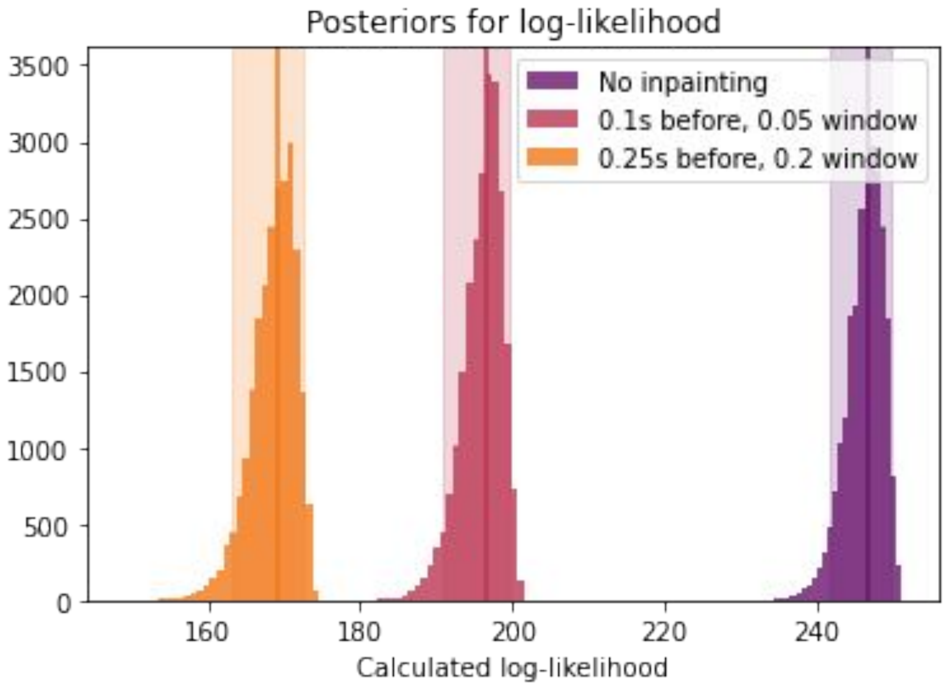


L1





PE results with inpainted data



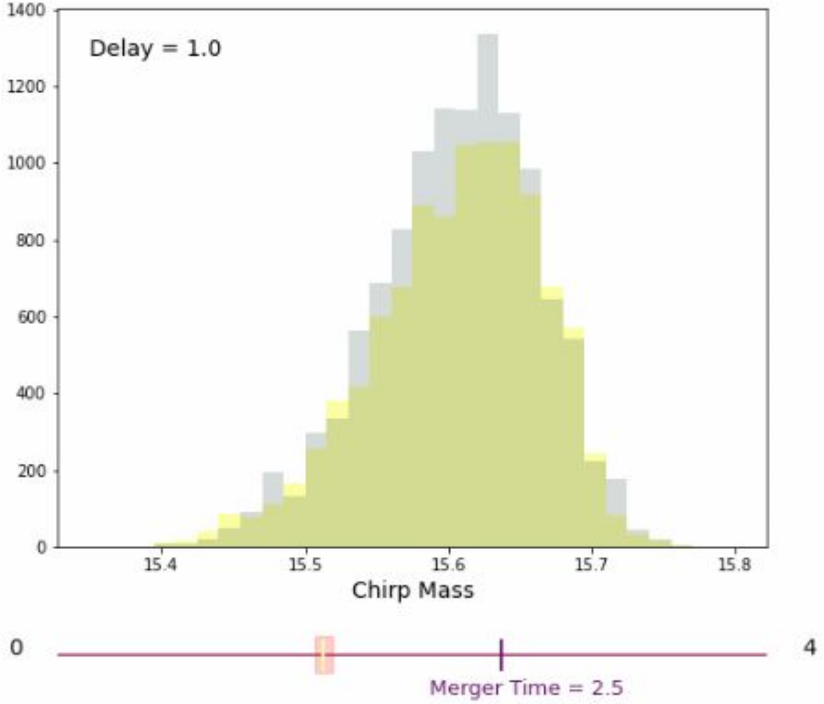
σ = 2.935

σ = 2.651

σ = 2.451

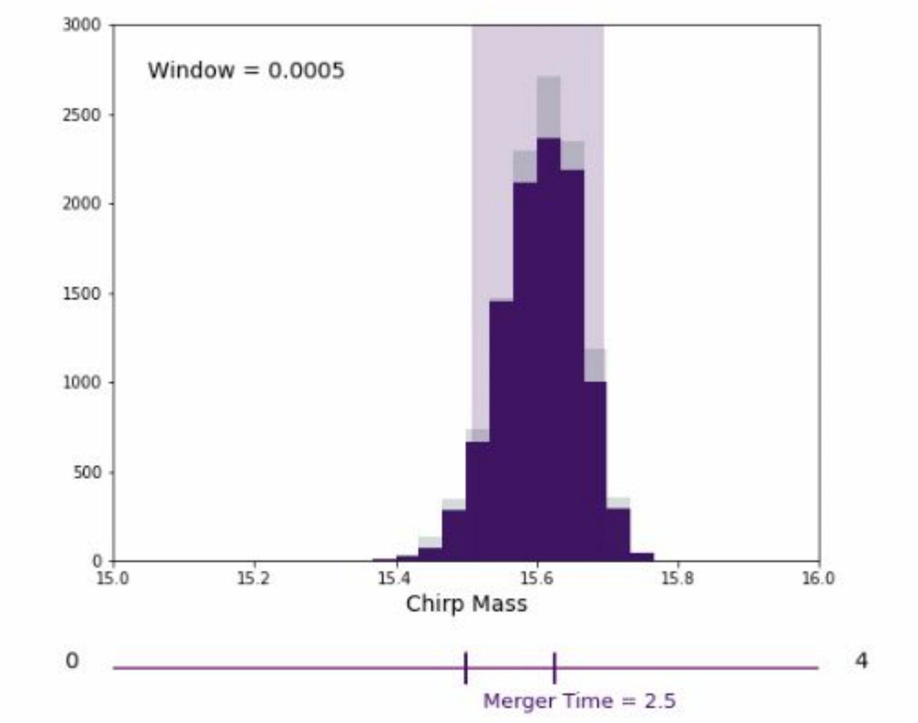
Changing center time in relation to t_c

- Inpainting very close to signal removes important information
- Plots shown were produced with many fixed parameters



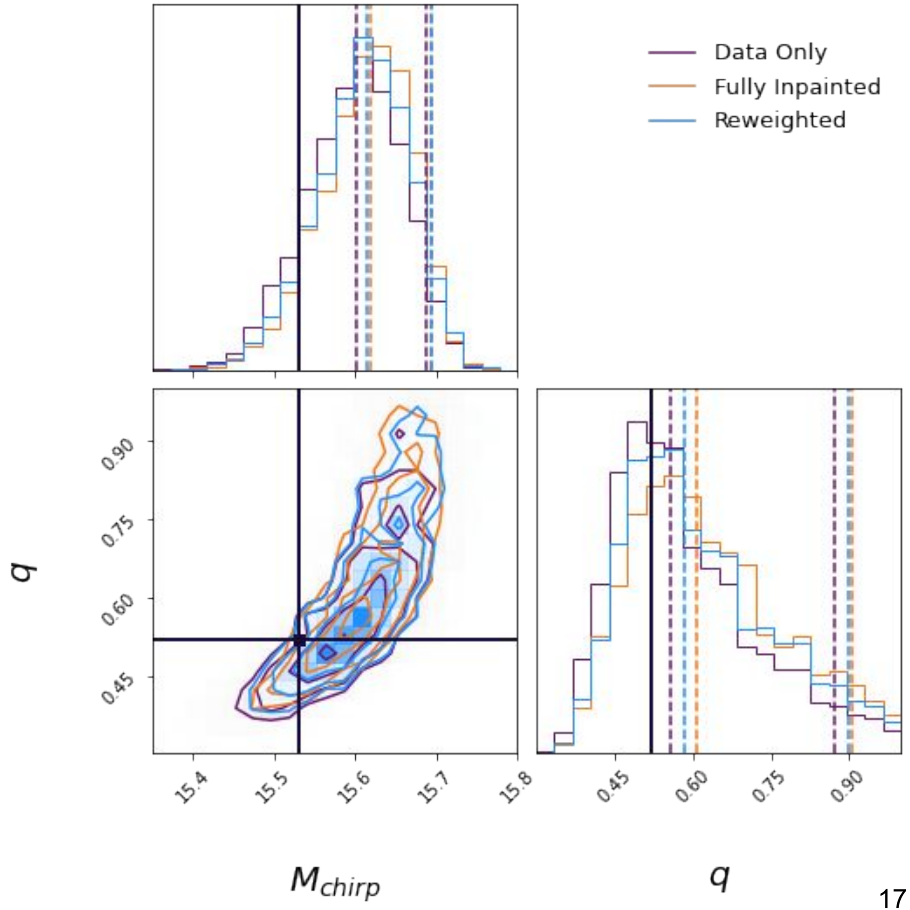
Changing window length

- Removing information via inpainting increases uncertainty
- Inpainting entire signal should return prior



Reweighting

- Run a standard analysis (only data inpainted) and reweight results with an inpainted analysis
- Take roughly the same amount of time as standard analysis
- Cannot be done if too much of the signal is inpainted



Next Steps

- Getting ready to add to Bilby
- Prepare code for review and use in O4
- Testing a large number of injections
- Testing on data with injected glitches
- Planning paper

Questions?

Thank you for your attention!

Additional Figures

Recovered parameters (inpainted 0.1 s before with 0.05s window)

	Injected	Standard	Inpainted
$\mathcal{M}/M_\odot$	15.53	$15.63^{+0.12}_{-0.11}$	$15.56^{+0.15}_{-0.14}$
q	0.52	$0.60^{+0.16}_{-0.12}$	$0.55^{+0.11}_{-0.09}$
a_1	0.65	$0.81^{+0.11}_{-0.15}$	$0.90^{+0.06}_{-0.11}$
a_2	0.65	$0.55^{+0.24}_{-0.24}$	$0.34^{+0.26}_{-0.23}$
ϕ_{12}	0.0	$3.25^{+2.69}_{-2.89}$	$3.07^{+2.88}_{-2.78}$
ϕ_{JL}	0.0	$3.74^{+0.45}_{-0.47}$	$3.16^{+2.15}_{-2.11}$
d_L	100	$104.41^{+15.47}_{-13.49}$	$104.49^{+17.54}_{-14.42}$
δ	1.00	$-0.93^{+0.08}_{-0.07}$	$-0.93^{+1.01}_{-0.08}$
α	2.00	$4.98^{+0.18}_{-0.25}$	$4.89^{+0.29}_{-0.46}$
θ_{JN}	1.65	$1.45^{+0.07}_{-0.07}$	$1.48^{+0.09}_{-0.10}$
ψ	1.50	$1.66^{+0.12}_{-1.49}$	$0.28^{+2.10}_{-0.18}$
ϕ	2.00	$2.87^{+2.48}_{-2.04}$	$3.10^{+2.22}_{-2.15}$
t_{geo}	2.5	$2.48^{+0.00}_{-0.00}$	$2.48^{+0.02}_{-0.00}$
θ_1	0.0	$0.26^{+0.13}_{-0.11}$	$0.24^{+0.14}_{-0.10}$
θ_2	0.0	$0.67^{+0.37}_{-0.31}$	$1.07^{+0.65}_{-0.57}$