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Glitch mitigation methods for parameter estimation of compact binary coalescences

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Motivation

- Parameter estimation (PE) of gravitational wave sources uses Bayes' Theorem:

$$p(\theta|d) = \frac{\mathcal{L}(d|\theta)\pi(\theta)}{z(d)}$$

- PE pipelines assume that noise is stationary and Gaussian, allowing us to use:

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

This is the probability of d given θ

This is a noise-weighted inner product

Powell 2018

Motivation

- Glitches invalidate our assumption of stationary Gaussian noise
- Existing glitch mitigation methods are complex and require a large amount of time
- Proposed method: *inpainting*

Can inpainting effectively prevent specific regions of data (*holes*) from contributing to the likelihoods in parameter estimation?

Zackay+ 2021
Kwok+ 2022

Background

- Inpainting is a filter F designed so that

$$A^T C^{-1} F d = 0_{N_d \times 1}$$

Inside the hole, the overwhitened inpainted data is zeroed.

- Samples inside hole will not contribute to noise-weighted inner products
- We must inpaint the data *and the waveforms*

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

Zackay+ 2021

Inpainting data: F Method

- Calculate F matrix and perform matrix multiplication with data and waveforms
  - F is calculated as a pre-processing step
  - Matrix multiplication occurs within analysis
- Matrix multiplication is of $O(N_d^2)$

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ \star & \star & \star & \star & \star \\ \star & \star & \star & \star & \star \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \end{bmatrix}$$

Zackay+ 2021

Inpainting data: Toeplitz method

- Calculate the difference between the original data and the inpainted data

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

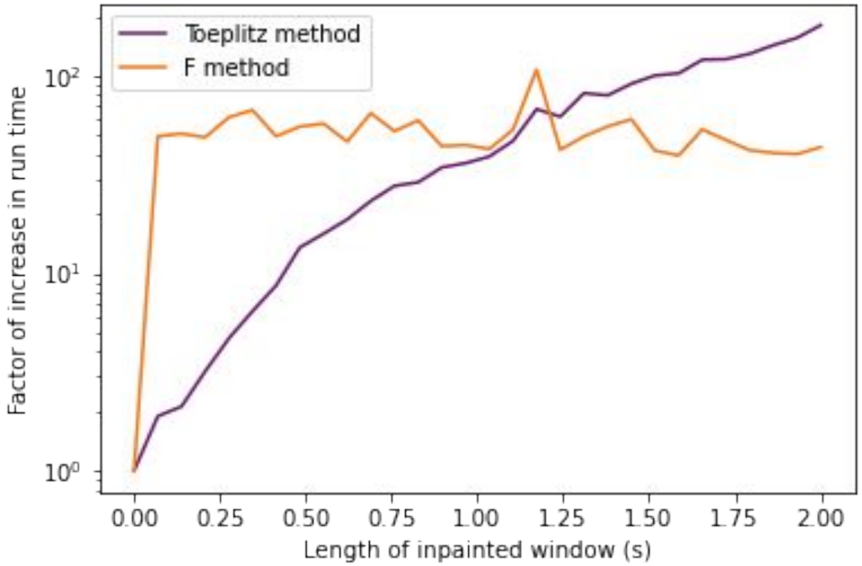
$$C^{-1} d_{proj} = C^{-1} d$$

↑ unknown

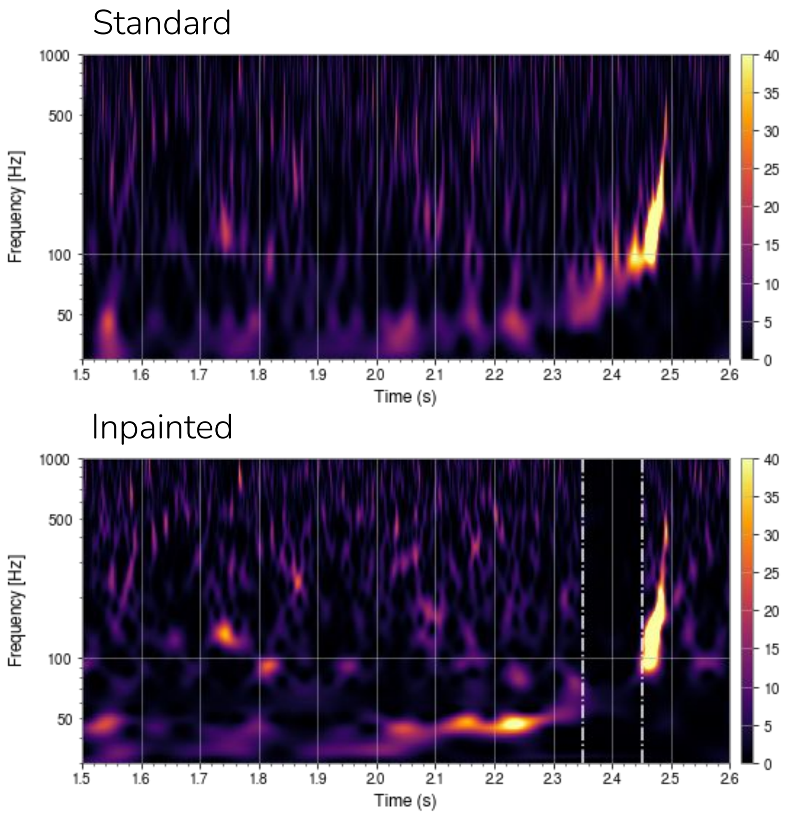
- C^{-1} is Toeplitz (diagonally constant)
- Toeplitz system can be solved in $O(N_h^2)$
- Cannot be used when inpainting more than one segment

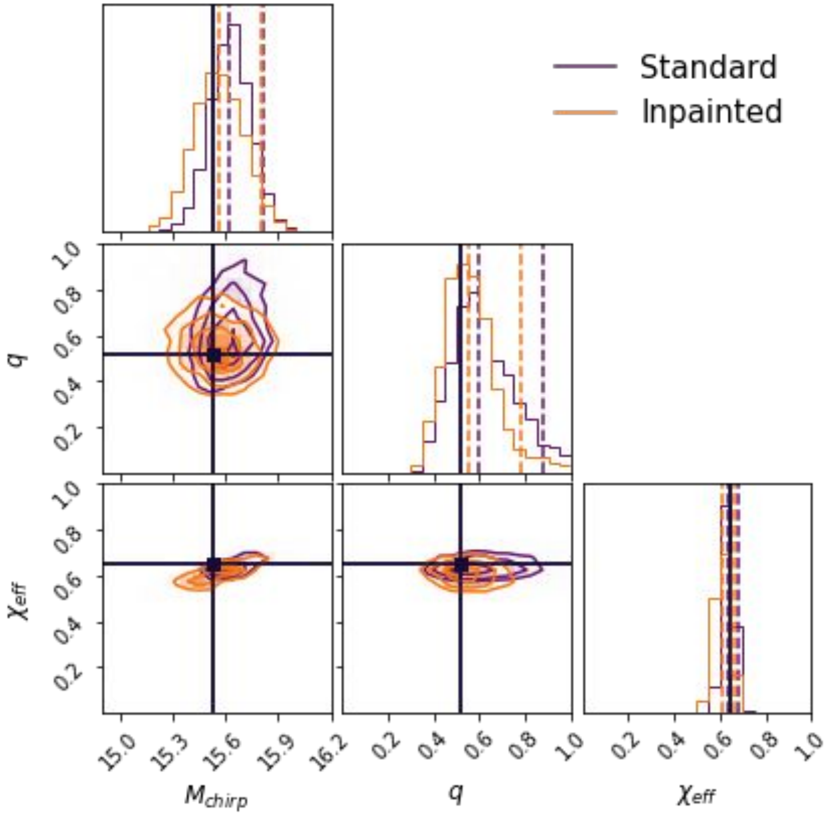
Increase in runtime

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



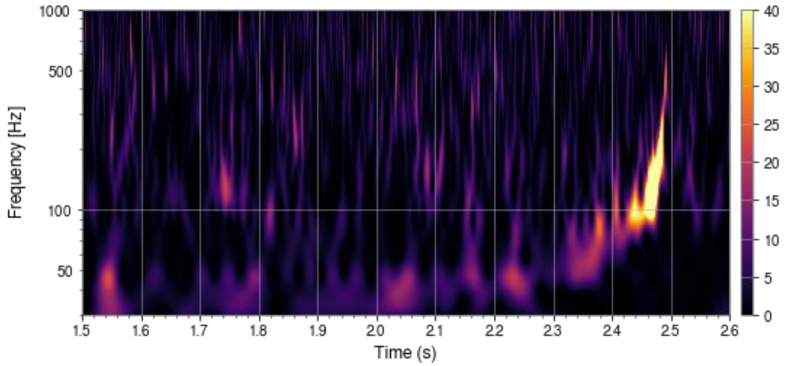
Inpainted injection



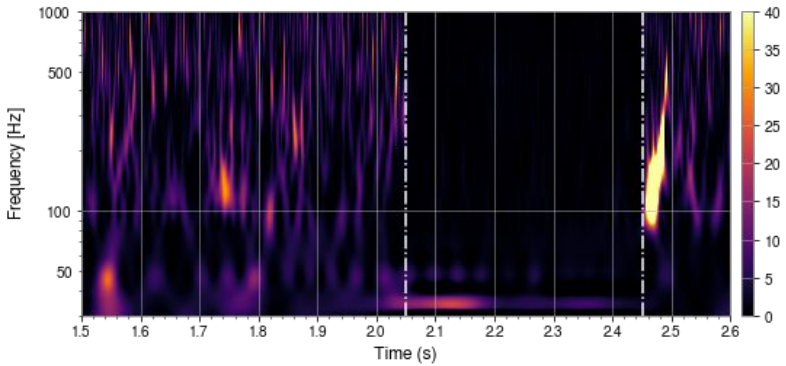


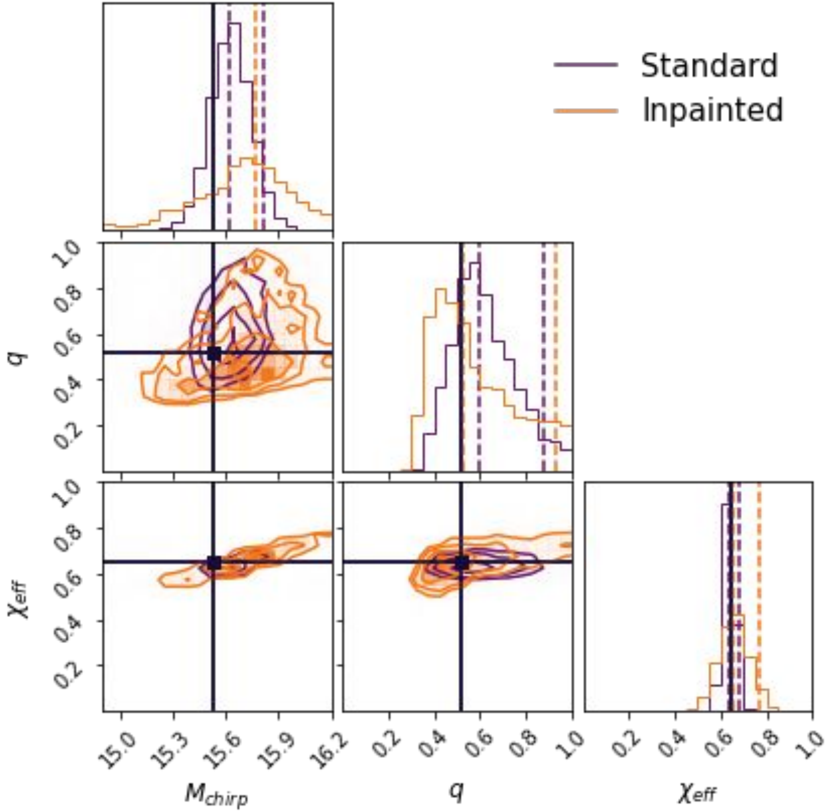
Inpainted injection

Standard



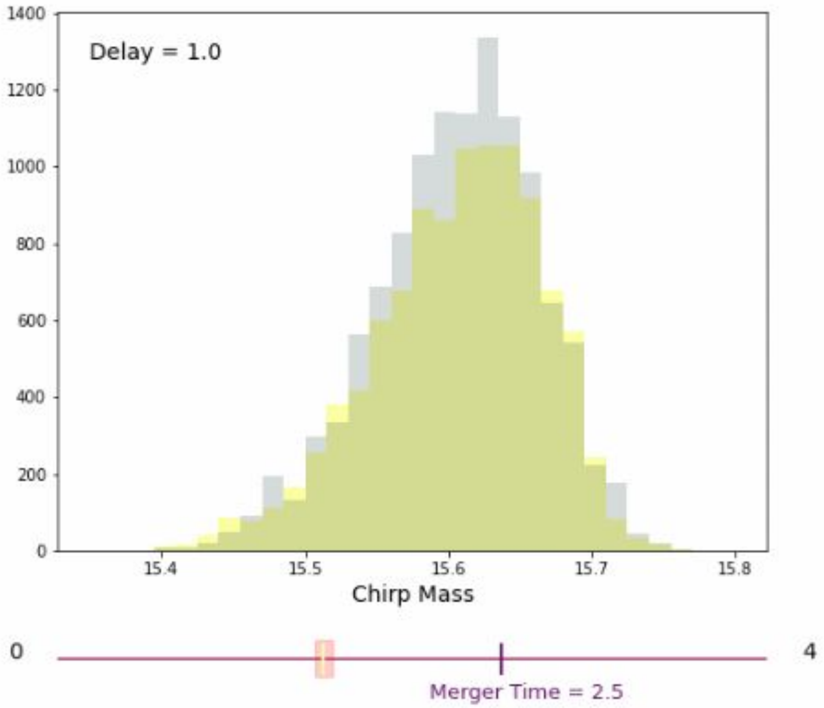
Inpainted





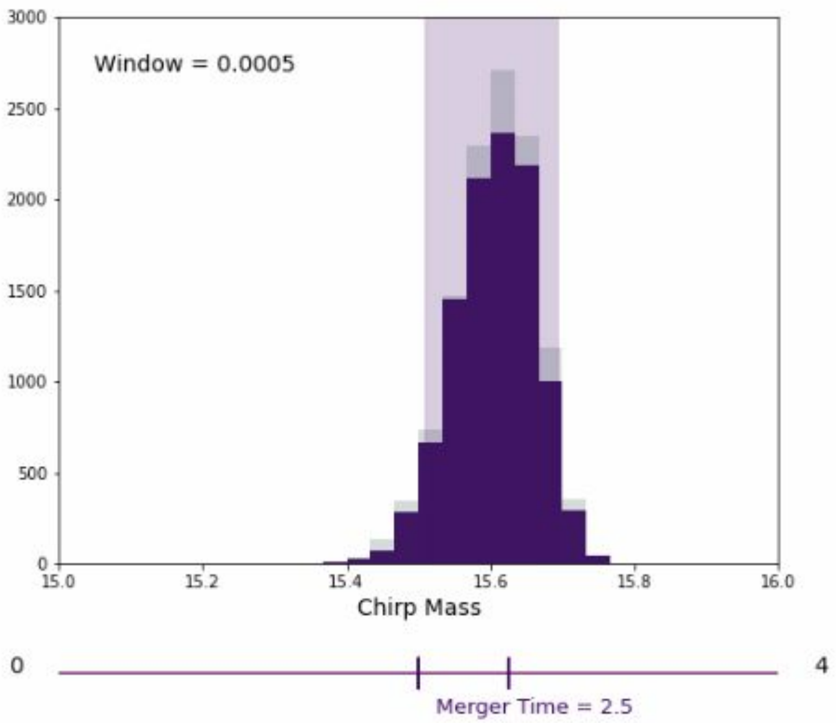
Changing center time in relation to t_c

- Most important information is near the merger time
- Fixing parameters may have affected our results here



Changing window length

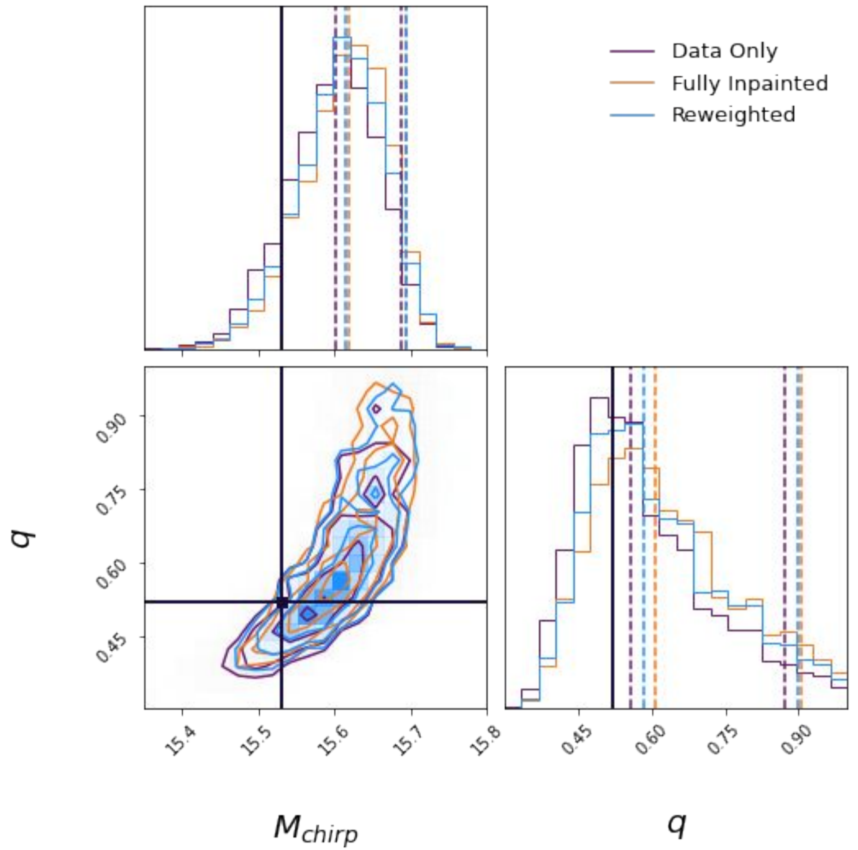
- The more information we remove, the more our posterior should look like our prior.

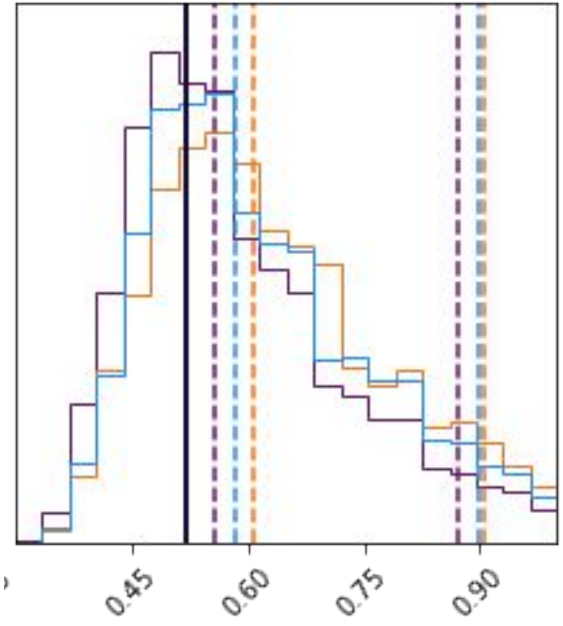


Reweighting: A faster alternative

- Procedure:
  - Run analysis only inpainting data $\exp\left[-\frac{1}{2}(d_{inp}|d_{inp}) + (d_{inp}|h_{\cancel{inp}}) - \frac{1}{2}(h_{\cancel{inp}}|h_{\cancel{inp}})\right]$
  - Reweight results by inpainting both data and waveform
- Take roughly the same amount of time as standard analysis
- Cannot be done if too much of the signal is inpainted

Reweighting: A faster alternative





Conclusions

- Inpainting can prevent holes from contributing to the likelihood without biasing results
- Run time can increase significantly, depending on run configurations, but this can be improved
- Future work:
  - Prepare code for review and use in Bilby and in O4
  - Improve efficiency of our algorithms
  - Large number of injections
  - Injections in data that contains glitches

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References

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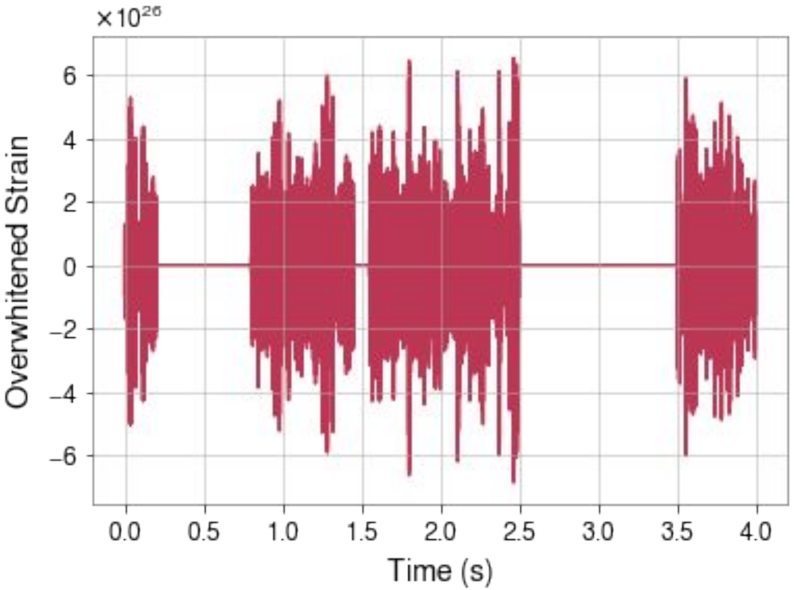
Questions?

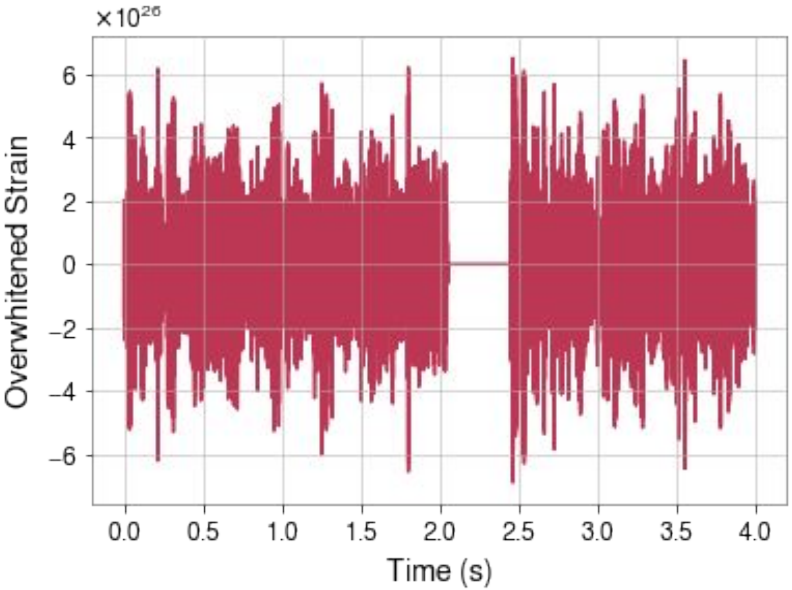
Thank you for listening!

Checking that the functions work

F method



Toeplitz method



F Matrix Example

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

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

More on the Toeplitz method

$$A^T C^{-1} F d = 0_{[N_d \times 1]}$$

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

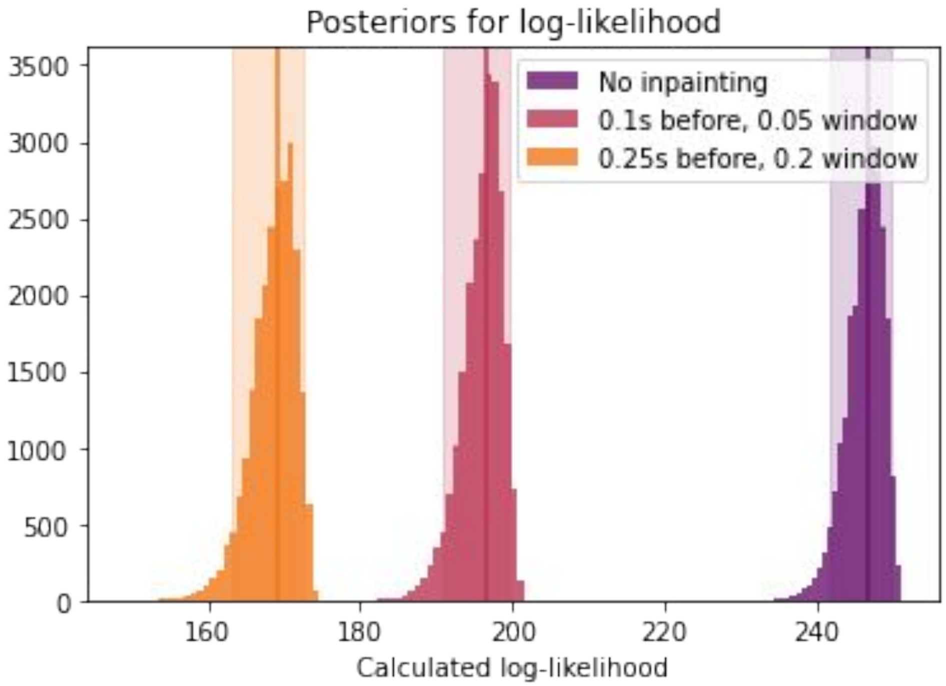
$$A^T C^{-1} (d - d_{proj}) = 0_{[N_d \times 1]}$$

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

Taking the values outside of the hole to be 0,

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

Likelihoods calculated



σ = 2.935

σ = 2.651

σ = 2.451

All recovered parameters

	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	$0.67^{+0.37}_{-0.31}$	$1.07^{+0.65}_{-0.57}$

Noise-Weighted Inner Product

$$(a|b) \equiv \sum_{j=0}^{\frac{N}{2}-1} 4\mathrm{Re}\left(\frac{\tilde{a}_j^* b_j}{S_n(f_j)}\Delta f\right)$$