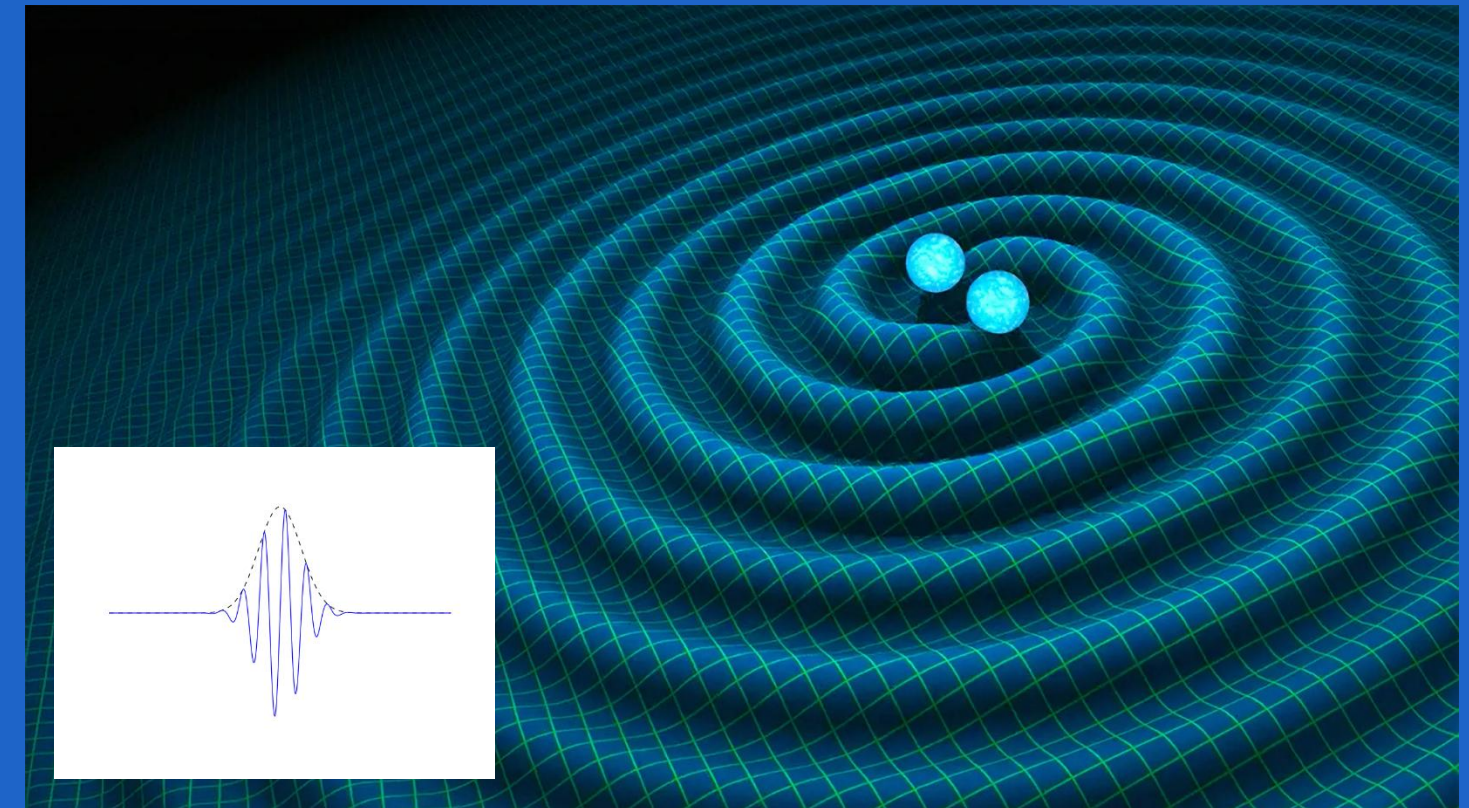


HUNTING FOR EXOTIC RESONANCES IN COMPACT BINARY MERGERS

Robin Chan
Intermediate thesis presentation

Supervisor: Prof. Dr. Archisman Ghosh

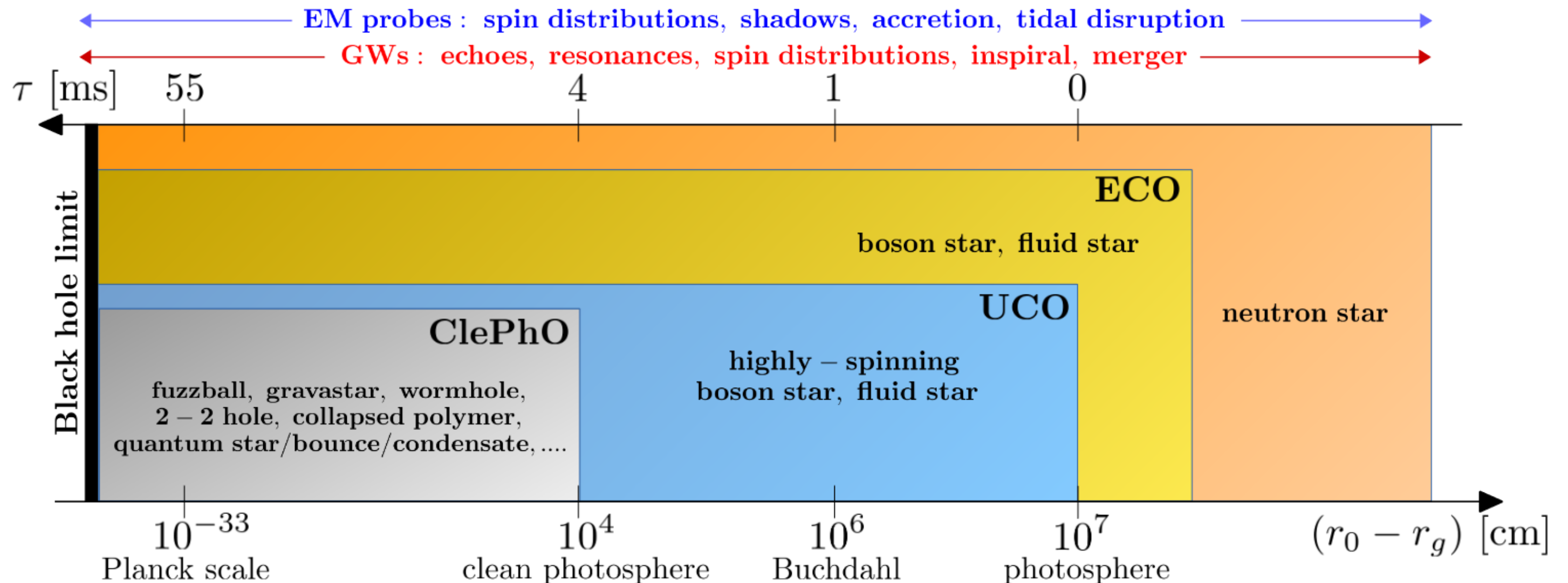


WHAT TO EXPECT?

- Quick recap
- Bilby inference runs
- Samplers
- tBilby inference runs
- NR waveforms update
- Next steps

EXOTIC COMPACT OBJECTS

- Hypothetical objects between neutron stars (NSs) and black holes (BHs) in compactness
- Hard to distinguish with EM observations



GRAVITATIONAL WAVES: ECOS

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*^{*}

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; pub

Gravitational-wave observations alone are able to measure the masses of the two objects and set a lower limit on their compactness, but the results presented here do not exclude objects more compact than neutron stars such as quark stars, black holes, or more exotic objects.

Observation of Gravitational Waves from the Coalescence of a $2.5\text{--}4.5\ M_{\odot}$ Compact Object and a Neutron Star

Although we cannot definitively determine the nature of the higher-mass (primary) compact object in the binary system, if we assume that all compact objects with masses below current constraints on the maximum neutron star mass are indeed neutron stars, the most probable source of GW230529 is the coalescence of a $2.5\text{--}4.5\ M_{\odot}$ compact object and a neutron star.

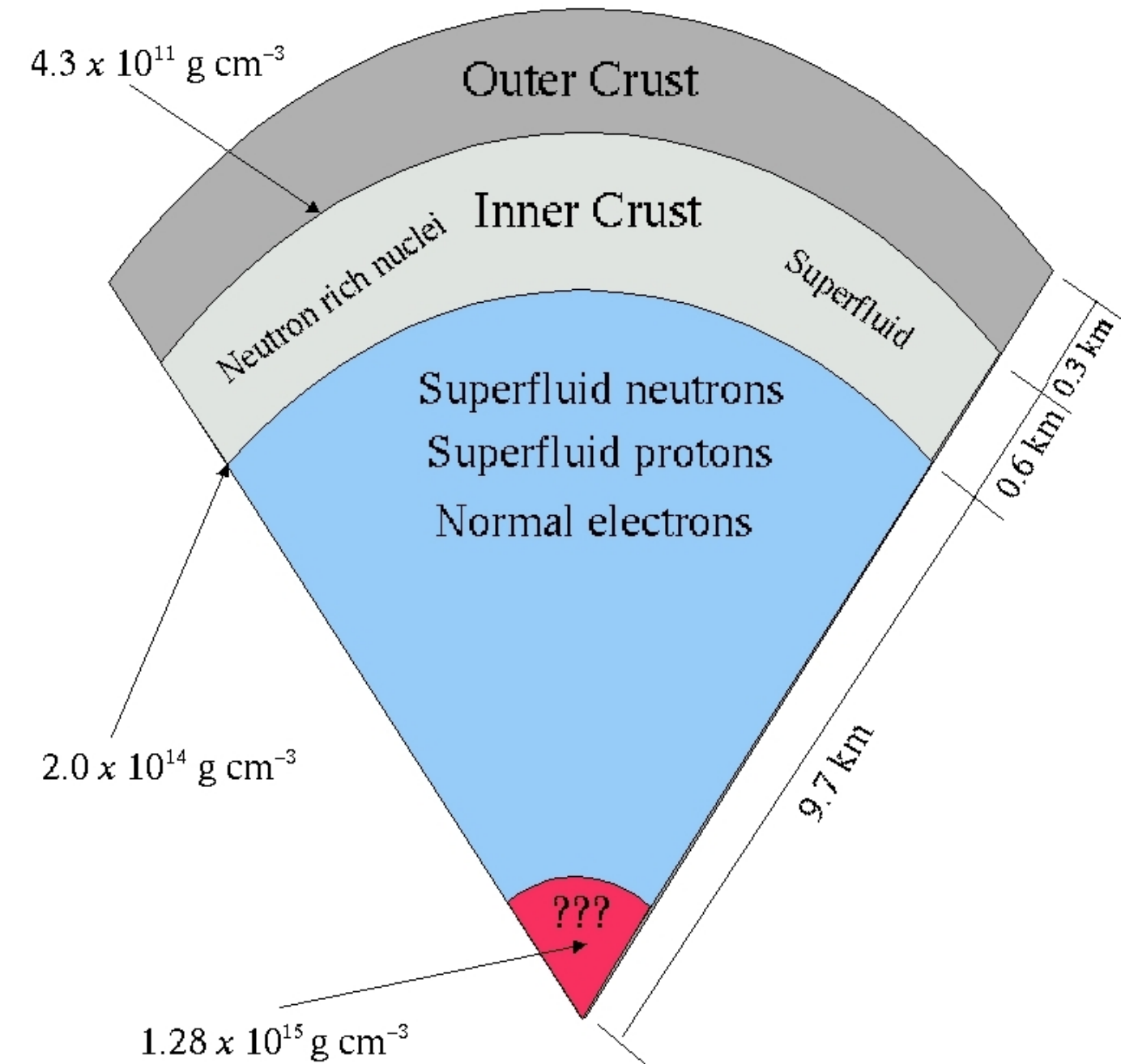
For instance, if such objects also exist within the NS mass range, models of primordial BHs predict a BH mass function at $\sim 1\ M_{\odot}$ (Carr et al. 2016). Models also predict that primordial BHs may form in binaries at mass ratios comparable to those of NS binaries (e.g., Carr et al. 2016; Carr & Kühnel 2019; Carr et al. 2020; Carr & Kühnel 2020; Carr et al. 2021; Carr & Kühnel 2021; Carr et al. 2022; Carr & Kühnel 2022; Carr et al. 2023; Carr & Kühnel 2023; Carr et al. 2024; Carr & Kühnel 2024; Carr et al. 2025; Carr & Kühnel 2025; Carr et al. 2026; Carr & Kühnel 2026; Carr et al. 2027; Carr & Kühnel 2027; Carr et al. 2028; Carr & Kühnel 2028; Carr et al. 2029; Carr & Kühnel 2029; Carr et al. 2030; Carr & Kühnel 2030; Carr et al. 2031; Carr & Kühnel 2031; Carr et al. 2032; Carr & Kühnel 2032; Carr et al. 2033; Carr & Kühnel 2033; Carr et al. 2034; Carr & Kühnel 2034; Carr et al. 2035; Carr & Kühnel 2035; Carr et al. 2036; Carr & Kühnel 2036; Carr et al. 2037; Carr & Kühnel 2037; Carr et al. 2038; Carr & Kühnel 2038; Carr et al. 2039; Carr & Kühnel 2039; Carr et al. 2040; Carr & Kühnel 2040; Carr et al. 2041; Carr & Kühnel 2041; Carr et al. 2042; 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GRAVITATIONAL WAVES

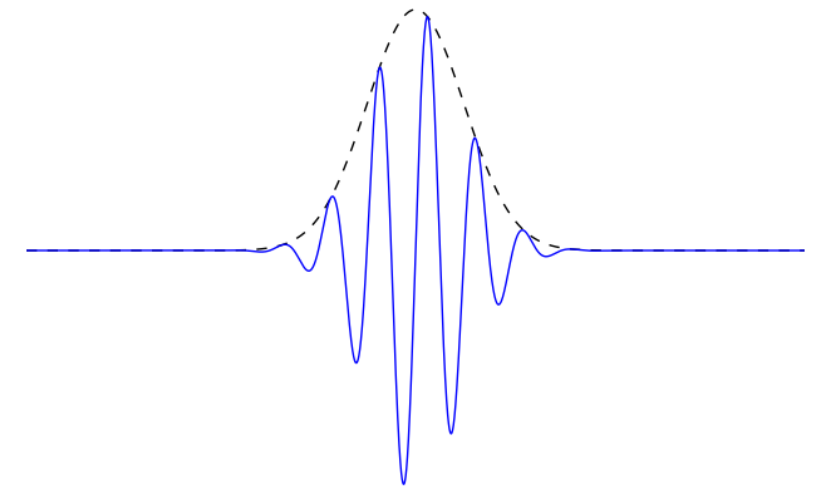
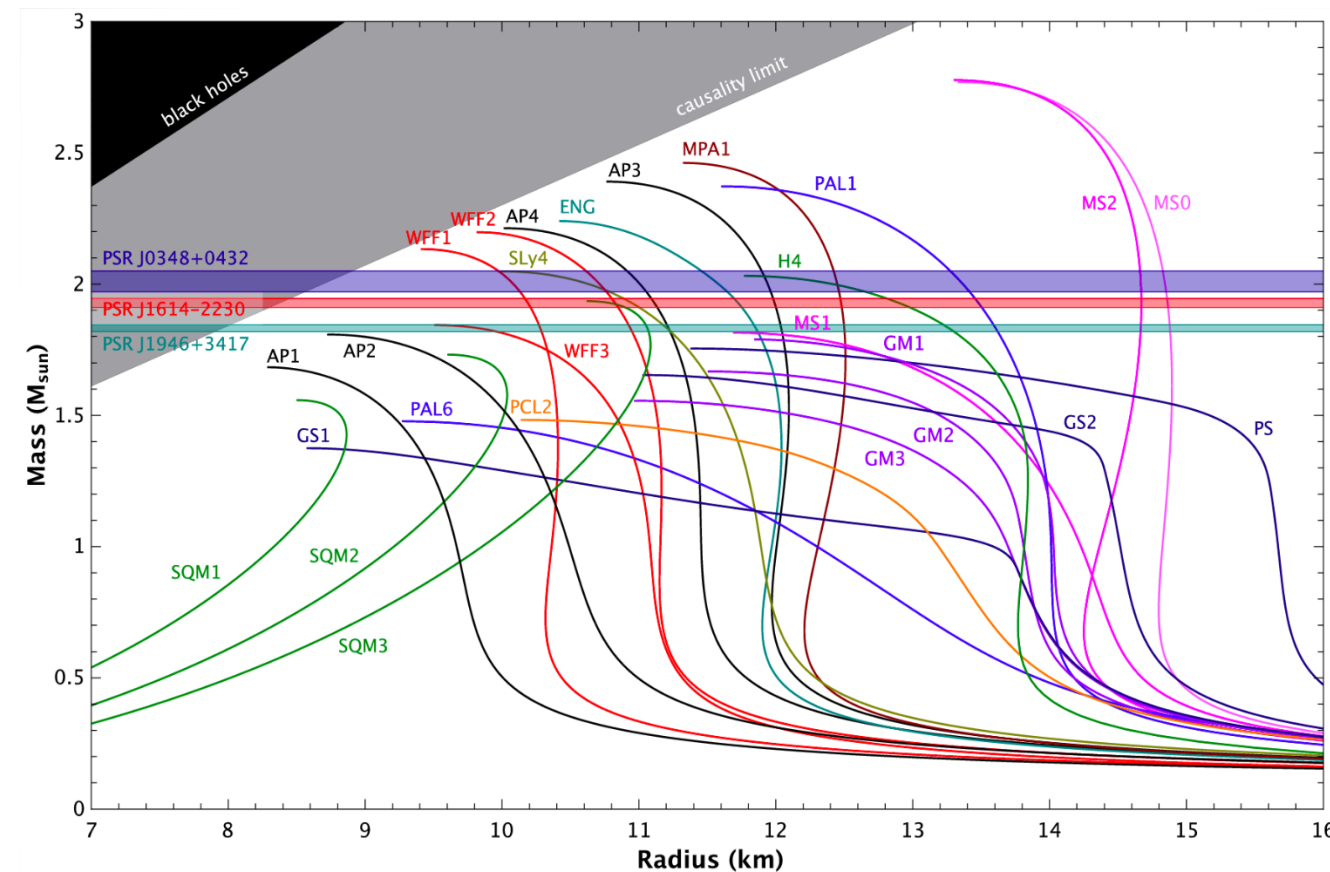
- EM observations probe surface emission
- GWs probe mass-distribution dynamics
 - Inner structure



Neutron Star Pizza

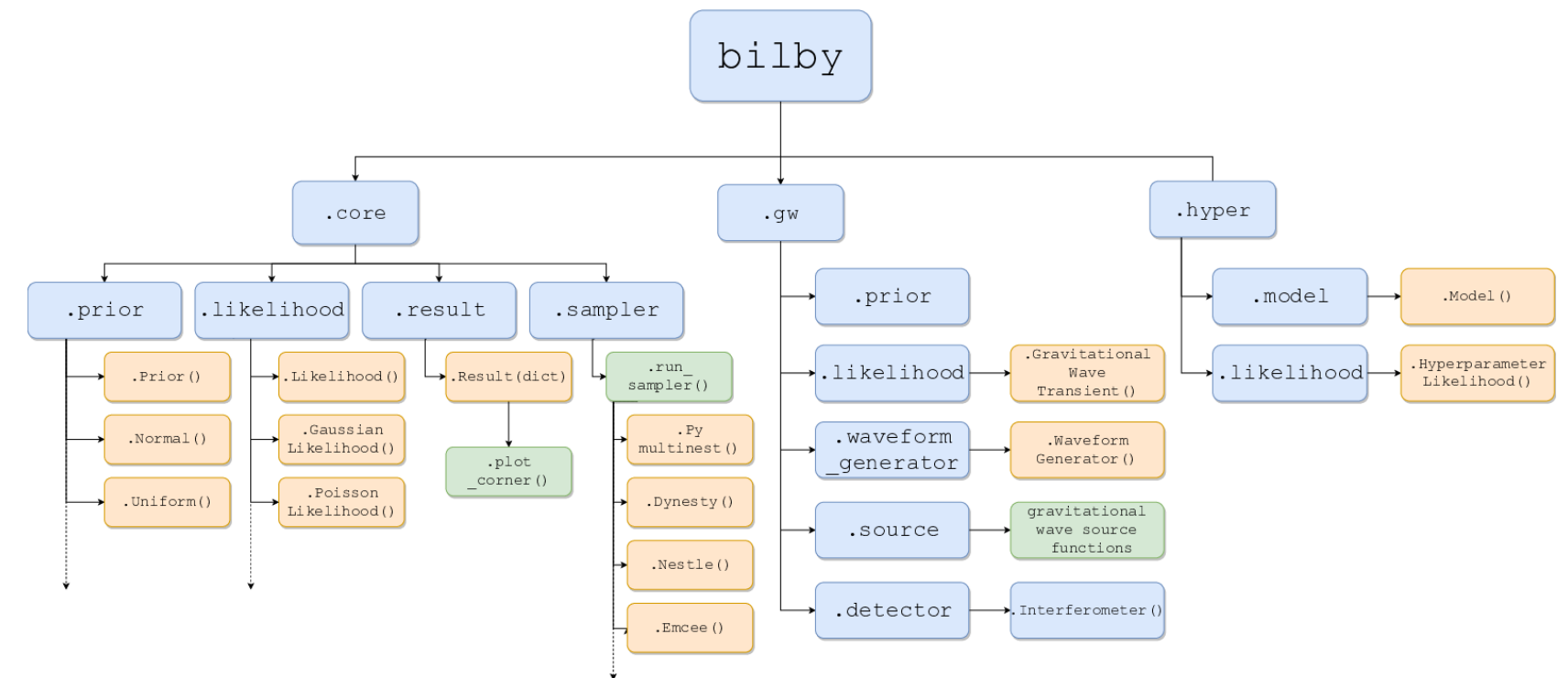
ECOS AND HOW FIND THEM

- Inspiral can pass through resonance of (E)CO
- Leaves imprint on GW signal
- Linked to composition of object $\rightarrow$ constrains EOS
- Find something more exotic?
- Basis of sine-gaussian wavelets to model resonance



BILBY

- General purpose Bayesian Inference Library, but developed for GW science
- Assumes gaussian detector noise
- Inconvenient to hack



Bilby documentation: <https://lscsoft.docs.ligo.org/bilby/index.html>

Ashton G. et al. (2018). Bilby: A user-friendly Bayesian inference library for gravitational-wave astronomy

BILBY RUNS: INJECTION

IMR signal

(Inspiral – Merger - Ringdown)

Wavelet

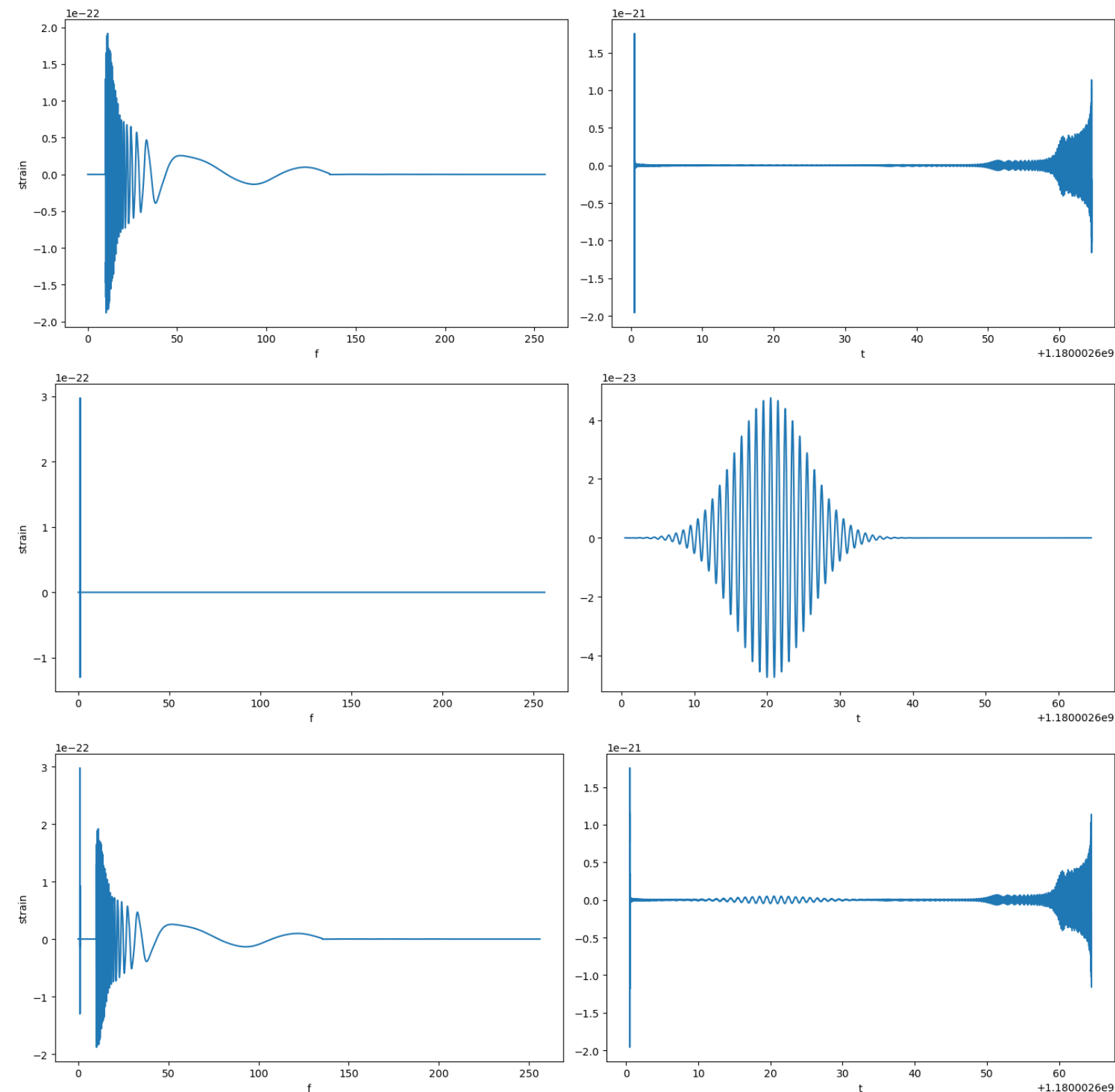
5 DOF: amplitude, width, time,
frequency, phase

Composite signal

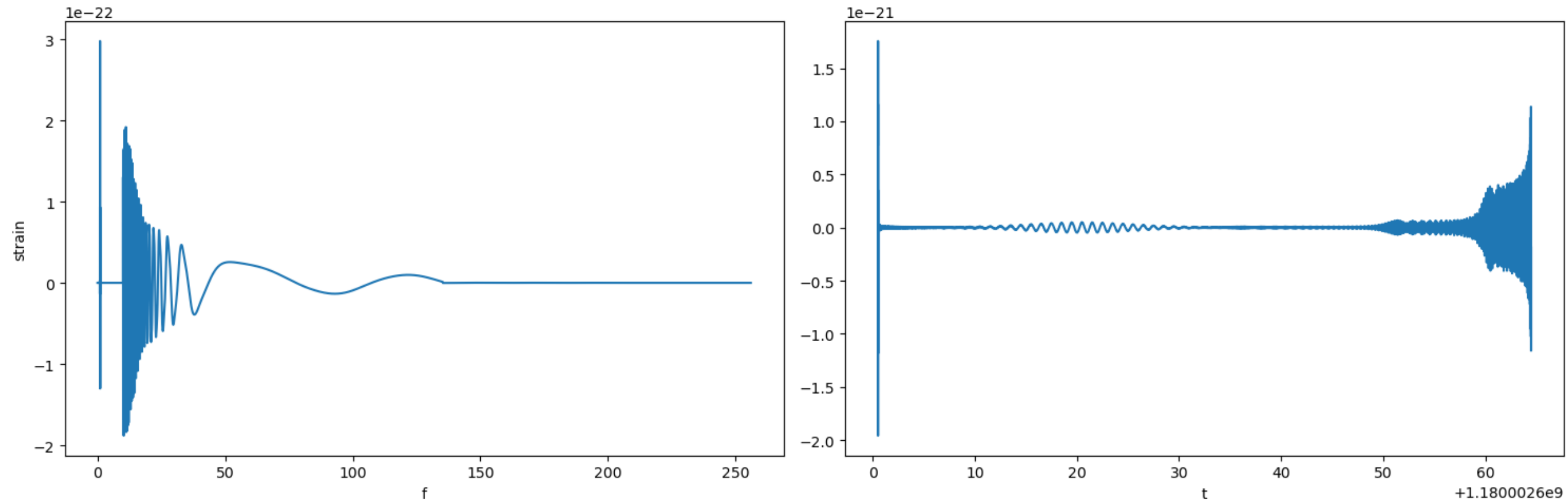
→ injected into detector noise

+

=



BILBY RUNS: RECOVERY

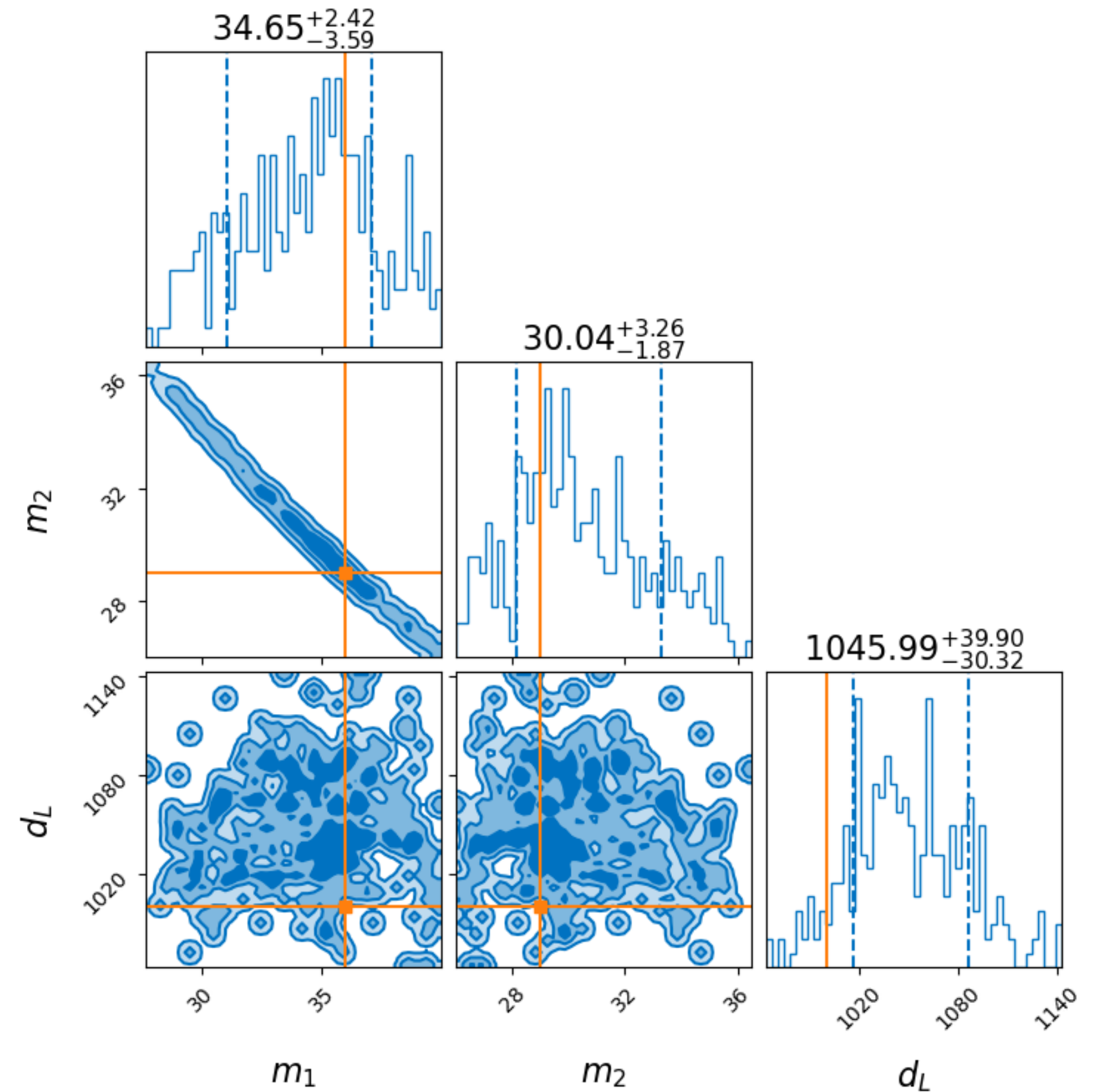


Sampler (Dynesty, ptemcee, ...)
Most extrinsic parameters fixed

Recovered parameters

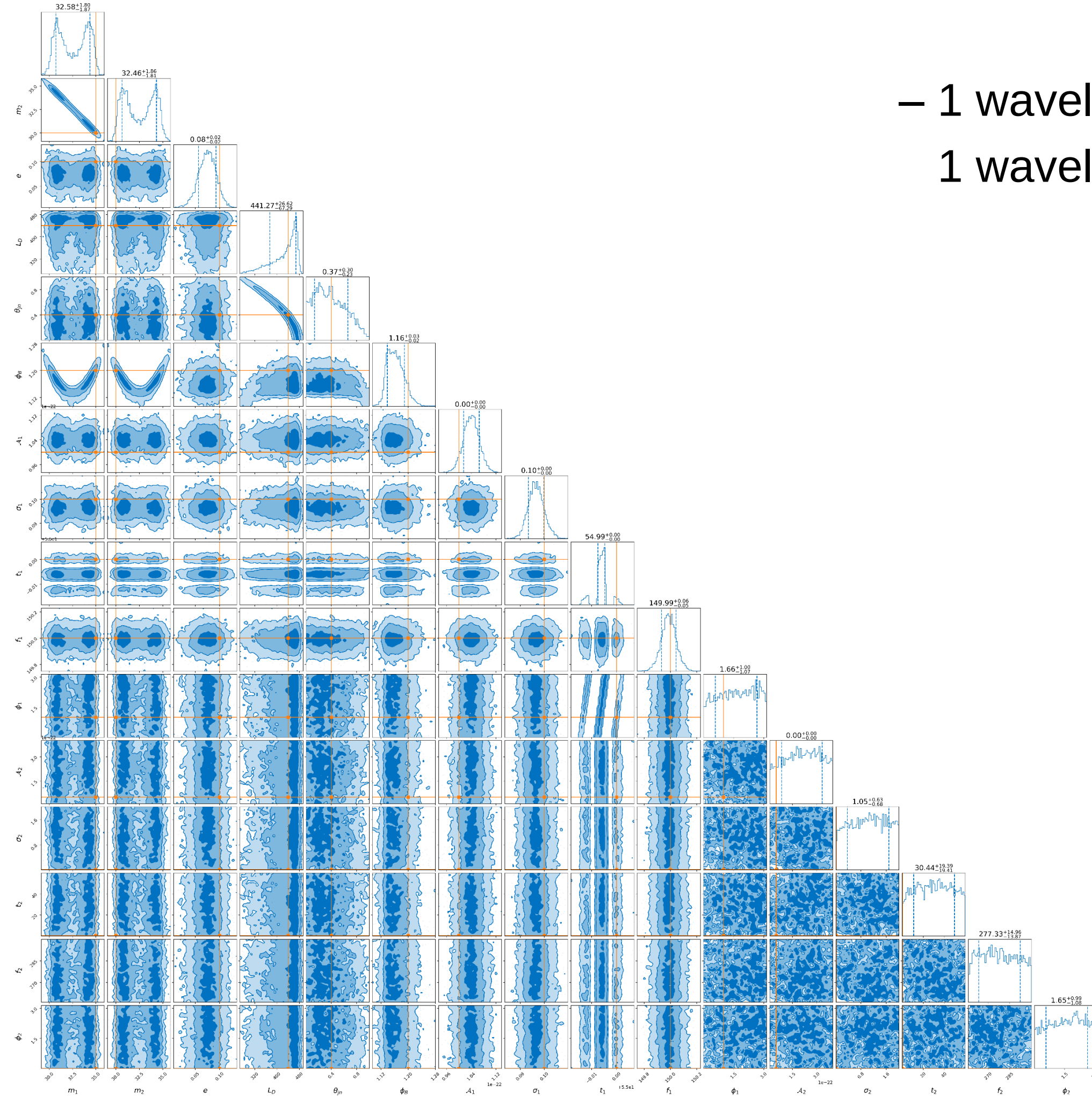
CORNER PLOTS

- Visualise multi-dimensional data
- On-diagonal: parameter distributions
- Off-diagonal: parameter correlations



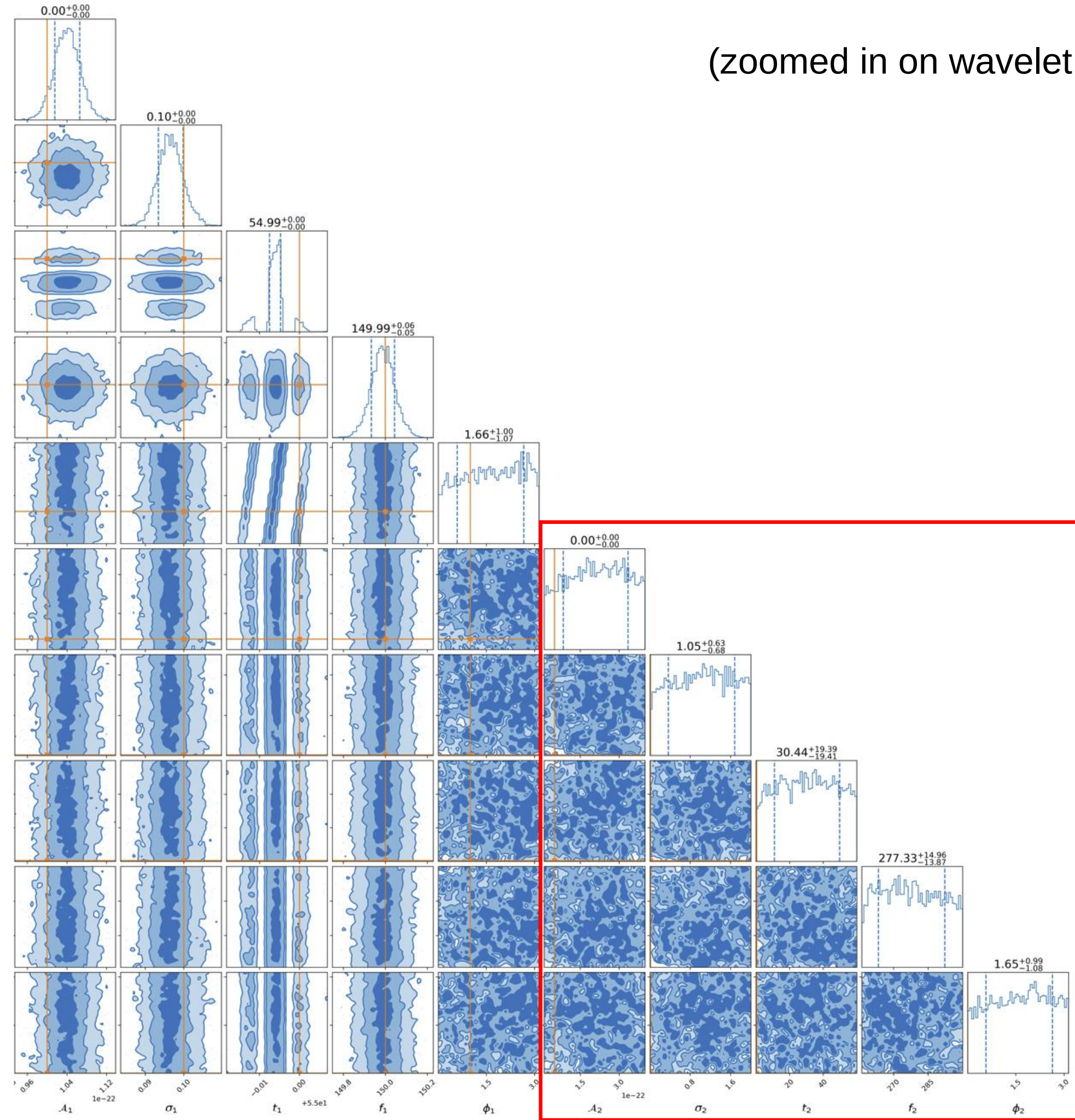
BILBY RESULTS: IMR + DOUBLE WAVELET

– 1 wavelet in merger
1 wavelet outside



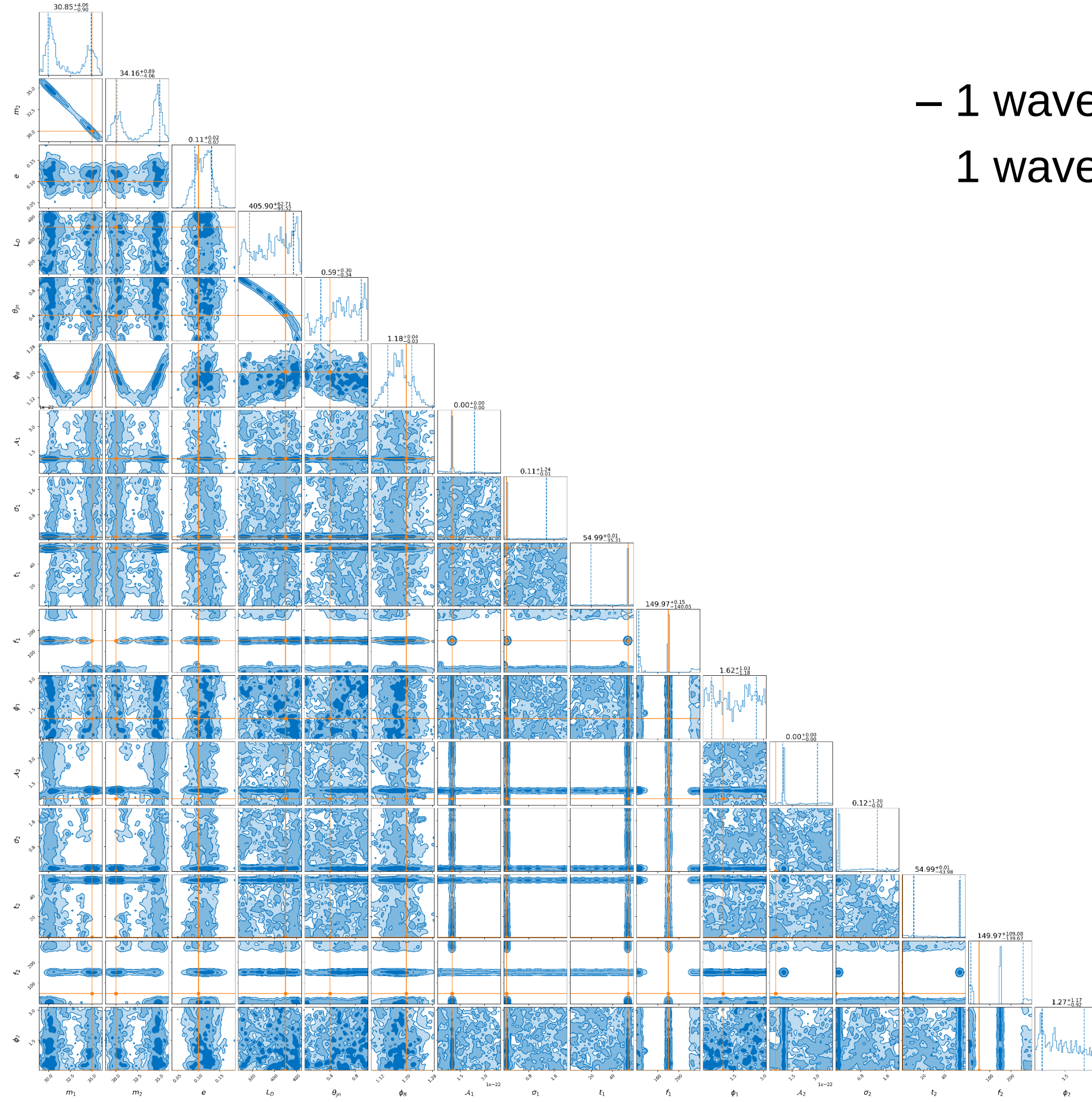
BILBY RESULTS: IMR + DOUBLE WAVELET

(zoomed in on wavelet parameters)



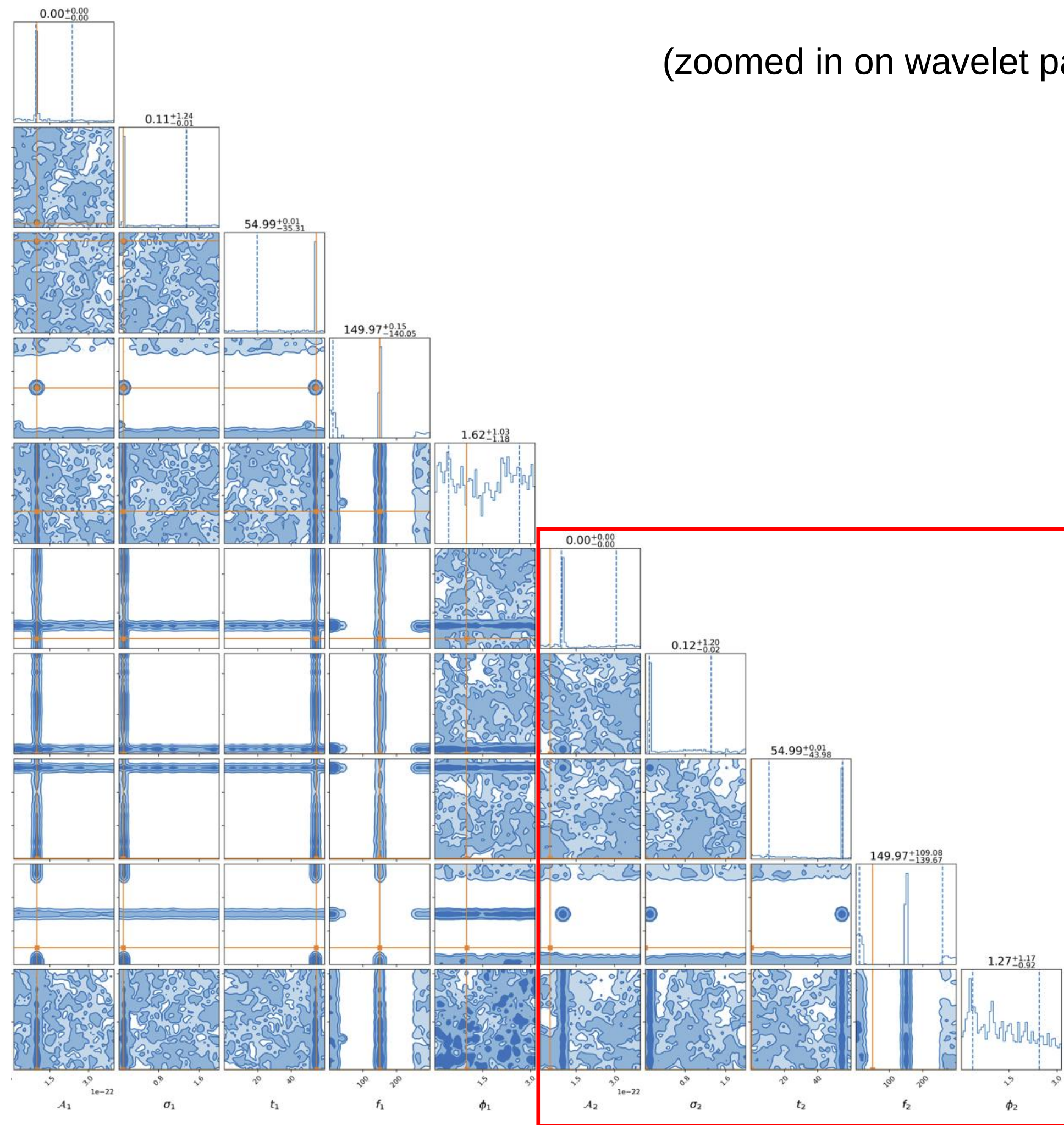
BILBY RESULTS: IMR + DOUBLE WAVELET (PTMCEE)

- 1 wavelet in merger
- 1 wavelet outside



BILBY RESULTS: IMR + DOUBLE WAVELET (PTMCEE)

(zoomed in on wavelet parameters)



DYNESTY VS PTEMCEE

- (pt)emcee: (Parallel-tempered) MCMC
 - Solve hard problem ONCE: distribution proportional to posterior
- dynesty: Dynamic Nested sampler
 - Solve easy problem MANY TIMES: sample inside iso-likelihood contour
 - Estimate posterior AND evidence (latter allows for model comparison)
 - Informative priors needed

Posterior

$$P(\Theta|\mathbf{D}, M) = \frac{P(\mathbf{D}|\Theta, M)P(\Theta|M)}{P(\mathbf{D}|M)} \equiv \frac{\mathcal{L}(\Theta)\pi(\Theta)}{\mathcal{Z}}$$

Likelihood

Prior

Evidence

source: Dynesty documentation

TBILBY

- Each wavelet adds 5 DOF => computational cost!
- Use tBilby
- *Transdimensional* Bilby

t

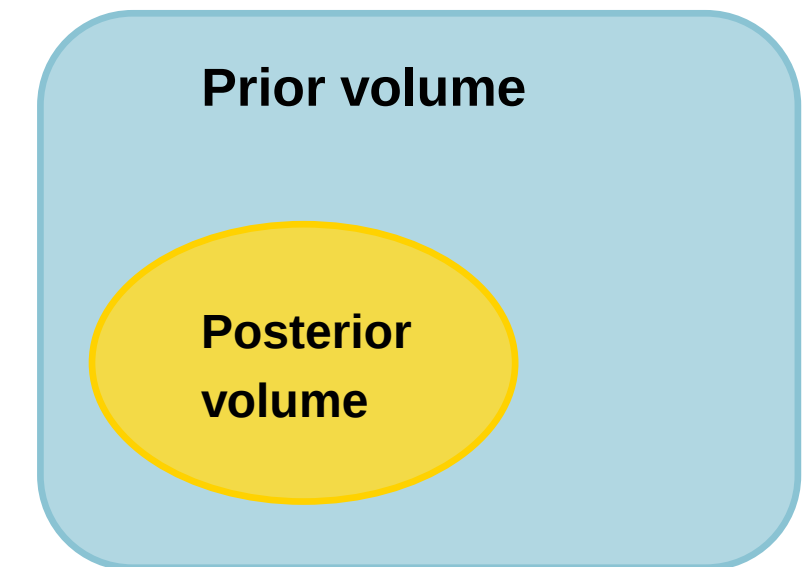


TRANSDIMENSIONAL SAMPLING

- Dimensionality N = sampling parameter
 - Reversible Jump MCMC
- Posterior penalised by Occam factor (weights model complexity)

$$Z = \int P(D|\Theta, M)P(\Theta|M)d\Theta$$

$$\approx P(D|\Theta, M)P(\Theta|M)\sigma_{\Theta|D} = P(D|\Theta, M) \cdot \frac{\sigma_{\Theta|D}}{\sigma_{\Theta}}$$

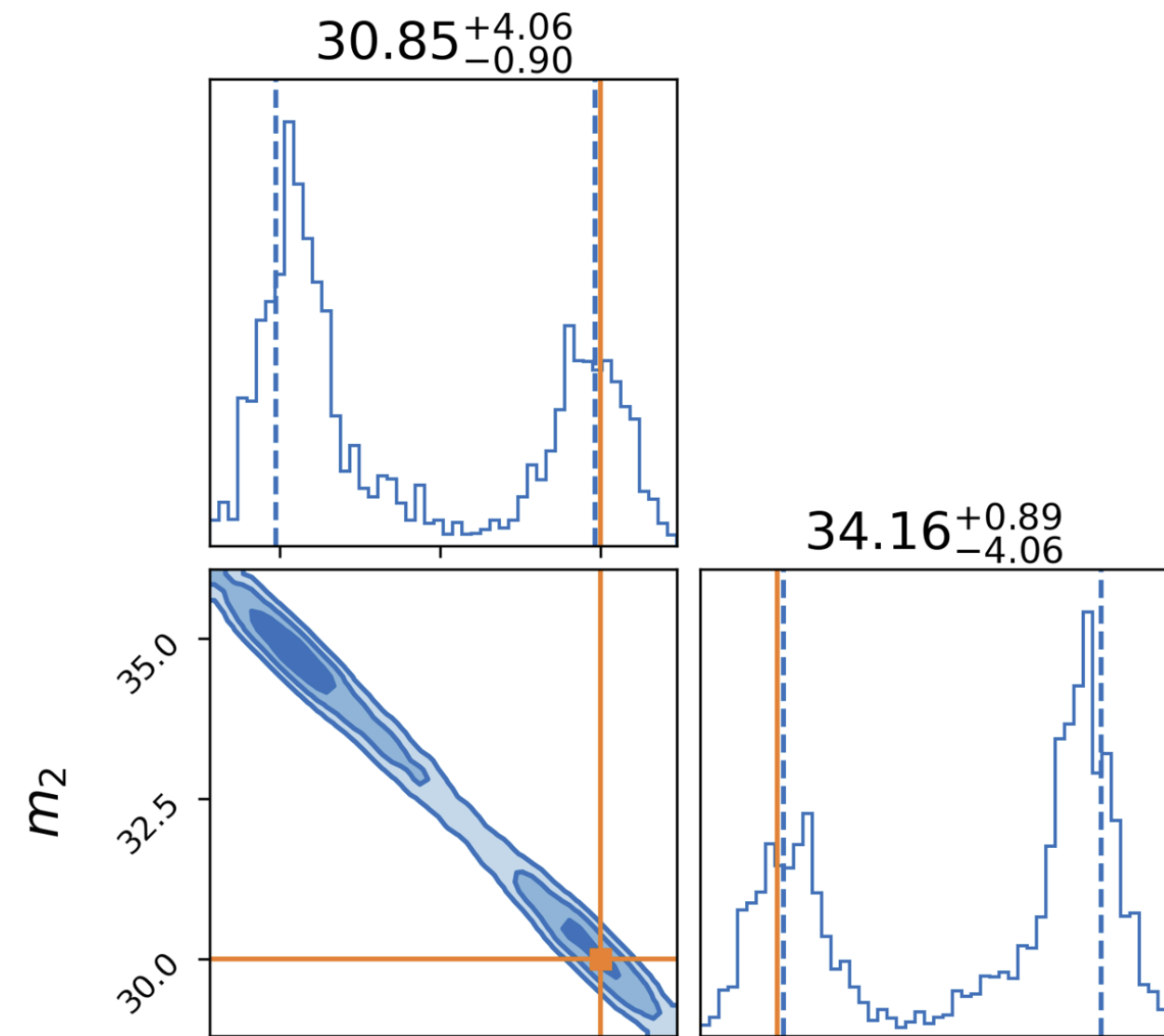


TBILBY

- tBilby samples in full N , but evaluates likelihood over $\leq N$
- Sampling from priors = cheap
- Evaluating likelihood = expensive
- Patched a possible bug in code

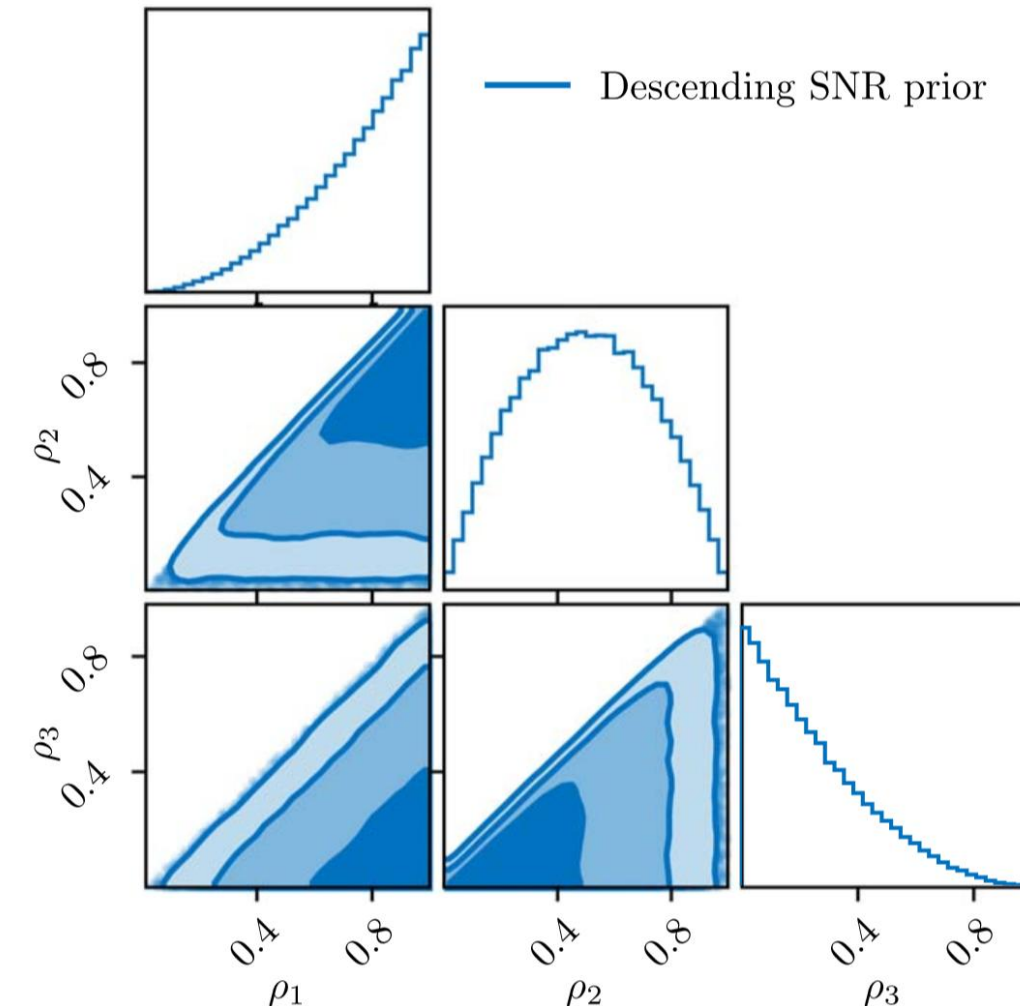
TBILBY: ORDER STATISTICS

- Identical component functions: parameter labels can be swapped without changing the likelihood
=> Symmetric likelihood multimodality
= INEFFICIENT TO SAMPLE
- E.g: IMR waveform is symmetric under $m_1 \leftrightarrow m_2$
- Degeneracy scales as $N!$



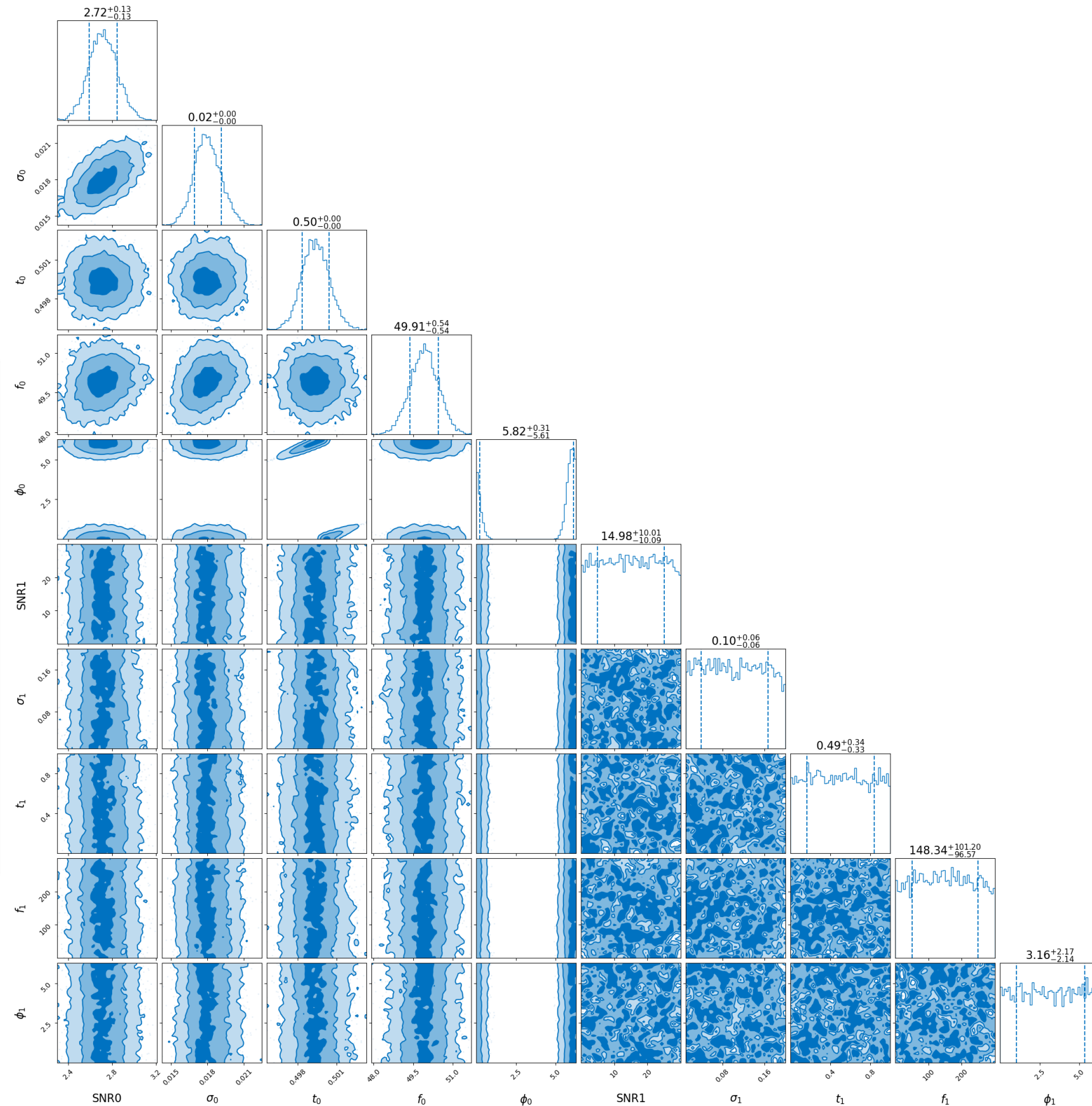
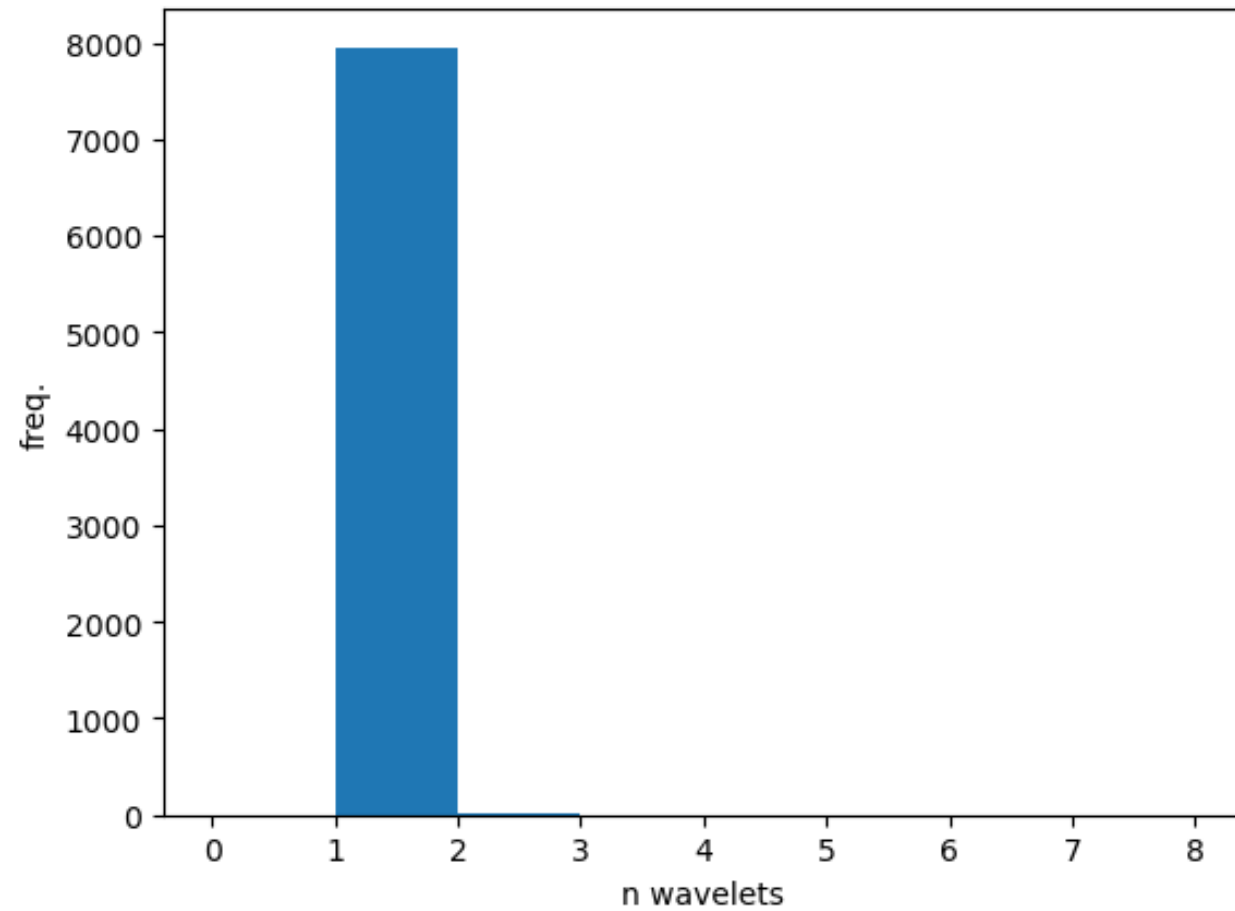
TBILBY: ORDER STATISTICS

- (a) SOLUTION: break symmetry
- Rank/order component functions (wavelets)
- Wavelets can be ordered by time, frequency, SNR, ...
- SNR is most natural: loudest wavelet most likely to be found first
- Ordering adopted in the priors



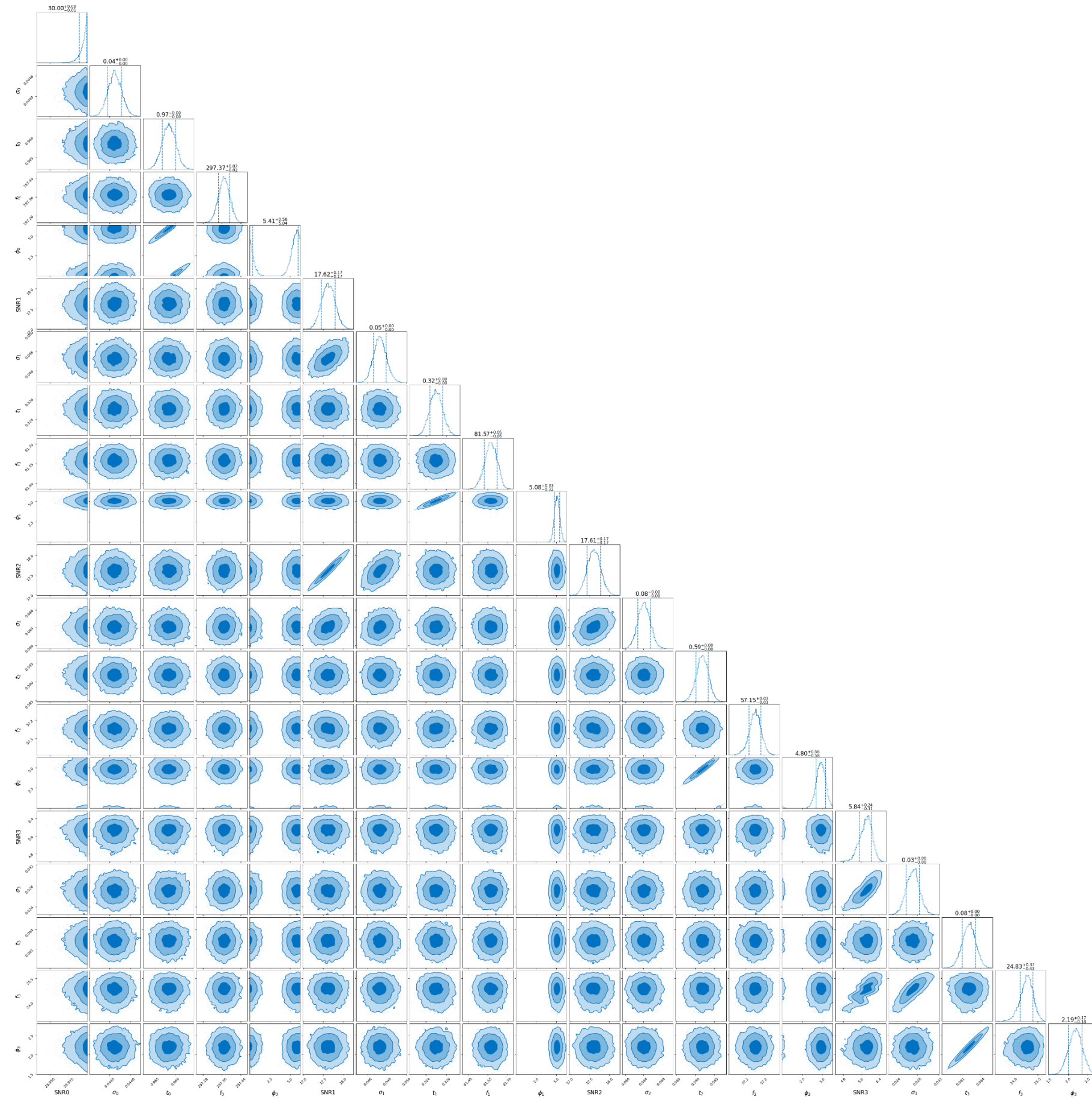
TBILBY RESULTS:

- 2 injected wavelets
- Very strong preference for loudest wavelet
- Same for different runs



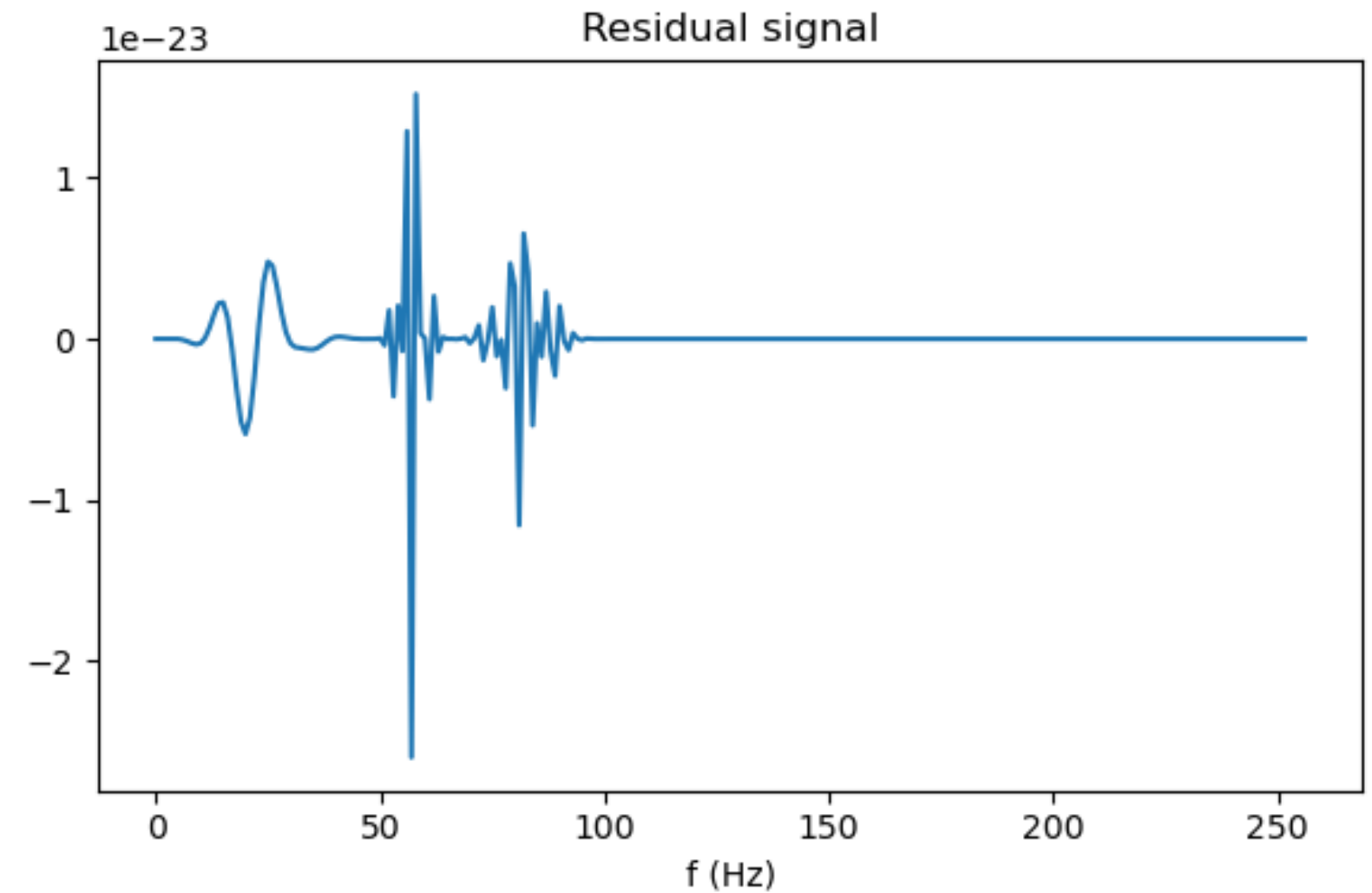
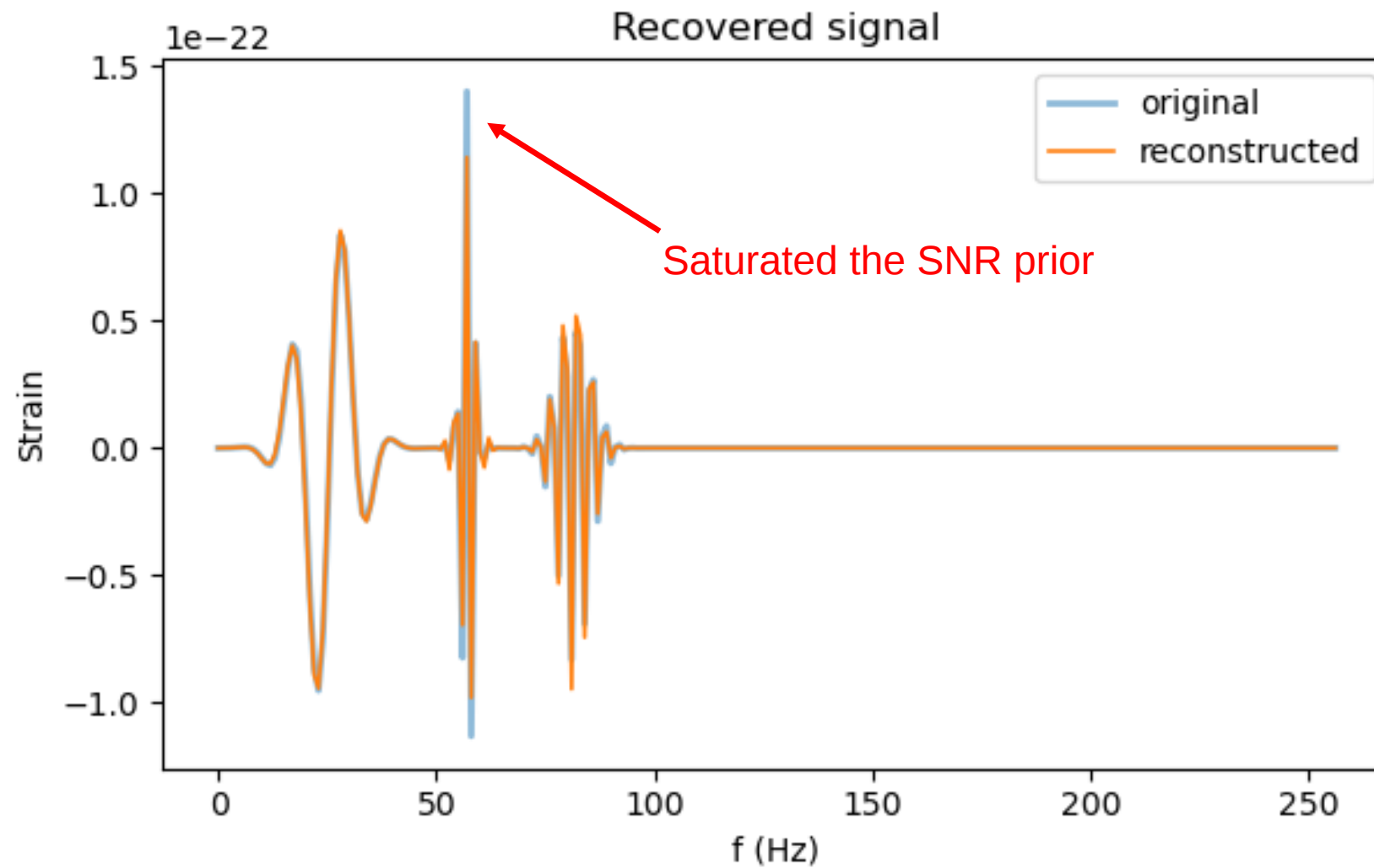
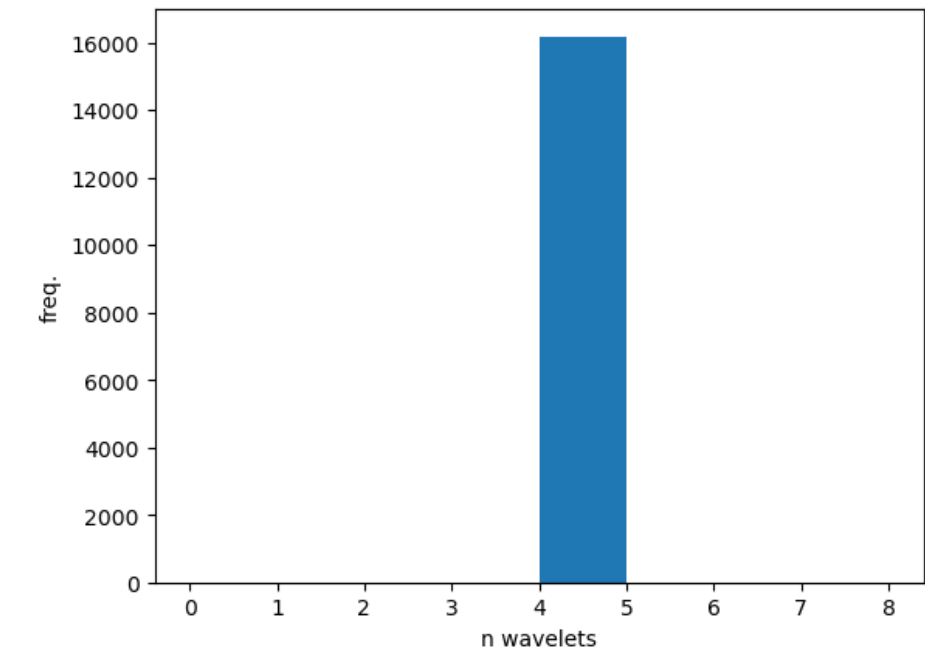
TBILBY RESULTS:

- 4 random wavelets
- Corner plots get very messy



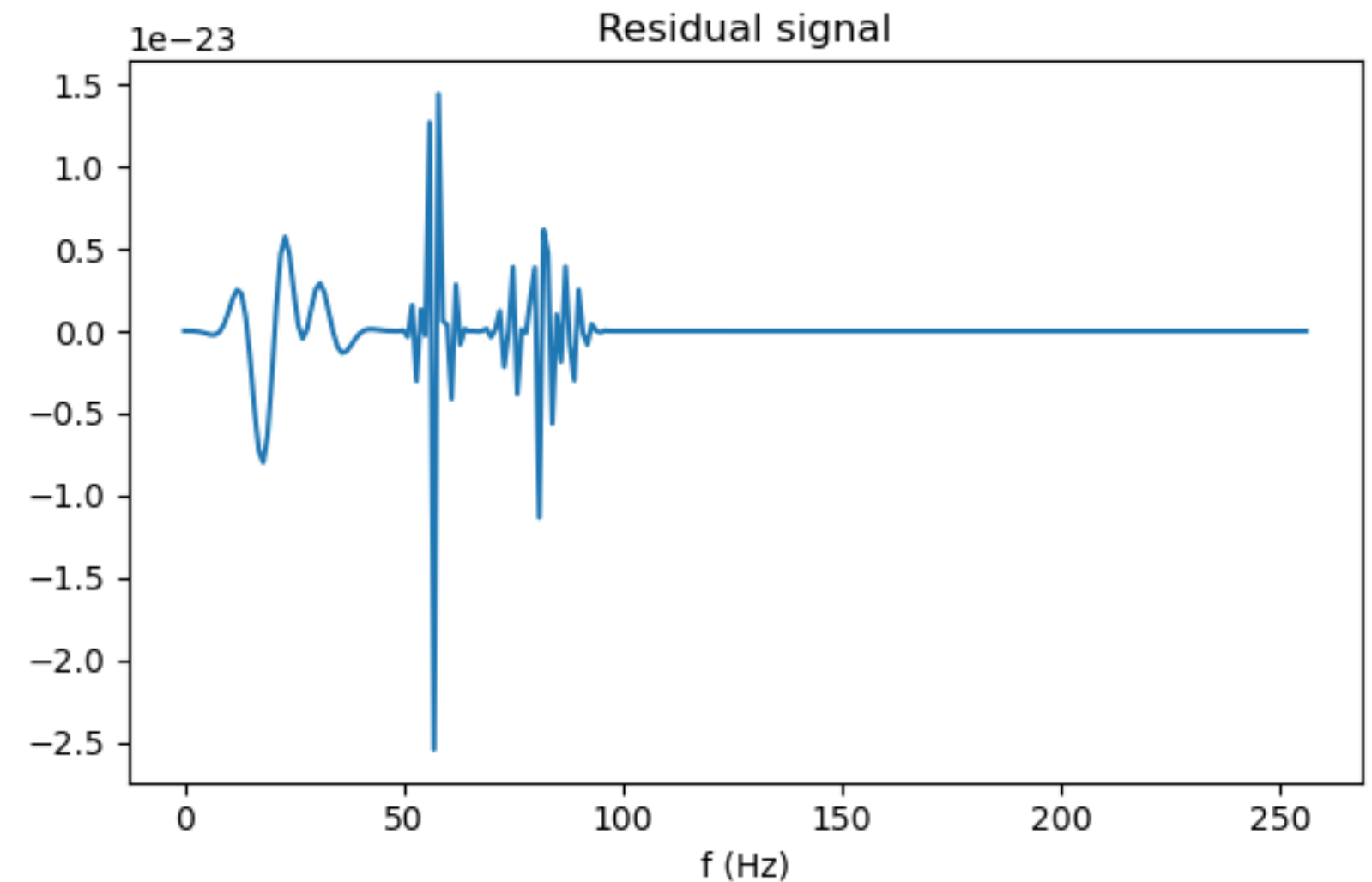
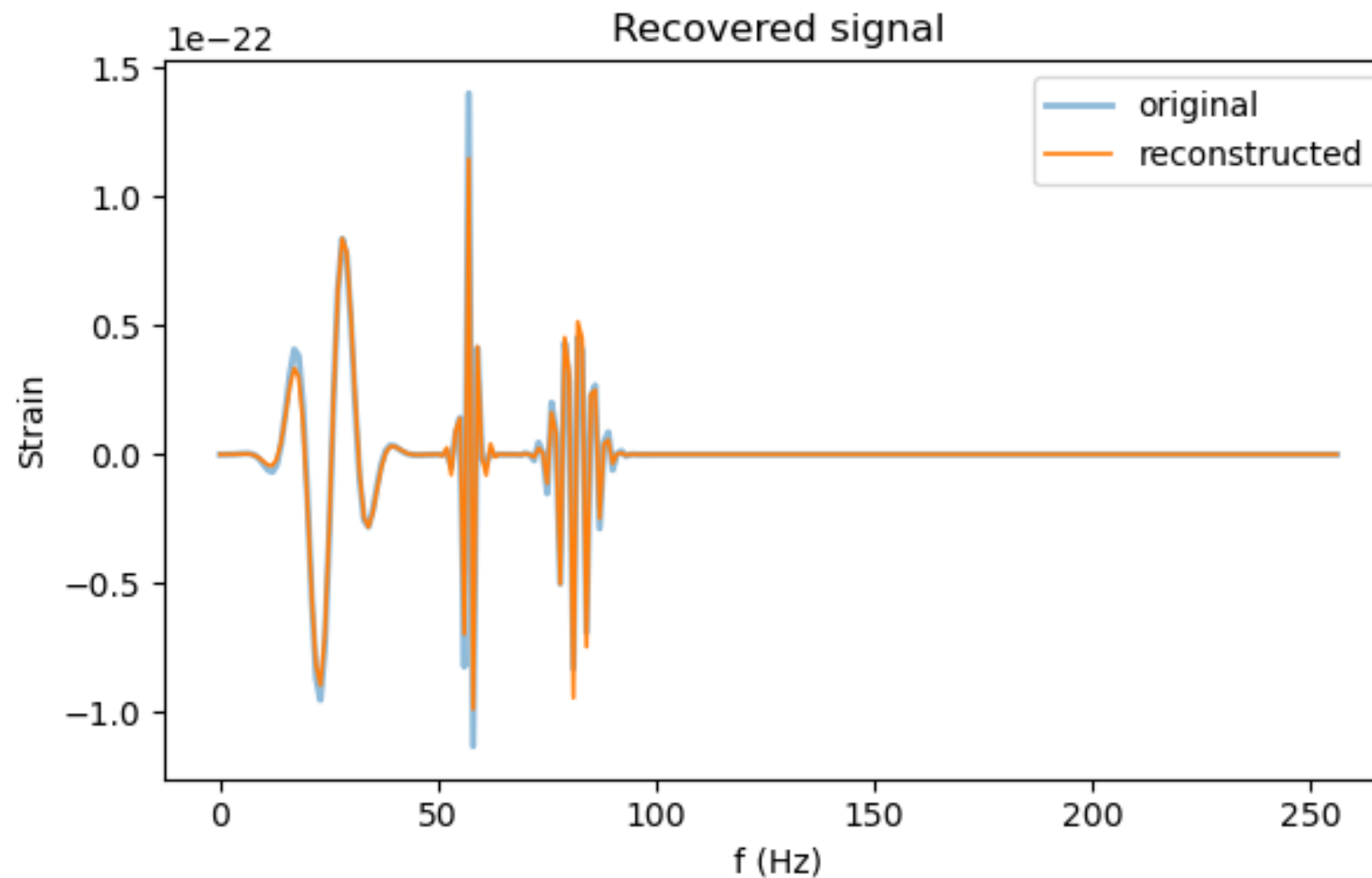
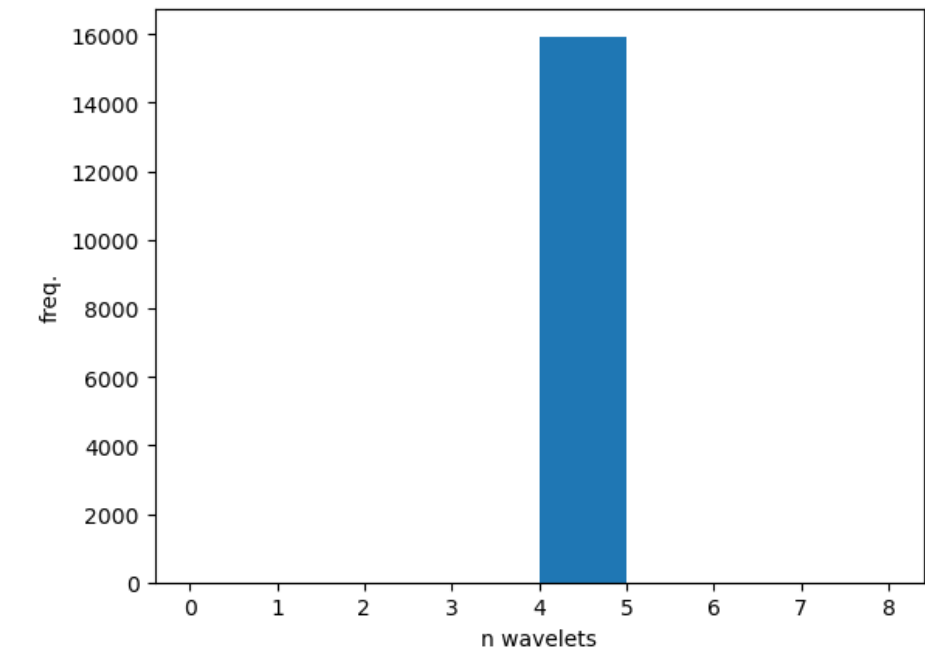
TBILBY RESULTS:

- tBilby only sampled in 4 wavelets
- Lucky initial guess?



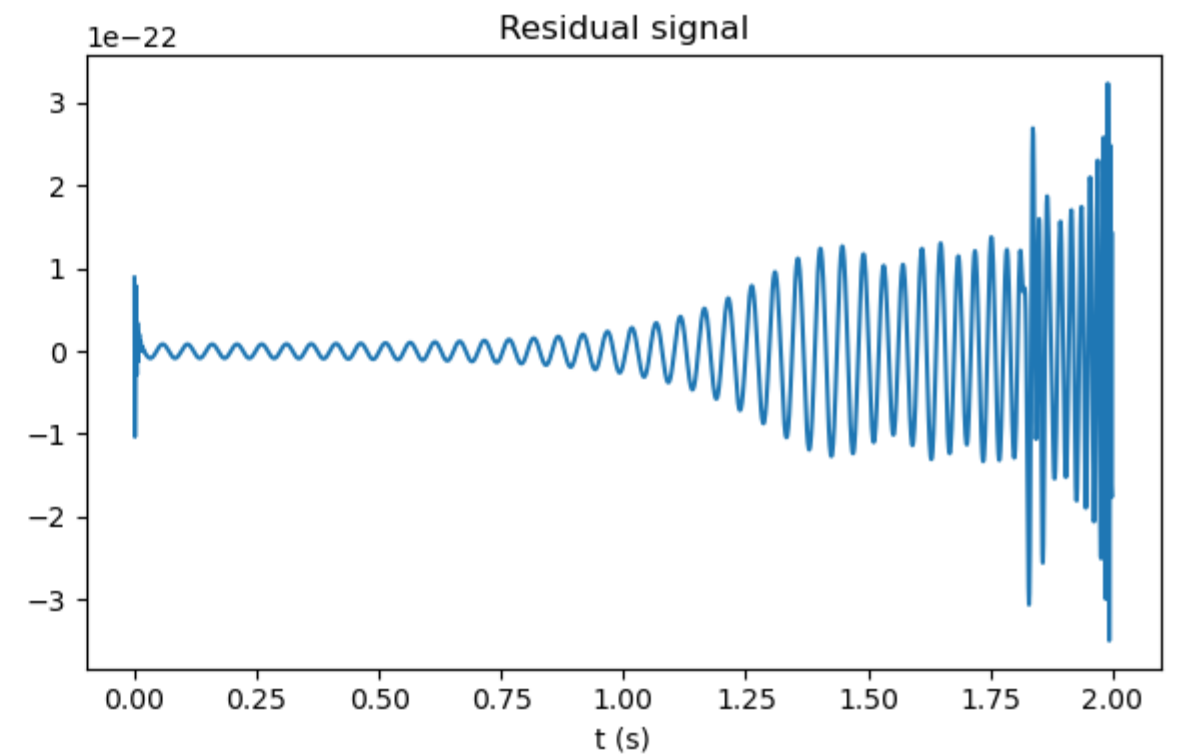
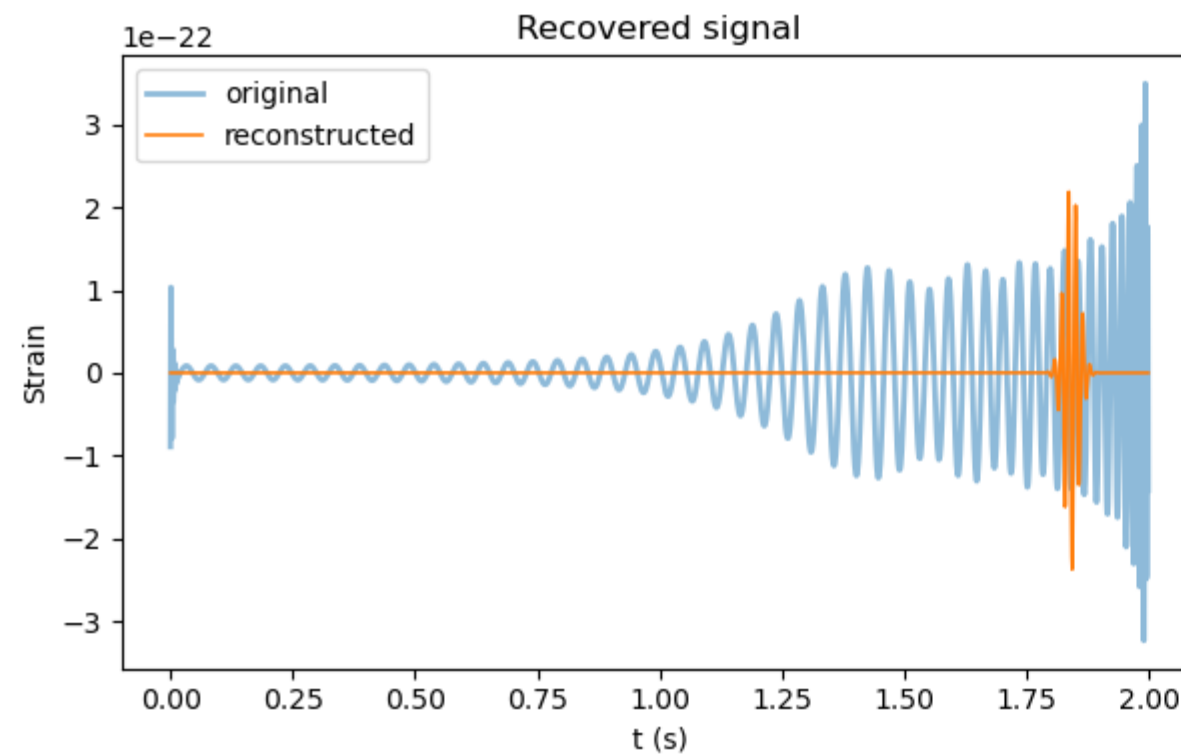
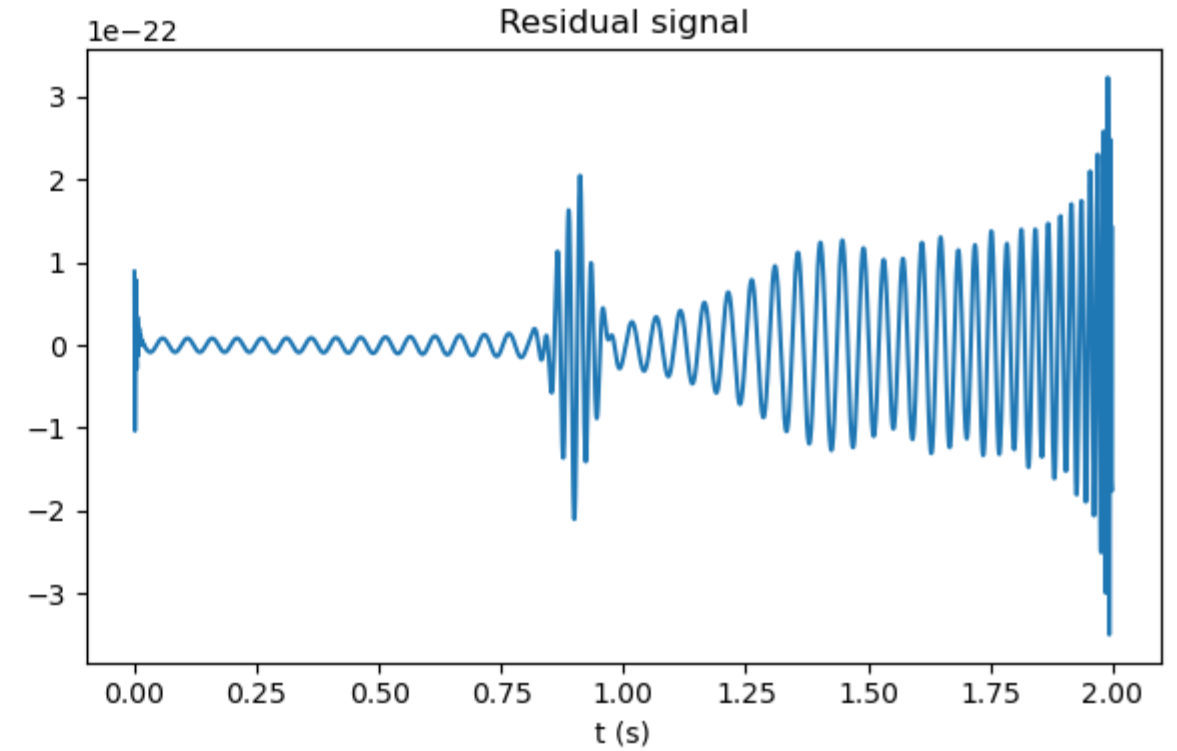
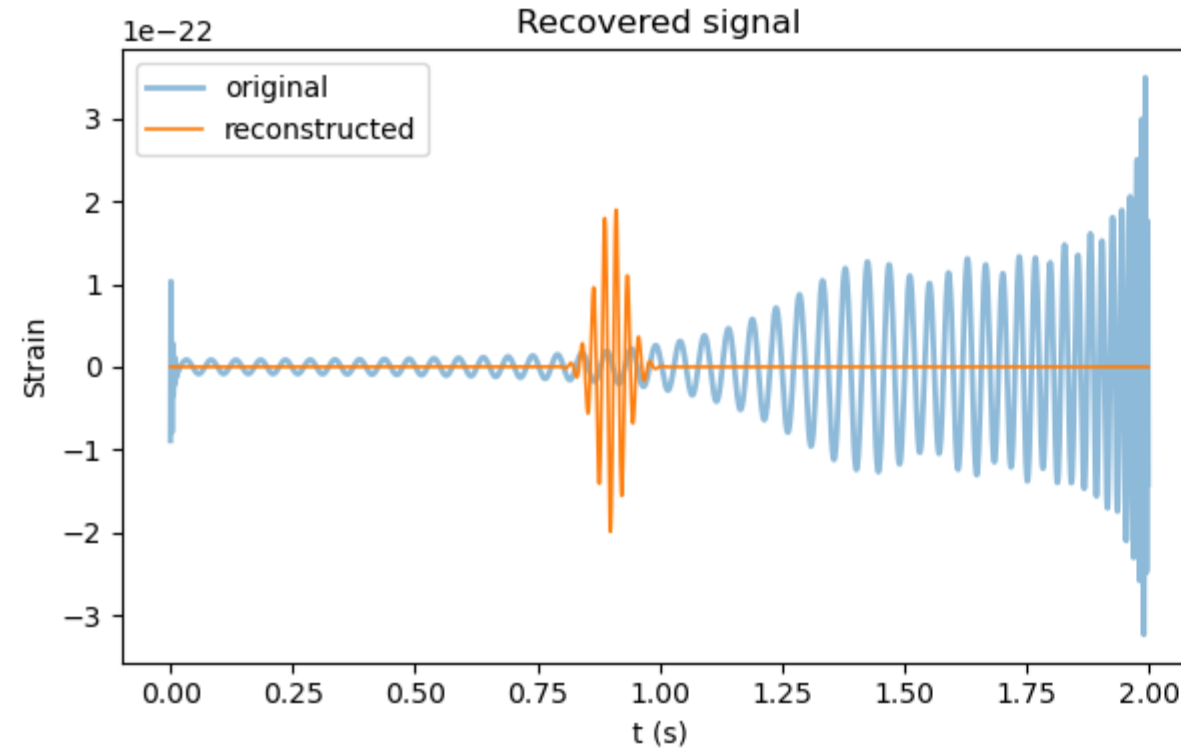
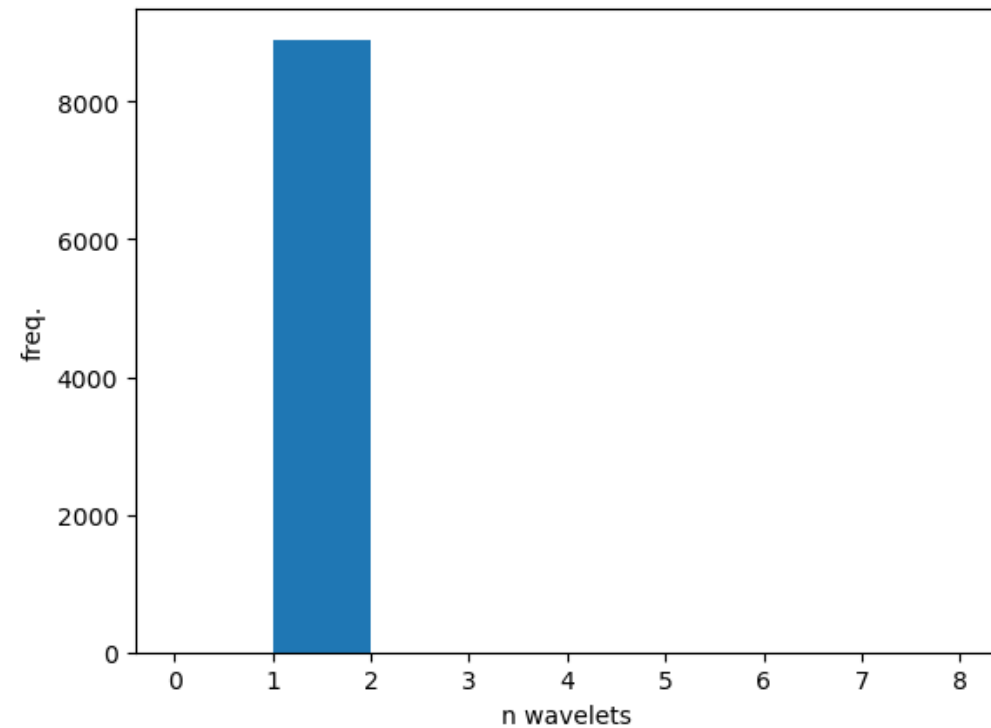
TBILBY RESULTS:

- Second run confirms result
- Does tBilby only work well on complex signals?



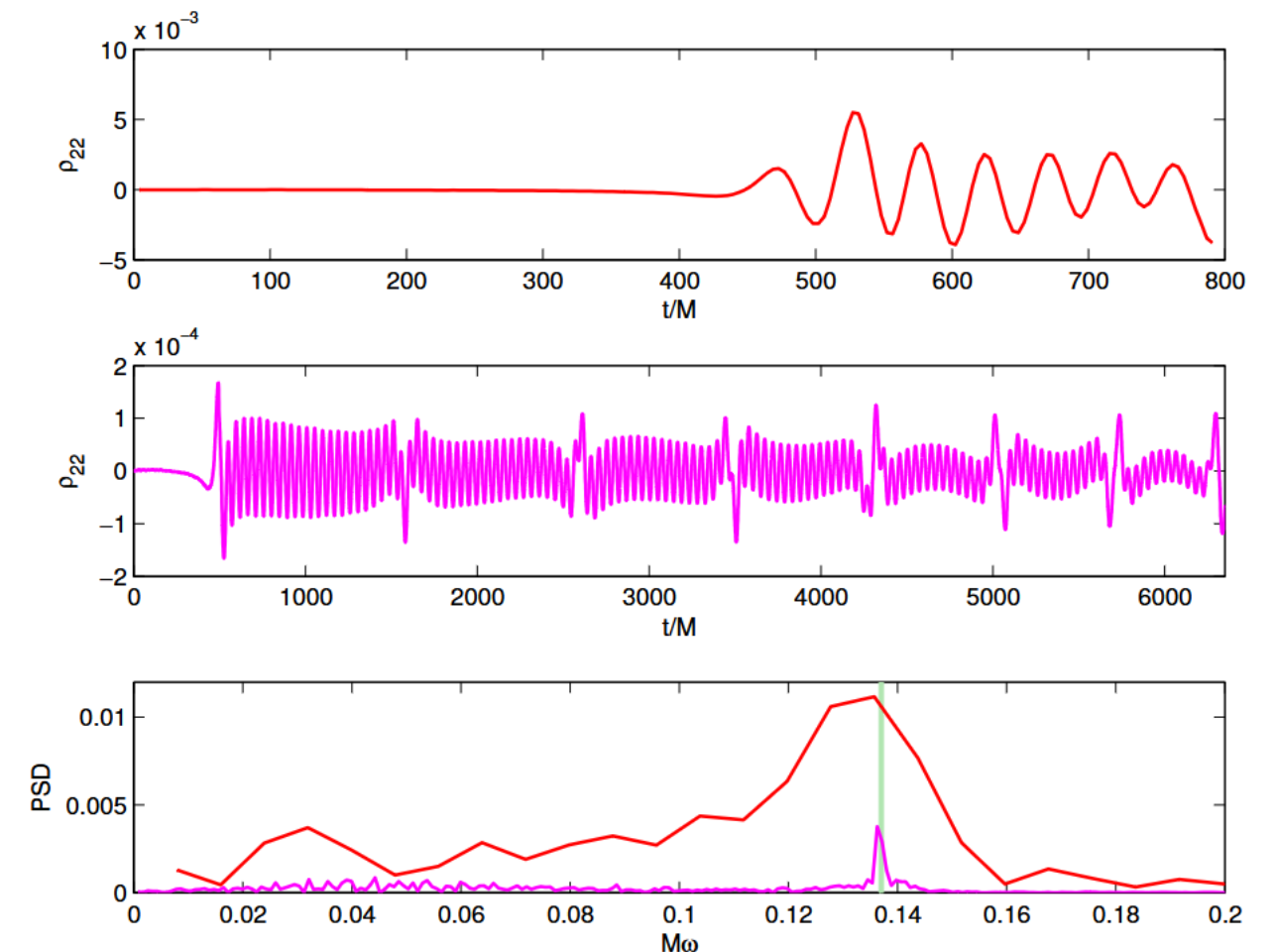
TBILBY RESULTS: BBH

- $N_{\text{max}} = 8$
- Only modelled with 1 wavelet each time



NR WAVEFORMS WITH RESONANCES

- Useful as a final test
- NR waveforms are expensive and thus rare!
- Found a few people who have such waveforms



Gold R. et al. (2013), Eccentric binary neutron star mergers

NEXT STEPS

- See what tBilby authors have to say about my patch
 - Perhaps I broke the code
- Modify sampling parameters
 - $\sigma \rightarrow Q$ (quality factor)
- tBilby: IMR + wavelet(s)
 - tBilby can model multiple resonances
- Test on NR waveforms

NEXT STEPS

- See what tBilby authors have to say about my patch
 - Perhaps I broke the code, again
- Modify sampling parameters
 - $\sigma \rightarrow Q$ (quality factor)
- tBilby: IMR + wavelet(s)
 - tBilby can model multiple resonances
- Test on NR waveforms

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