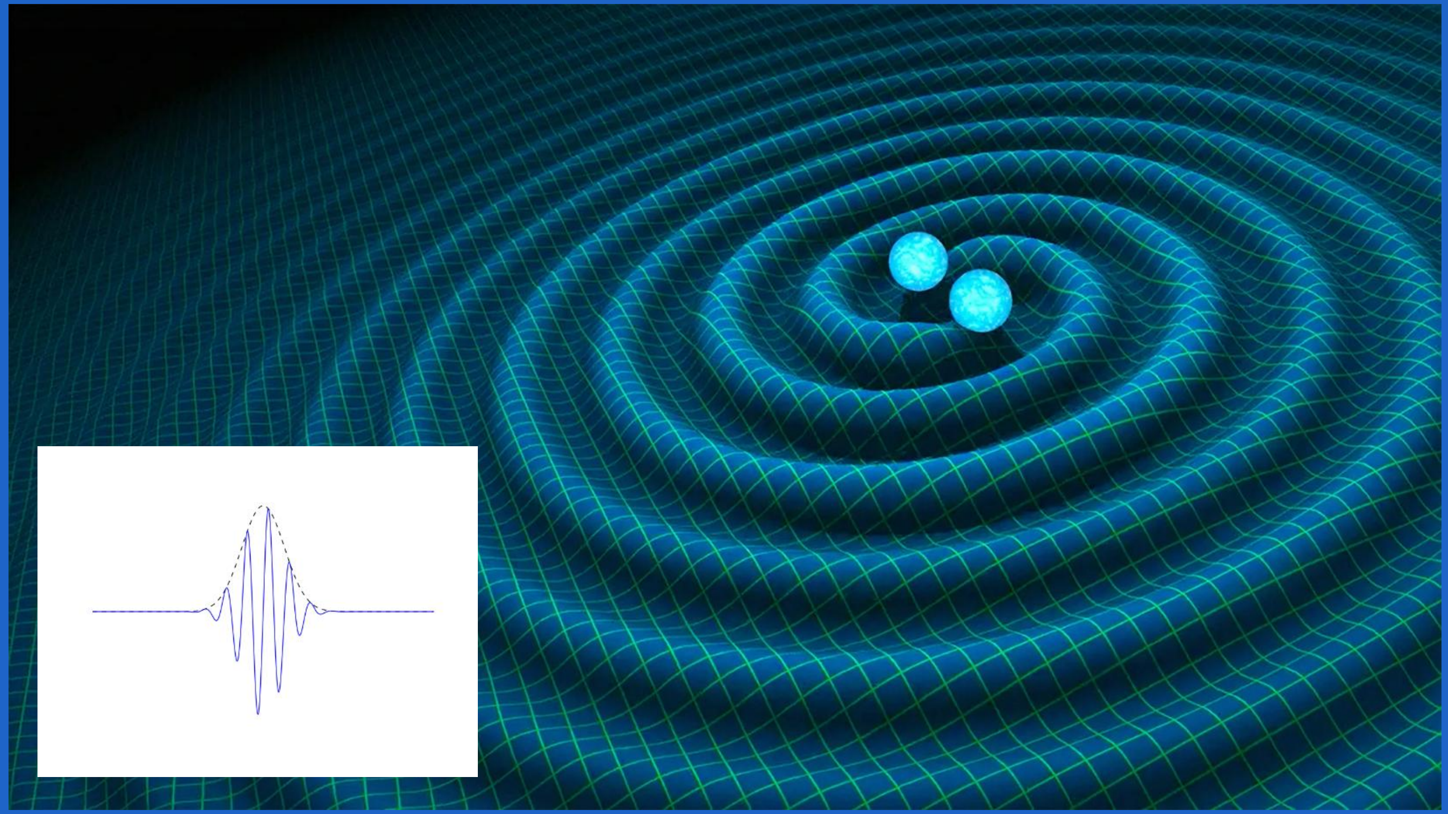
FACULTY
OF SCIENCES

DEPARTMENT OF PHYSICS AND ASTRONOMY
EXPERIMENTAL PARTICLE PHYSICS AND GRAVITY

HUNTING FOR EXOTIC RESONANCES IN COMPACT BINARY MERGERS

Robin Chan
Intermediate thesis presentation

Supervisor: Prof. Dr. Archisman Ghosh



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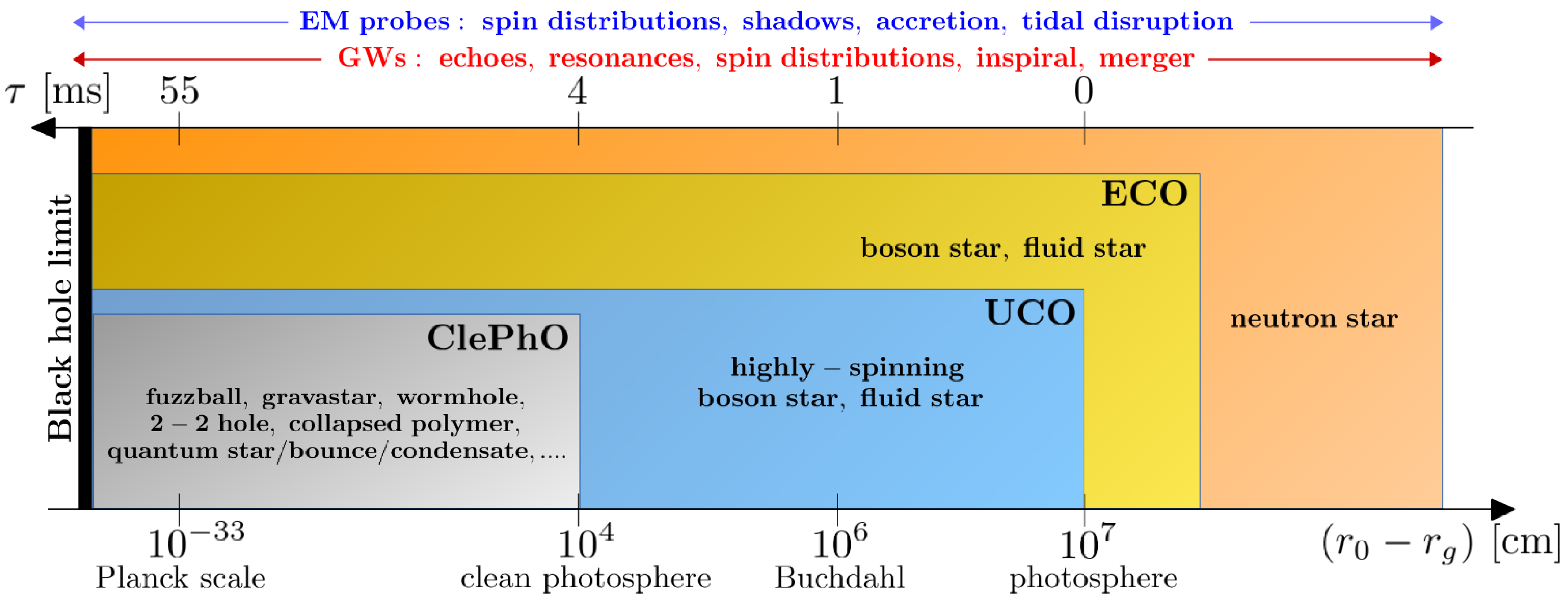
WHAT TO EXPECT?

- 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



Cardoso V., Pani P. (2017), *Tests for the existence of horizons through gravitational wave echoes*

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GRAVITATIONAL WAVES: ECOS

GW170817: Observation of Gravitational Waves from a B... Neutron Star Inspiral

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; publ... Octo...

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 Two Neutron Star–Black Hole Coalescences

However, consistency with the maximum NS mass does not exclude the possibility that the secondaries could be BHs or exotic compact objects, if such objects also exist within the NS mass range ... instance, models of primordial BHs predict a peak in ... ial BH mass function at $\sim 1\,M_\odot$ (Carr et al. 202... odels also predict that primordial BHs may ... ing binaries at mass ratios comparable to those

...Sola... Black Hole with a ...

...discussion has thus far neg... exotic ...ct, such as a boson star (Kaup 196... ...ead of an ...pending on the model, some exotic co... masses up ... 2.6 $M_\odot$ (Cardoso & Pani 2019). Our analysis do... ...sis for the

Observation of Gravitational Waves from the Coalescence of a 2.5–4.5 $M_\odot$ 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 interpretation for the source of GW230529 is the coalescence between a 2.5–4.5 $M_\odot$ black hole and a neutron star. GW230529 provides further evidence that a

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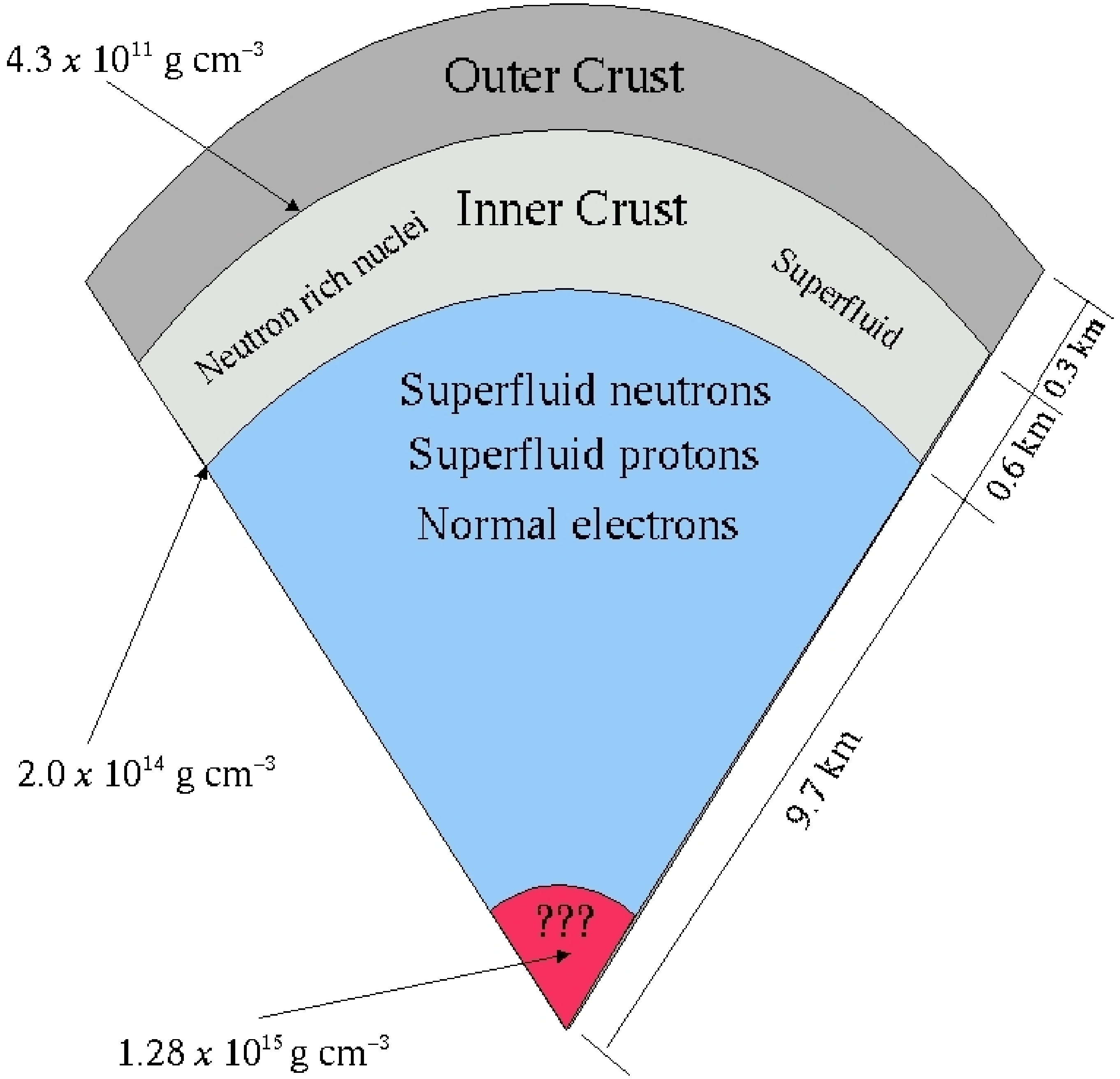
GRAVITATIONAL WAVES

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



Neutron Star Pizza

Tod Strohmayer's Webpage: https://asd.gsfc.nasa.gov/Tod.Strohmayer/ns_intro.html

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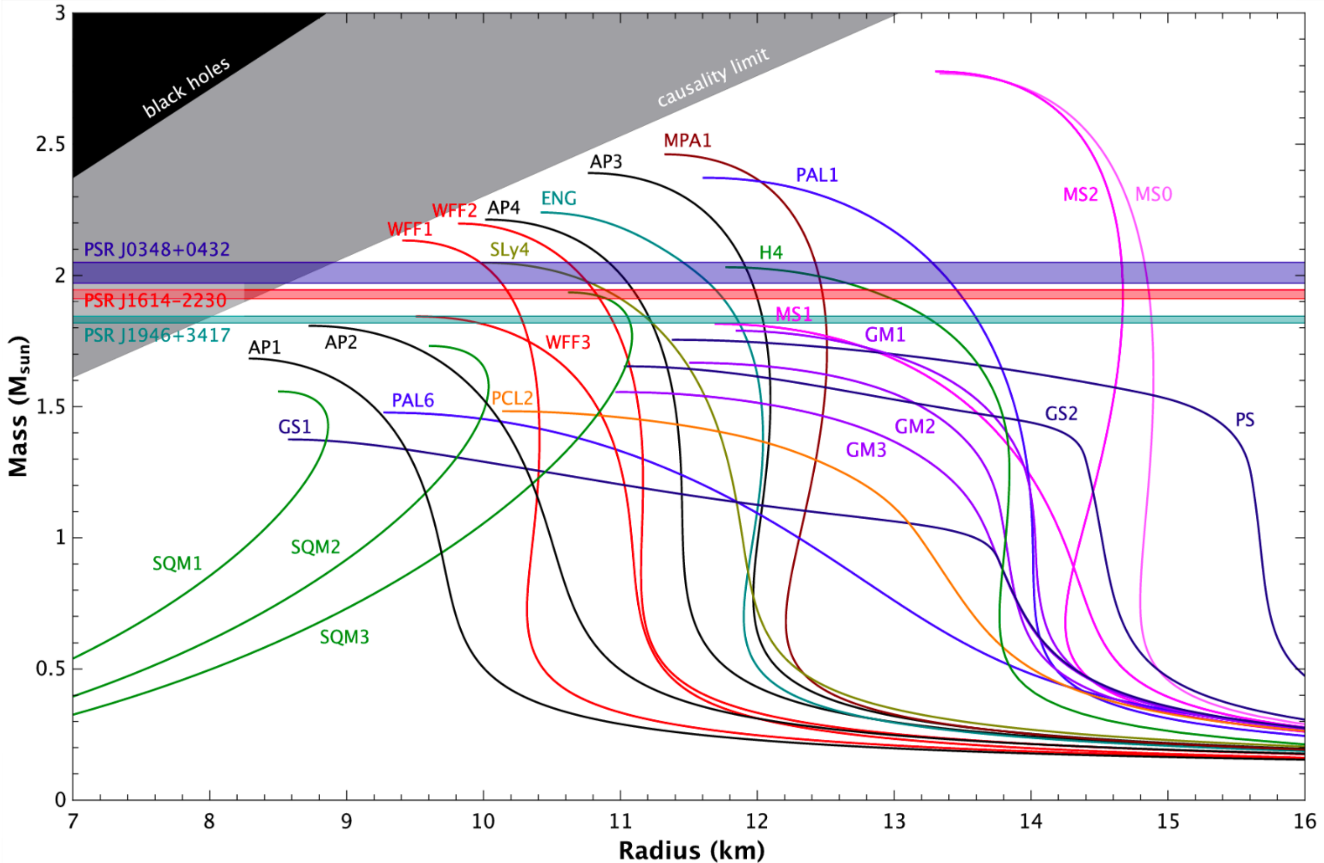
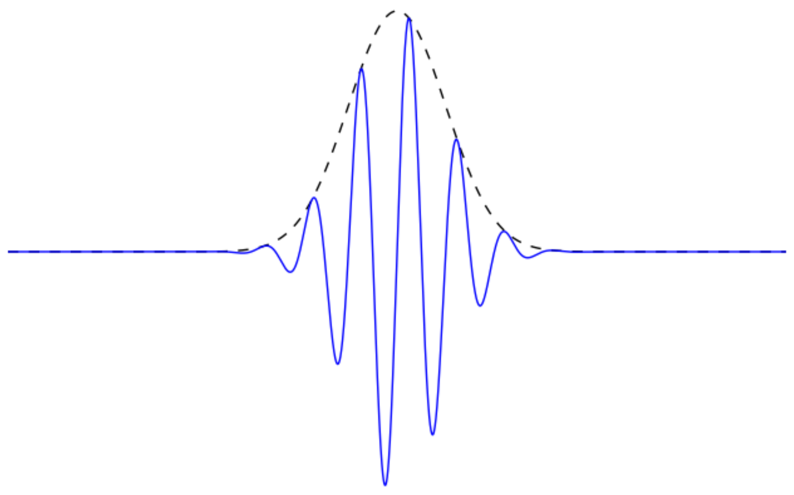
ECOS AND HOW FIND THEM

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



Karsai S., Barnaföldi G., Forgacs-Dajka E. Correspondence of Many-flavor Limit and Kaluza-Klein Degrees of Freedom in the Description of Compact Stars



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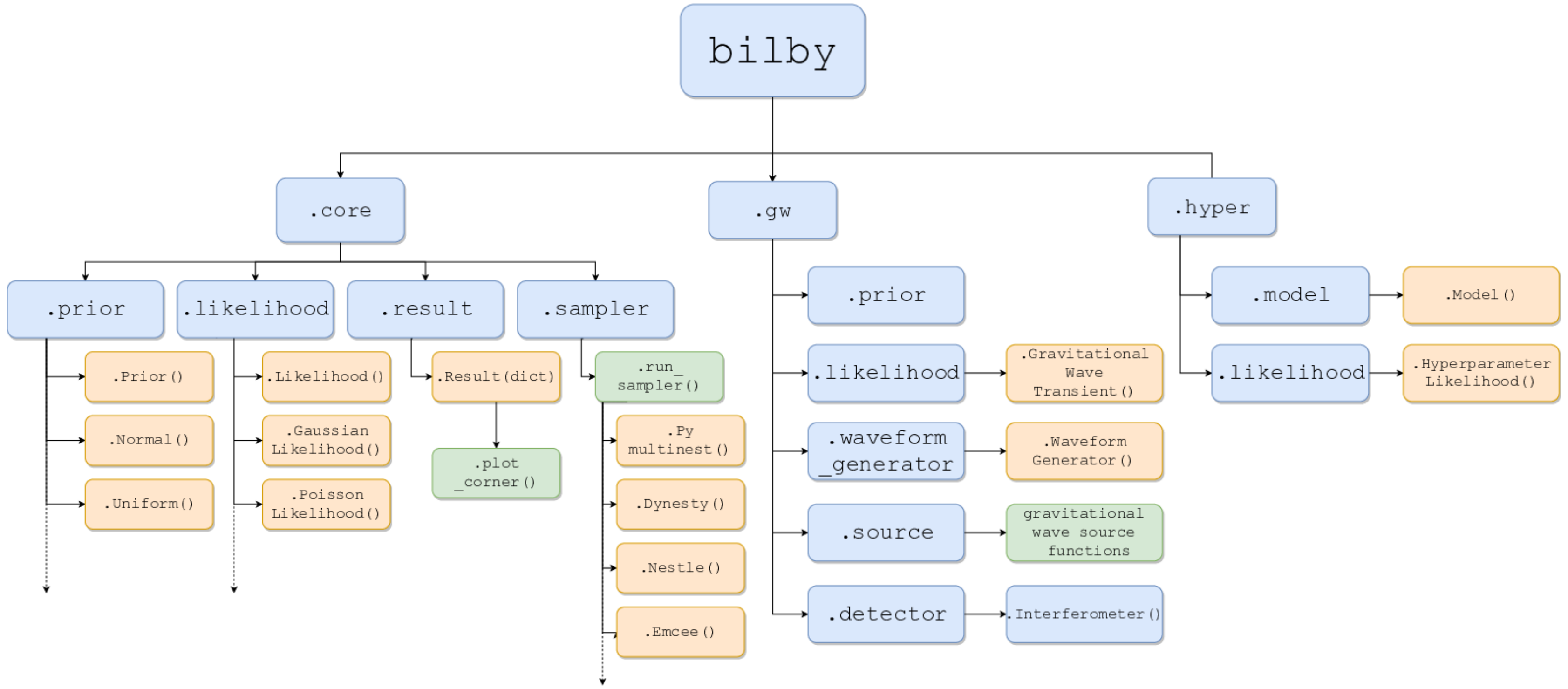
BILBY

- 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

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BILBY RUNS: INJECTION

IMR signal

(Inspiral – Merger - Ringdown)

+

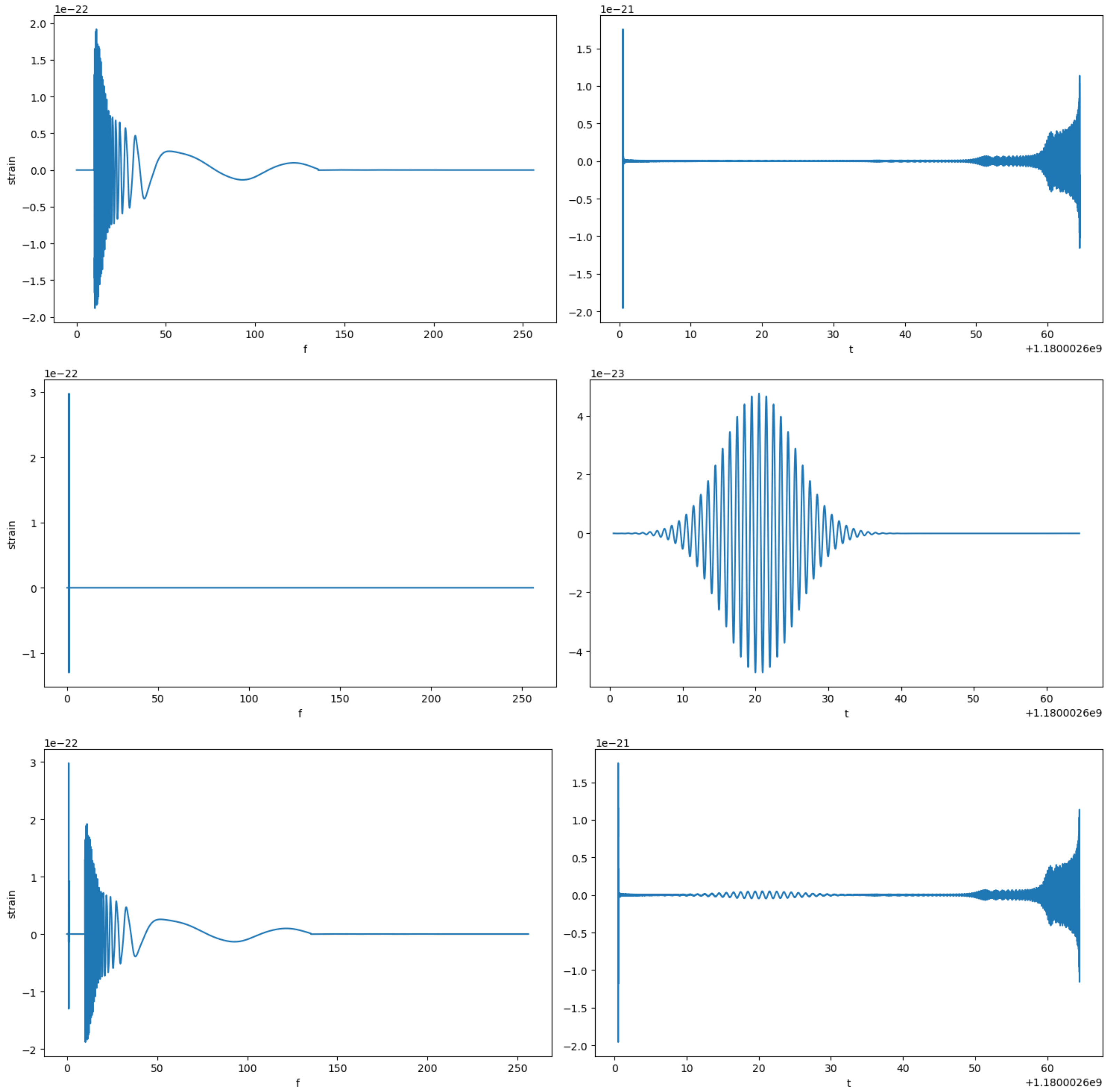
Wavelet

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

=

Composite signal

→ injected into detector noise



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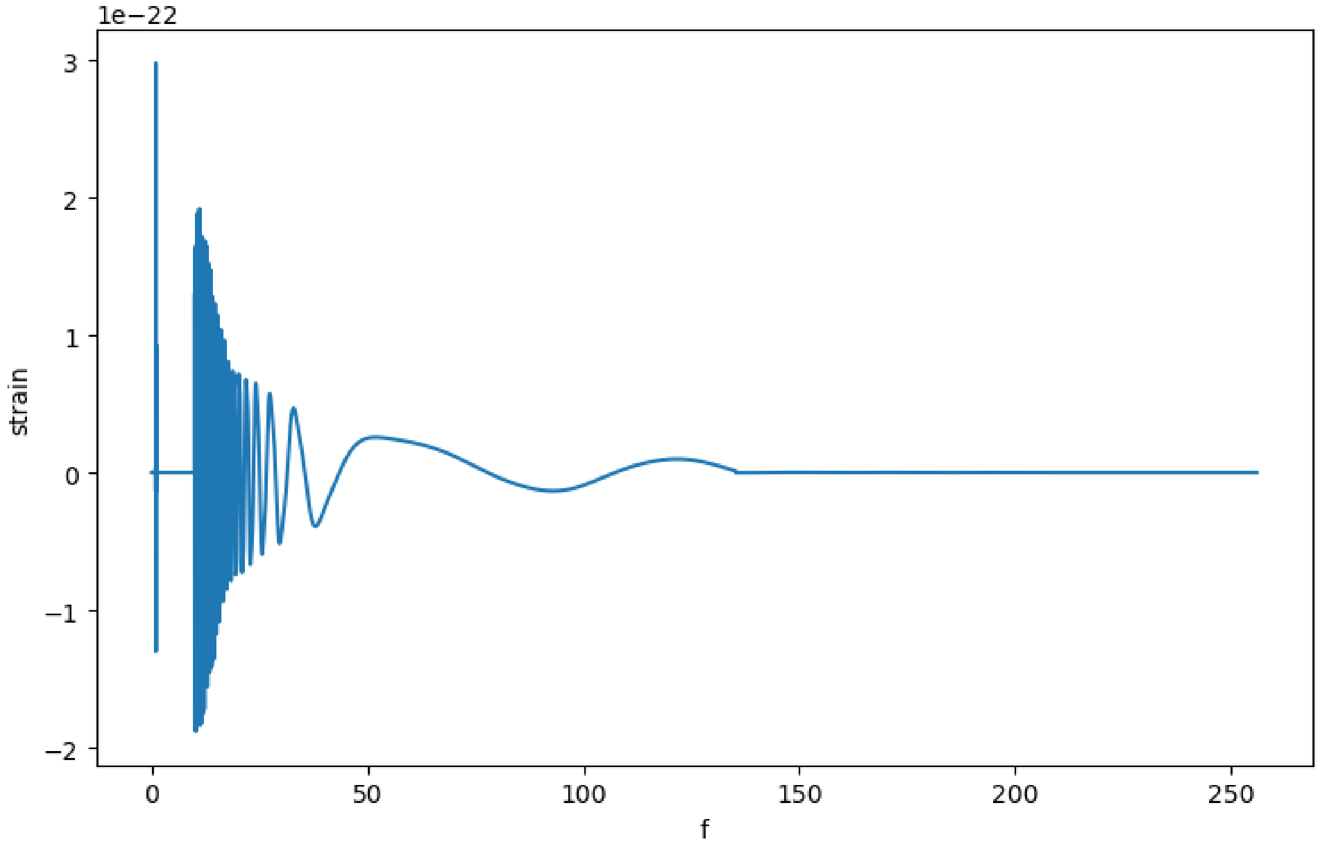
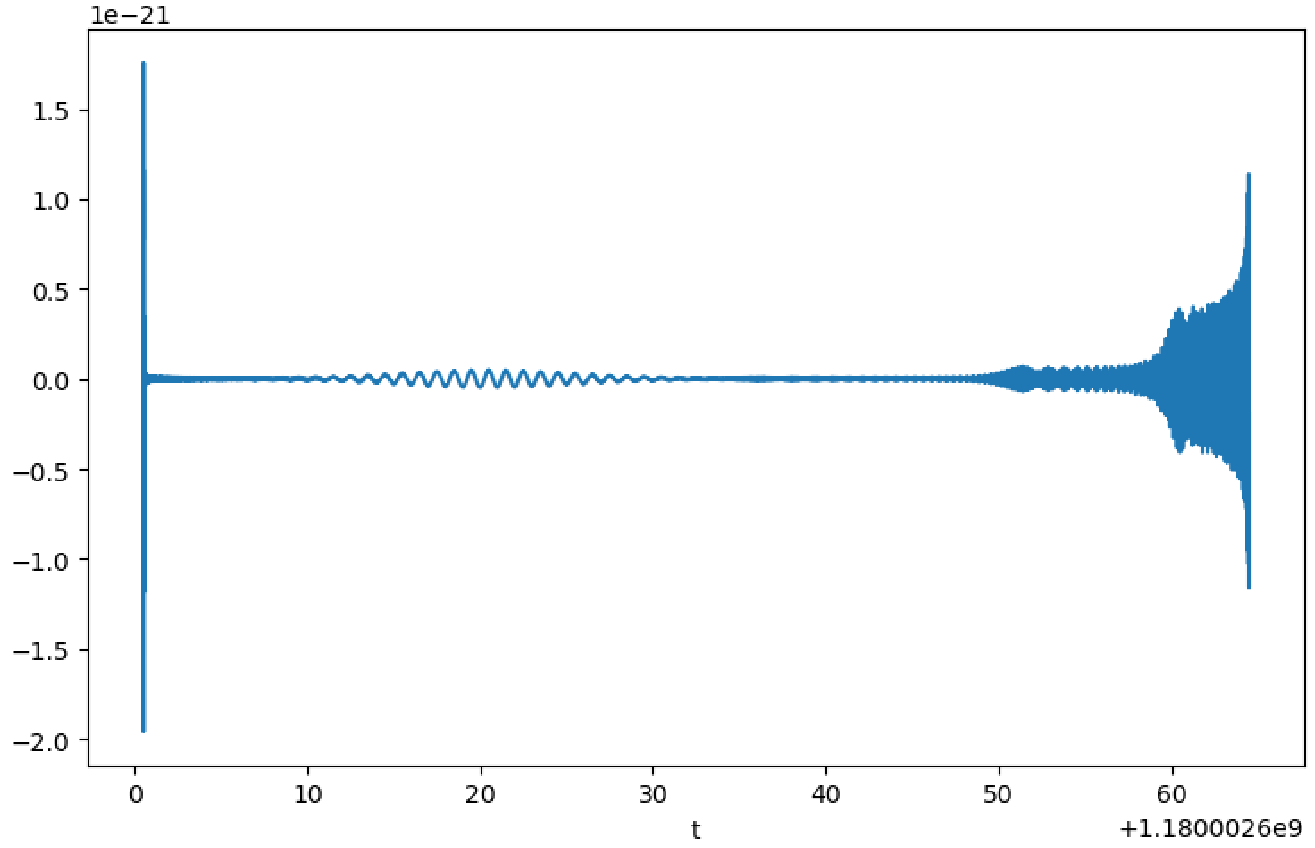
BILBY RUNS: RECOVERY





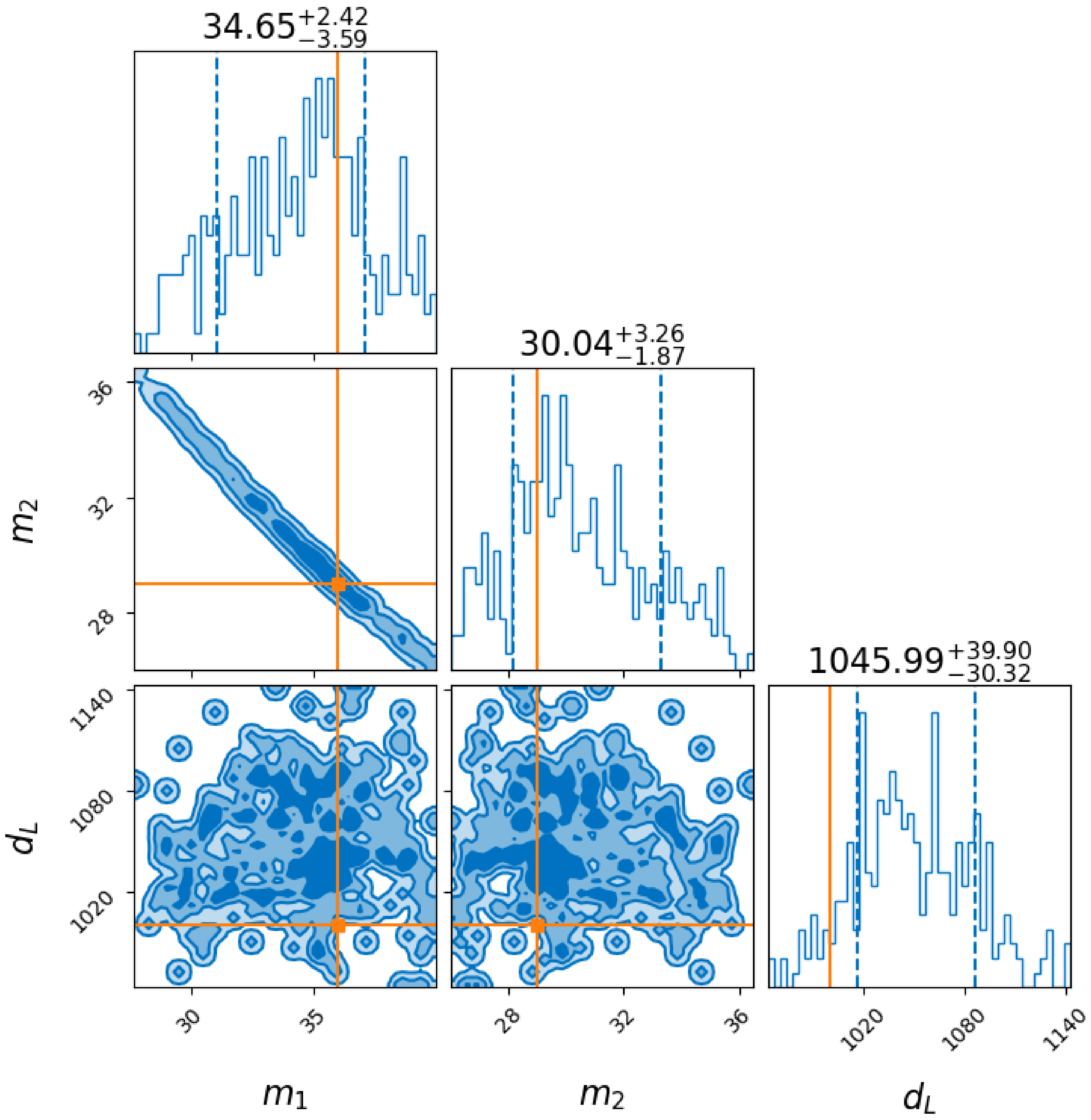
Sampler (Dynesty, ptemcee, …)

Most extrinsic parameters fixed

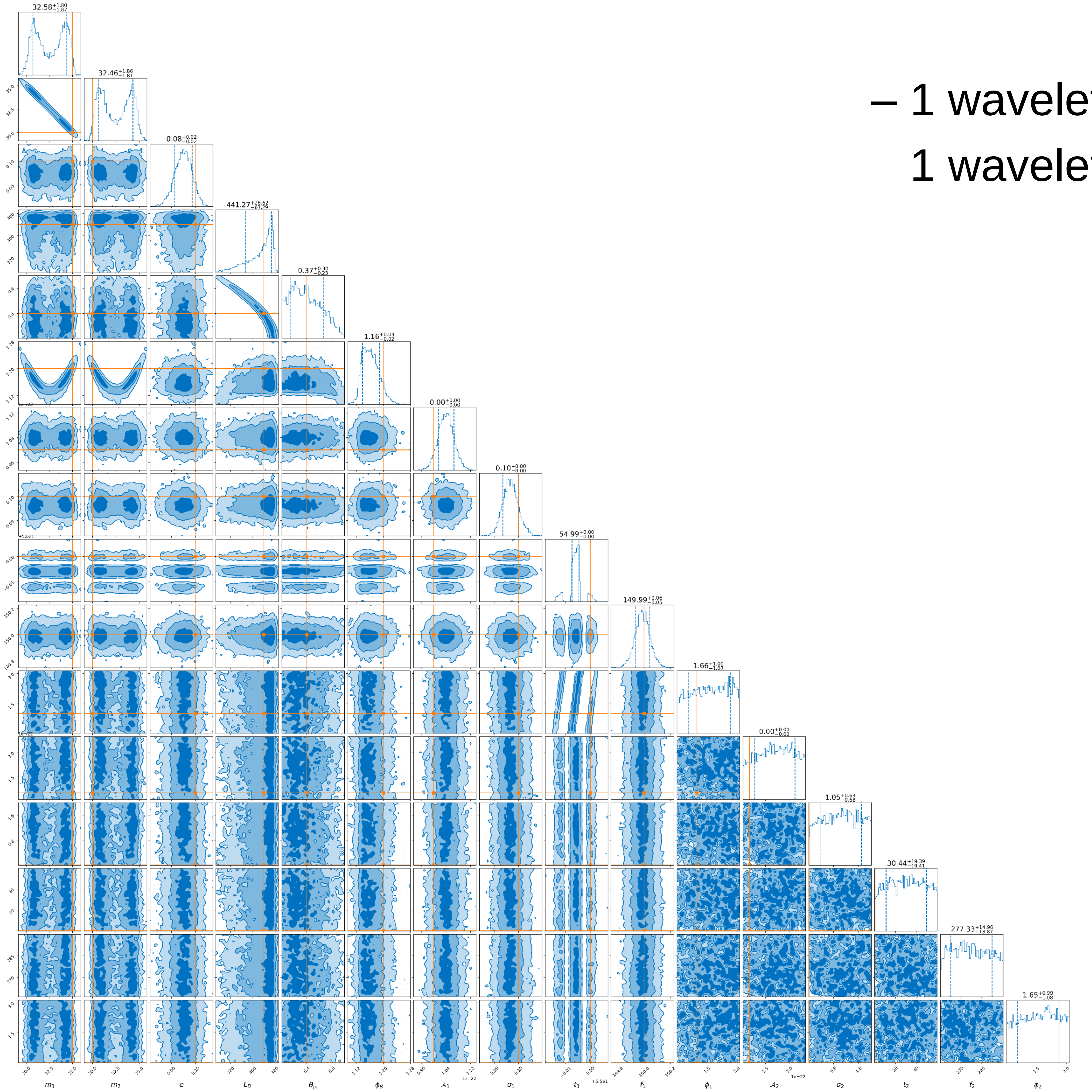
Recovered parameters

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

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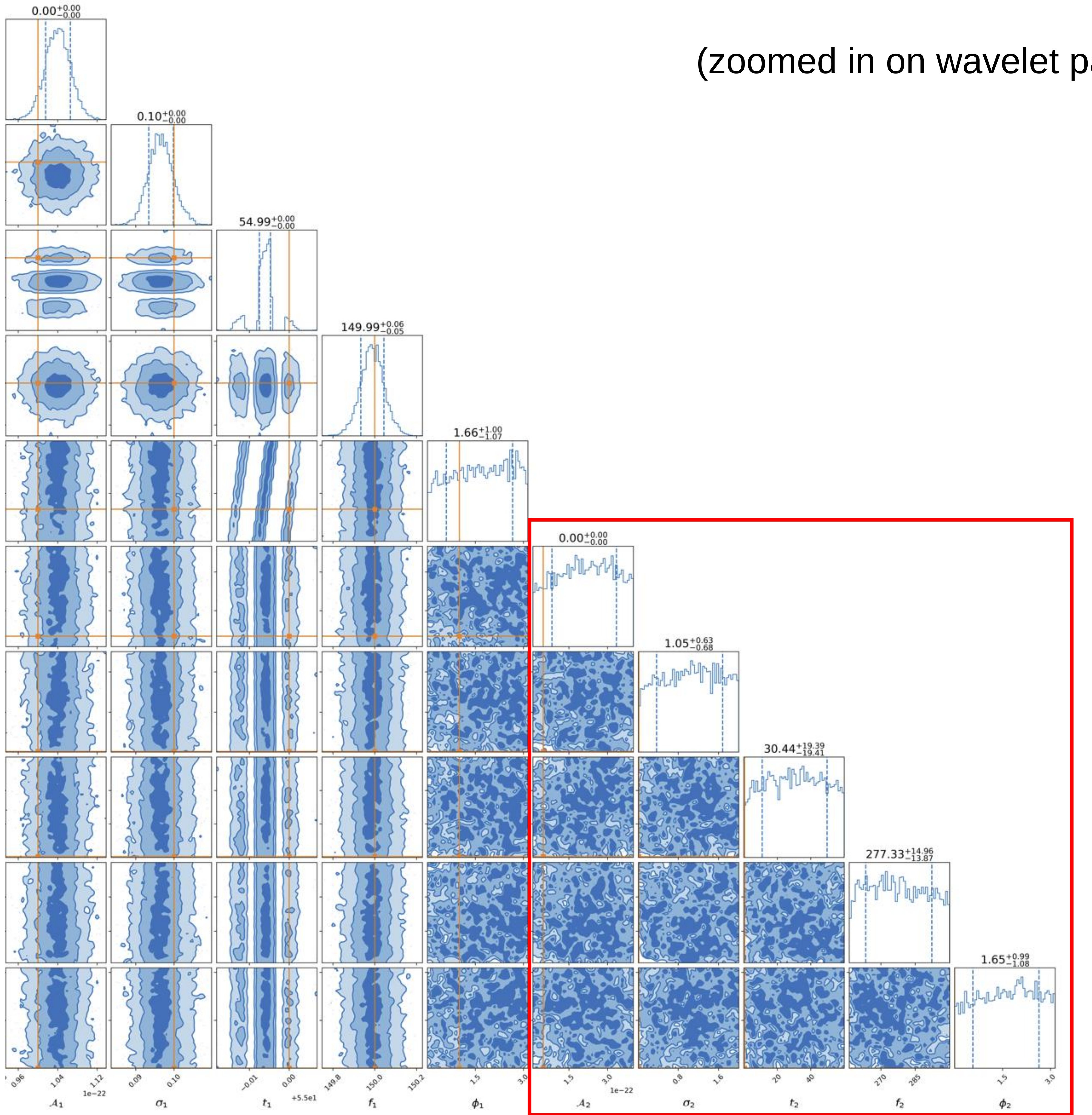
BILBY RESULTS: IMR + DOUBLE WAVELET

(zoomed in on wavelet parameters)



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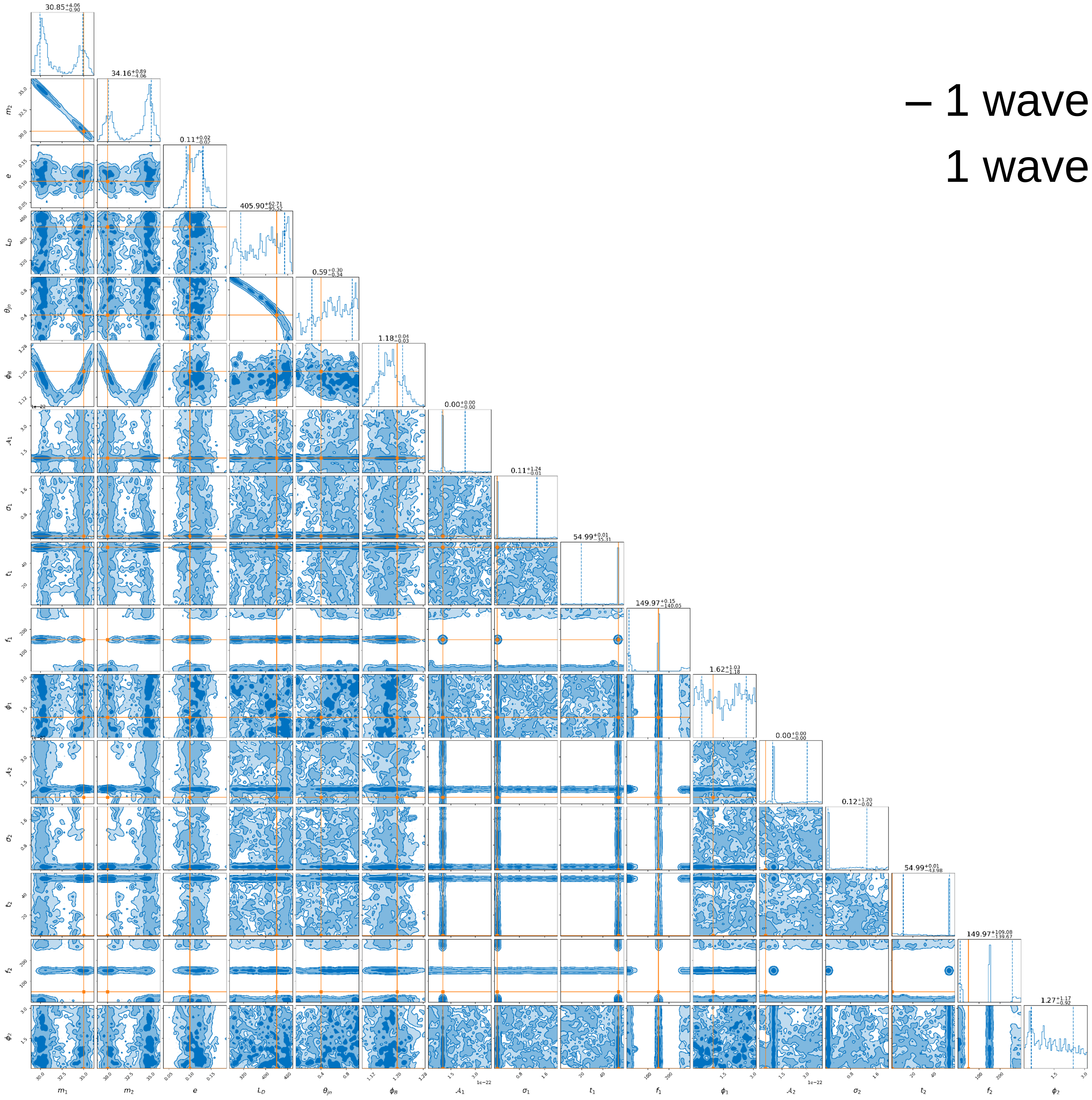
BILBY RESULTS: IMR + DOUBLE WAVELET (PTEMCEE)

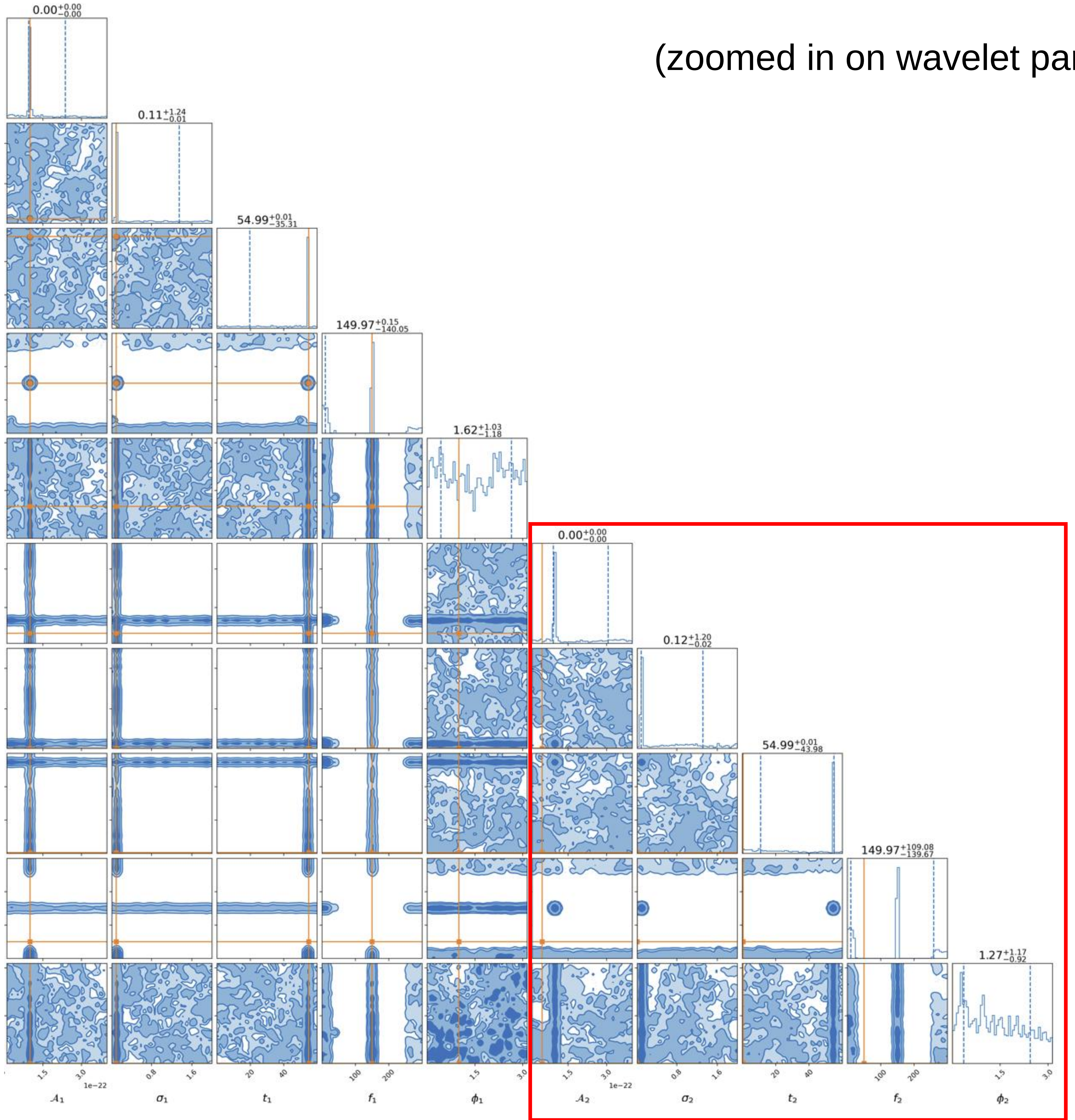


– 1 wavelet in merger

1 wavelet outside

BILBY RESULTS: IMR + DOUBLE WAVELET (PTEMCEE)

(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

Likelihood

Prior

Posterior

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

source: Dynesty documentation

Evidence

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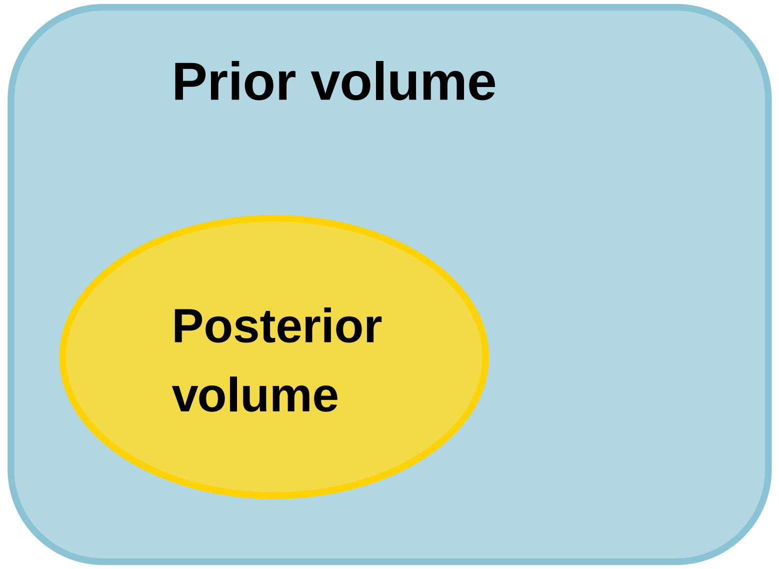
TBILBY

- 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 (weighs model complexity)



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

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

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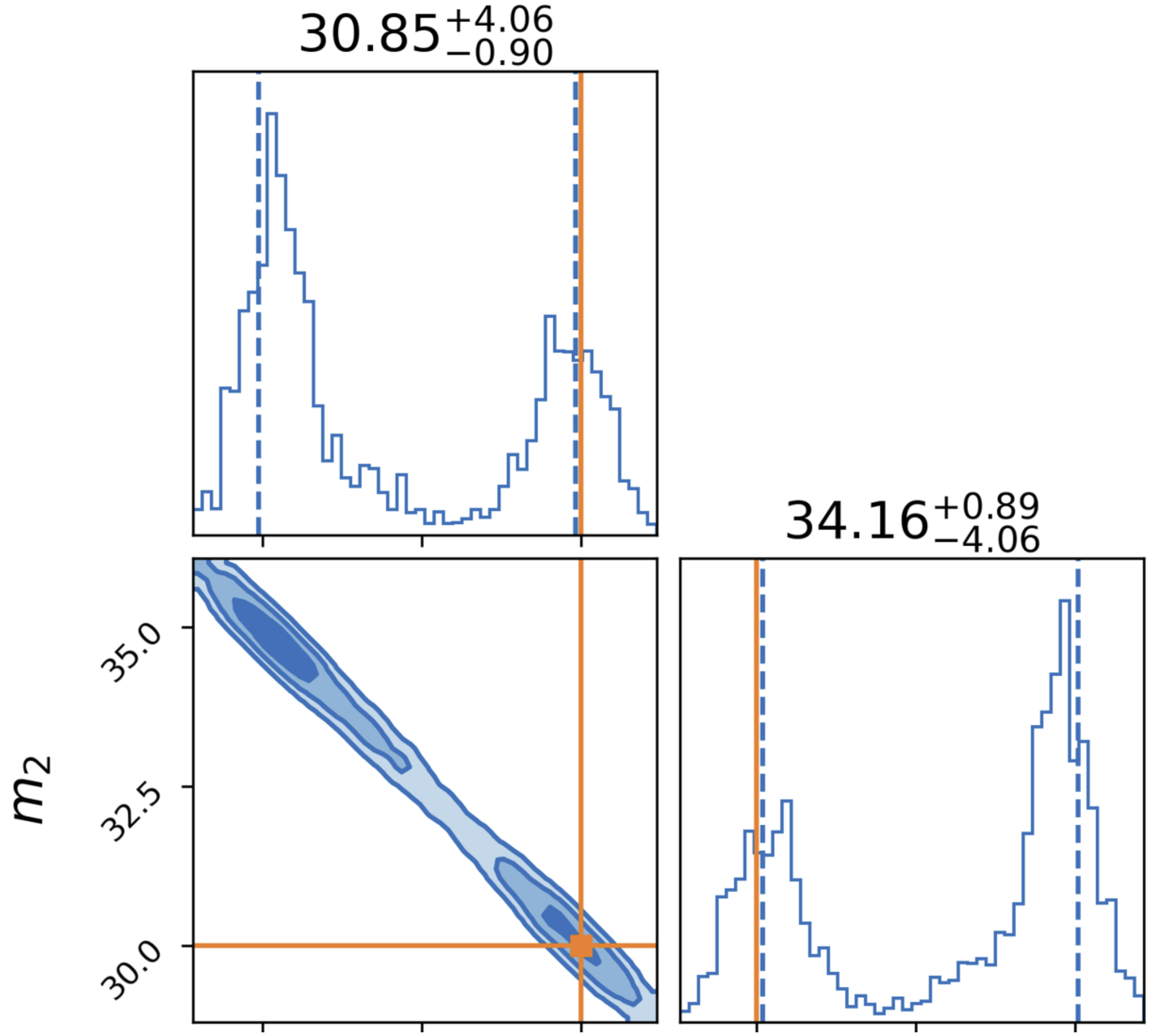
TBILBY

- 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!



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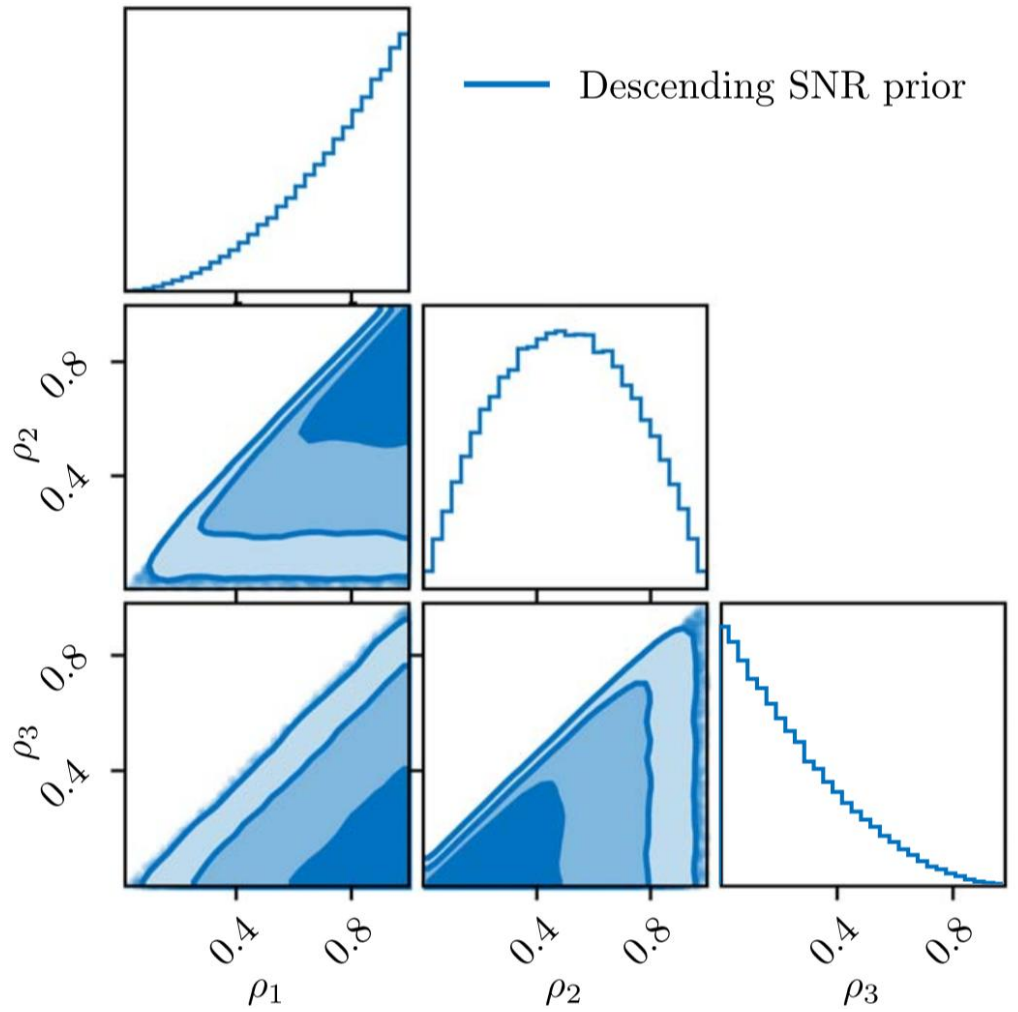
TBILBY: ORDER STATISTICS

- (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



Transdimensional Inference for Gravitational-wave Astronomy with Bilby (2025), Tong H. et. al

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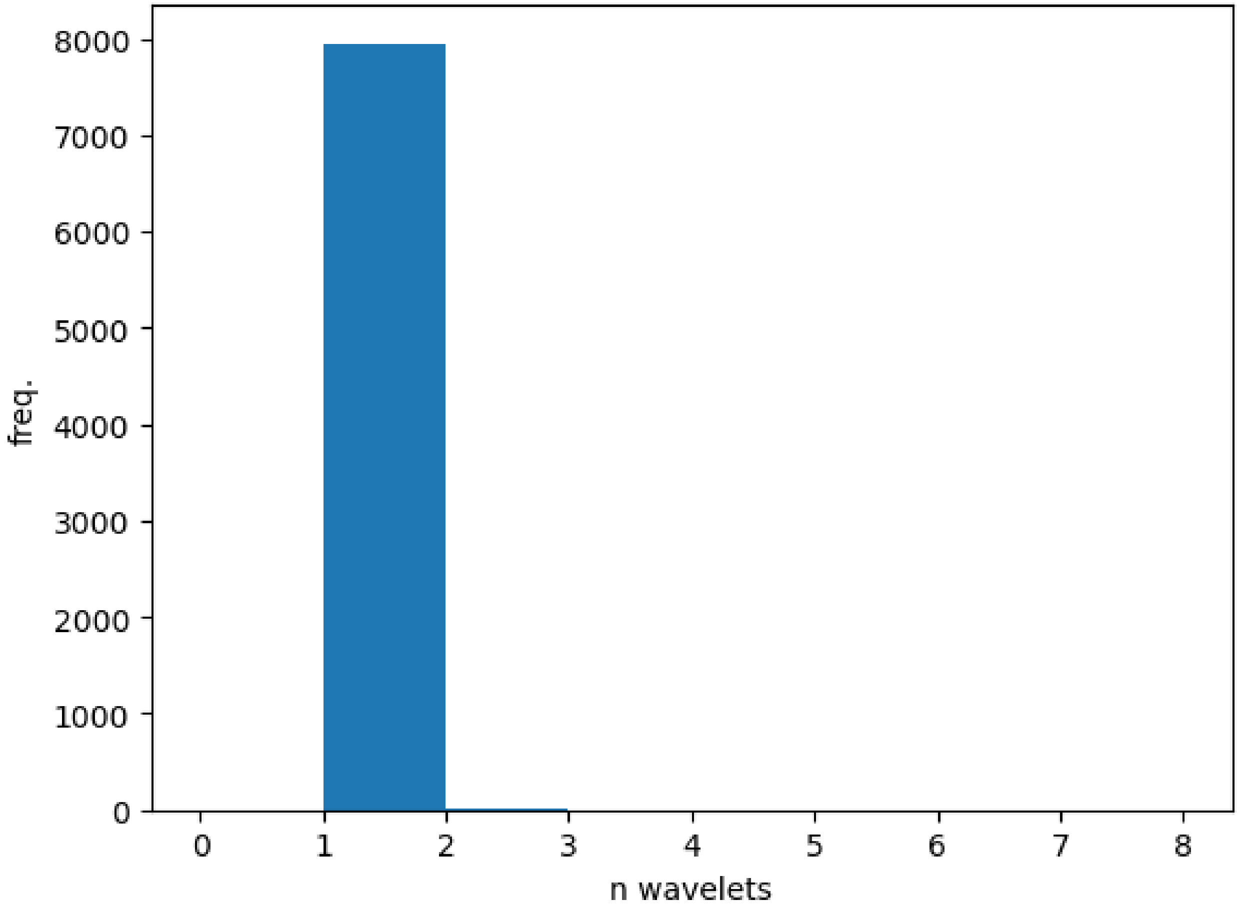
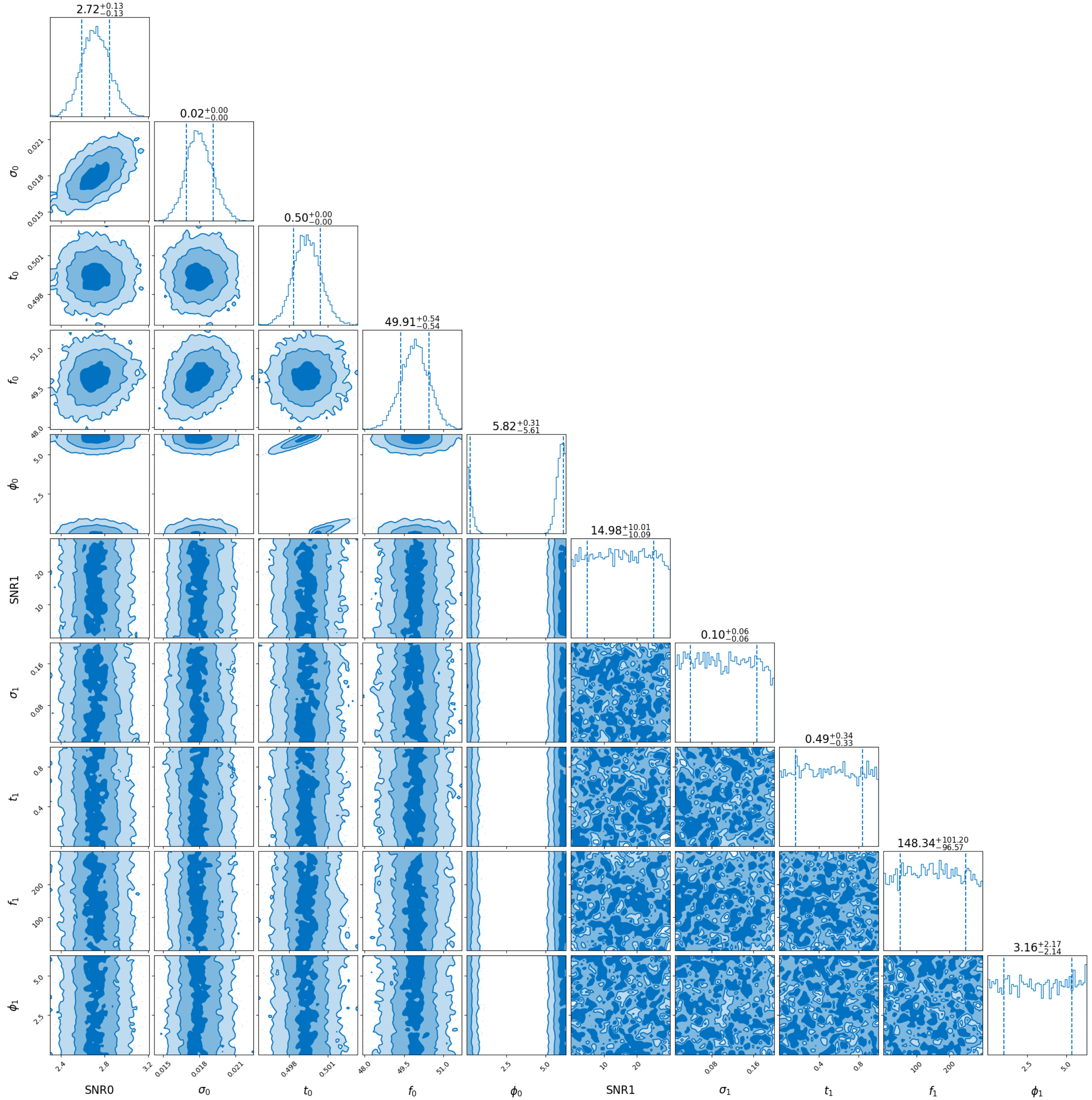
TBILBY RESULTS:

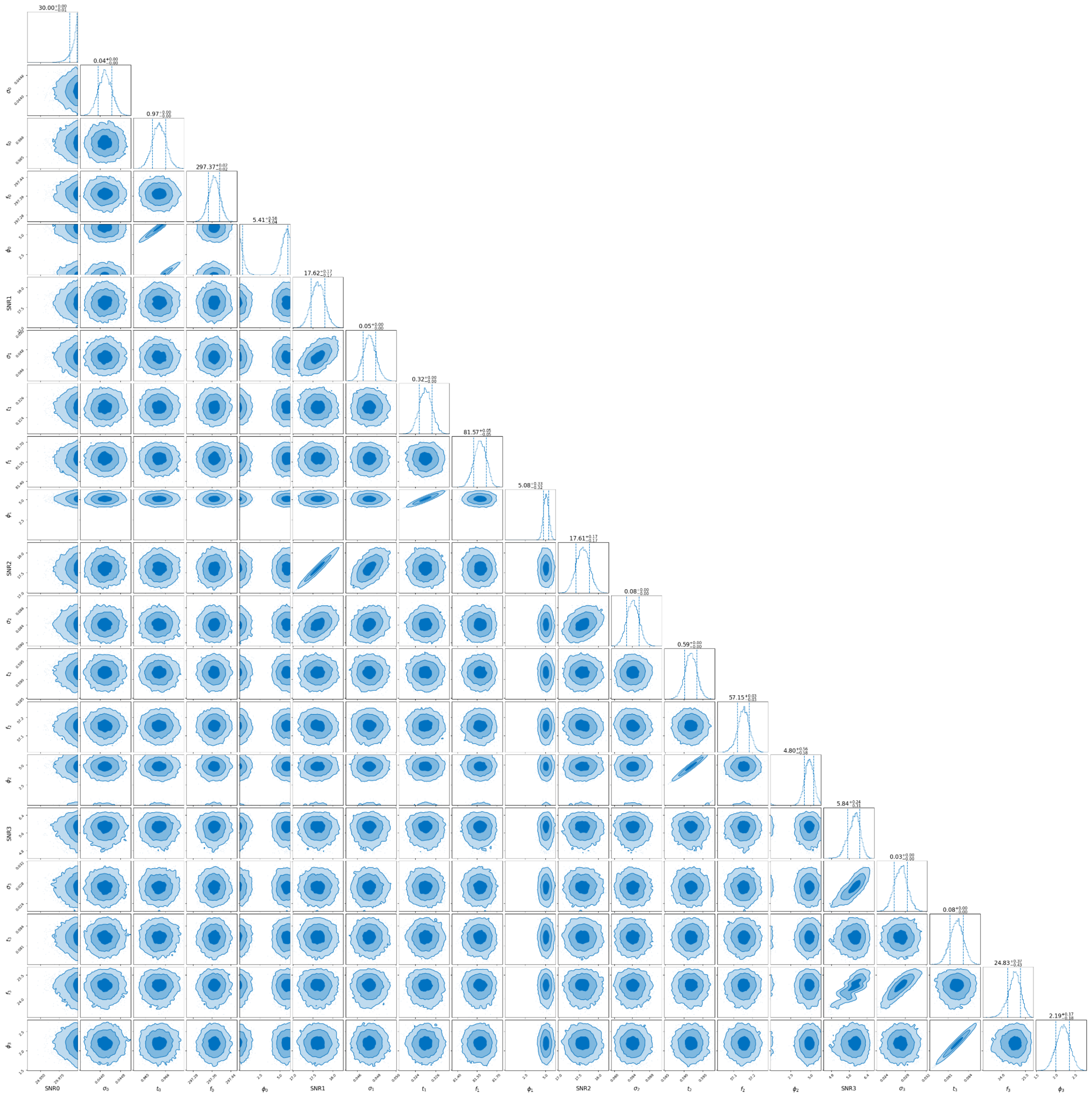
- 2 injected wavelets
- Very strong preference for loudest wavelet
- Same for different runs





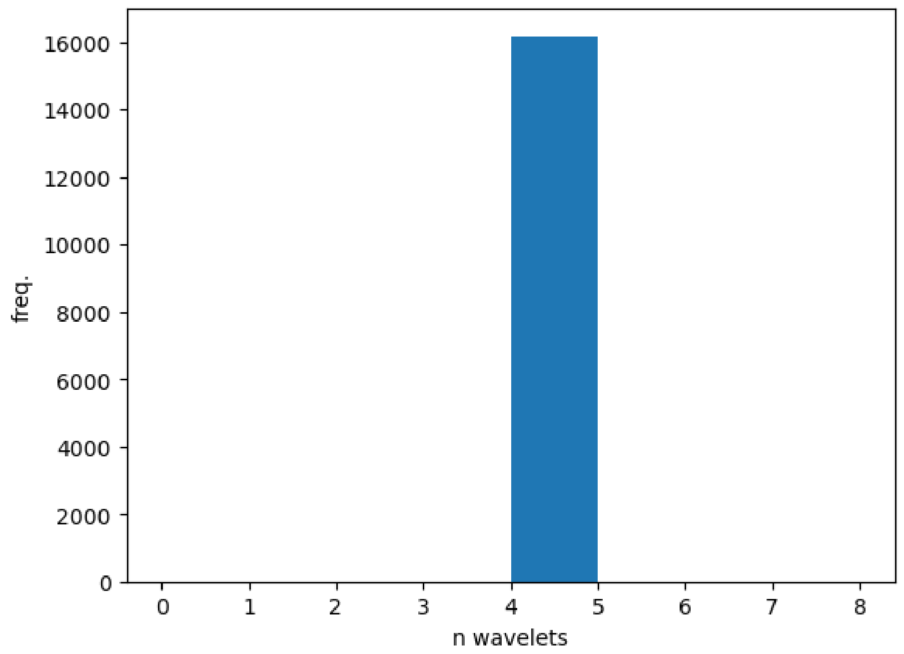
TBILBY RESULTS:

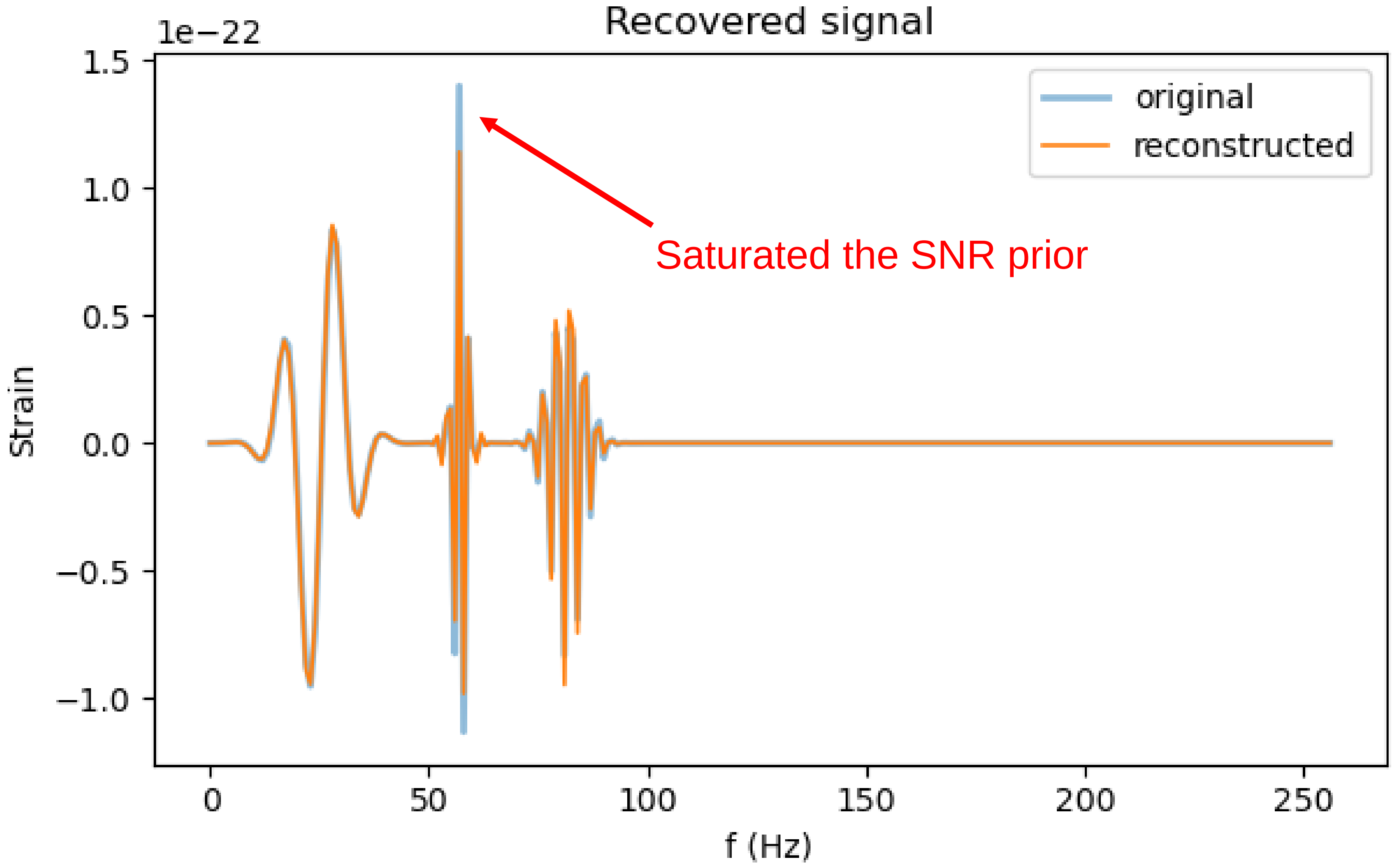
- 4 random wavelets
- Corner plots get very messy

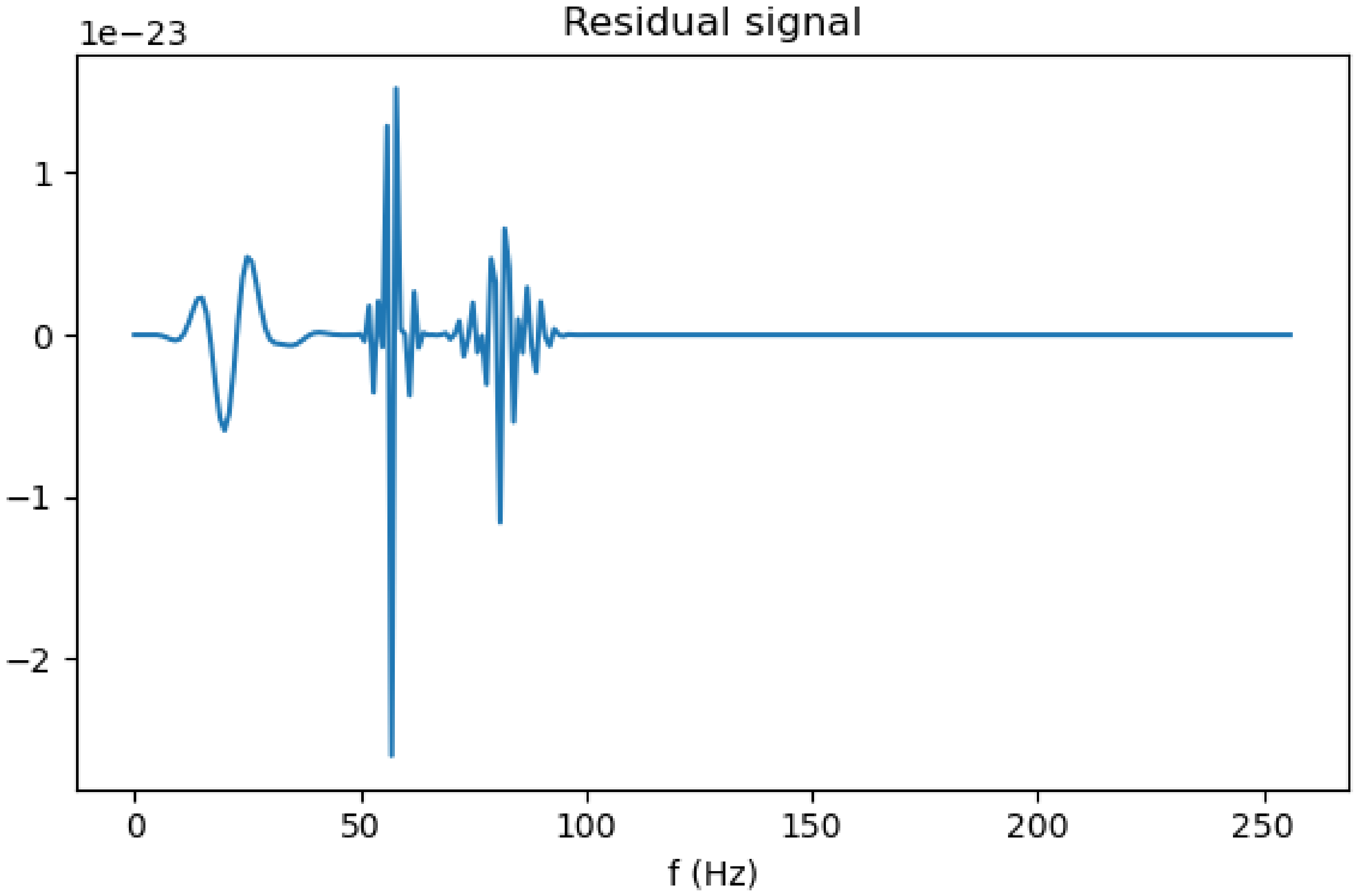


TBILBY RESULTS:

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







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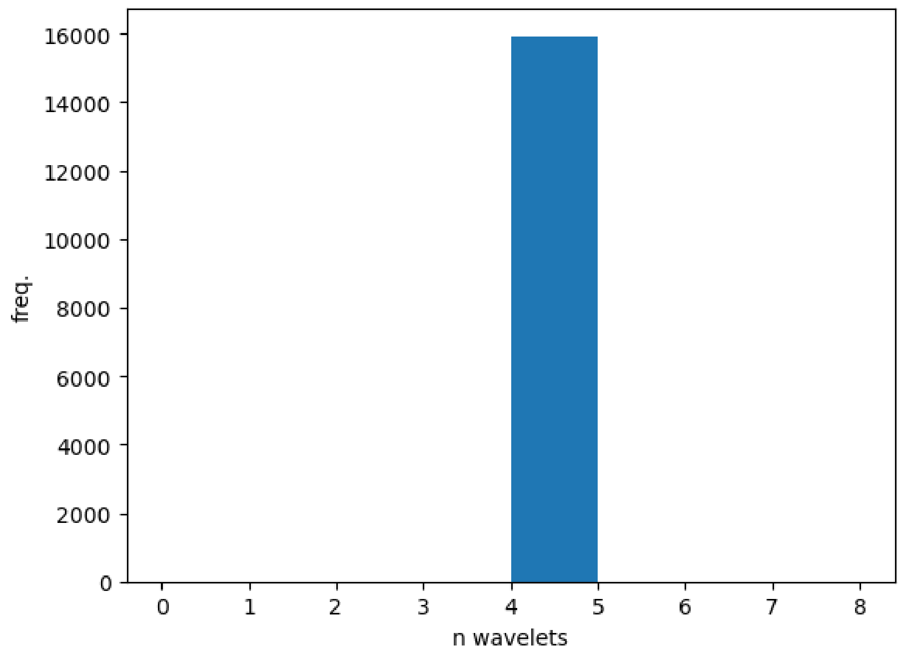
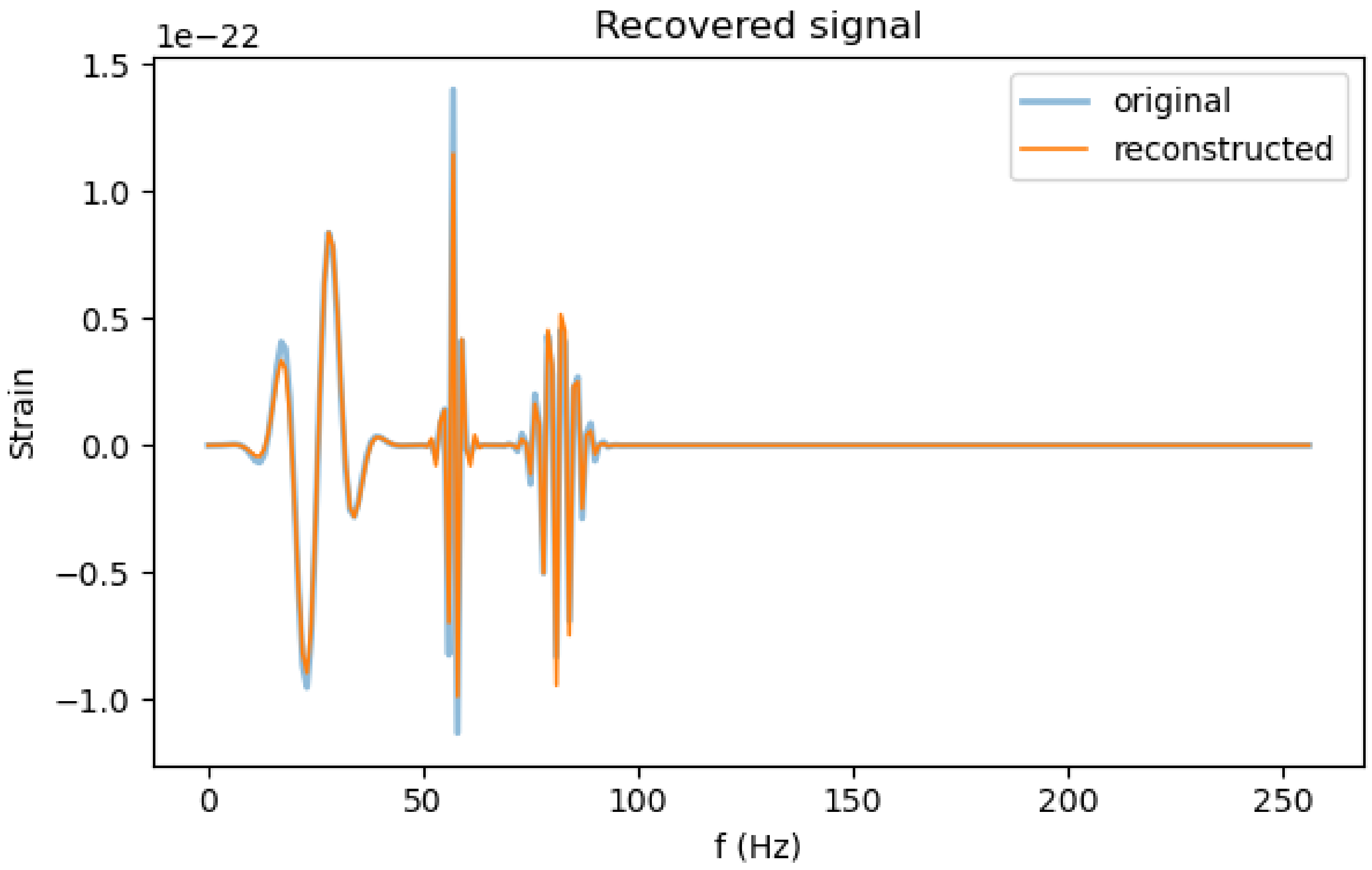
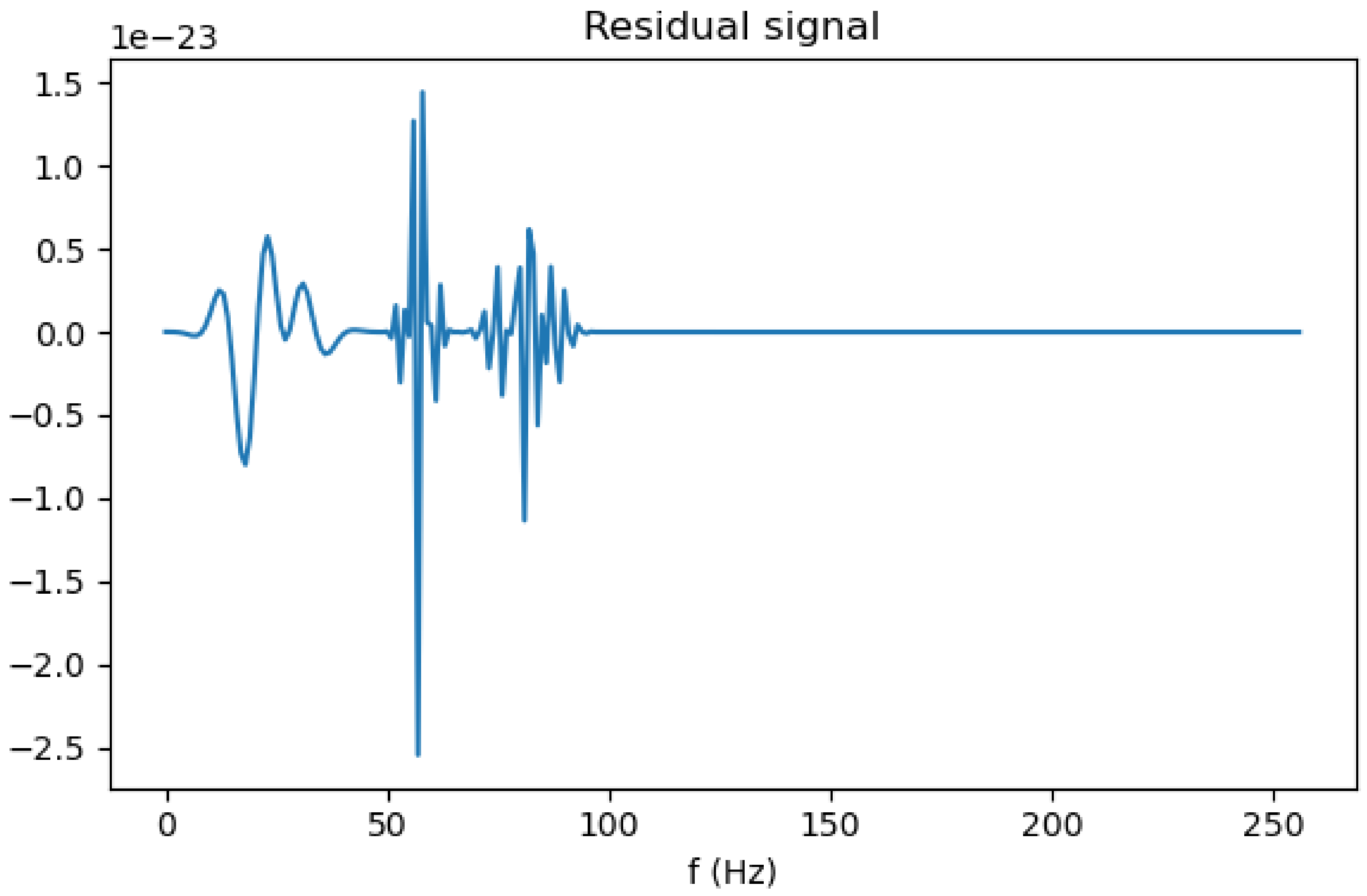
TBILBY RESULTS:

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







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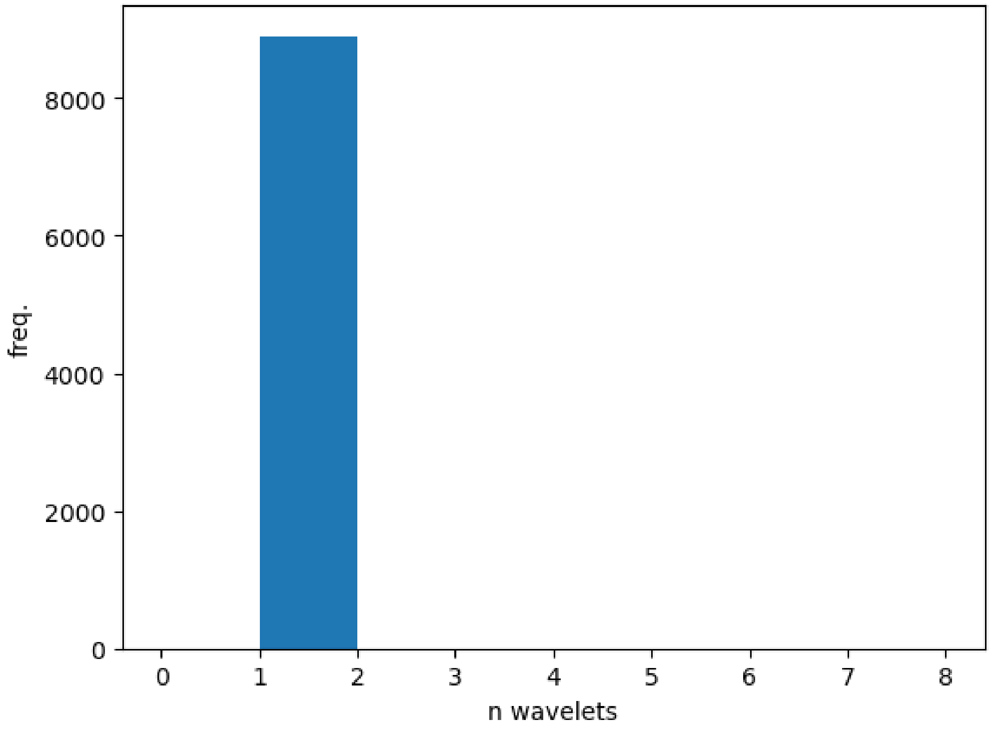
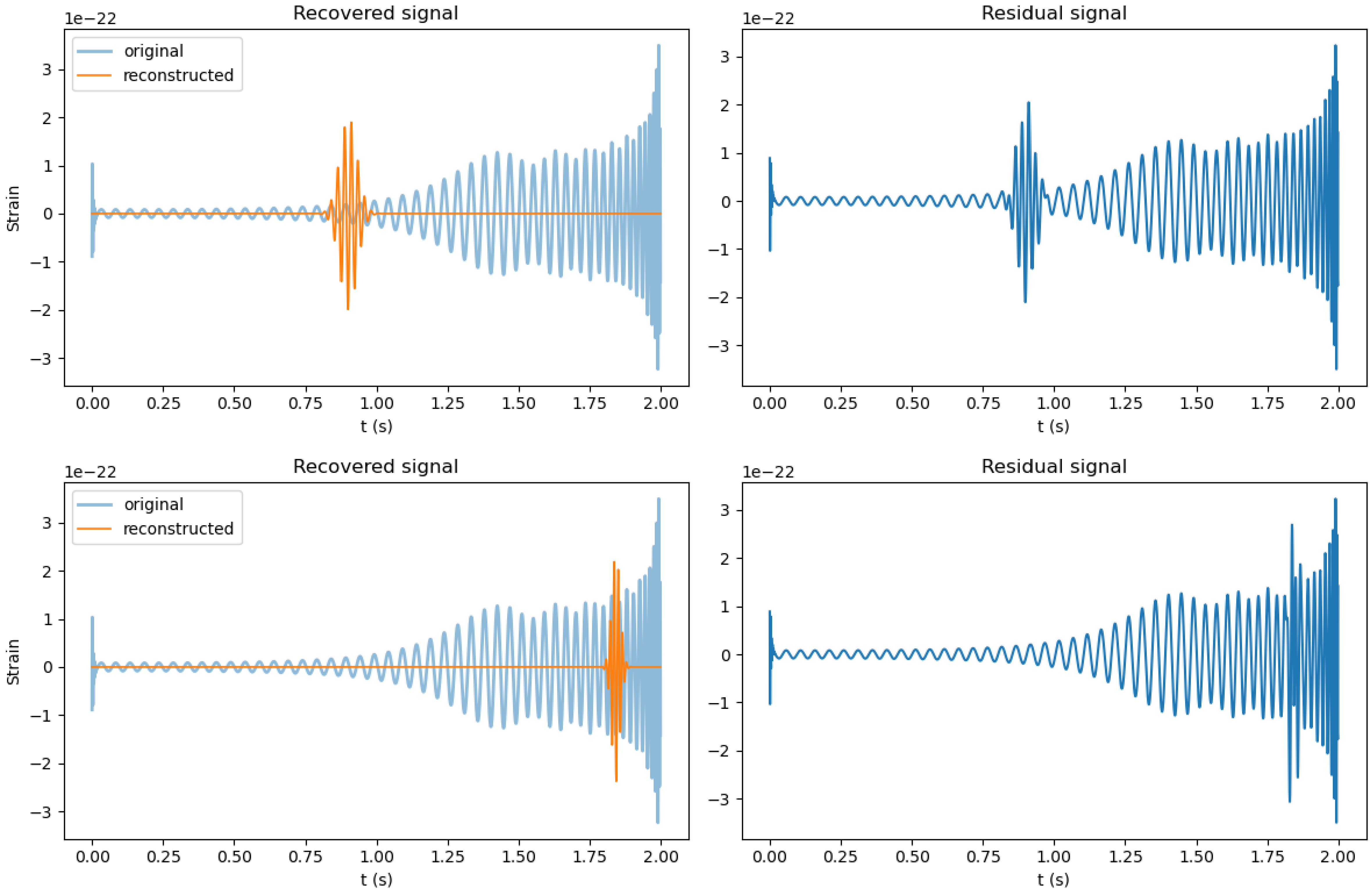
TBILBY RESULTS: BBH

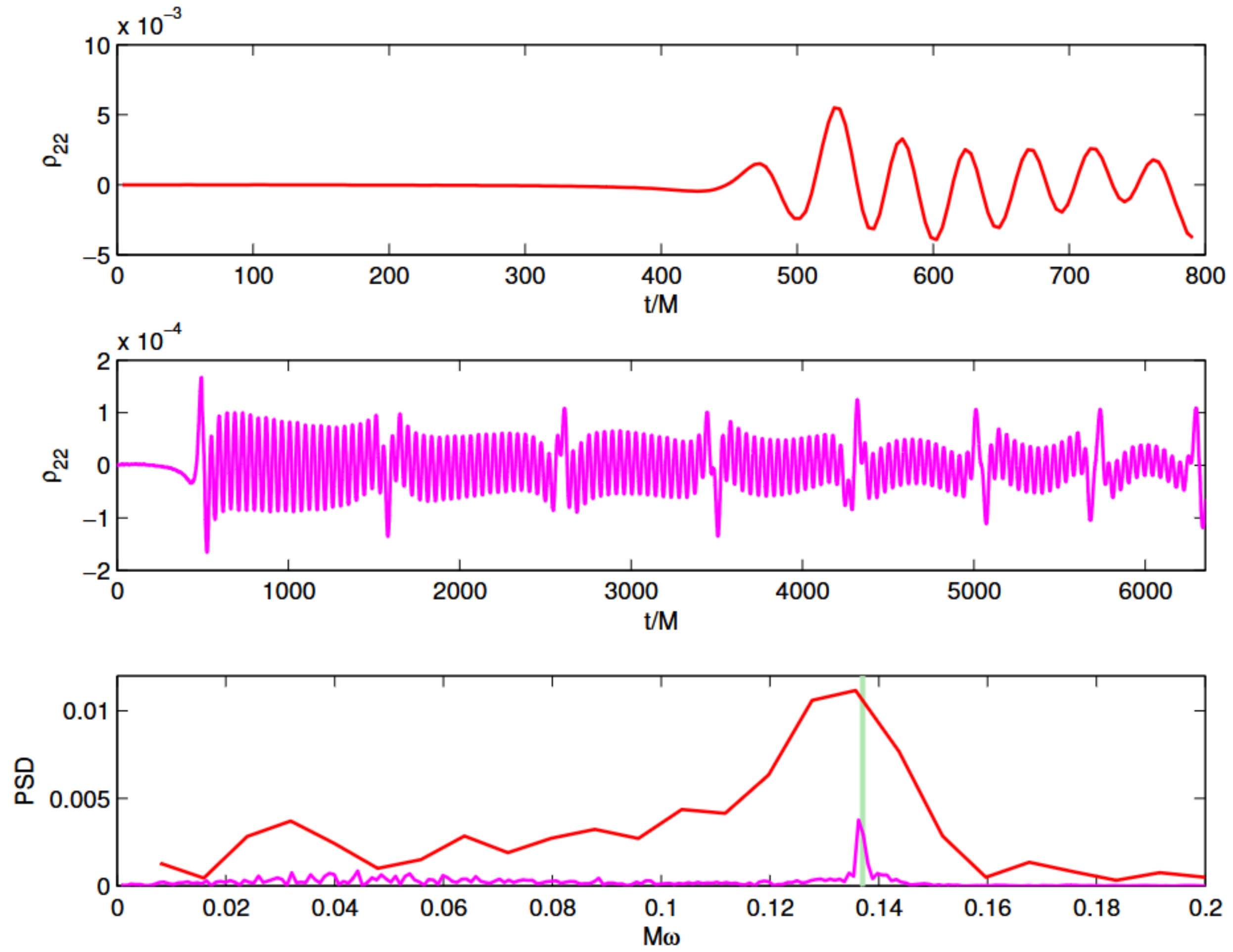
- Nmax = 8
- Only modelled with 1 wavelet each time





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

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NEXT STEPS

- See what tBilby authors have to say about my patch
  - Perhaps I broke the code
- Modify sampling parameters
  - $\sigma \to Q$ (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
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