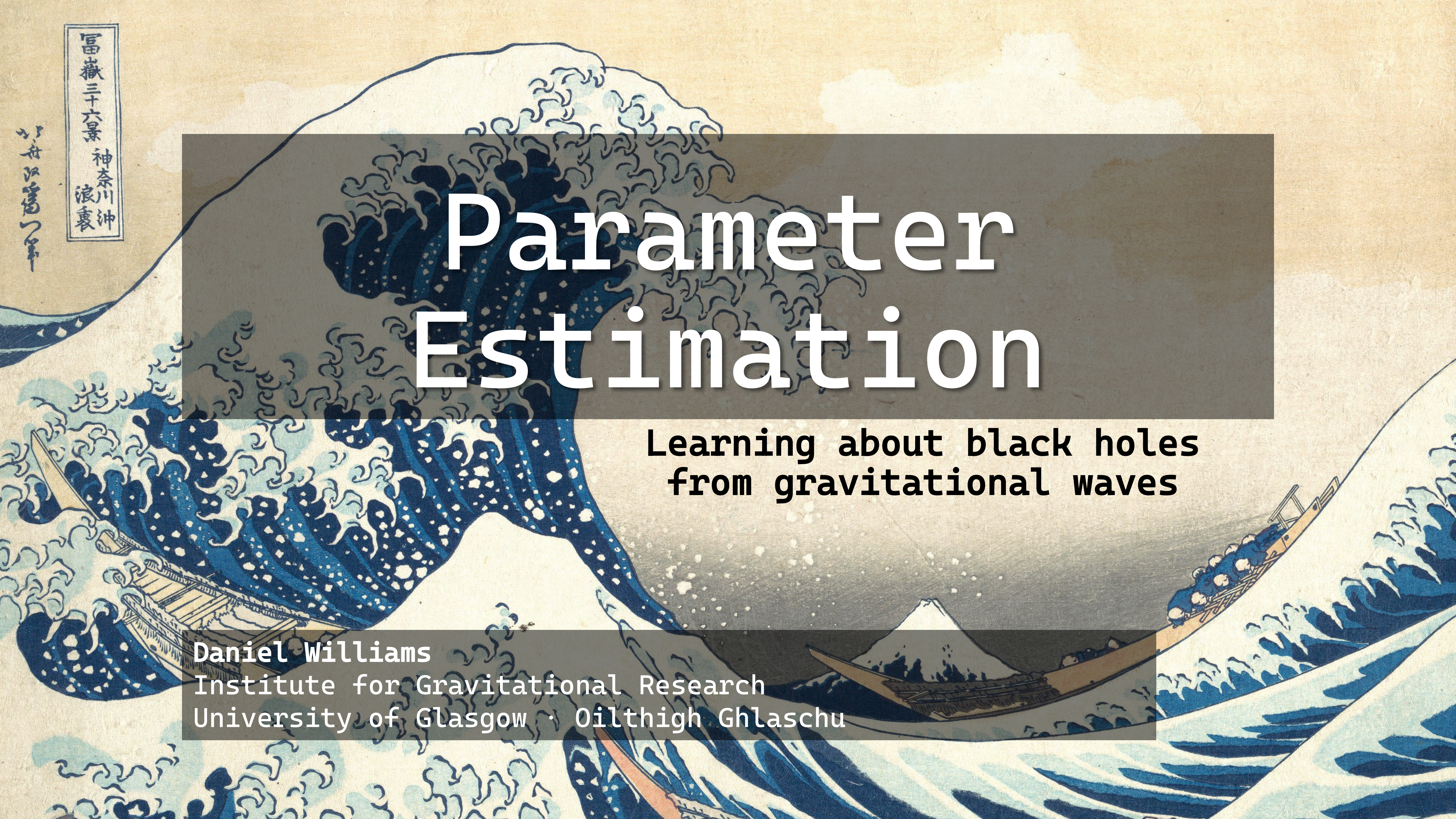


Parameter Estimation

Learning about black holes from gravitational waves

Daniel Williams
Institute for Gravitational Research
University of Glasgow · Oilthigh Ghlaschu

$ whoami

Postdoc in Institute for Gravitational Research at University of Glasgow

Research focused on compact binary coalescences, but worked on unmodelled sources in the past

I led the O3a, O3b, and O4a Parameter Estimation analyses for the LVK

What is parameter estimation?

From wave to black hole properties

Parameter estimation is the analysis which works out what sort of black holes or neutron stars produced a signal which we've identified in a GW detector.

Foundational analysis

Most of the scientific information we extract from GW observations relies on understanding the systems which produce these signals, so parameter estimation acts as the foundation for many other analyses.

What is parameter estimation?

Isn't this what searches are for?

GW searches scour all of the data produced by a detector looking for signals.

They provide a rough guess of the properties of the signal.

In-depth

PE analyses are much more detailed, but only performed over a very small amount of data overall.

We get much more detailed information about the system, and an understanding of the uncertainties from the analysis.

This talk

Bayesian statistics 101

why are all our answers probability distributions?

How the LVK perform PE analyses

Accessing and using samples from the LVK and friends

: ł ī Ð♂δł ╔╜l♂ʼnł ʼnδ ♂ʼnδČ♂

A whistle-stop tour

Bayesian Inference

posterior

likelihood

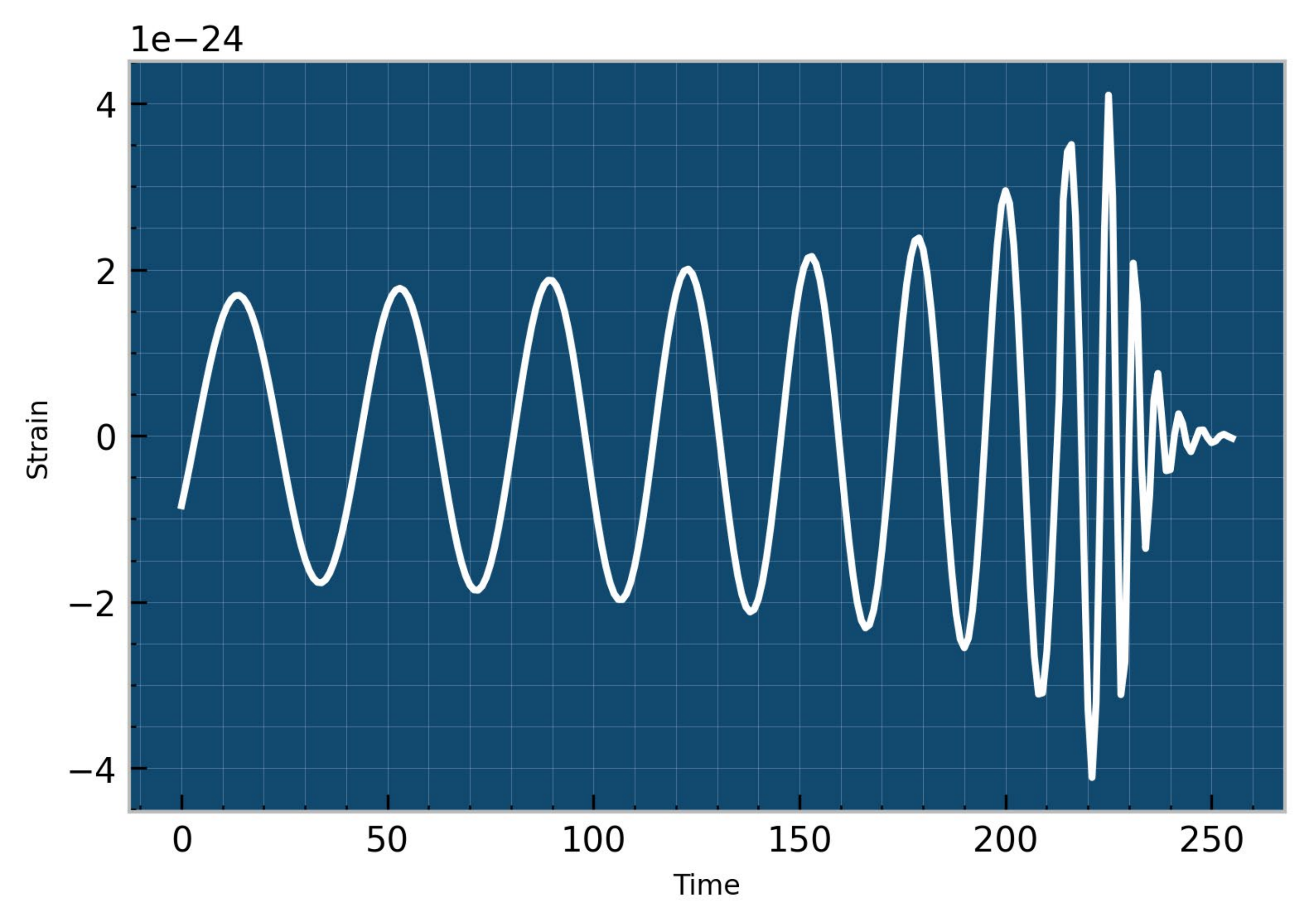
prior

p(parameters | data) ∝ p(data | parameters) p(parameters)

Bayesian parameter estimation

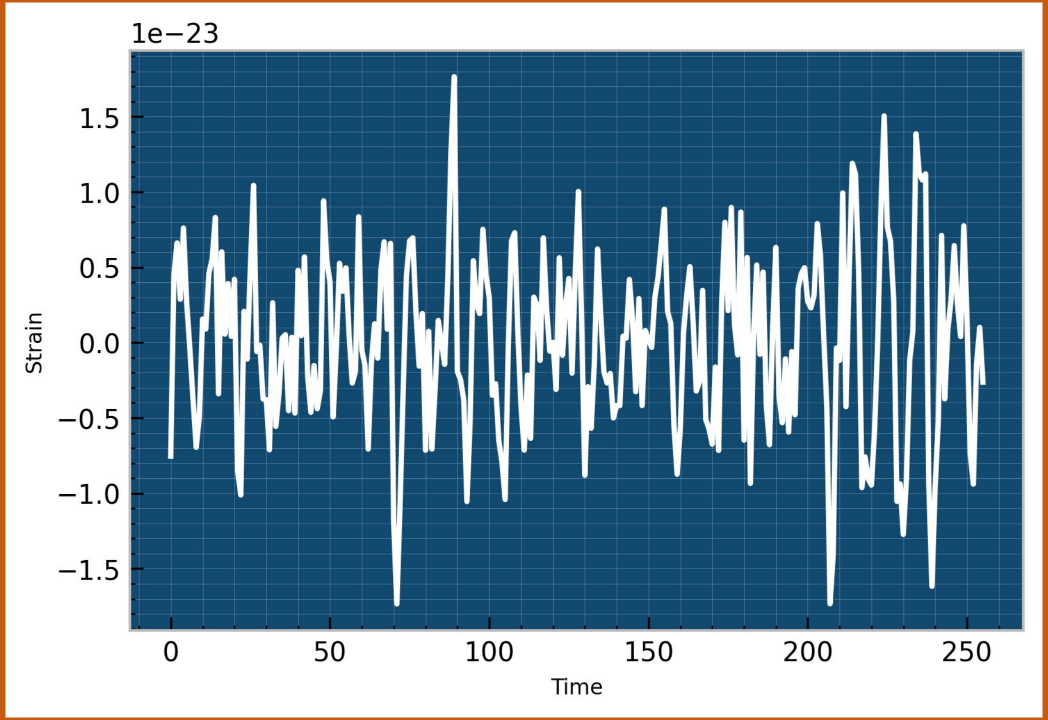
- Once we’ve detected a gravitational wave we want to work backwards to understand the properties of the astrophysical system which created it
- Data from current GW detectors are **extremely** noisy
- Rely on ***matched filtering***

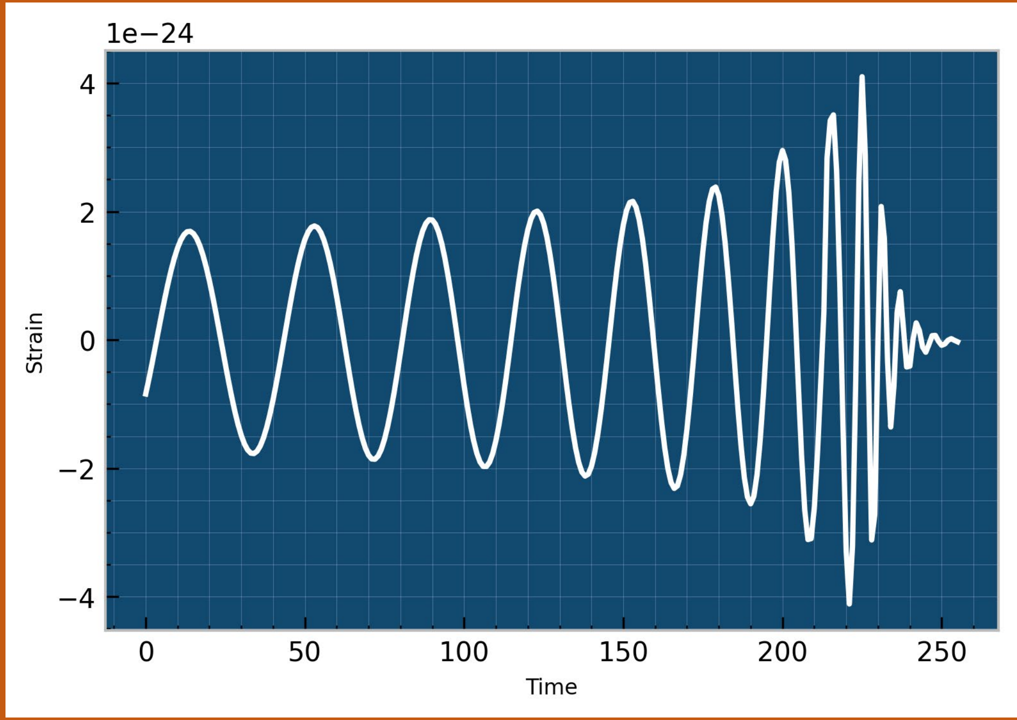
Bayesian Inference



Parameters

- Black hole masses
- Distance
- Position on sky
- Black hole spin


1e−23
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Strain
0
50
100
150
200
250
Time


1e−24
4
2
0
−2
−4
Strain
0
50
100
150
200
250
Time

Conventional Parameter Estimation

1. Evaluate waveform model
   - Based on “real” physics (General Relativity) but for speed we need to use an approximation
2. Cross-correlate with data
   - “Noise-weighted inner product”
3. Calculate likelihood of the signal wrt the waveform model
4. Multiply likelihood by the prior probability of the waveform model
5. Repeat (a lot)

Bayesian Inference

posterior

likelihood

prior

p(parameters | data) ∝ p(data | parameters) p(parameters)

Sampled using stochastic sampling methods

Markov Chain Monte Carlo

pymc pyro emcee

Nested Sampling

dynesty nestle nessai

Bayesian Inference

posterior

likelihood

prior

p(parameters | data) ∝ p(data | parameters) p(parameters)

Posterior probability distribution samples ←

Sampled using stochastic sampling methods

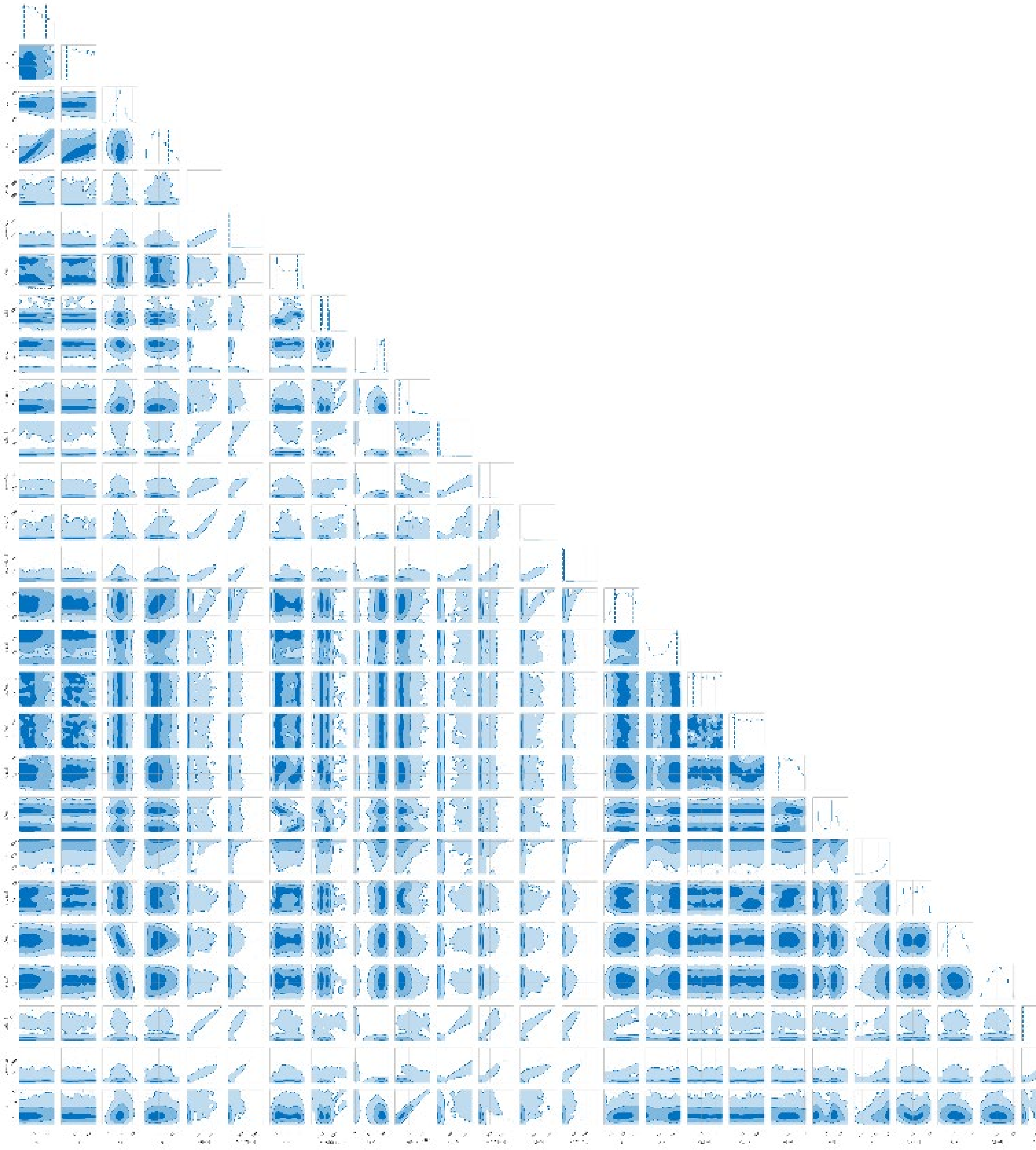
Markov Chain Monte Carlo

pymc pyro emcee

Nested Sampling

dynesty nestle nessai

Bayesian Inference

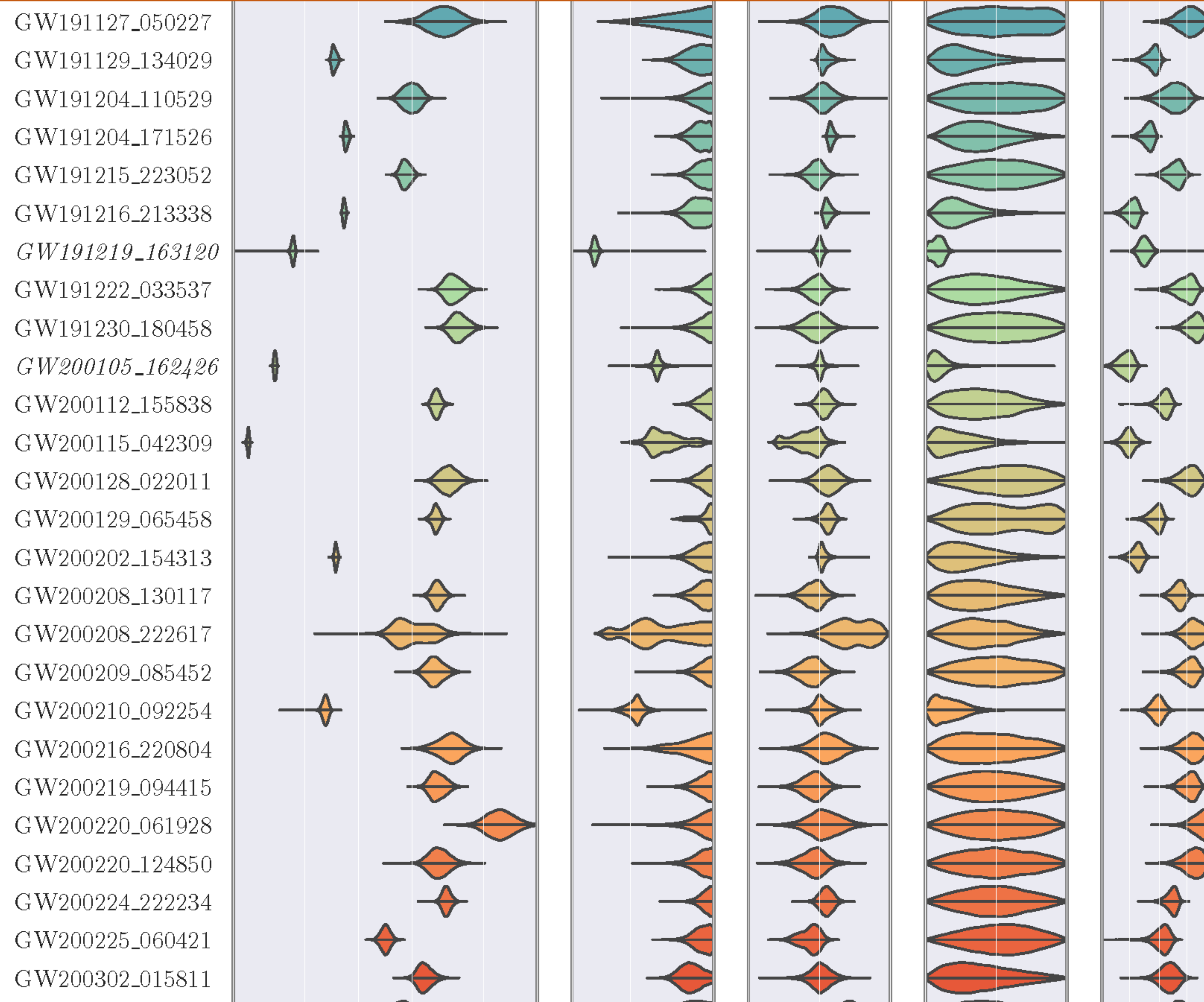


GW Analysis

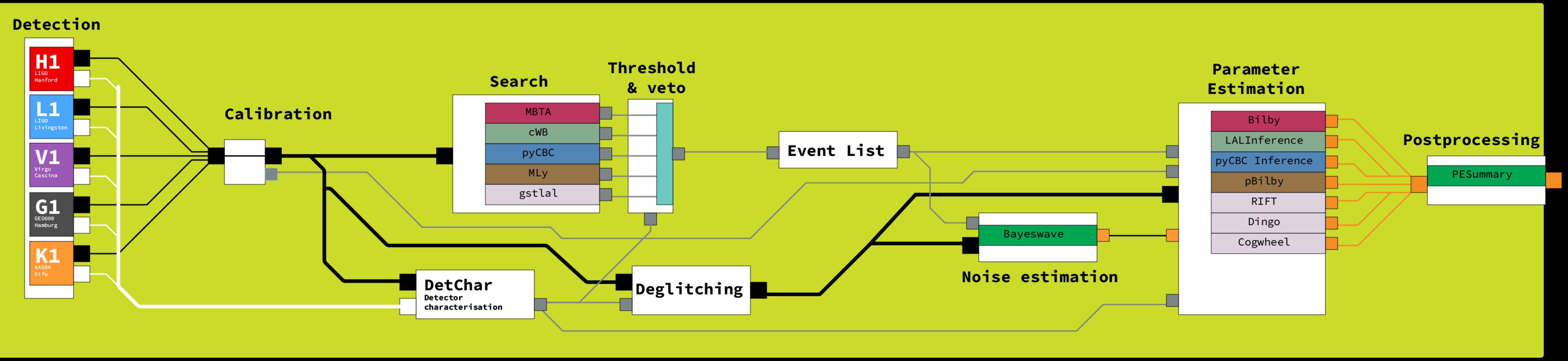
From raw observations to inferring source properties

Right: O3B event properties

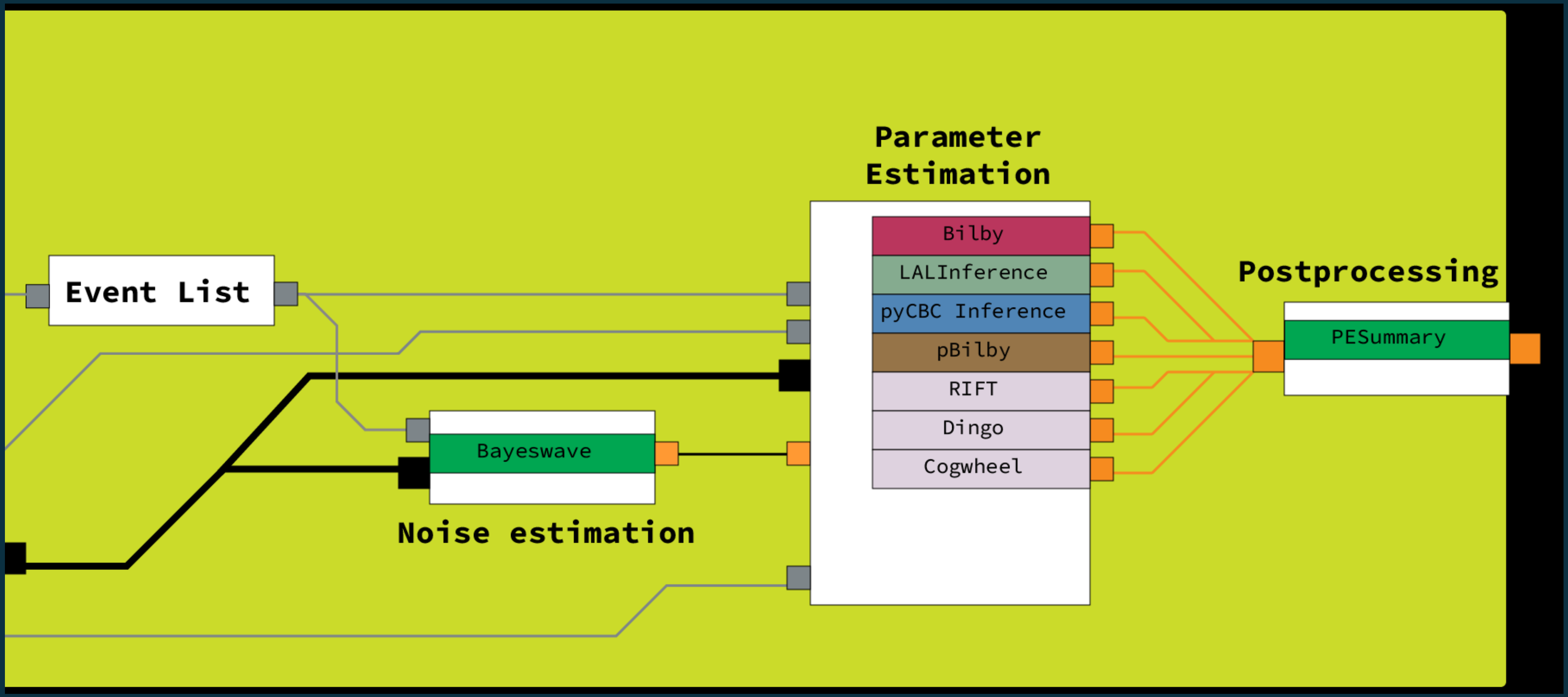
arxiv: 2111.03606



Anatomy of a LIGO analysis



A LIGO Analysis – PE



Multiple analyses per event

Multiple analysis codes

Bayeswave

This code is used to analyse the noise component of our data.

It produces Power spectral density estimates.

These are an essential component of the likelihood function.

Bilby

One of the main analysis codes used by the LVK is bilby.

Designed to be a flexible and easy-to-use package for analysis.

Written in python.

PESummary

This code handles post-processing of our data

It can be used to produce summary plots of the data

It also calculates derived parameters (ones which can be calculated from combinations of measured parameters).

Using our data

The LVK publish samples from probability distributions created by our analyses.

These are available via GWOSC, and are archived on Zenodo.

e.g. GWTC-3.0 which contains analysis from O3b:

https://zenodo.org/records/8177023

Using our data

Samples are distributed in HDF5 format and created with a structure defined by the PESummary tool.

Posterior samples are contained within this alongside prior samples and configuration data for the analysis.

Thank you!

daniel.williams@glasgow.ac.uk

🦋: @daniel-williams.co.uk