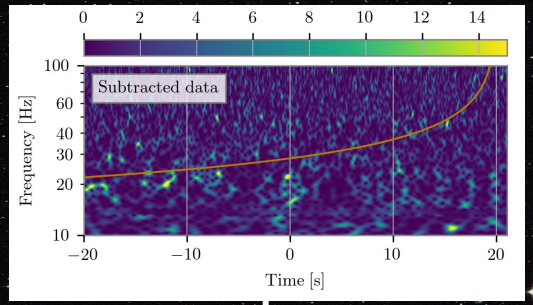
GWTC-3: Parameter Estimation Formalism & Results

José Francisco Nuño Siles

12th Iberian Gravitational Wave Meeting

Putting Parameter Estimation into context

Search pipelines (MBTA, GstLAL, PyCBC…) & IDQ



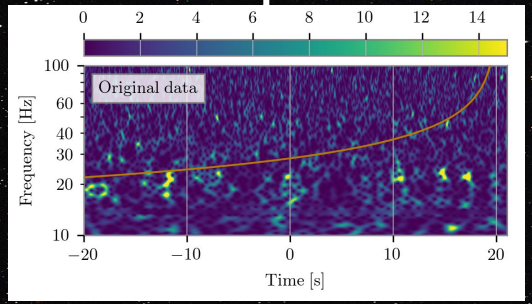
LALInference, Bilby & RIFT

(Offline) Candidate identification & validation

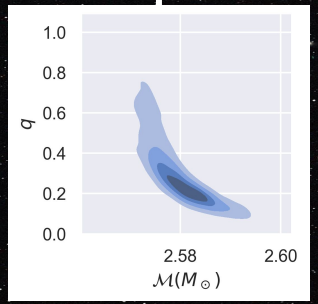
Noise & glitch removal

Parameter estimation

Population, Testing GR …

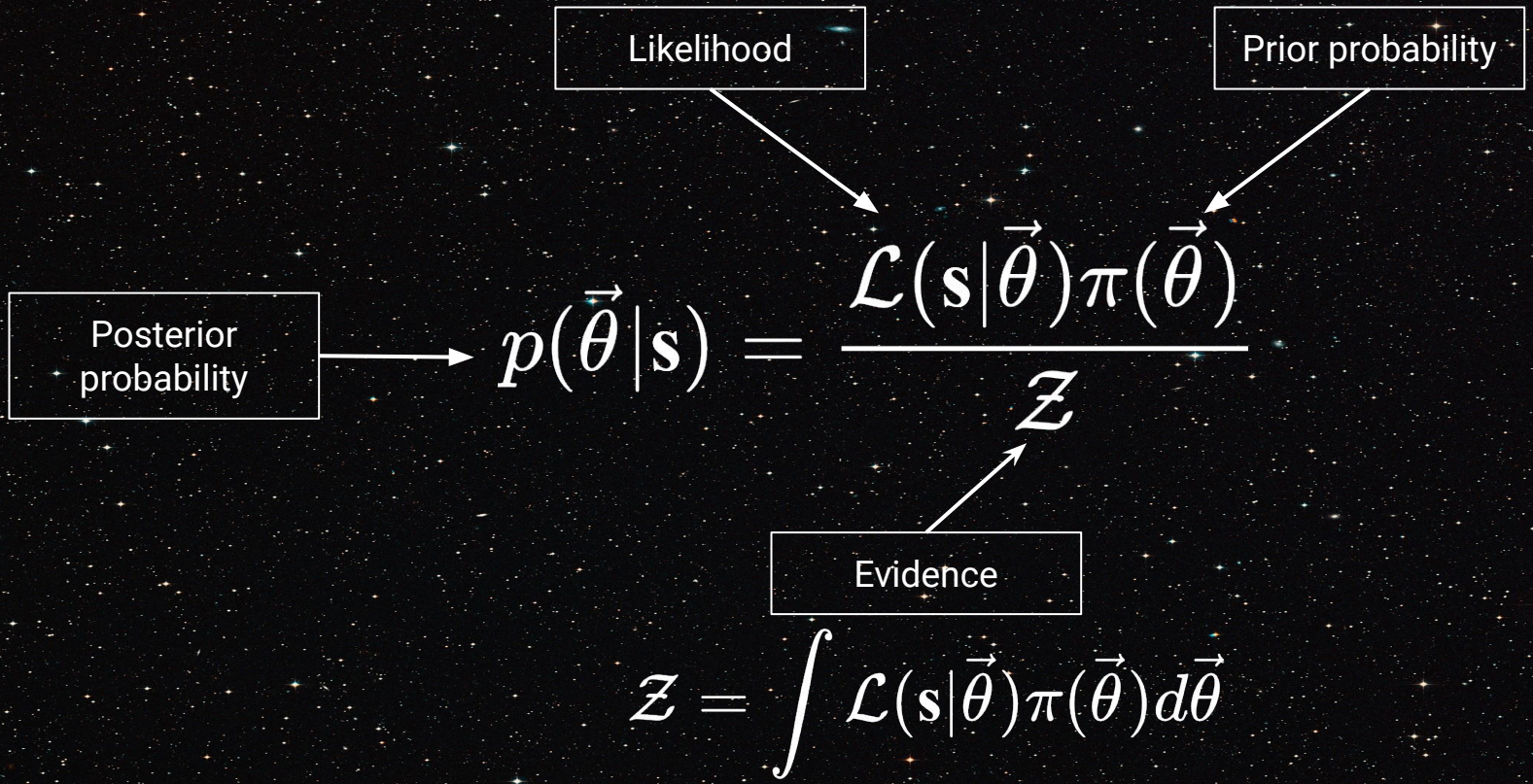


BayesWave



Parameter Estimation in LVK: The Framework

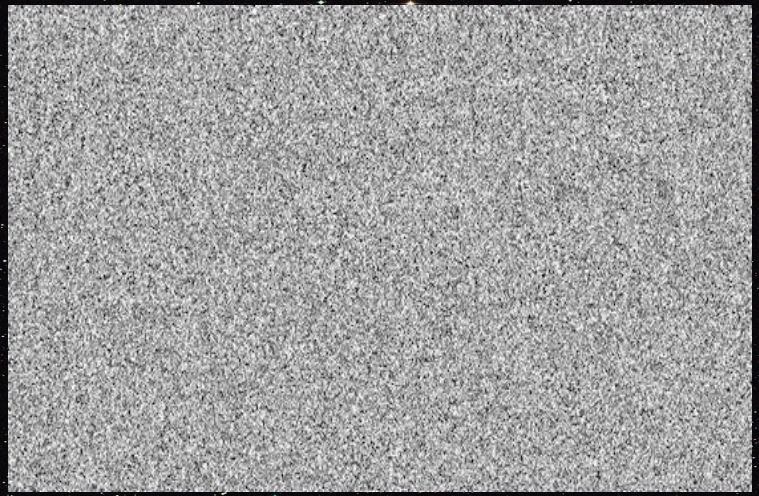
- Bayes' Theorem



Parameter Estimation in LVK: The Likelihood

- Gravitational waves likelihood

What is Gaussian noise?



$$\mathcal{L}(\mathbf{s}|\vec{\theta}) = \exp\left\{-\frac{1}{2}\sum_i \langle s_i - h_i(\vec{\theta}), s_i - h_i(\vec{\theta})\rangle_i\right\}$$

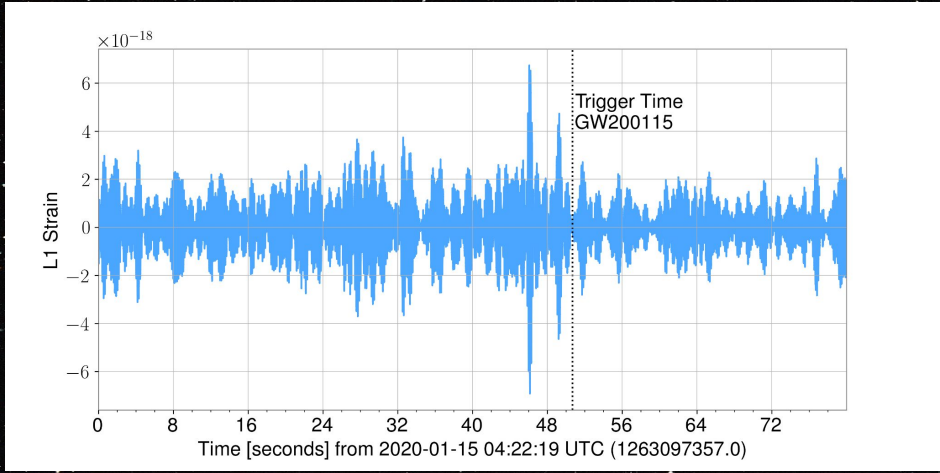
$$\langle a, b\rangle = 4\int_{f_{\min}}^{f_{\max}} \frac{\tilde{a}^*(f)\tilde{b}(f)}{S_n(f)} df$$

with $\mathbf{s}$ the strain, $h_i(\vec{\theta})$ our model evaluated at the parameters values of $\vec{\theta}$ and $S_n(f)$ the estimation of the PSD.

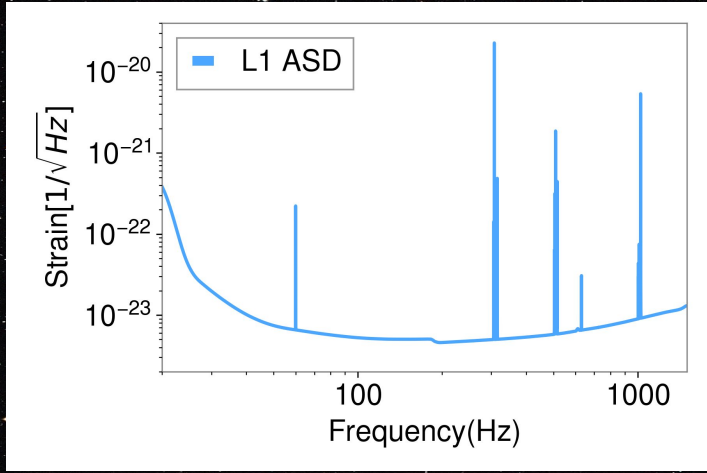
Parameter Estimation in LVK: The PSD

- Spectral estimation tool is BayesWave
- The PSD completely characterises the detector noise around the trigger time (assuming non-gaussianities/glitches have been extracted).
- It represents a critical component of template-based parameter estimation

BayesWave turns the strain …

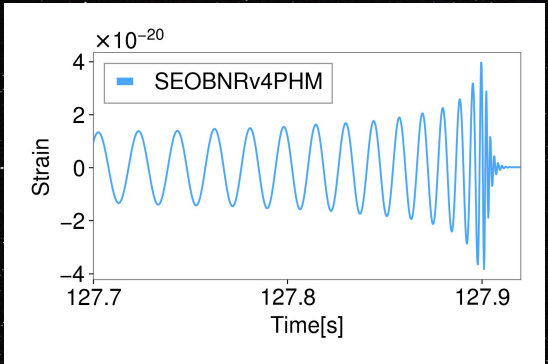


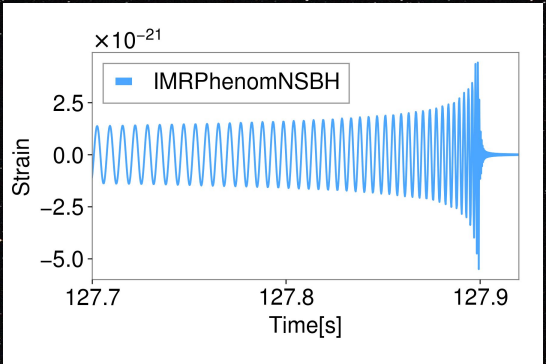
… into an ASD (PSD)

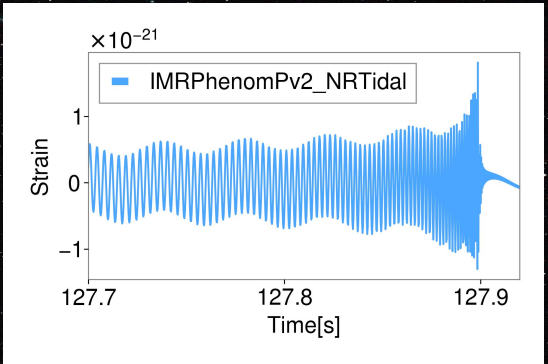


Parameter Estimation in LVK: The Priors I

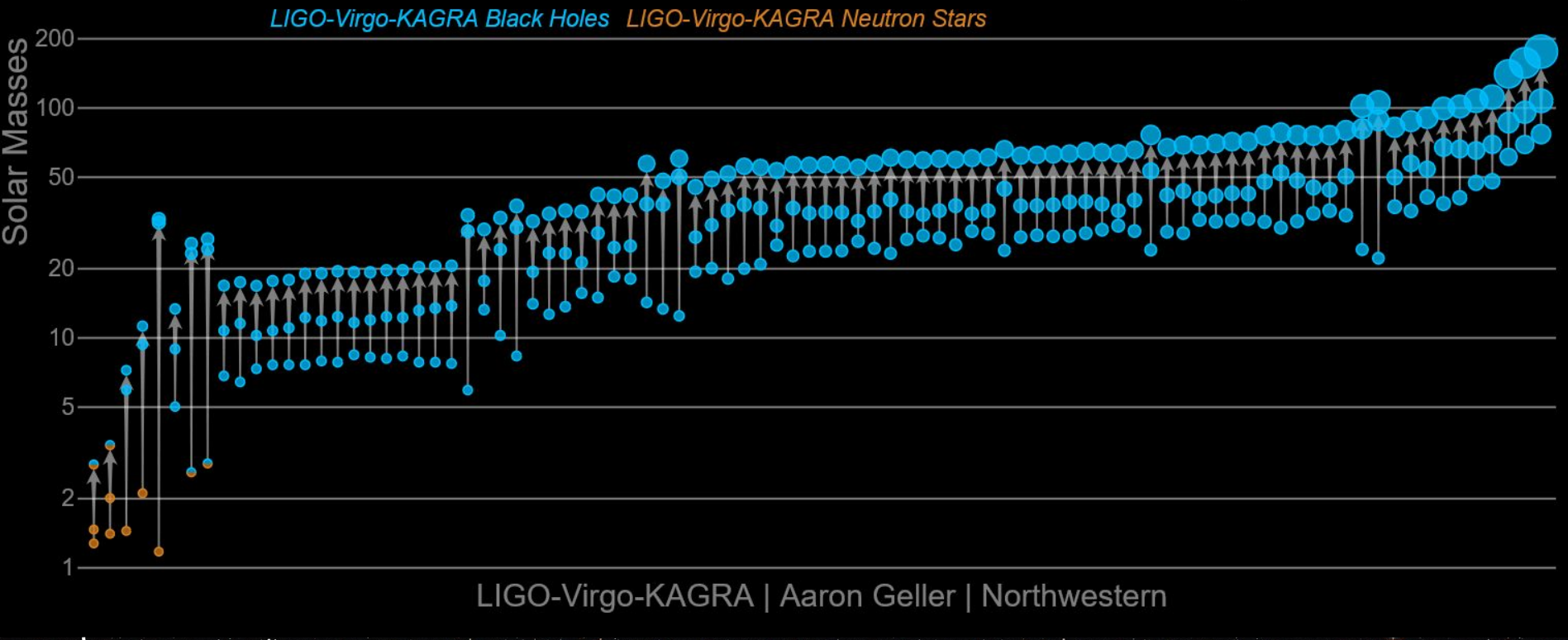
- What do we think we have found? Based on trigger parameters we make an educated guess. The following waveform list is not exhaustive.
  - BBH → SEOBNRv4PHM & IMRPhenomXPHM
  - NSBH → IMRPhenomNSBH & SEOBNRv4_ROM_NRTidalv2_NSBH
  - BNS → IMRPhenomPv2_NRTidal & SEOBNRv4_T







Masses in the Stellar Graveyard

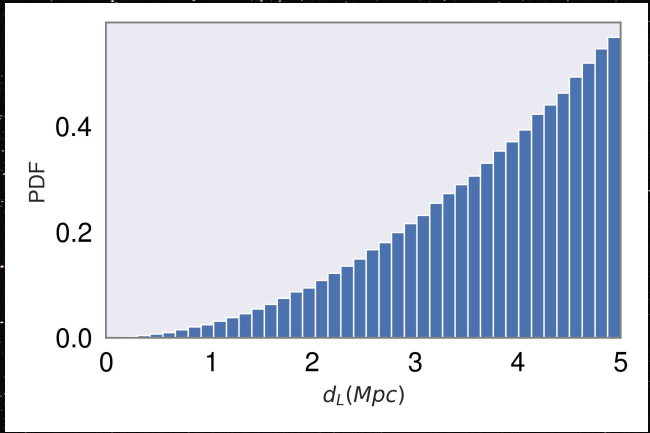


Matter effects?

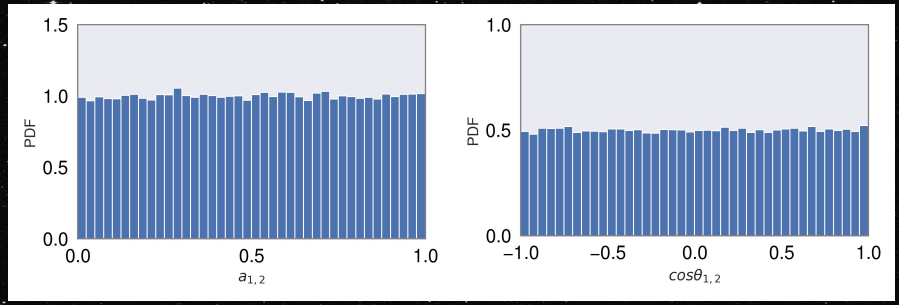
Higher Order Modes?

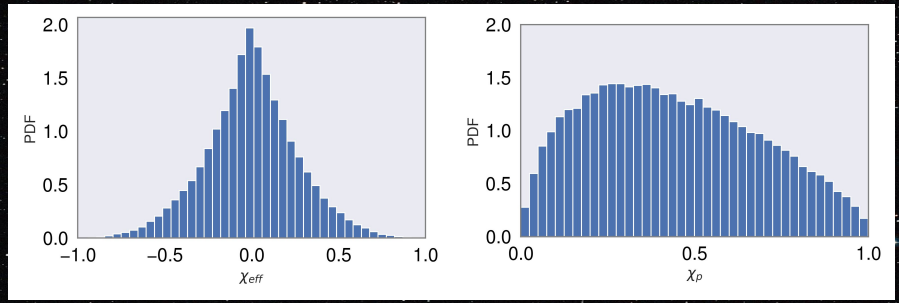
Parameter Estimation in LVK: The Priors II

- What prior range and distributions?
  - How wide? $\Delta\mathcal{M} \sim 1/N_{cycles}$
- What parameters do we sample from?
  - Parameters directly used in the waveform?
  - Physical parameters?



Uniform in physical parameters

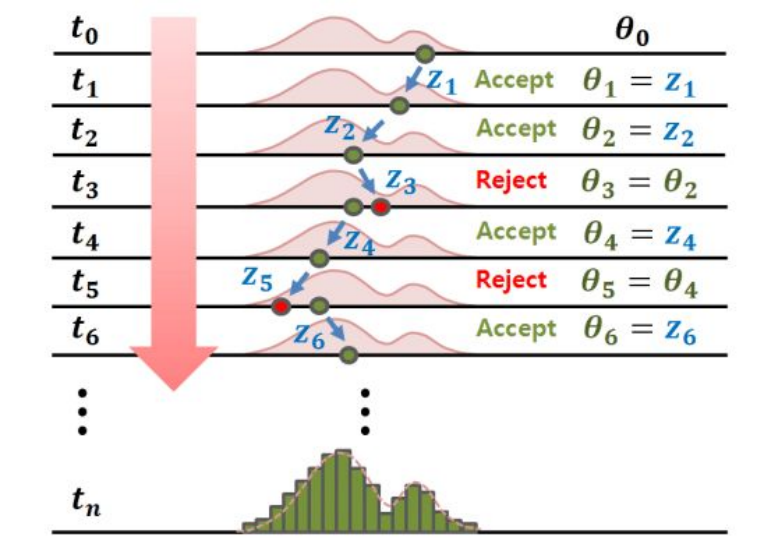




Parameter Estimation in LVK: The Algorithm

- How can we estimate the posterior PDF for our parameters?
  - Parallel Tempered MCMC with LALInference → Usually for exploratory runs/convergence checks
  - Nested Sampling with (Parallel) Bilby → Main production runs for the less computer intensive waveforms, IMRPhenomXPHM in GWTC-3
  - Gaussian-processes regression with RIFT → More costly time domain waveforms, SEOBNRv4PHM in GWTC-3

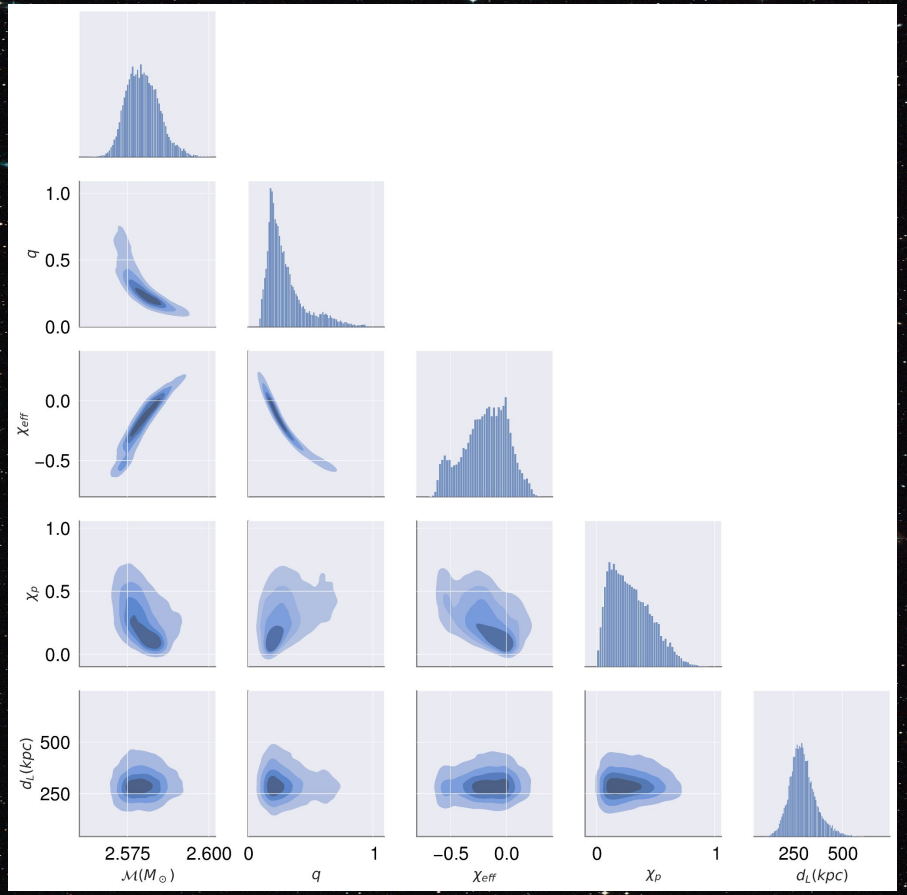
Markov Chain Monte Carlo overview



Credits: Seung-Seop Jin et al.

Visualizing the results

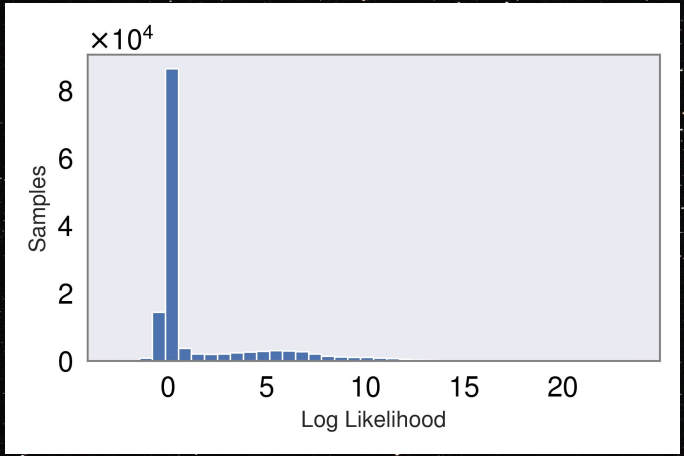
- Summary pages is your best friend
- Sanity checks:
  - Posterior railing into the prior bounds
  - Matched filter SNR in detectors consistent with each of their horizon distances
  - Imaginary part of matched filter SNR not compatible with 0
  - Median values that are very extreme can signify possible unidentified glitches



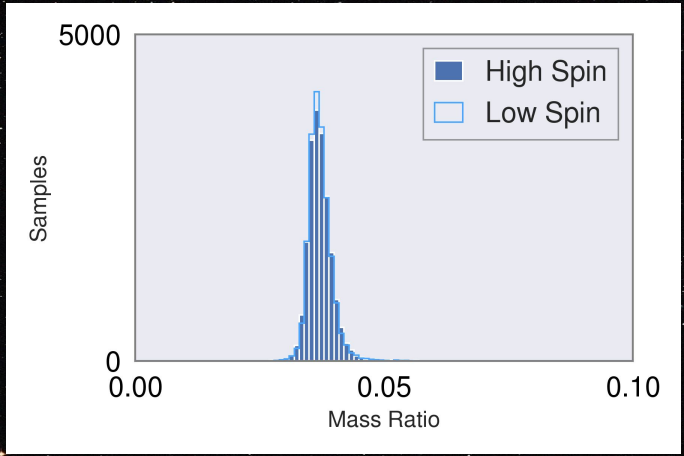
Challenges

- What if we don't have accurate models? Case of GW191219_163120
- What if the event is very quiet? Case of GW200322_091133

GW200322_091133



GW191219_163120



Conclusions

- We have seen the logic behind the Parameter Estimation pipeline within the LVK Collaboration
- Bayes' Theorem is the mathematical framework to be used
- Using a PSD obtained via BayesWave and a carefully chosen waveform, we sample from the prior using one of the three main algorithms MCMC (LALInference), Nested Sampling (Bilby) or Gaussian-processes (RIFT) to estimate the posterior
- We then perform basic visual sanity checks to our posteriors

Questions?