Parameter Estimation and Model Selection of Gravitational-Wave Signals Contaminated by Transient Detector Noise Glitches

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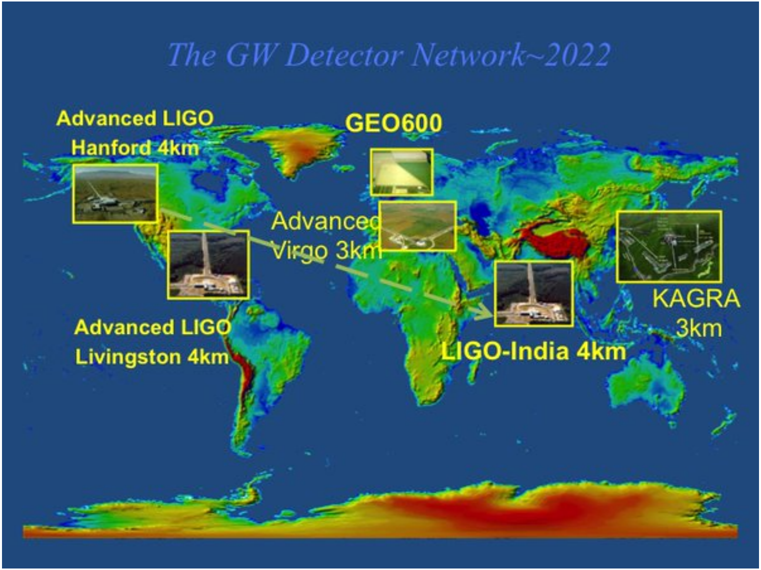
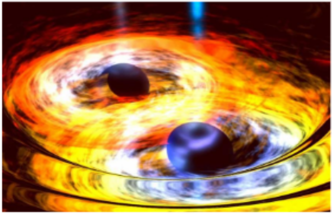
2. Gravitational Wave Detectors

3. Detector Locations

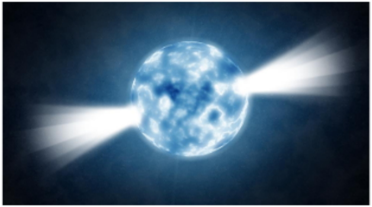


4. Gravitational Wave Sources

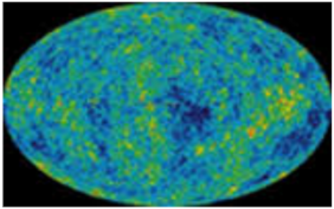


Compact Binary Systems

Bursts



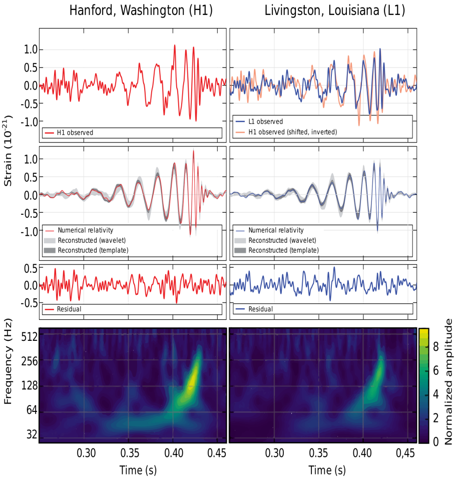
Isolated Compact Objects



Stochastic Background

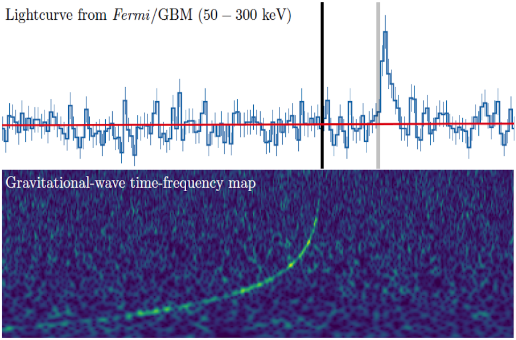
5. Current Black Hole Detections

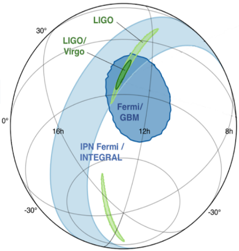
- 6 Binary black hole signals detected so far.
- Estimated distances between 340 and 1000 Mpc.
- One signal detected by three detectors.
- Image from first detection paper GW150914 (PhysRevLett.116.061102)



6. The Neutron Star Detection GW170817

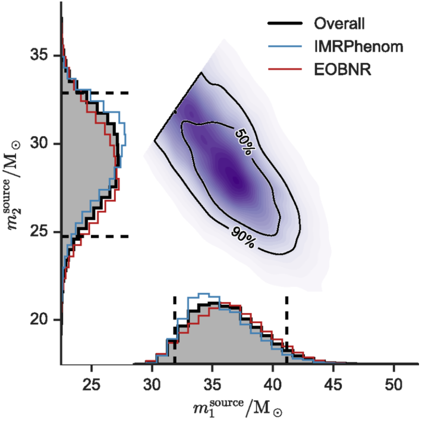
- Source masses $1.36 - 2.26\,M_\odot$ and $0.86 - 1.36\,M_\odot$
- Distance 40 Mpc





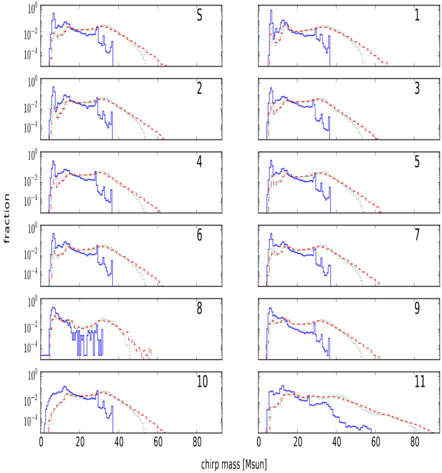
7. Parameter Estimation

- Measuring parameters of a source is essential for astrophysics with gravitational wave detections.
- With GW detectors we can measure the chirp mass, spin, eccentricity, distance, and sky position.
- Chirp mass is given by $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$



8. Astrophysics with Source Parameters

- Constrain the mass distribution of black hole binaries.
- Distinguish between different black hole formation channels.
- Attempt to constrain parameters in binary evolution using population synthesis models.
- Measure the evolution of merger rate / mass distribution with redshift.



9. Bayesian Model Selection

- Bayes Theorem:

$$p(M|D,I) = \frac{p(D|M,I) \times p(M|I)}{p(D|I)}$$

- Compute Bayes Factors for two competing models, M_S and M_N, to find the correct model

$$B_{S,N} = \frac{p(D|M_S)}{p(D|M_N)}$$

- log Bayes factor for comparing a signal model and noise only model is then

$$log(B_{S,N}) = log[p(D|M_S)] - log[p(D|M_N)]$$

- Compare two signal models S_i and S_j by computing

$$log(B_{S_i,S_j}) = log(B_{S_i,N}) - log(B_{S_j,N})$$

10. Parameter Estimation

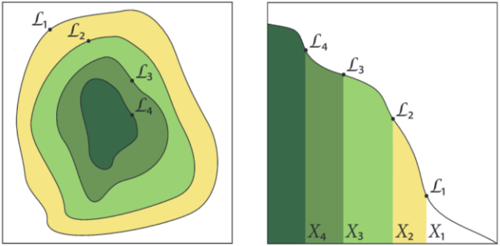
- To calculate the evidence for each model we integrate the likelihood multiplied by the prior over all possible parameter values θ

$$p(D|M) = \int_{\theta} p(\theta|M)p(D|\theta, M)d\theta. \quad (1)$$

- The evidence integral is difficult for a large number of parameters.
- This problem is solved using nested sampling.

11. Nested Sampling

- First the likelihood is calculated for selected points distributed over the entire prior.
- The point with the smallest likelihood and largest prior mass is selected and becomes the limiting values.
- A new point is generated inside the new limits.
- This is repeated so that it iterates inwards in prior mass and upwards in likelihood until the highest value is found.
- Produces Bayes factors and posterior distributions on the signal parameters.



12. Burst Sources

- For a burst source we don't know exactly what a signal should look like.
- We use sine Gaussian's as a signal model.
- They are defined as,

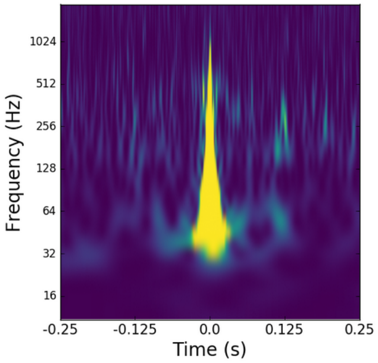
$$h_x(t) = h_0 \sin(2\pi f t) \exp(-t^2/\tau^2) \tag{2}$$

$$h_+(t) = h_0 \cos(2\pi f t) \exp(-t^2/\tau^2) \tag{3}$$

- where $\tau = Q/\sqrt{2}\pi f$, f is the frequency, Q is the quality factor, t is time of the signal and $h_0 = hrss/\sqrt{\tau}$, where hrss is the root sum squared amplitude of the signal.
- Produces posterior distributions on hrss, Q, f, and sky position.

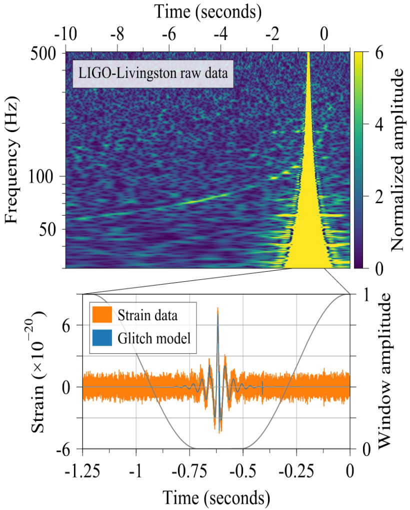
13. Glitches

- Glitches are short duration excess power noise created by the detector or the environment.
- The detectors have 1000's of auxiliary channels of data from monitors around the detector.
- Some glitches don't show up in any monitors making it difficult to determine their origin.
- They limit the sensitivity of gravitational wave searches.



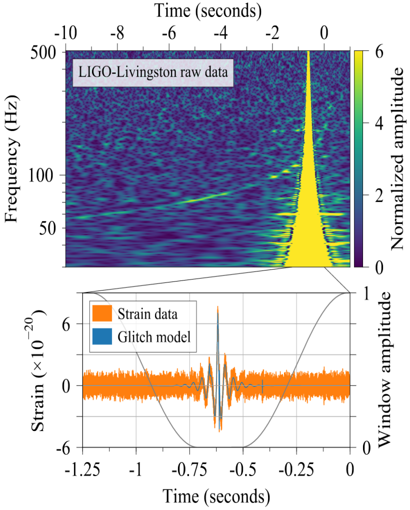
14. Signals with glitches

- 10^6 glitches above SNR 6 were observed in 51.5 days of O1.
- GW170817 had a large glitch in L1.
- High probability that as detections increase, more will occur at the same time as a glitch.



15. Glitch Removal

- For GW170817 we already know what we expected the signal to look like.
- The glitch was very loud and easy to identify as being a glitch.
- It was removed by gating and subtracting the reconstructed waveform.
- The glitch is short duration compared to the signal, which means some signal is still left over after gating.
- It might not be so easy next time!



16. This Analysis

- We inject three different types of gravitational wave signals on top of three different types of glitches.
- We measure the parameters of the signals at different signal to noise ratios and offsets in time between the signal and glitches.
- What happens if the glitch is not obvious because it does not occur in auxiliary channels and the exact shape of the signal waveform is unknown?
- We determine the effects of glitches that can't be gated.
- We investigate if the effects of glitches is worse when there is a mis-match between signal and template.

17. The Glitches

Three types of O1 glitches are used that occur in L1 at the same time as good quality H1 data.

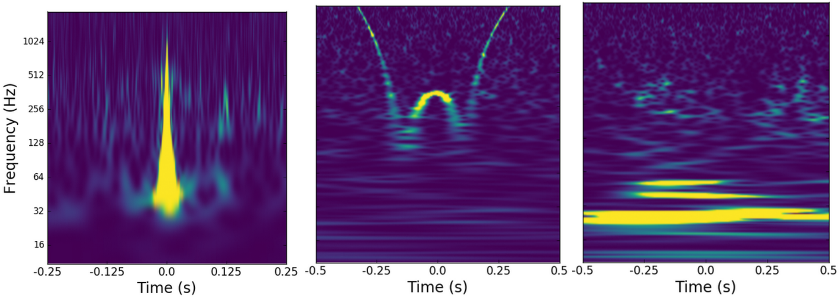
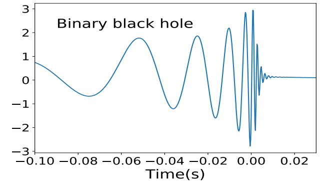
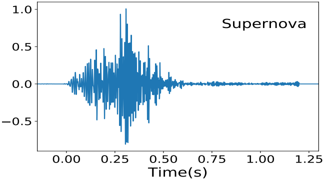


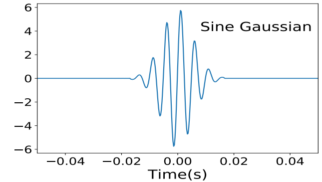
Figure: Images taken from Gravity Spy.

18. The Signals

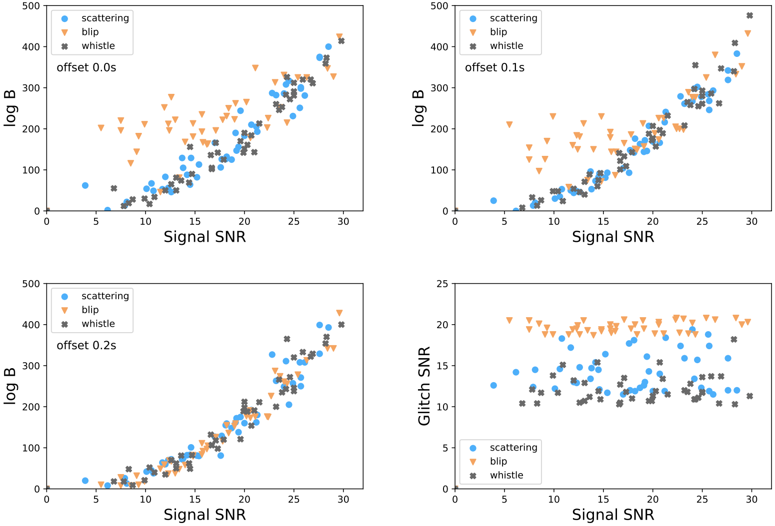
- We measure parameters of all signals injected near glitches with time offsets of 0.0 s, 0.1 s and 0.2 s.
- IMRPhenomPv2 signal model is used for the CBC signals.
- A sine Gaussian signal model is used for the sine Gaussian signals.
- A sine Gaussian model is used for the supernova signals to determine if effects are worse when there is a mis-match between signal and model.



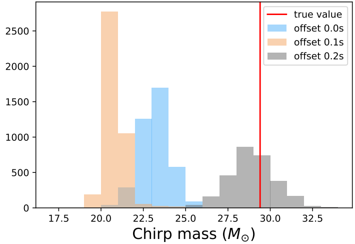


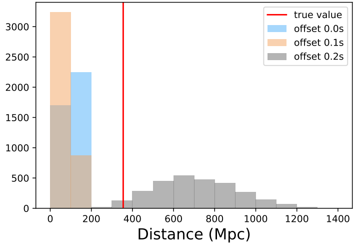


19. BBH Bayes Factors

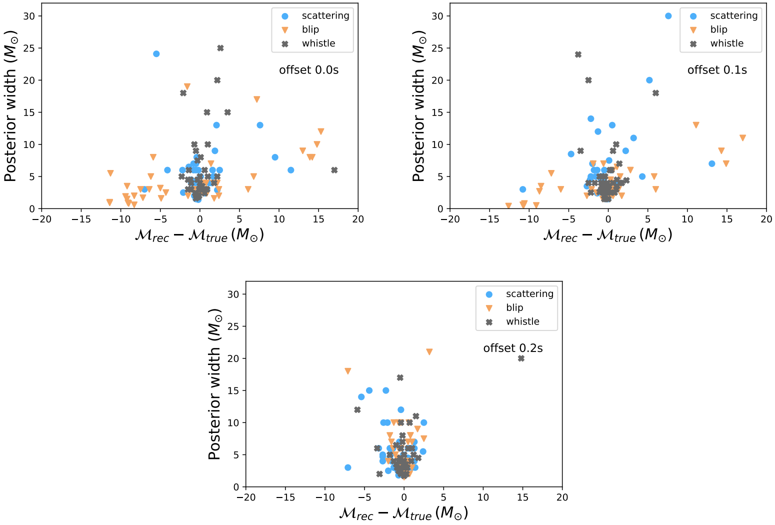


20. BBH Example Posteriors

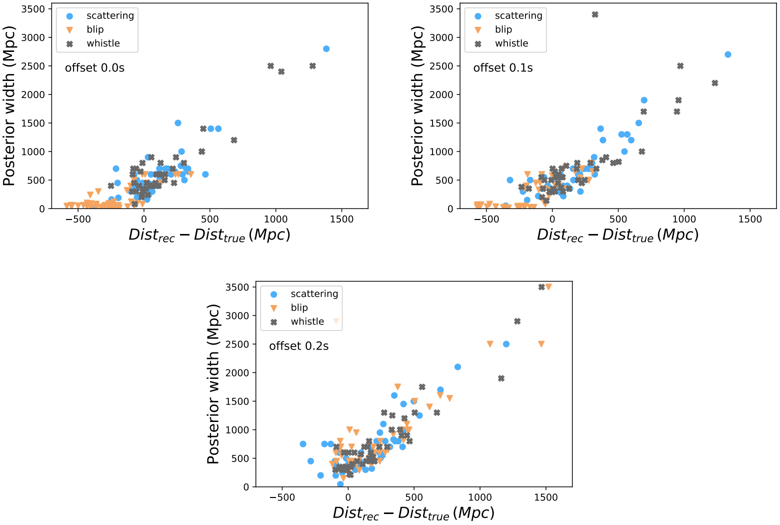




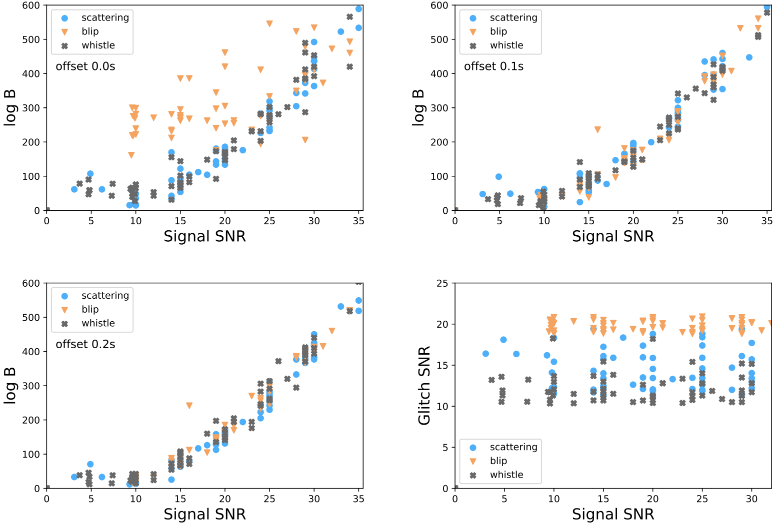
21. BBH Chirp Mass Summary



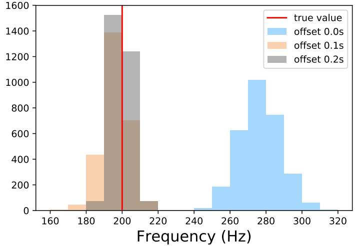
22. BBH Distance Summary

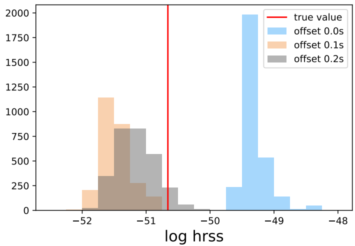


23. Sine Gaussian Bayes Factors

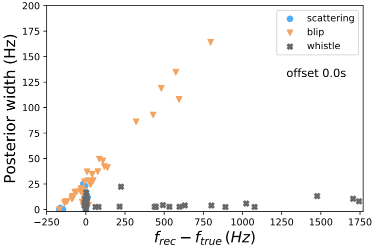


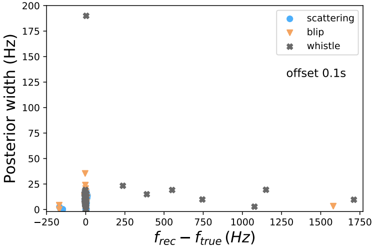
24. Sine Gaussian Example Posteriors

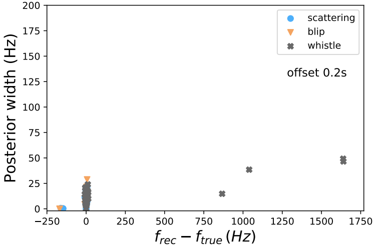




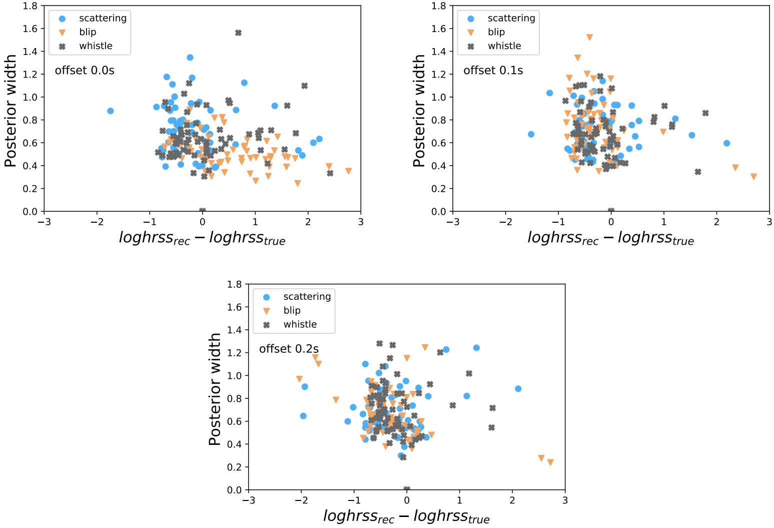
25. Sine Gaussian Frequency Summary



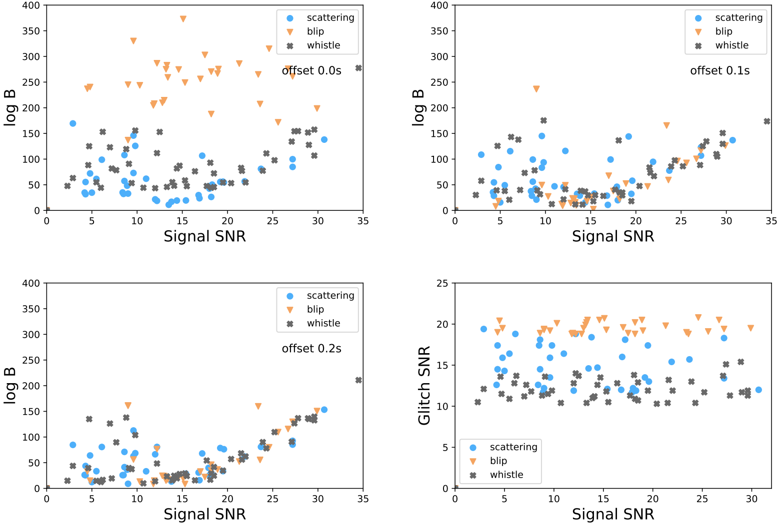




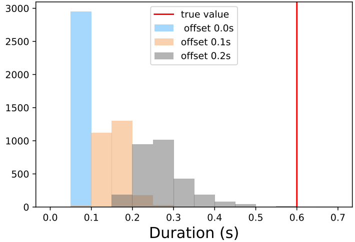
26. Sine Gaussian Log Hrss Summary

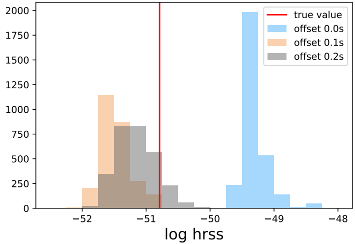


27. Supernova Bayes Factors

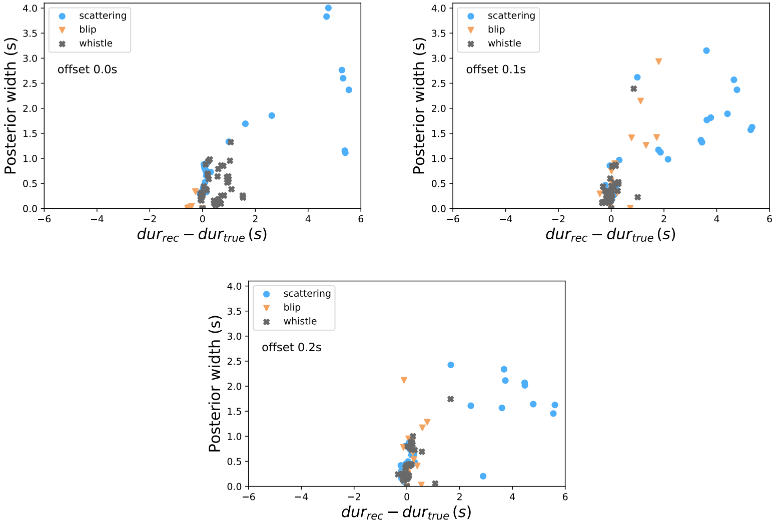


28. Supernova Example Posteriors

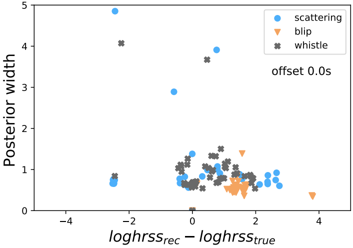


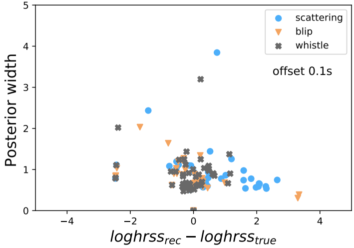


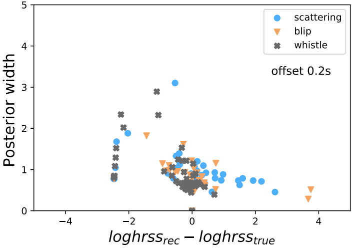
29. Supernova Duration Summary



30. Supernova Log Hrss Summary







31. What's next?

- Next step is to apply techniques designed to reduce the effect of glitches to the data set.
- We are attempting to reconstruct the glitch and the signal at the same time to reduce the error on signal parameters.
- Currently Bayes factors can be produced to tell you if their is a signal or a glitch in the data.
- Next we hope to produce a Bayes factor that tells you there is both a signal and a glitch.