Searching For Gravitational Wave Bursts From Binary Neutron Star Coalescence

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This Talk

Motivation

GW Bursts From BNS Mergers

Past/Present Analyses

GW Burst Analysis & BNS Bursts

Future Directions & Developments

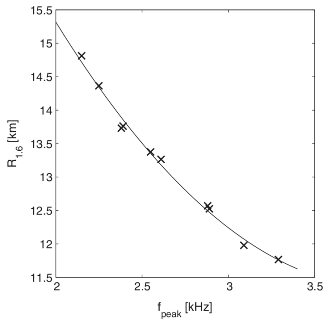
New Data Analysis Techniques

Long-duration Signals

Summary & Outlook

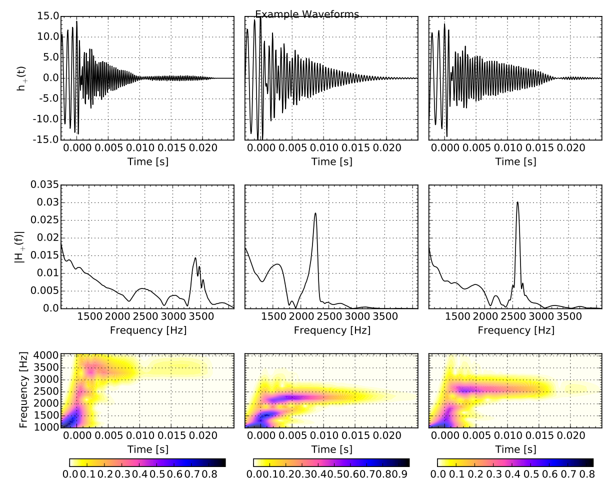
Burst Signals: Short

- BNS mergers: likely formation of a stable / quasi-stable, differentially rotating neutron star remnant [1, 2, 3, 4].
- Transient non-axisymmetric deformations and f-mode oscillations $\rightarrow$ short (10–100 ms) burst of high-frequency ($\sim$kHz) gravitational wave (GW) emission.
- Spectral properties $\rightarrow$ neutron star equation of state from (e.g.,) dominant peak frequency f_{peak} [5, 6].
- May be observable to $\sim$10's Mpc in advanced LIGO (c. 2020+).



Peak-frequency/fiducial-radius relation from [6]

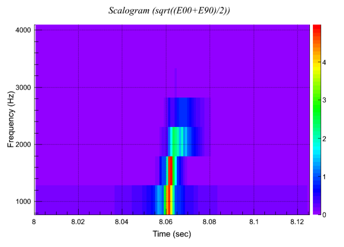
BNS Burst Signals: Merger/Post-Merger



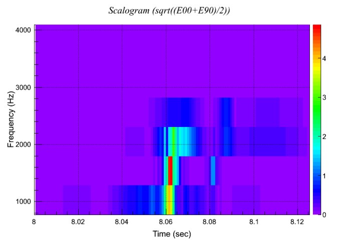
Examples for different EOS (APR, Shen, DD2). Waveforms taken from [7].

GW Burst Search: Coherent WaveBurst (CWB)

- Search for excess power in time-frequency plane
- Decompose data with multi-resolution wavelet basis
- Coherent analysis maximises likelihood over waveform & sky-location [8, 9]
- Identifies statistically significant coherent power (detection), reconstructs GW signal



Simulated signal



Reconstructed signal

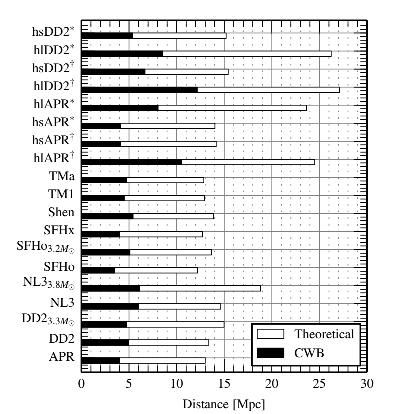
Previous Burst Detectability Study

"Prospects For High Frequency Burst Searches Following Binary Neutron Star Coalescence With Advanced Gravitational Wave Detectors" [7]

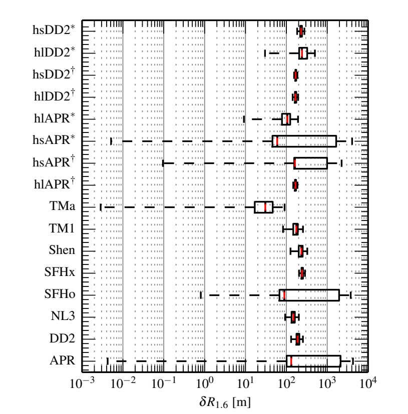
Monte-Carlo analysis of burst detectability and basic parameter estimation of post-merger bursts

- Family of numerical waveforms with various EoS
- Initial detector era noise recoloured to 2022 sensitivities
- Deployed CWB to detect & reconstruct signals
- Compared sensitivity with optimal matched filter expectation
- Very simple model selection procedure for spectral analysis of reconstructed signals (identify post-merger scenario, measure dominant frequency)

Detectability & Frequency Recovery



Effective range for theoretical matched filter & burst analysis (fixed false alarm probability=1%)



Absolute error in radius recovery, using $f_{\rm peak} - R_{1.6}$ relation in [4].

New Study: Prospects for…: Round 2

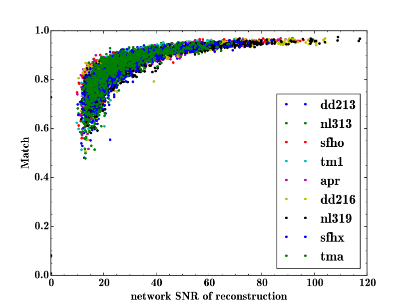
Motivation & Goals of Study:

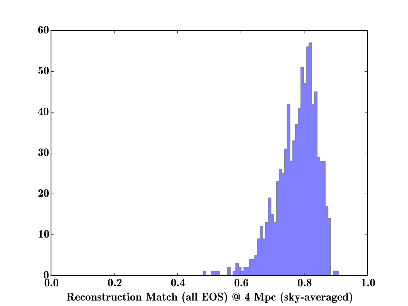
- Recent upgrades to flagship burst analysis algorithm [1]
- More post-merger waveforms from University of Trento (also home of various CWB experts)
- Point-comparison of SPH and NR waveform codes from independent groups
- Also recent development & availability of ‘unmodelled’ Bayesian analysis algorithm
- Tune the post-merger analysis for next year’s BNS inspiral detection!

Participants from GATech, Universities of Thessaloniki & Trento

Preliminary Results From New Study

- Going further than previous study and looking at full-reconstruction fidelity characterised by match *and* peak frequency measurements
- 'Ceiling' on matches $\rightarrow$ Missing late-time/high-frequency post-merger signal; goal is to tune the analysis to avoid this effect





Enhancements & Bayesian Methods

- CWB: fast, robust & familiar ‘flagship’ burst analysis; principal tool GW burst searches.
- Other recent efforts for burst waveform recovery & characterisation:

1. Bayesian wavelet analysis (‘BayesWave’); model dimension estimation & potential to encode prior information on time-frequency structure
2. Principal component analysis as a route to phenomelogical templates

Principal Component Analysis Of Short Bursts

Clark, Bauswein & Stergioulas (*in prep.*)

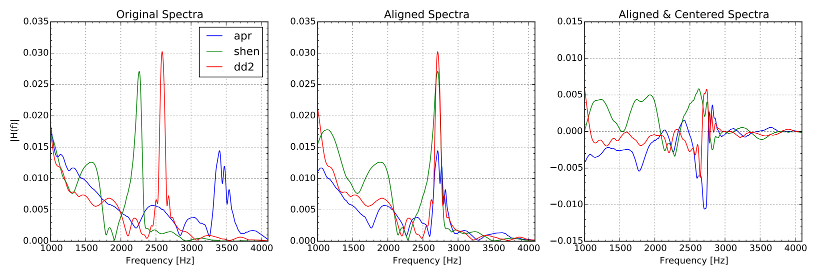
1. Goal: find a robust basis to accurately represent simulated waveforms
2. Organise M simulation waveforms, each containing N samples, from numerical simulations of binary neutron star mergers into an $M \times N$ data matrix, $\mathbf{X}$
3. Align dominant features, subtract the mean waveform $\bar{h}$ to get centered data matrix $\mathbf{Y}$
4. Eigenvectors $\mathbf{W}$ of the covariance matrix $\mathbf{C} \sim \mathbf{Y}\mathbf{Y}^{\top}$ provide a basis to represent deviations from the mean
5. Arbitrary waveform h is represented in the new basis by,

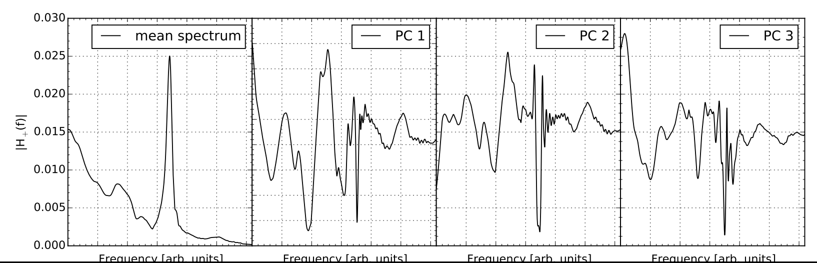
$$h = \bar{h} + \sum_{i=1}^{p} \beta_i w_i, \tag{1}$$

   where w_i are rows of $\mathbf{W}$ & β_i are projection coefficients from $\mathbf{B} = h'.\mathbf{W}$
6. See e.g., supernova waveform analyses [10], reduced order modelling for BBH [11]

Short Burst PCA

Clark, Bauswein & Stergioulas (*in prep.*)





Prospects for PCA Of Short Bursts

PCA provides an (approximate) template:

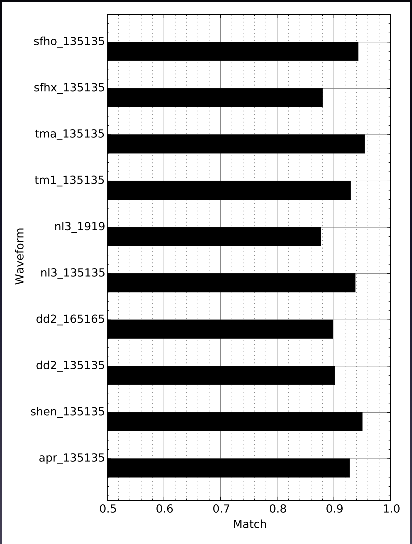
$$H(f) \approx A_{\rm PCA}(f)\exp[i\phi_{\rm PCA}(f)],$$

where,

$$A_{\rm PCA}(f) = \sum_{i=1}^{N} \beta_i^{(A)} u_i^{(A)} \quad (2)$$

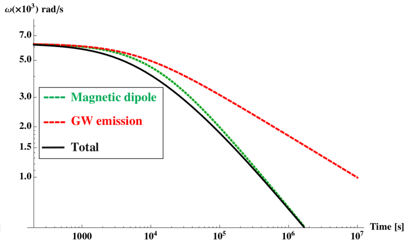
$$\phi_{\rm PCA}(f) = \sum_{i=1}^{N} \beta_i^{(\phi)} u_i^{(\phi)}$$

Right: matches for waveforms in [7] using 1st principal component ($N = 1$) from training data with test waveform excluded

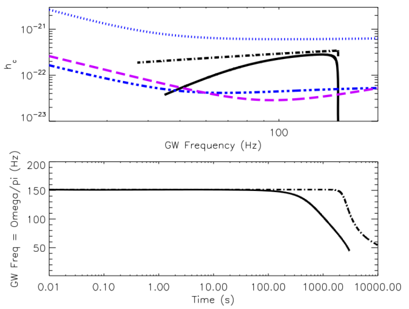


Burst Signals: Long

Longer, louder GW emission also possible with formation of stable post-merger remnants. Examples include:



Magnetic field amplification → stable magnetar with B-field induced quadrupole moment [12]. Emission over $\sim 10^6$ s, matched-filter effective range: $\sim 25 - 53$ Mpc

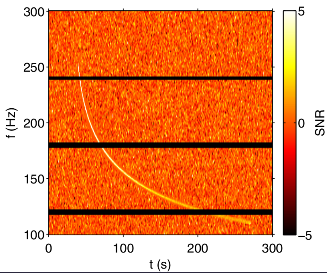


Secular bar-mode instability [13]. Emission over ~few$\times 10^2 - 10^3$ s, matched-filter effective range: ~ 45 Mpc.

Searching For Long Bursts

Also have tools to specifically target long (few 100–few 1000s) transients, where precise morphology is unknown. E.g., ‘STAMP’ analysis [14]:

- Cross-correlate strain time series from pairs of detectors
- Form cross-power time-frequency maps (e.g., right)
- Pattern-recognition problem: search for ‘tracks’ in cross-power maps



Example signal recovery with STAMP (accretion disk instability waveform).

Sensitivity studies & tuning now underway; interested in any/all long-transient signal scenarios

Summary

- Likely formation of post-merger NS remnant following coalescence
- GWs from merger & oscillations could constrain EOS for nearby mergers
- Challenges: weak signal & uncertain morphology; use unmodelled burst analysis
- Initial burst study: signals observable in advanced detectors to a few Mpc, dominant post-merger frequencies quite well recovered.
- Follow-up burst study underway: multi-resolution analysis, opportunity to tune, study more waveforms & characterise full waveform reconstruction fidelity
- Exciting new developments: PCA-based analysis could triple our range & mature long-duration transient searches ready to go

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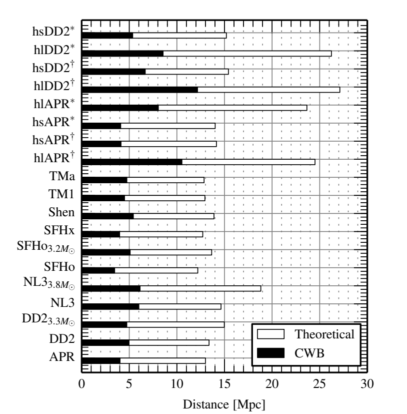
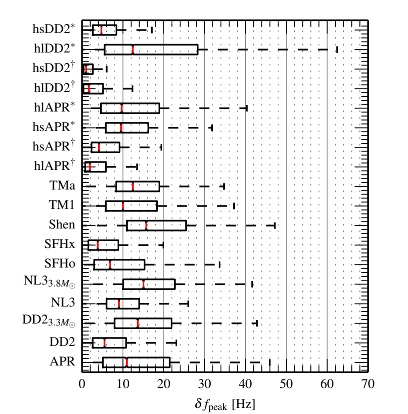
Detectability & Frequency Recovery

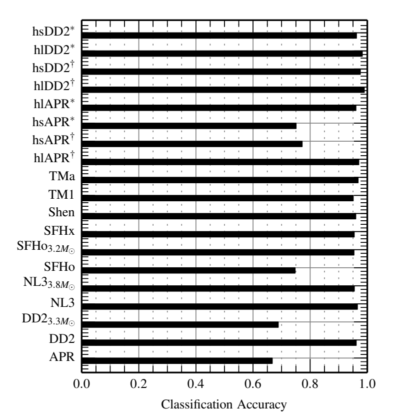


Effective range for theoretical matched filter & burst analysis (fixed false alarm probability=1%)

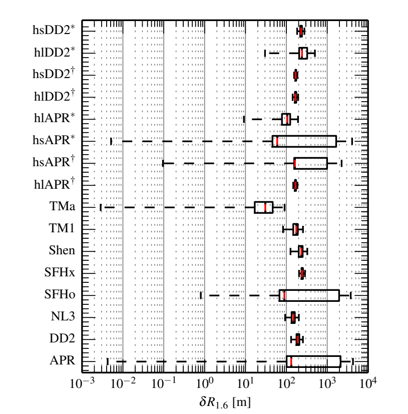


Absolute error in peak frequency recovery

Classification Accuracy & Radius Recovery



Probability of identifying correct post-merger scenario



Absolute error in radius recovery