Analysis of Post-merger Gravitational Waves From Binary Neutron Star Coalescence

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First multi-messenger observations of a neutron star merger and its implications for nuclear physics (INT 18-72R)
University of Washington, Seattle, March 2018

LIGO-G1800363

Post-merger Scenarios

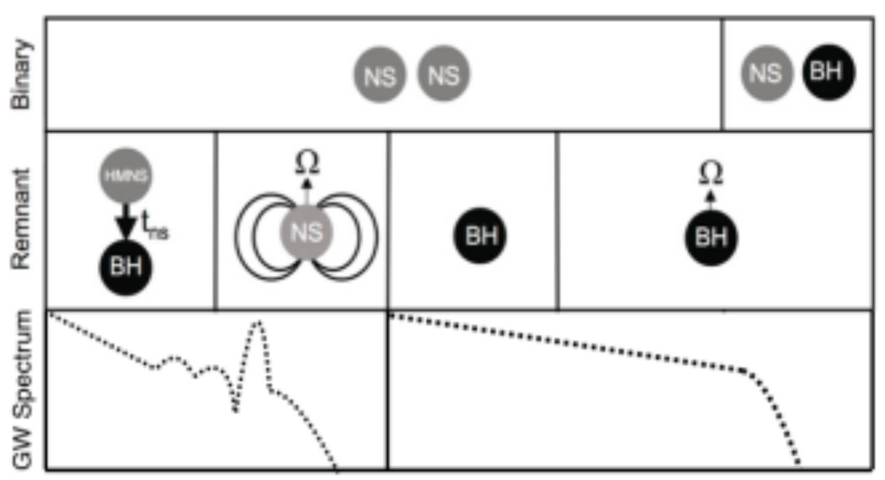


Figure adapted from Kasen, Fernandez and Metzger (2015)

Outcomes of NS-NS mergers:

- Prompt collapse (BH ringing >6 kHz)
- Hypermassive remnant (t_{GW}~few-10 ms)
- Supramassive remnant (t_{GW}~10-100 ms)
- Stable remnant (t_{GW}~100 ms, minutes-weeks+)

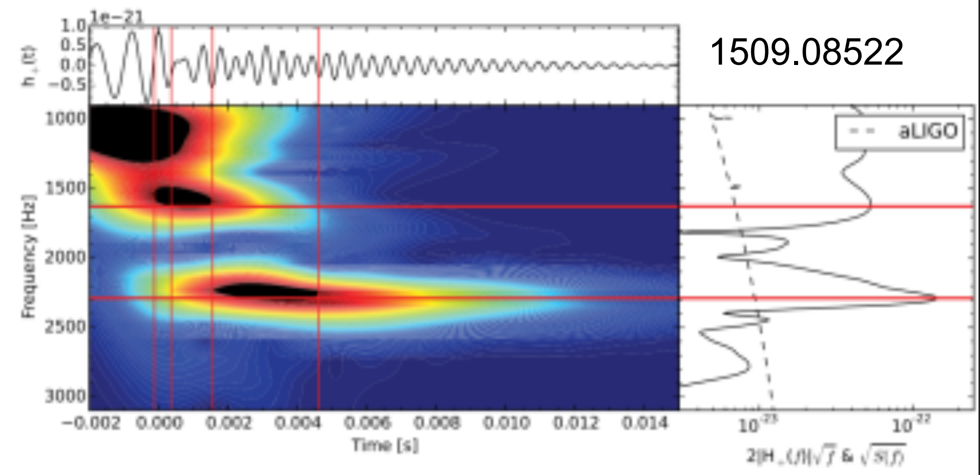
This talk: **ms merger/post-merger burst**

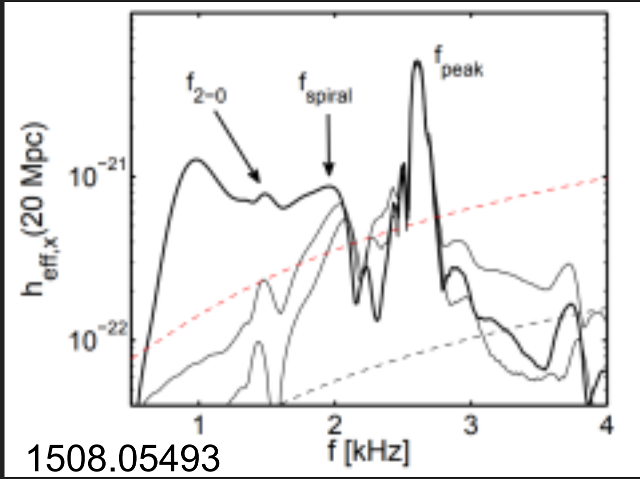
Evan's talk: hours - weeks-long signatures from stable remnant

"**Hypermassive**": NS entirely supported by differential rotation, thermal gradients

"**Supramassive**": NS mass low enough to be supported through rigid rotation

Post-merger Gravitational Waves: <1 second





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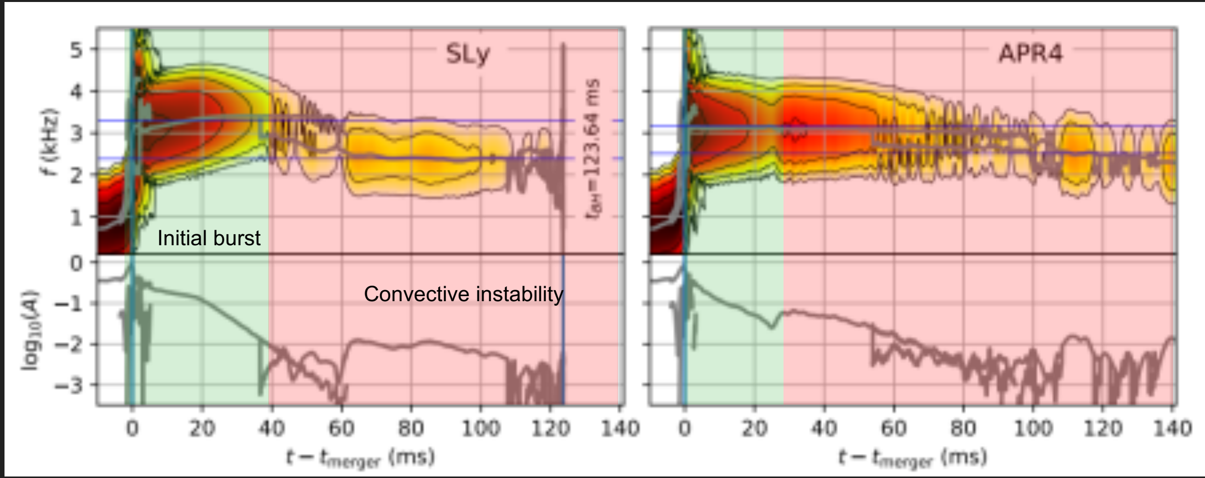
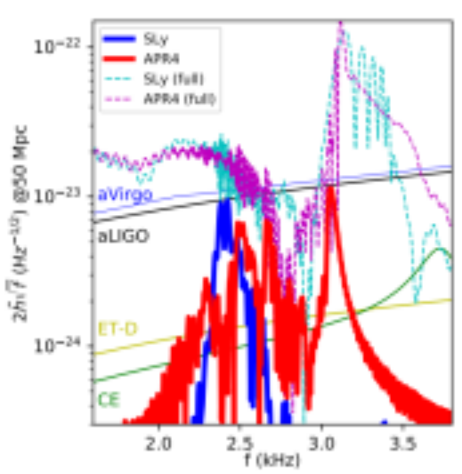
Dominant spectral peak: quadrupolar f-mode

Sub-dominant peaks - degree of each effect varies with mass ratio (1707.03368 for systematic review):

1. Coupling between quasi-radial 2-0 mode & f-mode -> triplet of peaks
2. Spiral/bar deformation excited during merger
3. Modulation of the dominant mode due to the radial oscillation of the rotating double core structure

Post-merger Gravitational Waves: <1 second





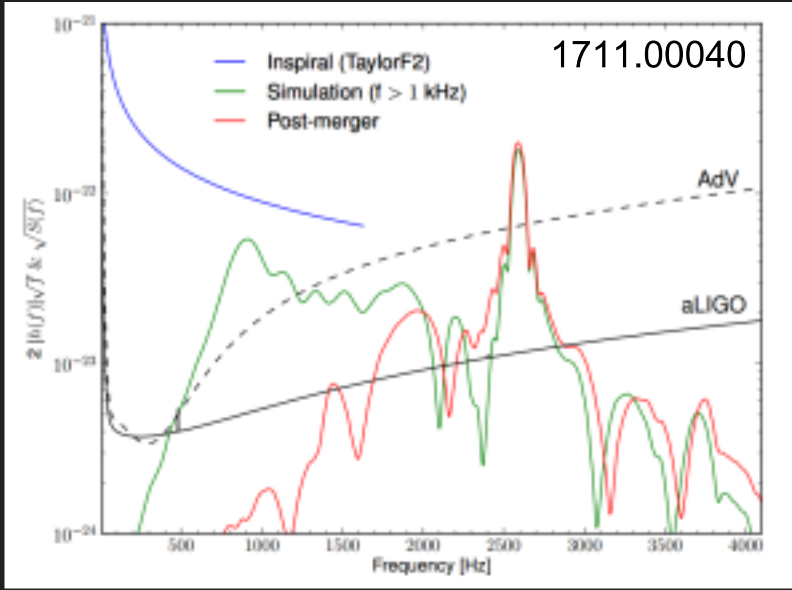
1802.03288: 30-50 ms after merger, convective instabilities develop

Additional GW emission beyond initial burst from oscillation couplings / bar structure

Potential probe of rotational & thermal properties of remnant

Post-merger Gravitational Waves: <1 second

1509.08522



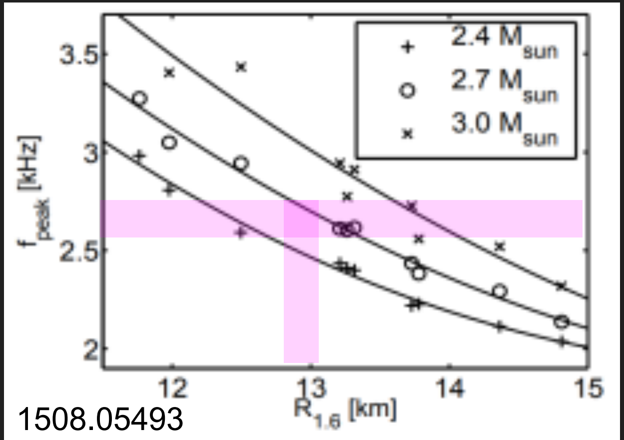
Instrument	$\mathrm{SNR_{full}}$	D_{hor} [Mpc]
aLIGO	$2.99^{3.86}_{2.37}$	$29.89^{38.57}_{23.76}$
A+	$7.89^{10.16}_{6.25}$	$78.89^{101.67}_{62.52}$
LV	$14.06^{18.13}_{11.16}$	$140.56^{181.29}_{111.60}$
ET-D	$26.65^{34.28}_{20.81}$	$266.52^{342.80}_{208.06}$
CE	$41.50^{53.52}_{32.99}$	$414.62^{535.221}_{329.88}$

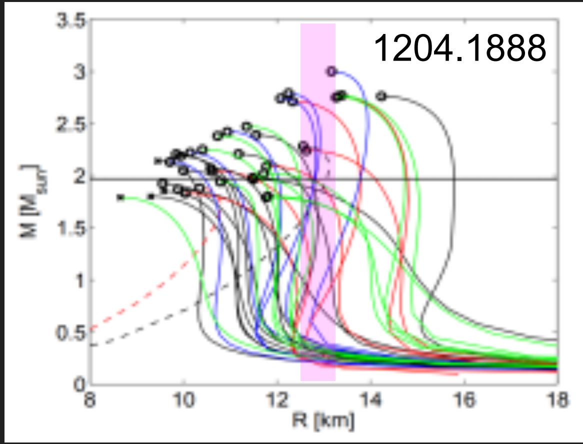
- Blue: post-Newtonian inspiral
- Green: simulation with ~3 pre-merger orbits
- Red: simulation truncated at merger

- $\mathrm{SNR_{full}}$: evaluated for f > 1 kHz
- *Post*-merger SNR ~ 0.5 x $\mathrm{SNR_{full}}$
- **GW170817 D ~ 40 Mpc: expect marginal high-frequency signature for full design-sensitivity aLIGO/AdVirgo *network* (for some masses / EOS)**

Quasi-Universal Relations: GW Spectra & Stellar Parameters

- No full, physically parameterized inspiral-merger-ringdown waveform model (yet)
- GW amplitude spectrum exhibits robust features -> EOS signature

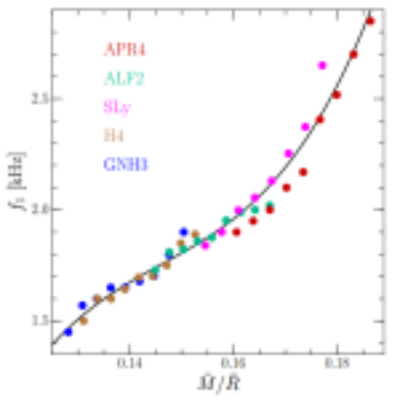


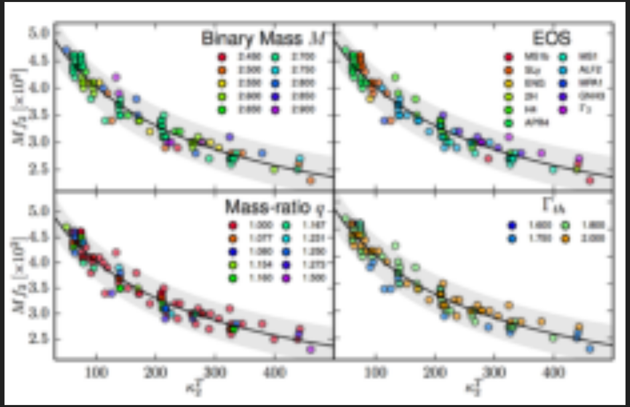


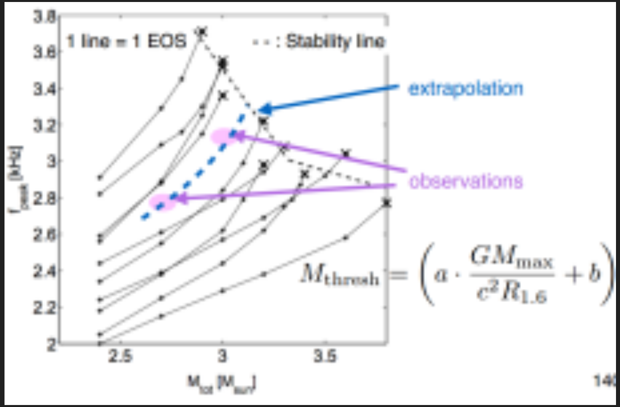
1. Pre-merger: measure M_{tot} to determine appropriate f_{peak}-$R_{1.6}$ relation (e.g., M_{tot}=2.7, f_{peak}~2.6 kHz)
2. Post-merger: measure fpeak; determine corresponding $R_{1.6}$ (e.g., f_{peak}~2.6 kHz -> $R_{1.6}$~13 km)
3. Exclude mass-radius relations which do not permit that $R_{1.6}$

Quasi-Universal Relations: GW Spectra & Stellar Parameters

- Many other similar relations have been found! Including, *not limited to*:
  - Compactness M/R - sub-dominant frequencies (1705.10850)
  - Tidal deformability - peak frequency (1504.01764)
  - Maximum mass constraints from multiple detections (1403.5301)





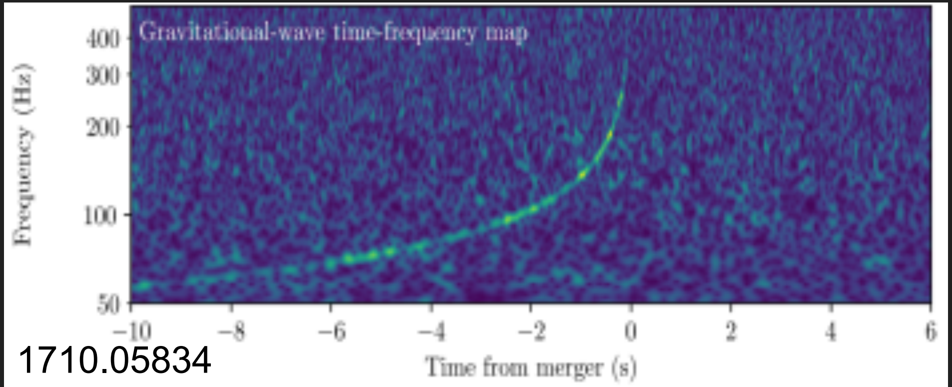


Quasi-Universal Relations: GW Spectra & Stellar Parameters

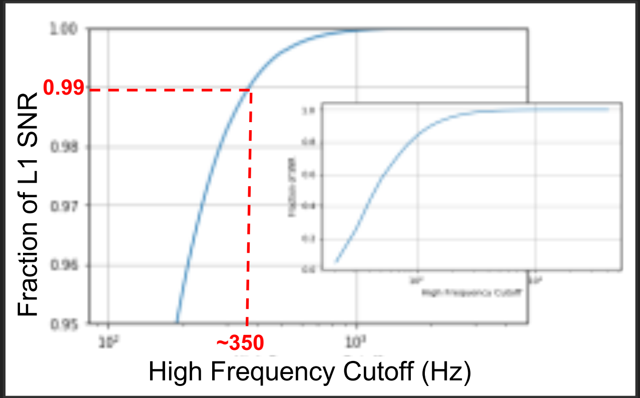
- Broad consistency in several studies estimating radius measurement prospects from a single post-merger observation*:
    - Bose et al (1705.10850): 2-component ring-down template: $\delta R \sim 200$ m @ 30 Mpc
    - Chatziioannou et al (1711.00040) Bayesian wavelets: $\delta R \sim 200$ m @ 20 Mpc
    - Clark et al (1509.08522) PCA-templates using simulations: $\delta R \sim 360$ m @ 30 Mpc
- Systematic uncertainty in fpeak-$R_{1.6}$: $\delta R \sim$ few x 100 m

* Modulo differences in simulations etc

GW170817: Remnant emission observed? No.



- Expect post-merger signature > 1kHz
- GW trace vanishes into the noise around 400 Hz
- Insufficient high-frequency sensitivity



(slightly) more quantitatively:

- 99% of matched-filter SNR already accumulated by 350 Hz
- Signal “ends” long before post-merger signature would be visible

SEARCH FOR POST-MERGER GRAVITATIONAL WAVES FROM THE REMNANT OF THE BINARY NEUTRON STAR MERGER GW170817

1710.09320

Post-merger observation unlikely but opportunities:

- Serendipitous discovery
- Exercise pipelines
- Verify expectations & determine future prospects, motivate development

2 forms of search (so far) using 3 algorithms:

- Short-duration (sub-second): coherent analysis targeting bursts immediately around inferred merger time (Hanford-Livingston only)
- Intermediate-duration: multiple algorithms targeting signals up to ~500 sec (Hanford-Livingston-Virgo used)
  - Secular bar-mode instabilities
  - Magnetar-like emission from misalinged B-field and spin-axis

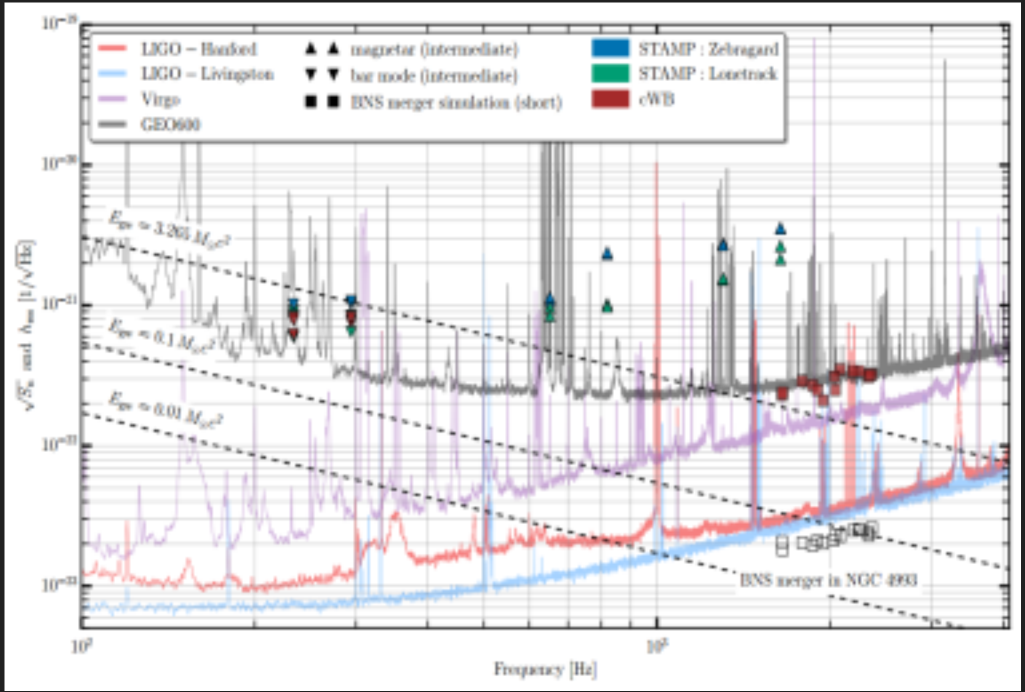
Descriptions in next talk

SEARCH FOR POST-MERGER GRAVITATIONAL WAVES FROM THE REMNANT OF THE BINARY NEUTRON STAR MERGER GW170817

1710.09320

Waveform-dependent upper limits on strain amplitude

- Triangles: intermediate-duration upper limits
- Dashed lines: amplitudes for fiducial energies
- $E_{gw} = 3.265\ M_{sun}c^2$: absolute upper bound on available energy



SEARCH FOR POST-MERGER GRAVITATIONAL WAVES FROM THE REMNANT OF THE BINARY NEUTRON STAR MERGER GW170817

1710.09320

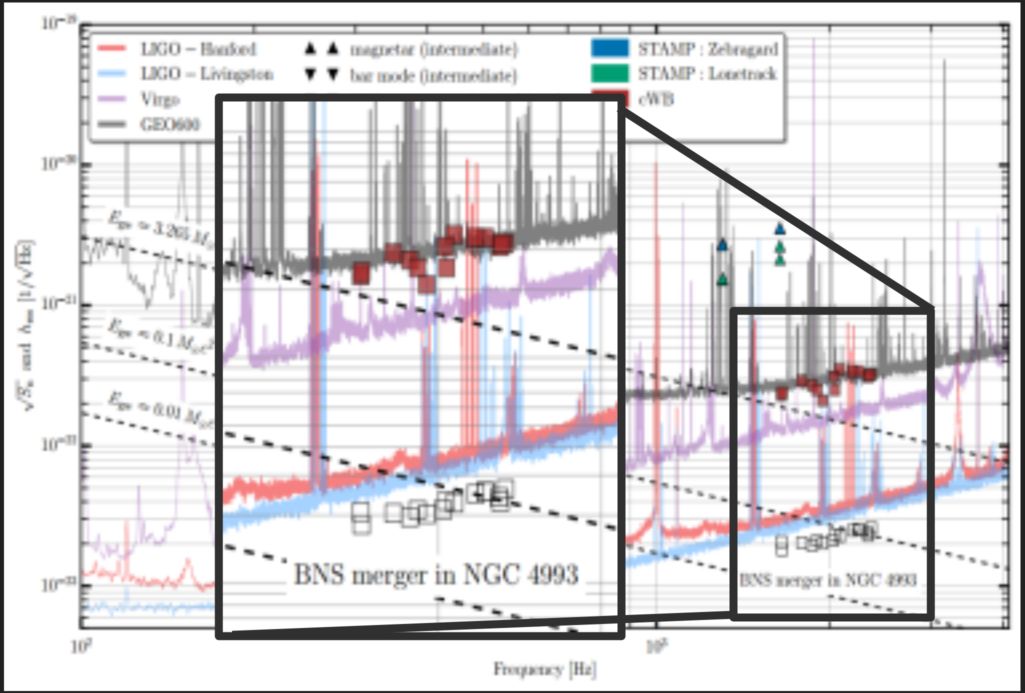
- Open boxes: NR simulations (different EOS, mass/spin configurations) in GW170817 host galaxy

- Red squares: burst search sensitivity

- Targeted follow-up could dig significantly deeper

- Note: GEO600 *can/will* play a role in future (but didn't in this case)

Waveform-dependent upper limits on strain amplitude



BayesWave

BayesWave [1410.3835]: evaluates Bayesian evidence & produces posterior samples for a) gravitational wave (GW) signal model of arbitrary morphology, b) instrumental glitch model, c) Gaussian noise

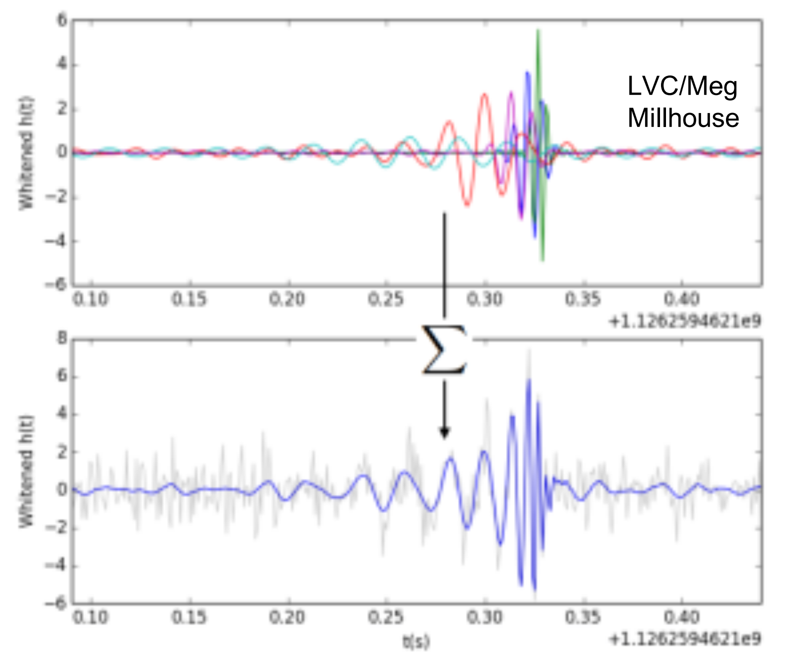
Signals modeled as superposition of arbitrary number of Gaussian wave-packets (wavelets)

$$h_+(t) = \sum_{i=0}^{N_s} \Psi(t; A_i, f_{0,i}, Q_i, t_{0,i}, \phi_i)$$

$$h_\times(t) = \epsilon h_+(t) e^{i\pi/2},$$

Number & parameters of wavelets determined by RJMCMC

Similar to multi-component ring-down model of 1705.10850

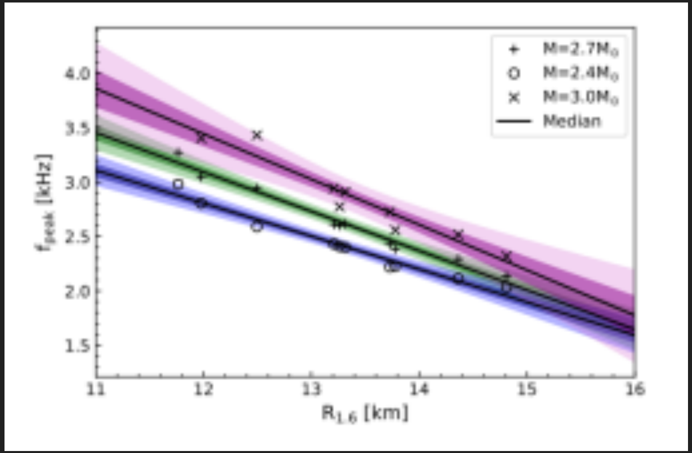


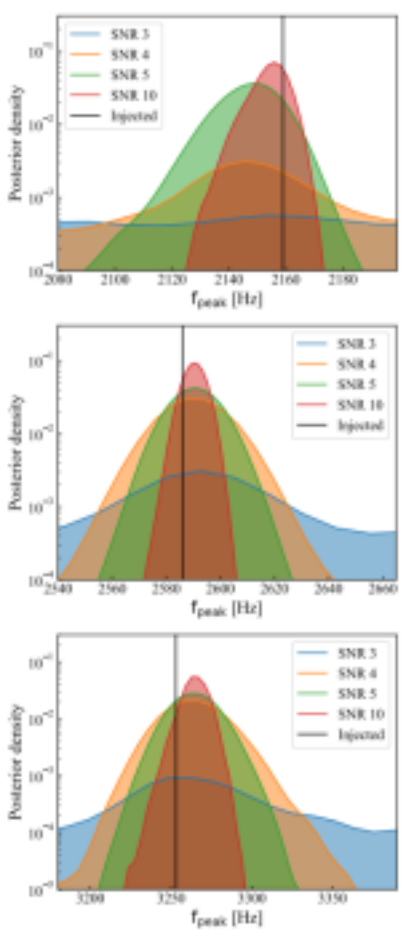
Post-merger parameter estimation

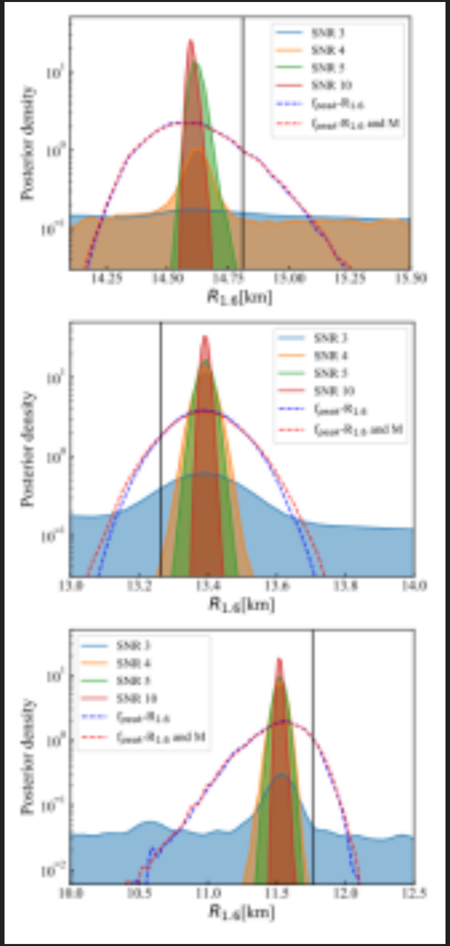
1711.00040: demonstration of Bayesian inference for f_{peak}-$R_{1.6}$ relation

Framework naturally incorporates systematic uncertainty in fitting

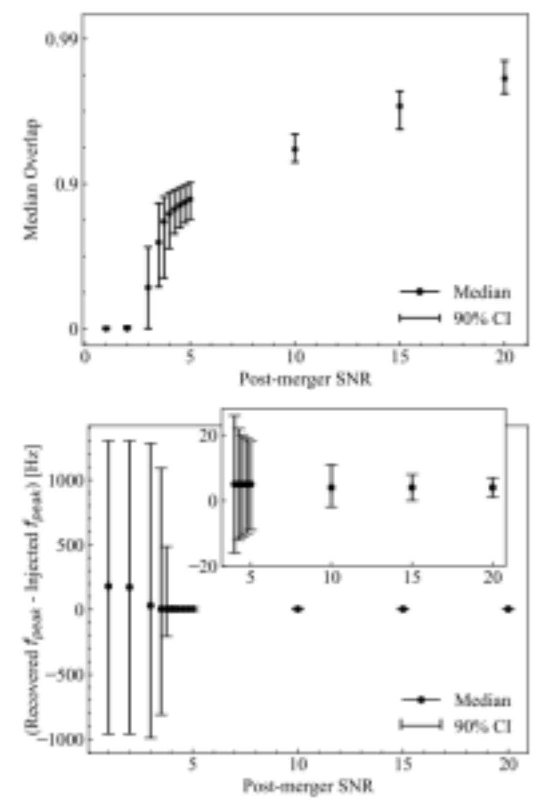
Method applicable to other relations







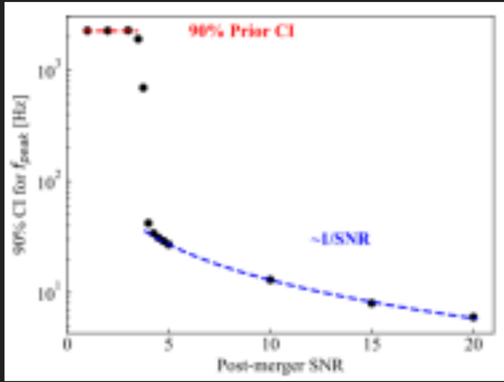
Post-merger parameter estimation



BayesWave quickly recovers f_{peak} as SNR>3

Comparable performance with matched-filtering

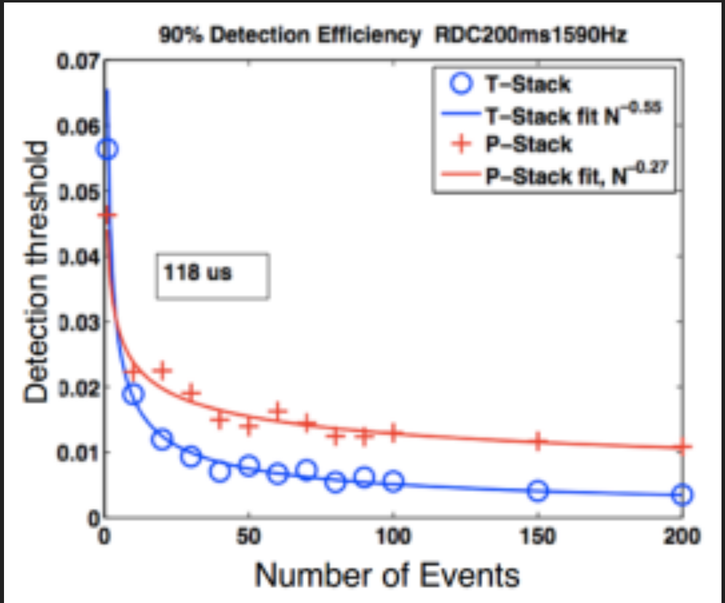
Framework for waveform-*independent* energy/amplitude upper limit as a function of frequency (coming soon)



As SNR>3, accuracy behaves as a matched filter: uncertainty~1/SNR

Stacking

Realistic scenario: multiple low-SNR events; combine & boost SNR?



- "Stacking" first applied to GWs in magnetar searches (0904.4906)
- Sum data streams from independent events
  - Coherent stacking: SNR ~ $N^{1/2}$
  - Power stacking: SNR ~ $N^{1/4}$

Stacking

- Bose et al (1705.10850): Stack amplitude spectra (**aLIGO**):
  - N_{obs} = 100: $\Delta R/R \sim 10\%$
- Yang et al (1707.00207): coherent stacking procedure (**Cosmic Explorer**):
  - N_{obs} = 30: $\Delta R/R \sim 0.1\ \%$
- Promising but measurements dominated by waveforms' different frequency content systematics
- Bayesian "stacking": combine *probabilities* instead of summing data
  - Natural treatment of systematics

Summary

- Quasi-Universal relations & post-merger signals: huge EOS potential
  - e.g., constrain fiducial NS radius to O(100) m [statistical uncertainty]
  - Currently limited by systematics in quasi-Universal relations
- GW170817-like events: *potentially* interesting for post-merger signals
  - Some EOS & full 3-detector network @ design sensitivity
  - Deep follow-up algorithms will dig deeper than fixed-threshold searches
  - Ansatz waveform templates (e.g., 1705.10850) available

GW170817 could still play a role in future stacked searches!

Numerical Relativity Simulation: T. Dietrich (Max Planck Institute for Gravitational Physics) and the BAM collaboration
Scientific Visualization : T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno (Max Planck Institute for Gravitational Physics)