Gravitational Wave Bursts: Inferences Without (Many) Assumptions

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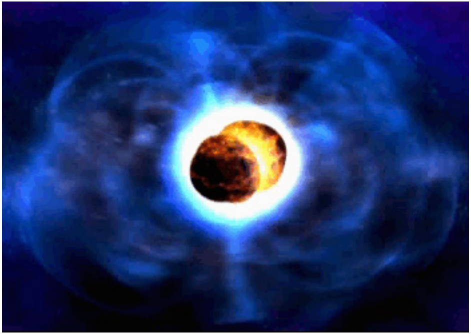


Outline

Current / past work

Highlights:

- Electromagnetically-triggered searches for transient gravitational waves (GWs) in LIGO data. E.g.,
  - Neutron star f-mode oscillations associated with pulsar glitches [1]
  - Searches for un-modelled GW bursts & inspiral signals associated with GRBs [2, 3]
- Prospects for ...
  - ... "joint gravitational wave and short gamma-ray burst observations" [4]
  - ... "high frequency burst searches following binary neutron star coalescence with advanced gravitational wave detectors" [5]

Generally, violent events in neutron stars, Bayesian inference & machine learning $\leftrightarrow$ astrophysical inference from gravitational wave bursts (GWBs)

GW Sources & Detectors

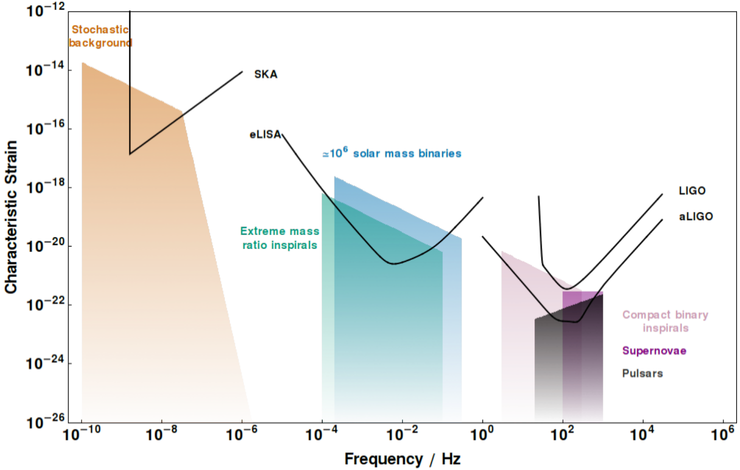


Figure from [6]

GW Sources & Search Methods

Continuous signals:

- Stochastic (e.g., cosmological/astrophysical GWB background) $\rightarrow$ correlate noise spectra between GWB detectors
- Isolated neutron stars (e.g., non-axisymmetry, "mountains" on pulsars; Accretion-induced quadrupole in LMXBs, r-modes $\rightarrow$ quasi-sinusoidal "always-on" signal, modulated by Earth's motion w.r.t source $\rightarrow$ matched-filtering

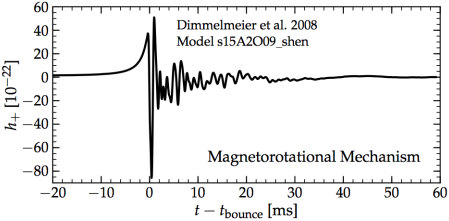
Transient signals broadly classified as:

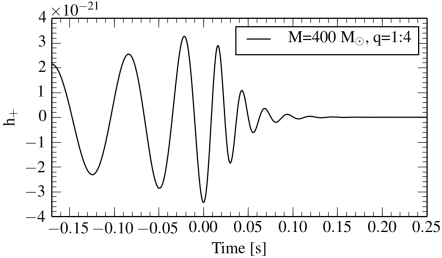
- Well-modeled: e.g., compact binary coalescence (NS-NS, NS-BH, stellar-mass BBH) $\rightarrow$ very accurate waveform "templates" $\rightarrow$ matched-filtering
- 'Bursts'[1]: e.g., SNe, neutron star oscillations / instabilities, merger/post-merger signals with matter, IMBBH

[1] today's focus

Gravitational Wave "Bursts"

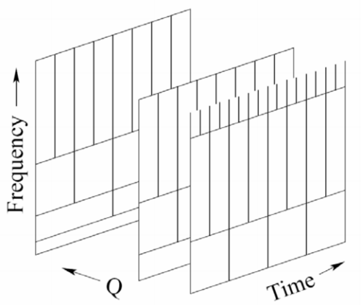
- Transient: duration $\sim \mathcal{O}(10^{-3} - 100)\,\mathrm{s}$
- Uncertain morphology: matched-filtering ineffective or biased
- More certain morphology but few waveform cycles: 'excess power' searches competitive with matched-filtering





GWB Analysis: Excess Power

- Time-frequency decomposition of detector time-series data
- 'Excess power' due to e.g., GWs manifests as hot pixels in time-frequency plane

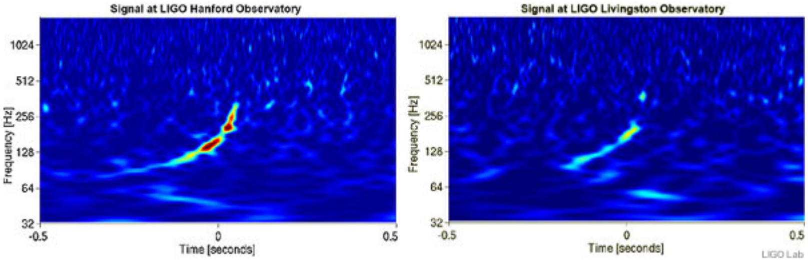


Time-Frequency Analysis

Typically decompose data at multiple resolutions via e.g., wavelets , Q-transforms, STFTs

GWB Analysis: Excess Power

Example: binary neutron star inspiral signal observed in Hanford and Livingston detectors (blind hardware injection during final science run)



GWBs: Coherent Analysis

- **Problem:** GW detector data: highly-nonstationary, *full* of excess power
- **Solution:** search for *coherent* power a detector network

Single-pixel network analysis (following e.g., [7]):

$$\underbrace{\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_D \end{bmatrix}}_{\text{measured data}} = \underbrace{\begin{bmatrix} F_1^+(\boldsymbol{\Omega})/\sigma_1 & F_1^\times(\boldsymbol{\Omega})/\sigma_1 \\ F_2^+(\boldsymbol{\Omega})/\sigma_2 & F_2^\times(\boldsymbol{\Omega})/\sigma_2 \\ \vdots & \vdots \\ F_D^+(\boldsymbol{\Omega})/\sigma_D & F_D^\times(\boldsymbol{\Omega})/\sigma_D \end{bmatrix}}_{\text{whitened antenna responses}} \underbrace{\begin{bmatrix} h_+ \\ h_\times \end{bmatrix}}_{\text{GW polarizations}} + \underbrace{\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_D \end{bmatrix}}_{\text{noise}} \tag{1}$$

i.e.,

$$\begin{aligned} \mathbf{d} &= [\mathbf{F}_+ \mathbf{F}_\times]\,\mathbf{h} + \mathbf{n} \\ &= \mathbf{F}\mathbf{h} + \mathbf{n} \end{aligned} \tag{2}$$

GWBs: Coherent Analysis

Likelihood for signal (h) vs noise (0):

$$\mathcal{L} = 2\log\frac{P(\mathbf{d}|\mathbf{h})}{P(\mathbf{d}|0)} = |\mathbf{d}|^2 - |\mathbf{d} - \mathbf{F}\mathbf{h}|^2 \tag{3}$$

- Treat waveform values $\mathbf{h} = (h_+,\ h_\times)$ in each pixel as free parameters; maximise $\mathcal{L}$ to form *standard likelihood*

$$E_{\mathrm{SL}} = \mathbf{d}^T \mathbf{F}\mathbf{F}_{\mathrm{MP}}^{-1}\mathbf{d} \tag{4}$$

- where $\mathbf{F}_{\mathrm{MP}}^{-1} = (\mathbf{F}^T\mathbf{F})^{-1}\mathbf{F}^T$
- $\mathbf{F}\mathbf{F}_{\mathrm{MP}}^{-1}$ projects data onto $(\mathbf{F}_+, \mathbf{F}_\times)$ sub-space
- Residual data with signal removed should be Gaussian. Can reject non-Gaussian glitches by looking at the null energy:

$$E_{\mathrm{null}} = \mathbf{d}^T(\mathbf{I} - \mathbf{F}\mathbf{F}_{\mathrm{MP}}^{-1})\mathbf{d} \tag{5}$$

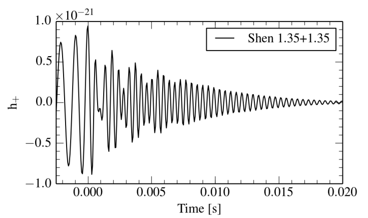
1. Gravitational Wave Sources
   - Search Methods
   - Burst Analysis Strategies

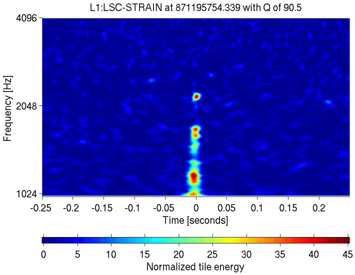
2. Gravitational Wave 'Bursts'
   - Burst Analysis Example: Binary Neutron Star Coalescence

3. Summary

Binary Neutron Star Mergers & GWBs

- BNS *inspiral* detectable to 200 Mpc in aLIGO[2]
- Post-merger scenarios:
  1. prompt-collapse
  2. quasi-stable NS
  3. stable NS
- 2, 3 favored by many simulations, equations of state
- GW morphology poorly known, broadband power in $\sim 1 - 4\,\mathrm{kHz}$ + dominant oscillation frequency
- Detectable to few–10’s Mpc

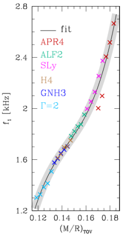




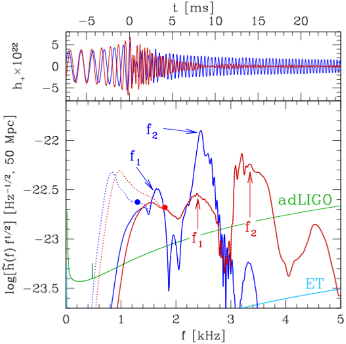
[1] at design sensitivity $\sim$ 2019

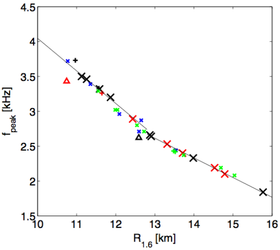
Post-merger Oscillations & NS EOS

- Bauswein et al [8]: dominant post-merger oscillation frequency (f_{peak}) correlates with fiducial NS radius
- Takami et al [9]: similar findings + possible correlation of sub-dominant freq. with NS compactness
- Bauswein et al [10]: constrain maximum NS mass with f_{peak}



Takami et al: $f_1 - M/R$ correlation





Bauswein et al: $f_{\text{peak}} - R_{1.6}$ correlation

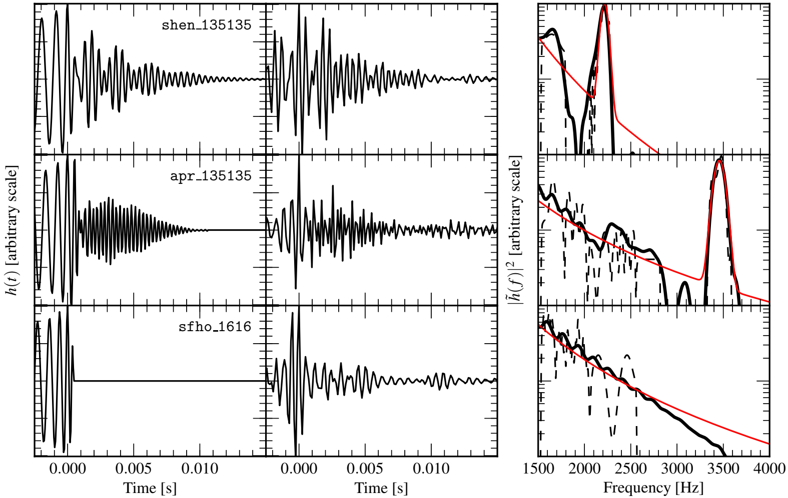
Measuring Post-merger Oscillations In GWs

Clark et al [5]: developed algorithm to analyze post-merger signatures detected (and reconstructed) by burst searches.
Basic idea:

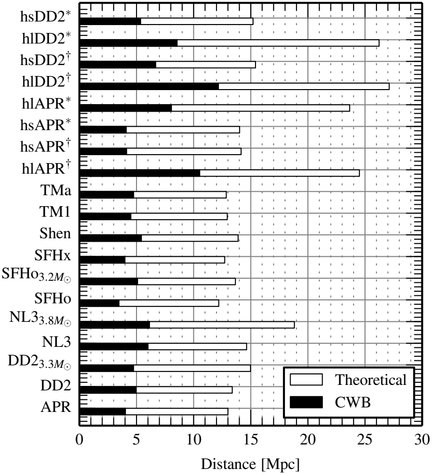
- Search for statistically significant, high-frequenccy power at time around BNS coalescence
- Detection $\rightarrow$ reconstructs signal $\hat{\mathbf{h}}$
- Spectral analysis of $\hat{\mathbf{h}}$ allows classification of prompt/delayed collapse, measurement of $f_{\rm peak}$

Allows to detect signal and extract astrophysically relevant information without precise waveform models, just generic features ($f_{\rm peak}$)

Measuring Post-merger Oscillations In GWs



Measuring Post-merger Oscillations In GWs



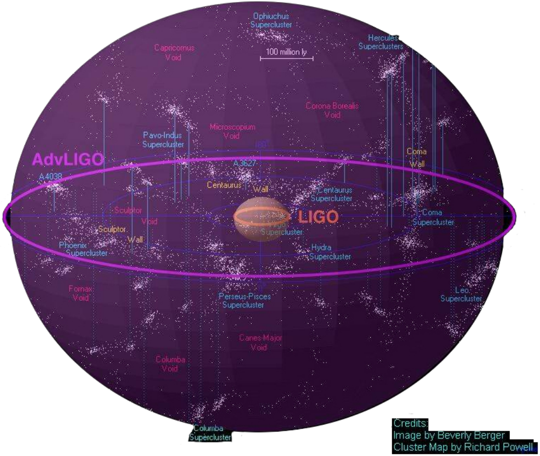
- Compared theoretical matched-filter & *realistic* burst search detectability for aLIGO network for different EoSs
- Translate f_{peak} measurement accuracy to inference on NS radius
- **recover radius to $\mathcal{O}(100\,m)$ within a sphere of 5 Mpc** (1/century – 1/1000 year) rate
- So..not likely, but extraordinary measurements possible with 3$^{\mathrm{rd}}$ generation detectors!

Summary

- Ground-based GWB detectors: sensitive to wide variety of (typically) compact sources (NS, BH, ...)
- Known signal: matched-filtering; project data onto waveform "template" basis
- Unknown signal: coherent time-frequency analysis; project data onto detector sub-space, compare with projection onto null-space
- Example application: merger/post-merger signal from BNS
    - Detect coherent power without a model
    - Reconstruct max-likelihood GWB $\hat{h}(t)$
    - Identify characteristic features in $|\hat{H}(f)|$ & determine post-merger scenario, constrain NS EoS
- aLIGO to come online $\sim$spring next year...

Advanced LIGO

See [11] for planned science runs, expected detections from *next year*



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