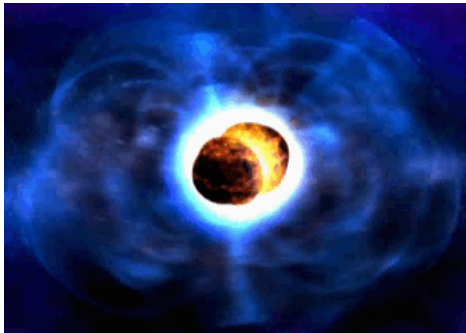


# Gravitational Wave Bursts: Inferences Without (Many) Assumptions

James A. Clark

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# Outline

- 1 Gravitational Wave Sources
  - Search Methods
  - Burst Analysis Strategies
- 2 Gravitational Wave 'Bursts'
  - Burst Analysis Example: Binary Neutron Star Coalescence
- 3 Summary

## 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

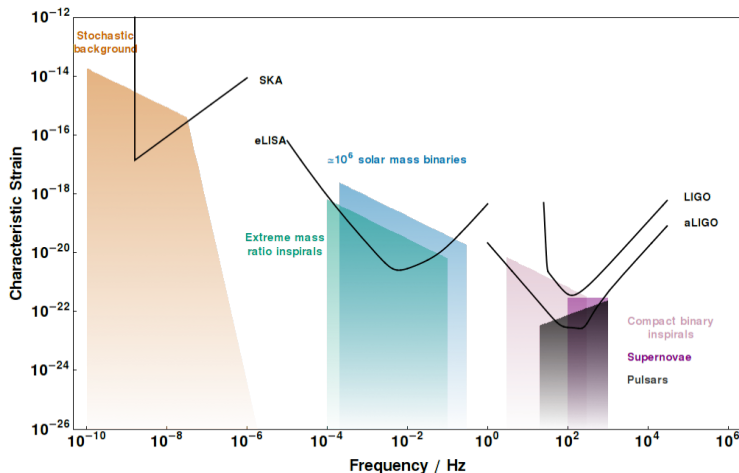


Figure from [6]

# GW Sources & Search Methods

Continuous signals:

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

Transient signals broadly classified as:

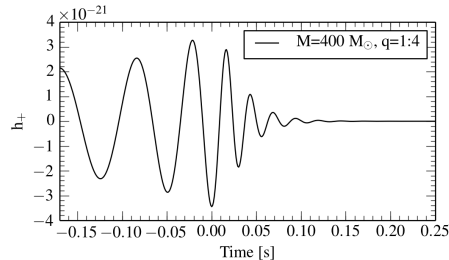
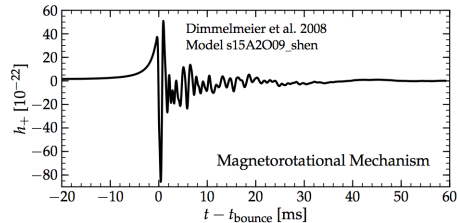
- Well-modeled: e.g., compact binary coalescence (NS-NS, NS-BH, stellar-mass BBH) → very accurate waveform “templates” → matched-filtering
- ‘Bursts’<sup>1</sup>: e.g., SNe, neutron star oscillations / instabilities, merger/post-merger signals with matter, IMBBH

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<sup>1</sup>today's focus

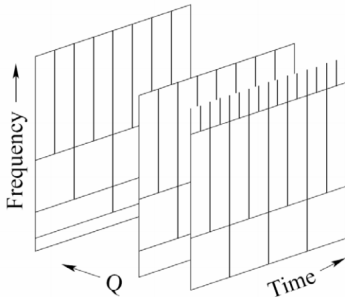
# Gravitational Wave “Bursts”

- Transient: duration  $\sim \mathcal{O}(10^{-3} - 100) \text{ s}$
- 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

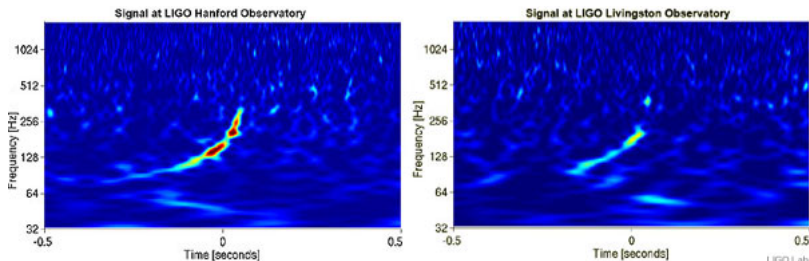


## Time-Frequency Analysis

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]):

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

i.e.,

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

# GWBs: Coherent Analysis

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

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

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

$$E_{\text{SL}} = \mathbf{d}^T \mathbf{F} \mathbf{F}_{\text{MP}}^{-1} \mathbf{d} \quad (4)$$

- where  $\mathbf{F}_{\text{MP}}^{-1} = (\mathbf{F}^T \mathbf{F})^{-1} \mathbf{F}^T$
- $\mathbf{F} \mathbf{F}_{\text{MP}}^{-1}$  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:

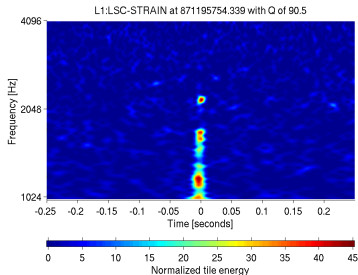
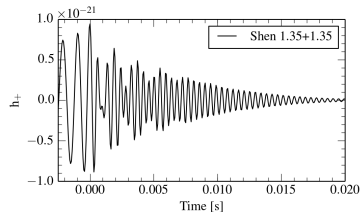
$$E_{\text{null}} = \mathbf{d}^T (\mathbf{I} - \mathbf{F} \mathbf{F}_{\text{MP}}^{-1}) \mathbf{d} \quad (5)$$

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# Binary Neutron Star Mergers & GWBs

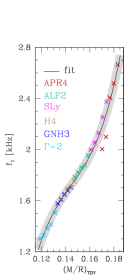
- BNS *inspiral* detectable to 200 Mpc in aLIGO<sup>2</sup>
- Post-merger scenarios:
  - 1 prompt-collapse
  - 2 quasi-stable NS
  - 3 stable NS
- 2, 3 favored by many simulations, equations of state
- GW morphology poorly known, broadband power in  $\sim 1 - 4$  kHz + dominant oscillation frequency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

<sup>1</sup> at design sensitivity  $\sim 2019$

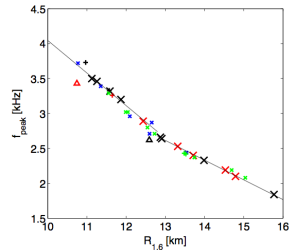
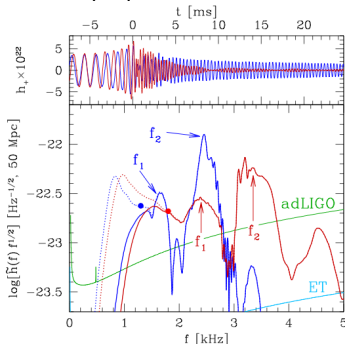


# Post-merger Oscillations & NS EOS

- Bauswein et al [8]: dominant post-merger oscillation frequency ( $f_{\text{peak}}$ ) 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  $f_{\text{peak}}$



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



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

# Measuring Post-merger Oscillations In GWs

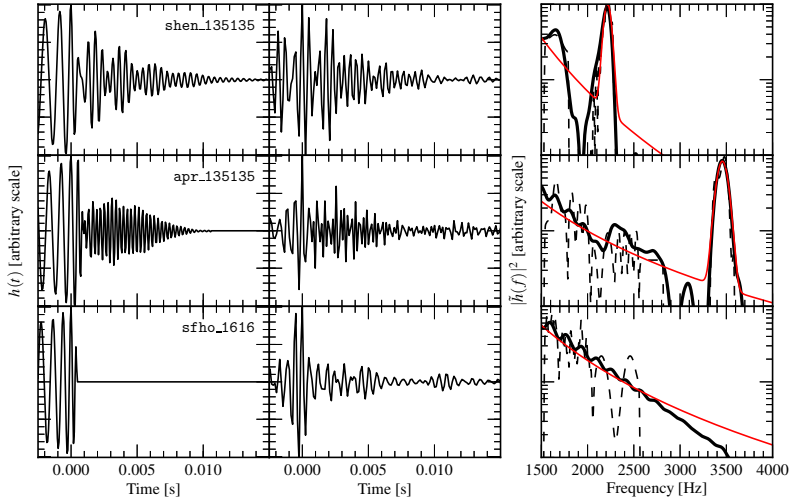
Clark et al [5]: developed algorithm to analyze post-merger signatures detected (and reconstructed) by burst searches.

Basic idea:

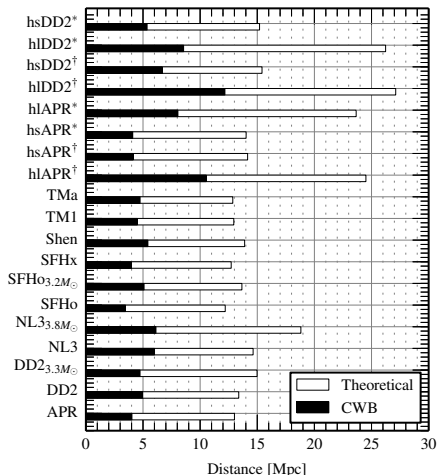
- Search for statistically significant, high-frequency power at time around BNS coalescence
- Detection  $\rightarrow$  reconstructs signal  $\hat{\mathbf{h}}$
- Spectral analysis of  $\hat{\mathbf{h}}$  allows classification of prompt/delayed collapse, measurement of  $f_{\text{peak}}$

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

# 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  $f_{\text{peak}}$  measurement accuracy to inference on NS radius
- **recover radius to  $\mathcal{O}(100\text{ m})$  within a sphere of 5 Mpc** (1/century – 1/1000 year) rate
- So..not likely, but extraordinary measurements possible with 3<sup>rd</sup> generation detectors!

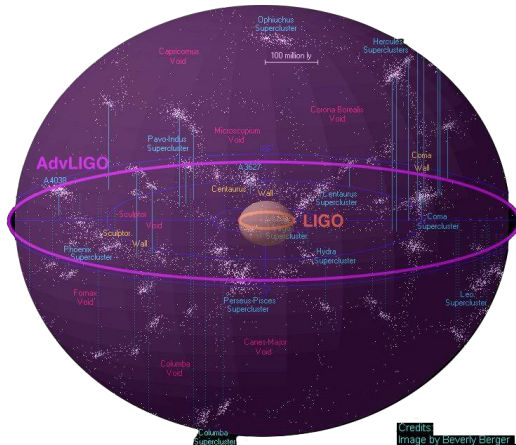


# Summary

- Ground-based GW 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 GW  $\hat{h}(t)$
  - 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*



Credits  
Image by Beverly Berger  
Cluster Map by Richard Powell

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