Astrophysics with Gravitational Wave Transients

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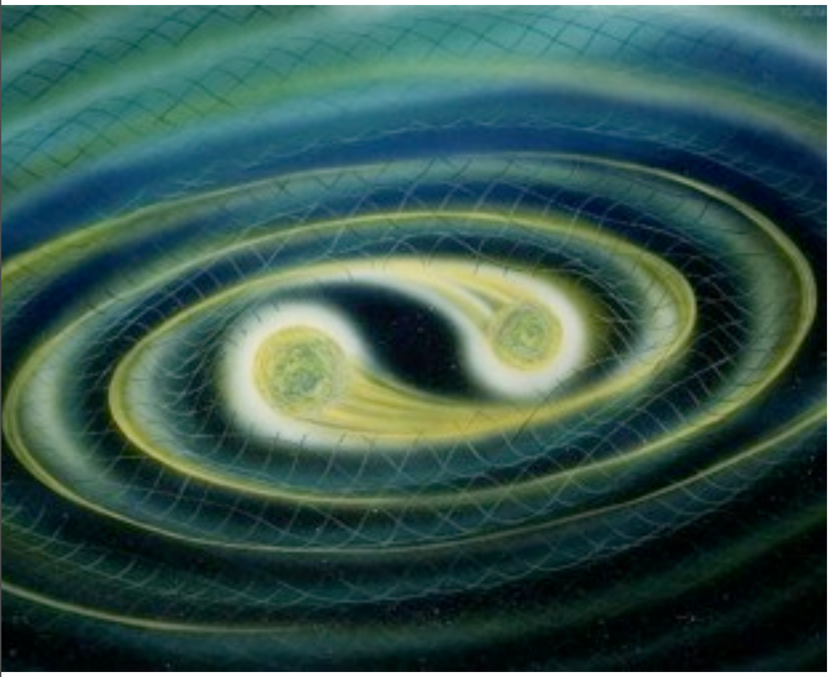
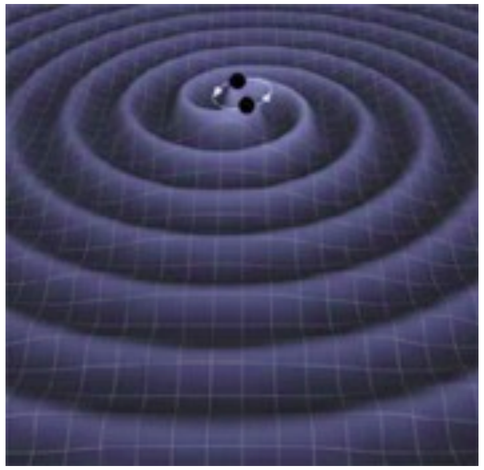
Outline

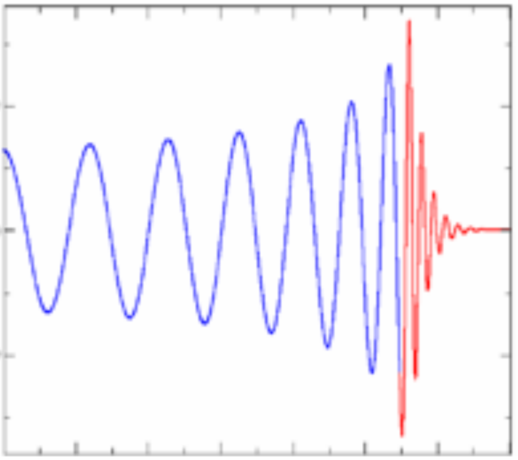
1. Gravitational Wave Bursts: how we look for them and the challenge of glitch hunting
2. “Burst First”: Binary Black Hole Coalescences
3. Post-Merger Oscillations



Gravitational Wave Bursts: how we look for them and the Challenge of Glitch Hunting

Searches for GW Transient Sources

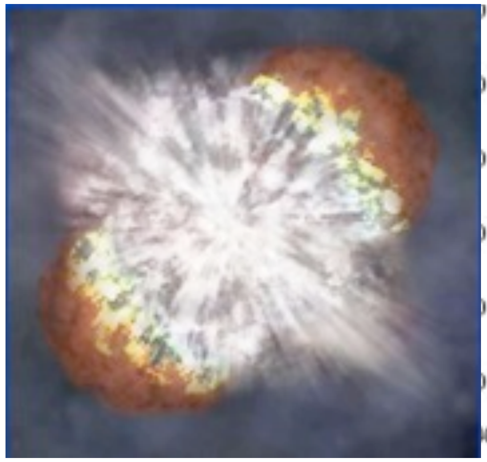


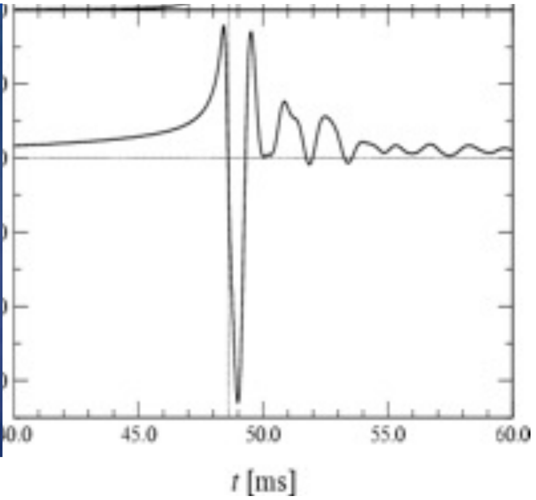


Compact Binary Coalescence (CBC)

Known waveform ⇒ Matched filtering

Templates for a range of component masses (spin affects waveforms too)





Generic GW Burst (< ~1 sec duration)

Arbitrary waveform ⇒ Excess power

Require coherent signals in multiple detectors, using direction-dependent antenna response

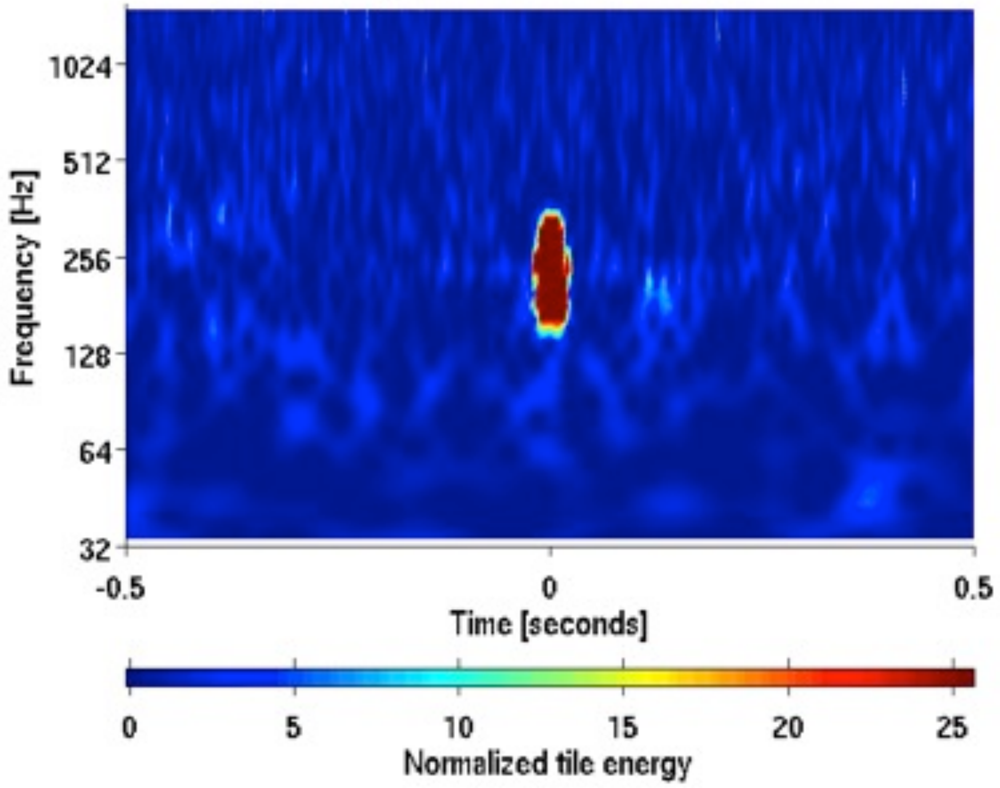
Burst Search Strategy: Excess Power

Sensitive to any signal with duration up to ~1 s.

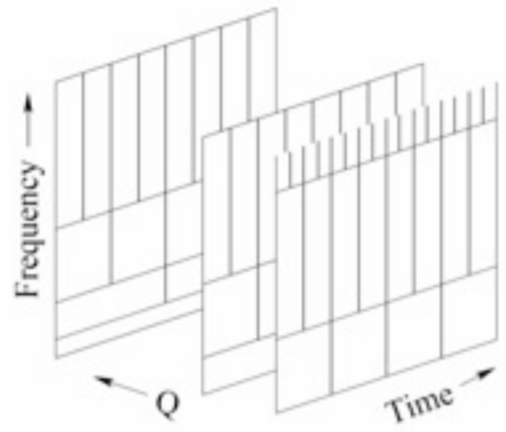
Do not use (high accuracy) templates, can be educated by robust features in astrophysics models.

All-sky, all-time search for transient increase in power in time-frequency maps, minimal assumptions:

1. **Duration**: 1 to 100 ms (characteristic time scale for stellar mass objects)
2. **Frequency**: 60 to 2,000 Hz (determined by detector's sensitivity)
3. **Coherence** in multiple detectors, consistent with antenna pattern ==> waveform, sky location

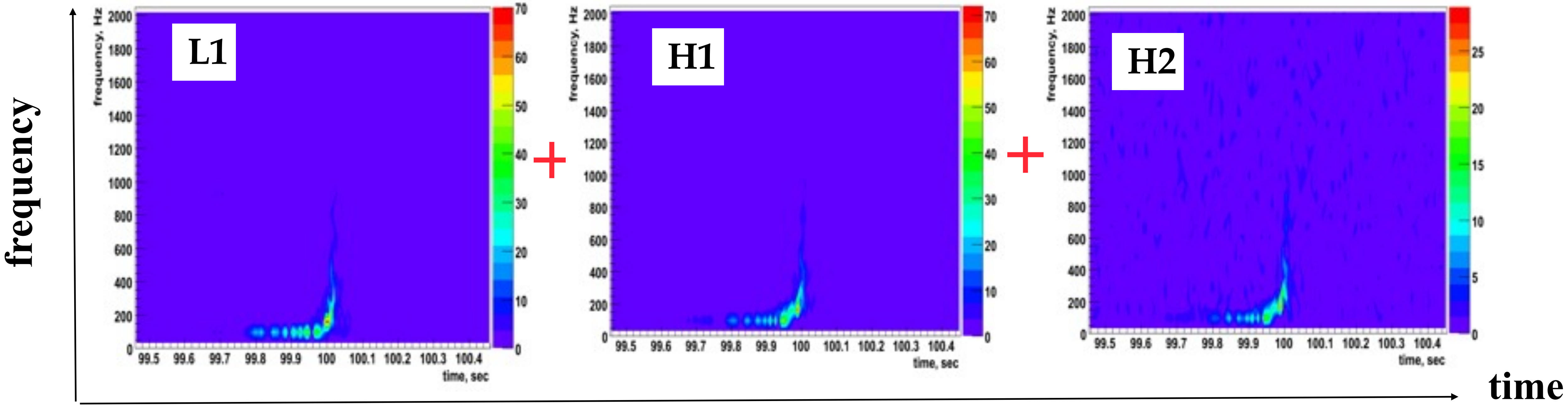


Time-frequency maps options: Fourier, wavelets, sine-Gaussians.... Multiple time/frequency resolutions



Coherent WaveBurst (CWB)

Example: simulated BBH in Initial LIGO: 18 M⊙, 2 Mpc

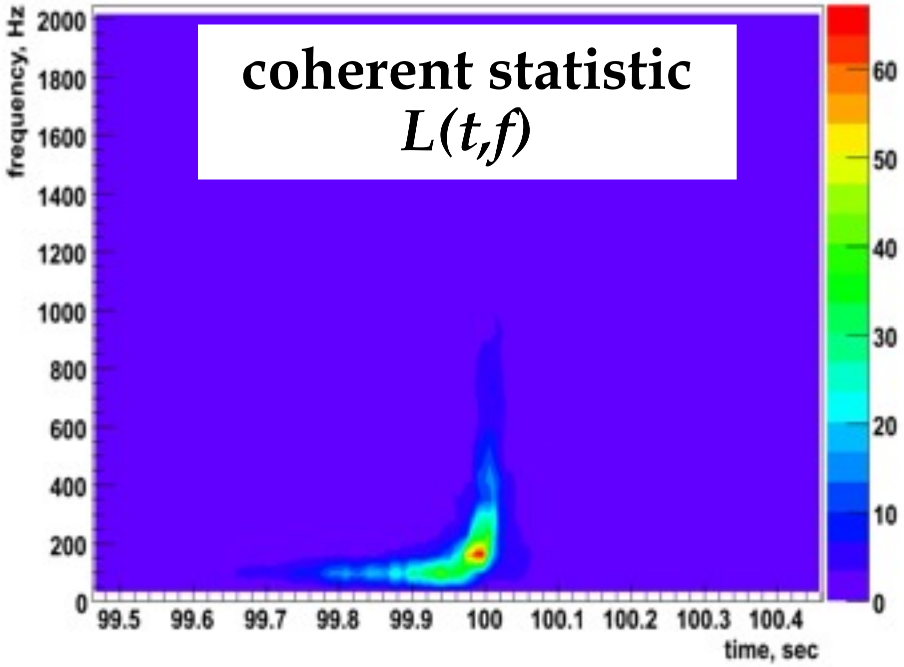


$$\xi_k = h_+ F_{+,k} + h_\times F_{\times,k}$$

$$L(t,f) = \max_{h_+,h_\times,\theta,\phi} \sum_k \frac{x_k^2[t,f] - (x_k[t,f] - \xi_k[t,f])^2}{\sigma_k^2(f)}$$

Coherent statistics, likelihood maximized over waveform, position.

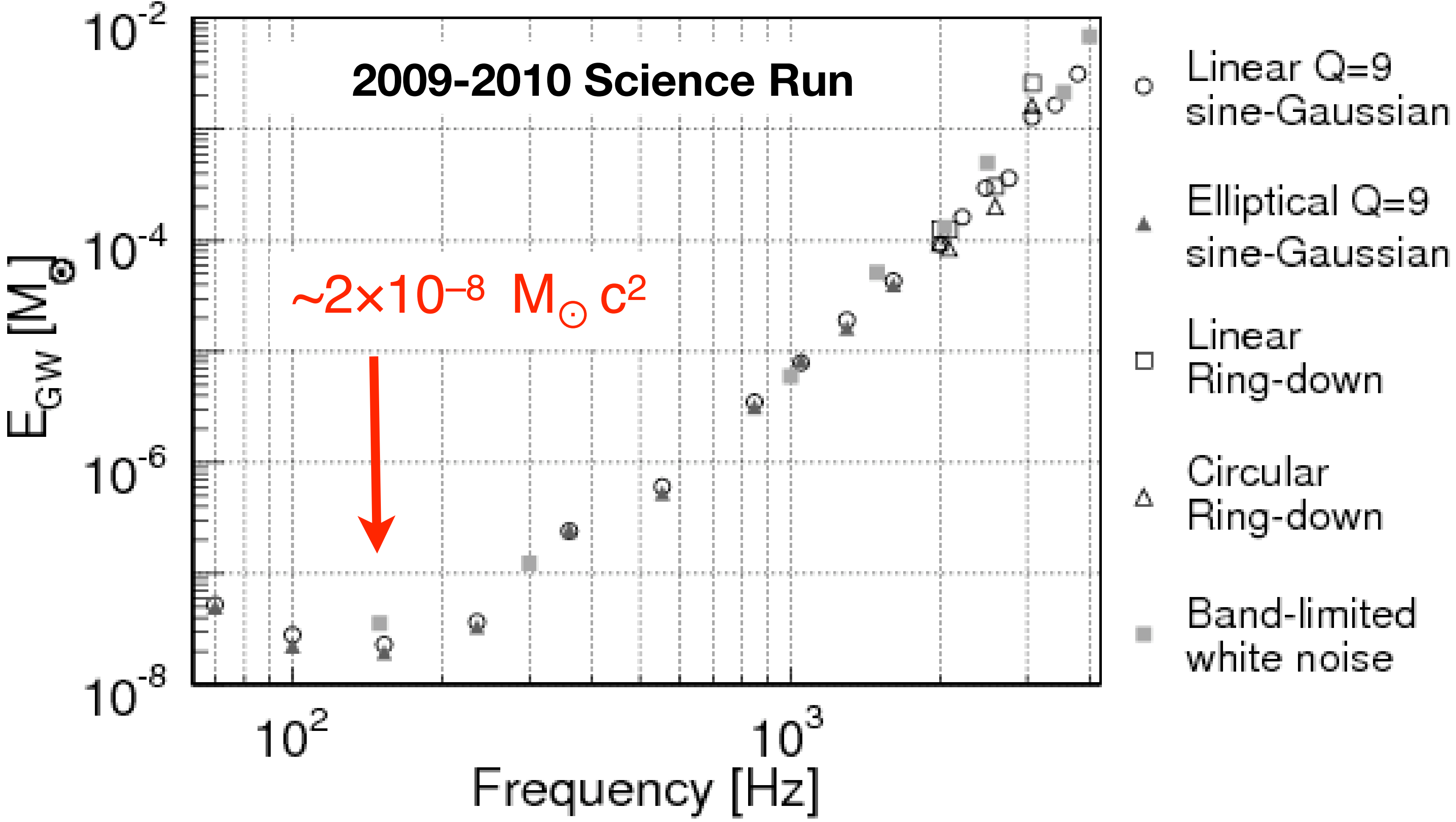
Can impose model-dependent constraints.



Klimenko et al, CQG 25:114029,2008

Search Sensitivity for Transients: Initial LIGO/Virgo

PRD 85 (2012) 122007



$\sim 2\times10^{-8}\ M_\odot c^2$

GW energy in short pulses **from the galactic center**, detectable with 50% probability.

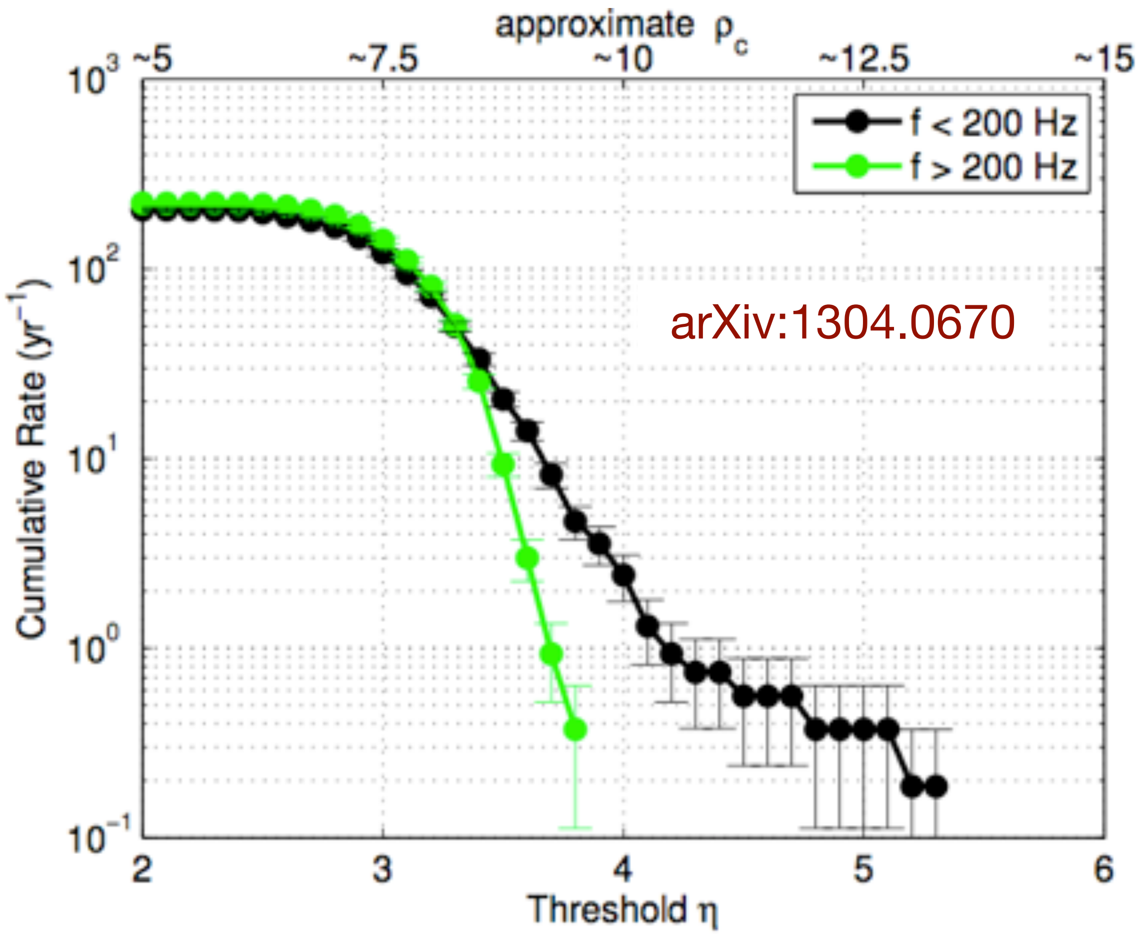
Function of frequency and waveform.

Distance scaling: $\mathbf{E_{GW} \propto D^2}$

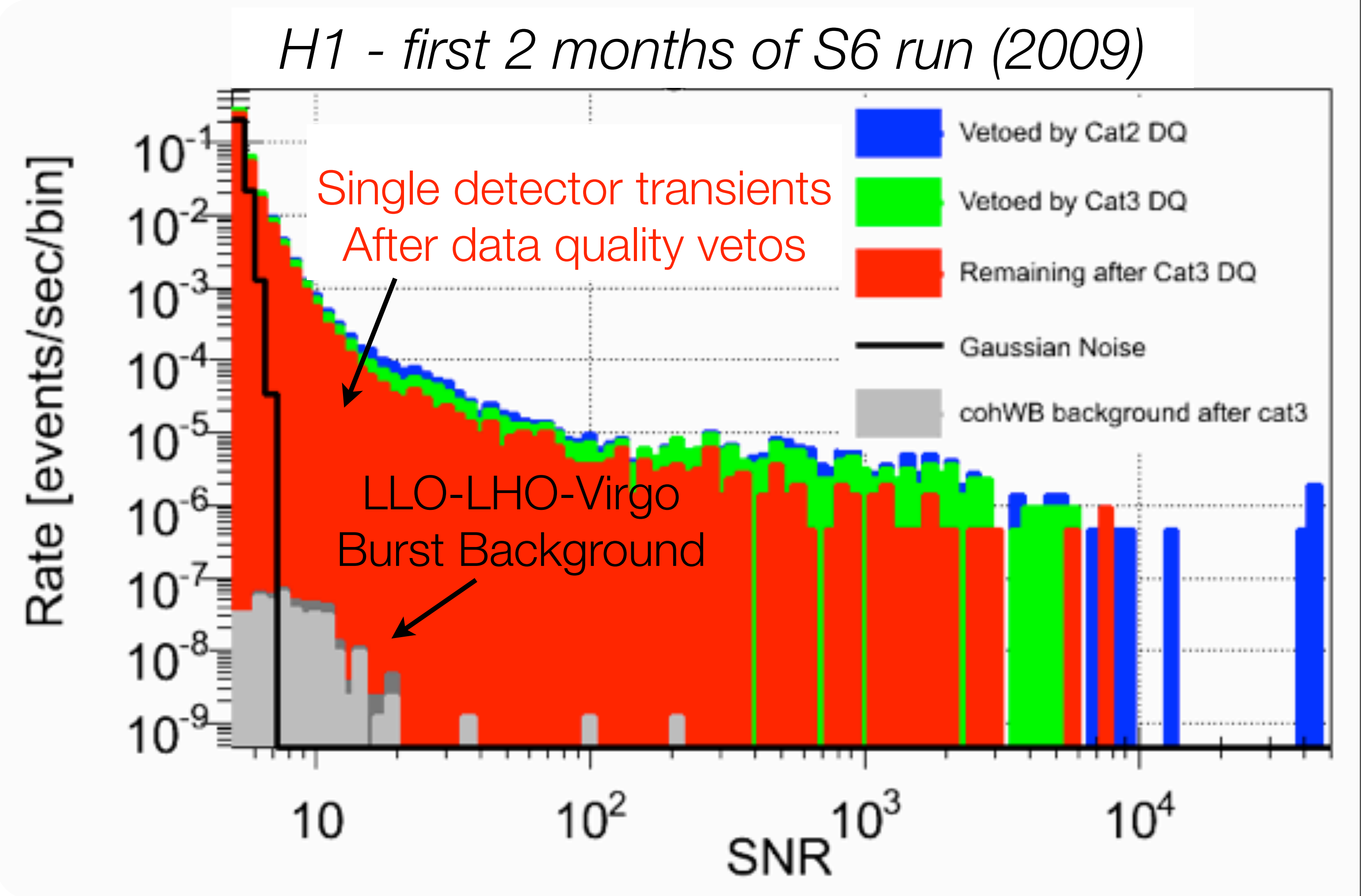
(so, need ~3×10^6 more E_{GW} for a signal from the Virgo Cluster to be detectable)

E.G. sensitive to galactic supernovae:
Core Collapse Supernovae numerical simulations: E_{GW} up to $10^{-7}\ M_\odot c^2$
Analytical calculations for extreme CCSN models: E_{GW} up to $10^{-2}\ M_\odot c^2$

Challenge: False Alarms from Noise Transients



arXiv:1304.0670



H1 - first 2 months of S6 run (2009)

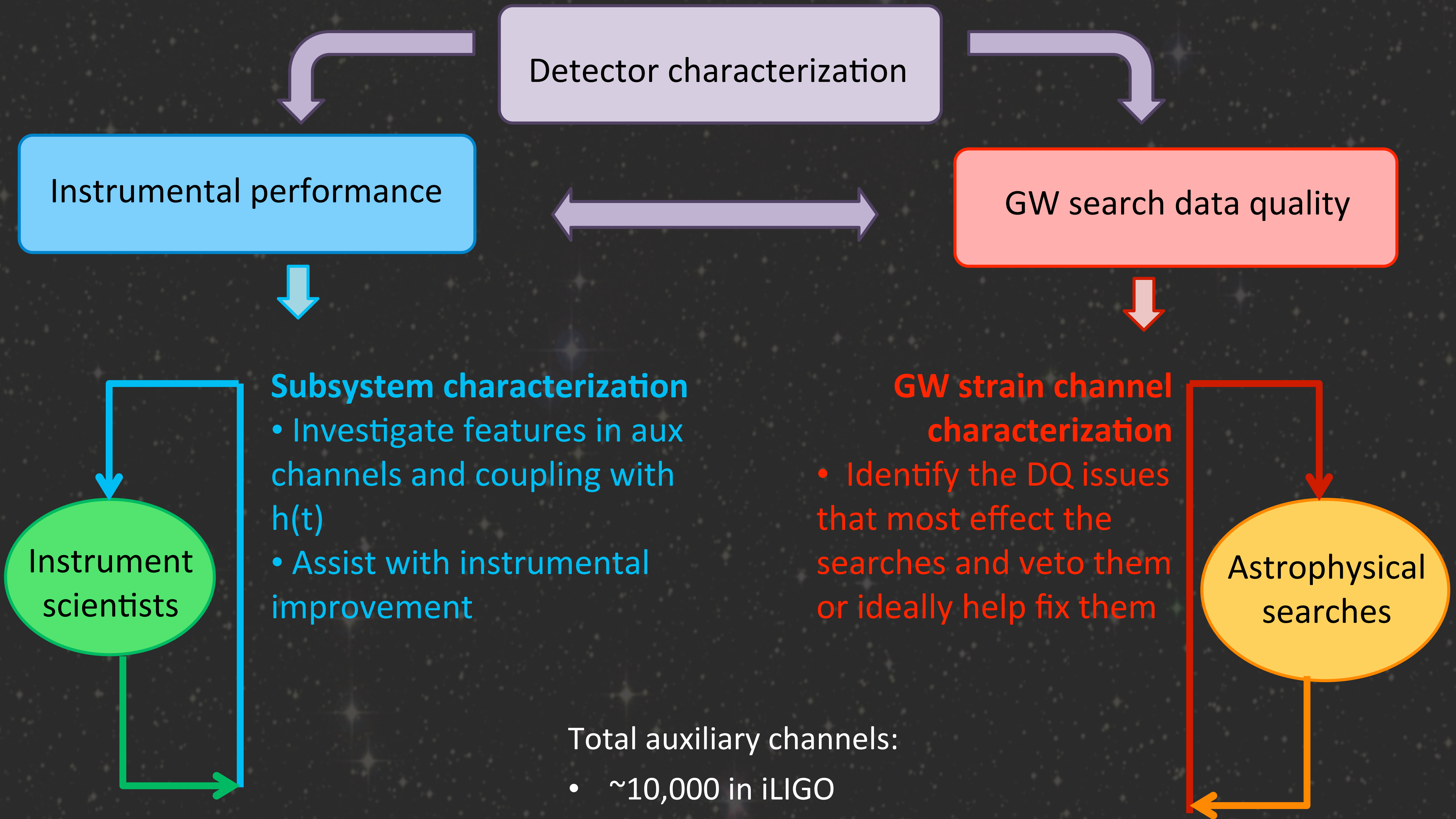
Single detector transients
After data quality vetos

LLO-LHO-Virgo
Burst Background

- Data from 2009-2010 run
- η = coherent network amplitude
- $\rho_c \sim \mathrm{sqrt}(2N)\ \eta$
- N= number of detectors

The LIGO-Virgo burst group is working to improve search algorithms and coherent cuts (Coherent WaveBurst 2G)
But to address the problem at the root: detector characterization

Detector Characterization in aLIGO



Detector characterization

Instrumental performance

GW search data quality

Instrument scientists

Subsystem characterization

- Investigate features in aux channels and coupling with h(t)
- Assist with instrumental improvement

GW strain channel characterization

- Identify the DQ issues that most effect the searches and veto them or ideally help fix them

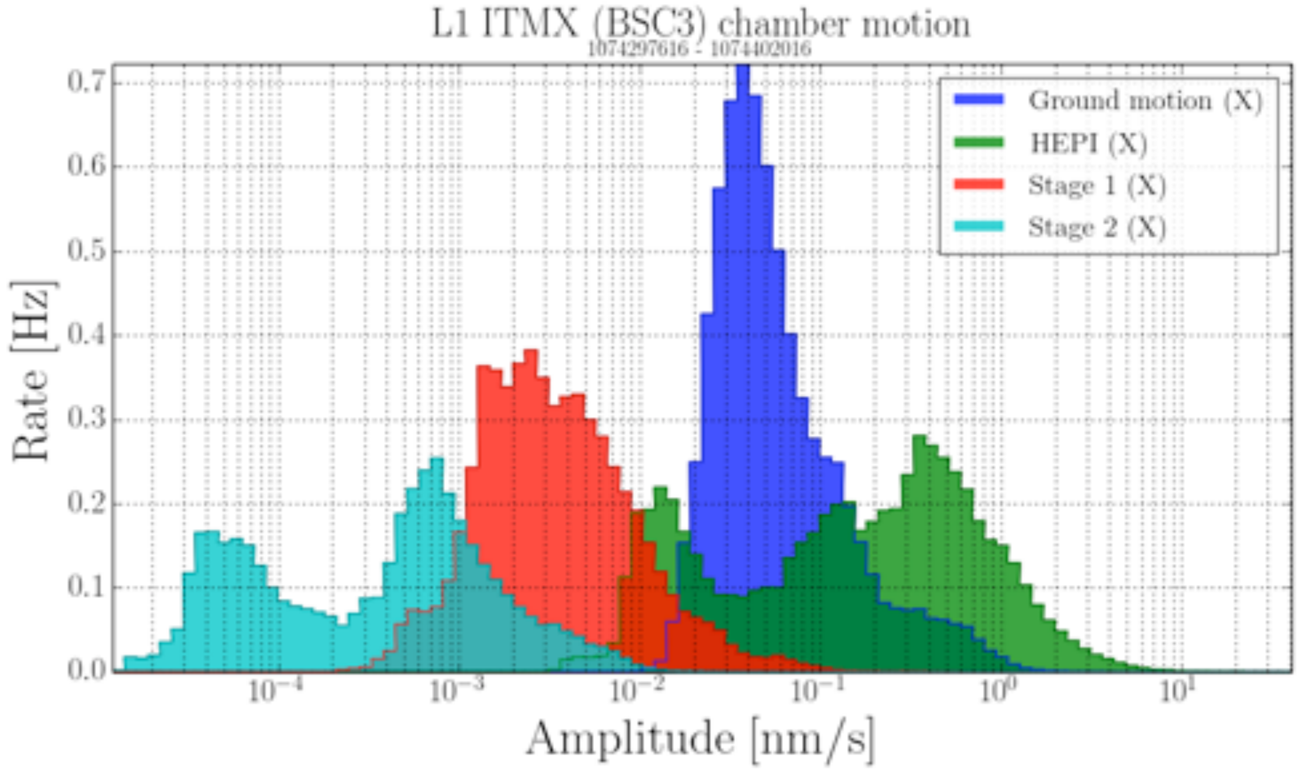
Astrophysical searches

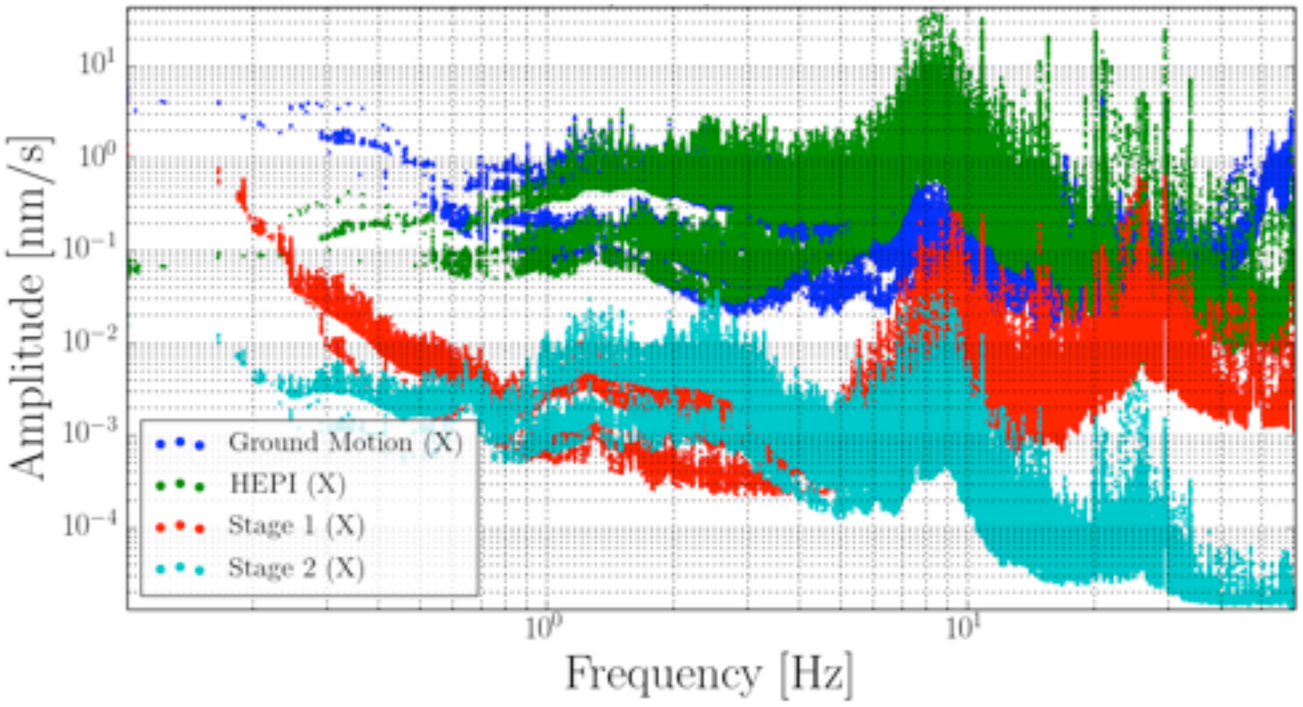
Total auxiliary channels:

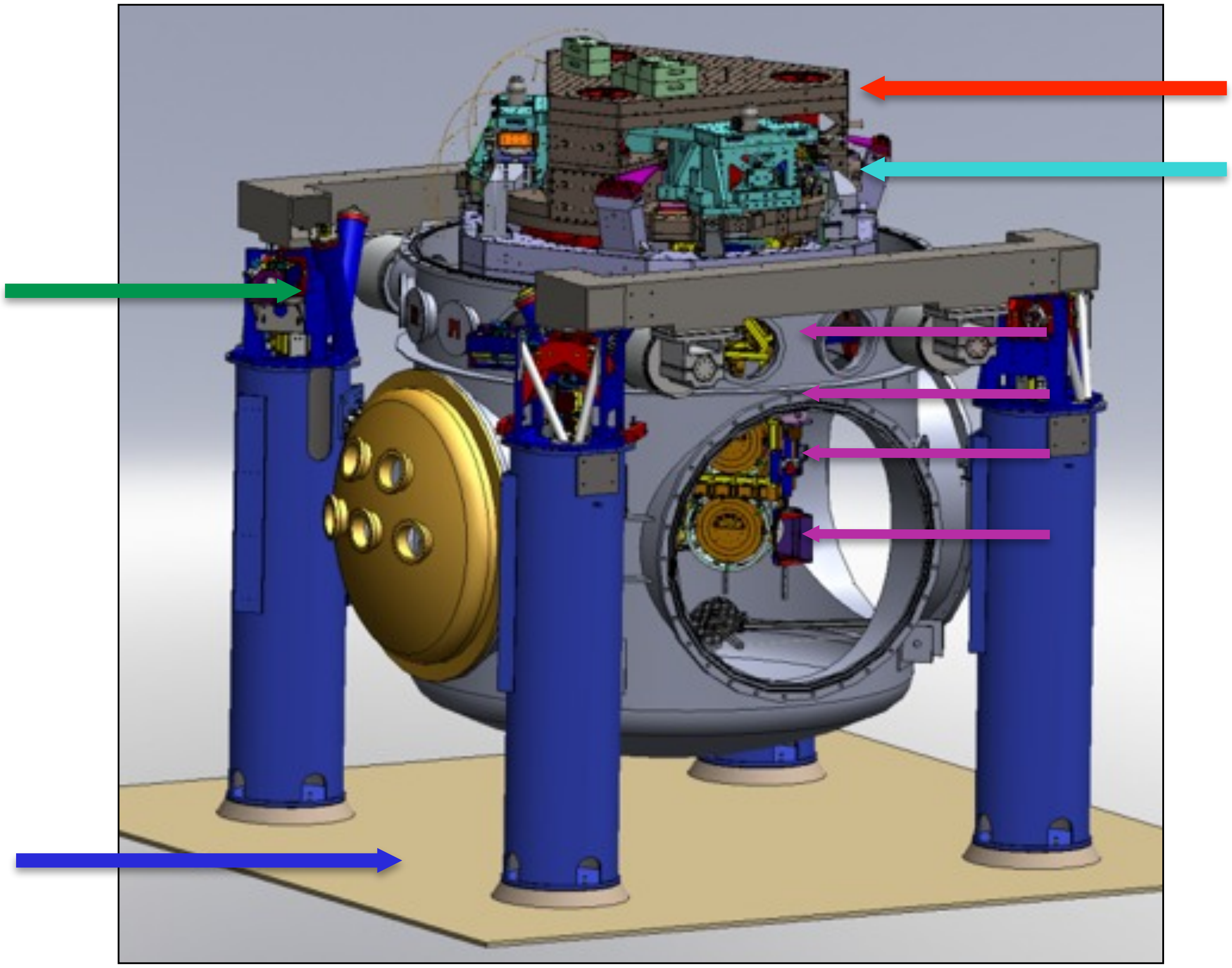
- ~10,000 in iLIGO
- **~170,000 in aLIGO**!

J. McIver 2014

Example: Propagation of Noise Transients in Active Seismic Isolation Stages





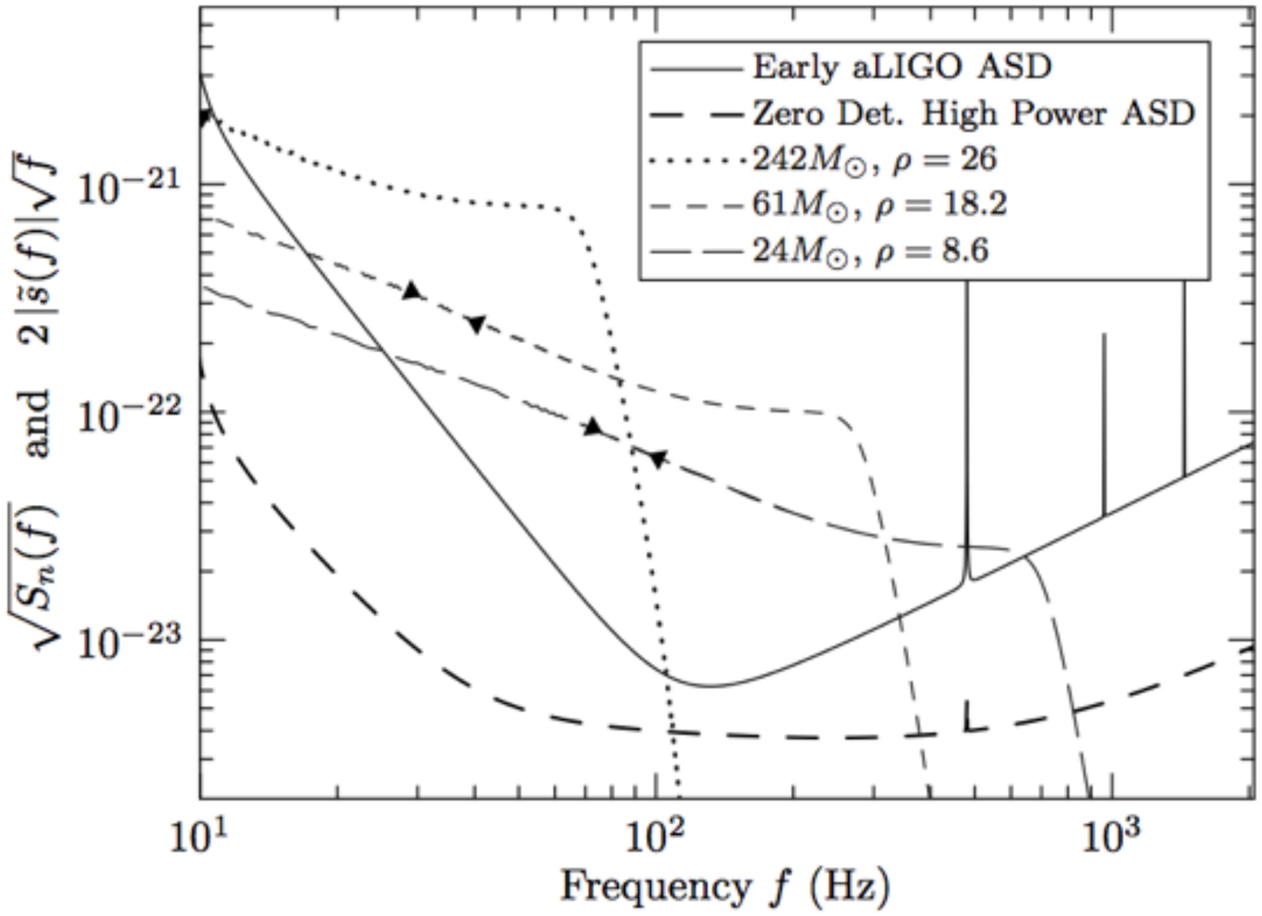


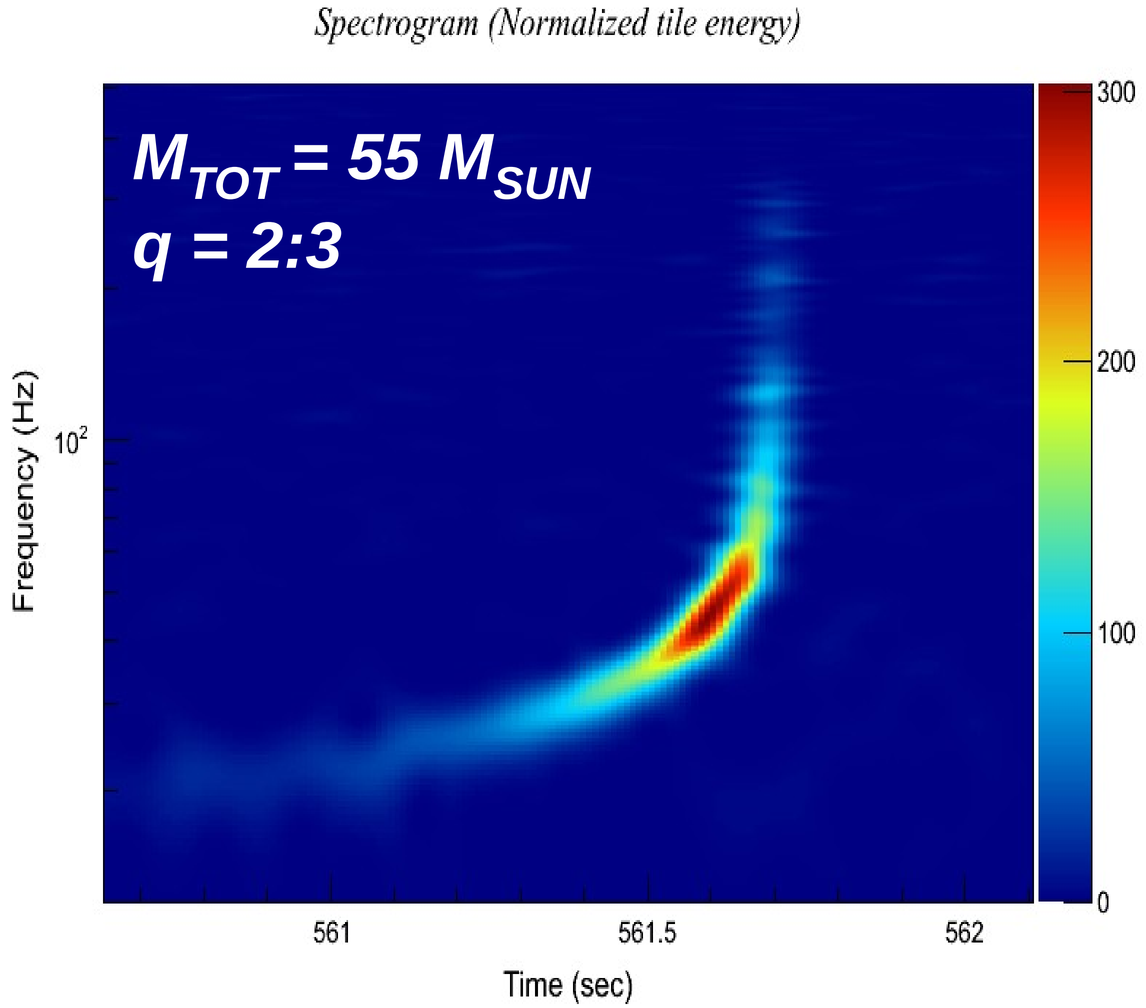
Results: transient motion is mostly reduced, except amplified at ~10Hz.
Investigating if this will upconvert to higher frequencies, but is limiting at lower frequencies.

J. McIver 2014

Semi-modeled analysis:
Black Hole Binary Systems

Stellar Mass Binary Black Holes (10-100 M⊙)





$M_{TOT} = 55\ M_{SUN}$

$q = 2:3$

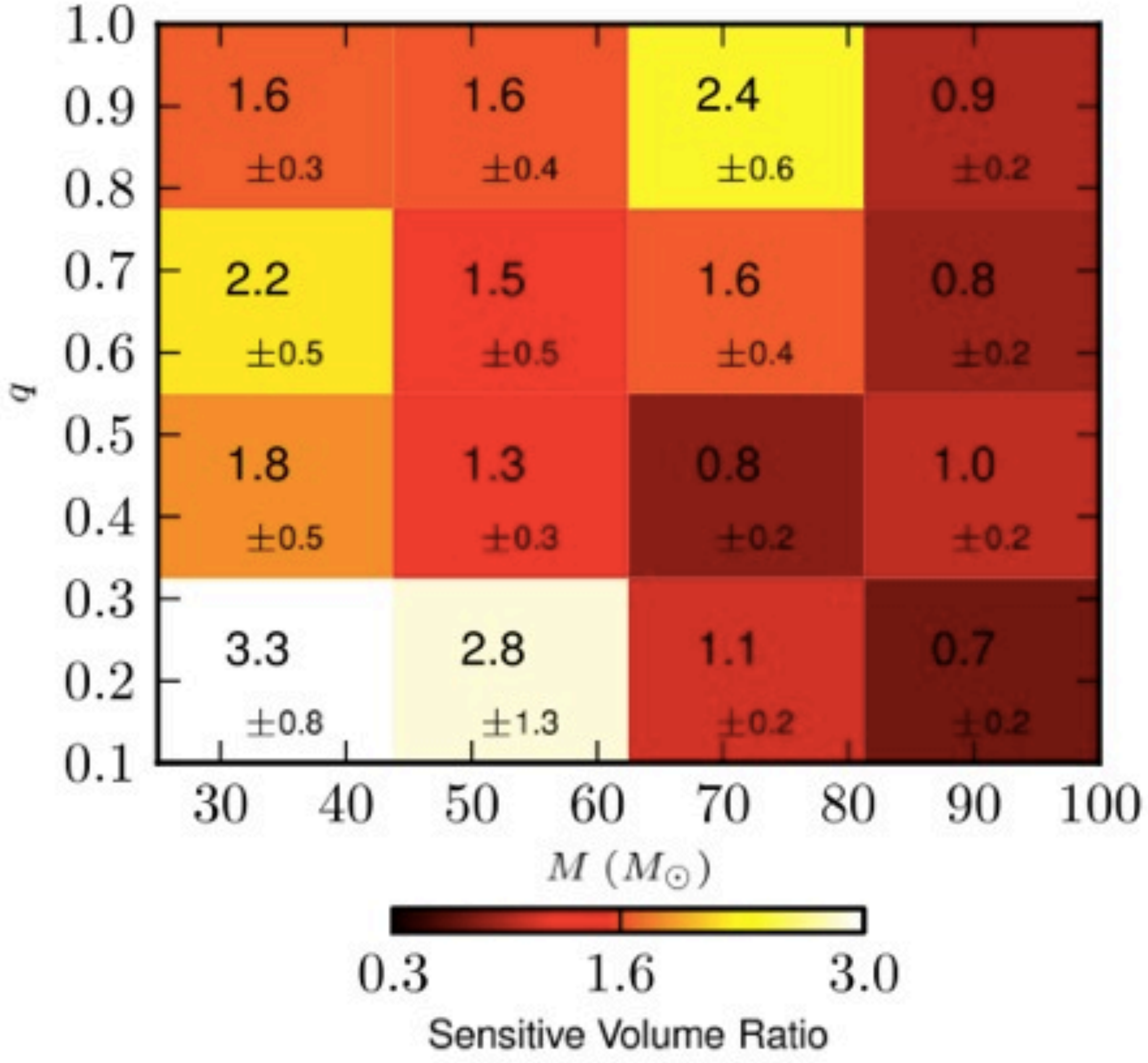
As mass increases, frequency decreases, fewer waveform cycles in band

Excess Power approach becomes competitive with matched filtering - but more robust (relies less on templates).

Dedicated search with elliptical polarization constraints.

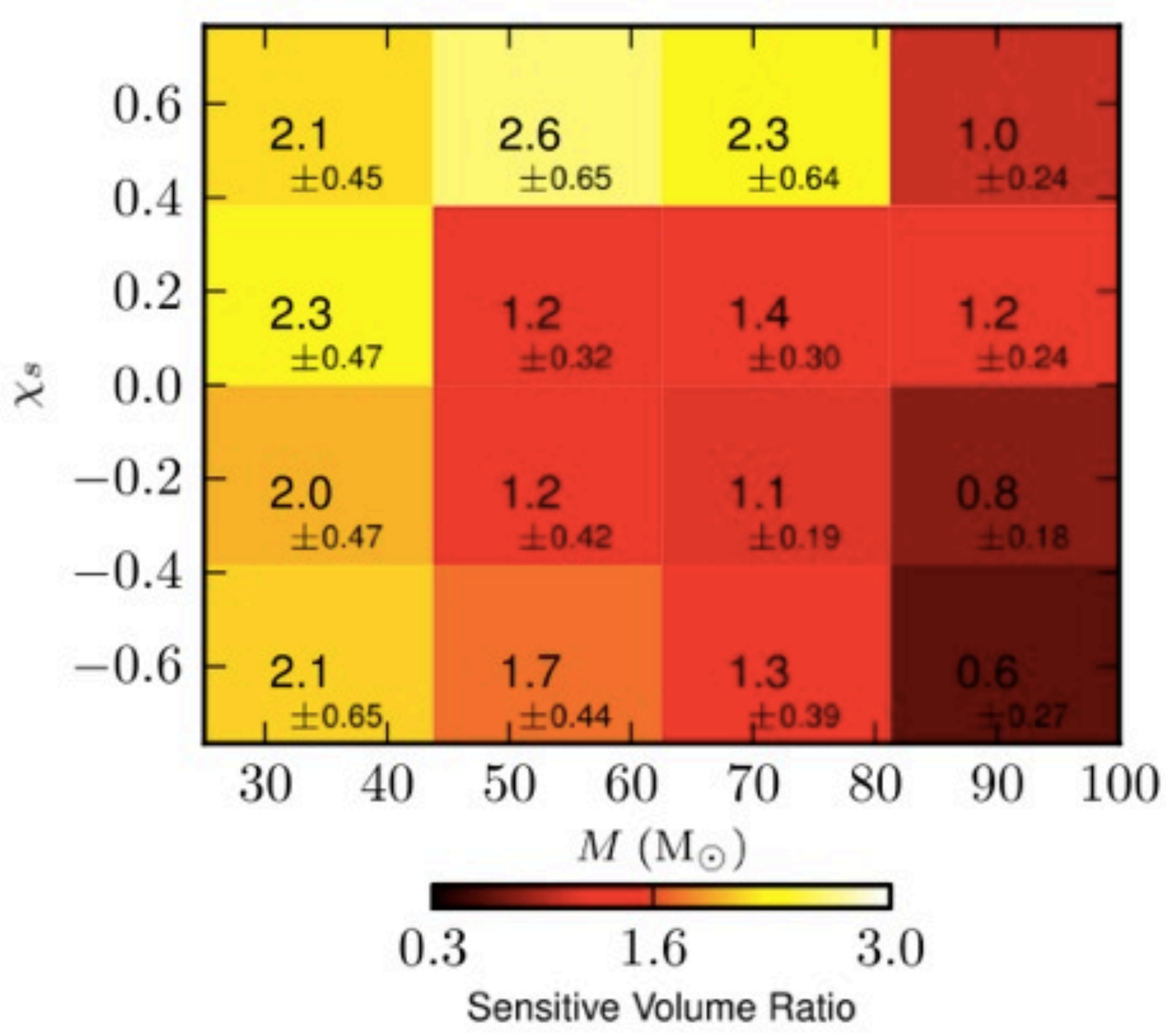
Stellar Mass Binary Black Holes (10-100 M⊙)

Mohapatra et al., PRD 90, 022001 (2014)



1.6 ±0.3	1.6 ±0.4	2.4 ±0.6	0.9 ±0.2
2.2 ±0.5	1.5 ±0.5	1.6 ±0.4	0.8 ±0.2
1.8 ±0.5	1.3 ±0.3	0.8 ±0.2	1.0 ±0.2
3.3 ±0.8	2.8 ±1.3	1.1 ±0.2	0.7 ±0.2

(a) IMR-templates and Coherent WaveBurst.



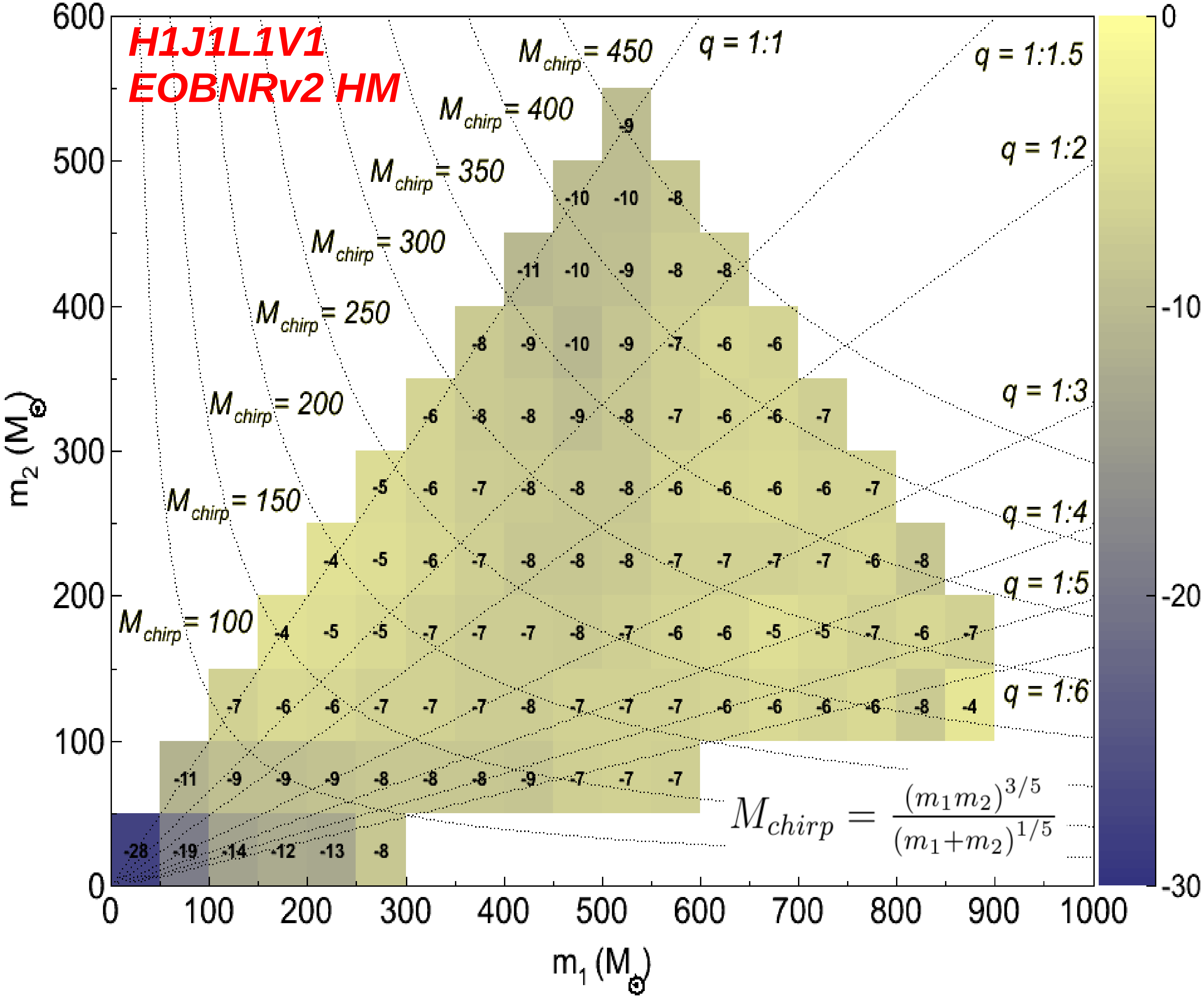
2.1 ±0.45	2.6 ±0.65	2.3 ±0.64	1.0 ±0.24
2.3 ±0.47	1.2 ±0.32	1.4 ±0.30	1.2 ±0.24
2.0 ±0.47	1.2 ±0.42	1.1 ±0.19	0.8 ±0.18
2.1 ±0.65	1.7 ±0.44	1.3 ±0.39	0.6 ±0.27

(a) IMR-templates and Coherent WaveBurst.

$$\chi_s = \frac{m_1\chi_1 + m_2\chi_2}{m_1 + m_2}.$$

Sensitive volume for matched filter vs burst searches, compared at FAR of 3 events/year

Intermediate Mass Binary Black Holes (100-1000 M⊙) Projected Performance of Coherent WaveBurst 2G



Preliminary: study of SNR losses [%] of burst cWB-2G compared to matched optimal filter

Mazzolo et al, Amaldi 2013

Identification of BBH Merger Phenomenology Through Principal Component Analysis

Clark et al., arXiv:1406.5426

a.k.a. *BHextractor*: black hole evidence-extractor

UMASS AMHERST

University of Glasgow

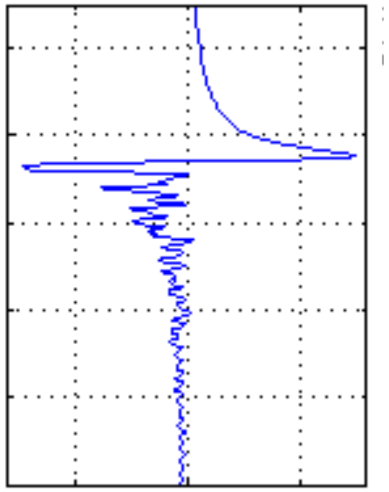
Georgia Tech

- Logue, J. et al. 2012: Bayesian model selection technique (SMEE: Supernova Model Evidence Extractor) to identify supernova core-collapse mechanism from generic features in GW signal
- Can we do something similar with BBH signals?
  - **Rapid** identification of BBH GW phenomenology (spin, no spin, precession, ...) - e.g. distinguish between detected signals from spinning/non-spinning/precessing systems
  - Waveform reconstruction
- Preliminary proof-of-concept to distinguish BBH signal morphologies with SMEE-like techniques
- Could extend to SN vs. BBH, difficult-to-model GW signals with existing NR simulations (e.g., post-BNS merger bursts), detector characterization (common instrumental glitch morphology)...

Principal Component Analysis

- For a catalogue with N waveforms, each M samples long
- We arrange each waveform into columns of an MxN matrix

$$h_1 = \begin{bmatrix} h_1(t_1) \\ h_1(t_2) \\ \vdots \\ h_1(t_N) \end{bmatrix}$$



$$\mathbf{A} = \begin{bmatrix} h_1(t_1) h_2(t_1) \ldots h_M(t_1) \\ h_1(t_2) h_2(t_2) \ldots h_M(t_2) \\ \vdots \quad \ddots \quad \vdots \\ h_1(t_N) h_2(t_N) \ldots h_M(t_N) \end{bmatrix}$$

- With Singular Value Decomposition of **A**, we find the principal components, i.e. a basis from which any waveform in **A** can be reconstructed as:

$$h = \sum_{i=1}^{N} \beta_i u_i \approx \sum_{i=1}^{k} \beta_i u_i \text{ for } k < N$$

Bayesian Model Selection

$$h = \sum_{i=1}^{N} \beta_i u_i \approx \sum_{i=1}^{k} \beta_i u_i \text{ for } k < N$$

- The parameter estimation problem is now to find the posterior probability distribution of β
- Bayesian model selection is performed by comparing relative posterior probabilities for different catalogues M_1, M_2 etc:

‘evidence’

‘Bayes Factor’ ⟶

$$B_{1,2} = \frac{p(D|M_1)}{p(D|M_2)} = \frac{\int_{B_1} \mathrm{d}\beta \; p(\beta|M_1) p(D|\beta, M_1)}{\int_{B_2} \mathrm{d}\beta \; p(\beta|M_2) p(D|\beta, M_2)}$$

- Here, M_1 and M_2 are the different waveform catalogues, containing different physics (these models can also be the ratio of the likelihood that the data contains a signal versus noise only)

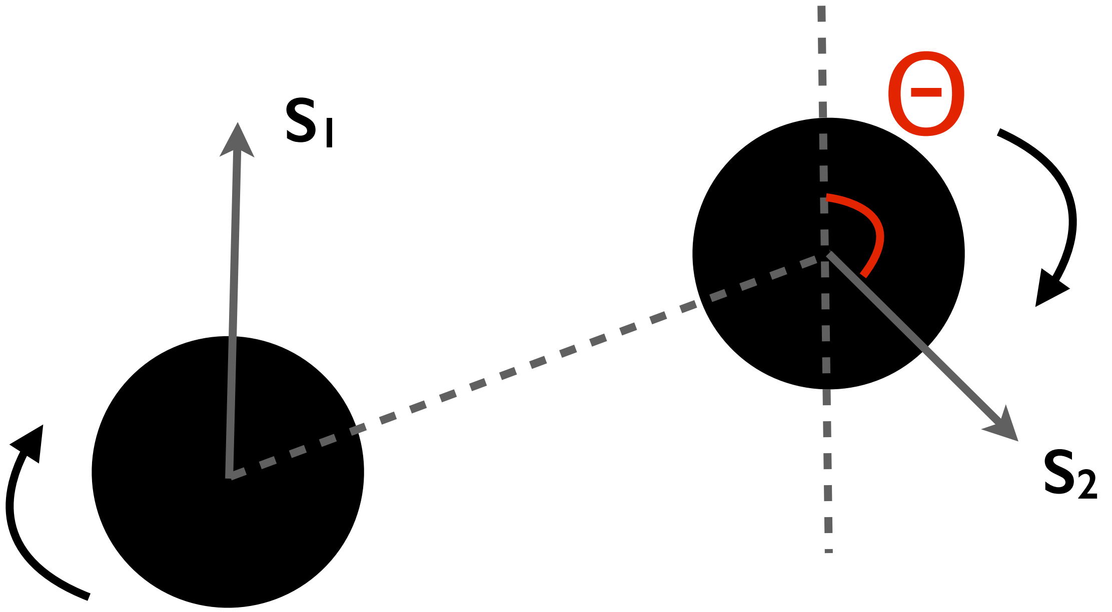
The Experiment

- Categorize NR BBH signals according to phenomenology:

  non-spinning (Q), **spinning (HR)**, **spinning & precessing (RO3)**

- Perform PCA on each catalog to form models
- Inject population of waveforms from each catalogue into Gaussian noise (aLIGO design spectrum)
- Perform Bayesian model selection and reconstruct waveforms
- Focus on distinguishing between catalogs

Name:	**Q**	**HR**	**RO3**
Mass ratio, q:	1-2.5	1-4	1.5-4
Spin, a:	0	0.0-0.9	0.4, 0.6
Tilt angle, Θ:	0	0	45
N waveforms:	13	15	20



Preliminary results here use optimal source location/orientation and assume total mass & waveform peak time is known. 250 Msol, **SNR=50**.

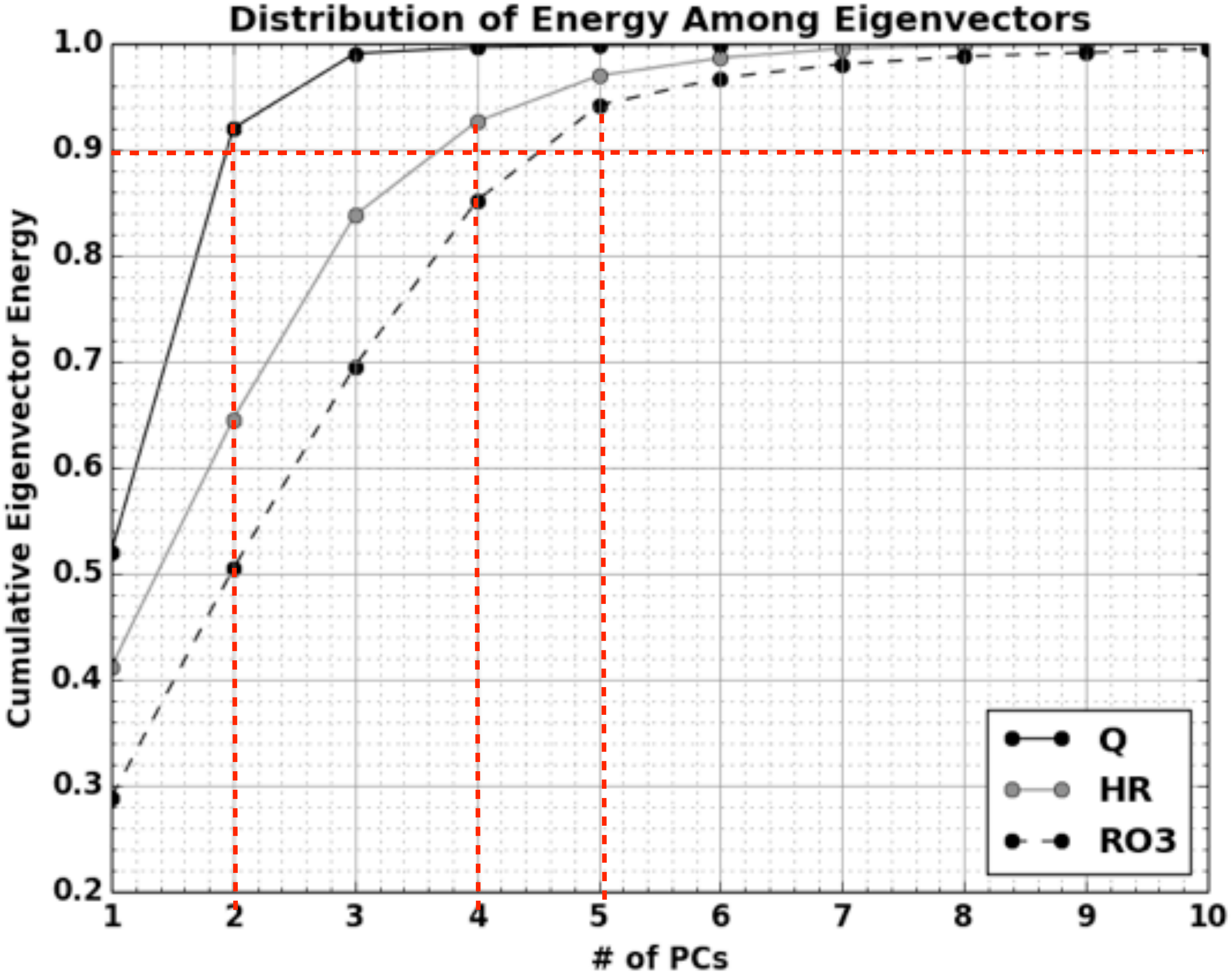
How Many Principal Components?

$$h = \sum_{i=1}^{N} \beta_i u_i \approx \sum_{i=1}^{k} \beta_i u_i \text{ for } k < N$$

- Aim to use as few PCs as possible while remaining able to faithfully reconstruct signals: avoids over-fitting, reduces computational cost of evidence integrals
- Cumulative eigenvalue energy content:

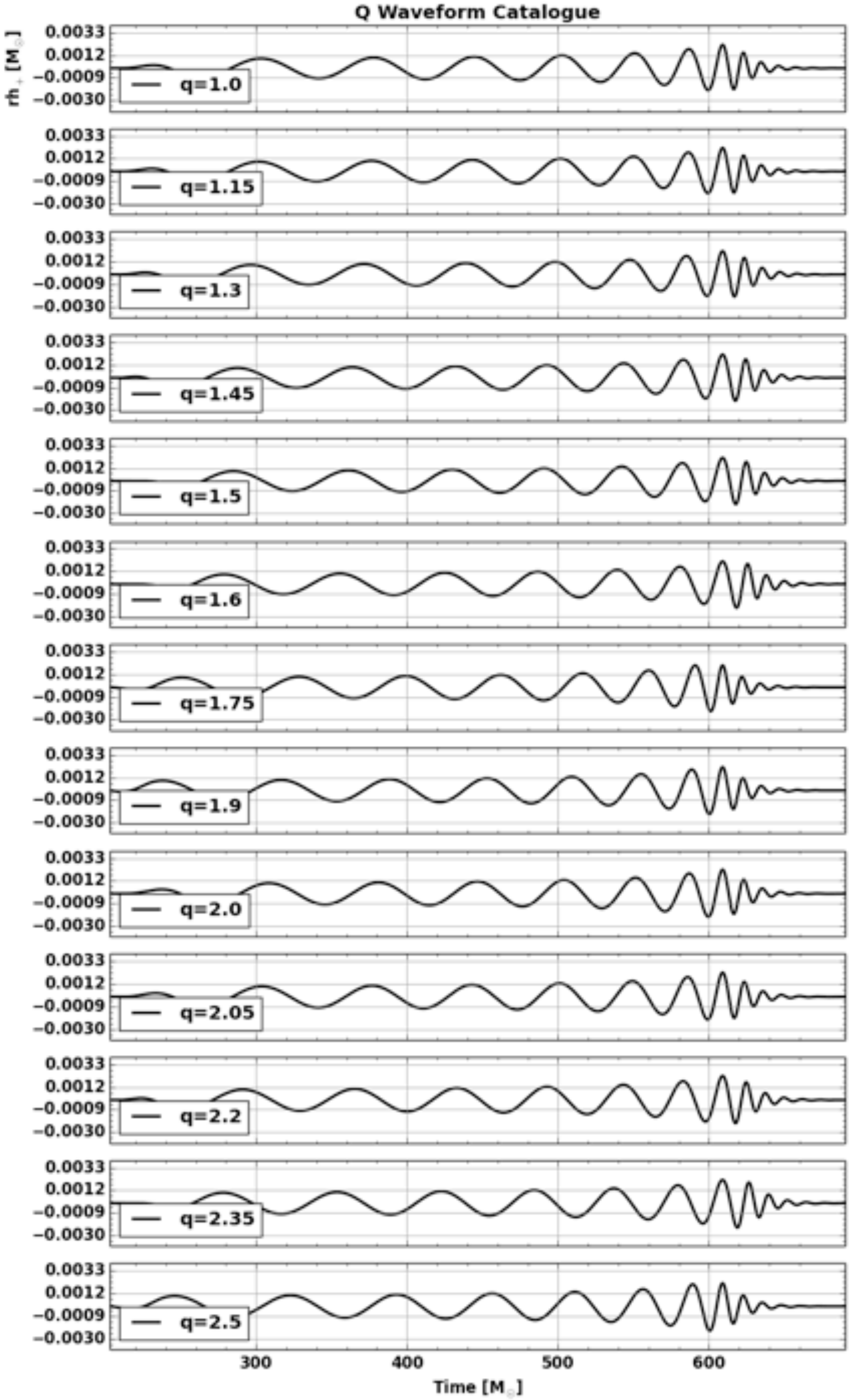
$$E[k] = \frac{\sum_{i=1}^{k} D[i,i]}{\sum_{j=1}^{N} D[j,j]}$$

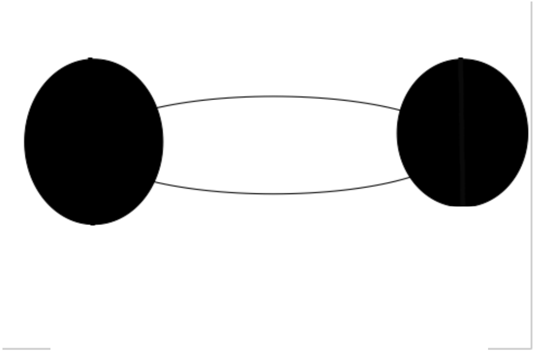
- D is the eigenvalue matrix
- Find k: E[k]>=0.9
- then k PCs represent 90% of the variance in the catalog

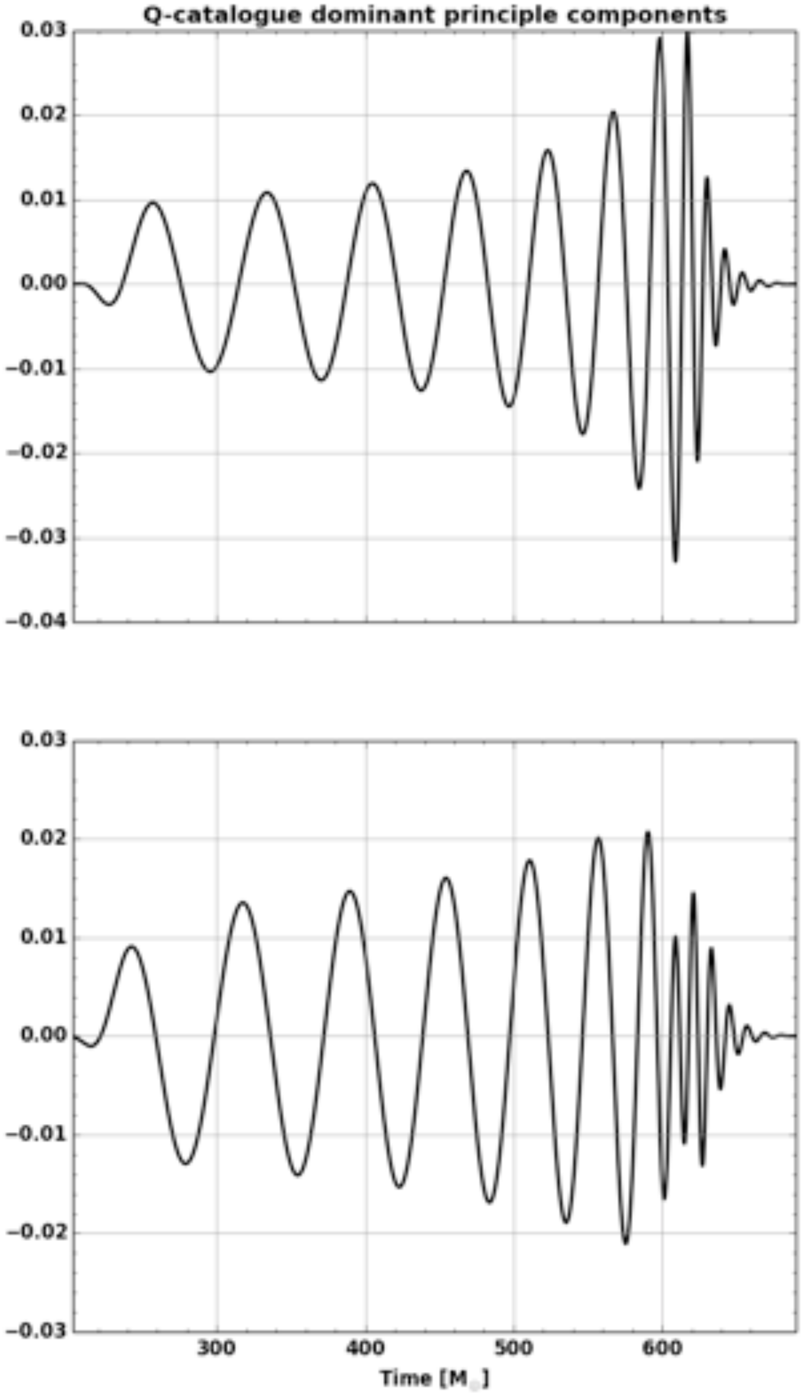


Q catalog: non-spinning

13 waveforms, 2 PCs

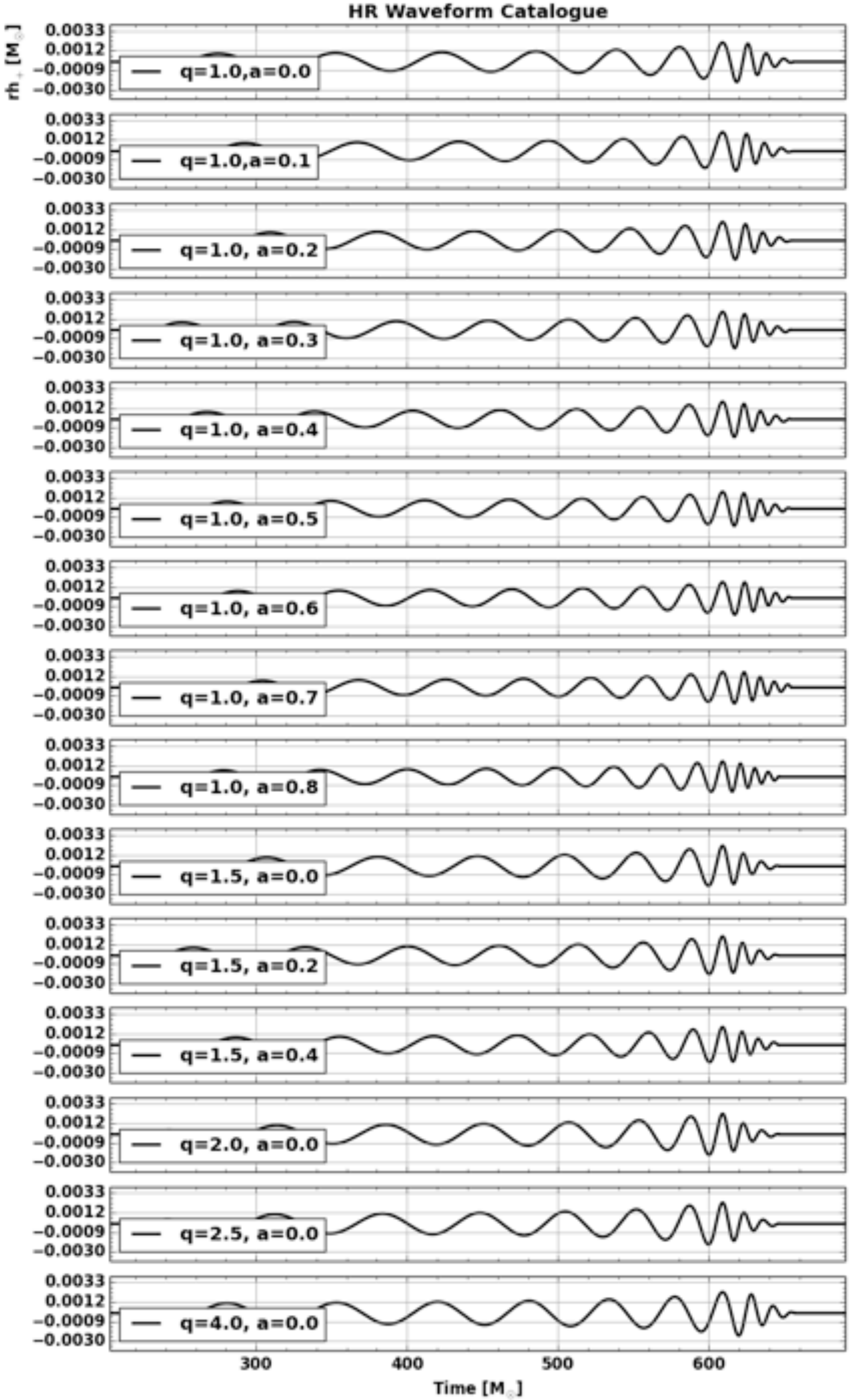


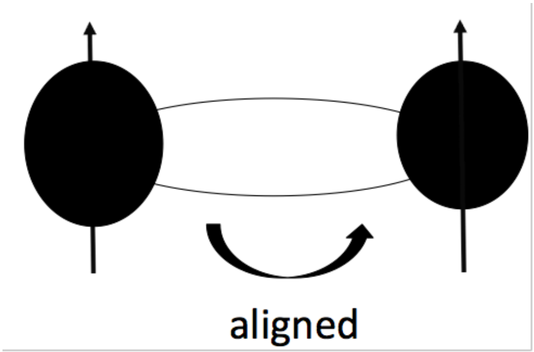


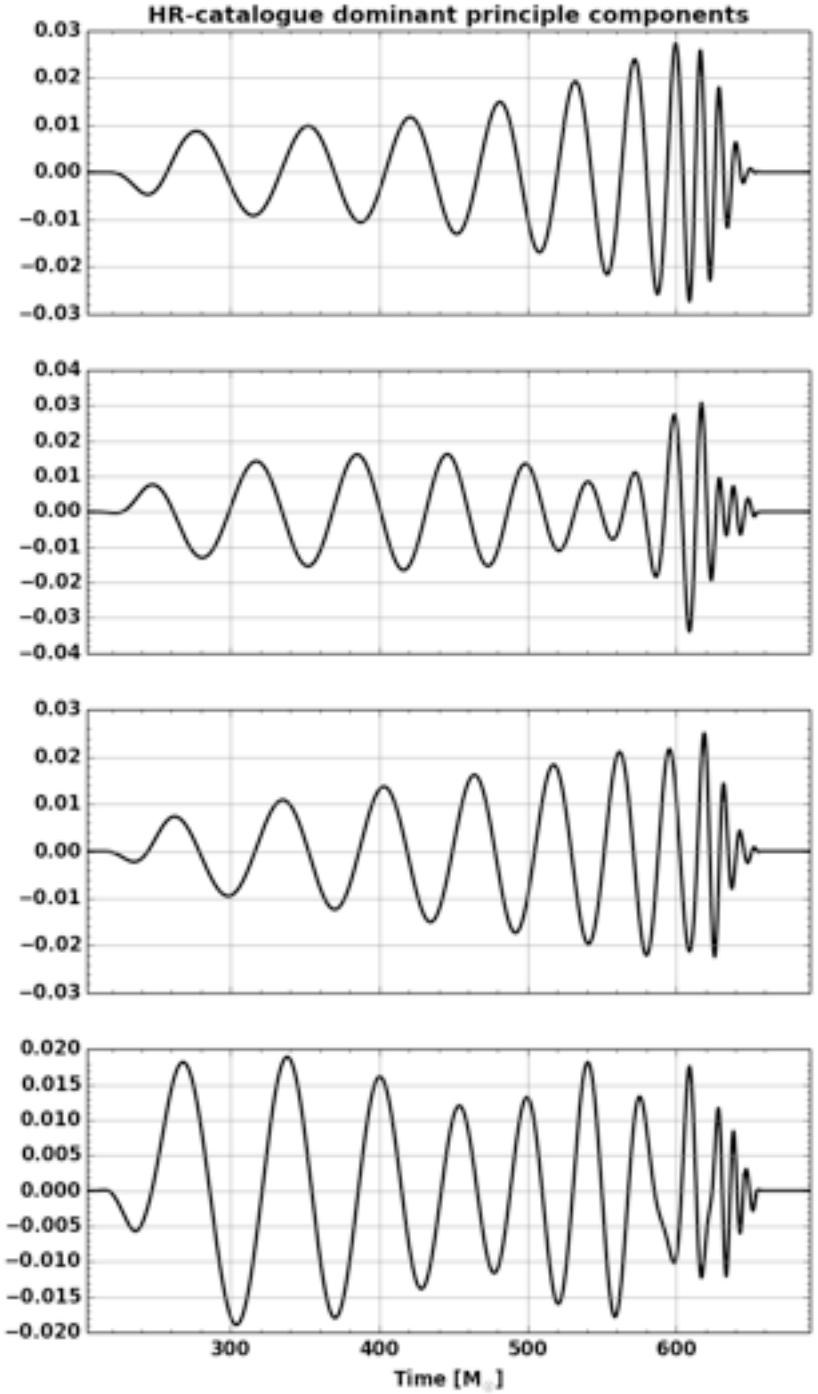


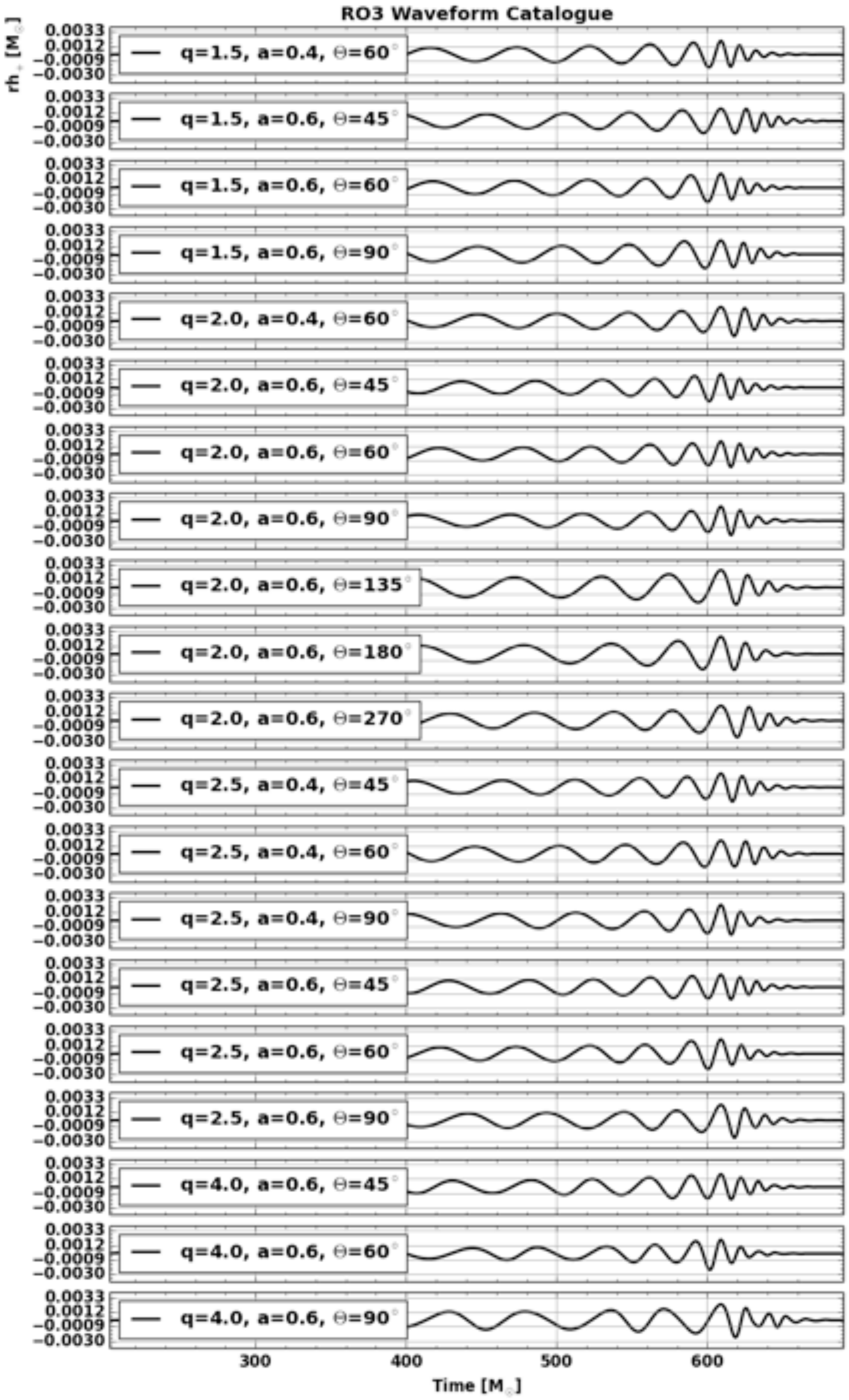
HR catalog: spinning

15 waveforms, 4 PCs



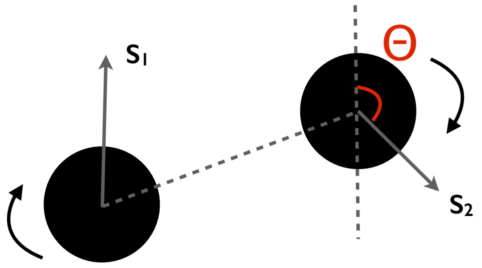


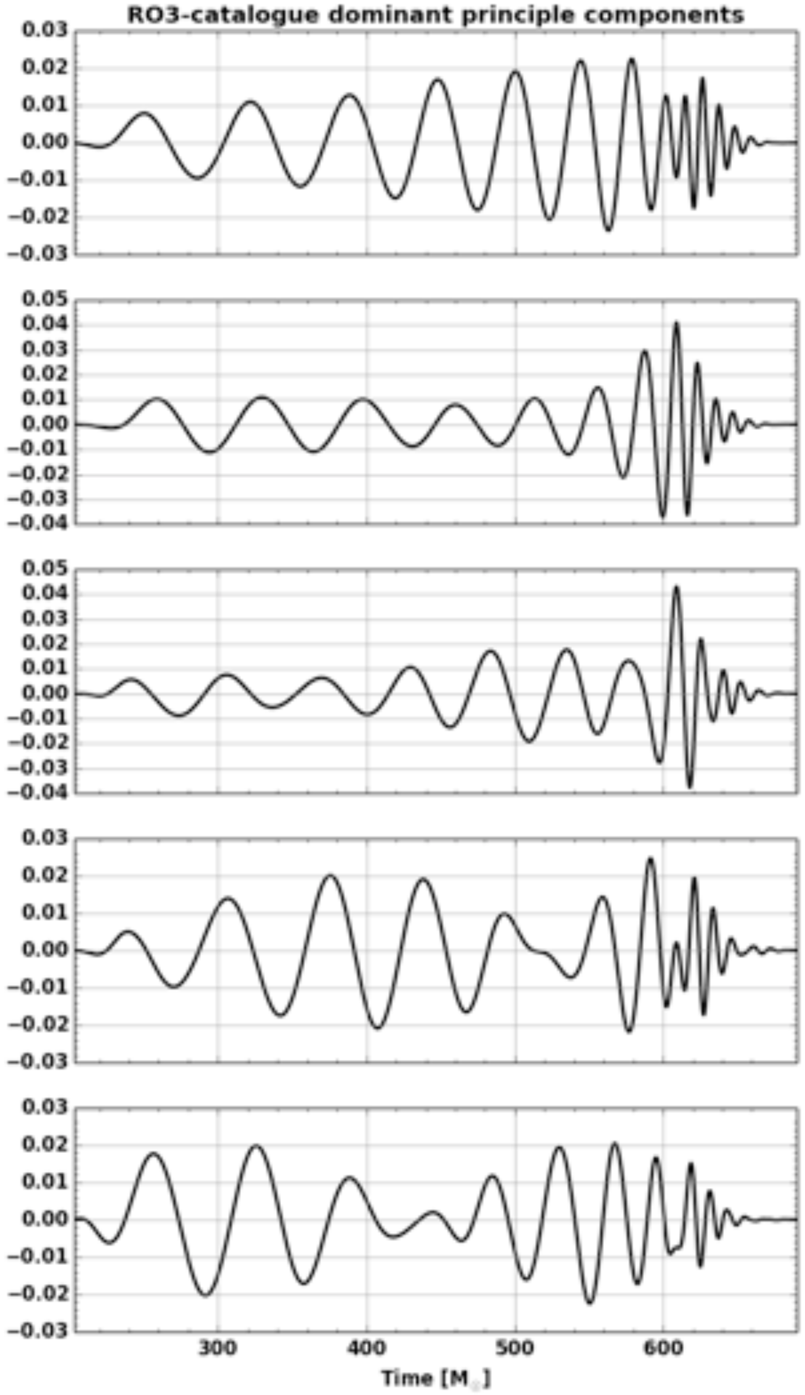




RO3 catalog: precessing

20 waveforms, 5 PCs

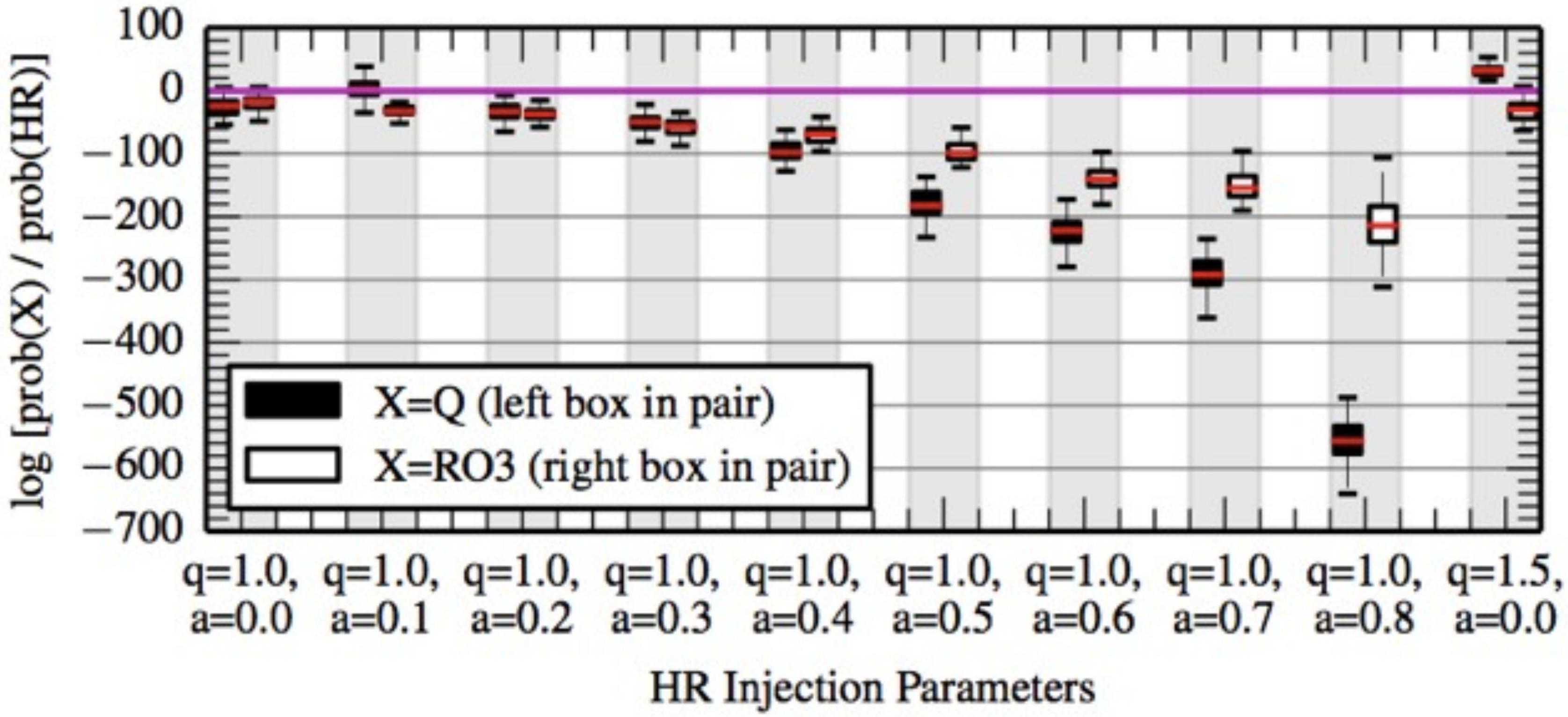




Classification

HR injections

- Recover with Q, HR, RO3
- log(Bayes factors)~relative probability between injected model and X



log(B)<0:

HR preferred to X

Red = median

Box = interquartile range in 50 noise realizations

- Nested Sampling algorithm returns Bayesian evidence & samples from β-posterior PDF
- Reconstruct waveform from max-likelihood βs for each model
- Compute match for reconstructions and injected waveform:

$$\mathbf{match} = \sum_{i=1}^{L} \hat{h}_{\mathrm{inj}} \hat{h}_{\mathrm{rec}}$$

Best match generally occurs for preferred catalog

Status

- Tantalizing signs that a handful of NR simulations is sufficient to form principal components which allow discrimination of BBH phenomenology
- Preliminary Monte-Carlo studies are encouraging: model selection works with ~90% success rate, best reconstructions occur for the most probable catalogue
- Limited studies so far: only first 10 waveforms from each catalogue injected, fixed SNR=50. Results are encouraging.
- Currently scaling up this study to more waveforms/statistics, refine catalogue choices, experiment with analytic (EOB) waveforms

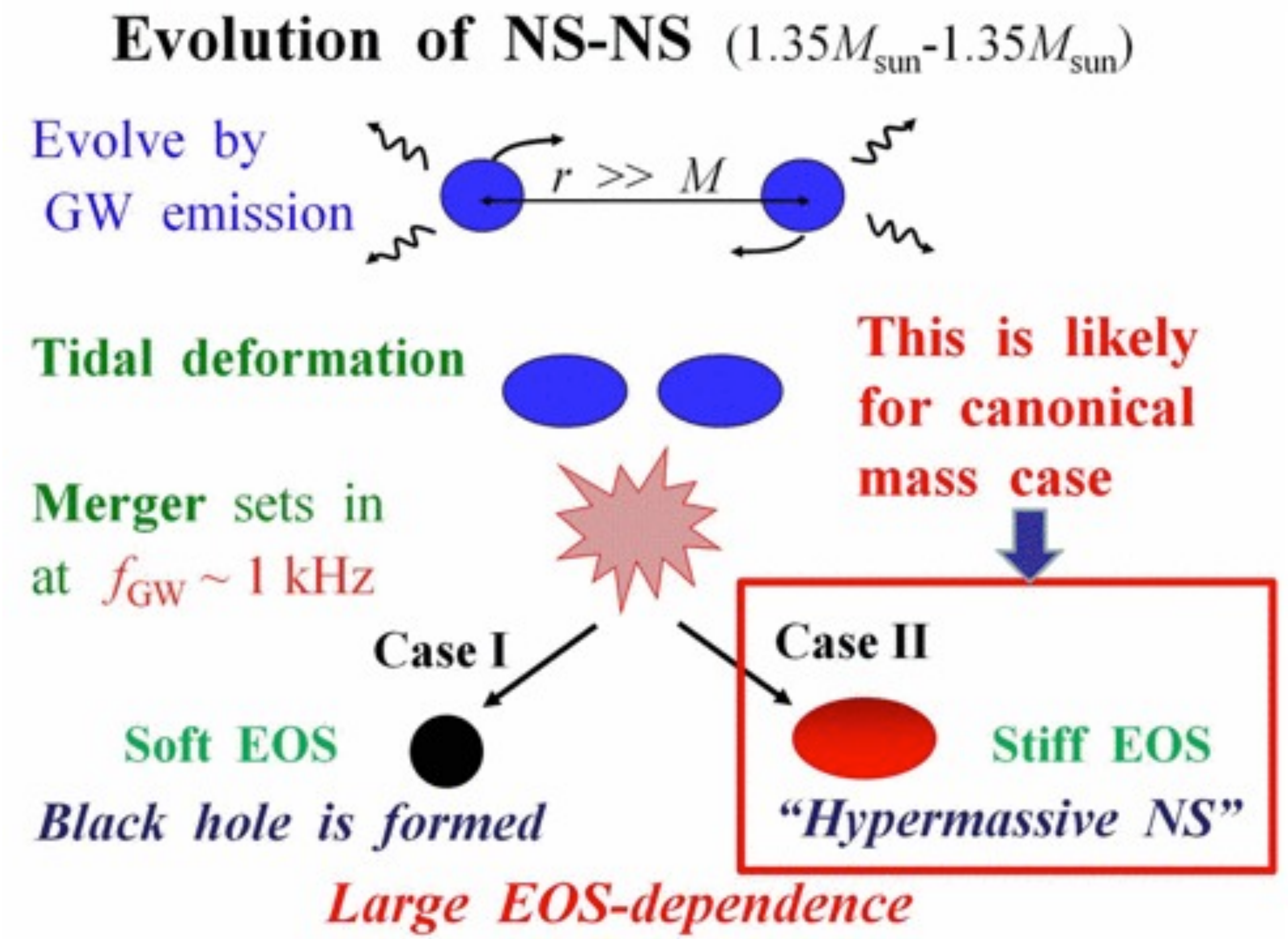
Semi-Modeled Analysis: Post-Merger Oscillations

Neutron Star Equation of State

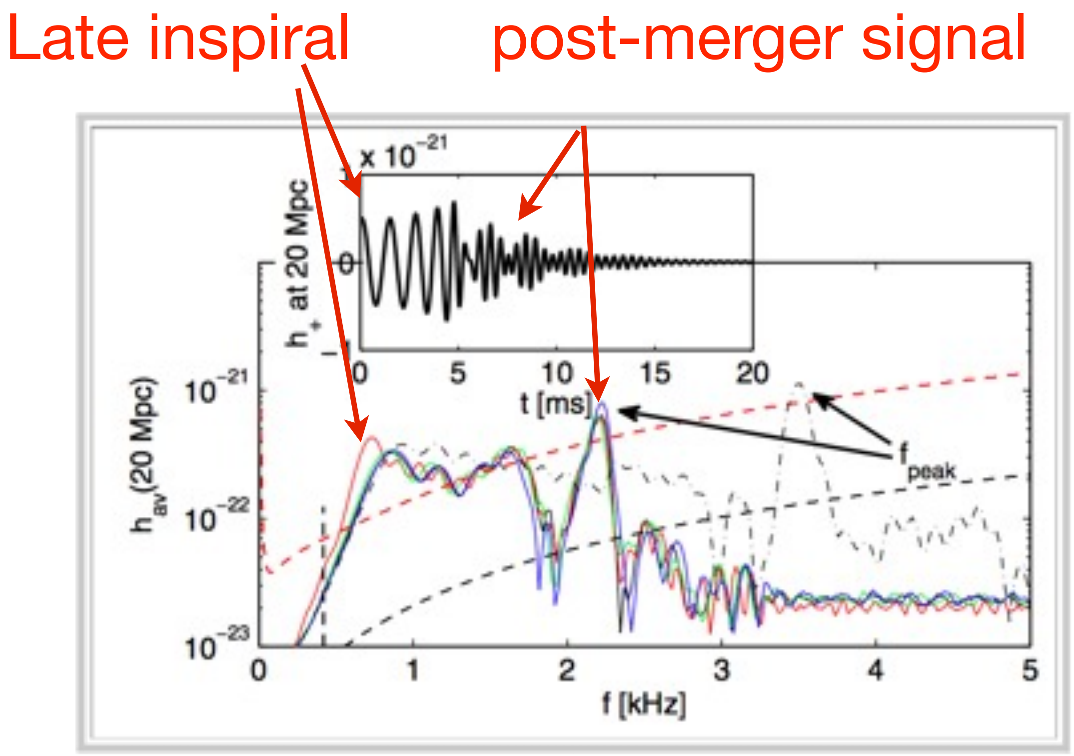
- Relation between the **density of matter** and its **pressure**: how squeezable matter is.
  - water has a **stiff** EoS (can change the shape, but not the volume).
  - steam has a **soft** EoS (can change volume with a little pressure).

- For a neutron star, knowledge of the **mass** and **radius** would tell us the equation of state. The more mass the star has the more gravity squeezes it. For a given mass:
  - If the star has a **large radius** (~15 km), it was relatively successful in resisting gravity and thus has a very **stiff** equation of state.
  - If the star has a **small radius** (~ 8 km), it was not as successful in resisting gravity and it has a **softer** equation of state.

Post-Merger Oscillations



"Numerical Simulations of Gravitational Waves with Matter" (M.Shibata 2012)



Bauswein, Janka, PRL 108, 011101 (2012)

- HMNS emits short (10-100ms) burst ~2-4 kHz. BH ringdown ~6-7 kHz.
- Determination of post-merger oscillation frequency constrains the Neutron Star's Equation of State (EoS): stars with a stiff EoS are less dense, have lower f_{peak}.
- SNR dependent on EOS, mass configuration, NR code, ... SNR~5 @ few - 20 Mpc

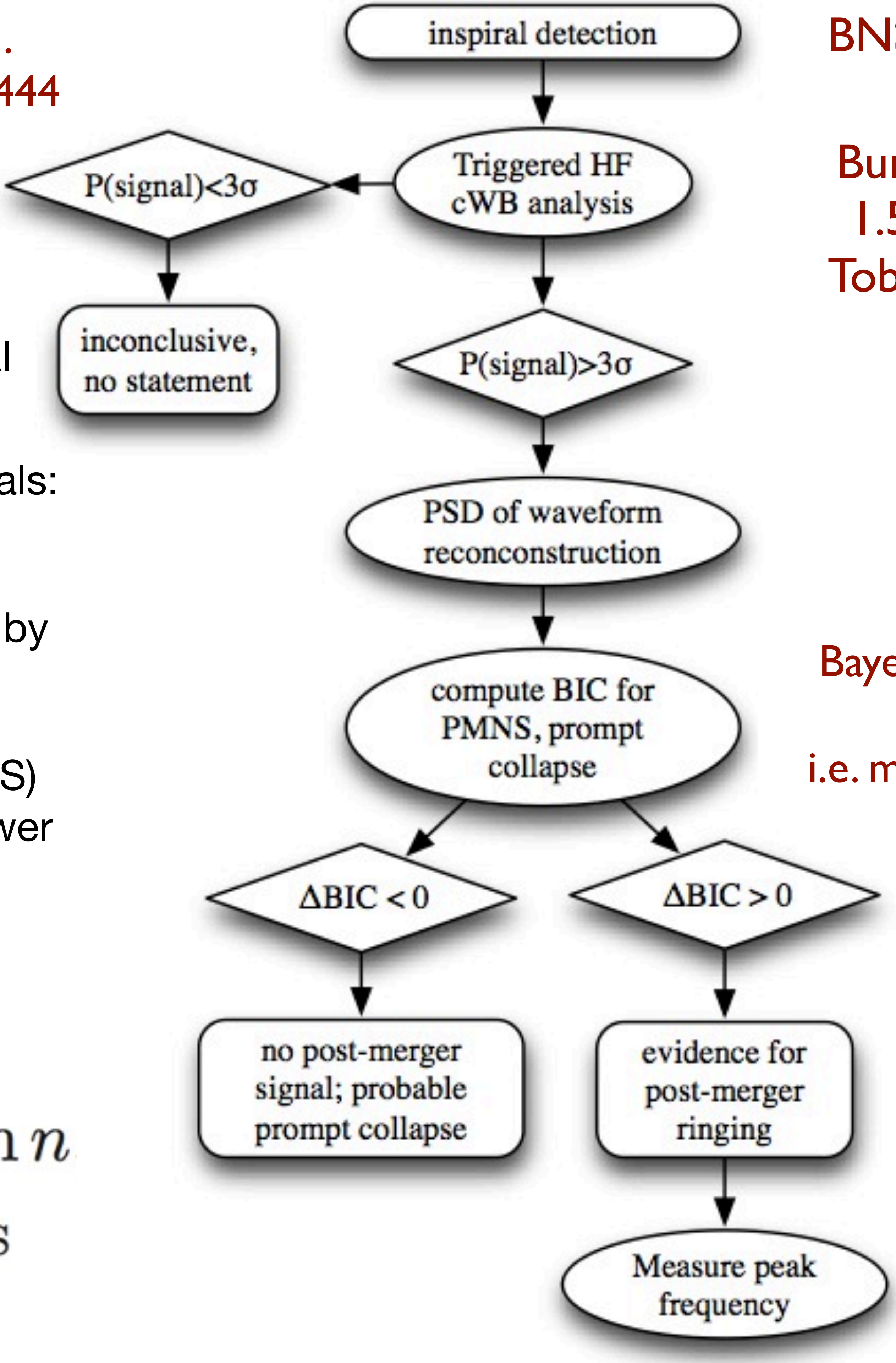
Analysis Procedure

Clark et al.
arXiv:1406.5444

- Analysis triggered by a BNS-inspiral detection, O(100) BNS/year
- Detection criterion: 3-σ after 100 trials: FAP~10^{-5}
- SNR-averaged PSD reconstructed by CWB (1G) in each IFO.
- Model prompt (BH) and delayed (NS) collapse spectra as power law, power law + Gaussian.
- Bayesian Information Criterion as evidence ratio:

$$\mathrm{BIC} = n \ln \chi^2_{\mathrm{min}} + k \ln n$$

$$\Delta\mathrm{BIC} = \mathrm{BIC}_{\mathrm{BH}} - \mathrm{BIC}_{\mathrm{NS}}$$



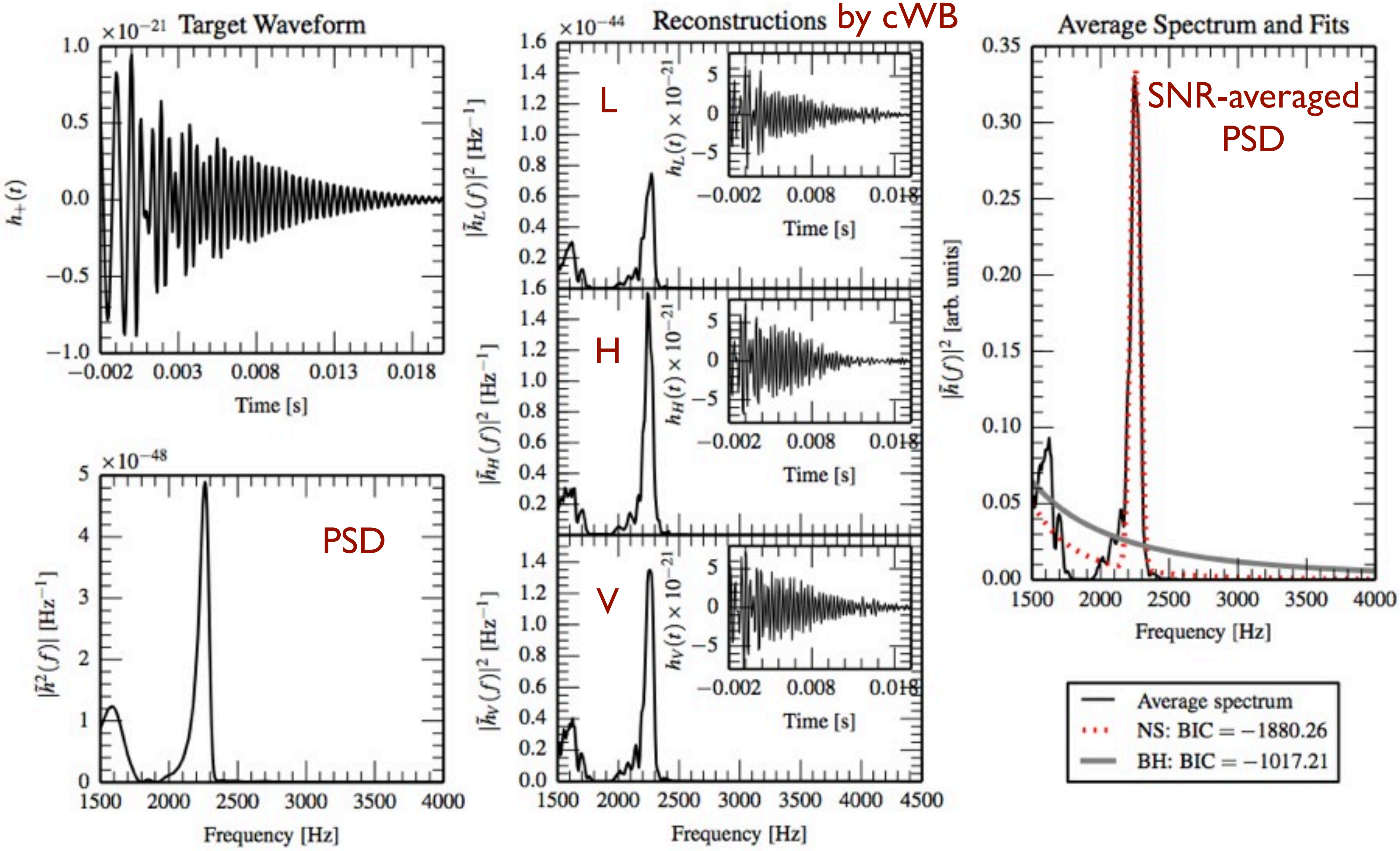
BNS search

Burst search
1.5 - 4 kHz
Tobs=100 ms

Bayes Information Criterion
i.e. model selection

An Example of Delayed Collapse (Shen EoS, stiff)

Clark et al.
arXiv:1406.5444



by cWB

L

H

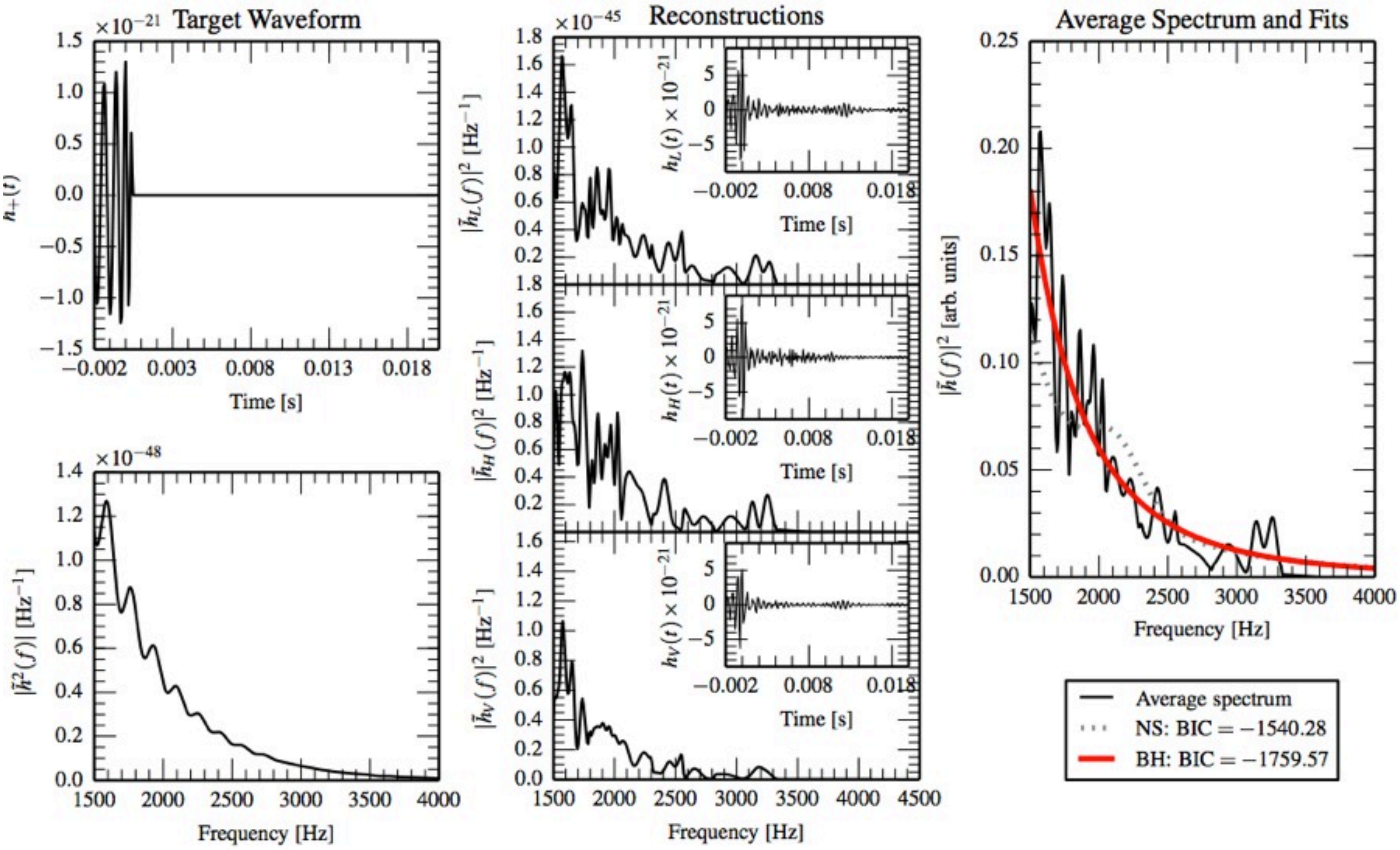
V

PSD

SNR-averaged PSD

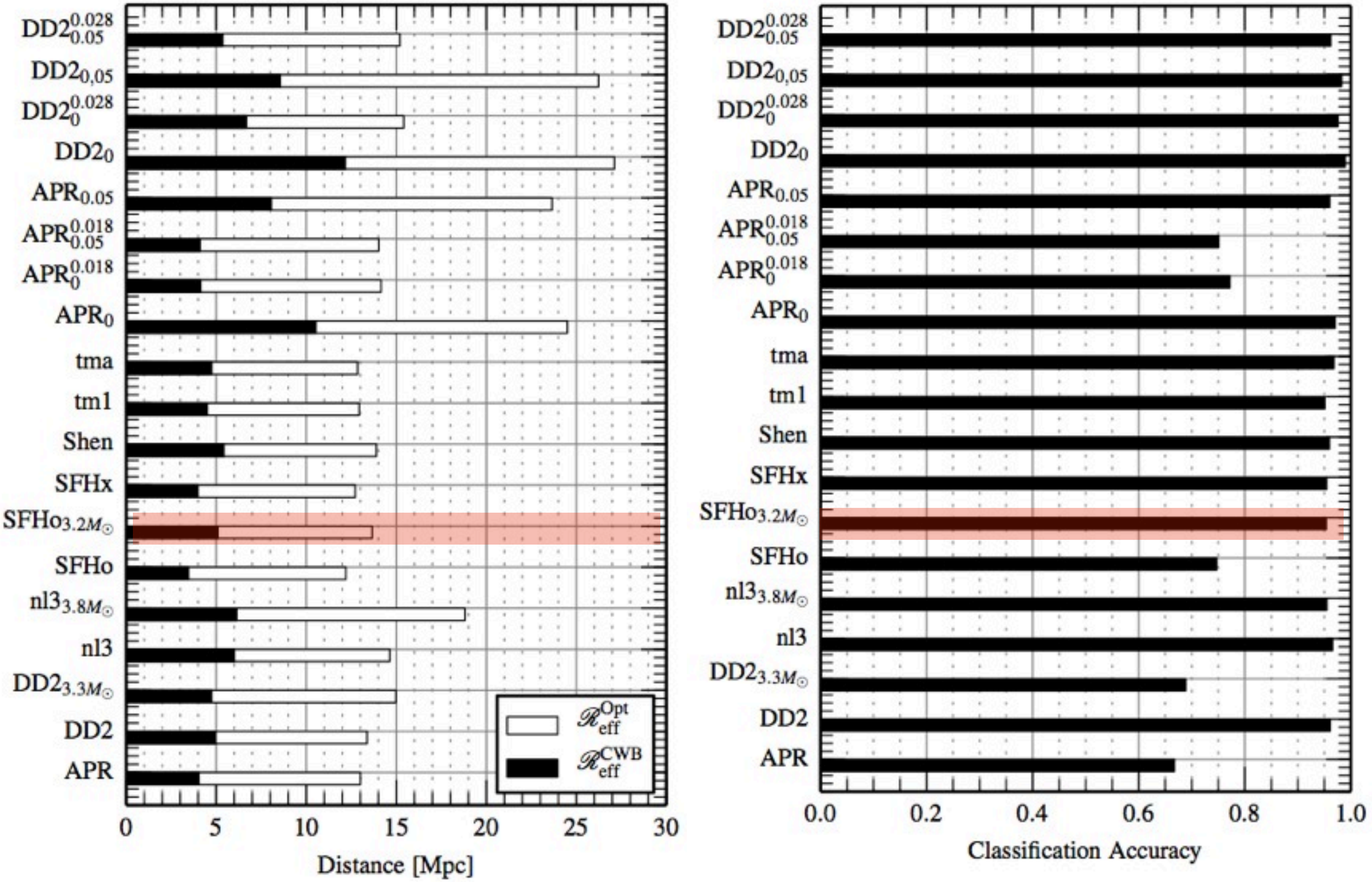
An Example of Prompt Collapse
(SFHo EoS, soft)

Clark et al.
arXiv:1406.5444



Detectability and Classification

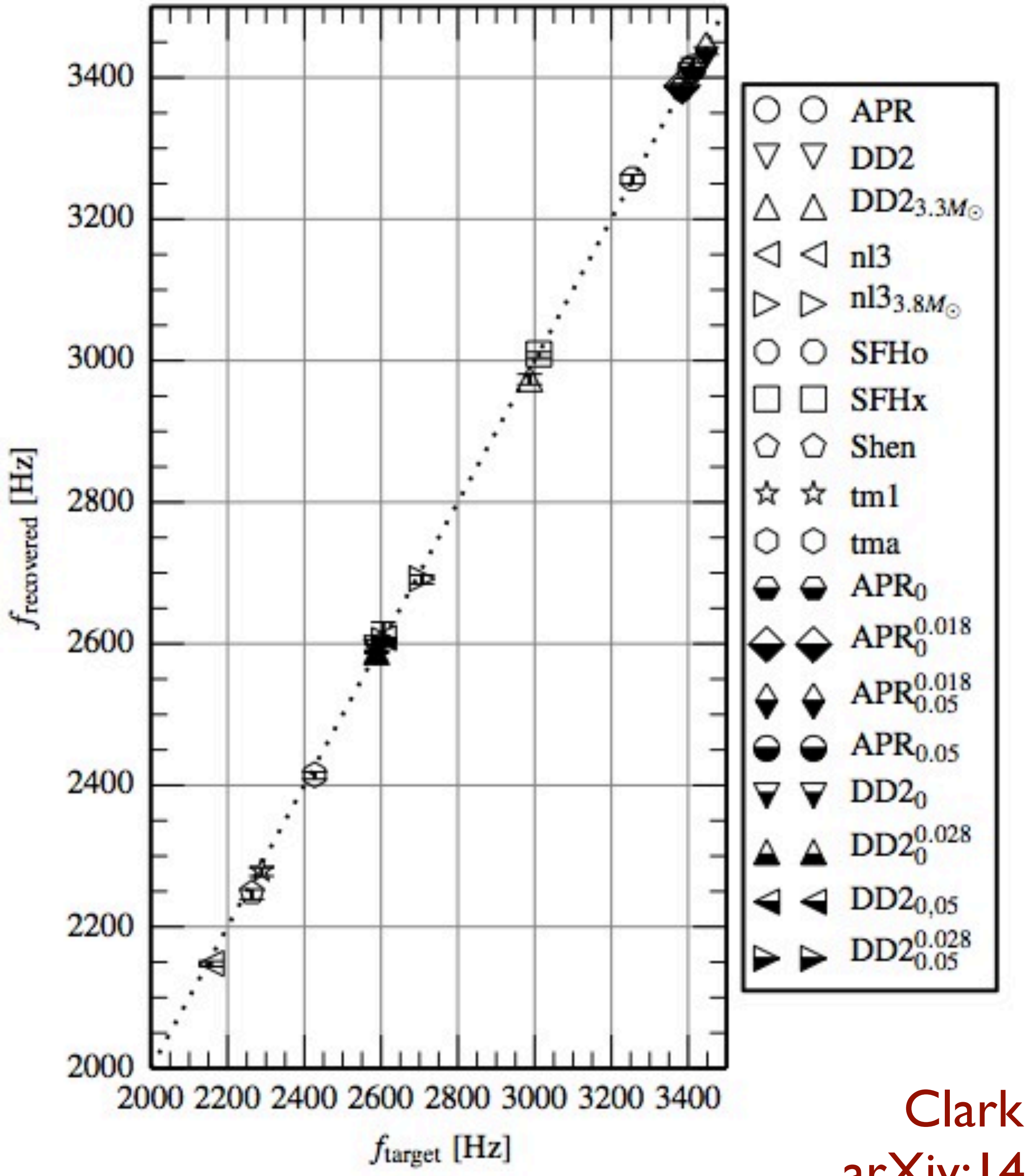
Clark et al.
arXiv:1406.5444



prompt collapse

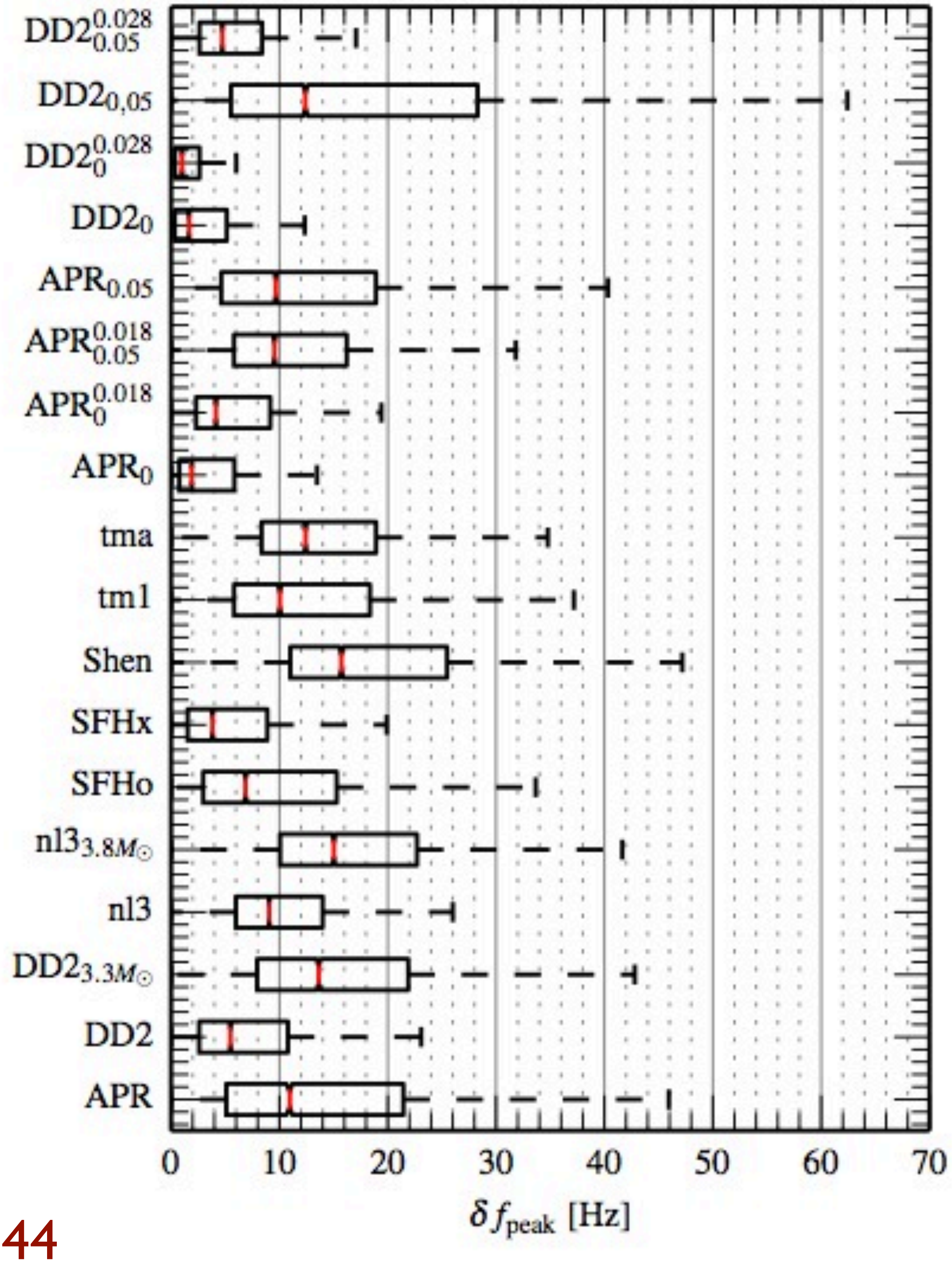
Peak Frequency Estimation

$$\delta f_{\text{peak}} \equiv \left| f_{\text{peak}} - f'_{\text{peak}} \right|$$



(a) Median recovered frequencies

Clark et al.
arXiv:1406.5444



(b) Error in recovered frequencies

Summary

1. Gravitational Wave Bursts: how we look for them and the challenge of glitch hunting
2. “Burst First”: Binary Black Hole Coalescences
3. Post-Merger Oscillations