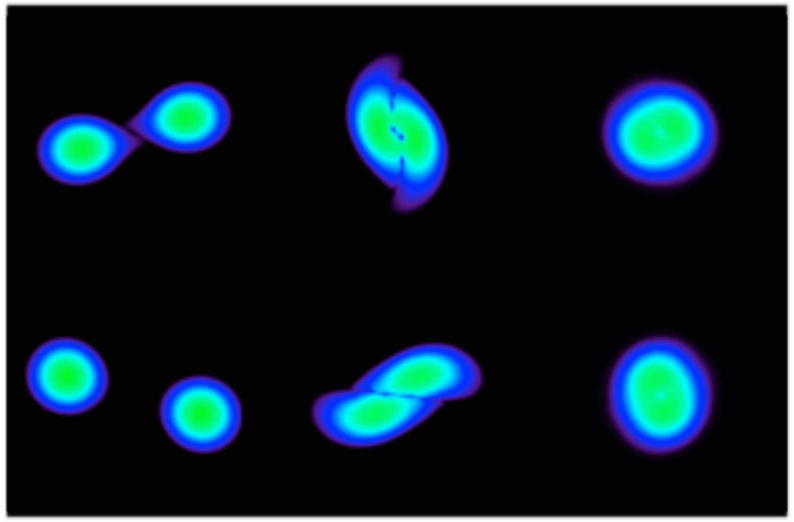
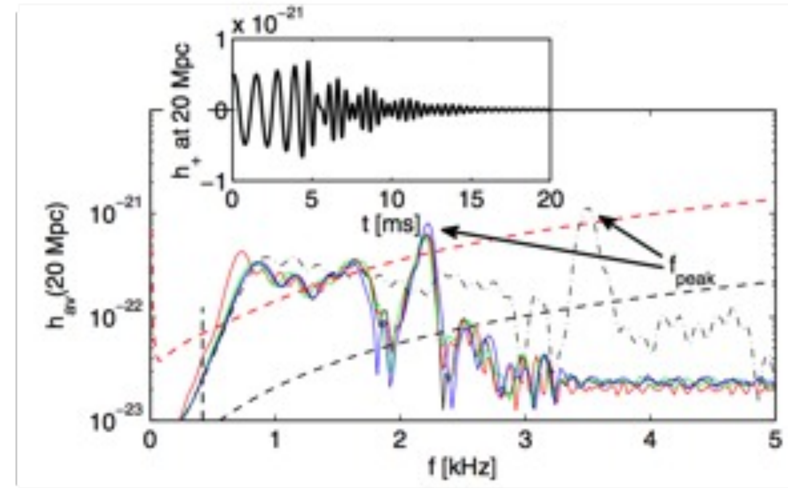
Observing The Gravitational-Wave Afterglow From Binary Neutron Star Coalescence





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

http://arxiv.org/abs/1406.5444

(submitted to PRD)

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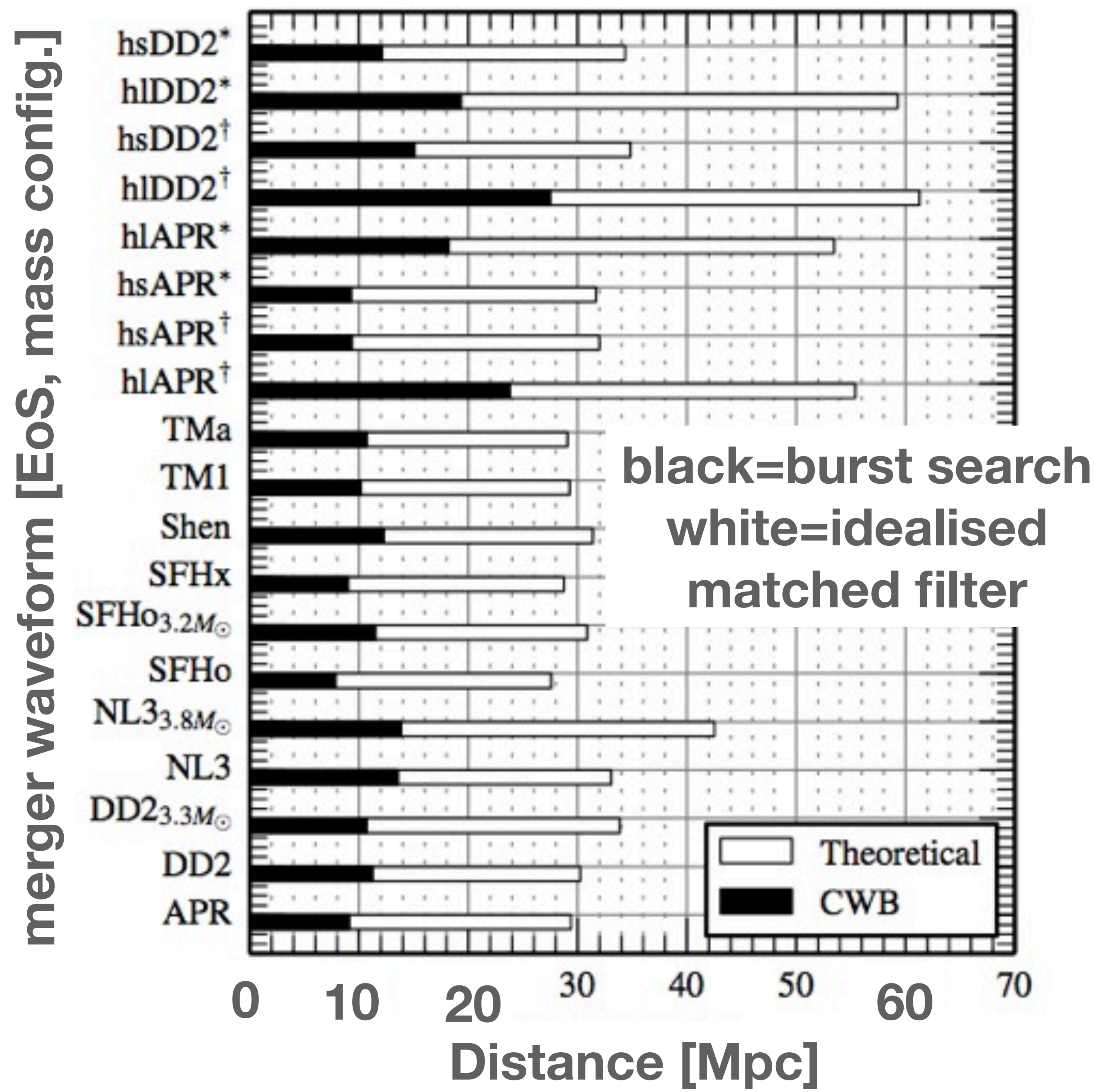
Outline / Scope (and spoiler...)

Questions:

- how far can we see post-merger signal?
- can we distinguish prompt collapse & post-merger signal?
- how well can we recover frequency & implications for radius?
- This study: compare reach of un-modelled analysis in realistic data & theoretical expectation for matched filtering

Horizon Distances (optimal orientation, location)



BNS Merger Simulations

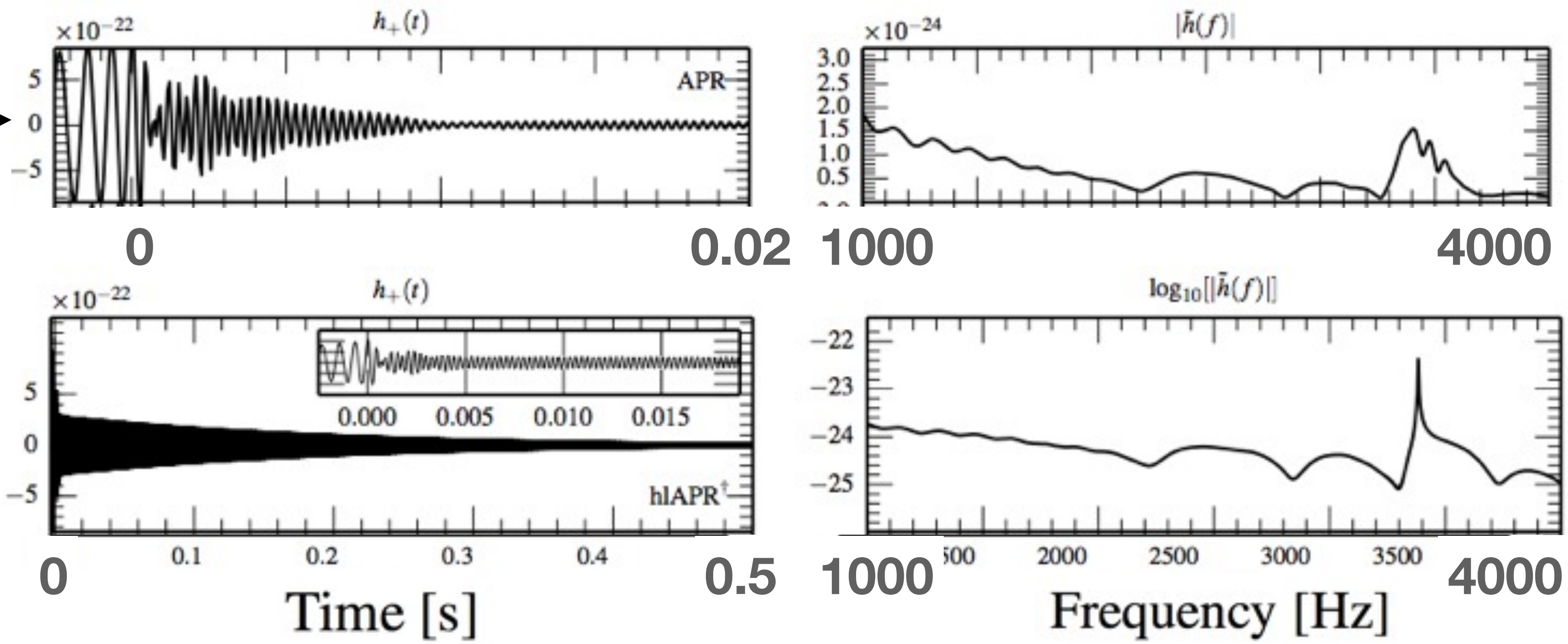
- Catalogue of 19 waveforms
- Hybrids constructed to gauge detectability for more physical damping times (numerical signals suffer numerical damping)
- Hybrid species: stationary ringdowns and linear chirps (from contraction of remnant during post-merger evolution)

Hybrid Characteristics

Hybrid	EoS	$\Delta f/f$ [%]	τ_0 [ms]
hlAPR†	APR	0.00	180
hlAPR*	APR	0.05	200
hsAPR†	APR	0.00	18
hsAPR*	APR	0.05	18
hlDD2†	DD2	0.00	200
hlDD2*	DD2	0.05	200
hsDD2†	DD2	0.00	28
hsDD2*	DD2	0.05	28

Purely numerical →

Hybridized with ring-down →

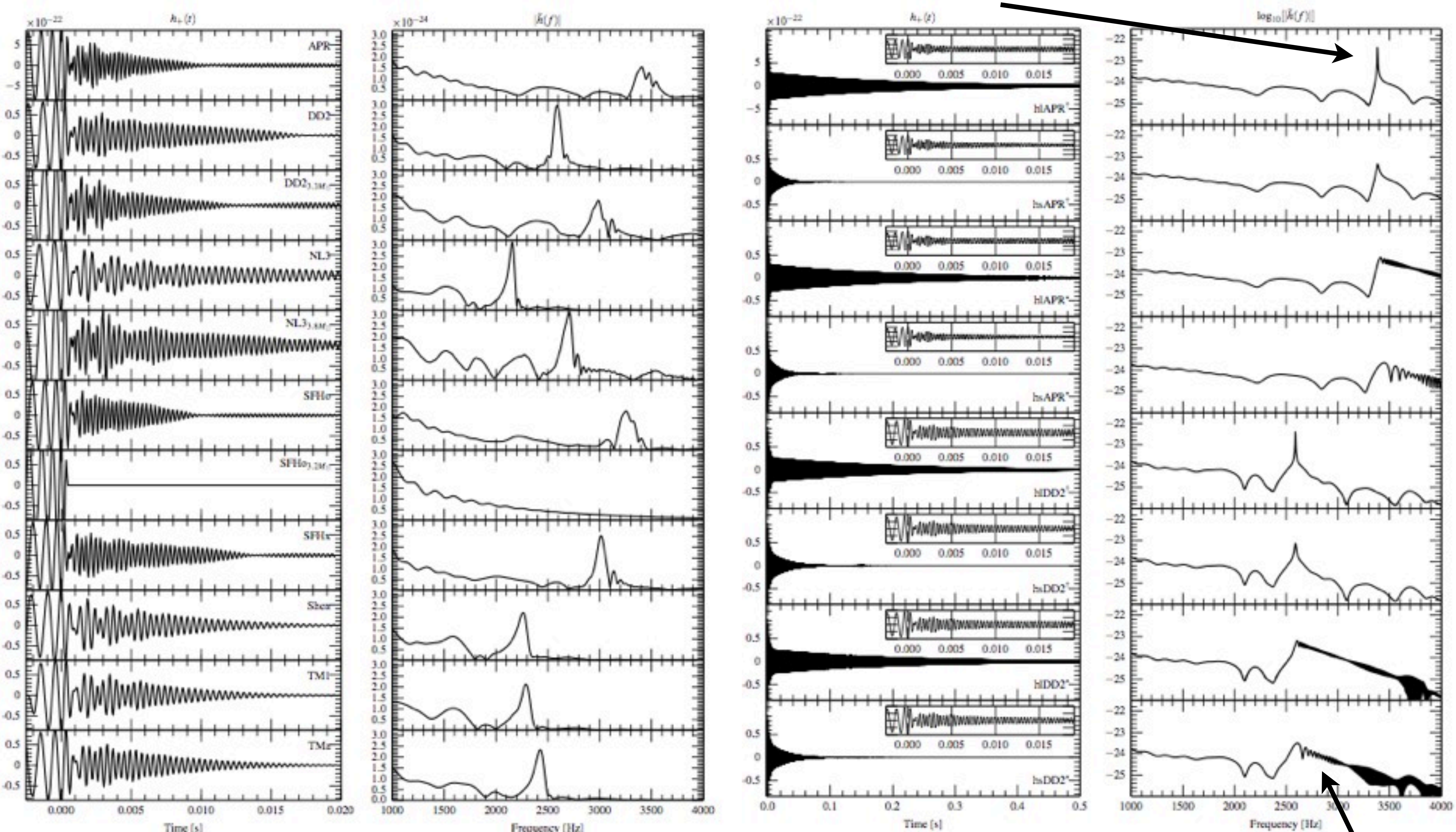


All the waveforms

Purely Numerical

Hybrids

Stationary frequency



Frequency evolves

Waveform Characteristics

- Simple definition of 'post-merger' signal for this study: everything >1.5 kHz
- Signal will have some power from sub-dominant peaks <1.5 kHz which we lose here
- Goal is to measure f_{peak} (>1.5 kHz) so not too concerned (for now...)

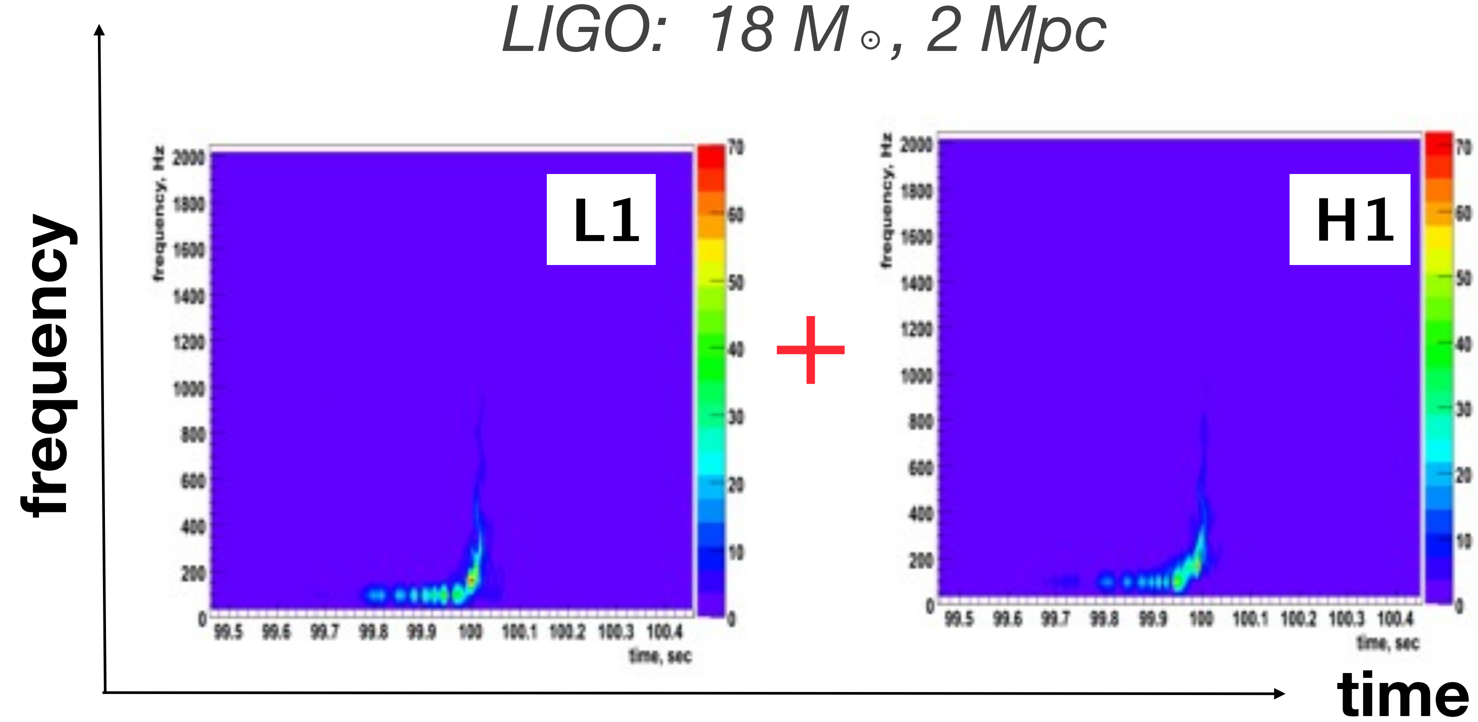
Horizon distance for SNR~3

Waveform	$\mathrm{SNR}_{\mathrm{full}}$	$\mathrm{SNR}_{\mathrm{peak}}$	D_{Opt} [Mpc]	$\dot{N}_{\mathrm{det}}^{\mathrm{opt}}$ [year^{-1}]	E_{GW} [$M_\odot$]	$E_{\mathrm{GW}}^{\mathrm{peak}}$ [$M_\odot$]	f_{peak} [Hz]
APR	4.07	1.66	29.39	0.36	0.09	0.05	3405.40
DD2	4.19	3.13	30.24	0.39	0.07	0.06	2588.60
$\mathrm{DD2}_{3.3M_\odot}$	4.69	2.00	33.86	0.54	0.09	0.04	2987.00
NL3	4.58	3.34	33.08	0.51	0.04	0.03	2156.80
$\mathrm{NL3}_{3.8M_\odot}$	5.89	3.46	42.53	0.74	0.14	0.08	2706.60
SFHo	3.82	2.06	27.56	0.30	0.08	0.06	3255.20
$\mathrm{SFHo}_{3.2M_\odot}$	4.28	-	30.86	0.42	0.04	-	-
SFHx	3.98	2.44	28.74	0.33	0.09	0.06	3011.40
Shen	4.35	2.96	31.40	0.44	0.04	0.03	2263.20
TM1	4.05	2.73	29.25	0.35	0.04	0.03	2288.60
TMa	4.03	2.84	29.06	0.35	0.05	0.04	2426.80
hlAPR†	7.67	5.54	55.39	0.74	0.76	0.49	3383.40
hsAPR†	4.43	2.00	31.99	0.46	0.14	0.06	3384.20
hlAPR*	7.41	4.05	53.46	0.74	0.82	0.27	3412.60
hsAPR*	4.39	2.23	31.69	0.45	0.14	0.09	3447.20
hlDD2†	8.49	6.74	61.28	0.74	0.38	0.26	2587.80
hsDD2†	4.83	3.32	34.84	0.58	0.10	0.06	2588.00
hlDD2*	8.21	6.11	59.29	0.74	0.41	0.22	2606.00
hsDD2*	4.76	3.28	34.35	0.56	0.11	0.06	2609.00

GW burst searches

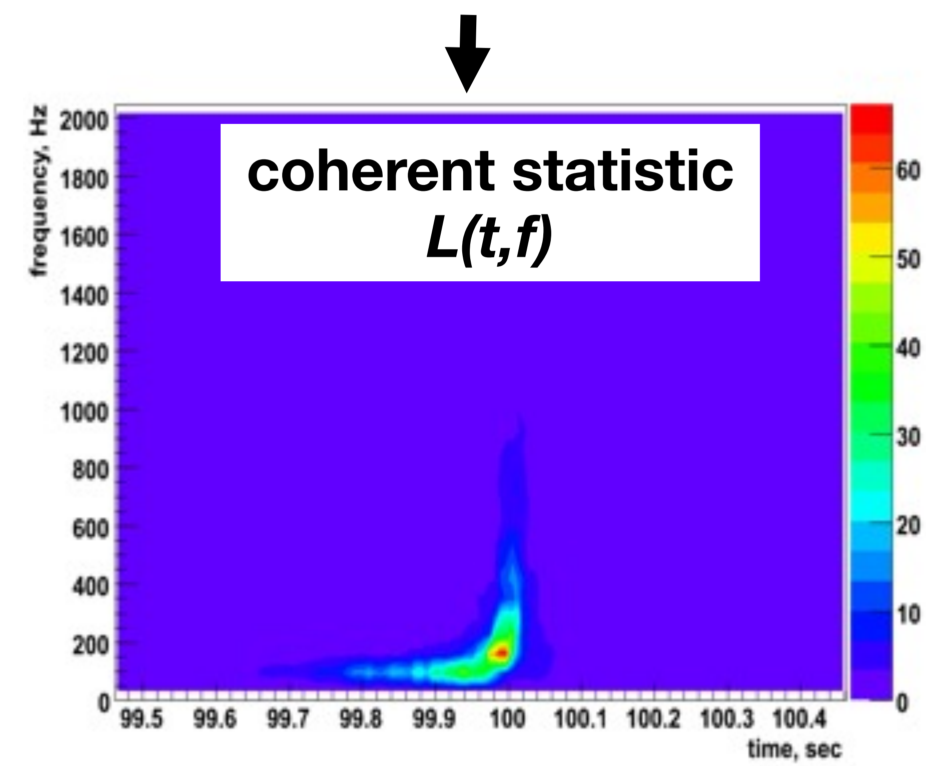
- Search for excess power in time-frequency plane (instead of matched filtering)
- Decompose data with multi-resolution wavelet basis
- Coherent analysis: likelihood maximized over waveform, sky-location.

Example: simulated BBH in Initial LIGO: 18 M$_\odot$, 2 Mpc



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

$$\xi_k = h_+ F_{+,k} + h_\times F_{\times,k}$$ - k^{th} detector response

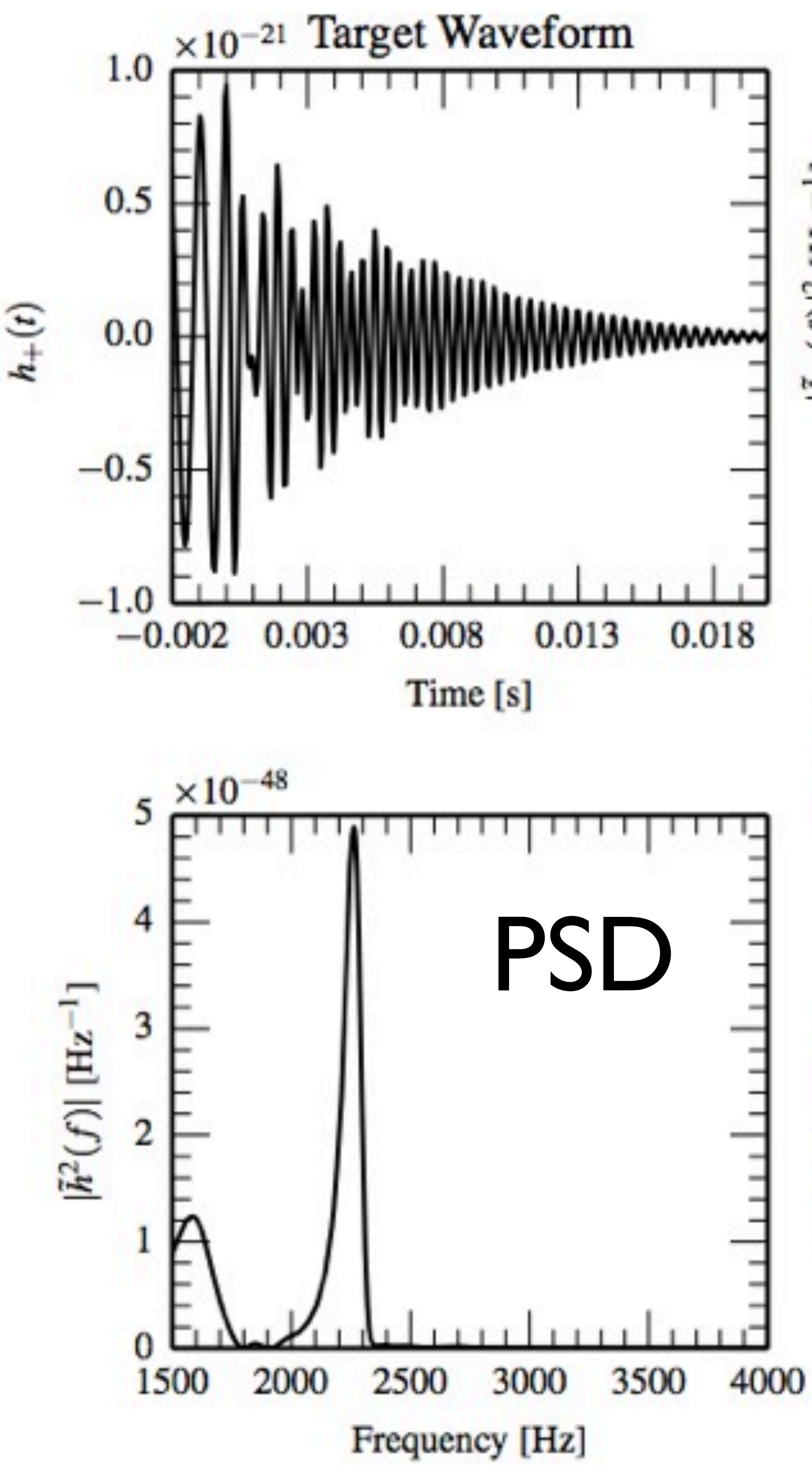


Klimenko et al, CQG 25:114029,2008

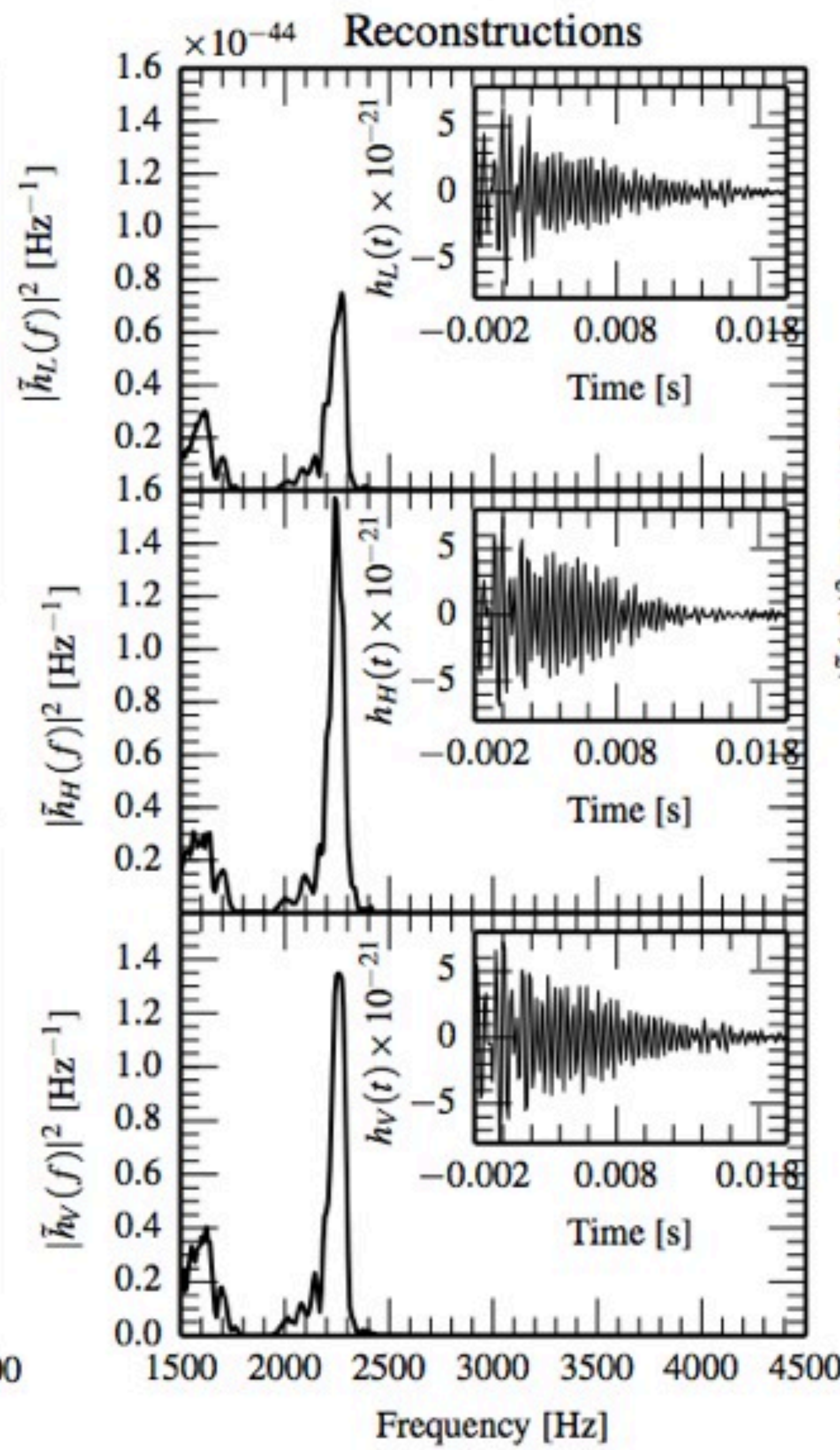
- Search in 1500-4000 Hz, determine & characterise post-merger scenario from **spectrum of reconstructed signal**
- Model prompt (BH) and delayed (NS) collapse spectra as power law, power law + Gaussian...

Example analysis: PMNS formation

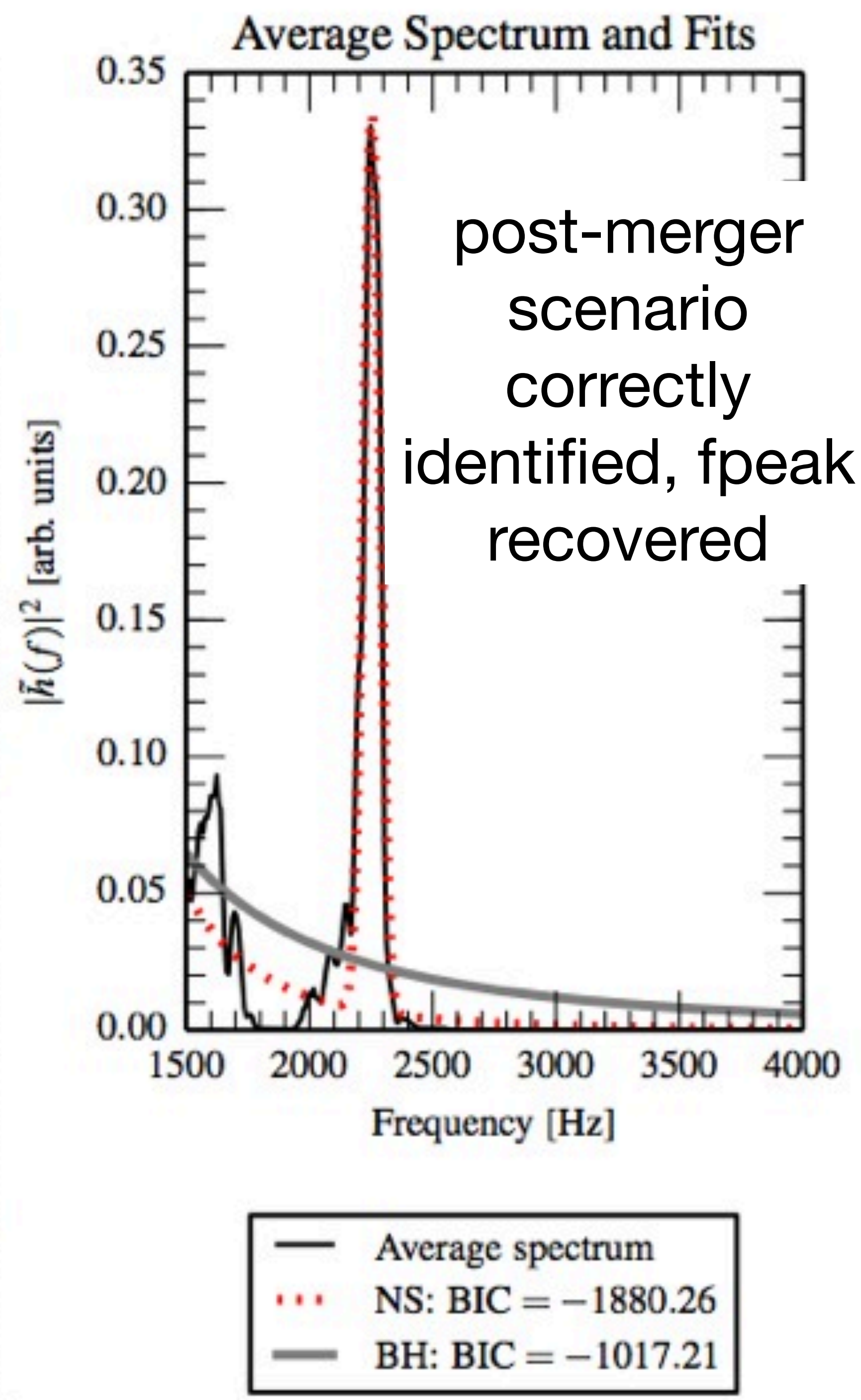
Target (noise free)



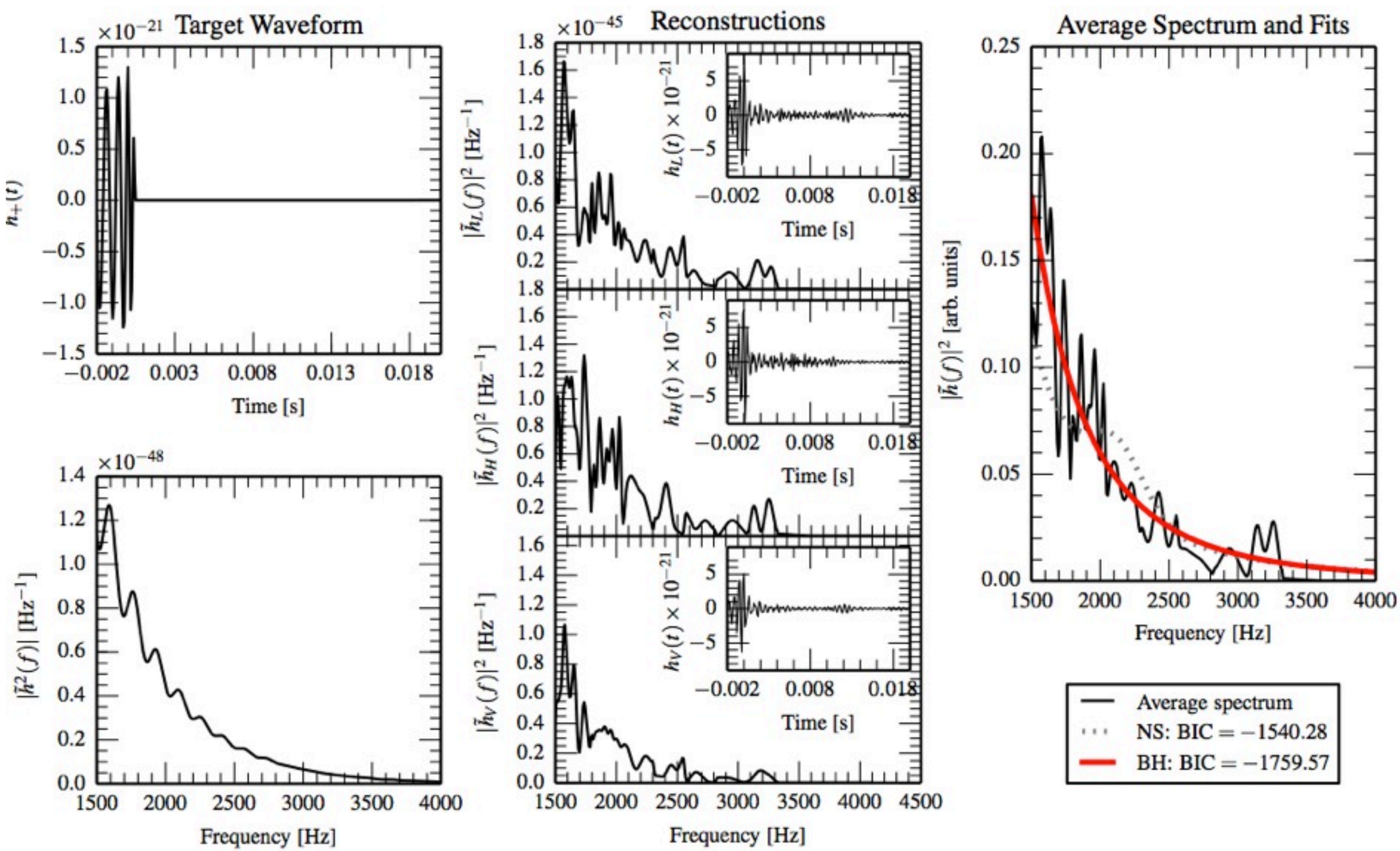
Reconstructions



Fit to reconstructed spectrum



Example analysis: prompt collapse



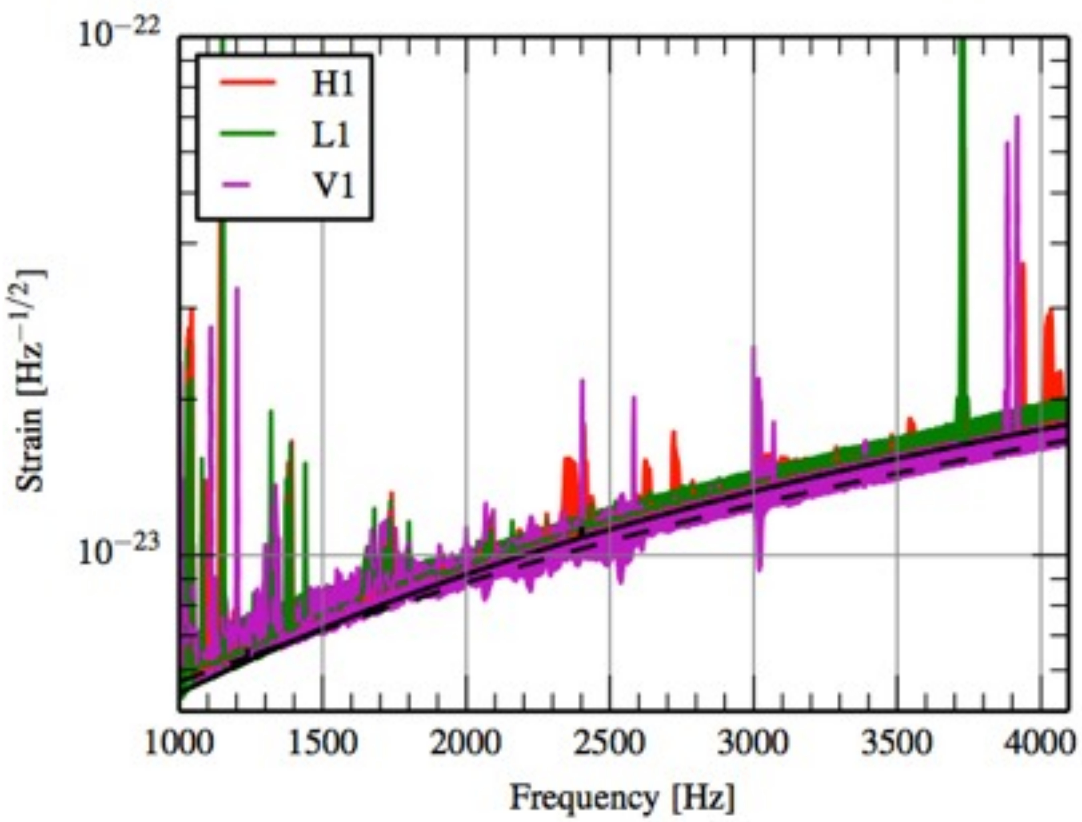
Monte Carlo Detectability Study

- Simulations: inject populations of merger waveforms in *recoloured* iLIGO/Virgo data (advanced detector sensitivities expected for ~2020)

- Measure sky-, orientation-averaged range for CWB, scale to horizon distance (D_{hor} = 2.26 x Range):

$$\mathcal{R}_{\rm eff}^{\rm CWB} = \left[3 \int_0^\infty {\rm d}r r^2 \epsilon(r) \right]^{1/3}$$

ε: detection efficiency



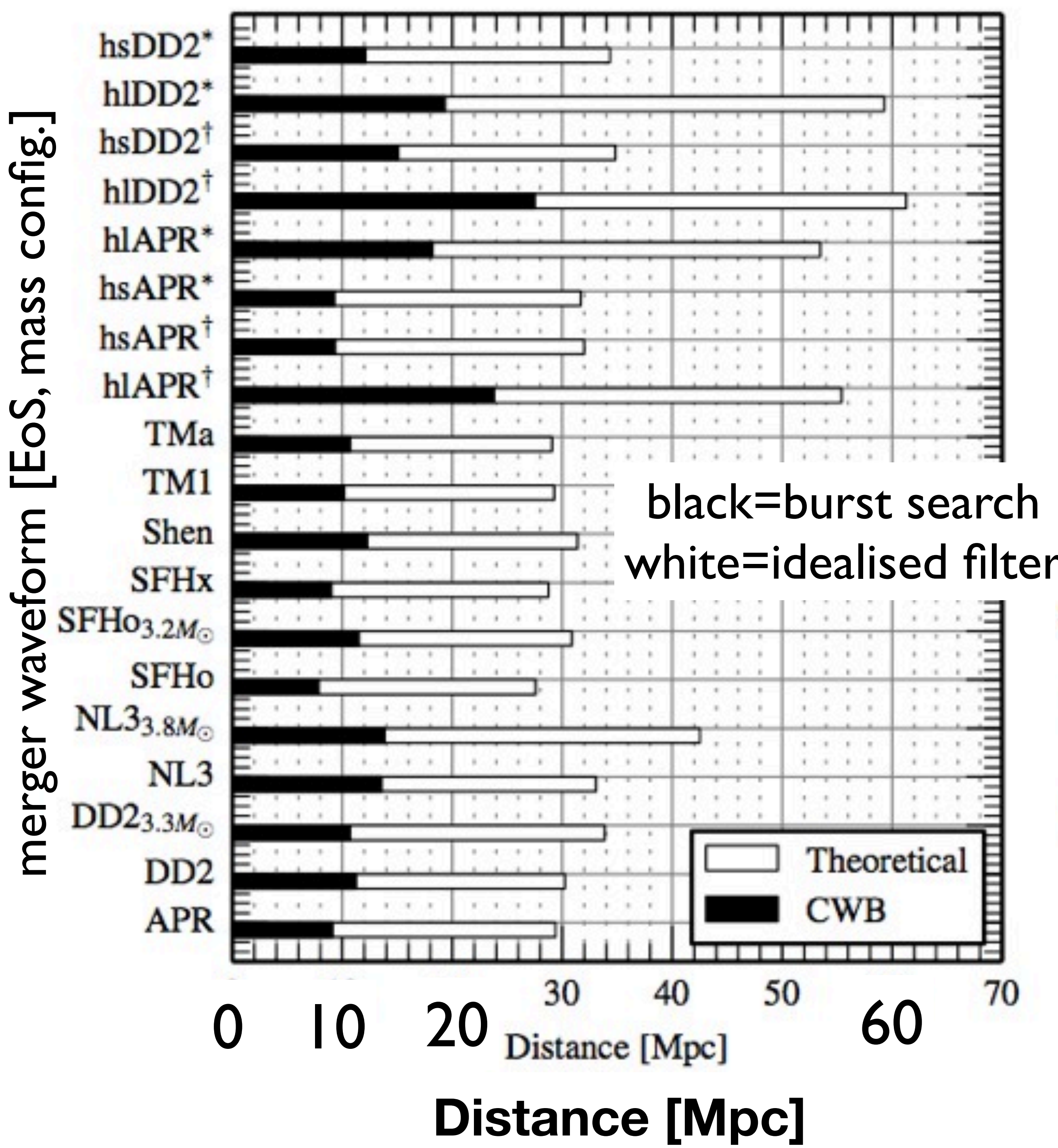
- Compare: effective range for **idealised** *optimal* matched-filter strategy (for 1500-4000 Hz)

- In both cases, assume **3σ significance** after ~100 trials (following up BNS inspiral detections with aLIGO)

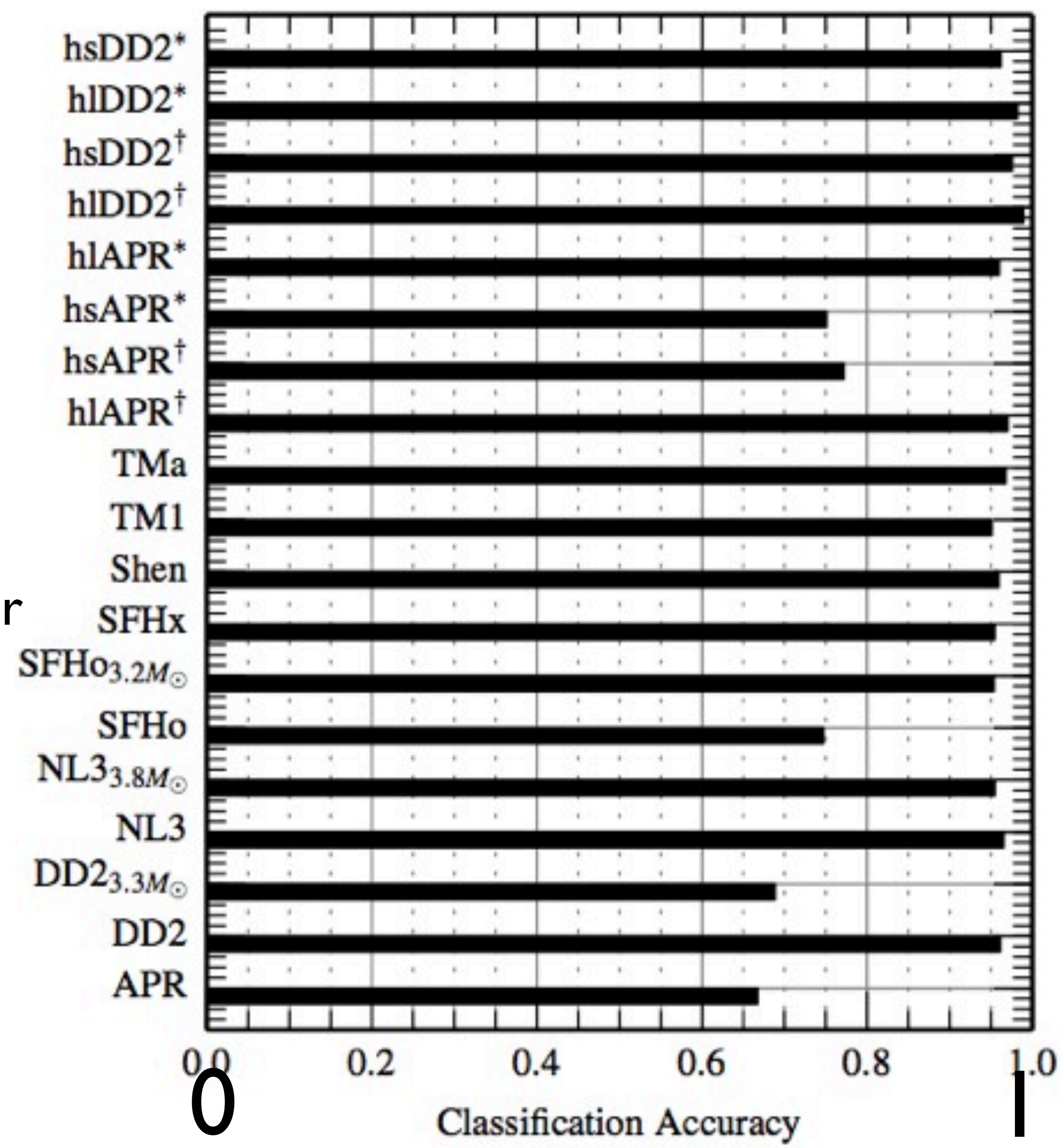
- For 3-detector **idealised** search: SNR~3

Detectability & Classification Results

Horizon Distances (optimal orientation, location)

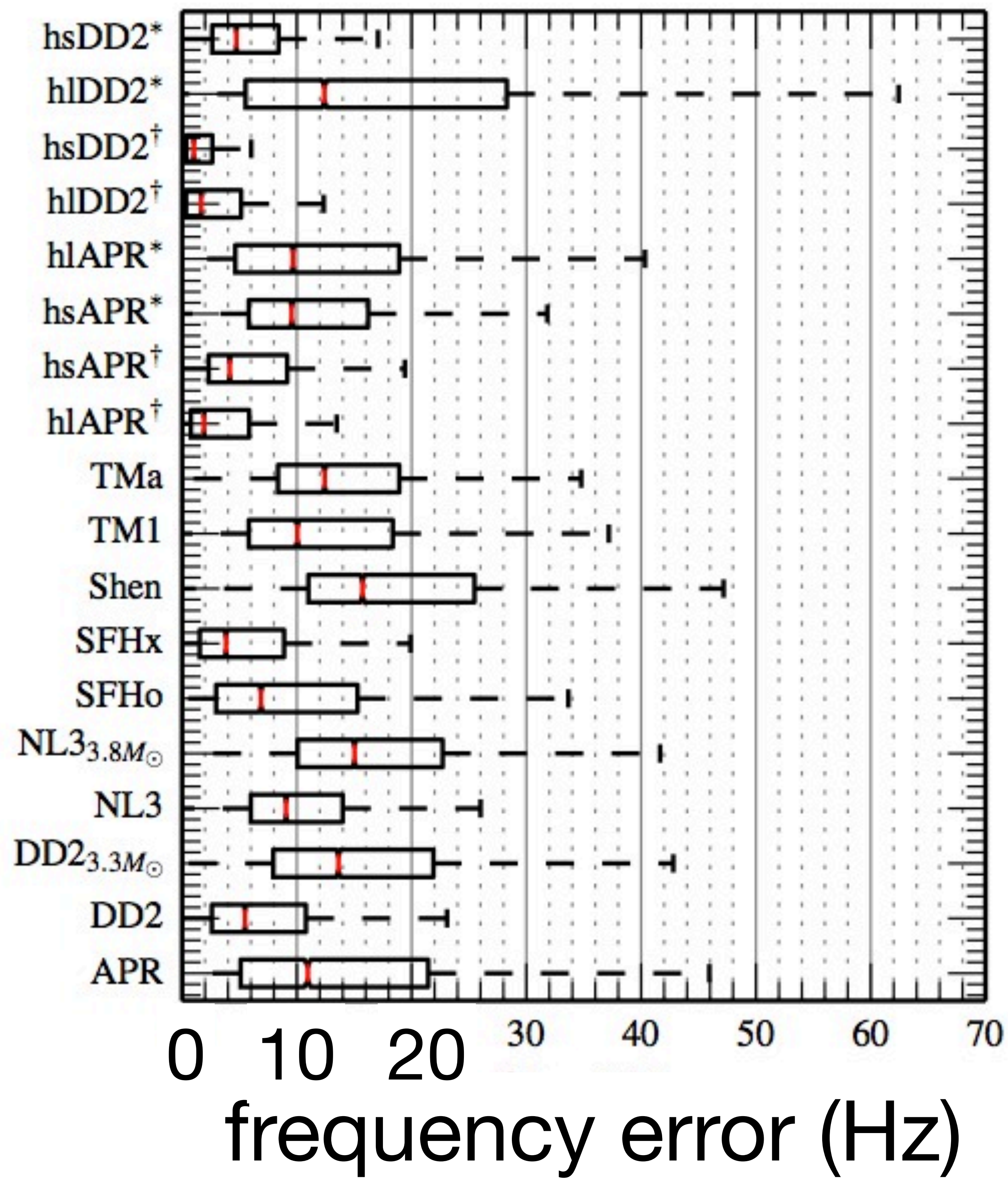


Classification Accuracy (probability of identifying correct post-merger scenario)

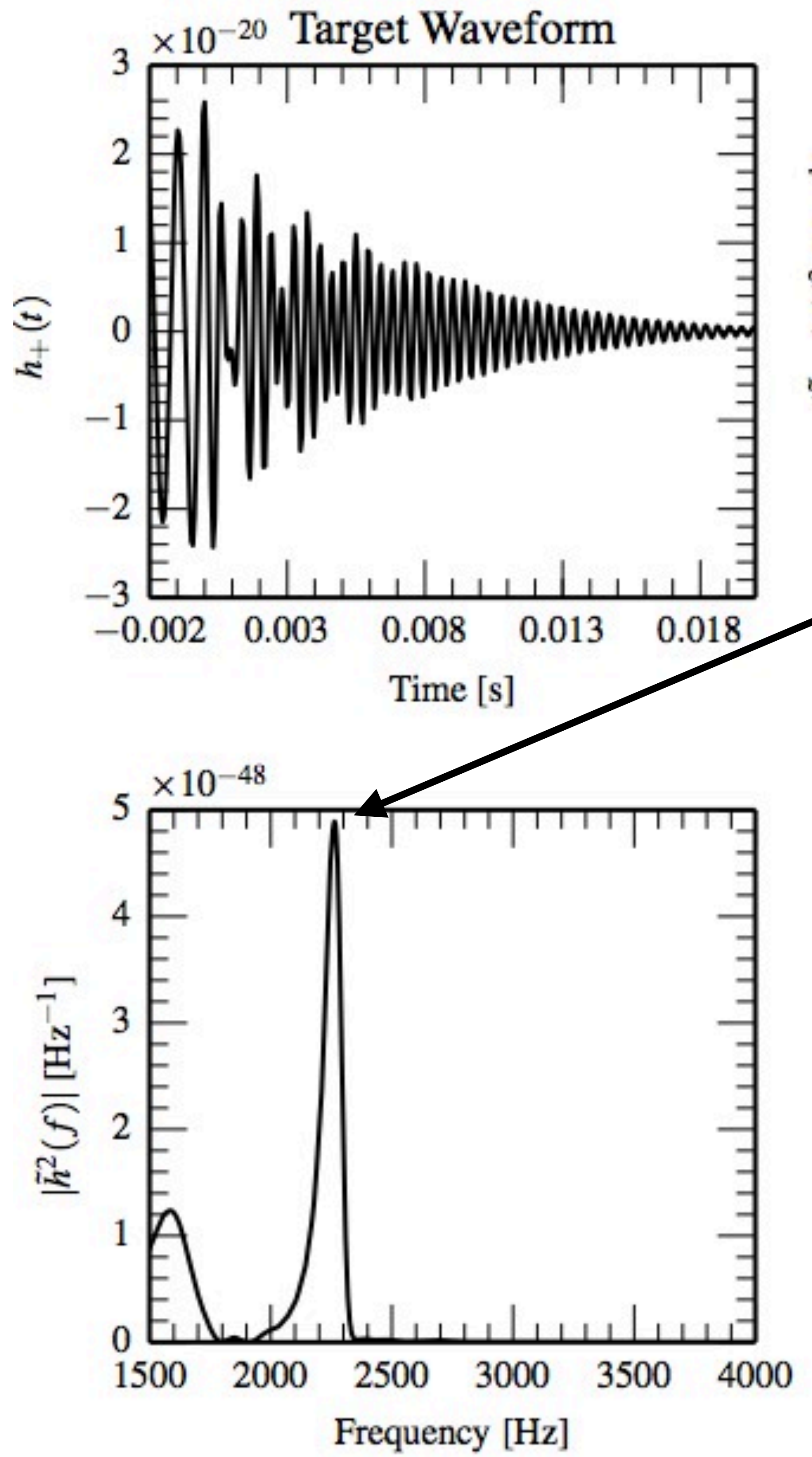


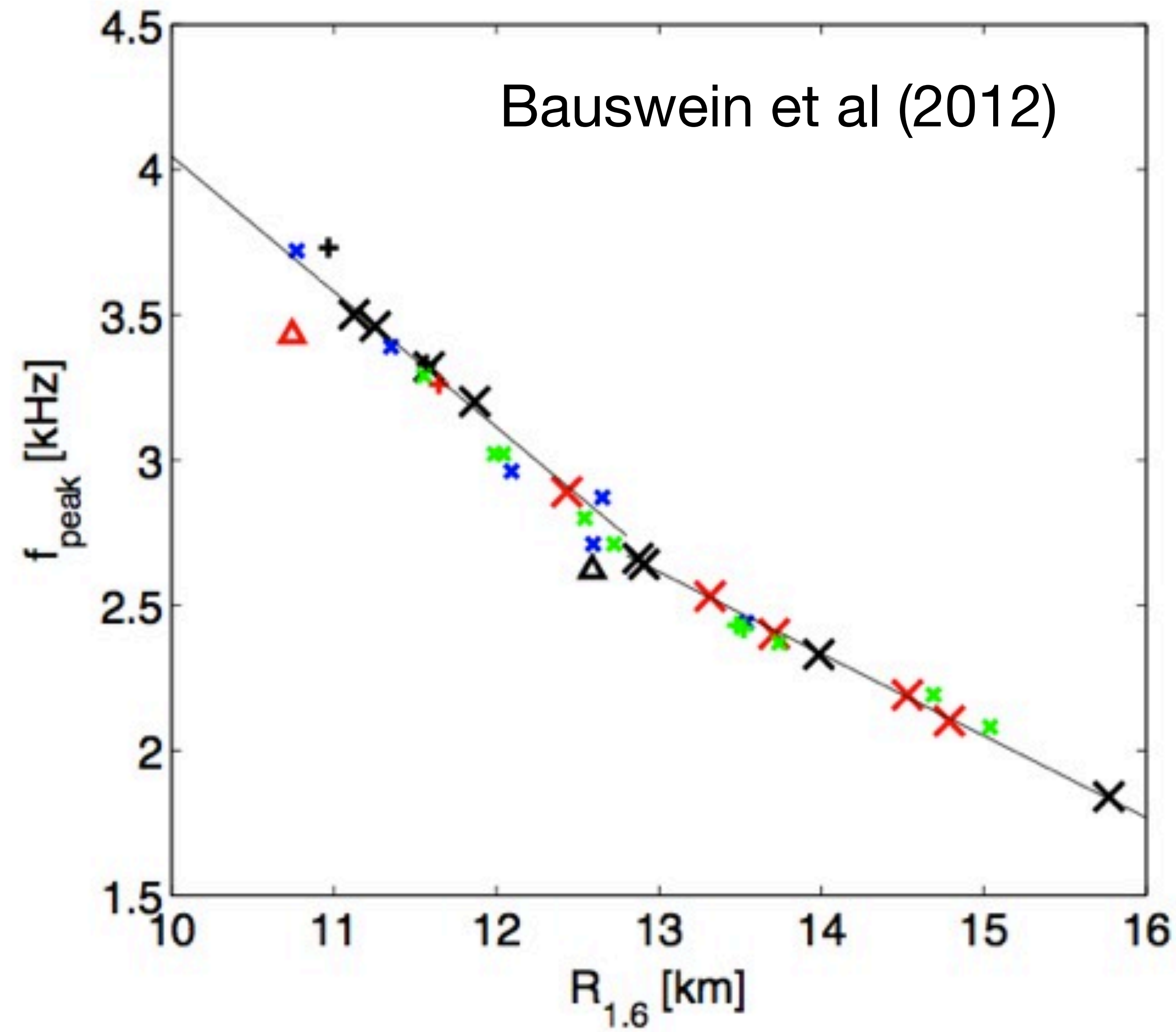
Peak Frequency Estimation

- red = median
- box = interquartile range
- whiskers = outliers
- Averaged over extrinsic parameters
- Result: Recover peak frequency to ~10 Hz



Frequency -> Radius



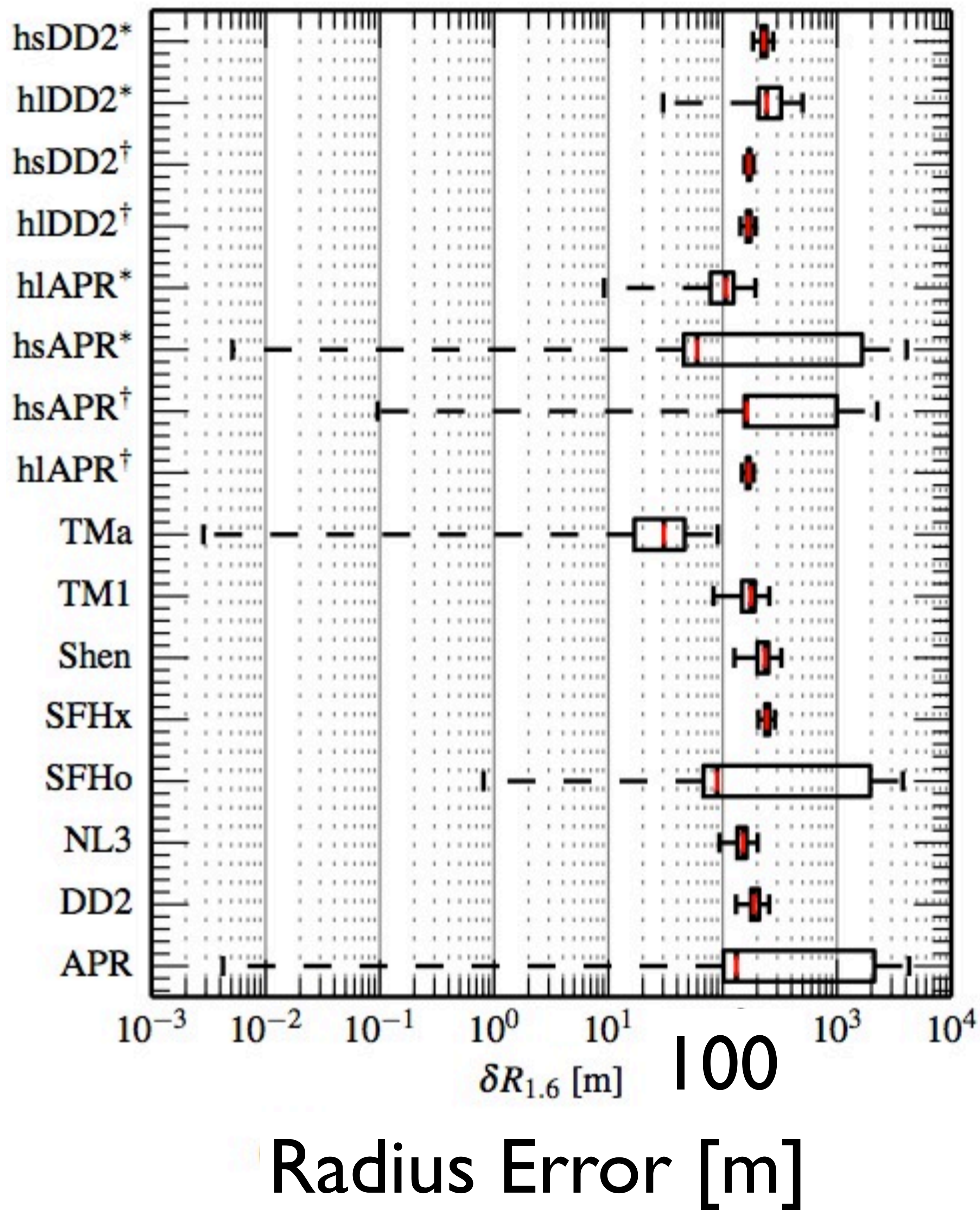


- f_{peak}-$R_{1.6}$ relation for 1.35-1.35 system

$$f_{\rm peak} = \begin{cases} -0.2823 R_{1.6} + 6.284 & \text{for } f_{\rm peak} < 2.8\,\text{kHz} \\ -0.4667 R_{1.6} + 8.713 & \text{for } f_{\rm peak} > 2.8\,\text{kHz} \end{cases}$$

- Similar relationships exist for other masses
- Masses likely measured to ~few % from inspiral

Radius Recovery



Summary

- First systematic study of post-BNS burst detectability with real(istic) data & algorithm
    - Estimates for *theoretical optimal* analysis and *existing* burst analysis with minimal tuning: upper/lower bounds for future studies
- Assume we require ~3σ significance for post-merger detection after analysing O(100) BNS inspirals (c.f., GRB-triggered GW analyses)
    - Quite conservative (in terms of threshold - optimistic for BNS...)!
- Burst horizon: 10-20 Mpc [10^{-3} - 0.1 events/year for R_{bns}=100 $MWEG^{-1}Myr^{-1}$]
- Theoretical matched filter horizon (SNR~3): ~30-60 Mpc [0.03 - 0.3 events/year]
- Simple model selection algorithm distinguishes BH and PMNS formation with >95% success rate [~70% success for waveforms with smaller post-merger peaks]
- Frequency estimation accurate to ~10 Hz; radius recovery accurate to ~50-250 m [for a fiducial cold, non-rotating NS & assuming Bauswein fit]
- This is just the beginning...

Moving Forward (from the analysis side)...

- This study (1406.5444): determine bounds for 'what we could do tomorrow' vs theoretically achievable
- Gap between CWB & theoretical horizons = motivation for more targeted analyses
- Examples:
  - C. Messenger, K. Takami, S. Gossan, L. Rezzolla, and B. S. Sathyaprakash, ArXiv e-prints (2013), 1312.1862 - fully Bayesian analysis of power spectra
  - Constrained time-frequency analyses (Sukanta's suggestion, Monday)
  - Hotokezaka et al Phys. Rev. D 88, 044026 (2013): analytic description of post-merger signal (albeit with up to 10 parameters)
  - Ad hoc templates: how far could we get with a ring-down or similar? [Hint: surprisingly far, if we're willing to perform quite aggressive data conditioning...]
  - Recent un-modelled search developments include: 'CWB 2G' and a Bayesian Wavelet analysis algorithm
- Anything which leads to a posterior PDF on $R_{1.6}$ (or similar) would be great!

- end.

Optimal Detectability

- Also compute effective range, rates for **hypothetical** optimal-filter [single, 100% accurate template matching the true signal]

$$\rho^2 = 4\Re \int_{f_{\rm low}}^{f_{\rm upp}} \frac{\tilde{d}(f)\tilde{h}^*(f)}{S(f)} \mathrm{d}f$$

- f_{low}=1500 Hz
- f_{upp}=4000 Hz

- ρ^2 distribution in Gaussian noise: central-χ^2, 2 d,o.f

$$\mathrm{FAP} = 1 - P_{\chi^2}(\rho^2 \leq \rho^2_{\rm thresh} | k = 2)^{N_t}$$

- N_t = trials factor for template-bank. Here, N_t=1 [optimal search]

- Set FAP=1e-5: Single-IFO SNR threshold~5; Horizon distance D_{hor} is physical distance to optimally oriented, overhead signal with SNR=ρ_{thresh}

- X detectors: √X more sensitive than single-IFO; ρ_{thresh}~3

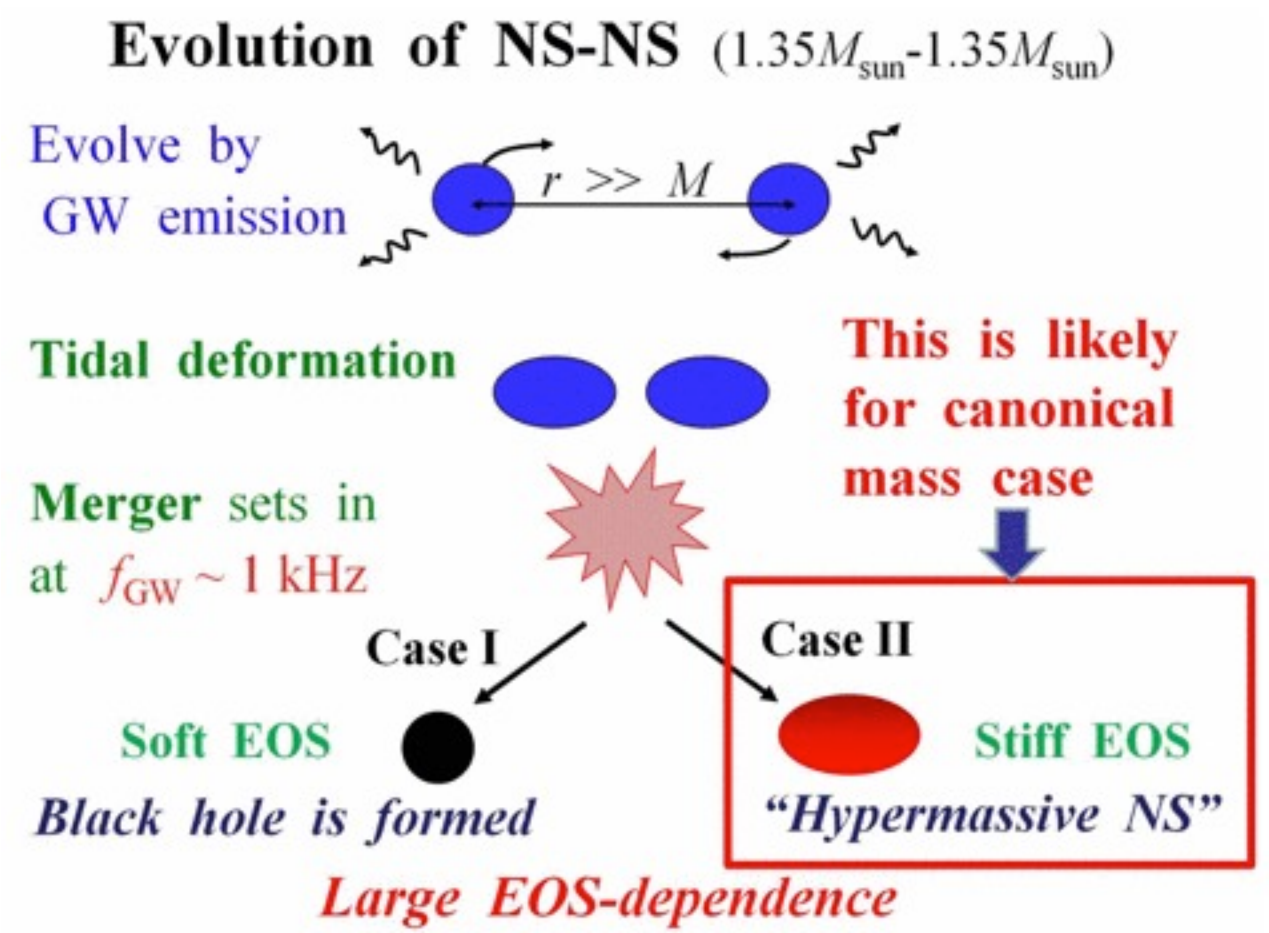
Post-BNS Bursts: Motivation

- Post-merger signal has *enormous* science potential. Examples include (non-exhaustive list!):
  - Correlation between dominant post-merger frequency (fpeak) and fiducial NS radius (e.g., Bauswein et al PRD 86 063001 (2012)) - measure radius to ~100 m:

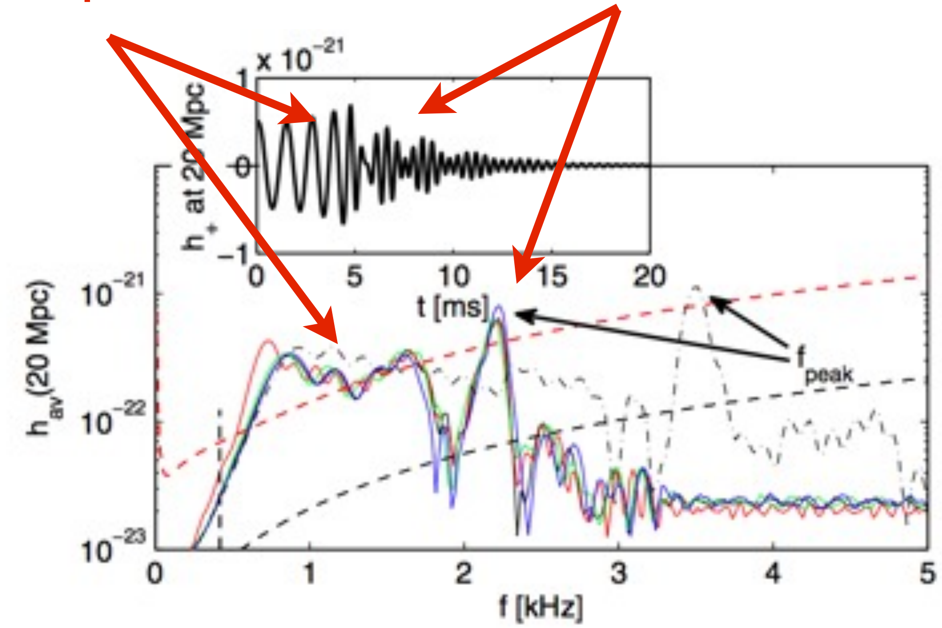
$$f_{\text{peak}} = \begin{cases} -0.2823 R_{1.6} + 6.284 & \text{for } f_{\text{peak}} < 2.8\,\text{kHz} \\ -0.4667 R_{1.6} + 8.713 & \text{for } f_{\text{peak}} > 2.8\,\text{kHz} \end{cases}$$

  - Constrain threshold mass for collapse / maximum mass of NS [Bauswein et al, PRL 111 131101 (2013)]
  - Multiple fpeak measurements could constrain NS mass to 0.1Msun, radius to a few % [Bauswein et al, arXiv 1403.5301]
  - Subdominant frequency peak may constrain NS *compactness* (M/R) [Takami et al, arXiv 1403.5672]
  - ... could even be useful for cosmology if the EOS is already known! [Messenger et al, arXiv 1312.1862]

Post-BNS Bursts: Motivation



Slide from "Numerical Simulations of Gravitational Waves with Matter" (M.Shibata @ Rattle & Shine)



Bauswein, Janka, PRL 108, 011101 (2012)

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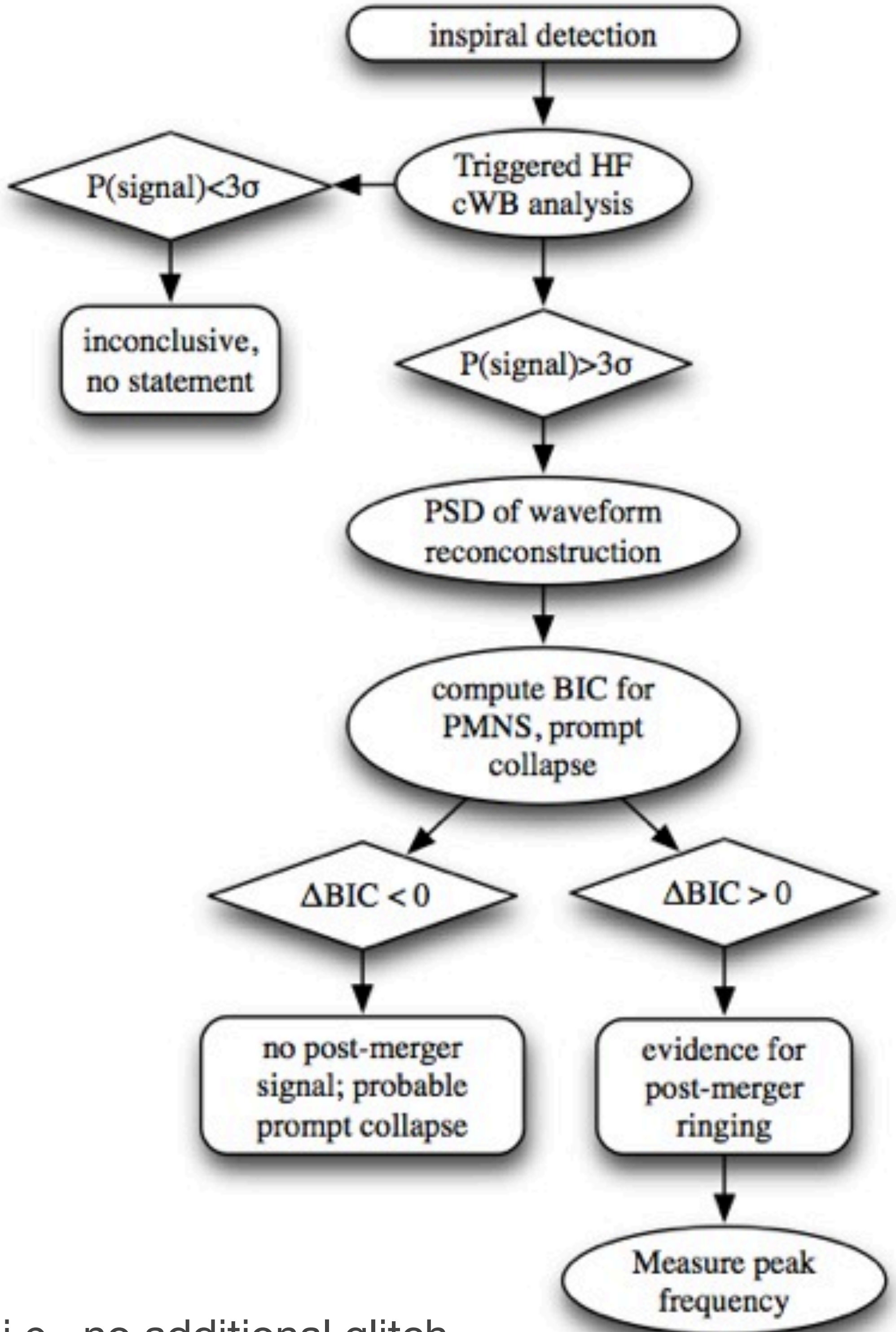
- BNS merger outcome: prompt collapse to black hole or formation of stable/quasi-stable post-merger neutron star (PMNS)
- PMNS emits short (10-100ms) burst with dominant power ~2-4 kHz. BH ringdown will be ~6-7 kHz - too high freq.
- SNR dependent on codes, EOS, mass configurations, ... but SNR~5 @ few - 20 Mpc
- Dominant post-merger oscillation freq. correlates with radius of a 1.6 M_{sun} NS across many EoS

Post-merger Analysis Procedure

- Envisage BNS-inspiral-triggered followup, O(100) BNS/year
- Assume T_{obs}=100 ms [known time of coalescence], search in [1500, 4000] Hz with CWB
- Detection criterion: 3σ after 100 trials: FAP~10^{-5}
- Detection candidate: *assume* GW power present *and* it's associated with the BNS*
- CWB: reconstructed detector responses for each IFO. Take SNR-weighted average of reconstructions' spectra
- Model prompt (**BH**) and delayed (**NS**) collapse spectra as **power law**, **power law + Gaussian**:
- Select using Bayesian Information Criterion (very approximate evidence ratio):

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

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



* i.e., no additional glitch rejection tests after getting a CWB trigger