Estimation of the Precision for Future KAGRA from Post-Merger Gravitational Waves of BNS Coalescences

OVERVIEW :

Quantitative assessment of the detectability of
post-merger *kHz* GWs from BNS mergers
using NR waveforms and the high-frequency sensitivity model of KAGRA

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This work

- Background : BNS **post-merger remnant**
- System : **kHz** GWs from BNS post-merger and **KAGRA PSD**
- Motivation : **Performance evaluation** of future KAGRA for f_{peak}
- Method : **BayesWave** analysis : model-agnostic reconstruction
- Results : "How far for f_{peak}?" / "Can we detect?"

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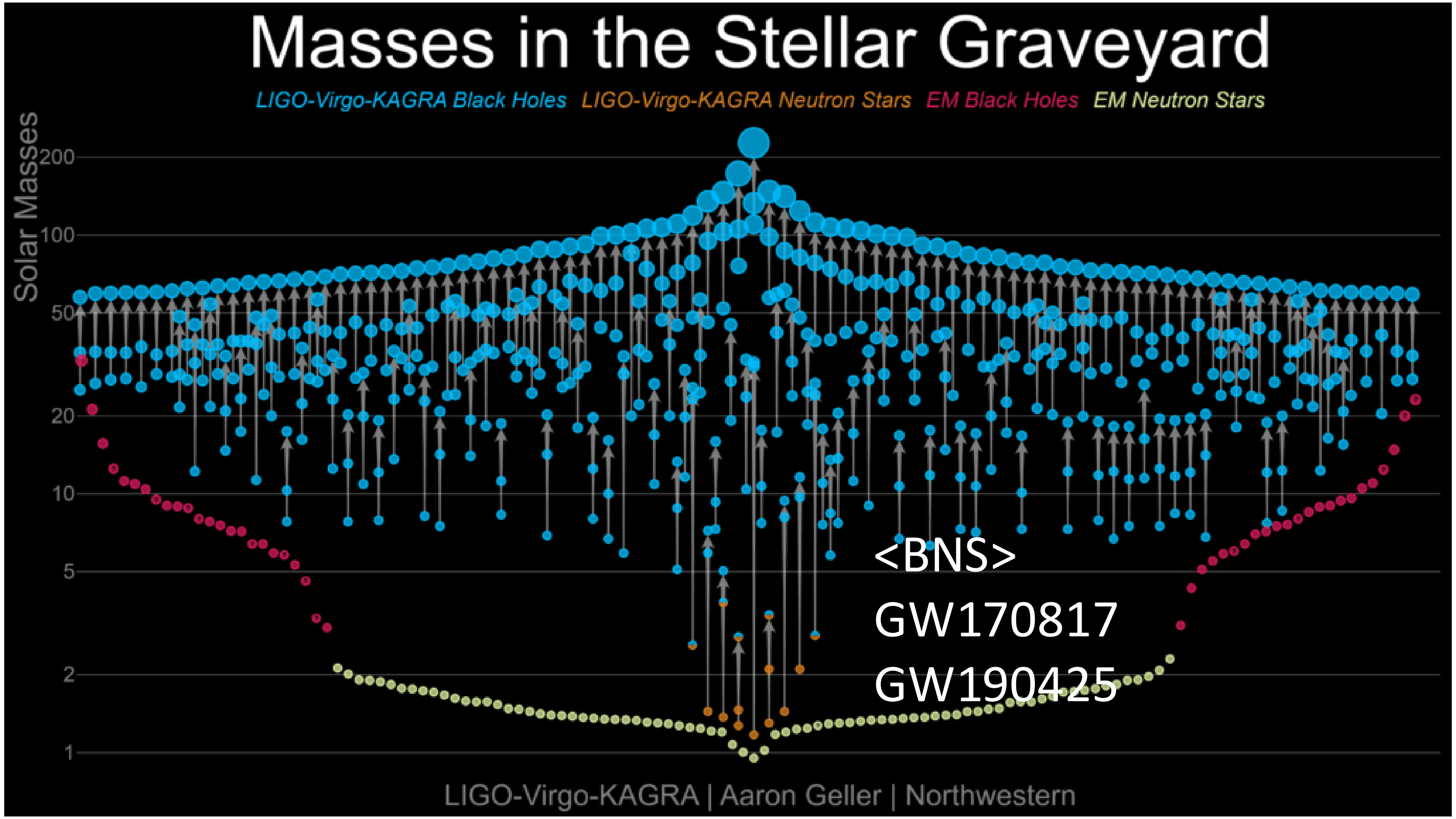
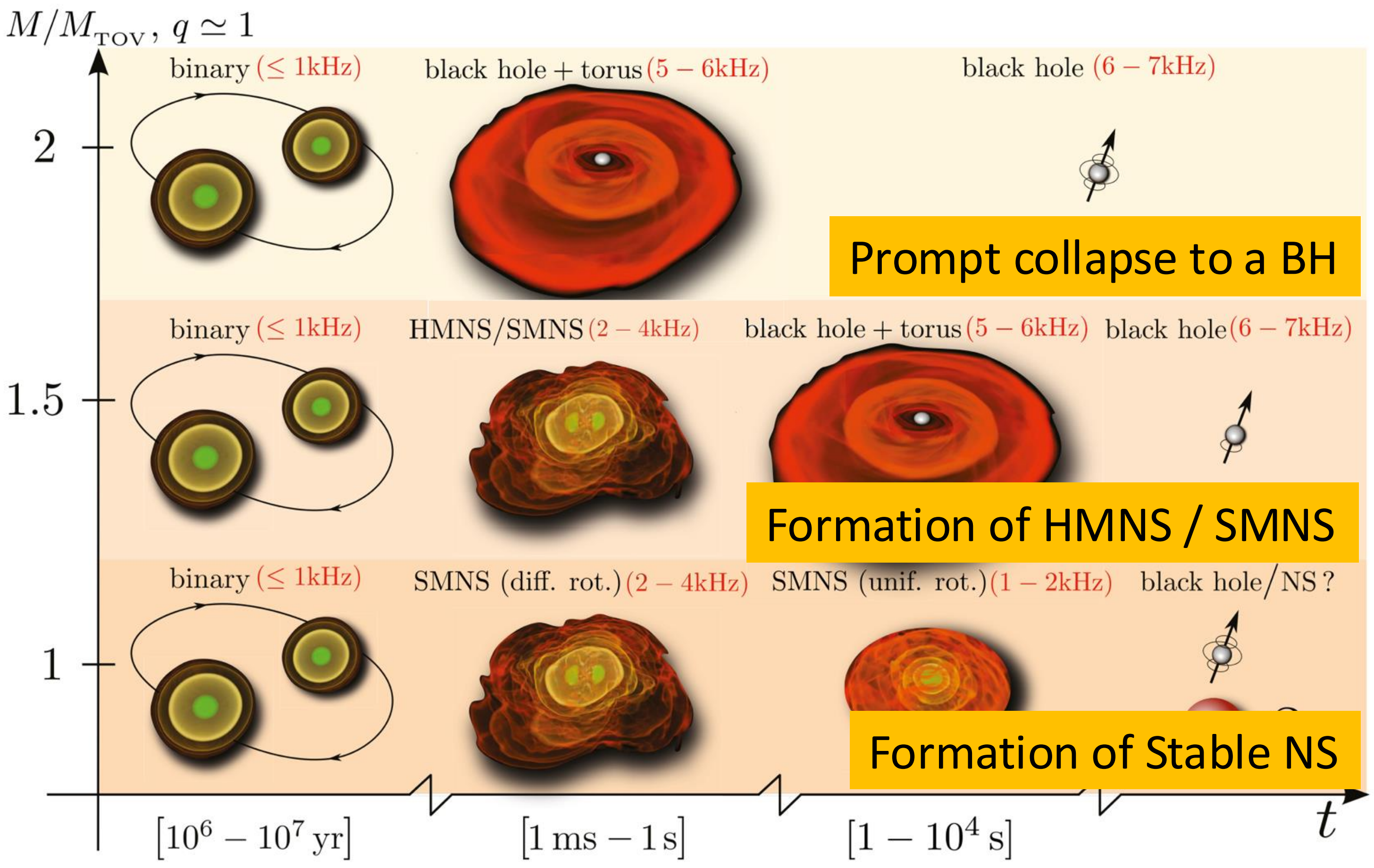
BNS Mergers and Missing Post-Merger Signal



No detectable *post-merger* BNS GW signals!

GW observations of BHs(blue) and NSs(orange) from the LVK GWTC-4.0 catalog

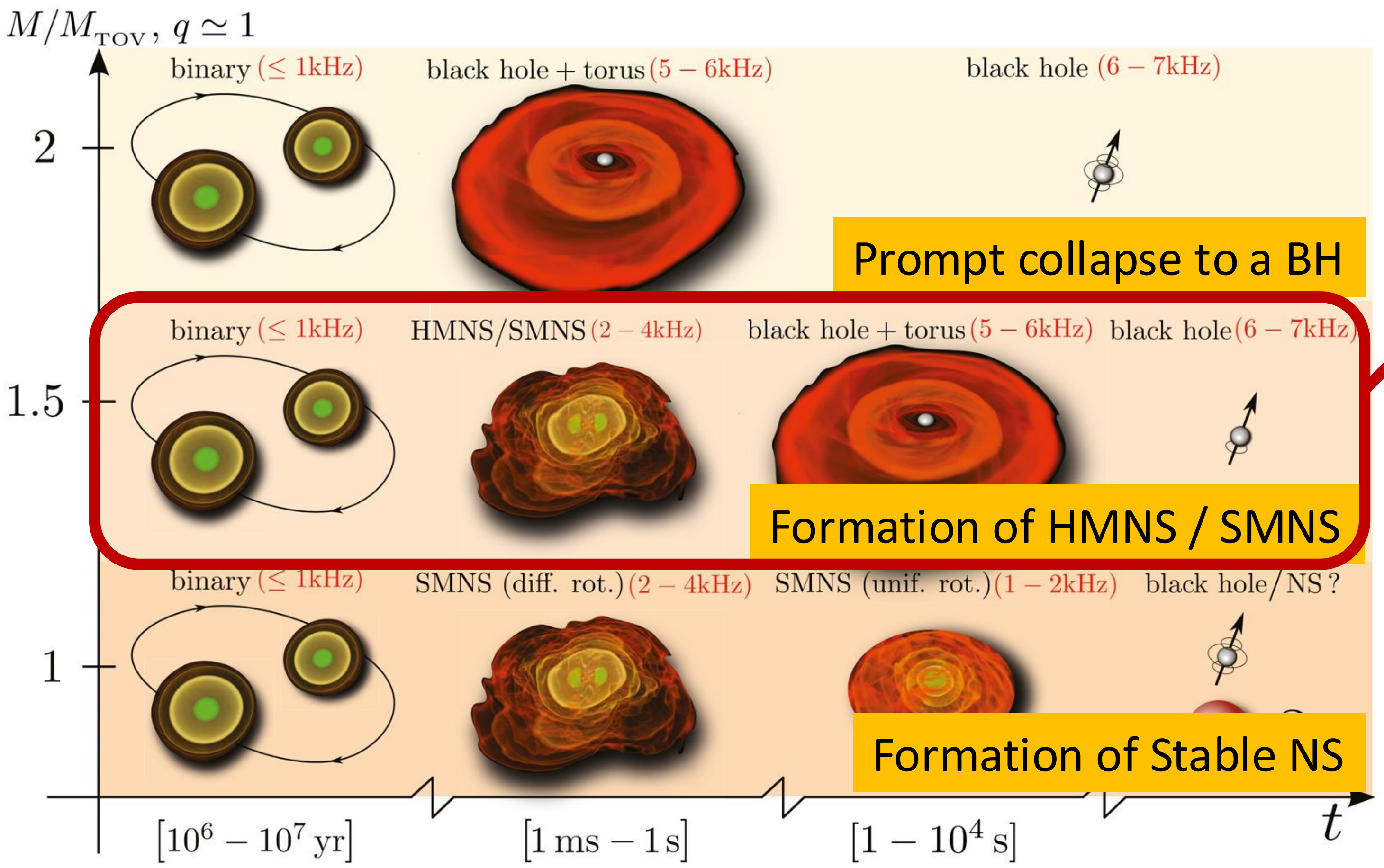
BNS Post-Merger Remnant



Schematic diagram illustrating the various stages
as a function of the initial mass of the binary (Baiotti, 2017)

Depending on the **initial total mass** and **equation of state**, BNS merger can produce **different type of remnant**.

BNS Post-Merger Remnant



Schematic diagram illustrating the various stages
as a function of the initial mass of the binary (Baiotti, 2017)

Candidate sources detectable by ground-based GW detectors

Depending on the **initial total mass** and **equation of state**,
BNS merger can produce
different type of remnant.

Hyper-Massive NS

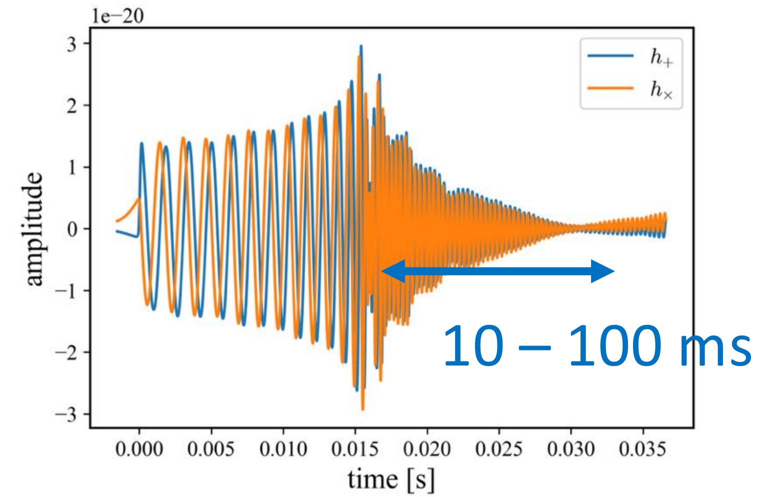
- Supported by **differential rotation** and **thermal effect**
- Survive for 10 – 100 ms -> collapse to a BH
- Emit GWs with **2 – 4 kHz** and the **spectral peak frequency($f_{\mathbf{peak}}$)** of the fundamental (f-) mode

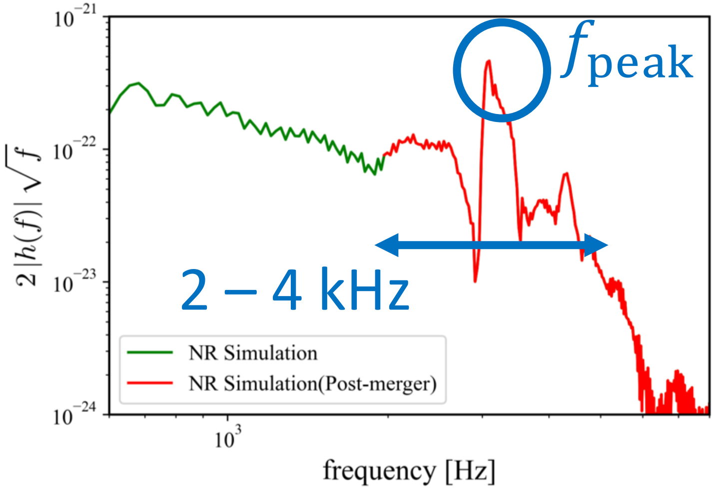
Key to the inner information

Environment

Extremely **high density** (a few times nuclear saturation density) and **high temperature** (tens MeV)

Natural laboratory for extreme matter





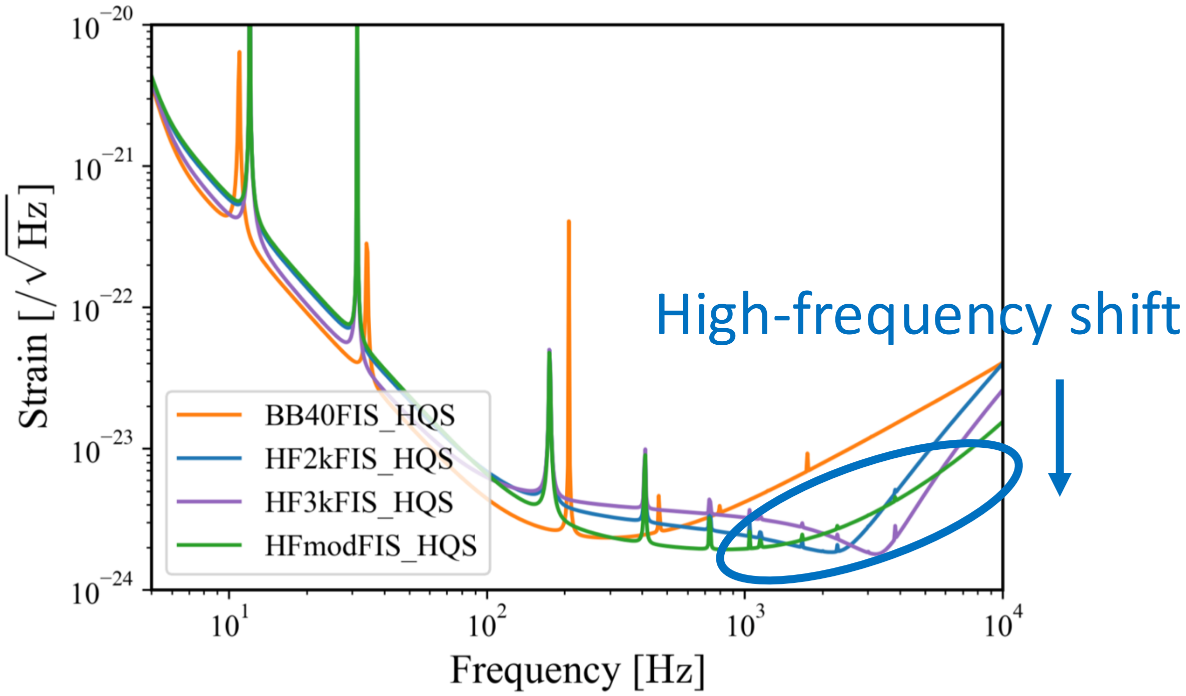
Example of NR HMNS waveform: time and frequency

KAGRA Upgrade Strategy

KAGRA is aiming to improve its **high-frequency** sensitivity band to detect GWs emitted during **the post-merger phase** of BNS coalescence.

The difference of sensitivity curves

- BB40 : Broadband configuration using 40 kg test masses
- HFmod : Moderated high frequency configuration
- HF2/3k : High frequency configuration focused at 2/3 kHz

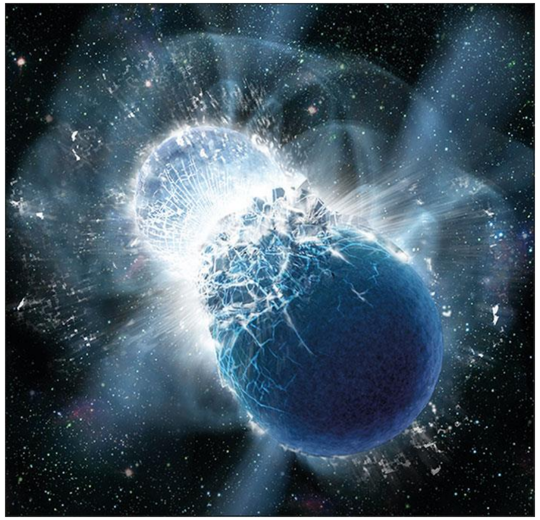


Examples of sensitivity curves for 4 upgrade options considered in KAGRA Collab. 2025

Motivation

KAGRA detector

Analytical preparation is required
to identify BNS post-merger signals
with future KAGRA!



BNS post-merger remnant

Our task is to quantitatively evaluate
the future KAGRA performance for f_{peak}.

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- Results : "How far for f_{peak}?" / "Can we detect?"

BayesWave

BayesWave provides a **model-agnostic** reconstruction of the post-merger waveform using a **sum of sine-Gaussian** (**Morlet–Gabor**) **wavelets** (Cornish et al. 2015):

$$h_+(t) = \sum_{i=0}^{N_s} \Psi(t; A_i, f_{0,i}, Q_i, t_{0,i}, \phi_i)\,, h_\times(t) = \epsilon h_+(t) e^{i\pi/2}$$

$$\Psi(t; A_i, f_{0,i}, Q_i, t_{0,i}, \phi_i) = A e^{-(t-t_0)^2/\tau^2} \cos[2\pi f_0 (t - t_0) + \phi_0]$$

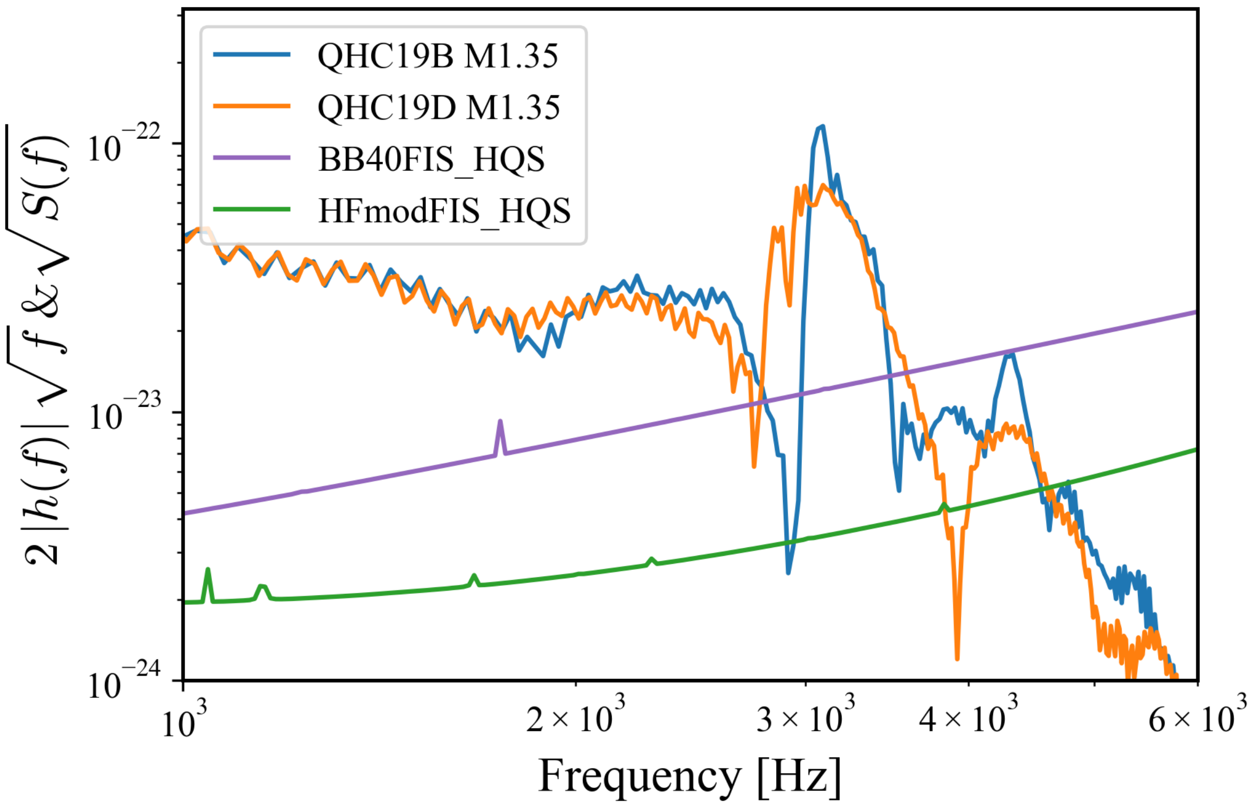
Time
Central frequency
Amplitude
Quality factor
Phase
Number of wavelet

The parameter and **the number** of the wavelets are marginalized using a reversible jump Markov chain Monte Carlo (RJMCMC).

This flexible, template-free approach captures generic morphology **beyond limited numerical simulations**!

Credit: Caltech

Analysis Setup: NR waveforms and KAGRA PSD



NR waveforms at 40 Mpc and KAGRA PSD

Two NR BNS waveform models

Quark-Hadron Crossover, NS masses

$1.35 M_{\odot}$

QHC19B-M1.35(Soft), QHC19D-M1.35(Stiff)

uang et al. 2022)

Two KAGRA PSD models

Broad-Band and High-Frequency

BB40FIS-HQS, HFmodFIS-HQS

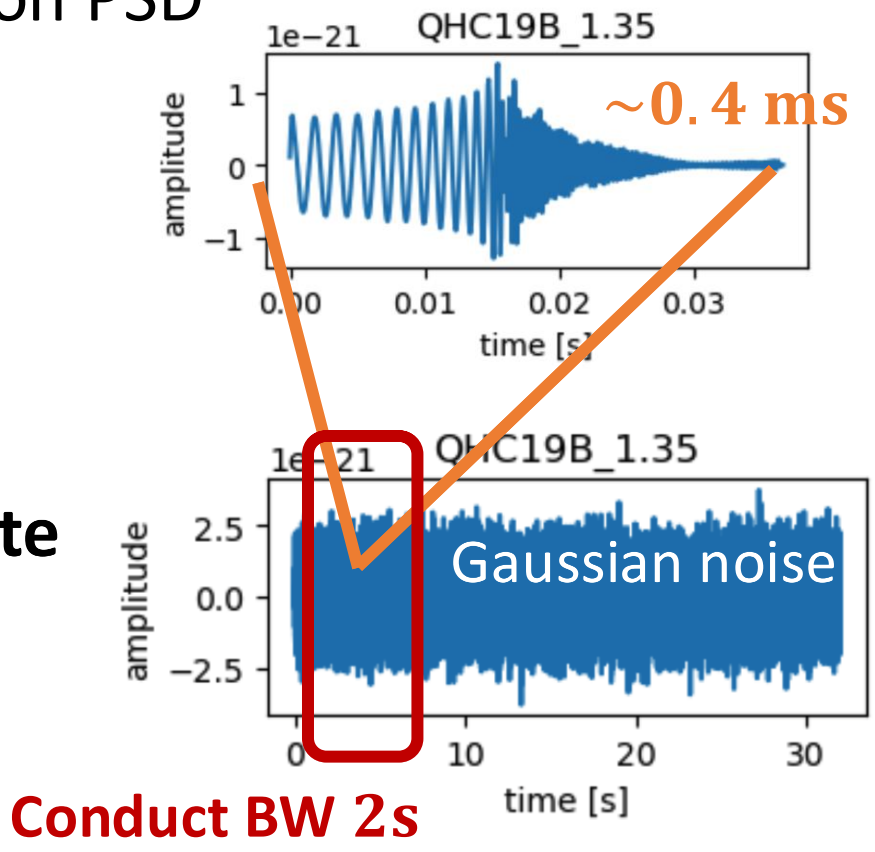
(KAGRA Collab. 2025)

*FIS-HQS : Frequency-Independent Squeezing & High-Quality Squeezing

Injection of NR Waveforms into KAGRA noise

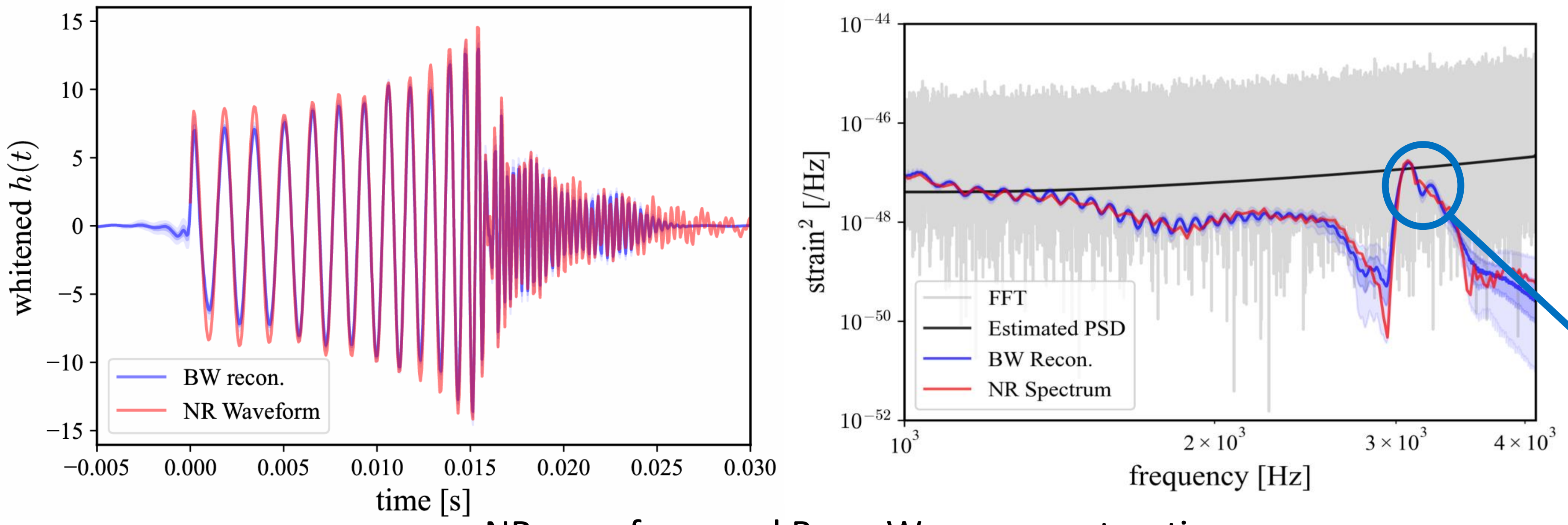
1. Generate **100 Gaussian noise realizations** based on PSD and inject NR waveform (h_+) scaled distance (Assuming zenith incidence)

2. Conduct BayesWave using a 2s segment centered on the signal start time, and **simultaneously estimate the PSD and reconstruct the waveform**
RJMCMC iteration; 10^7



BayesWave Output and Estimate f_{peak}

Example output of BW analysis at 10 Mpc



NR waveform and BayesWave reconstruction

Reconstructed f_{peak}

define as

$$max\left(\frac{d|h(f)|^2}{df} = 0\right)$$

We evaluated f_{peak} for each set of 20,000 samples during the iteration(10^7)→ Posterior; **500 f_{peak} samples**

Evaluate Detectability

Peak Classification

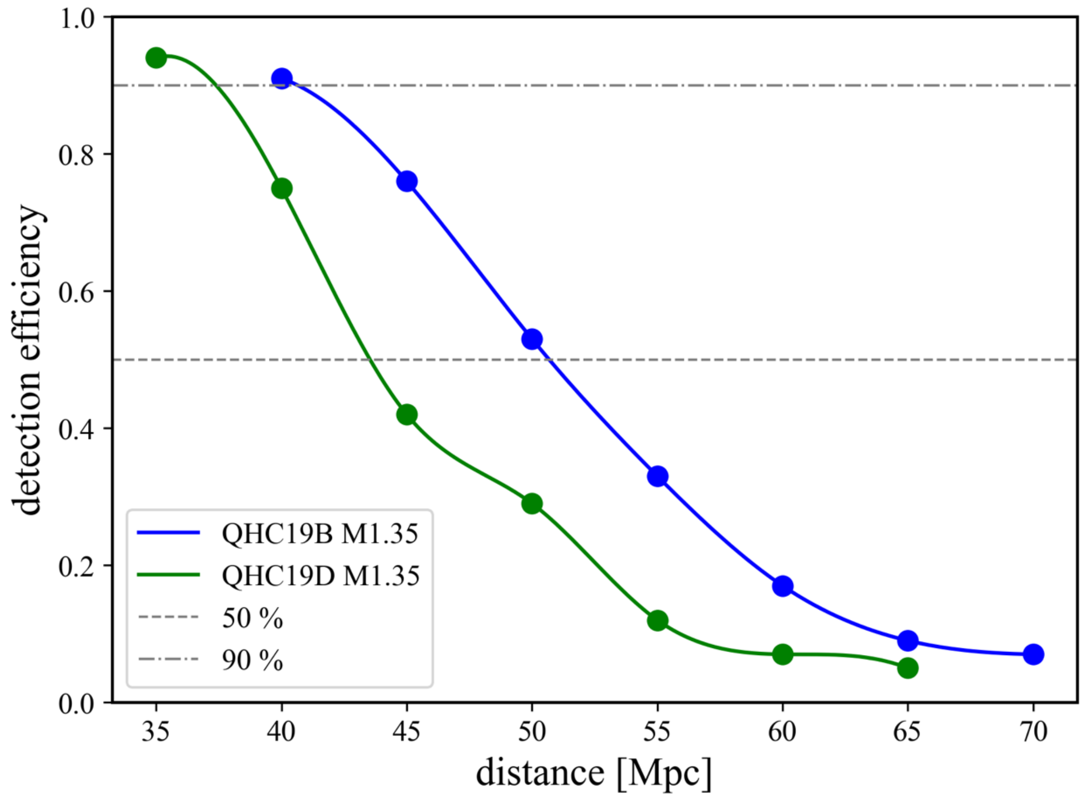
Count “peak”(exhibit local maximum) vs “no peak”(monotonically decreasing) at $f \geq f_{\mathrm{mer}}$(=Merger frequency) in 500 samples.
*Small fluctuations are removed by smoothing.

Peak Detection

“Peak detected”
if more than 475 out of 500 samples **(95% detected)** show a spectral peak.

Results1: Detectable Distance

HFmod



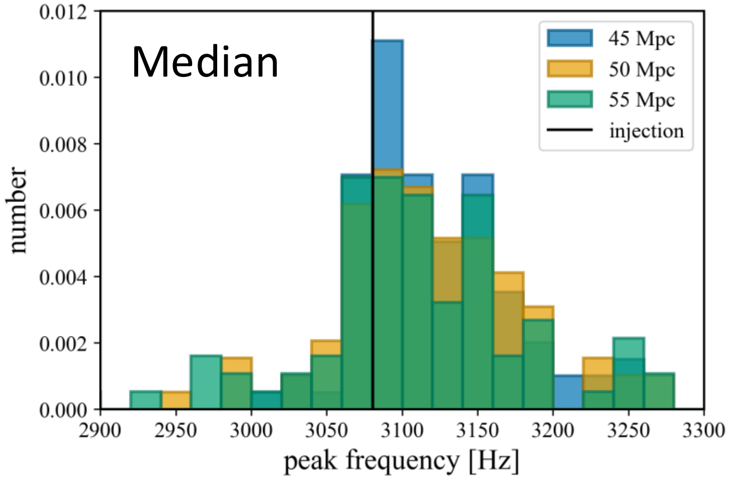
Detection efficiency as a function of distance.

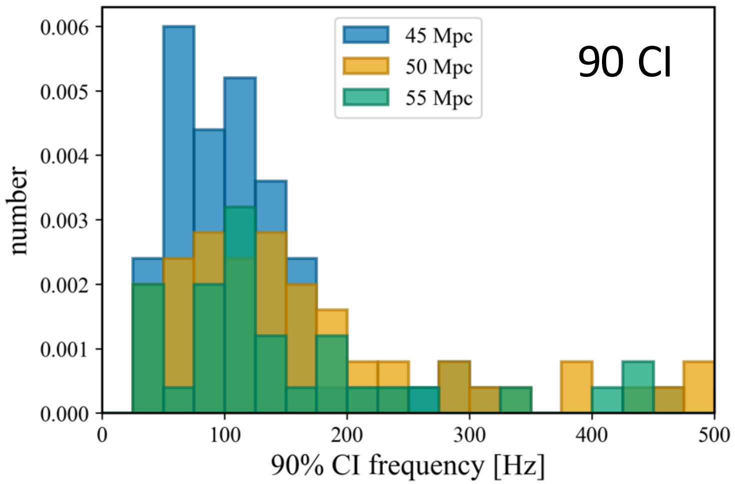
	50 % [Mpc]	90 % [Mpc]
HFmod QHC19B	50.68	40.65
QHC19D	43.54	37.39
BB40 QHC19B	14.79	11.86
QHC19D	12.73	10.94

*BB40 scaled from HFmod analysis

The difference of EOS

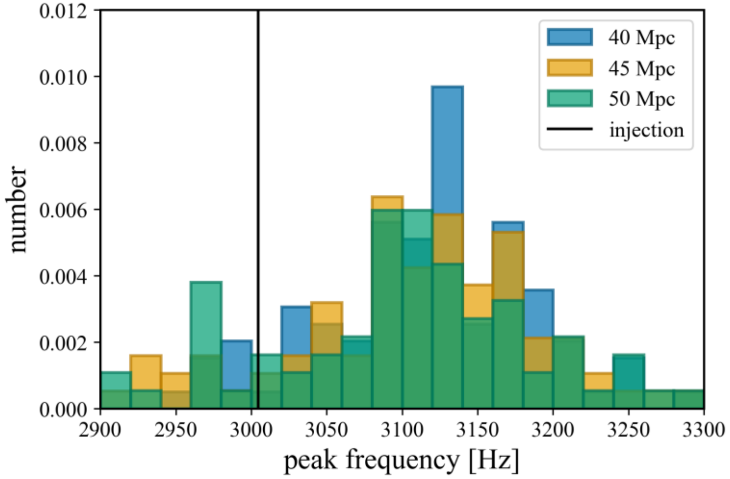
QHC19B-M1.35
(Soft)

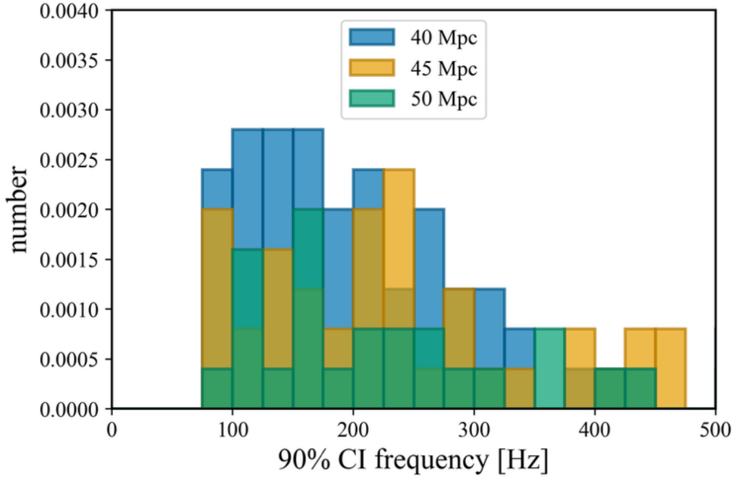




The distance corresponding to nearly identical detection efficiencies

QHC19D-M1.35
(Stiff)



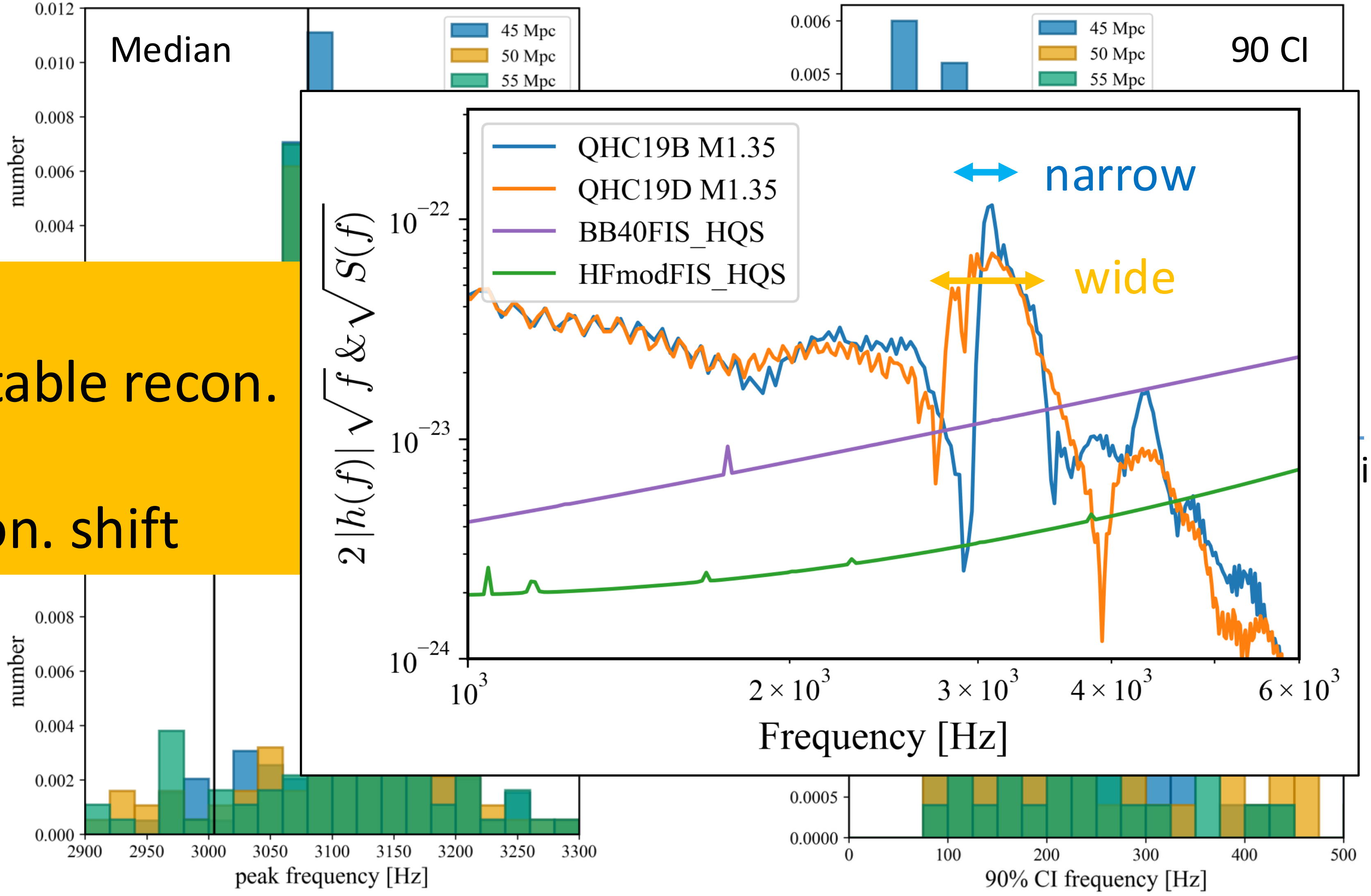


The difference of EOS

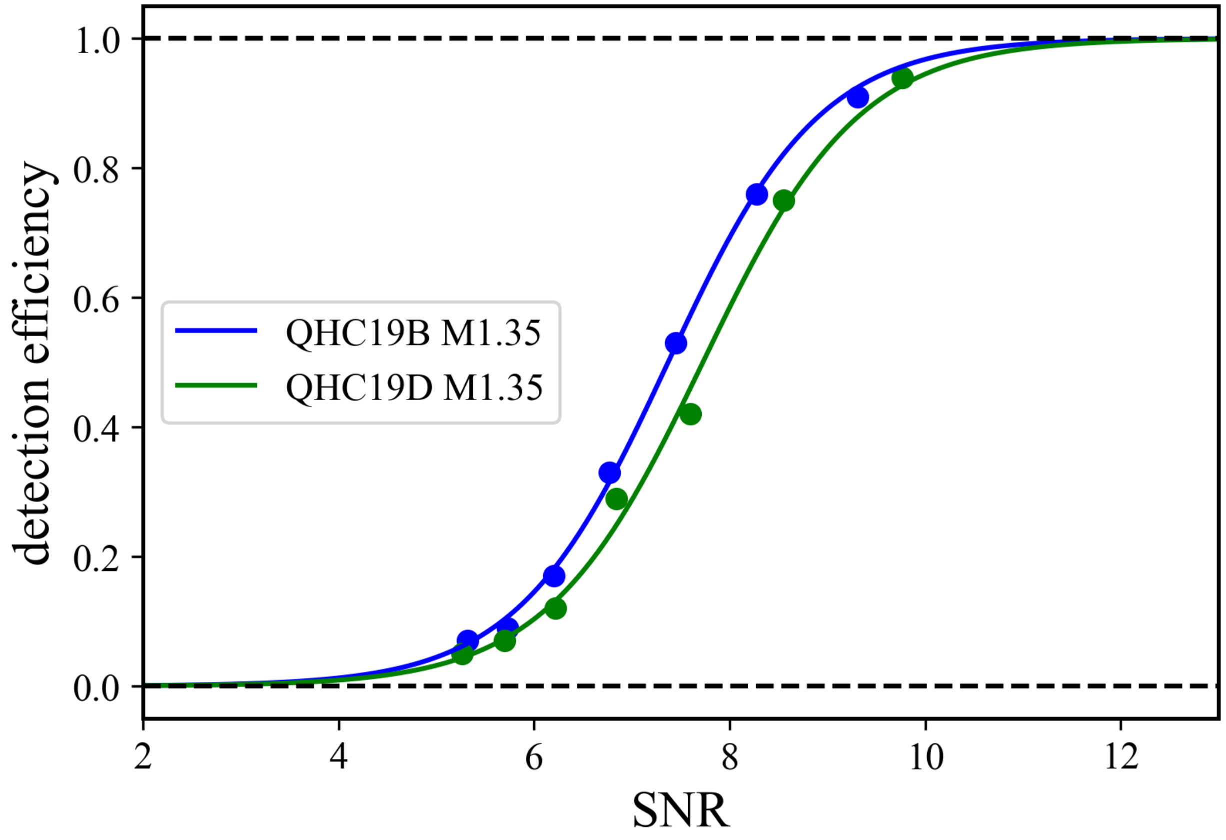
QHC19B-M1.35

Soft EOS
“narrow” peak → stable recon.
Stiff EOS
“wide” peak → recon. shift

QHC19D-M1.35
(Stiff)



Results2 : Detection Efficiency Curves



Calculate the SNR using only
the post-merger phase ($f \geq f_{\mathrm{mer}}$)

Curve fit as

$$\boxed{f(x) = \frac{1}{1 - e^{-k(x - x_0)}}}$$

$$(k, x_0)_{\mathrm{B}} = (1.292, 7.340)$$
$$(k, x_0)_{\mathrm{D}} = (1.250, 7.725)$$

x_0: 50 % detection efficiency

Results3 : Number of events

$$N\ [\mathrm{yr}^{-1}] = R_{\mathrm{merger}} \underbrace{\frac{4\pi}{3}\left(\frac{D_{SNR=2}}{1000}\right)^3}_{\text{Effective volume}} \mathrm{Fraction}$$

Random sampling SNR_i
for Monte Carlo Simulation

$$\begin{cases} \mathrm{Fraction} = \sum_i^{n_{\mathrm{total}}} f(SNR_i) / n_{\mathrm{total}} \\ R_{\mathrm{merger}} = 89^{+159}_{-69}\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1} \end{cases}$$

$*\ n_{\mathrm{total}}$: BNS total events in the effective volume →10^6

	$R_{\mathrm{merger,max}}$	$R_{\mathrm{merger,ave}}$	$R_{\mathrm{merger,min}}$
HFmod QHC19B	$1.367e-02$	$4.907e-03$	$1.213e-03$
QHC19D	$8.740e-03$	$3.136e-03$	$7.753e-04$
BB40 QHC19B	$3.382e-04$	$1.214e-04$	$3.000e-05$
QHC19D	$2.175e-04$	$7.804e-05$	$1.929e-05$

HF is better than BB40, but still extremely small.

Summary

・KAGRA_HF can detect BNS post-merger GW events form distances **around 40 Mpc**. (almost the same distance as GW170817!)

・However, the expected number of events is still extremely small, below **0.01 per year**.

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→The result is based on KAGRA alone; need to perform with a detector network.

Appendix