Auto-Regressive approach to find ring-down gravitational wave

Hisaaki Shinkai
(Osaka Institute of Technology)
hisaaki.shinkai@oit.ac.jp

Outline & Summary

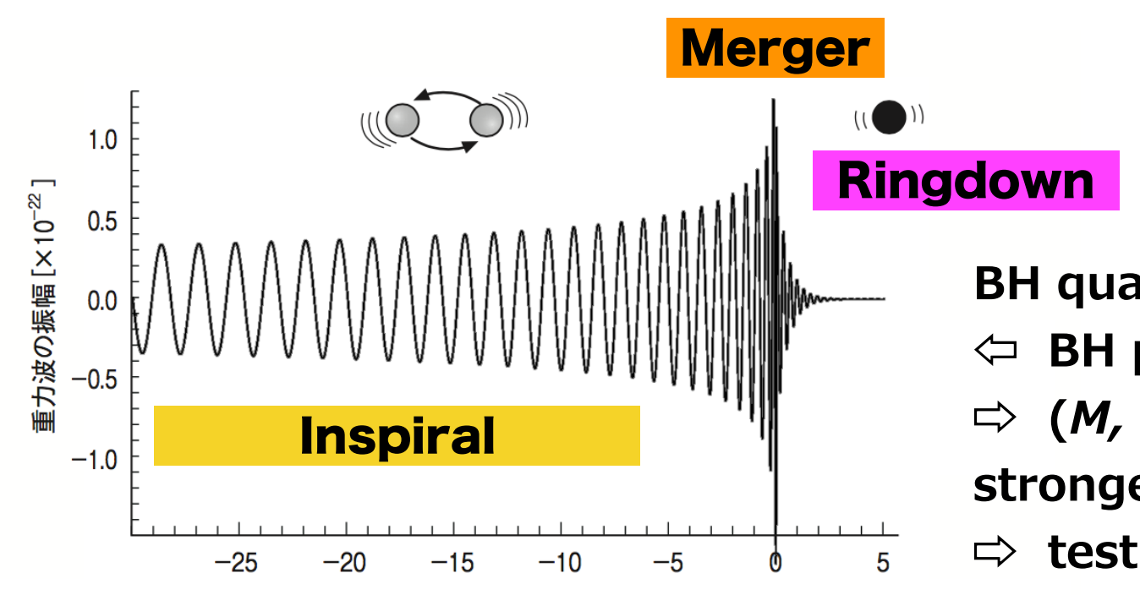
The ring-down part of gravitational waves in the final stage of merger of compact objects tells us the nature of strong gravity which can be used for testing the theories of gravity. The ring-down wave, however, fades out in a very short time with a few cycles, and hence it is challenging for gravitational wave data analysis to extract the ringdown frequency and its damping time scale.

We develop a new method, the autoregressive modeling (AR) approach, which extracts waveform by fitting a linear function from bare data. It works well for small number of data points, and does not require any templates. After obtaining the best parameters using mockdata, we applied this method for black-hole merger events of the LIGO/Virgo O1 and O2. We find that for high SNR events, we can extract ring-down waves properly.

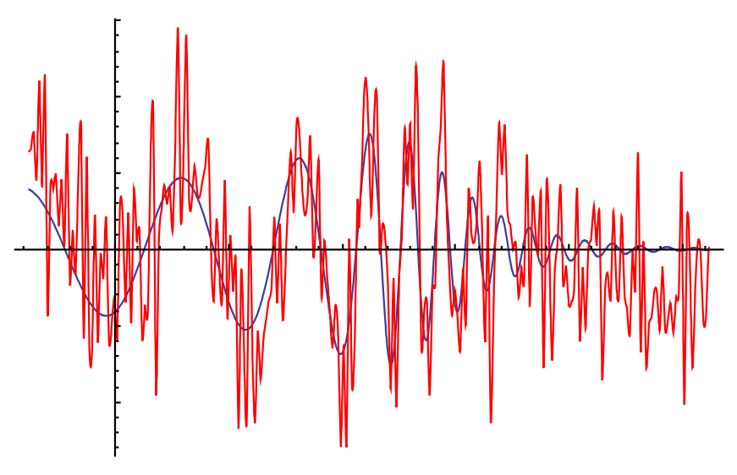
This method may work for extracting higher modes of ring-down waves, and implementations are on-going.

Motivation & O1/O2 data

Towards testing gravity theories ⇒ Ringdown-part extraction is a key



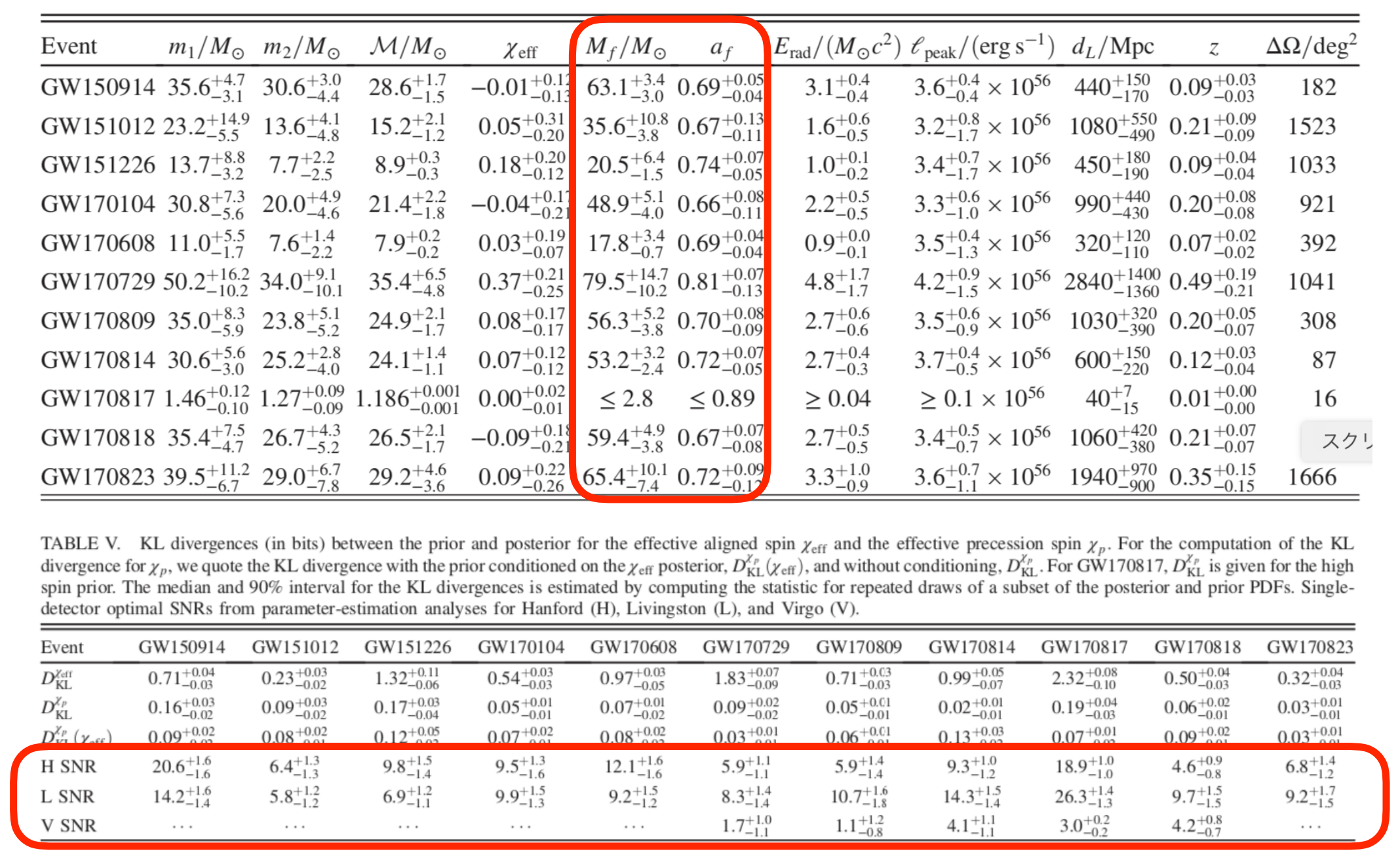
BH quasi-normal modes
⇦ BH perturbation theory
⇨ (*M, a*)
strongest gravity we can observe
⇨ test of gravity theories



For *60M* BH of *a*=0.75,
frequency = 300 Hz
damping time scale = 3.7 ms

LVC, PRX9 (2019) 031040

LIGO/Virgo O1/O2 catalogue



Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_f/M_\odot$	a_f	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\,s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/{\rm deg}^2$
GW150914	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.4}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	440^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	182
GW151012	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	$35.6^{+10.8}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.6^{+0.6}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1080^{+550}_{-490}	$0.21^{+0.09}_{-0.09}$	1523
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	450^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	$48.9^{+5.1}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-1.0}\times10^{56}$	990^{+440}_{-430}	$0.20^{+0.08}_{-0.08}$	921
GW170608	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	392
GW170729	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	$79.5^{+14.7}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}\times10^{56}$	2840^{+1400}_{-1360}	$0.49^{+0.19}_{-0.21}$	1041
GW170809	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	$56.3^{+5.2}_{-3.8}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	1030^{+320}_{-390}	$0.20^{+0.05}_{-0.07}$	308
GW170814	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	$53.2^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}\times10^{56}$	600^{+150}_{-220}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\ge 0.1\times10^{56}$	40^{+7}_{-15}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.4^{+4.9}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1060^{+420}_{-380}	$0.21^{+0.07}_{-0.07}$	スクリ
GW170823	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	$65.4^{+10.1}_{-7.4}$	$0.72^{+0.09}_{-0.12}$	$3.3^{+1.0}_{-0.9}$	$3.6^{+0.7}_{-1.1}\times10^{56}$	1940^{+970}_{-900}	$0.35^{+0.15}_{-0.15}$	1666

TABLE V. KL divergences (in bits) between the prior and posterior for the effective aligned spin $\chi_{\rm eff}$ and the effective precession spin χ_p. For the computation of the KL divergence for χ_p, we quote the KL divergence with the prior conditioned on the $\chi_{\rm eff}$ posterior, $D_{\rm KL}^{\chi_p}(\chi_{\rm eff})$, and without conditioning, $D_{\rm KL}^{\chi_p}$. For GW170817, $D_{\rm KL}^{\chi_p}$ is given for the high spin prior. The median and 90% interval for the KL divergences is estimated by computing the statistic for repeated draws of a subset of the posterior and prior PDFs. Single-detector optimal SNRs from parameter-estimation analyses for Hanford (H), Livingston (L), and Virgo (V).

Event	GW150914	GW151012	GW151226	GW170104	GW170608	GW170729	GW170809	GW170814	GW170817	GW170818	GW170823
$D_{\rm KL}^{\chi_{\rm eff}}$	$0.71^{+0.04}_{-0.03}$	$0.23^{+0.03}_{-0.02}$	$1.32^{+0.11}_{-0.06}$	$0.54^{+0.03}_{-0.03}$	$0.97^{+0.03}_{-0.05}$	$1.83^{+0.07}_{-0.09}$	$0.71^{+0.03}_{-0.03}$	$0.99^{+0.05}_{-0.07}$	$2.32^{+0.08}_{-0.10}$	$0.50^{+0.04}_{-0.03}$	$0.32^{+0.04}_{-0.03}$
$D_{\rm KL}^{\chi_p}$	$0.16^{+0.03}_{-0.02}$	$0.09^{+0.03}_{-0.02}$	$0.17^{+0.03}_{-0.04}$	$0.05^{+0.01}_{-0.01}$	$0.07^{+0.01}_{-0.02}$	$0.09^{+0.02}_{-0.02}$	$0.05^{+0.01}_{-0.01}$	$0.02^{+0.01}_{-0.01}$	$0.19^{+0.04}_{-0.03}$	$0.06^{+0.02}_{-0.01}$	$0.03^{+0.01}_{-0.01}$
$D_{\rm KL}^{\chi_p}(\chi_{\rm eff})$	$0.09^{+0.02}$	$0.08^{+0.02}$	$0.12^{+0.05}$	$0.07^{+0.02}$	$0.08^{+0.02}$	$0.03^{+0.01}$	$0.06^{+0.01}$	$0.13^{+0.03}$	$0.07^{+0.01}$	$0.09^{+0.02}$	$0.03^{+0.01}$
H SNR	$20.6^{+1.6}_{-1.6}$	$6.4^{+1.3}_{-1.3}$	$9.8^{+1.5}_{-1.4}$	$9.5^{+1.3}_{-1.6}$	$12.1^{+1.6}_{-1.6}$	$5.9^{+1.1}_{-1.1}$	$5.9^{+1.4}_{-1.4}$	$9.3^{+1.0}_{-1.2}$	$18.9^{+1.0}_{-1.0}$	$4.6^{+0.9}_{-0.8}$	$6.8^{+1.4}_{-1.2}$
L SNR	$14.2^{+1.6}_{-1.4}$	$5.8^{+1.2}_{-1.2}$	$6.9^{+1.2}_{-1.1}$	$9.9^{+1.5}_{-1.3}$	$9.2^{+1.5}_{-1.2}$	$8.3^{+1.4}_{-1.4}$	$10.7^{+1.6}_{-1.8}$	$14.3^{+1.5}_{-1.4}$	$26.3^{+1.4}_{-1.3}$	$9.7^{+1.5}_{-1.5}$	$9.2^{+1.7}_{-1.5}$
V SNR	…	…	…	…	…	$1.7^{+1.0}_{-1.1}$	$1.1^{+1.2}_{-0.8}$	$4.1^{+1.1}_{-1.1}$	$3.0^{+0.2}_{-0.2}$	$4.2^{+0.8}_{-0.7}$	…

Mockdata Comparison

Phys. Rev. D 99, 124032 (2019) [arXiv:1811.06443]

Mockdata preparation

SXS data + shifted ringdown injection + aLIGO noise
modified after t_merger (set A) 60 set
modified before/after t_merger (set B) 60 set

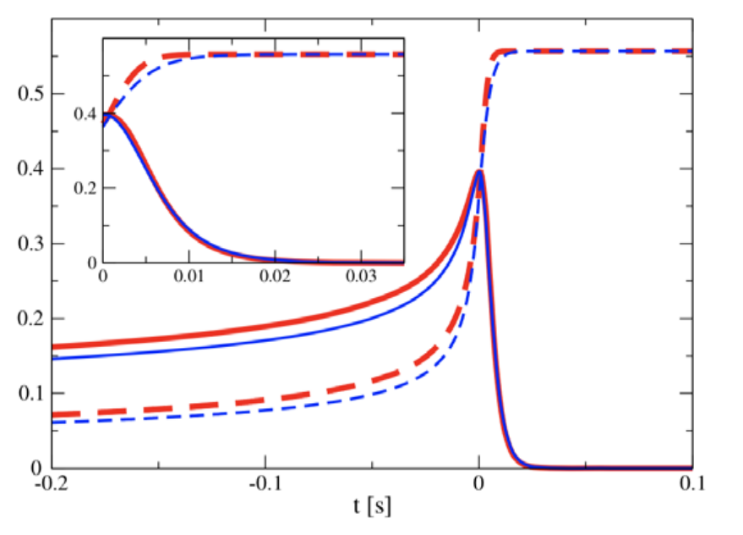
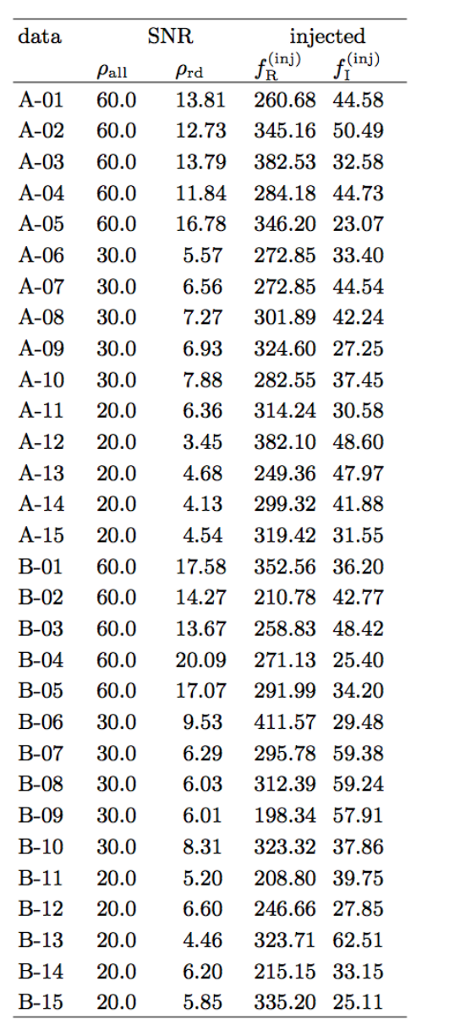


FIG. 1. Examples of sets A and B. (Inset) The ringdown part. Here, set A [(red) thick] with SXS:BBH:0174 and set B [(blue) thin] with SXS:BBH:0002 are shown. The solid lines denote the modified amplitude $A_{22}(t)$, and the dashed lines are the GW frequency $\omega_{22}(t)/(2\pi)$. The total mass is $M = 60M_\odot$, and the real and imaginary parts of the ringdown frequency are 300 and 40 Hz, respectively. The real frequency is obtained by multiplying by 538.609 Hz, and the real amplitude of set A is derived by dividing by 1.37903. The large difference in the inspiral phase is due to the difference of the binary parameters.

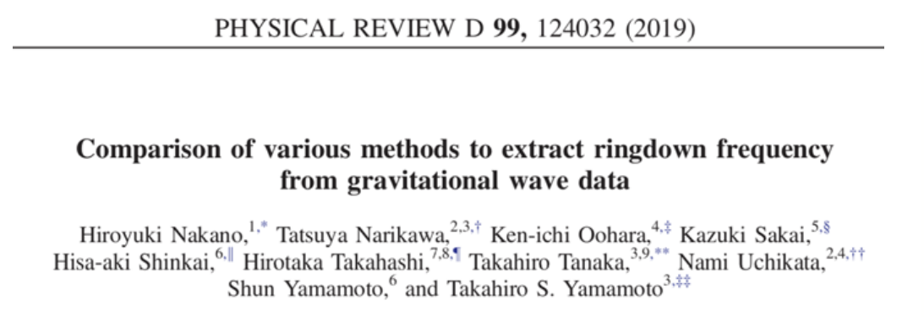


data	SNR		injected	
	$\rho_{\rm all}$	$\rho_{\rm rd}$	$f_{\rm R}^{\rm (inj)}$	$f_{\rm I}^{\rm (inj)}$
A-01	60.0	13.81	260.68	44.58
A-02	60.0	12.73	345.16	50.49
A-03	60.0	13.79	382.53	32.58
A-04	60.0	11.84	284.18	44.73
A-05	60.0	16.78	346.20	23.07
A-06	30.0	5.57	272.85	33.40
A-07	30.0	6.56	272.85	44.54
A-08	30.0	7.27	301.89	42.24
A-09	30.0	6.93	324.60	27.25
A-10	30.0	7.88	282.55	37.45
A-11	20.0	6.36	314.24	30.58
A-12	20.0	3.45	382.10	48.60
A-13	20.0	4.68	249.36	47.97
A-14	20.0	4.13	299.32	41.88
A-15	20.0	4.54	319.42	31.55
B-01	60.0	17.58	352.56	36.20
B-02	60.0	14.27	210.78	42.77
B-03	60.0	13.67	258.83	48.42
B-04	60.0	20.09	271.13	25.40
B-05	60.0	17.07	291.99	34.20
B-06	30.0	9.53	411.57	29.48
B-07	30.0	6.29	295.78	59.38
B-08	30.0	6.03	312.39	59.24
B-09	30.0	6.01	198.34	57.91
B-10	30.0	8.31	323.32	37.86
B-11	20.0	5.20	208.80	39.75
B-12	20.0	6.60	246.66	27.85
B-13	20.0	4.46	323.71	62.51
B-14	20.0	6.20	215.15	33.15
B-15	20.0	5.85	335.20	25.11

https://gw-genesis.scphys.kyoto-u.ac.jp/ilias/goto_root_fold_669.html
http://www.oit.ac.jp/is/shinkai/mockdatachallenge/

Nakano+, PRD99 (2019) 124032

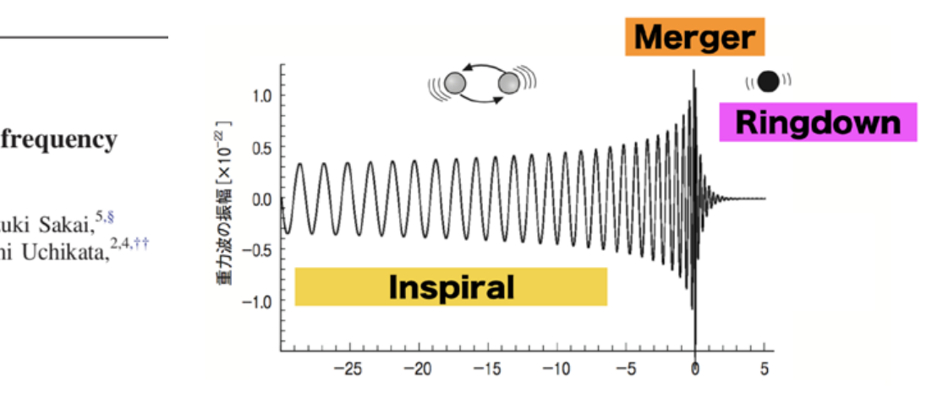
mockdata-challenge comparison



PHYSICAL REVIEW D **99,** 124032 (2019)

Comparison of various methods to extract ringdown frequency from gravitational wave data

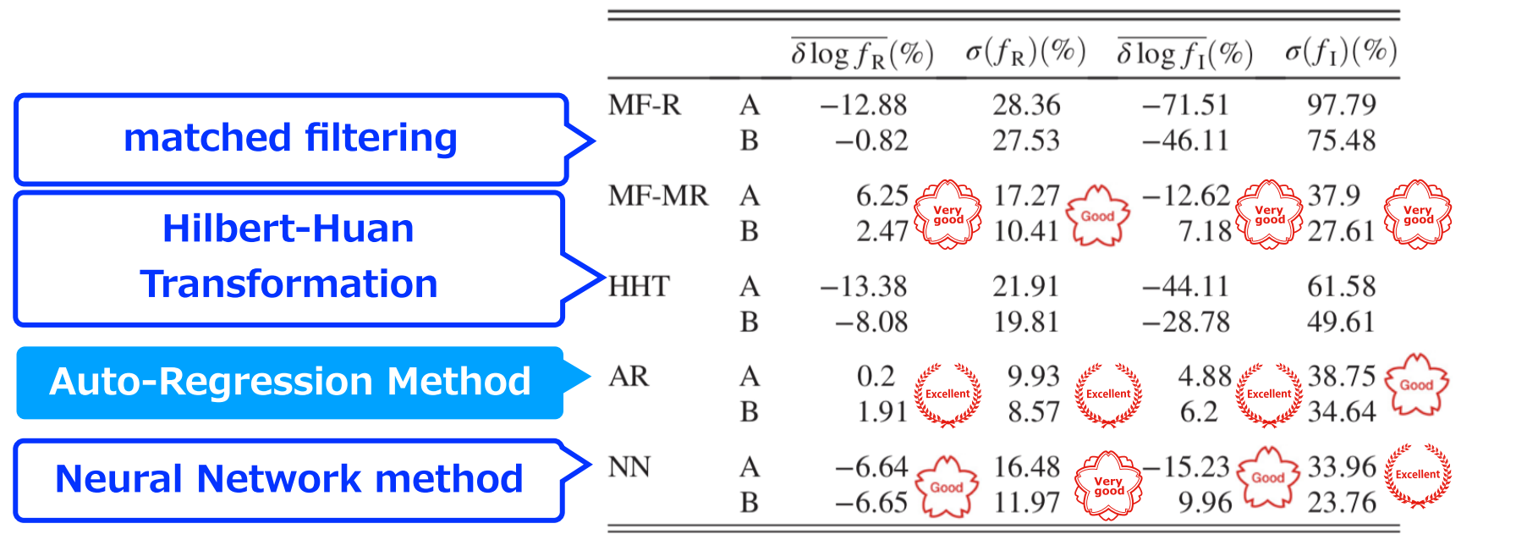
Hiroyuki Nakano,[1,*] Tatsuya Narikawa,[2,3,†] Ken-ichi Oohara,[4,‡] Kazuki Sakai,[5,§] Hisa-aki Shinkai,[6,‖] Hirotaka Takahashi,[7,8,¶] Takahiro Tanaka,[3,9,**] Nami Uchikata,[2,4,††] Shun Yamamoto,[6] and Takahiro S. Yamamoto[3,‡‡]



ringdown search
60 mockdata

TABLE III. We show the values of $\overline{\delta \log f_{\rm R}}$, $\sigma(f_{\rm R})$, $\overline{\delta \log f_{\rm I}}$, and $\sigma(f_{\rm I})$ for various methods. The results limited to set A are given on the first law of each method, while those limited to set B are on the second.

- **matched filtering**
- **Hilbert-Huan Transformation**
- **Auto-Regression Method**
- **Neural Network method**



		$\overline{\delta \log f_{\rm R}}(\%)$	$\sigma(f_{\rm R})(\%)$	$\overline{\delta \log f_{\rm I}}(\%)$	$\sigma(f_{\rm I})(\%)$
MF-R	A	−12.88	28.36	−71.51	97.79
	B	−0.82	27.53	−46.11	75.48
MF-MR	A	6.25 Very good	17.27 Good	−12.62 Very good	37.9 Very good
	B	2.47	10.41	7.18	27.61
HHT	A	−13.38	21.91	−44.11	61.58
	B	−8.08	19.81	−28.78	49.61
AR	A	0.2 Excellent	9.93 Excellent	4.88 Excellent	38.75 Good
	B	1.91	8.57	6.2	34.64
NN	A	−6.64 Good	16.48 Very good	−15.23 Good	33.96 Excellent
	B	−6.65	11.97	9.96	23.76

Method

Auto-Regressive model (idea)

Fitting data with linear func.

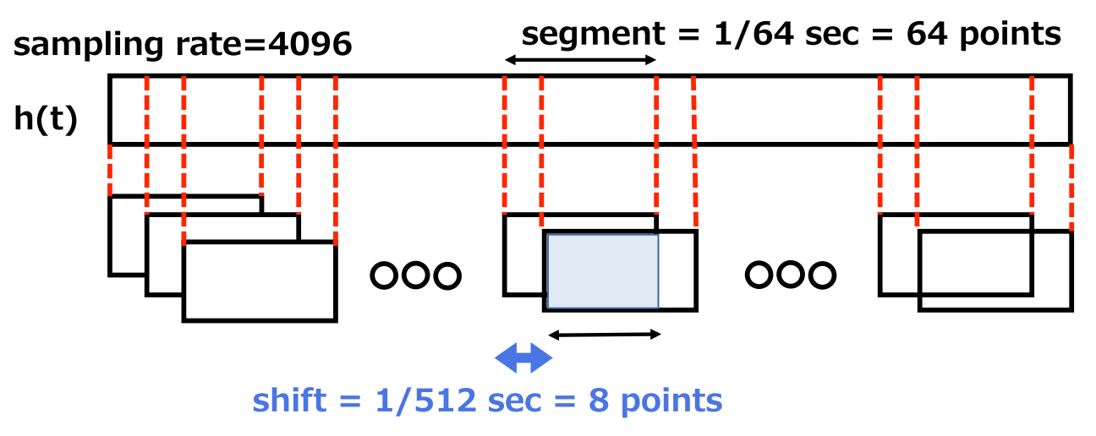
$$x_n = a_1 x_{n-1} + a_2 x_{n-2} + \cdots + a_M x_{n-M} + \varepsilon = \sum_{j=1}^{M} a_j x_{n-j} + \varepsilon$$

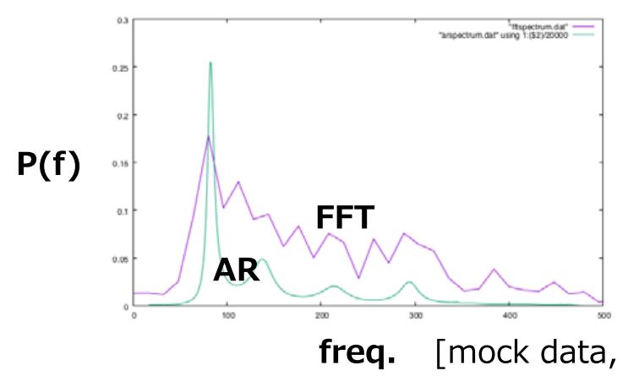
e.g. $x_n = A e^{-rn\Delta t}\cos(\omega n \Delta t)$

$$Z_1 = e^{-(r-j\omega)\Delta t},\quad Z_2 = e^{-(r+j\omega)\Delta t} \Rightarrow x_n = \frac{A}{2}(Z_1^n + Z_2^n) = (Z_1+Z_2)x_{n-1} - Z_1 Z_2 x_{n-2}$$

can be applied also to noisy data by adjusting *M*

Auto-Regressive model vs Short FFT





[mock data, SNR=40, inspiral part]

The order *M* can be fixed at 2~8.

Even for short segment, AR model shows precise power-spectrum.

Auto-Regressive model (Method, general)

Fitting data with linear func.

$$x_n = a_1 x_{n-1} + a_2 x_{n-2} + \cdots + a_M x_{n-M} + \varepsilon = \sum_{j=1}^{M} a_j x_{n-j} + \varepsilon$$

- find a_j (Burg method)
- find M (FPE final prediction error method)
- re-construct wave signal from fitted function
- apply FFT with arbitrary precision.

power spectrum

$$p(f) = \frac{\sigma^2}{\left|1 - \sum_{j=1}^{M} a_j e^{-I2\pi j f \Delta t}\right|^2}$$

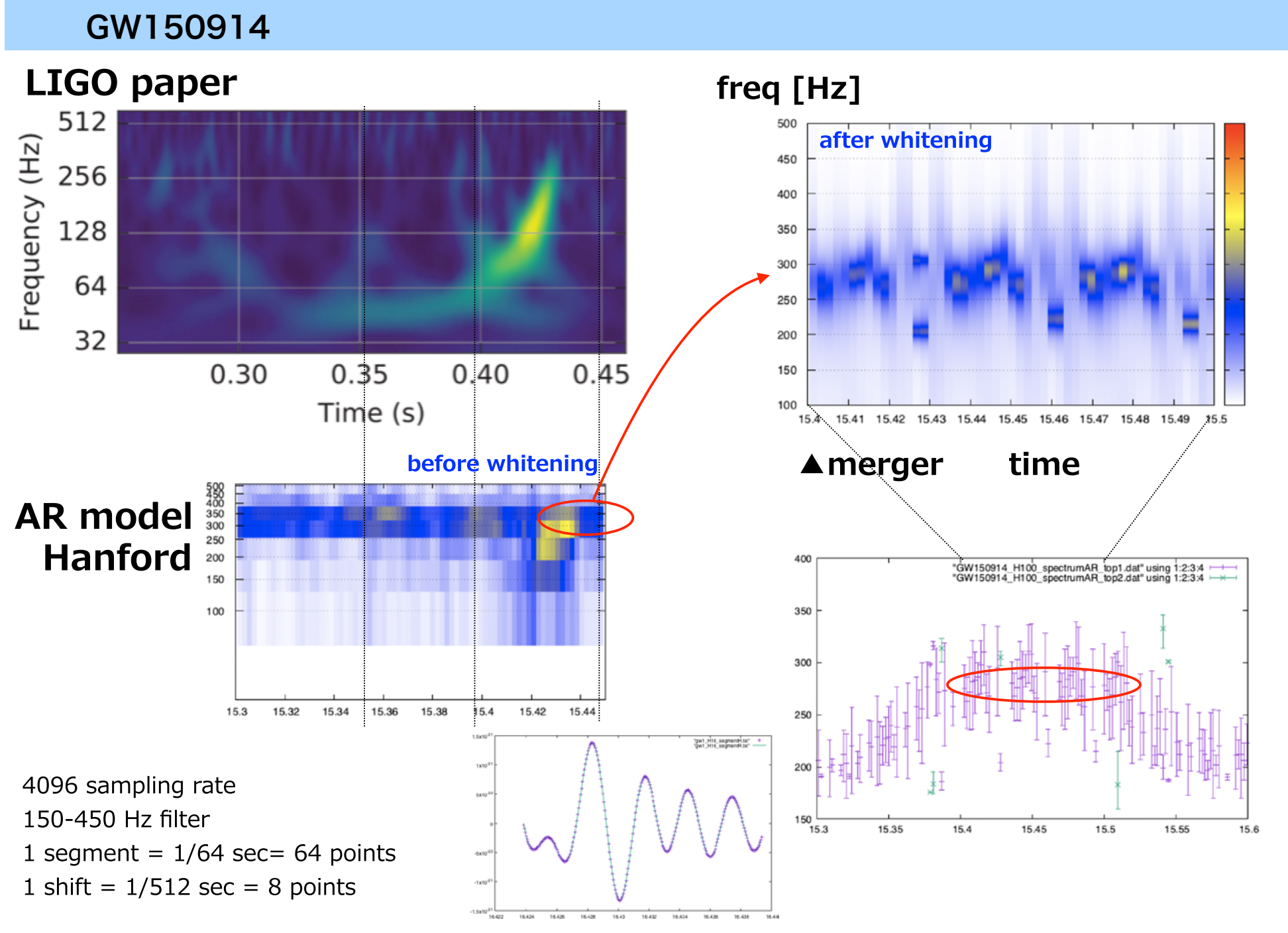
characteristic eq.

$$f(z) = 1 - \sum_{j=1}^{M} a_j z^j = 0$$

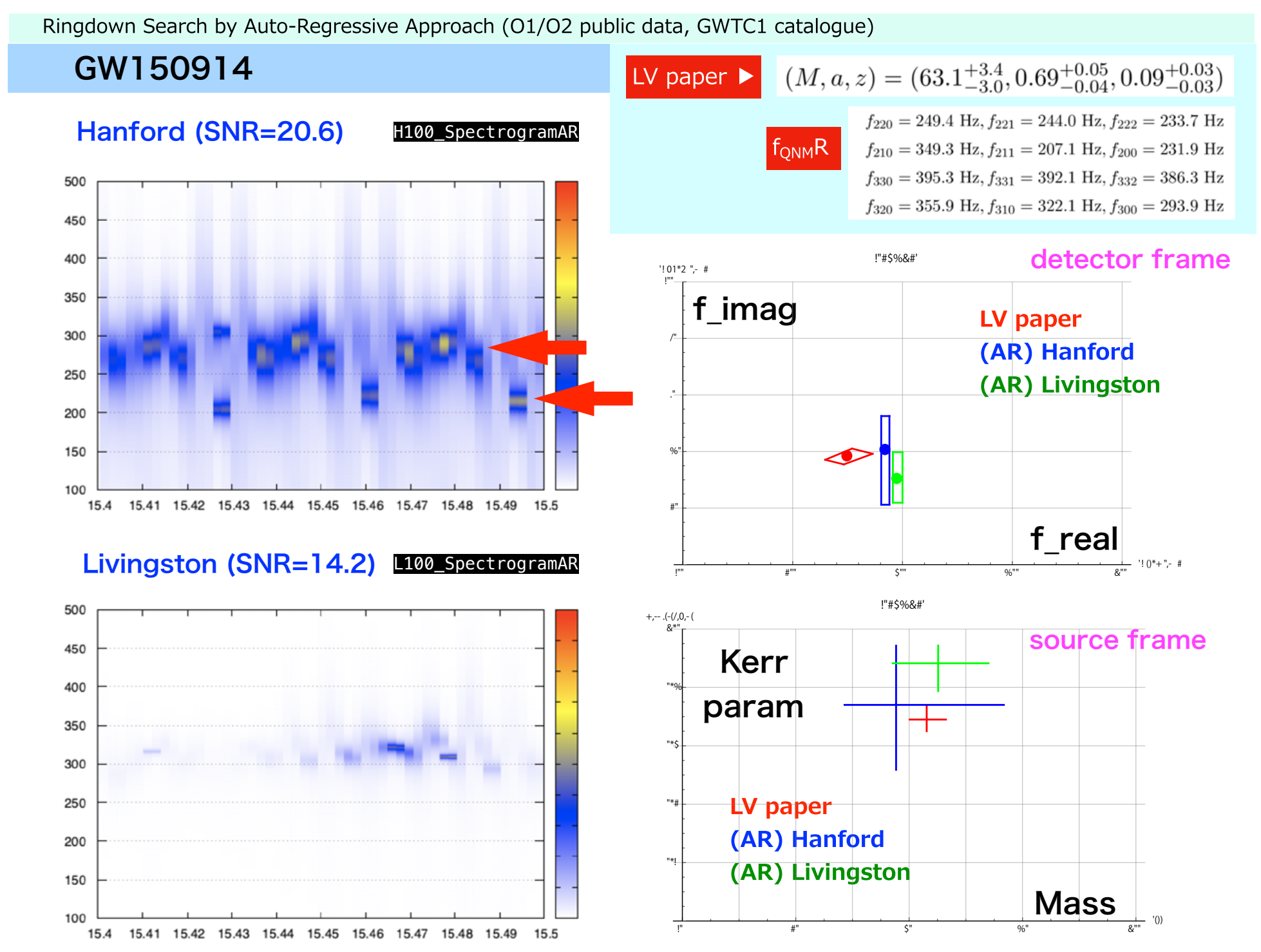
$|z_k|$ says amplitude,
$\arg(z_k)$ says frequency.

Results

GW150914



4096 sampling rate
150-450 Hz filter
1 segment = 1/64 sec= 64 points
1 shift = 1/512 sec = 8 points

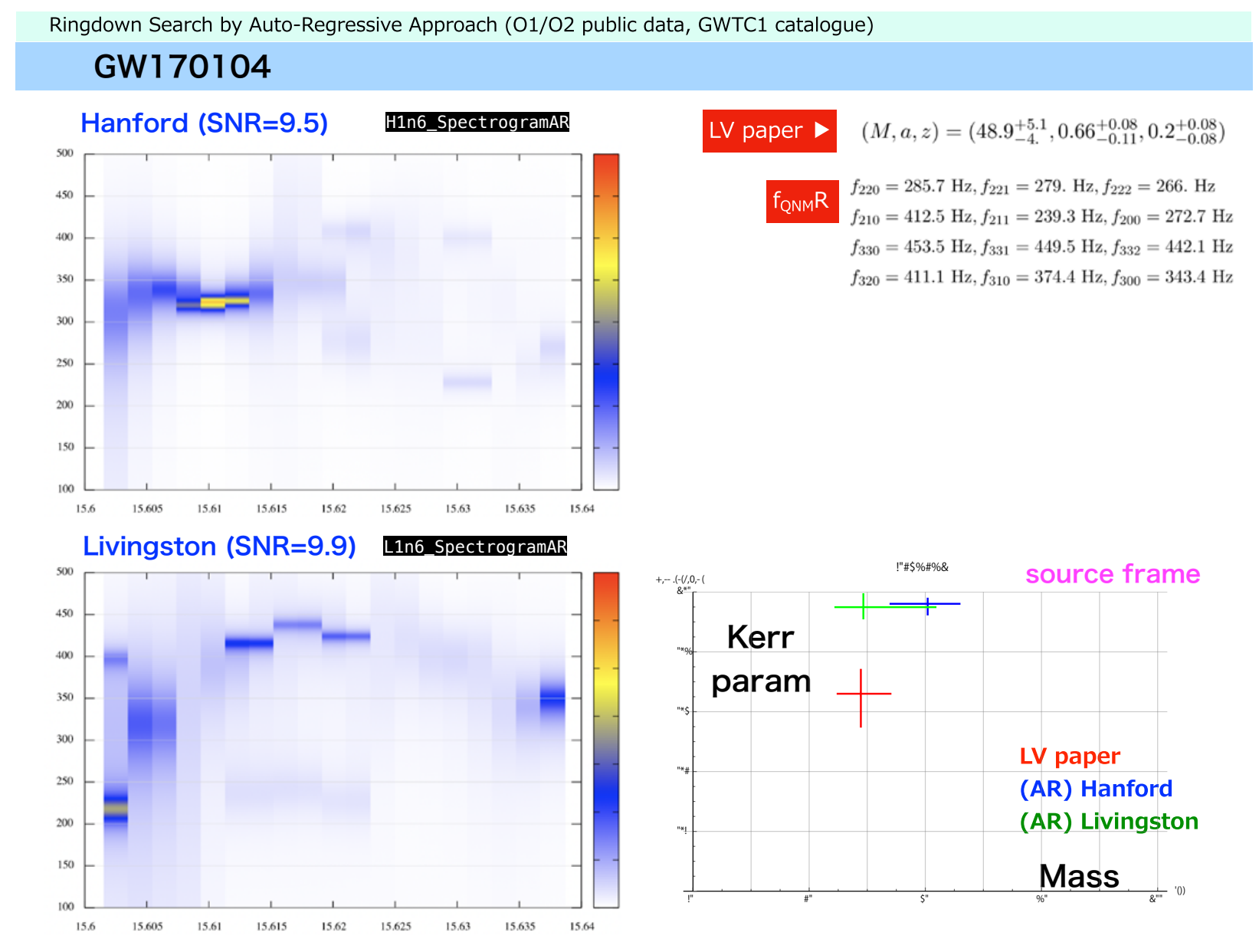


Ringdown Search by Auto-Regressive Approach (O1/O2 public data, GWTC1 catalogue)

GW150914

LV paper ▶ $(M,a,z) = (63.1^{+3.4}_{-3.0}, 0.69^{+0.05}_{-0.04}, 0.09^{+0.03}_{-0.03})$

$f_{\rm QNM}$R
$f_{220} = 249.4$ Hz, $f_{221} = 244.0$ Hz, $f_{222} = 233.7$ Hz
$f_{210} = 349.3$ Hz, $f_{211} = 207.1$ Hz, $f_{200} = 231.9$ Hz
$f_{330} = 395.3$ Hz, $f_{331} = 392.1$ Hz, $f_{332} = 386.3$ Hz
$f_{320} = 355.9$ Hz, $f_{310} = 322.1$ Hz, $f_{300} = 293.9$ Hz

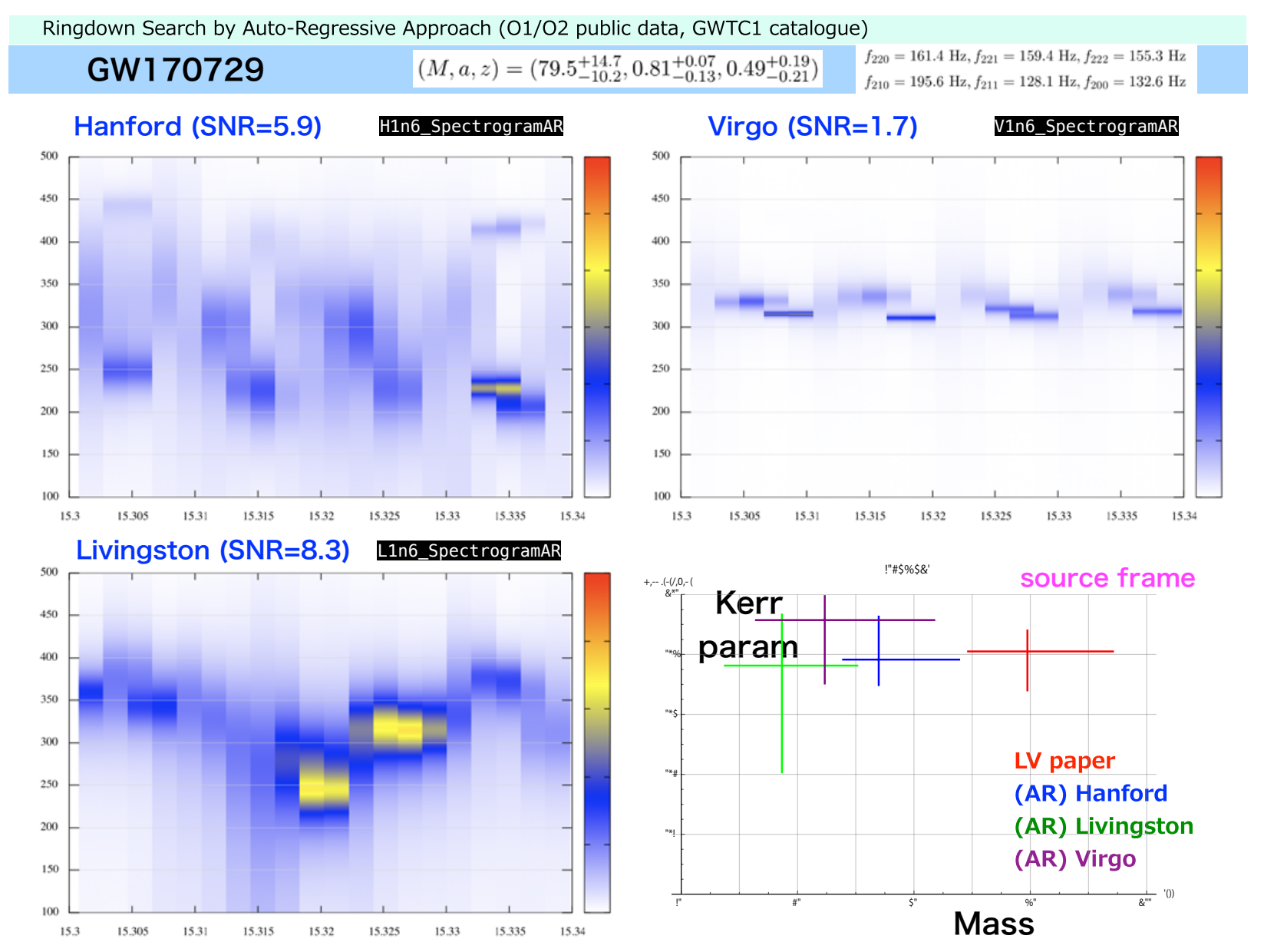


Ringdown Search by Auto-Regressive Approach (O1/O2 public data, GWTC1 catalogue)

GW170104

LV paper ▶ $(M,a,z) = (48.9^{+5.1}_{-4.}, 0.66^{+0.08}_{-0.11}, 0.2^{+0.08}_{-0.08})$

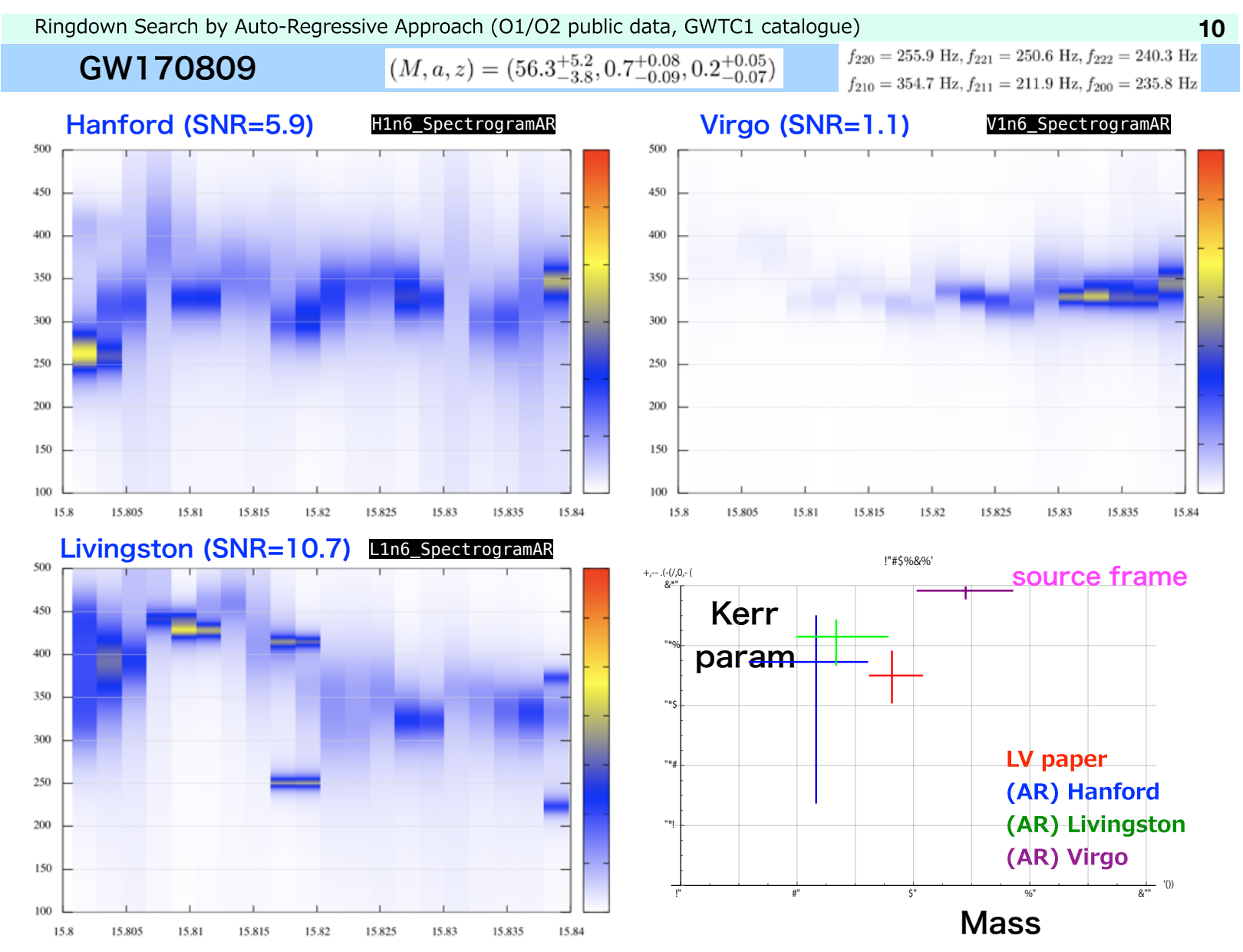
$f_{\rm QNM}$R
$f_{220} = 285.7$ Hz, $f_{221} = 279.$ Hz, $f_{222} = 266.$ Hz
$f_{210} = 412.5$ Hz, $f_{211} = 239.3$ Hz, $f_{200} = 272.7$ Hz
$f_{330} = 453.5$ Hz, $f_{331} = 449.5$ Hz, $f_{332} = 442.1$ Hz
$f_{320} = 411.1$ Hz, $f_{310} = 374.4$ Hz, $f_{300} = 343.4$ Hz



Ringdown Search by Auto-Regressive Approach (O1/O2 public data, GWTC1 catalogue)

GW170729 $(M,a,z) = (79.5^{+14.7}_{-10.2}, 0.81^{+0.07}_{-0.13}, 0.49^{+0.19}_{-0.21})$

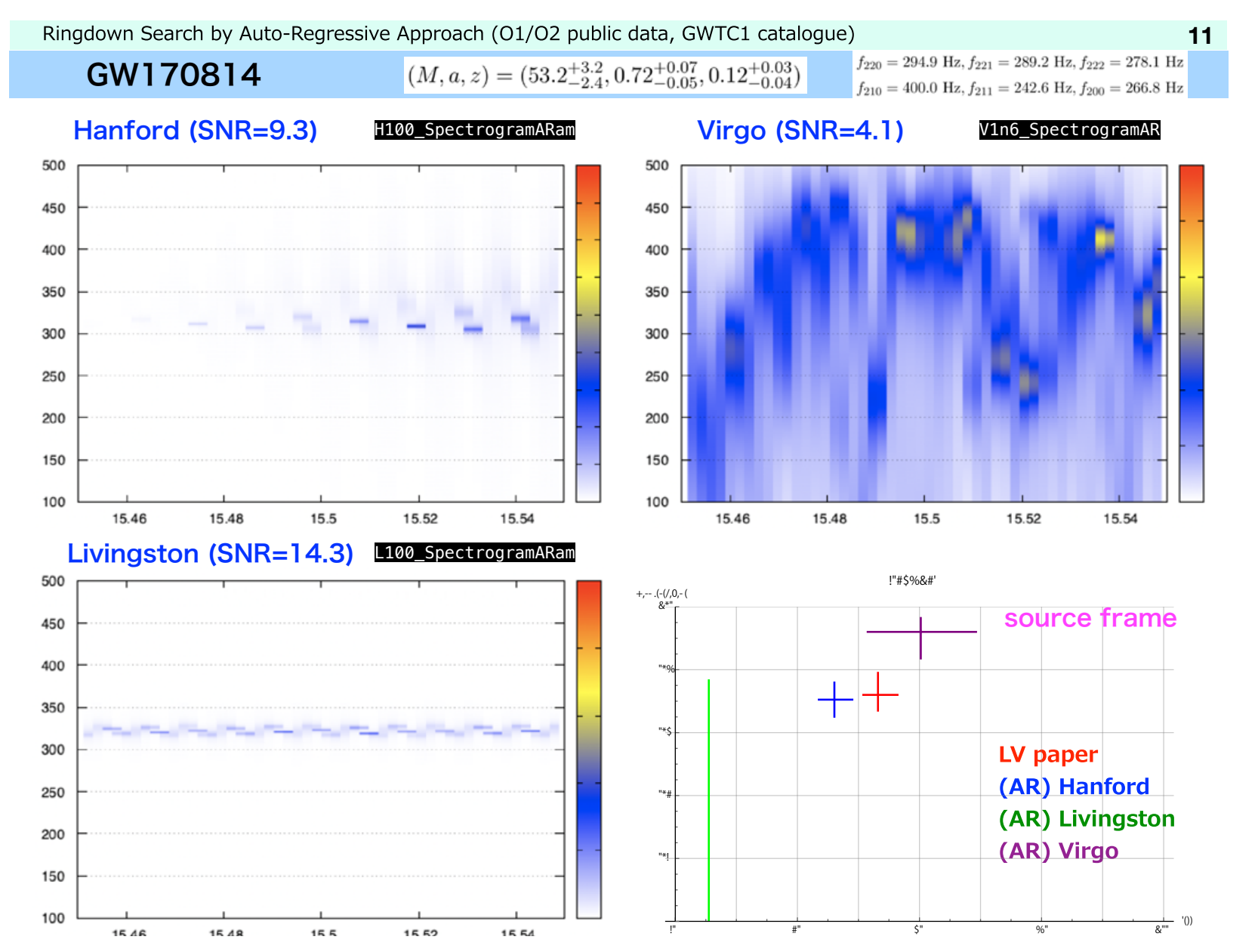
$f_{220} = 161.4$ Hz, $f_{221} = 159.4$ Hz, $f_{222} = 155.3$ Hz
$f_{210} = 195.6$ Hz, $f_{211} = 128.1$ Hz, $f_{200} = 132.6$ Hz



Ringdown Search by Auto-Regressive Approach (O1/O2 public data, GWTC1 catalogue)

GW170809 $(M,a,z) = (56.3^{+5.2}_{-3.8}, 0.7^{+0.08}_{-0.09}, 0.2^{+0.05}_{-0.07})$

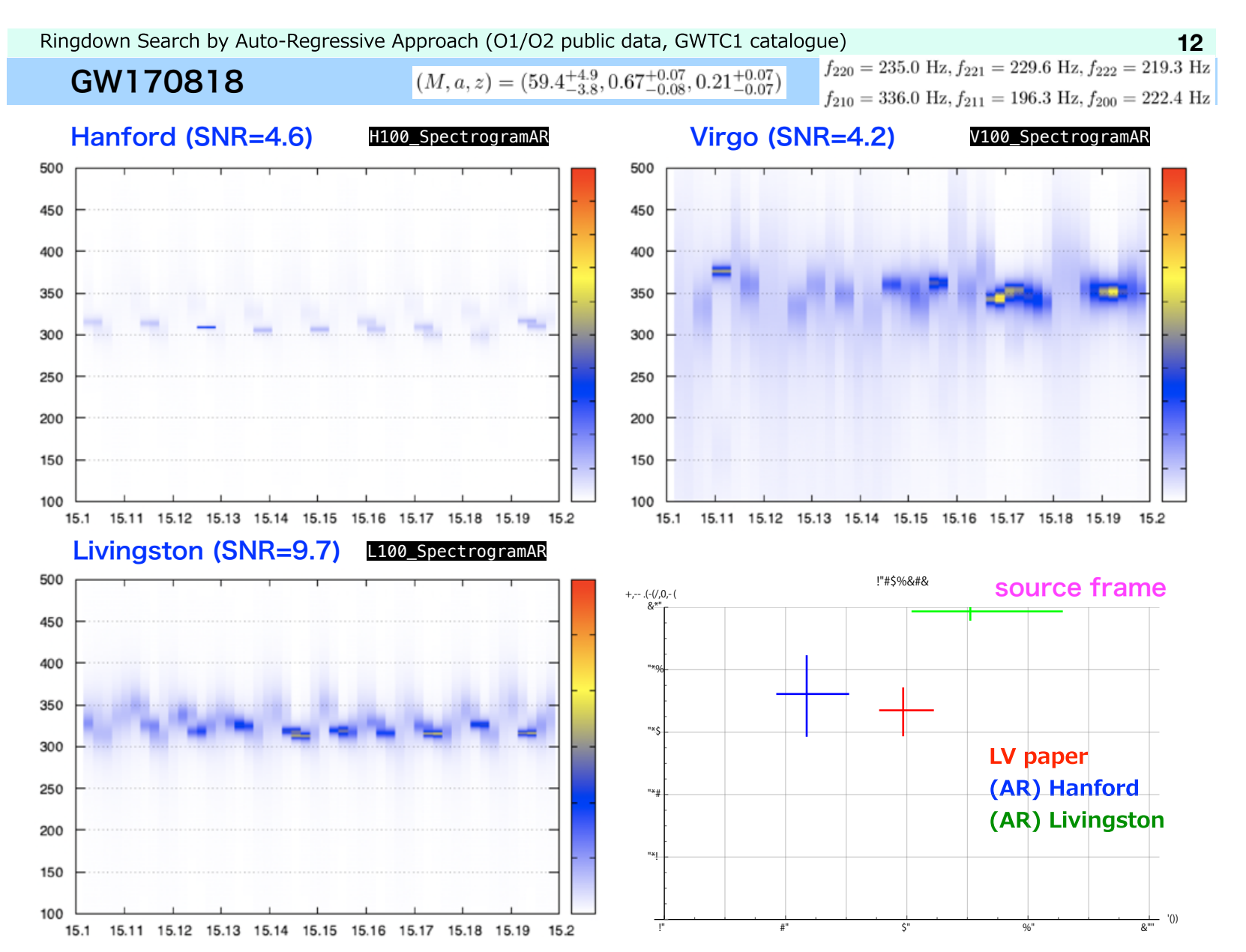
$f_{220} = 255.9$ Hz, $f_{221} = 250.6$ Hz, $f_{222} = 240.3$ Hz
$f_{210} = 354.7$ Hz, $f_{211} = 211.9$ Hz, $f_{200} = 235.8$ Hz



Ringdown Search by Auto-Regressive Approach (O1/O2 public data, GWTC1 catalogue)

GW170814 $(M,a,z) = (53.2^{+3.2}_{-2.4}, 0.72^{+0.07}_{-0.05}, 0.12^{+0.03}_{-0.04})$

$f_{220} = 294.9$ Hz, $f_{221} = 289.2$ Hz, $f_{222} = 278.1$ Hz
$f_{210} = 400.0$ Hz, $f_{211} = 242.6$ Hz, $f_{200} = 266.8$ Hz



Ringdown Search by Auto-Regressive Approach (O1/O2 public data, GWTC1 catalogue)

GW170818 $(M,a,z) = (59.4^{+4.9}_{-3.8}, 0.67^{+0.07}_{-0.08}, 0.21^{+0.07}_{-0.07})$

$f_{220} = 235.0$ Hz, $f_{221} = 229.6$ Hz, $f_{222} = 219.3$ Hz
$f_{210} = 336.0$ Hz, $f_{211} = 196.3$ Hz, $f_{200} = 222.4$ Hz

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI Grant No. JP17H06358 (and also JP17H06357) [A01: Testing gravity theories using gravitational waves, as a part of the innovative research area, "Gravitational wave physics and astronomy: Genesis"], by JSPS KAKENHI Grant No. JP18K03630 [Non-linear dynamics in the modified gravity theories as a test of string theory] and by No. 19H01901 [New directions in gravitational-wave data analysis: both in computing algorithms and hardwares including its outreach activities].

http://www.oit.ac.jp/is/shinkai/

JGRG29 @ Kobe Univ., 2019/11/25-29