大型低温重力波望遠鏡 KAGRA に関する研究（データ解析関連）

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Contents

- O3
- KAGRA
  - O3GK
  - Data transfer system
- Topic from ICRR Inter-University Research Program

A global GW network

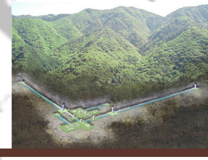
KAGRA and GE0600
O3GK: :2020/4/7-2020/4/21

LIGO-Hanford (H)

LIGO-Livingston (L)

GEO60
0

Virgo (V)



KAGRA (K)
2019 ～

LIGO India
2025? ～

Advanced LIGO
O1: 2015/9/12 - 2016/1/19
O2: 2016/11/30 - 2017/8/25
O3a: 2019/4/1 - 2019/10/30
O3b: 2019/11/1 - 2020/3/27

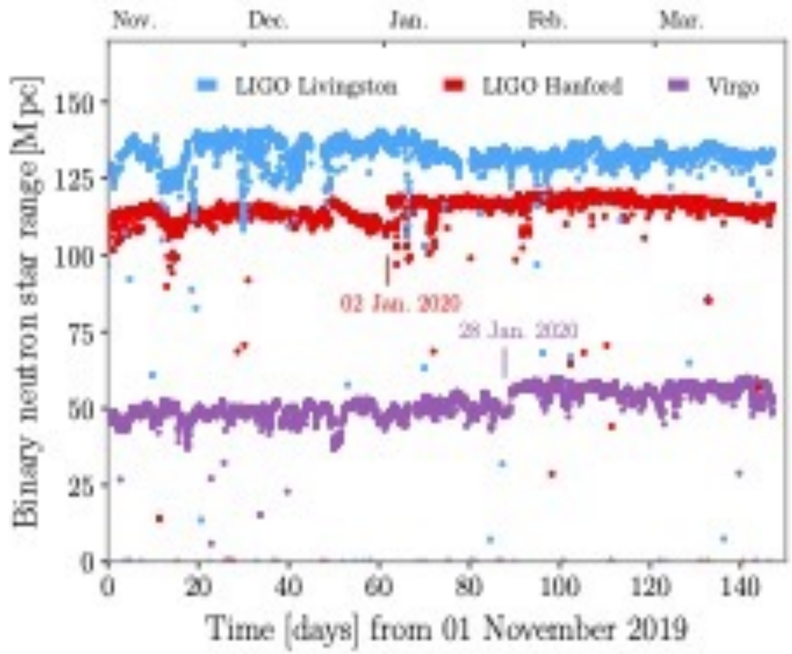
Advanced Virgo
O2: 2017/8/1 - 8/25
O3a: 2019/4/1 - 2019/10/30
O3b: 2019/11/1 - 2020/3/27

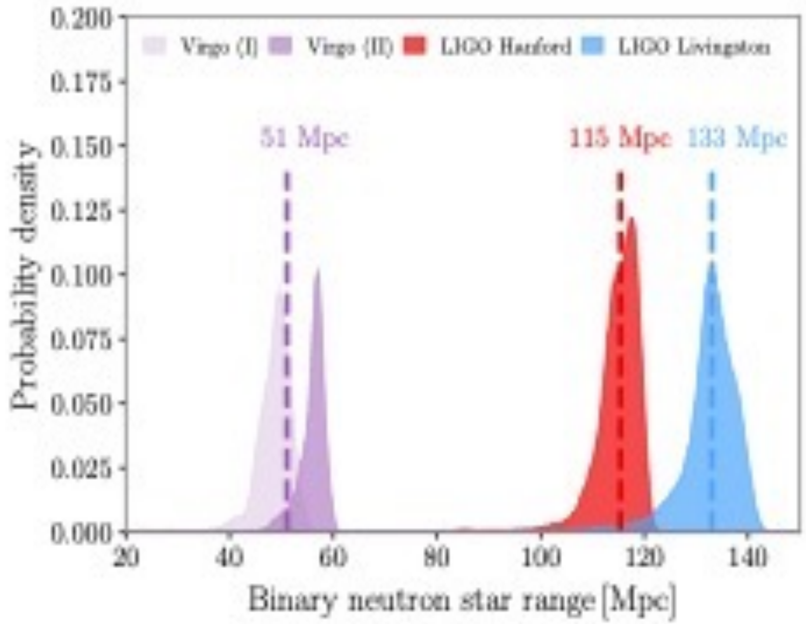
O3b Results

GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run

https://arxiv.org/abs/2111.03606

- Latest observation
  - O3a April 1 – Oct 1st, 2019
  - O3b Nov 1, 2019 – Mar 27, 2020





- Network duty factor: triple 51.0%, double 85.3%, single 96.6% (Down 3.4%)

GWTC-3 (O3b) catalog

GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run

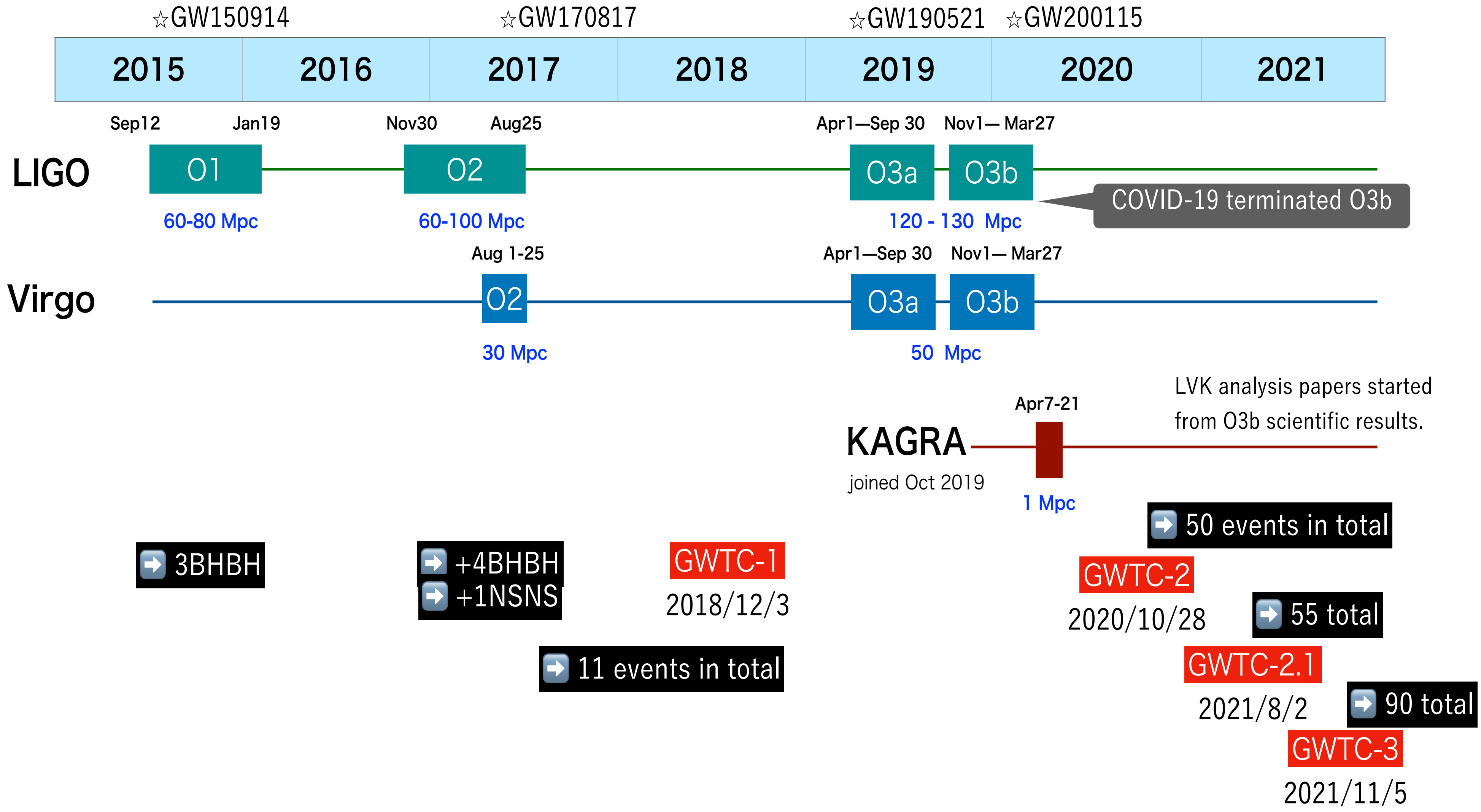
https://arxiv.org/abs/2111.03606

Name	Inst.	cWB FAR (yr^{-1})	cWB SNR	cWB p_{astro}	GstLAL FAR (yr^{-1})	GstLAL SNR	GstLAL p_{astro}	MBTA FAR (yr^{-1})	MBTA SNR	MBTA p_{astro}	PyCBC-broad FAR (yr^{-1})	PyCBC-broad SNR	PyCBC-broad p_{astro}	PyCBC-BBH FAR (yr^{-1})	PyCBC-BBH SNR	PyCBC-BBH p_{astro}
GW191103_012549	HL	–	–	–	–	–	–	*27*	*9.0*	*0.13*	4.8	9.3	0.77	0.46	9.3	0.94
GW191105_143521	HLV	–	–	–	*24*	*10.0*	*0.07*	0.14	10.7	> 0.99	0.012	9.8	> 0.99	0.036	9.8	> 0.99
GW191109_010717	HL	< 0.0011	15.6	> 0.99	0.0010	15.8	> 0.99	1.8×10^{-4}	15.2	> 0.99	0.096	13.2	> 0.99	0.047	14.4	> 0.99
GW191113_071753	HLV	–	–	–	–	–	–	26	9.2	0.68	*1.1×10^{4}*	*8.3*	*< 0.01*	*1.2×10^{3}*	*8.5*	*< 0.01*
GW191126_115259	HL	–	–	–	*80*	*8.7*	*0.02*	*59*	*8.5*	*0.30*	*22*	*8.5*	*0.39*	3.2	8.5	0.70
GW191127_050227	HLV	–	–	–	*0.25*	*10.3*	*0.49*	1.2	9.8	0.73	*20*	*9.5*	*0.47*	4.1	8.7	0.74
GW191129_134029	HL	–	–	–	$< 1.0 \times 10^{-5}$	13.3	> 0.99	0.013	12.7	> 0.99	$< 2.6 \times 10^{-5}$	12.9	> 0.99	$< 2.4 \times 10^{-5}$	12.9	> 0.99
GW191204_110529	HL	–	–	–	*21*	*9.0*	*0.07*	*1.3×10^{4}*	*8.1*	*< 0.01*	*980*	*8.9*	*< 0.01*	3.3	8.9	0.74
GW191204_171526	HL	$< 8.7 \times 10^{-4}$	17.1	> 0.99	$< 1.0 \times 10^{-5}$	15.6	> 0.99	$< 1.0 \times 10^{-5}$	17.1	> 0.99	$< 1.4 \times 10^{-5}$	16.9	> 0.99	$< 1.2 \times 10^{-5}$	16.9	> 0.99
GW191215_223052	HLV	0.12	9.8	0.95	$< 1.0 \times 10^{-5}$	10.9	> 0.99	0.22	10.8	> 0.99	0.0016	10.3	> 0.99	0.28	10.2	> 0.99
GW191216_213338	HV	–	–	–	$< 1.0 \times 10^{-5}$	18.6	> 0.99	9.3×10^{-4}	17.9	> 0.99	0.0019	18.3	> 0.99	7.6×10^{-4}	18.3	> 0.99
GW191219_163120	HLV	–	–	–	–	–	–	–	–	–	4.0	8.9	0.82	–	–	–
GW191222_033537	HL	$< 8.9 \times 10^{-4}$	11.1	> 0.99	$< 1.0 \times 10^{-5}$	12.0	> 0.99	0.0099	10.8	> 0.99	0.0021	11.5	> 0.99	9.8×10^{-5}	11.5	> 0.99
GW191230_180458	HLV	0.050	10.3	0.95	0.13	10.3	0.87	*8.1*	*9.8*	*0.40*	*52*	*9.6*	*0.29*	0.42	9.9	0.96
GW200112_155838	LV	–	–	–	$< 1.0 \times 10^{-5}$†	17.6	> 0.99	–	–	–	–	–	–	–	–	–
GW200115_042309	HLV	–	–	–	$< 1.0 \times 10^{-5}$	11.5	> 0.99	0.0055	11.2	> 0.99	$< 1.2 \times 10^{-4}$	10.8	> 0.99	–	–	–
GW200128_022011	HL	1.3	8.8	0.63	0.022	10.1	0.97	3.3	9.4	0.98	0.63	9.8	0.95	0.0043	9.9	> 0.99
GW200129_065458	HLV	–	–	–	$< 1.0 \times 10^{-5}$	26.5	> 0.99	–	–	–	$< 2.3 \times 10^{-5}$	16.3	> 0.99	$< 1.7 \times 10^{-5}$	16.2	> 0.99
GW200202_154313	HLV	–	–	–	$< 1.0 \times 10^{-5}$	11.3	> 0.99	–	–	–	–	–	–	0.025	10.8	> 0.99
GW200208_130117	HLV	–	–	–	0.0096	10.7	0.99	0.46	10.4	> 0.99	0.18	9.6	0.98	3.1×10^{-4}	10.8	> 0.99
GW200208_222617	HLV	–	–	–	*160*	*8.2*	*< 0.01*	*420*	*8.9*	*0.02*	–	–	–	4.8	7.9	0.70
GW200209_085452	HLV	–	–	–	0.046	10.0	0.95	12	9.7	0.97	*550*	*9.2*	*0.04*	1.2	9.2	0.89
GW200210_092254	HLV	–	–	–	*1.2*	*9.5*	*0.42*	–	–	–	17	8.9	0.53	7.7	8.9	0.54
GW200216_220804	HLV	–	–	–	0.35	9.4	0.77	*2.4×10^{3}*	*8.8*	*0.02*	*970*	*9.0*	*< 0.01*	7.8	8.7	0.54
GW200219_094415	HLV	0.77	9.7	0.85	9.9×10^{-4}	10.7	> 0.99	0.18	10.6	> 0.99	1.7	9.9	0.89	0.016	10.0	> 0.99
GW200220_061928	HLV	–	–	–	–	–	–	–	–	–	–	–	–	6.8	7.5	0.62
GW200220_124850	HL	–	–	–	*150*	*8.2*	*< 0.01*	1.8×10^{3}	8.2	0.83	–	–	–	*30*	*7.8*	*0.20*
GW200224_222234	HLV	$< 8.8 \times 10^{-4}$	18.8	> 0.99	$< 1.0 \times 10^{-5}$	18.9	> 0.99	$< 1.0 \times 10^{-5}$	19.0	> 0.99	$< 8.2 \times 10^{-5}$	19.2	> 0.99	$< 7.7 \times 10^{-5}$	18.6	> 0.99
GW200225_060421	HL	$< 8.8 \times 10^{-4}$	13.1	> 0.99	0.079	12.9	0.93	0.0049	12.5	> 0.99	$< 1.1 \times 10^{-5}$	12.3	> 0.99	4.1×10^{-5}	12.3	> 0.99
GW200302_015811	HV	–	–	–	0.11†	10.6	0.91	–	–	–	–	–	–	–	–	–
GW200306_093714	HL	–	–	–	–	–	–	410	8.5	0.81	*3.4×10^{3}*	*7.8*	*< 0.01*	*24*	*8.0*	*0.24*
GW200308_173609	HLV	–	–	–	*680*	*8.1*	*< 0.01*	*6.9×10^{4}*	*8.3*	*0.24*	*770*	*7.9*	*< 0.01*	2.4	8.0	0.86
GW200311_115853	HLV	$< 8.2 \times 10^{-4}$	16.2	> 0.99	$< 1.0 \times 10^{-5}$	17.7	> 0.99	$< 1.0 \times 10^{-5}$	16.5	> 0.99	$< 6.9 \times 10^{-5}$	17.0	> 0.99	$< 7.7 \times 10^{-5}$	17.4	> 0.99
GW200316_215756	HLV	–	–	–	$< 1.0 \times 10^{-5}$	10.1	> 0.99	*12*	*9.5*	*0.30*	0.20	9.3	0.98	0.58	9.3	0.98
GW200322_091133	HLV	–	–	–	–	–	–	450	9.0	0.62	*1.4×10^{3}*	*8.0*	*< 0.01*	*140*	*7.7*	*0.08*

Table I. Candidate GW signals. The time (UTC) of the signal is encoded in the name, as GWYYMMDD_hhmmss (e.g., GW200112_155838 occurred on 2020-01-12 at 15:58:38). The names of candidates not previously reported are given in **bold**. The detectors observing at the merger time of the event are indicated using single-letter identifiers (e.g., H for LIGO Hanford); these are not necessarily the same detectors that contributed triggers associated with the candidate. Where a candidate was found above the p_{astro} of 0.5 threshold by at least one analysis but below threshold by others, we include in *italics* the results from the other analyses, where available. A dash indicates that a candidate was not found by an analysis. The 2 candidates labeled with a dagger (†) were only found above threshold in a single detector with the GstLAL analysis, and the FAR estimates were made using significant extrapolation of the background data, meaning that single-detector events have higher uncertainty than coincident events. A conservative estimate of the FAR for these single-detector events is one per live time of the analysis; this is $\sim 3.16\ yr^{-1}$ for both LIGO Hanford and LIGO Livingston.

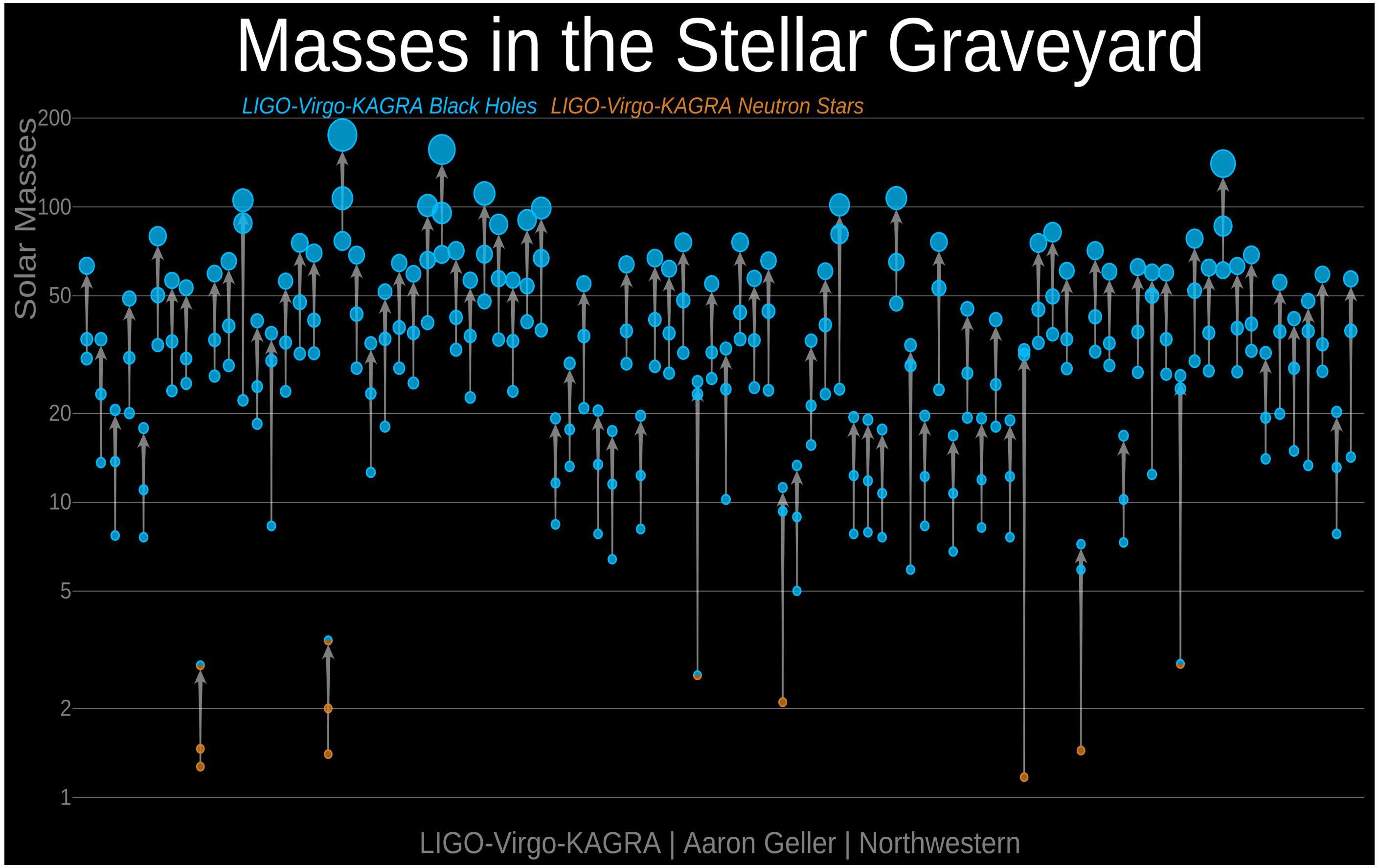
- 35 CBC candidates in O3b
- These include 17 new events that were not found in low latency analysis

Observation Period



Slide from H. Shinkai

O3b (2020/11/1 - 2021/3/27) **After O3b : GWTC-3 (2021/11/7 released)**



BHs

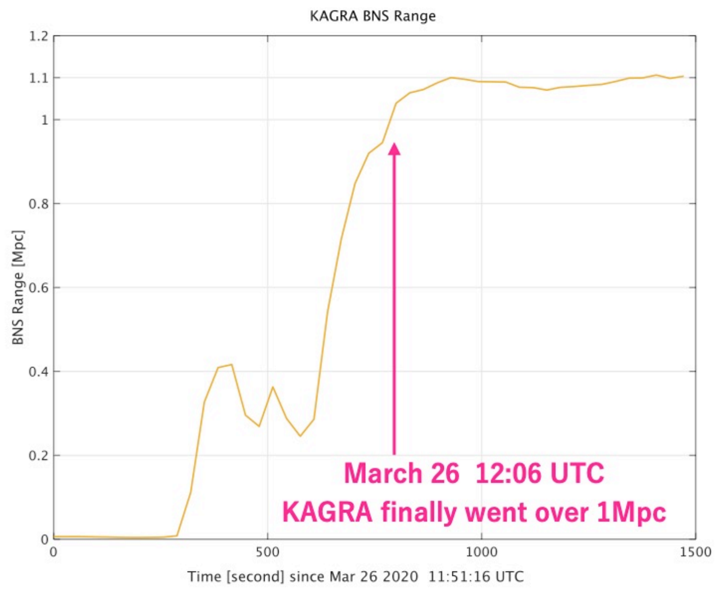
unknowns (2.5-5M)

NSs

O1 | O2 | O3a | O3b

https://media.ligo.northwestern.edu/gallery/mass-plot

Overview of O3GK



- Initial plan:
  - Join the O3 observation coordinated by LIGO and Virgo, once KAGRA sensitivity reached the goal sensitivity decided on MoA.
- Actual situation:
  - We reached the goal sensitivity at the end of March, 2020.
  - However, LIGO and Virgo stopped their operation due to COVID-19 infection.
  - Under such a situation, GEO600, Germany, and KAGRA carried out a joint observation run in April, 2020.
  - This was first joint observation for KAGRA
  - This observation run was named “O3GK”

LIGO-Virgo-KAGRAの協定に基づいて行われた正式な観測運転

O3GK

Official start and end time

Start : April 7　8:00 2020 UTC, GPS Time : 1270281618

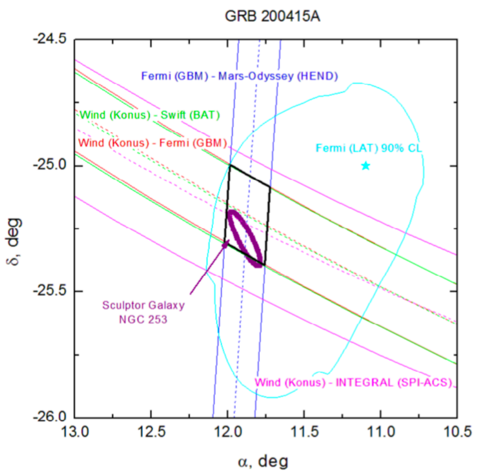
End : April 21 0:00 2020 UTC, GPS Time : 1271462418

KAGRA Duty Cycle : Locked 69%, Observing 58%

Longest lock 8h05m

Coincident time with GEO600 : 6.4 days

Sensitivity : 500-700 kpc

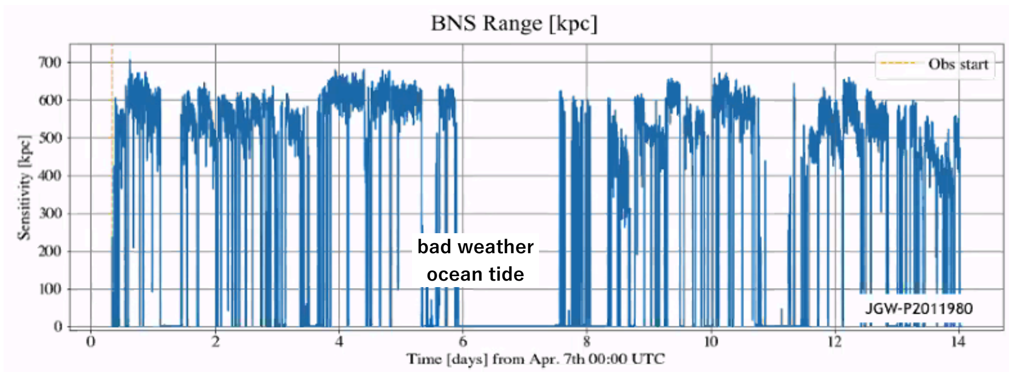


GRB200415A

NGC 235 (Sculptor galaxy)

3.5 Mpc, one of the brightest galaxies

https://gcn.gsfc.nasa.gov/fermi_grbs.html



Takahiro Yamamoto, JGW-P2011980

↑

GRB200415A

O3GK analysis

O3GK team

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O3GK analysis

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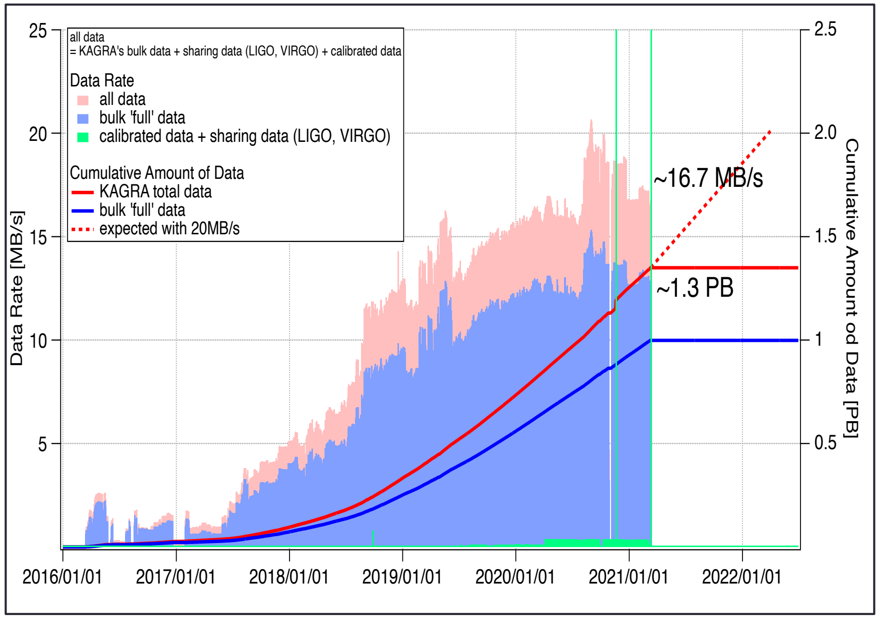
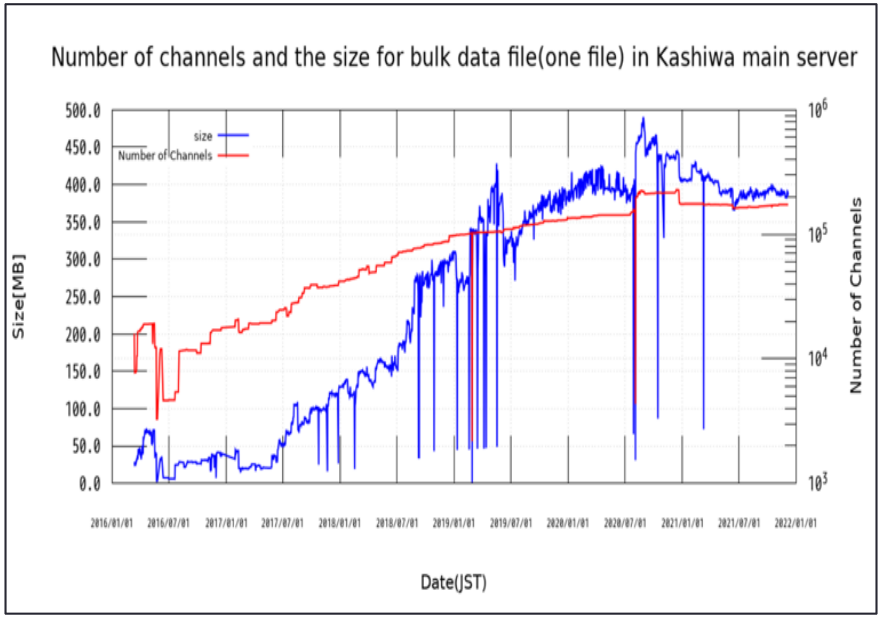
LVKの枠組みで解析は進行

Data amount

- The cumulative amount will exceed 2PB in 2022.
- The typical size of a data file is ~400MB (for 32sec), # of channels >10^5, now.
- We need a new (additional) data server for O4.

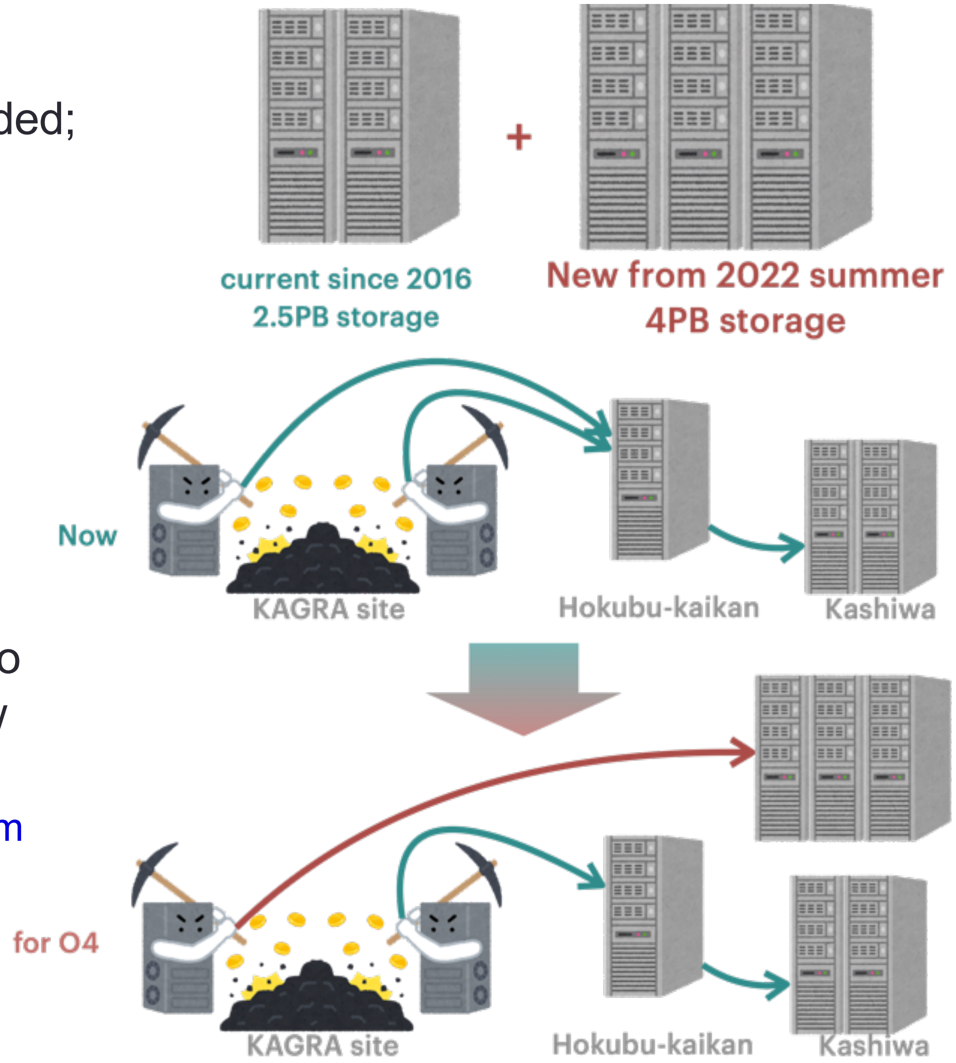




New data server for O4-O5 era

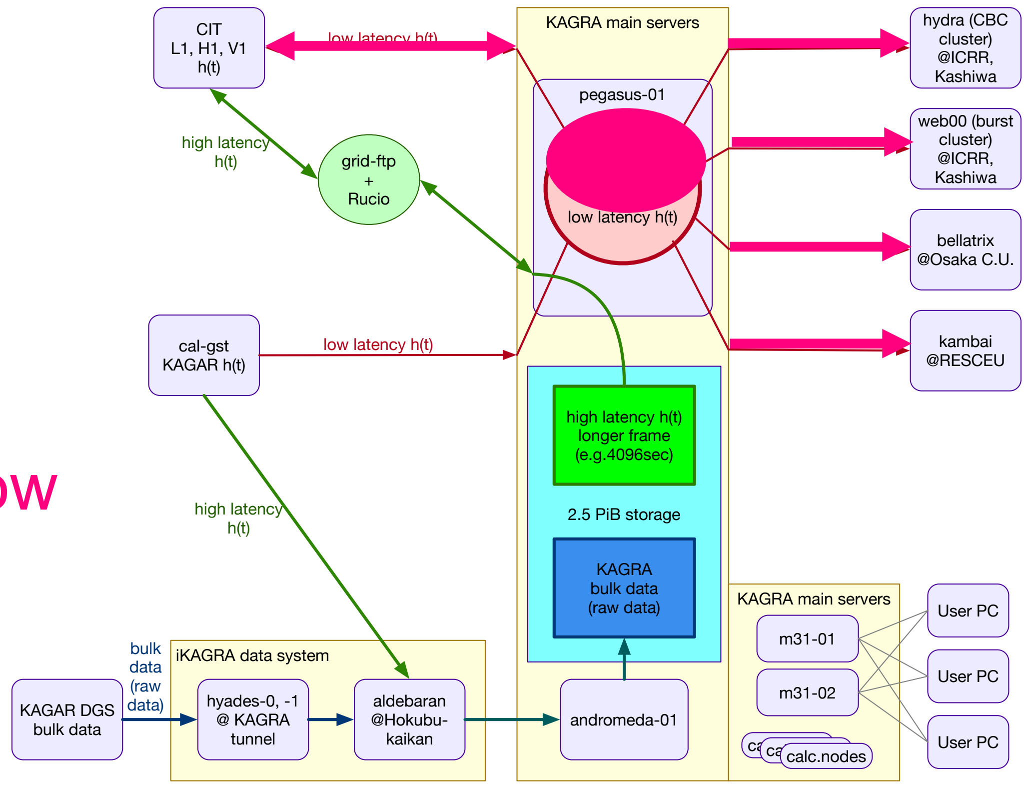
- A new system of KAGRA Main Data System: The bidding was completed, and the supplier was decided; assembling has begun.
  - It will be installed in the end of May 2022; the operation will begin in June.
  - OS: Rocky Linux 8 (compatible with RHEL8)
  - 4 PB (+ the current system = 6.5 PB in total.)
  - Computation server: 512 cores (848 cores in total)

- A part of the data transfer system (from Kamioka to Kashiwa; iKAGRA system) will be replaced by new servers.
  - For redundancy, we keep one of current data path from KAGRA tunnel to Kashiwa via Data Analysis Building (a.k.a Hokubu-kaikan).



Data flow, sharing LVK

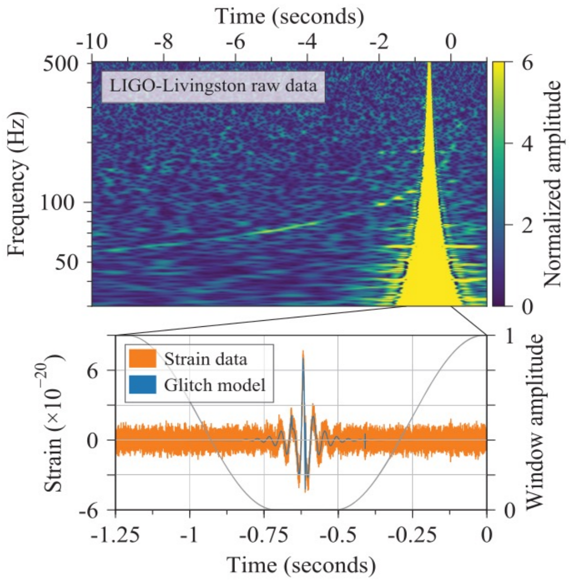
- **Main data flow is already constructed.**
- **Toward O4**:
  - data services for end users
  - update for LVK framework
  - "Kafka" is method of new low latency data sharing.
  - We are now testing and connected between CIT-Kashiwa-Osaka.



機械学習・深層学習を用いたノイズの特徴の分析と干渉計診断への応用

arXiv:2111.10053

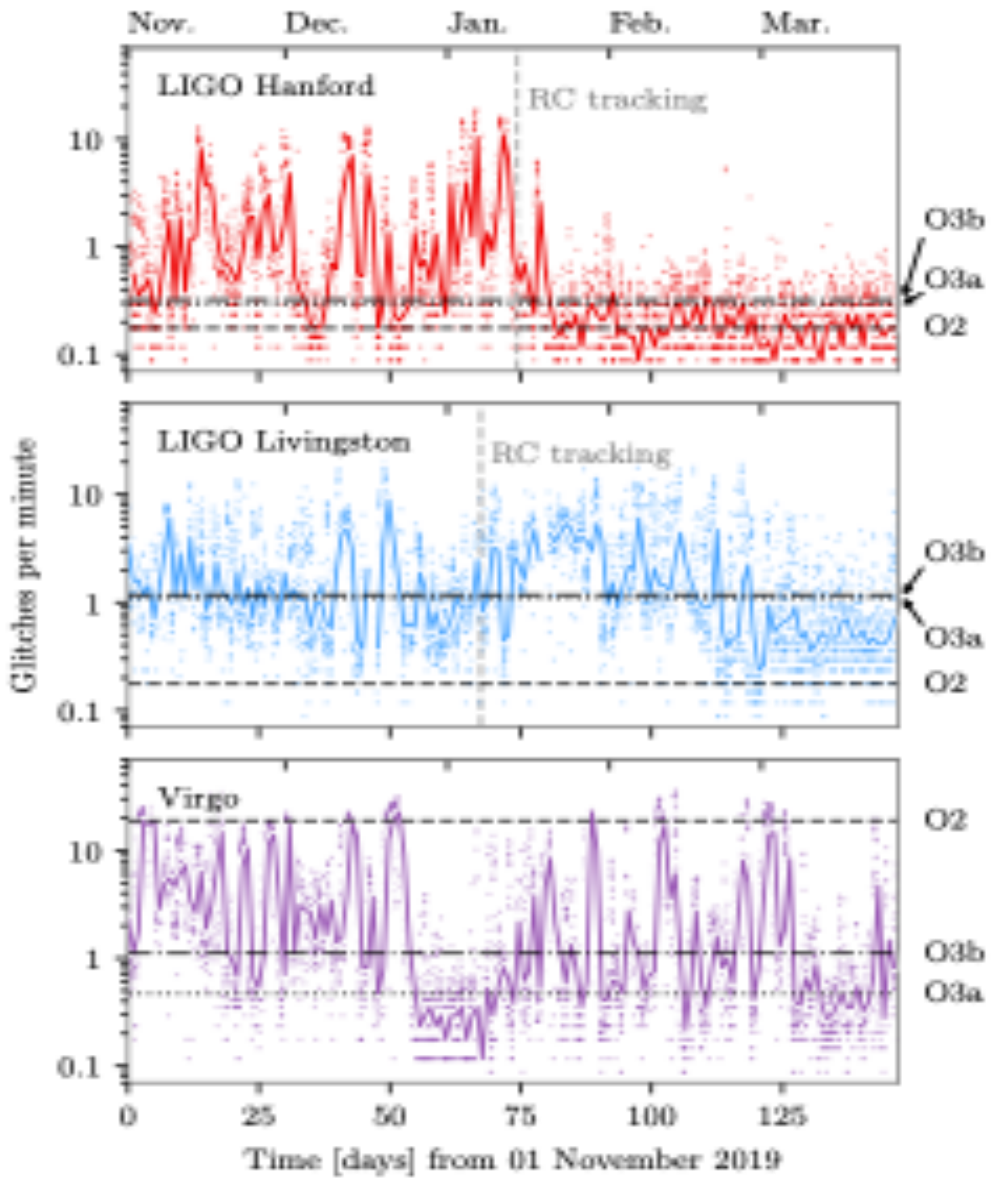
突発性雑音(glitch)が問題になることがしばしば



Data of GW170817 [1]

[1] B. P. Abbott et al., PRL 119, 161101 (2017)

The rate of single-interferometer glitches



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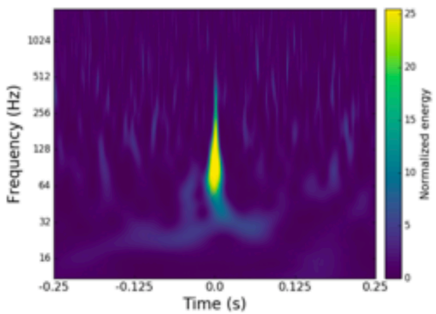
突発性雑音が問題になることがしばしば

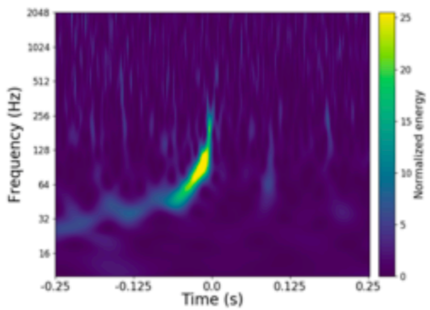
- 人手によるラベル付けを回避するために，<u>教師なし学習に基づいて</u>突発性雑音を分類するための新しい手段
- 畳み込みニューラルネットワークモデルおよびその学習方法を提案

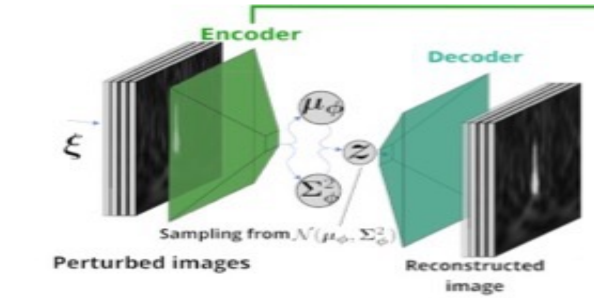
⇒
- 深層学習を用いて分類に適した特徴量の生成方法を学習 (**Variational Autoencoder, VAE**)
- 生成された特徴量を用いて教師なし分類を行う (**Invariant Information Clustering, IIC**)

Gravity Spy（LIGO O1 の突発性雑音データ）を用いたテスト



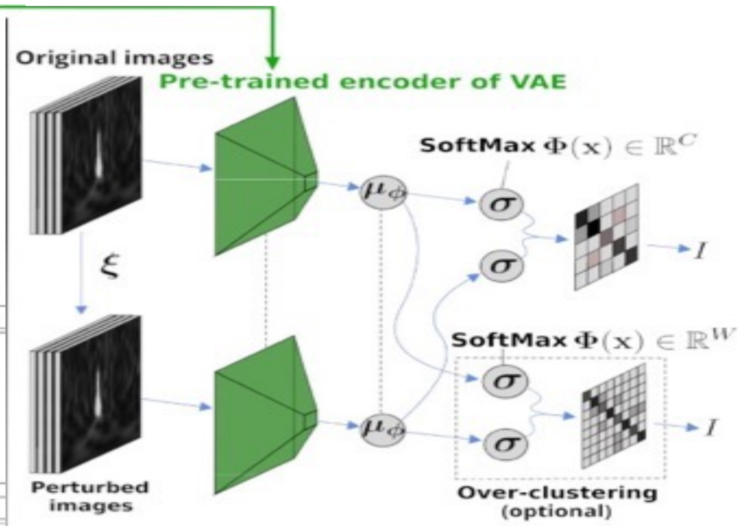
突発性雑音（上）と重力波信号（下）の時間-周波数特性





Encode Layer	Output	Activation
Input	(M, 4, 224, 224)	
Convolution	(M, 64, 112, 112)^B	ReLU
Max-Pooling	(M, 64, 56, 56)	
Convolution	(M, 256, 14, 14)^B	ReLU
Convolution	(M, 512, 7, 7)^B	ReLU
Average-Pooling	(M, 512, 1, 1)	
Fully-Connected	(M, 1024)	

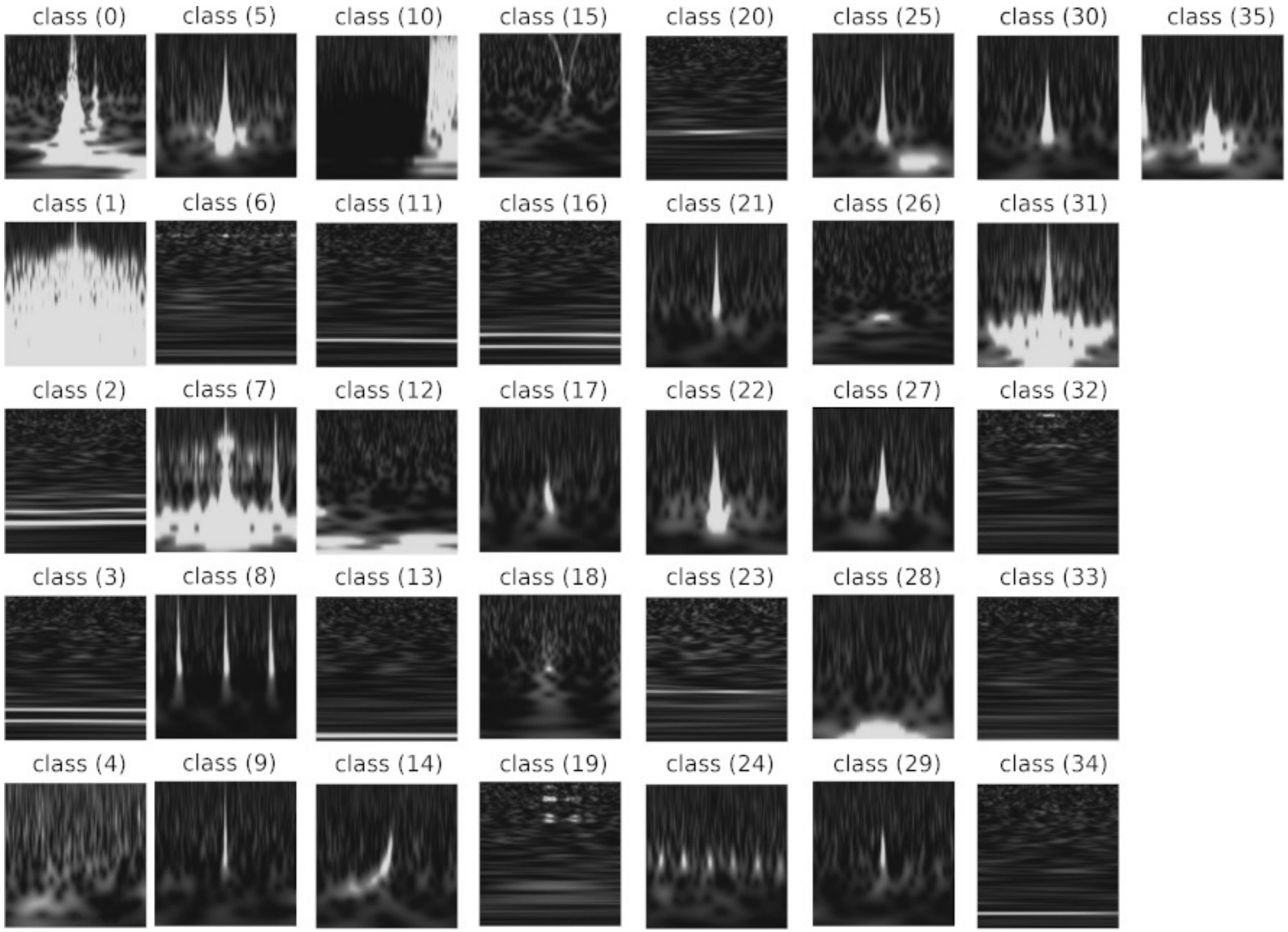
Decode Layer	Output	Activation
Input	(M, 512)	
Fully-Connected	(M, 512*7*7)^B	ReLU
Unsampling-Nearest	(M, 512, 28, 28)	
Convolution	(M, 256, 28, 28)^B	ReLU
Unsampling-Nearest	(M, 256, 56, 56)	
Convolution	(M, 128, 56, 56)^B	ReLU
Unsampling-Nearest	(M, 128, 112, 112)	
Convolution	(M, 64, 112, 112)^B	ReLU
Unsampling-Nearest	(M, 64, 224, 224)	
Convolution	(M, 4, 224, 224)^B	ReLU



IIC Layer	Output	Activation
Input	(M, 4, 224, 224)	
Pre-trained Encoder	(M, 512)	
Fully-Connected	(M, 512)^B	ReLU
Fully-Connected	(M, C)	

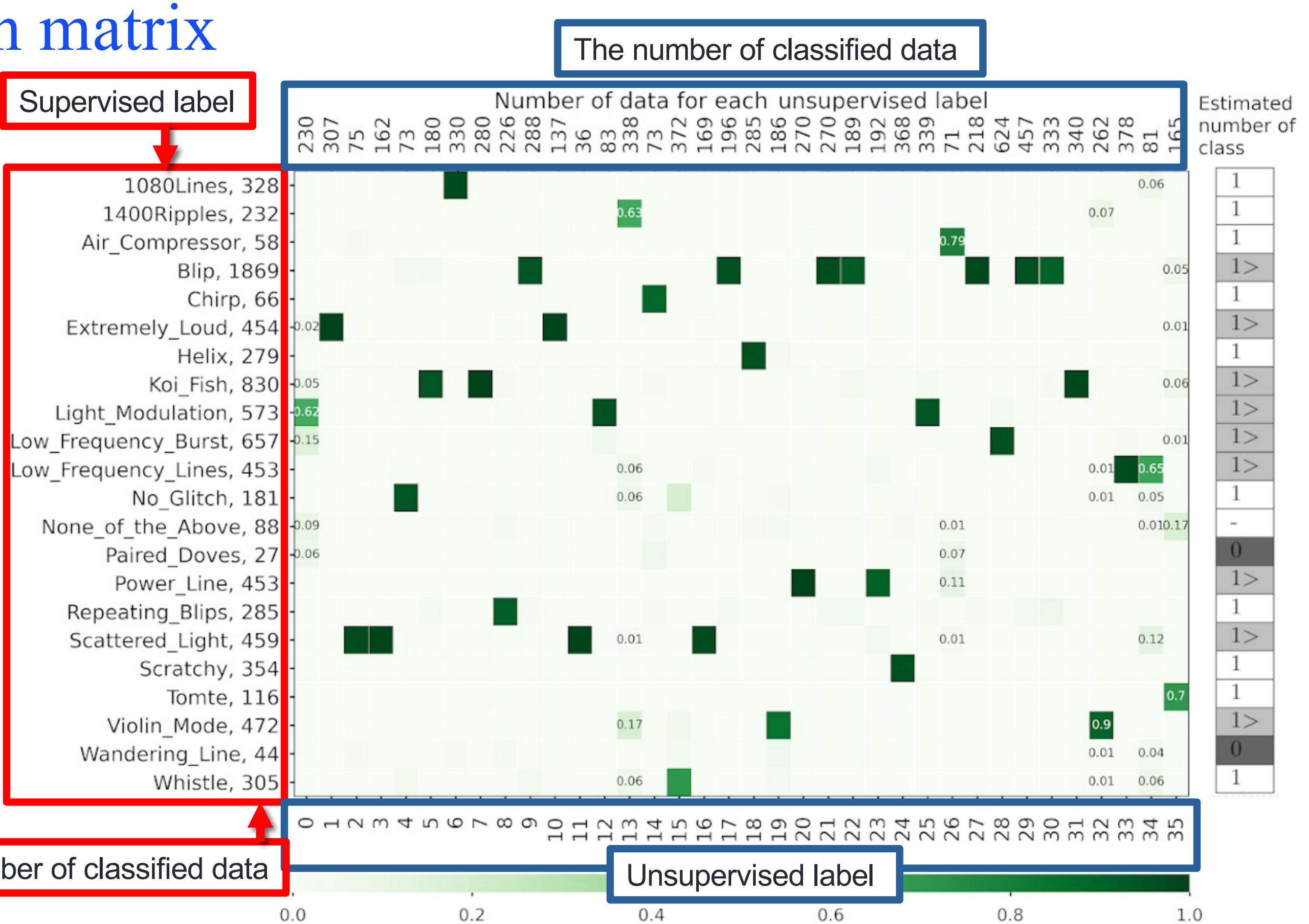
突発的雑音の分類結果の例 (1)

Representative image in all unsupervised classes.



突発的雑音の分類結果の例 (2)

Confusion matrix



We use **Gravity Spy labels** on a confusion matrix to investigate the correspondence between the results of supervised and unsupervised learning.

Then this confusion matrix show us that how original dataset is classified.

Future works:

- Extend our architecture to self-supervised learning to enhance the accuracy of classification.
- Based on proposed architecture, we will build a classification system of transient noise.

Summary

- Many analysis of O3 data are ongoing within LVK

- LVK O4 will be done with improved detector sensitivity
- More BBH/BNS detections are expected in O4 and beyond
- Detections of new sources might be happen

- KAGRA will participate O4 from the beginning
- We want to observe signals with KAGRA as soon as possible
- If detections with 4 detectors are realized, there are great scientific merits.