



Search for electromagnetic counterparts of gravitational wave events during the O4 period with CALET

# 重力波観測O4におけるCALETの 重力波電磁波対応天体の探査

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## LIGO/Virgo/KAGRA Observing Run 4

(Distances shown are for BNS mergers.)



LIGO has started O4 on May 23, 2023.

Search for electromagnetic counterparts of gravitational wave events

### CALET (CALorimetric Electron Telescope)



**Calorimeter (CAL)** 

Electrons: 1 GeV - 20 TeV

Gamma rays: 1 GeV – 10 TeV

Protons and nuclei: 10 GeV – 1 PeV



### High-energy gamma rays

- In operation on the Japanese Experiment Module (JEM) `Kibo'-Exposed Facility of the International Space Station since 2015
- Japan-USA-Italy collaboration

#### **CALET Gamma Ray Burst Monitor (CGBM)**

• Hard X-ray Monitor (HXM)



### 7 - 1000 keV LaBr<sub>3</sub>(Ce) + PMT (2 sets)

• Soft Gamma-ray Monitor (SGM)



0.04 – 20 MeV BGO + PMT (1 set)

#### Prompt emission from transients

## Performance of CAL and CGBM

	CAL			нхм	SGM	
<b>F</b>	~3 % @ 10 GeV 1 GeV – 10 TeV ~ 2 sr ~0.5 deg. @ 10 GeV		Crystal	LaBr3(Ce)	BGO	
resolution			Number of detectors	2	1	
Energy range			Diameter	66.1 (small)	102	
Field of view			[mm]	78.7 (large)	101	
Angular resolution			Thickness [mm]	12.7	76	
			Energy range	7-1000	40-20000	

[keV]

Field of view

N. Cannady et al., ApJS, 238, 5, 2018

Yamaoka et al., Proc. 7th Huntsville Gamma-Ray Burst Symposium, 41, C1304143, 2013

~3 sr

~8 sr

## Effective area for gamma rays

Adriani et al., ApJ 933, 85 (2022)



### CGBM



**Figure 6.** (a) CAL effective area for gamma rays as a function of energy in four zenith angle ranges for both the LEG (CC Track, solid symbols) and HE (EM Track, open symbols) trigger configurations, from Adriani et al. (2018).

Figure 2. CGBM effective areas vs. gamma-ray energy for the individual HXM1 and HXM2 detectors and for SGM at vertical incidence.

# Operation and data acquisition

- CGBM monitor data
  - Time History (TH data): 4+4ch, 1/8 s
  - Pulse Height data (PH data): 102+410 ch, 4 s
  - HV off at high latitude and around SAA



- CGBM onboard trigger
  - S/N calculation every 1/4 s
  - Trigger is issued when the S/N is above threshold
  - Acquisition of event data when triggered
- CGBM alert to GCN
  - GCN notice when triggered (1min)
  - GCN circular after ground analysis (a few days)

Trigger setting	НХМ	SGM
Threshold	8.5σ	7.0σ
Energy band	25 – 100 keV	50 – 300 keV



- CAL data acquisition
  - High energy trigger (HE, >10 GeV): always ON
  - Low energy gamma-ray trigger (LE-γ, > 1 GeV): low latitude & after CGBM trigger
  - Automated ground analysis (gamma-ray selection, in several hours)

### Kawakubo et al., PoS(ICRC2023)1517

## Gamma-ray bursts observed by CGBM



Figure 3. Duration distribution measured by SGM (40 – 1000 keV)

### Adriani et al., ApJ 933, 85 (2022) Kawakubo et al., PoS(ICRC2023) 1517 Search for GW counterparts

- CGBM:
  - No CGBM <u>onboard</u> trigger happened around any GW events during O3 (and O4 up to now).
  - <u>Ground</u> search was performed for  $T_0 \pm 60$ s where summed probability ( $P_h$ ) above the horizon  $\ge 1\%$ , but no significant signals were found.
- CAL:
  - Gamma-ray events within  $T_0\pm60$ s are searched for events selected in HE (>10 GeV) and LE- $\gamma$  (>1 GeV) modes in the case of "coverage" (fraction of CALET FOV covers LIGO/Virgo localization map)  $\geq 5\%$ ,
  - No candidate was found during O3 (and O4 up to now).
    Upper limits on energy flux were calculated.

## An example of upper limit maps

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Adriani et al., ApJ 933, 85 (2022)



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Figure 10. 90% confidence level upper limits observed by CAL in the energy range 1–10 GeV during the interval  $\pm 60$  s around the time of GW190408an reported by LIGO/Virgo. The intensity scale is given in units of erg cm<sup>-2</sup> s<sup>-1</sup>. Red and blue circles are the HXM and SGM fields of view, respectively.

## Another example of upper limit maps

Kawakubo et al., PoS(ICRC2023)1517)



**Figure 4:** 90 % confidence level upper limits observed by CAL in the energy range 10 - 100 GeV during the interval  $\pm 60$  s around the time of S230529ay reported by LIGO/Virgo/KAGRA. The intensity scale is given in units of ergs cm<sup>-2</sup> s<sup>-1</sup>. Green contour is the LIGO/Virgo high probability region. Black cross marks the pointing direction of CAL at  $T_0$  and the track of the pointing direction is marked cyan broad line in the interval  $\pm 60$  s.

## Examples of light curves by CGBM



Figure 9. Time histories of counts detected by CGBM within  $\pm 60$  s of LIGO/Virgo event S200112r. Dashed lines show time  $T_0 - 1.41$  prior to LIGO/Virgo event S200112r, CGBM signal excess is seen only in the lowest energy channel of HXM2.

60

### Kawakubo et al., PoS(ICRC2023)1517 Time histories by CGBM for likely NSBHs

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High CH2	500 230 - 450 keV High CH2
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High CH3	200 450 - 1000 keV High CH3
Low CH0	550 - 830 keV Low CH0
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Low CH2	1.5 - 2.6 keV Low CH2
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Low CH3	400 2.6 - 28 MeV Low CH3
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627c (HXM2)	S230627c (SGM)
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Figure 4. Time history of CGBM count rates around S230518h (Top) and S230627c (Bottom).

### S230518h (O4) [NSBH 86%]

S230627c (O4)

[NSBH 62%]

counts / s]

<sup>20</sup> Sate

100

100

10

208

100 100

100

200 100

Rate [counts / s]

S2

100

7 - 10

## CALET summary for Observing Run 3

56 events in GraceDB + 1 sub-threshold event (Fermi GBM-190816) (5 are BNS candidates)

Adriani et al., ApJ 933, 85 (2022) Kawakubo et al., PoS(ICRC2023)1517

Event ID	Possible Source	Time ( <i>T</i> ₀)	Coverage	CAL upper limit [erg cm <sup>-2</sup> s <sup>-1</sup> ]	CGBM Observation	Ph	Event ID	Possible Source	Time ( <i>T</i> ₀)	Coverage	CAL upper limit [erg cm <sup>-2</sup> s <sup>-1</sup> ]	CGBM Observation	Ph
S200316bj	MassGap (>99 %)	21:57:56.157	0 %	Outside of the FOV	No detection	90%	\$190910h	BNS (61 %)	08:29:58.544	10 %	5.3x10 <sup>-7</sup> (1 - 10 GeV)	No detection	78%
S200311bg	BBH (>99 %)	11:58:53.398	0 %	Outside of the FOV	HV off	-	S190910d	NSBH (98 %)	01:26:19.243	0 %	Outside of the FOV	No detection	77%
S200302c	BBH (89 %)	01:58:11.519	0 %	Outside of the FOV	No detection	81%	S190901ap	<u>BNS (86 %)</u>	23:31:01.838	5 %	2.8 x 10 <sup>-5</sup> (1 - 10 GeV)	No detection	82%
S200225q	BBH (96 %)	06:04:21.397	0 %	Outside of the FOV	HV off	-	S190828I	BBH (>99 %)	06:55:09.887	0 %	Outside of the FOV	No detection	79%
S200224ca	BBH (>99 %)	22:22:34.406	95 %	9.0 x 10 <sup>-7</sup> (10 - 100 Ge	V) HV off	-	S190828j	BBH (>99 %)	06:34:05.756	0 %	Outside of the FOV	No detection	28%
S200219ac	BBH (96 %)	09:44:15.195	0 %	Outside of the FOV	No detection	71%	GBM-180816	sub-threshold	21:22:13.027	25 %	2.8x10 <sup>-5</sup> (10 - 100 GeV)	No detection	66%
S200213t	<u>BNS</u> (63 %)	04:10:40.328	0 %	Outside of the FOV	No detection	18%	S190814bv	NSBH (>99 %)	21:10:39.013	0 %	Outside of the FOV	HV off	-
S200208q	BBH (>99 %)	13:01:17.991	0 %	Outside of the FOV	HV off	-	S190728q	MassGap (52 %)	06:45:10.529	0 %	Outside of the FOV	Outside of the FOV	0%
S200129m	BBH (>99 %)	06:54:58.435	5 %	4.8 x 10 <sup>-4</sup> (10 - 100 Ge	V) HV off	-	S190727h	BBH (92 %)	06:03:33.986	0 %	Outside of the FOV	No detection	14%
S200128d	BBH (97 %)	02:20:11.903	5 %	4.5 x 10 <sup>-6</sup> (10 - 100 Ge	V) No detection	60%	S190720a	BBH (99 %)	00:08:36.704	0 %	Outside of the FOV	HV off	-
S200115j	MassGap (>99 %)	04:23:09.742	15 %	8.5 x 10 <sup>-5</sup> (10 - 100 Ge	V) HV off	-	S190718y	Terrestrial (98 %)	14:35:12.068	10 %	1.2x10 <sup>-5</sup> (1-10GeV)	No detection	22%
S200114f	-	02:08:18.239	85 %	1.2x10 <sup>-5</sup> (10 - 100 GeV	/) HV off	-	S190707q	BBH (>99 %)	09:33:26.181	25%	3.8x10 <sup>-6</sup> (1-10 GeV)	No detection	76%
S200112r	BBH (>99 %)	15:58:38.094	5 %	1.1x10 <sup>-6</sup> (10 - 100 GeV	/) No detection	67%	S190706ai	BBH (99 %)	22:26:41.345	0 %	Outside of the FOV	HV off	-
S200105ae	Terrestrial (97 %)	16:24:26.057	45 %	3.1x10 <sup>-5</sup> (10 - 100 GeV	/) No detection	67%	S190701ah	BBH (93 %)	20:33:06.578	0 %	Outside of the FOV	No detection	19%
S191222n	BBH (>99 %)	03:35:37.119	0 %	Outside of the FOV	No detection	60%	\$190630ag	BBH (94 %)	18:52:05.180	0 %	Outside of the FOV	HV off	-
S191216ap	BBH (>99 %)	21:33:38.473	0 %	Outside of the FOV	No detection	40%	S190602aq	BBH (>99 %)	17:59:27.089	0 %	Outside of the FOV	No detection	99%
S191215w	BBH (>99 %)	22:30:52.333	0 %	Outside of the FOV	No detection	83%	\$190521r	BBH (>99 %)	07:43:59.463	0 %	Outside of the FOV	HV off	-
S191213g	BNS (77 %)	04:34:08.142	5 %	1.5x10 <sup>-5</sup> (1 - 10 GeV)	No detection	71%	S190521g	BBH (97 %)	03:02:29.447	30 %	7.4x10 <sup>-7</sup> (10-100 GeV)	HV off	-
S191205ah	NSBH (93 %)	21:52:08.569	0 %	Outside of the FOV	HV off	-	S190519bj	BBH (96 %)	15:35:44.398	0 %	Outside of the FOV	No detection	100%
S191204r	BBH (>99 %)	17:15:26.092	0 %	Outside of the FOV	No detection	4%	S190517h	BBH (98 %)	05:51:01.831	0 %	Outside of the FOV	No detection	86%
S191129u	BBH (>99 %)	13:40:29.197	0 %	Outside of the FOV	No detection	70%	\$190513bm	BBH (94 %)	20:54:28.747	15 %	4.5x10 <sup>-5</sup> (1-10 GeV)	No detection	100%
S191109d	BBH (>99 %)	01:07:17.221	0 %	Outside of the FOV	HV off	-	\$190512at	BBH (99 %)	18:07:14.422	0 %	Outside of the FOV	No detection	100%
S191105e	BBH (95 %)	14:35:21.933	0 %	Outside of the FOV	HV off	-	\$190510g	Terrestrial (58 %)	02:59:39.292	0 %	Outside of the FOV	No detection	16%
S190930t	NSBH (74 %)	14:34:07.685	0 %	Outside of the FOV	No detection	74%	\$190503bf	BBH (96 %)	18:54:04.294	25 %	7.1 x 10 <sup>-5</sup> (10-100 GeV)	HV off	-
S190930s	MassGap (95 %)	13:35:41.247	5 %	4.5x10 <sup>-5</sup> (10 - 100 GeV)	No detection	100%	\$190426c	Terrestrial (58 %)	15:21:55.337	10 %	9.2 x 10 <sup>-6</sup> (10-100 GeV)	HV off	-
S190924h	MassGap (> 99 %)	02:18:46.847	0 %	Outside of the FOV	HV off	-	\$190425z	<u>BNS (</u> >99 %)	08:18:05.017	10 %	8.5 x 10 <sup>-5</sup> (10-100 GeV)	HV off	-
S190923y	NSBH (68 %)	12:55:59.646	0 %	Outside of the FOV	No detection	68%	\$190421ar	BBH (97 %)	21:38:56.251	0 %	Outside of the FOV	Outside of the FOV	0%
S190915ak	BBH (>99 %)	23:57:02.691	0 %	Outside of the FOV	No detection	100%	\$190412m *	BBH (>99 %)	05:30:44.166	-	HV off	HV off	-
							\$190408ap	BBH (>99 %)	18-18-02 288	95 %	$3.0 \times 10^{-7} (1 - 10 \text{ GeV})$	No detection	100%

# Summary for CALET O4 follow-ups

15 events in GraceDB (no BNS candidate)

Kawakubo et al., PoS(ICRC2023)1517

Event ID	Possible Source	Time (To)	Coverage	CAL upper limit [erg cm <sup>-2</sup> s <sup>-1</sup> ]	CGBM Observation	Ph
S230630bq	BBH (97%)	23:45:32	10%	1.5 x 10 <sup>-3</sup> (10 – 100 GeV)	No detection	82%
S230630am	BBH <mark>(</mark> 98%)	12:58:06	40%	3.3 x 10 <sup>-4</sup> (10 – 100 GeV)	HV off	-
S230628ax	BBH (>99%)	23:12:00	0%	-	HV off	-
S230627c	NSBH (49%)	01:53:37	0%	-	No detection	100%
S230624av	BBH (95%)	11:31:03	0%	-	HV off	-
S230609u	BBH (96%)	06:49:58	5%	4.2 x 10 <sup>-5</sup> (1 – 10 GeV)	No detection	87%
S230608as	BBH (>99%)	20:50:47	50%	5.0 x 10 <sup>-5</sup> (1 – 10 GeV)	No detection	100%
S230606d	BBH (>99%)	00:43:05	0%	-	No detection	100%
S230605o	BBH (99%)	06:53:43	0%	-	No detection	69%
S230601bf	BBH (>99%)	22:41:34	15%	1.6 x 10 <sup>-3</sup> (10 – 100 GeV)	HV off	-
S230529ay	NSBH (62%)	18:15:00	15%	6.5 x 10 <sup>-5</sup> (10 – 100 GeV)	HV off	-
S230522n	BBH (99%)	15:30:33	5%	1.5 x 10 <sup>-6</sup> (10 – 100 GeV)	HV off	-
S230522a	BBH (>99%)	09:38:05	-	-	HV off	-
S230520ae	BBH (>99%)	22:48:42	10%	1.5 x 10 <sup>-4</sup> (1 – 10 GeV)	No detection	61%
S230518h	NSBH (86%)	12:59:08	0%	-	No detection	62%



## Summary and prospects

- We are looking for electromagnetic (EM) counterparts of GW events using CALET CAL and CGBM data.
- No candidate of EM counterparts to GW events was found in CALET CAL and CGBM data during O3 and O4 (up to June 2023). [Adriani et al., ApJ 933, 85 (2022); Kawakubo et al., ICRC2023]
- For O4, with higher event rates, we have developed automatic pipelines to process CGBM and CAL data.
- Other pipelines to check CGBM data for events alerted by other GRB detectors (Fermi, Swift, INTEGRAL, KONUS and MAXI) via GCN notice are under development.