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# High-Energy Gamma-ray Observations Using the CALorimetric Electron Telescope (CALET) on the ISS

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The CALorimetric Electron Telescope (CALET) cosmic ray detector on the International Space Station (ISS) has been in operation since its launch in 2015. The main instrument, the CALorimeter (CAL), is monitoring the gamma ray sky from  $\sim 1$  GeV up to  $\sim 10$  TeV with a field-of-view of about 2 sr for more than three and a half years. In this paper, we describe the improvement on gamma ray analysis to reduce secondary gamma rays produced by interaction of cosmic rays with the ISS structures and the automated search system for transient gamma-ray events such as gamma ray bursts and flares of active galaxies, and set upper limits on gamma-ray emission from gravitational-wave event candidates reported by the LIGO/Virgo third observing run since 2019 April.

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## 1. Introduction

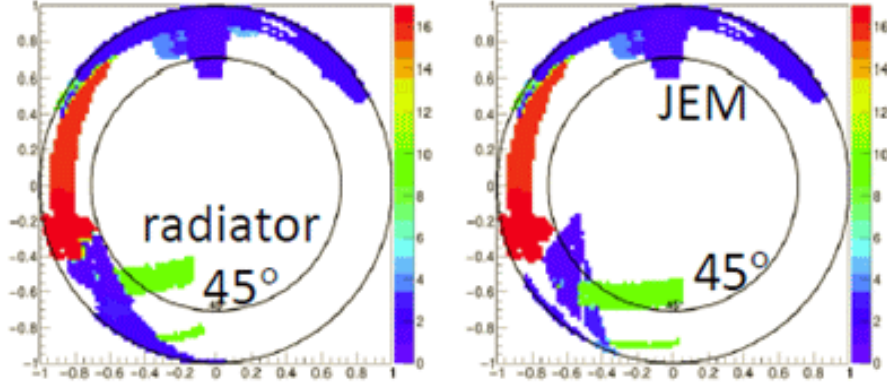
The CALorimetric Electron Telescope (CALET) mission [1], which was successfully launched and emplaced on the Japanese Experiment Module (JEM) ‘Kibo’-Exposed Facility of the International Space Station (ISS) in 2015 August, has been operational without any serious faults up to the time of this writing (2019 June). The main target of CALET is observation of high-energy cosmic rays, especially electrons, in the energy range from  $\sim 1$  GeV to tens of TeV, but its fine detector structure allows us to observe high-energy gamma-rays from  $\sim 1$  GeV to  $\sim 10$  TeV. Details of our analysis to extract gamma-ray candidates are described in [2, 3]. Here we just mention that we have two trigger modes of the CALET/CAL (calorimeter, the main instrument of CALET) related to gamma-ray observation: a high-energy (HE) mode with an energy threshold  $\sim 10$  GeV used in normal operation irrespective of geomagnetic latitude, and a low-energy gamma-ray (LE- $\gamma$ ) mode with a threshold  $\sim 1$  GeV, activated when the geomagnetic latitude is below  $20^\circ$  and following a CALET Gamma-ray Burst Monitor (CGBM) burst trigger (see [4] for details on our trigger scheme).

In this paper, recent progress in our gamma-ray analysis and observation, especially search for signal from gravitational-wave event candidates alerted by the LIGO/Virgo third observing run, are reported. Gamma-ray burst observations by CALET/CAL [5] and CGBM [6] are reported separately.

## 2. Progress in gamma-ray analysis

Since CALET is attached to the exposed facility of the JEM on the ISS, gamma-ray observation with CALET/CAL suffers from secondary gamma rays produced in interactions of high-energy cosmic rays with various structures of the ISS surrounding the detector. Some structures, such as the ISS truss and the JEM, are fixed to the ISS, and we can easily cut those secondary gamma rays by limiting our field-of-view. However, moving structures, such as solar panels and robotic arms, produce time-varying backgrounds for gamma ray observation (see Fig. 1). In our preceding analysis, we simply rejected events coming from the field-of-view affected by moving structures [3]. We have recently developed moving filter algorithms to reject time-varying portions of our field-of-view by taking account of moving structures, whose operational data are supplied by JAXA, operating the ‘Kibo’ module, in order to maximize our exposure for cosmic gamma rays.

As a result of the improved structure cut, the exposure which can be used for gamma-ray analysis is significantly increased. For example, in the LE- $\gamma$  trigger mode, the fraction of survival after the cut increased from  $\sim 60\%$  to  $> 90\%$  around the peak region of the exposure map (around 3 GeV). Fig. 2 shows a comparison of exposures for gamma rays calculated assuming the old cuts and the new ones in the LE- $\gamma$  mode. Note that our exposure in the galactic coordinate is not uniform (there are ‘holes’ corresponding to north and south poles), because of the orbit of the ISS (inclination  $51.6^\circ$ ). The skymap of gamma-ray candidates taken in the LE- $\gamma$  mode during the observation period from 2015 November to 2018 May is shown in Fig. 3. Total number of gamma-ray candidates after the improved cut is more than 3 times that remaining after the old cut, since we can accept more inclined events without reducing our field-of-view. Fig. 4 shows the energy spectra of gamma-ray candidates taken in the LE- $\gamma$  data for the ‘on plane’ ( $|b| < 8^\circ$ ,  $|\ell| < 80^\circ$ )



**Figure 1:** Typical ISS stuctures seen from CALET at different times. Outer circles indicate regions within  $60^\circ$  from zenith and inner circles within  $45^\circ$ . One can see moving structures like radiators, in addition to fixed stuctures like the Japanese Experiment Module (JEM).

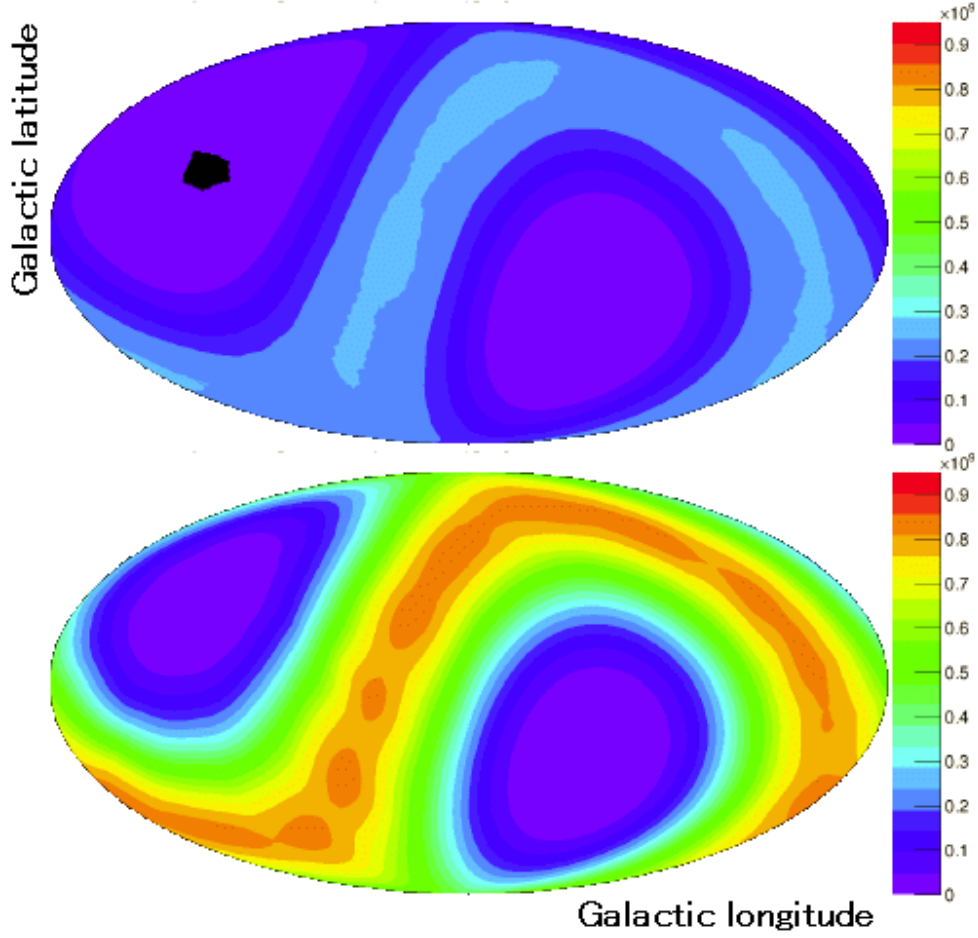
region, compared with our previous results [3] and the averaged data of *Fermi*-LAT [7]. One can easily see statistical errors are significantly reduced, but there are some discrepancies with the *Fermi*-LAT data, especially in the ‘off plane’ region, which may indicate remaining backgrounds and possible systematic errors, and should be studied further.

### 3. Automated search system for transient gamma-ray events

Data from CALET onboard the ISS are downloaded every hour via the TDRSS link to the JAXA ground stations. Thus, although we cannot analyze data in real-time, we would like to reduce delay time as much as possible to study transient phenomena, e.g., gamma ray bursts, flares of active galaxies, and electromagnetic counterparts of gravitational wave events.

With our limited effective area in high-energy gamma-rays, we define a ‘transient event’ as a gamma-ray pair coming from the same direction (within our angular resolution) in a 120-s time window. We judge an event pair came from the same direction when the opening angle of the directions of the pair is less than the 68% containment angle derived from our point spread function described in [3] (see Fig 5). We searched for such events using the CALET data taken in the LE- $\gamma$  mode from 2015 November to 2018 September without imposing the time window. Positions on the skymap of 307 pairs found in this search distribute around the Galactic plane and known point sources (Geminga etc.) and indicate the search algorithm works properly. Especially, a flare of an active galactic nucleus, CTA 102, in 2017 January was detected during the search.

We have developed a parallel-processing analysis server to search for gamma-ray pairs which are coming from the same direction dedicated for this quasi-real-time analysis. One server, with a 64-thread CPU, searches for gamma-ray pairs by dividing received one-hour data into 60 threads (each thread handles about the same number of events, corresponding to about one-minute data), and another server, with a 8-thread CPU, produces various plots based on results generated by the first server. A schematic of the automated search system is shown in Fig. 6. Events triggered in the LE- $\gamma$  mode and the HE modes are treated separately, and events within 60 seconds from the CGBM triggers are also checked to see if they come from the same direction. For the LE- $\gamma$  mode, gamma-



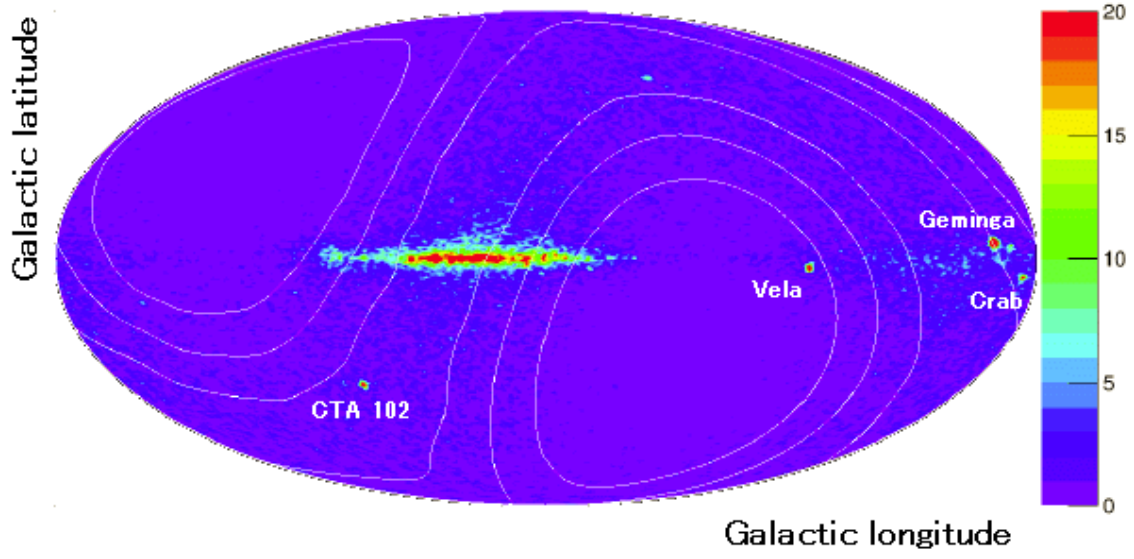
**Figure 2:** Comparison of exposures for gamma rays (LE- $\gamma$  trigger) calculated assuming different cuts shown in the galactic coordinates. The upper panel shows the exposure for the old cuts and the lower panel shows that for the new cuts. The unit is  $10^9 \text{ cm}^2\text{s}$  for the period from 2015 November to 2018 May. The exposures are nonuniform due to the orbit of the ISS (inclination  $51.6^\circ$ ).

ray pairs are searched for within the duration of each LE- $\gamma$  run, which lasts about 10 minutes, by combining the results from corresponding threads. With this system, the time necessary to obtain results has been reduced to about 2 hours after occurrence of transient events.

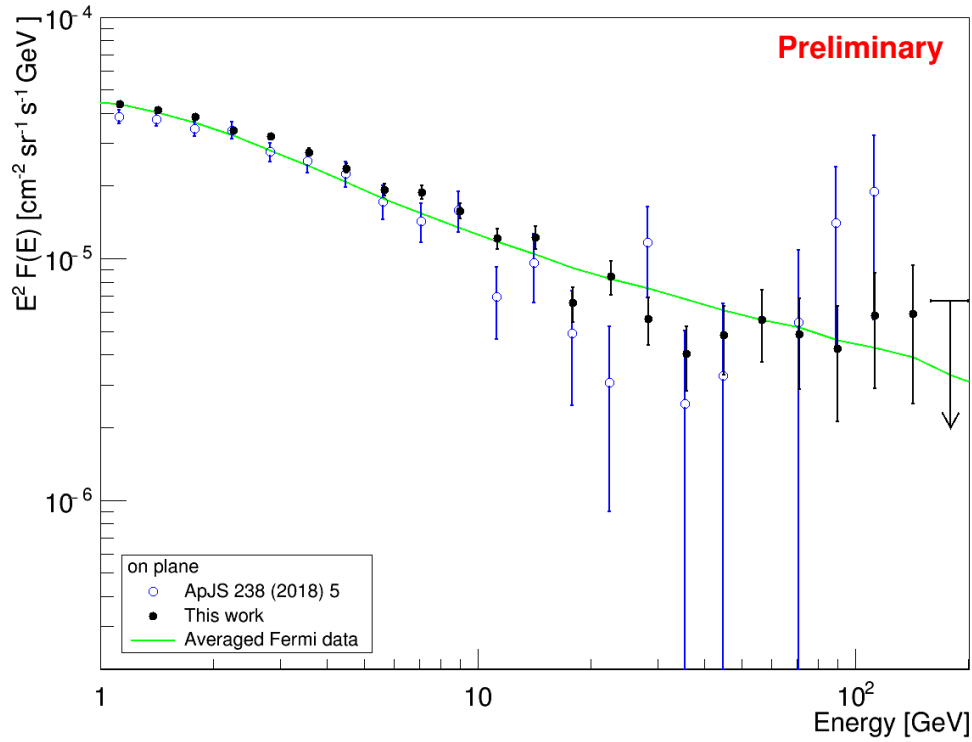
#### 4. Limits on electromagnetic emission from gravitational wave events

We have already reported the results on the search for gamma ray emission from gravitational wave events detected during the second observing run of LIGO/Virgo [8, 9].

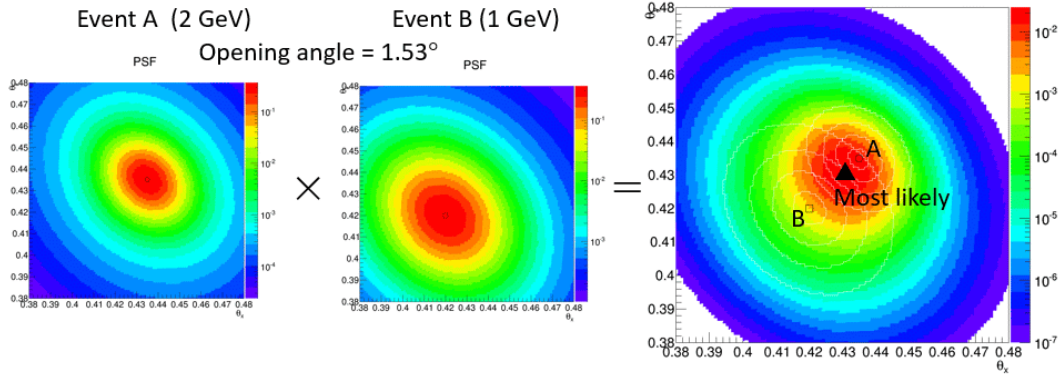
Since the beginning of the third observing run of LIGO/Virgo, we are monitoring possible gamma-ray emission based on the triggers on gravitational-wave event candidates supplied by the LIGO/Virgo team, based on the memorandum of understanding between CALET and LIGO and Virgo. In Table 1 we summarize the CALET/CAL observations reported in GCN circulars [10] from 2019 April 1 to 2019 June 17. An example of the energy flux limit maps are shown in Fig. 7 for the LIGO/Virgo trigger S190408an.



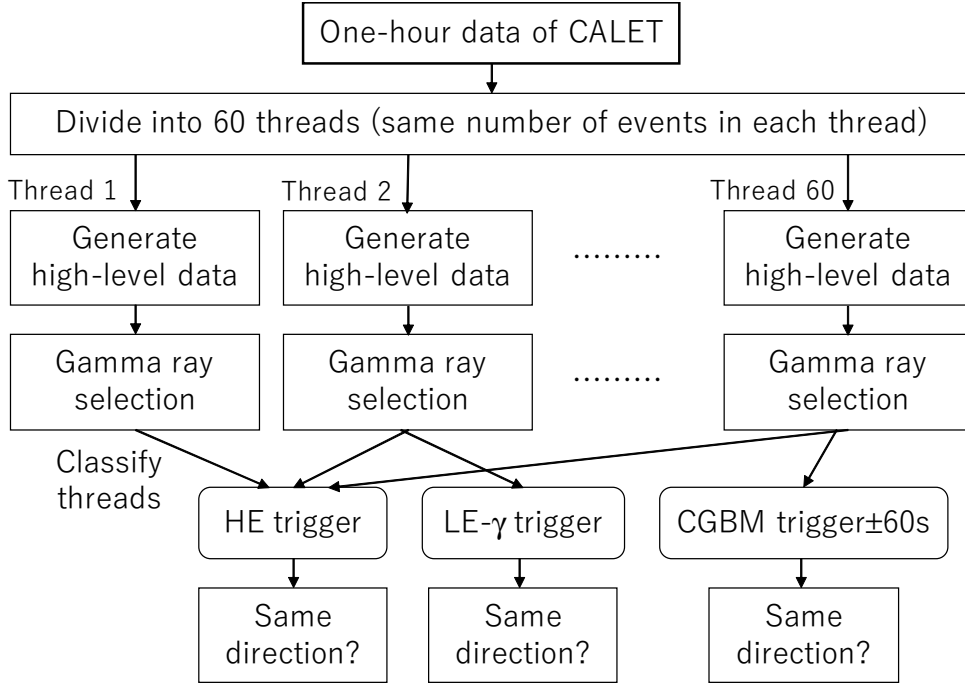
**Figure 3:** Skymap of gamma-ray candidates (LE- $\gamma$  trigger) shown in the galactic coordinates. White contours show exposures (see Fig. 2). Individual sources are marked.



**Figure 4:** Energy spectra of gamma-ray candidates (LE- $\gamma$  trigger) for the 'on plane' ( $|b| < 8^\circ$ ,  $|\ell| < 80^\circ$ ; filled circles) region. Previous results [3] and the averaged data of Fermi-LAT [7] are also shown by open circles and a solid line.



**Figure 5:** An example of a gamma-ray pair judged to have come from the same direction based on the product of point spread functions of each event.

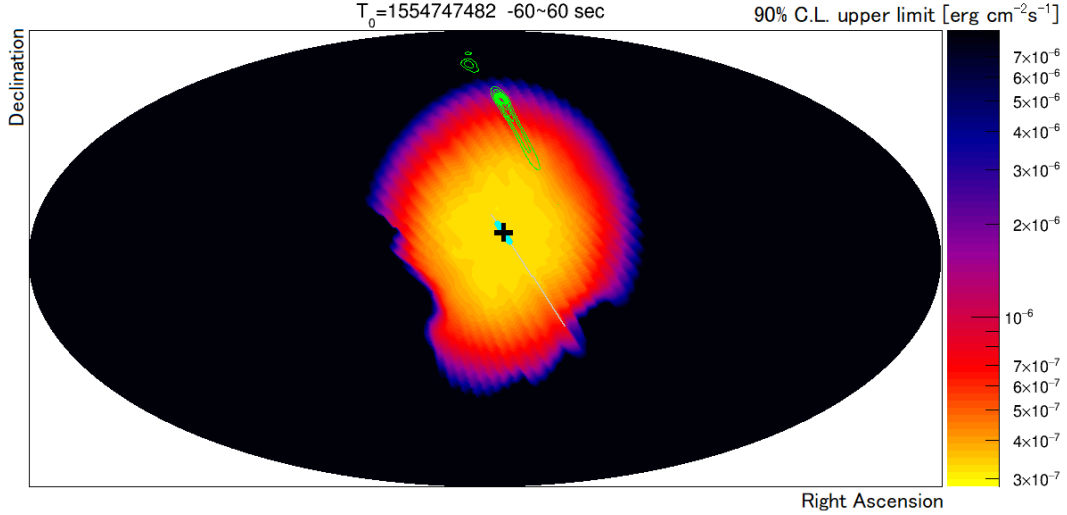


**Figure 6:** A schematic of the automated search system for transient gamma-ray events. Hourly data are divided into 60 threads, and processed in parallel to search for gamma-ray pairs in each trigger mode (HE, LE- $\gamma$ , and CGBM).

Considering the field-of-view of CAL extends to  $\sim 45^\circ$  from the zenith, chances to have overlap with the LIGO/Virgo probable region is fair. Although no gamma-ray event has been found in the time window within 60 seconds from the trigger time ( $T_0$ ) of 8 events for which there are some overlapping sky area between the CALET field-of-view and the summed LIGO/Virgo probability maps, upper limits obtained by CALET set some constraints on electromagnetic emission from gravitational wave events as discussed in [9].

GCN No.	LIGO/Virgo trigger	Trigger time $T_0$ (2019)	Events $T_0 \pm 60$ s	90% C.L. U.L.	Summed probability	CAL $\alpha$ ( $^\circ$ )	CAL $\delta$ ( $^\circ$ )
24088	S190408an	04-08 18:18:02.288 UTC	0	$2.3 \times 10^{-6}\dagger$	80%	352.9	8.3
24218	S190425z	04-25 08:18:05.017 UTC	0	$1.0 \times 10^{-4}$	5%	131.3	-43.6
24276	S190426c	04-26 15:21:55.337 UTC	0	$2.5 \times 10^{-5}$	10%	183	-50.9
24403	S190503bf	05-03 18:54:04.294 UTC	0	$4.2 \times 10^{-5}$	10%	169	-45.5
24495	S190510g	05-10 02:59:39.292 UT	0	–	No	295.7	50.8
24531	S190512at	05-12 18:07:14.422 UT	0	$1.9 \times 10^{-5}$	10%	214.9	37.7
24548	S190513bm	05-13 20:54:28.747 UT	0	$6.0 \times 10^{-5}\dagger$	5%	348	4.4
24593	S190517h	05-17 05:51:01.831 UT	0	–	No	126.2	-31.9
24617	S190519bj	05-19 15:35:44.398 UT	0	–	No	243.1	51.1
24648	S190521g	05-21 03:02:29.447 UT	0	$6.0 \times 10^{-6}$	30%	205.7	49.2
24649	S190521r	05-21 07:43:59.463 UT	0	–	No	225.3	51.4
24735	S190602aq	06-02 17:59:27.089 UT	0	$2.9 \times 10^{-4}$	5%	127.5	45.1

**Table 1:** Summary of CALET/CAL gamma-ray observations on gravitational-wave event candidates in the LIGO/Virgo third observing run reported in GCN circulars [10]. Upper limits (U.L.) are given in unit of  $\text{erg cm}^{-2}\text{s}^{-1}$  for the energy range 10–100 GeV except for those marked with  $\dagger$  which are for 1–10 GeV, which corresponds to the HE and the LE- $\gamma$  mode of the trigger condition of CAL around  $T_0$ . ‘Summed probability’ is the maximum probability in the overlap region of the CAL field-of-view at  $T_0$  with the summed LIGO/Virgo probability map (‘No’ means there is no overlap). Also shown are the coordinates of the center of CAL field-of-view at  $T_0$ .



**Figure 7:** 90% C.L. upper limit on S190408an energy flux in the energy region 1–10 GeV and time window  $[T_0 - 60\text{s}, T_0 + 60\text{s}]$  shown in the equatorial coordinates. The thick cyan line shows the locus of the FOV center of CAL, and the plus symbol is that at  $T_0$ . Also shown by green contours is the localization significance map of S190408an reported by LIGO/Virgo.



## 5. Summary

The CALET cosmic ray detector onboard the ISS has been monitoring cosmic gamma-rays above 1 GeV since 2015 October. In this paper we reported our progress in gamma-ray analysis. Firstly, we have developed new cuts to reduce secondary gamma-ray background produced in the various ISS structures, which increase our event statistics significantly. Secondly, a parallel-processing analysis server to search for gamma-ray pairs has been developed to reduce delay time from occurrence of transient events. Finally, we reported our search for electromagnetic counterparts of gravitational-wave events upon triggers supplied by LIGO/Virgo interferometers during their third observing run and gave upper limits on gamma-ray emission.

We continue observation at least until 2021, hoping for a further extension, sharing the GeV gamma-ray sky with other satellites such as Fermi-LAT and DAMPE.

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