Analysis for GW events and GRBs

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Analysis systems for transient events

For transient analysis, we have three analysis systems.

- The CAL pipeline for GW events & GRBs
  - To search for gamma-rays associating with GW events & GRBs
  - To calculate gamma-ray flux upper limits
- The CGBM pipeline
  - To search for signals associating with GW events & GRBs
- The transient search system
  - To search for gamma-ray transients rapidly & automatically

The CAL pipelines and the transient search system were developed by graduate students in Waseda University and Asaoka-san. I have taken over their works.

The CAL pipelines for GW event & GRB

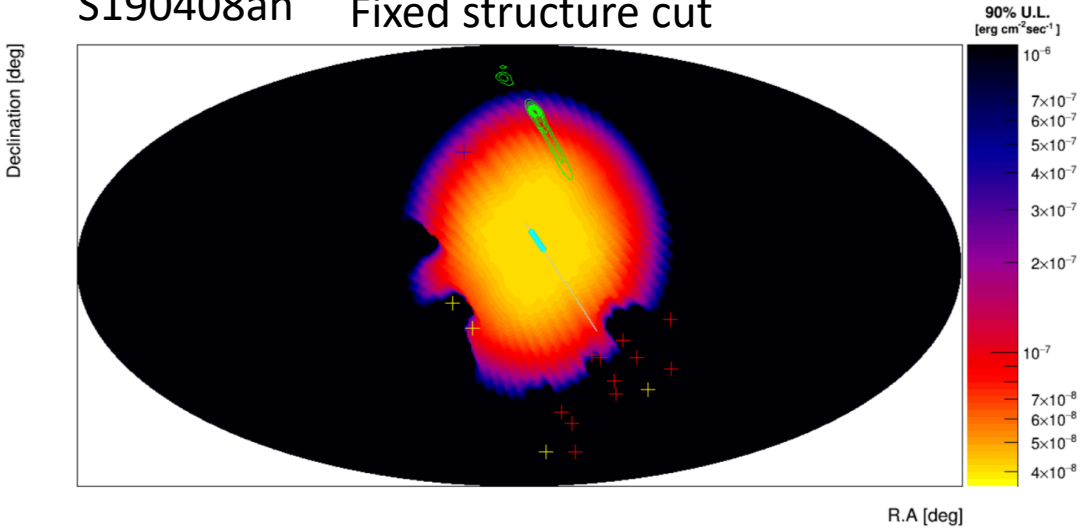
Input information (Start python script)	GW: event name GRBs: trigger time and position (R.A., Dec.)
Getting information from GCN	GW: the GW sky map, trigger time GRB: Skip
Checking Run mode at the trigger time	HE or LEG
Search for gamma-ray events	EM track (HE) and CC track (LEG)
Making event displays	Using L2 viewer.
Calculate exposure & upper limits Estimate background counts	Plotting upper limits map with the GW skymap or GRB position
Making a pdf report	

Red: manual
Blue: automatic

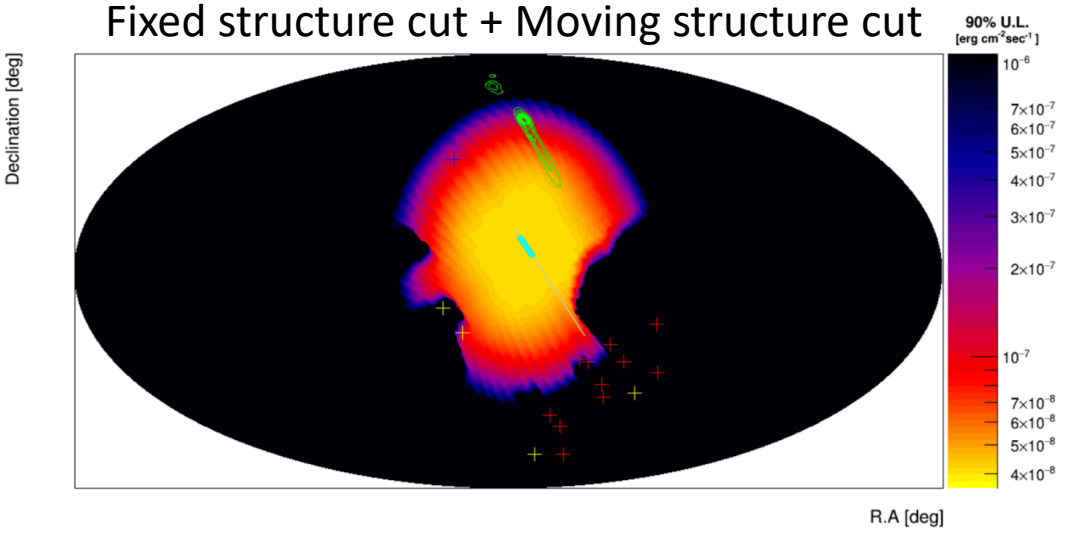
Moving structure cut

- Moving structure cut has equipped with GW & GRB pipelines.

S190408an Fixed structure cut



Fixed structure cut + Moving structure cut



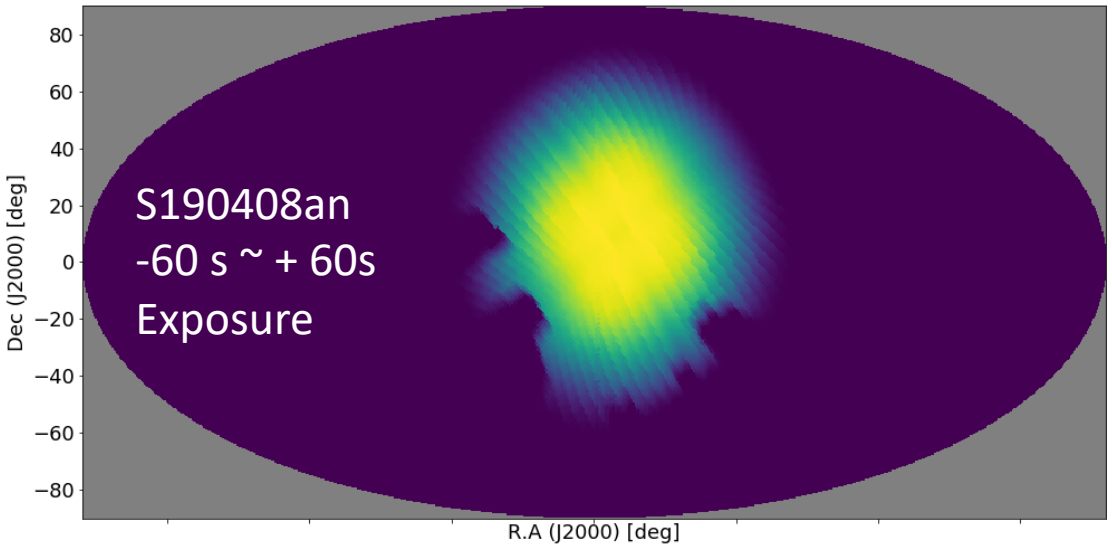
The fixed structure map was stored in the database.

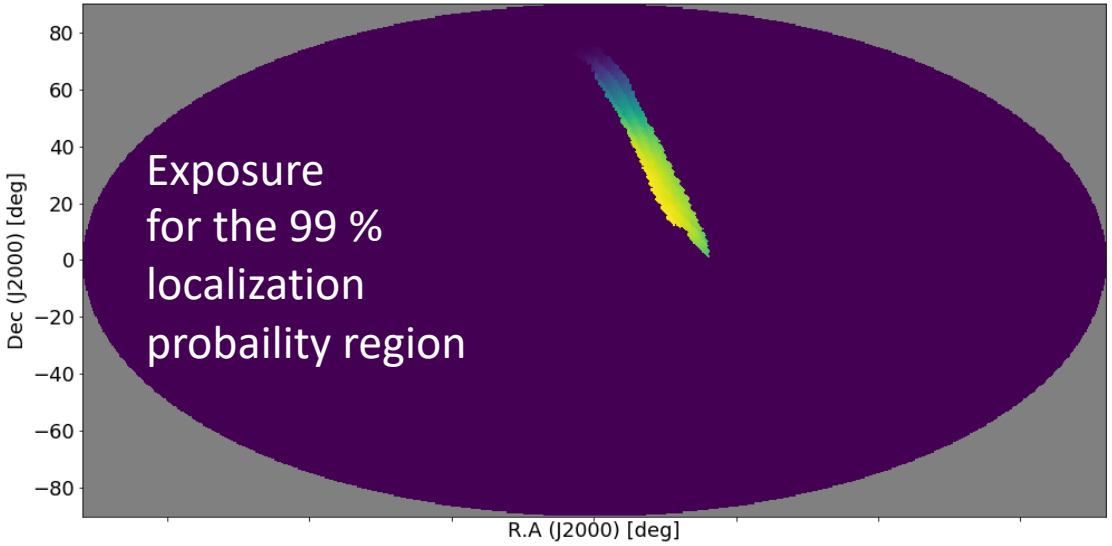
The blocking by moving structures was calculated for every 30 seconds.

Robot arms and other obstruction due to the ISS activity is not included in the moving structure cut

The pdf report contains results with and without the moving structures cut.

How to increase the region we consider





If we add pixels of HEALPix to the region we consider, expected background counts increase.

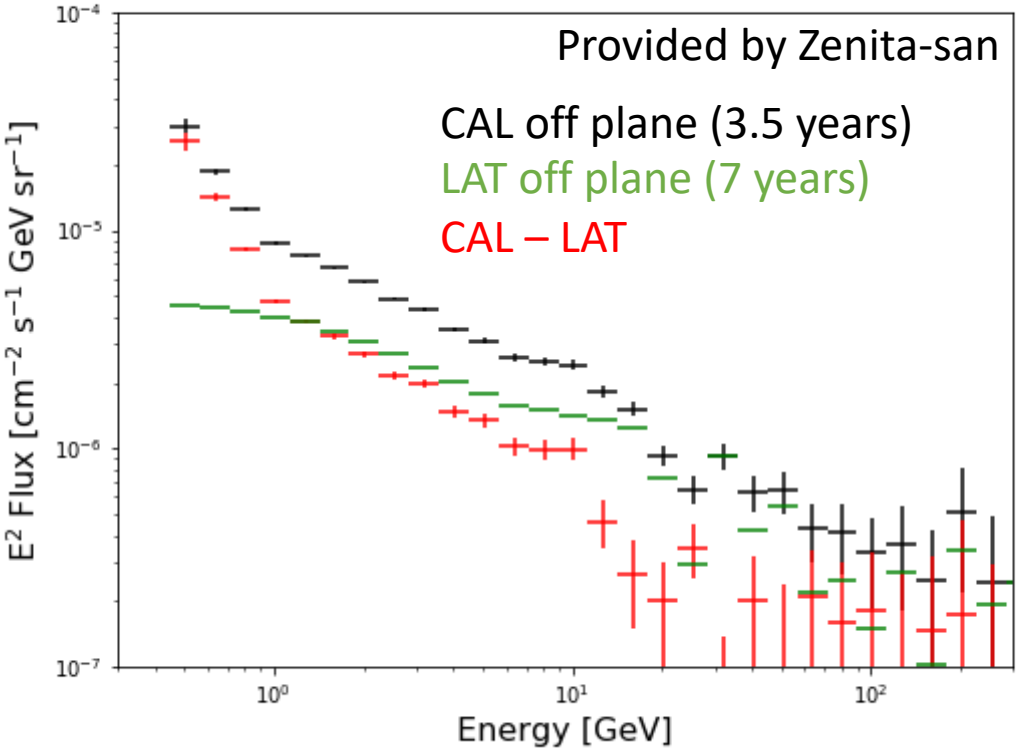
We don‘t want to add meaningless pixels to the consider region.

- Exposure is zero.
- Probability is quite low.

1. Cumulating the localization probability in descending order.
2. Checking the 99 % localization probability region.
3. We add pixels to the consider region in descending order of exposure from the 99 % localization probability region.

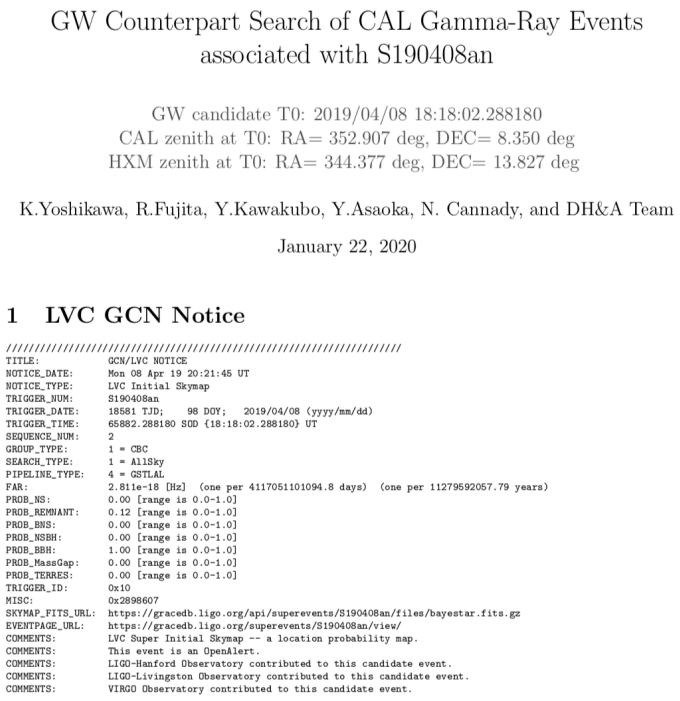
Instrumental background

- Just the FOV cuts cannot remove the inclusion of secondary gamma-rays from the ISS structures.
- We estimated instrumental BG counts using the difference between gamma-ray flux from the off galactic plane region observed by Fermi-LAT and CAL.



1. Calculate difference of CAL flux and Fermi flux
2. Perform logarithmic, linear interpolation and integration over energy range (LE: 1 – 10 GeV, HE: 10 -100 GeV)

PDF report



GW Counterpart Search of CAL Gamma-Ray Events associated with S190408an

GW candidate T0: 2019/04/08 18:18:02.288180
CAL zenith at T0: RA= 352.907 deg, DEC= 8.350 deg
HXM zenith at T0: RA= 344.377 deg, DEC= 13.827 deg

K.Yoshikawa, R.Fujita, Y.Kawakubo, Y.Asaoka, N. Cannady, and DH&A Team

January 22, 2020

1 LVC GCN Notice

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/LVC NOTICE
NOTICE_DATE:      Mon 08 Apr 19 20:21:45 UT
NOTICE_TYPE:      LVC Initial Skymap
TRIGGER_NUM:      S190408an
TRIGGER_DATE:     18581 TJD;    98 DOY;   2019/04/08 (yyyy/mm/dd)
TRIGGER_TIME:     65882.288180 SOD {18:18:02.288180} UT
SEQUENCE_NUM:     2
GROUP_TYPE:       1 = CBC
SEARCH_TYPE:      1 = AllSky
PIPELINE_TYPE:    4 = GSTLAL
FAR:              2.811e-18 [Hz]  (one per 4117051101094.8 days)  (one per 11279592057.79 years)
PROB_NS:          0.00 [range is 0.0-1.0]
PROB_REMNANT:     0.12 [range is 0.0-1.0]
PROB_BNS:         0.00 [range is 0.0-1.0]
PROB_NSBH:        0.00 [range is 0.0-1.0]
PROB_BBH:         1.00 [range is 0.0-1.0]
PROB_MassGap:     0.00 [range is 0.0-1.0]
PROB_TERRES:      0.00 [range is 0.0-1.0]
TRIGGER_ID:       0x10
MISC:             0x2898607
SKYMAP_FITS_URL:  https://gracedb.ligo.org/api/superevents/S190408an/files/bayestar.fits.gz
EVENTPAGE_URL:    https://gracedb.ligo.org/superevents/S190408an/view/
COMMENTS:         LVC Super Initial Skymap -- a location probability map.
COMMENTS:         This event is an OpenAlert.
COMMENTS:         LIGO-Hanford Observatory contributed to this candidate event.
COMMENTS:         LIGO-Livingston Observatory contributed to this candidate event.
COMMENTS:         VIRGO Observatory contributed to this candidate event.
```

Contents

- Trigger time (T_0) & Zenith direction at T_0
- GCN Notice
- Run mode & observation range
- Event lists
  - Time, fileID, EventID, Energy, R.A & Dec., FOV information, Normalized probability, Survival probability
- Event display
- Exposure & Upper limit map
  - LVC high probability region
  - Gamm-ray candidate position
- Exposure & summed probability vs. enclosed solid angle
- Exposure & summed probability vs. enclosed solid angle
- Exposure & Upper limits table
  - Summed probability, enclosed probability, Exposure, Upper limits, Instrumental BG, Diffuse BG

I will also attach an example of the report to the TIM agenda.
I would appreiciate it if you check the report and give us your comments.

The CGBM pipeline

Input information (Start shell script)	GW Trigger time, zenith direction at the trigger time
Making light curves	Using Time history data in CGBM L3 data
Calculate signal-to-noise ratio (SNR)	For 1680 conditions every 1/8s
Summarizing SNR results	Picking up high significance conditions and summarizing trigger due to the same event
Making FOV plot & Calculating the summed probability in the FOV	Checking overlaps between the CGBM FOV and the GW sky map
Creating an HTML file for the web page	For the summary web page, including plots and SNR calculation results.
Upload the HTML file and plots to the web server in AGU	Aoyama Gakuin University (AGU)

Red: manual
Blue: automatic

Signal-to-noise ratio calculation

$$\mathrm{SNR} = \frac{N_{\mathrm{tot}} - \frac{N_{\mathrm{BG}}}{\Delta t_{\mathrm{BG}}}\Delta t}{\sqrt{\frac{N_{\mathrm{BG}}}{\Delta t_{\mathrm{BG}}}\Delta t}}$$

Δt : Integration time for foreground (1/8, 1/4, 1/2, 1, 4, 8 s)

N_{tot}: total counts in Δt

Δt_{BG} = Integration time for background (8, 16, 32, 64 s)

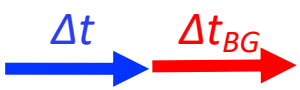
N_{BG} : BG counts in Δt_{BG}

two-side

$\Delta t_{BG} = \Delta t_{BG1} + \Delta t_{BG2}$

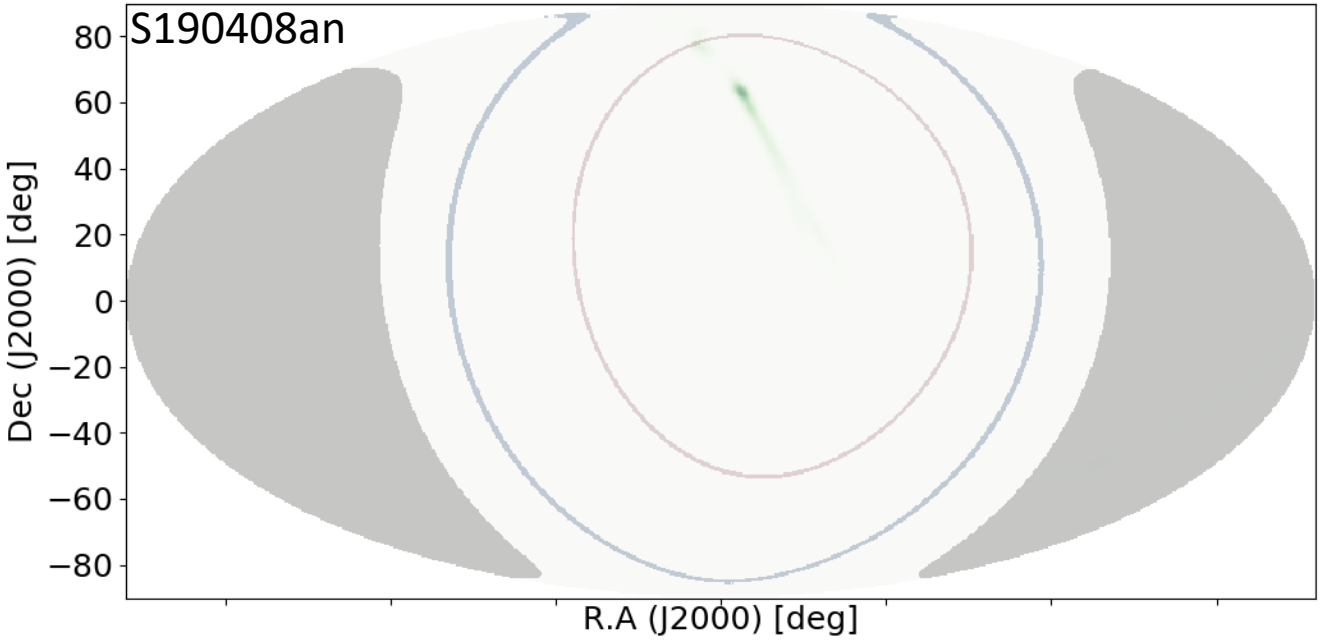
one-side (before)

one-side (after)



- We calculate signal-to-noise ratios (SNRs) using CGBM time history data (time resolution: 1/8 s).
- **We use "two-side" basically, but we use "one-side" when CGBM high voltages are turning on/off.**
- 7 (Δt) x 4 (Δt_{BG}) x 10 (E band) x 2 (gain) x 3 (detector)
  = 1680 conditions for each 1/8 s
- **We search for signals of which SNR exceeds 7.**
  - **SNR = 7 is comparable with the onboard trigger system threshold.**
  - **SNR ~ 7 is required for further analysis, at least.**
  - **Excepting single-channel events which looks charged particles**

Summed probability in the CGBM FOV

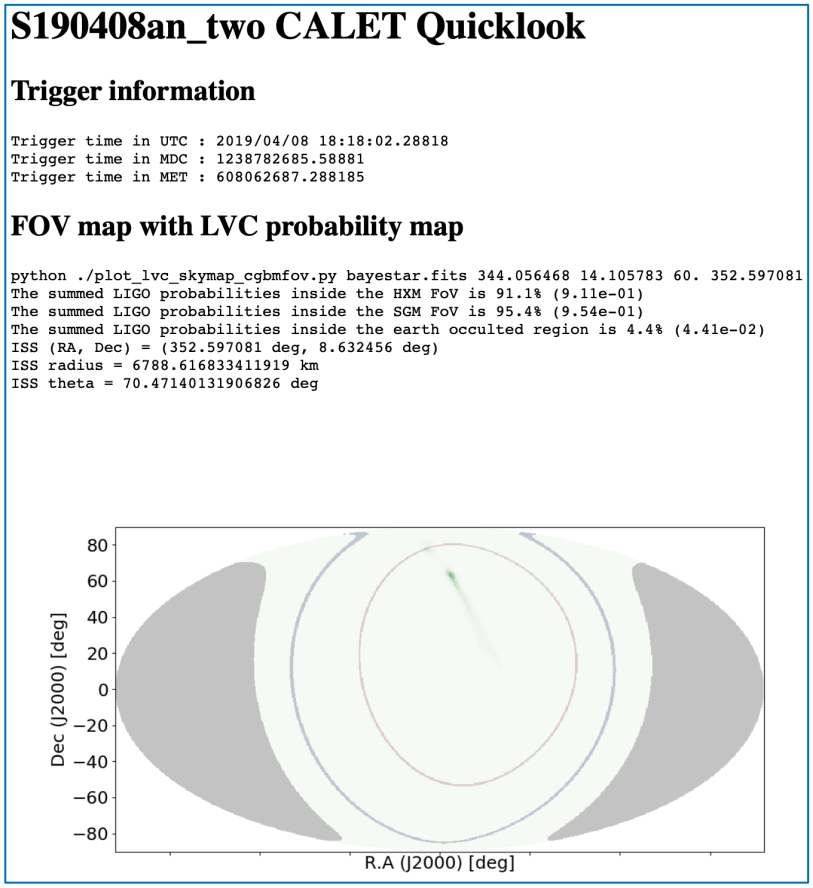


SGM FOV
HXM FOV
GW high probability region
The earth occulted region

Summed probability
SGM: 95.4 %
HXM: 91.1 %
The earth: 4.4 %

- We calculate the summed GW probability in the CGBM FOV assuming the HXM and SGM FOVs are 60 degrees and 90 degrees, respectively.
- However, some part of the CGBM FOV is blocked by the ISS structures. We need to consider the ISS structures.

CGBM analysis web page



S190408an_two CALET Quicklook

Trigger information

```
Trigger time in UTC : 2019/04/08 18:18:02.28818
Trigger time in MDC : 1238782685.58881
Trigger time in MET : 608062687.288185
```

FOV map with LVC probability map

```
python ./plot_lvc_skymap_cgbmfov.py bayestar.fits 344.056468 14.105783 60. 352.597081
The summed LIGO probabilities inside the HXM FoV is 91.1% (9.11e-01)
The summed LIGO probabilities inside the SGM FoV is 95.4% (9.54e-01)
The summed LIGO probabilities inside the earth occulted region is 4.4% (4.41e-02)
ISS (RA, Dec) = (352.597081 deg, 8.632456 deg)
ISS radius = 6788.616833411919 km
ISS theta = 70.47140131906826 deg
```


Contents

- GW (GRB) Trigger time
- Summed probability
- LIGO & Virgo skymap plot
- CGBM Light curves
  - time binning = 1/8s, 1/4s, 1/2s, 1s, 2s, 4s, 8s
- SNR vs time plots
  - For all 1680 conditions.
- SNR summary
  - Highest SNR condition in the search interval
  - Highest SNR condition at the trigger time
  - Triggered (SNR > 7) time interval

http://yoshidalab.mydns.jp/CGBM/GW_ana_dev/

The transient search system

The transient search system is running automatically (crontab) in the analsysis machines in JAXA.

Find the duration of each run mode & Checking CGBM trigger	For the gamma-ray pair search
Data conversion from L1 to L1root to L2 to DST	Multithreading process
Exposure calculation & Gamma-ray selection	with EM track & CC track
Gamma-ray pair search	Please see Mori-sensei‘s presentation
Making GAM plots & Making lists of gamma-ray pairs	For the GAM & GAM_PAIRS pages on the DQC
Making event display images for gamma-ray pair events	Using L2 Viewer
rsync plots & lists to RAID (For the DQC page)	

Red: manual
Blue: automatic

GAM_PAIRS page

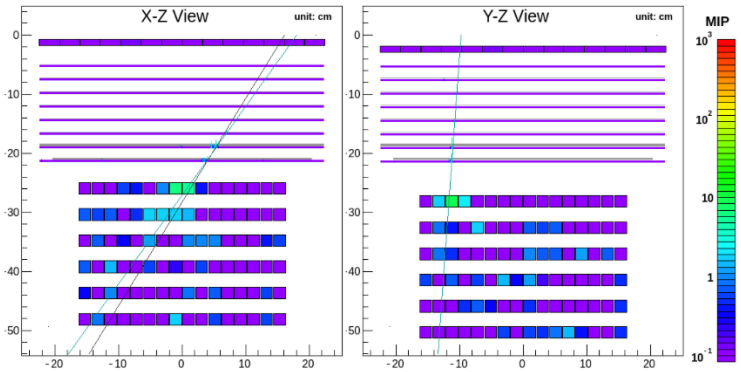
200122 GAM_PAIRS

Pair event list

try77											
EventID_1	**EventID_2**	**Probability**	**(R.A, Dec) [degree]**	**Opening angle [degree]**	**MDCTIME [s]**	**UT [s]**	**Time difference [s]**	**Energy_1 [GeV]**	**Energy_2 [GeV]**	**(dir0_1, dir1_1)**	**(dir0_2, dir1_2)**
61215	640	0.625	(138.516, 39.354)	2.050	1263694847	2020/01/22 02:24:21.110422	131.287375	1.294	1.154	(-0.553, -0.055)	(-0.642, -0.071)
631	640	0.230	(140.010, 39.066)	0.798	1263694978	2020/01/22 02:26:32.043422	0.354375	1.413	1.154	(-0.633, -0.079)	(-0.642, -0.071)
2081	2902	0.320	(143.789, 38.206)	1.323	1263695017	2020/01/22 02:27:10.864391	21.462250	1.238	0.942	(-0.627, -0.084)	(-0.649, -0.107)

No pairs were found with try17.

Event display



Event display for EventID: 61215

- GAM_PAIRS page was newly equipped on the DQC web page.
- Pair search result is shown in the table, and event display for pair events are available.

GW counterparts search in the O3.

- The LIGO & Virgo third observation run (the O3 run) started on April 1, 2019.
- 48 (+ Fermi GBM-190816) GW events have been reported in the O3.

CAL analysis (using the CAL pipeline)

- Checking overlaps between the CAL FOV and the GW localization probability region
- Seach for gamma-rays in -60 s ~ + 60 s (-1200s ~ + 1200s).
- Even if there is no gamma-ray from the overlap region, we calculated 90% upper limits.

CGBM analysis (using the CGBM pipeline)

- Checking whether CGBM high voltages were on or not
- Checking overlaps between the CGBM FOV and the GW localization probability region.
- Search for signal, of which SNR exceeds 7, in -60 s ~ + 60 s.

Results

CAL statistics
1 : HV off *
24 : Outside of the FOV
24 : No detection

CGBM statistics
17 : HV off
3 : Outside of the FOV
29 : No detection

* For safety during a special ISS activity

- **CALET has found no counterpart candidate so far.**
- **We have reported our analysis for 46 events to GCN circular.**
  - **Excepting S190412m, S190421ar, Fermi GBM-190816**
- **I summarized analysis for GW events in the CGBM wiki page**

http://www.phys.aoyama.ac.jp/~yoshida/wiki/cgbm_int/index.php?Status%2FGW

Event ID	Time (UT)	CAL upper limit [erg cm^{-2} s^{-1}]	CGBM status	GCN #
S200129m	06:54:58.435104	5.7×10^{-5} (10 - 100 GeV)	HV off	26941
S200128d	02:20:11.903320	4.6×10^{-6} (10 - 100 GeV)	No detection	26924

Event ID	Time (UT)	CAL upper limit [erg cm^{-2} s^{-1}]	CGBM status	GCN #
S200115j	04:23:09.742047	$1.7x10^{-6}$ (10 - 100 GeV)	HV off	26797
S200114f	02:08:18.239300	$4.7x10^{-6}$ (10 - 100 GeV)	HV off	26761
S200112r	15:58:38.093931	$1.1x10^{-6}$ (10 - 100 GeV)	No detection	26740
S200105ae	16:24:26.057208	$6.4x10^{-6}$ (10 - 100 GeV)	No detection	26664
S191222n	03:35:37.119478	Outside of the FOV	No detection	26602
S191216ap	21:33:38.472999	Outside of the FOV	No detection	26481
S191215w	22:30:52.333152	Outside of the FOV	No detection	26465
S191213g	04:34:08.142224	Outside of the FOV	No detection	26419
S191205ah	21:52:08.568738	Outside of the FOV	HV off	26377
S191204r	17:15:26.091822	Outside of the FO	No detection	26358
S191129u	13:40:29.197372	Outside of the FOV	No detection	26321
S191109d	01:07:17.220703	Outside of the FOV	HV off	26236
S191105e	14:35:21.933105	Outside of the FOV	HV off	26195
S190930t	14:34:07.685342	$1.7x10^{-5}$ (10 - 100 GeV)	No detection	25892
S190930s	13:35:41.246810	$3.5x10^{-5}$ (10 - 100 GeV)	No detection	25891

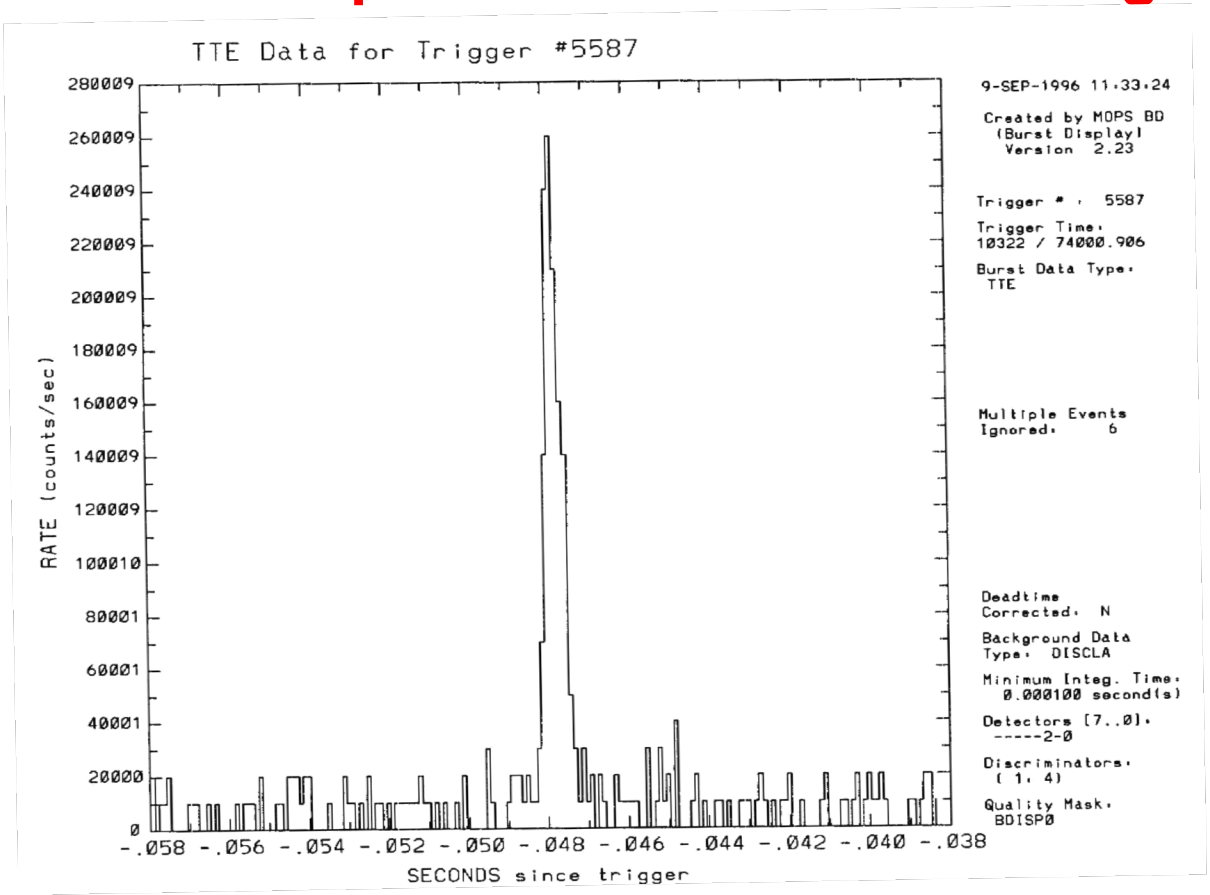
Event ID	Time (UT)	CAL upper limit [erg cm^{-2} s^{-1}]	CGBM status	GCN #
S190924h	02:18:46.846654	Outside of the FOV	HV off	25844
S190923y	12:55:59.645508	$1.2x10^{-5}$ (10 - 100 GeV)	No detection	25830
S190915ak	23:57:02.690891	Outside of the FOV	No detection	25770
S190910h	08:29:58.544448	$9.4x10^{-6}$ (1 - 10 GeV)	No detection	25735
S190910d	01:26:19.242676	Outside of the FOV	No detection	25734
S190901ap	23:31:01.837767	$6.3x10^{-5}$ (1 - 10 GeV)	No detection	25647
S190828l	06:55:09.886557	Outside of the FOV	No detection	25537
S190828j	06:34:05.756472	Outside of the FOV	No detection	25536
GBM-180816	21:22:13.027	$2.1x10^{-6}$ (10 - 100 GeV)	No detection	No
S190814bv	21:10:39.012957	Outside of the FOV	HV off	25390
S190728q	06:45:10.529205	Outside of the FOV	Outside of the FOV	25214
S190727h	06:03:33.985887	Outside of the FOV	No detection	25184
S190720a	00:08:36.704102	$3.0x10^{-5}$ (10 - 100 GeV)	HV off	25134
S190718y	14:35:12.067865	$1.7x10^{-6}$ (1 - 10 GeV)	No detection	25099
S190707q	09:33:26.181226	$2.1x10^{-6}$ (1-10 GeV)	No detection	25033
S190706ai	22:26:41.344727	Outside of the FOV	HV off	25027

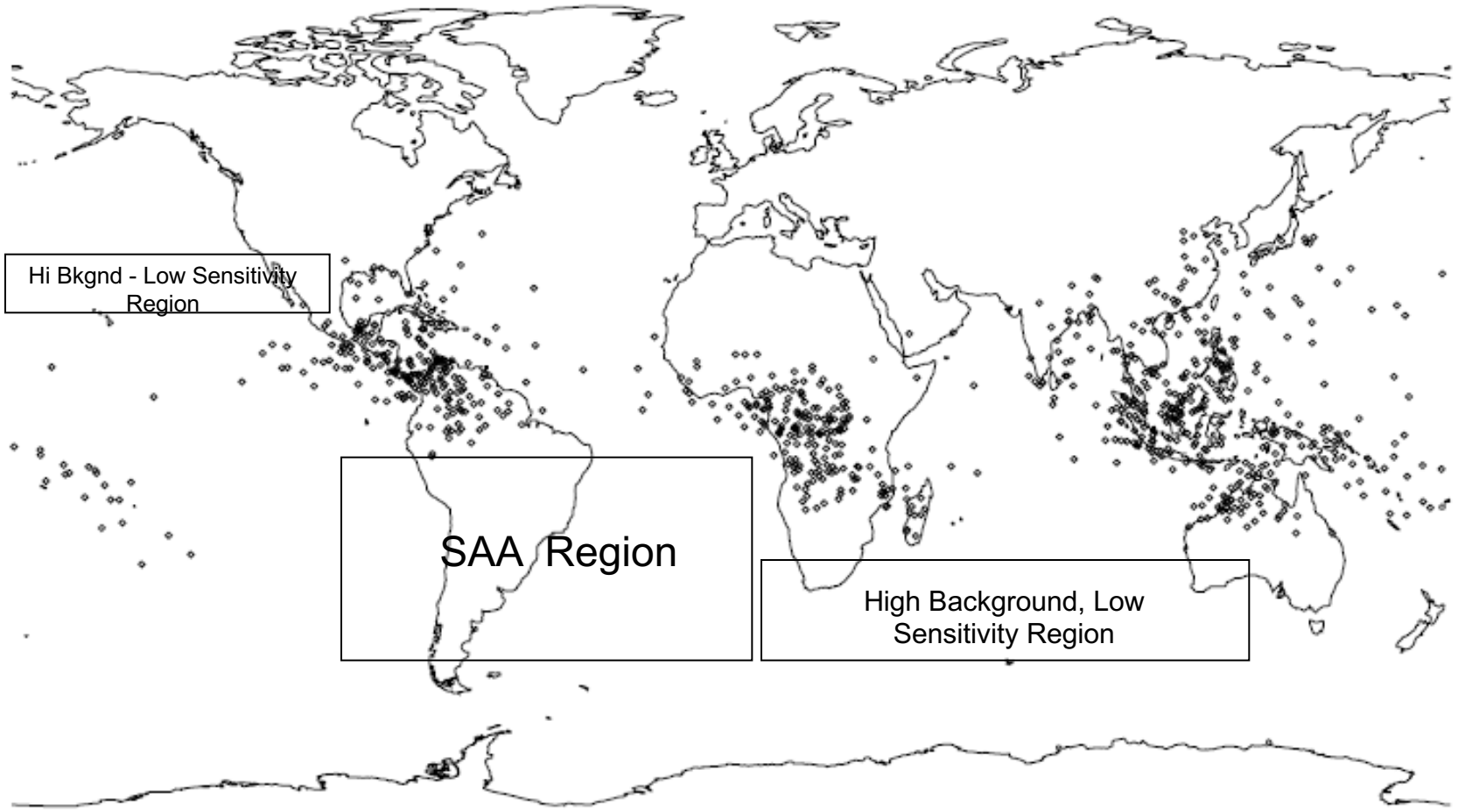
Event ID	Time (UT)	CAL upper limit [erg cm^{-2} s^{-1}]	CGBM status	GCN #
S190701ah	20:33:06.577637	Outside of the FOV	Outside of the FOV	24970
S190630ag	18:52:05.179550	$1.2x10^{-5}$ (10-100 GeV)	HV off	24960
S190602aq	17:59:27.089355	$2.9x10^{-4}$ (10-100 GeV)	No detection	24735
S190521r	07:43:59.463379	Outside of the FOV	HV off	24649
S190521g	03:02:29.447266	$6.0x10^{-6}$ (10-100 GeV)	HV off	24648
S190519bj	15:35:44.397949	Outside of the FOV	No detection	24617
S190517h	05:51:01.830582	Outside of the FOV	No detection	24593
S190513bm	20:54:28.747089	$6.0x10^{-5}$ (1-10 GeV)	No detection	24548
S190512at	18:07:14.422363	$1.9x10^{-5}$(10-100 GeV)	No detection	24531
S190510g	02:59:39.291636	Outside of the FOV	No detection	24495
S190503bf	18:54:04.294490	$4.2x10^{-5}$ (10-100 GeV)	HV off	24403
S190426c	15:21:55.336540	$2.5x10^{-5}$ (10-100 GeV)	HV off	24276
S190425z	08:18:05.017147	$1.0x10^{-4}$ (10-100 GeV)	HV off	24218
S190421ar	21:38:56.250977	Outside the FOV	Outside the FOV	No
S190412m	05:30:44.165622	HV off	HV off	No
S190408an	18:18:02.288180	2.3×10^{-6} (1-10 GeV)	No detection	24088

Terrestrial Gamma-ray Flashes

TGFs (Terrestrial Gamma-ray Flashes) first detected by Burst and Transient Source Experiment (BATSE) on Compton Observatory (CGRO) 1991-2000

➔ **The electric fields in ordinary lightning here on Earth accelerate particles to >30 MeV energies**

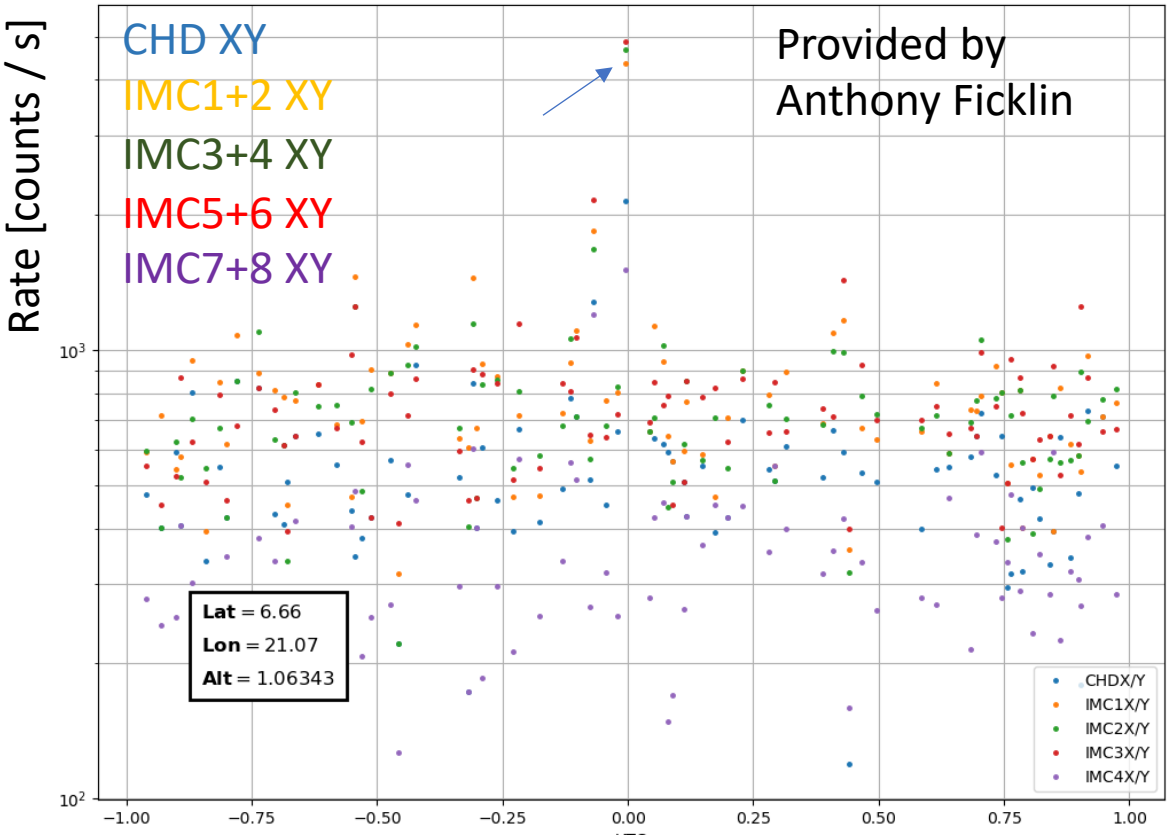


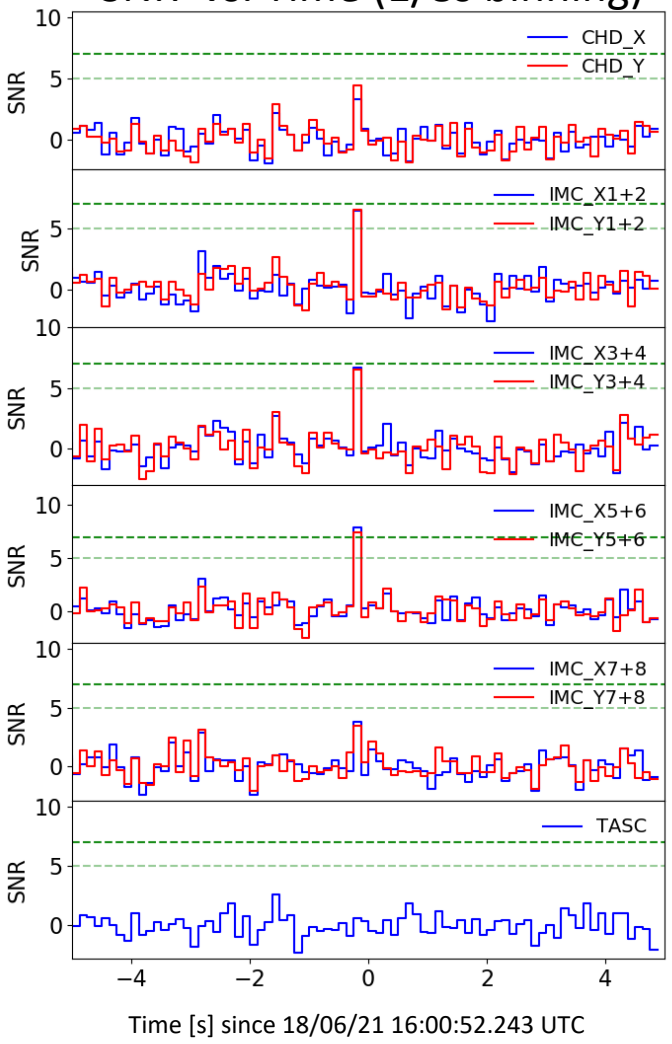


Map of RHESSI TGFs (820)

CHD & IMC signal due to TGF

A TGF detected by ASIM and Fermi-GBM at 2018-06-21 16:00:52 (Østgaard et al. 2019).
Information was provided by Prof. Mike Cherry and Samer Al Nussirat, who is Mike's postdoc.





CHD & IMC detected a signal due to the TGF!

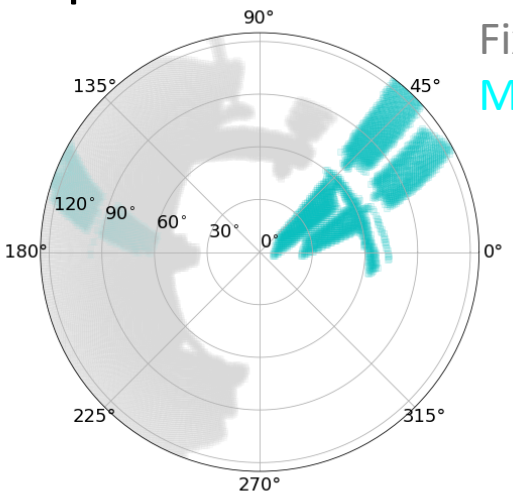
(There is no signal in CGBM data although.)

Future works

- Analysis systems
  - The CGBM pipeline
    - Improvement with summed probability calculation
    - Improvement with BG estimation method
    - The upper limit calculation for any direction
  - The transient search system
    - Gamma-ray candidate list after the CGBM trigger (DQC)
    - Reprocess for past data.
- GRB analysis
  - Systematic gamma-ray search for GRBs (including afterglow)
    - Fermi-LAT -> other HE ground telescope -> Swift & Fermi-GBM -> others

Future updates with the CGBM pipeline

- Improvement with the summed probability calculation



Fixed
Moving

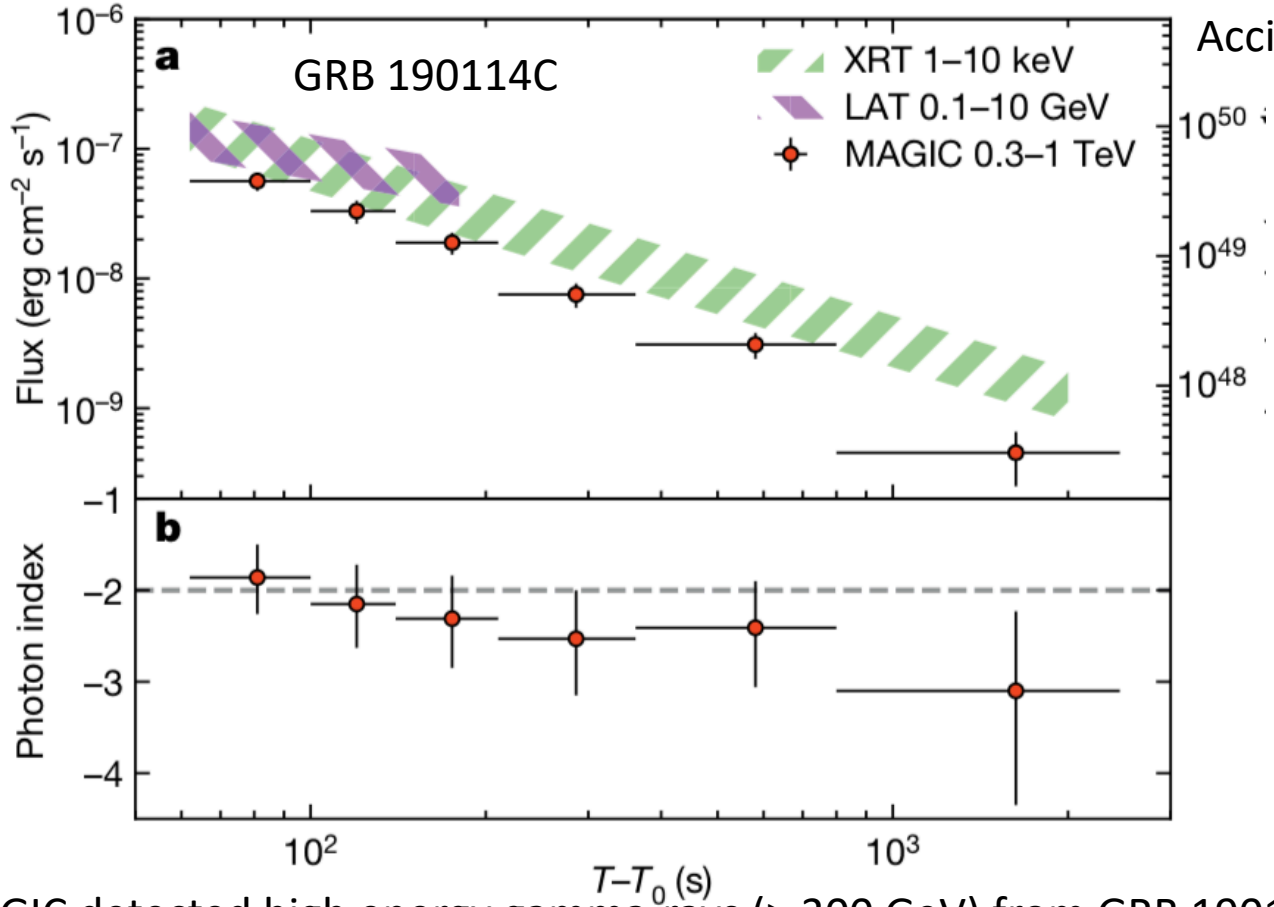
Currently, the summed probability in CGBM FOV is calculated, assuming no obstruction by the ISS structures.

We will improve the calculation to take into account the actual CGBM FOV.

- Improvement with BG estimation method
  - Currently, BG is estimated by the summation of counts before & after the region of interest.
  - We plan to develop a database of background counts for any position (latitude & longitude).

- The upper limit calculation for any direction
  - Since GW high probability region is spread, the upper limit for one direction is not enough.
  - We plan to develop tools to calculate the upper limit for any direction, which is like CAL analysis.

High energy afterglow



Acciari et al. 2019

- MAGIC detected high energy gamma-rays (> 300 GeV) from GRB 190114C.
- Although gamma-ray flux decrease with time, high energy emission continues after the prompt emission (GRB 940217, ~1.5h).

We need to care about high energy afterglow emission.
We should make sure our (instrumental & diffuse) background estimation is reasonable because exposure is large.

Summary

- We updated the GW & GRB pipelines and transient search system.

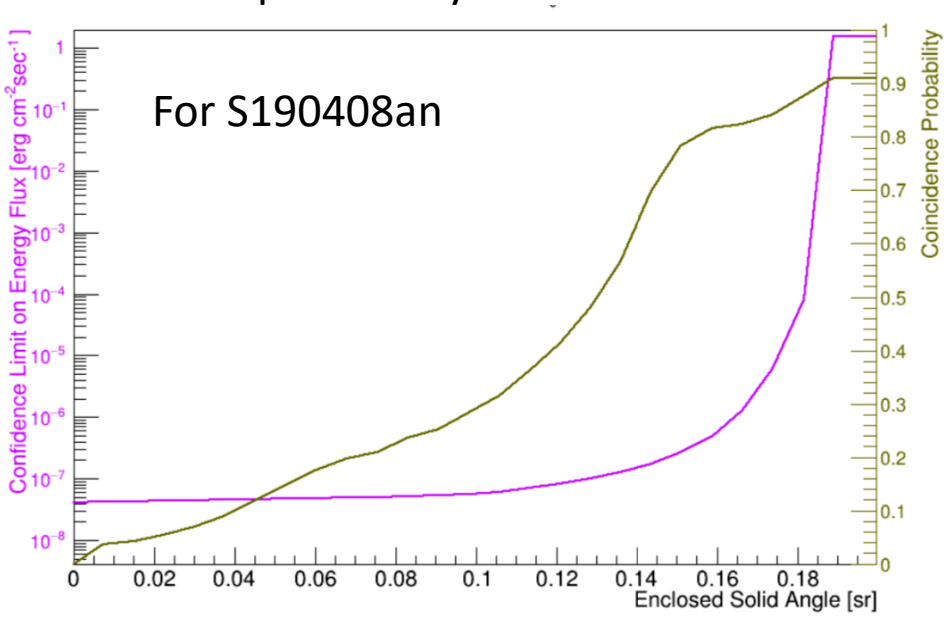
- We searched for electromagnetic counterparts of 49 gravitational wave events in the O3.
  - CAL and CGBM found no counterpart candidates.
- CHD and IMC detected signal due to the TGF.
- We will continue to update our pipelines and perform the systematic analysis for GRBs using the pipelines.

Backup

Upper limits vs. enclosed solid angle

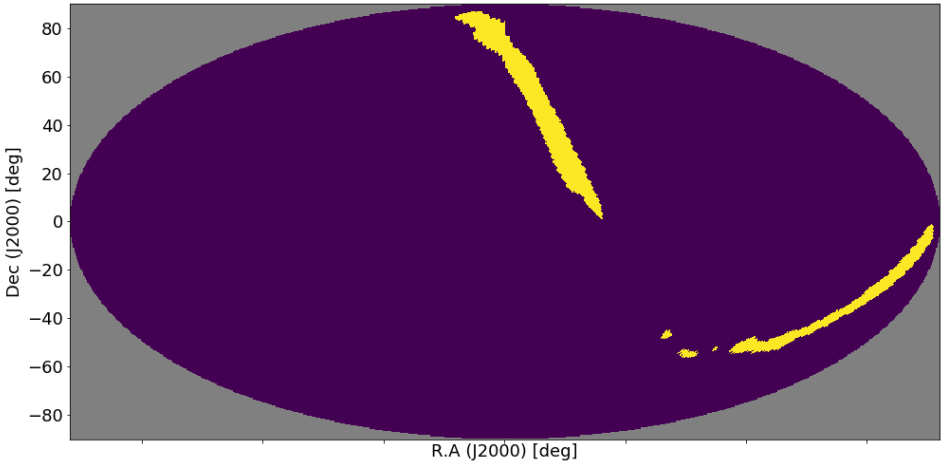
- If we increase enclosed solid angles in which we estimate the upper limit, background counts that come from the enclosed solid angles should increase.
- We need to sort pixels of HEALPix when we calculate the summed probability in the enclosed solid angles to reduce expected background counts.

Highest upper limit vs. Enclosed solid angle & summed probability

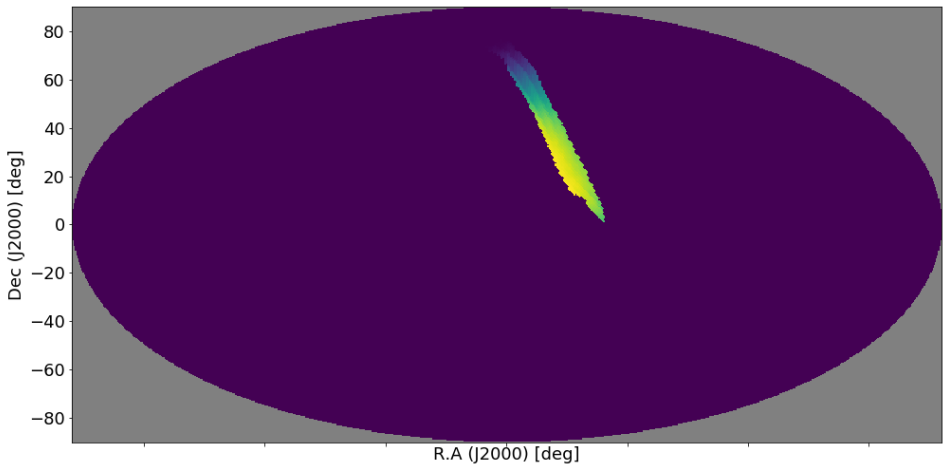


1. Sorting Healpix to descending order with probability in the pixel.
2. Calculating the cumulating probability with the descending order.
3. We set the threshold of probability, which corresponds to the 99% point of the cumulating probability.
4. For pixels of which probability above the threshold, we sort the HEALPix to descending order with exposure in the pixel
5. We add pixels to the enclosed solid angles according to the descending order, and we calculate the summed probability and the highest upper limits in the region.

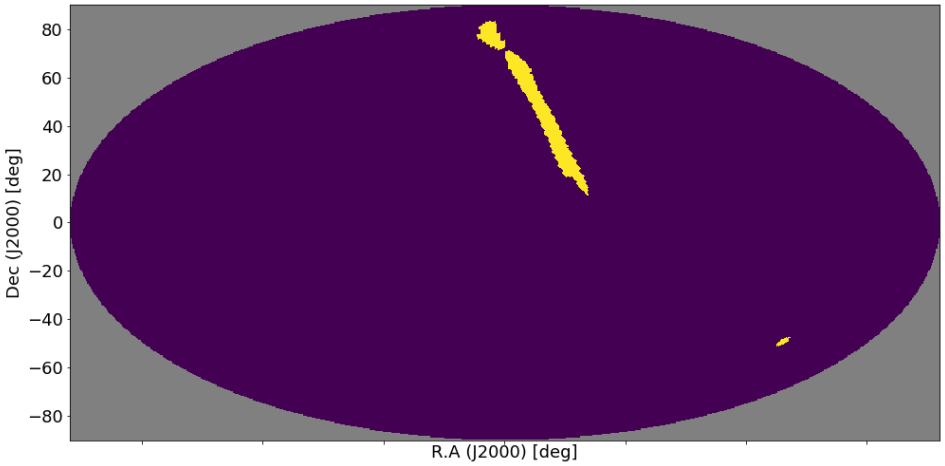
the cumulating probability <= 99%



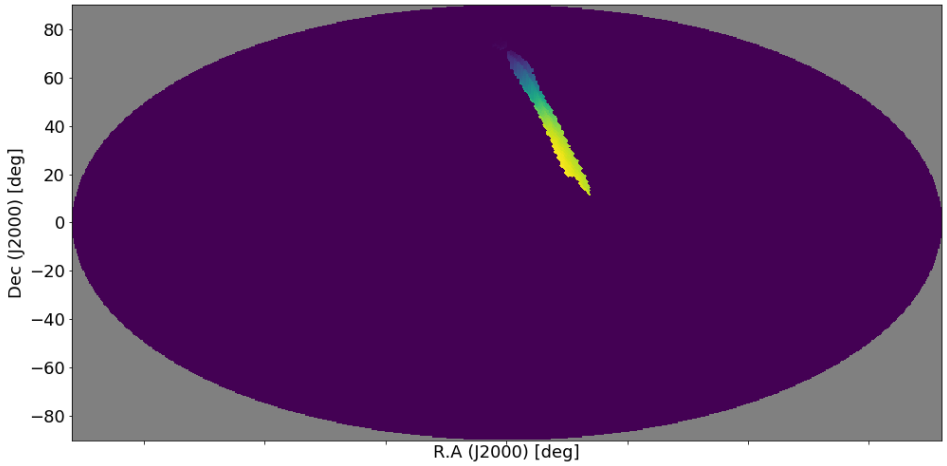
Masked exposure (> 99%)



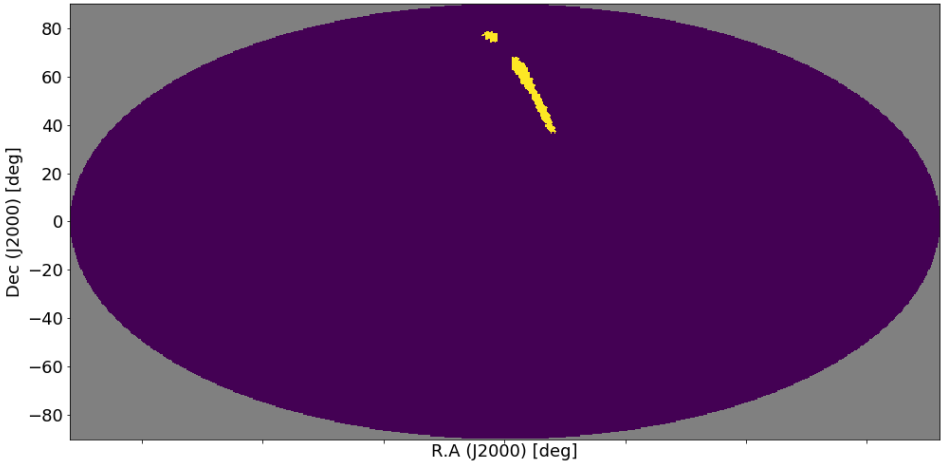
the cumulating probability <= 90%



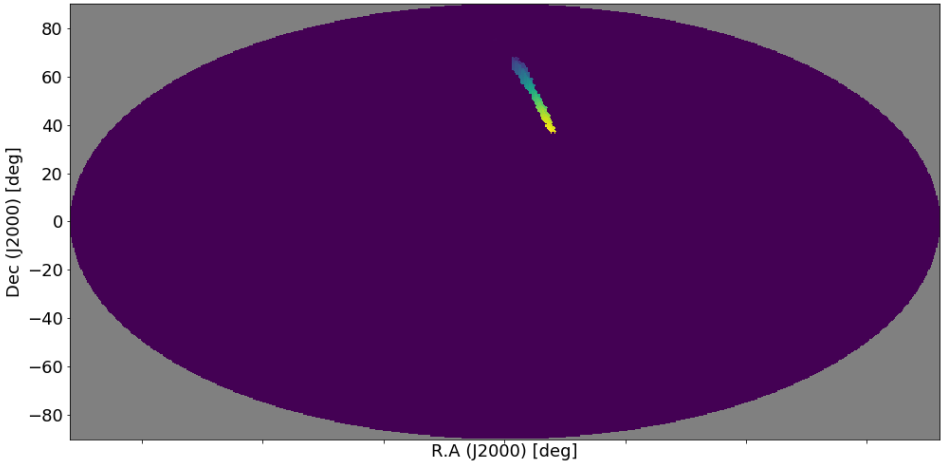
Masked exposure (> 90%)



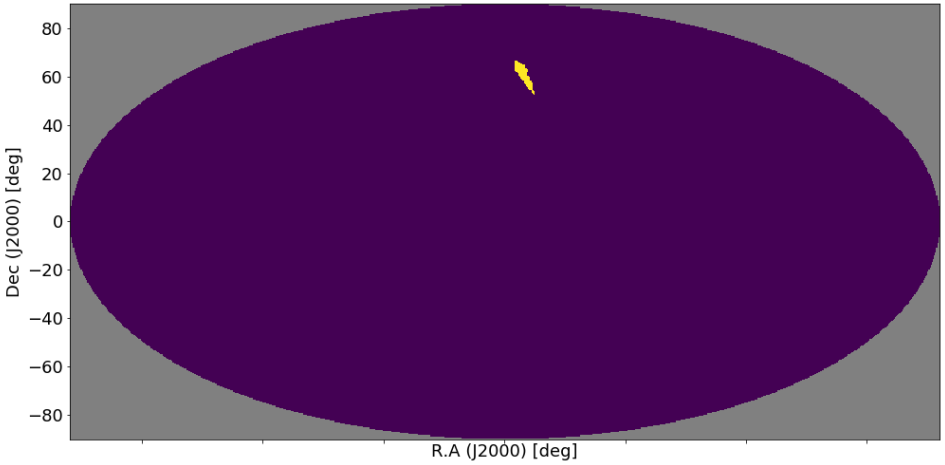
the cumulating probability <= 60%



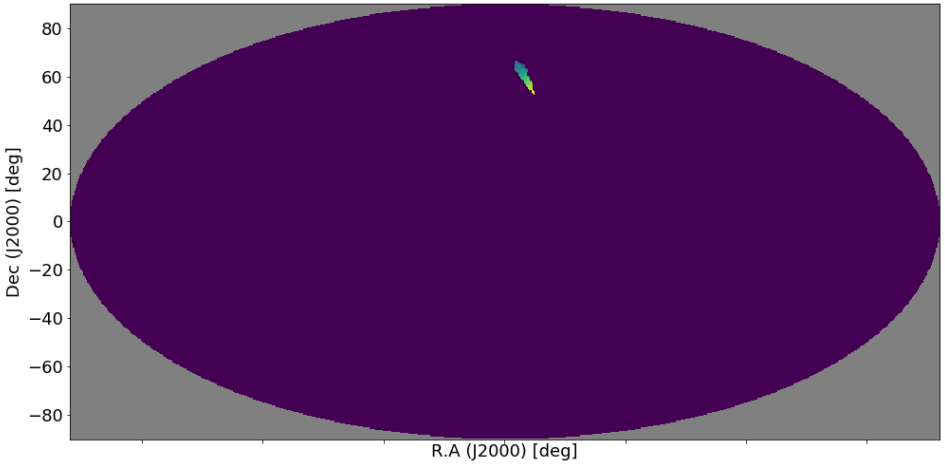
Masked exposure (> 60%)



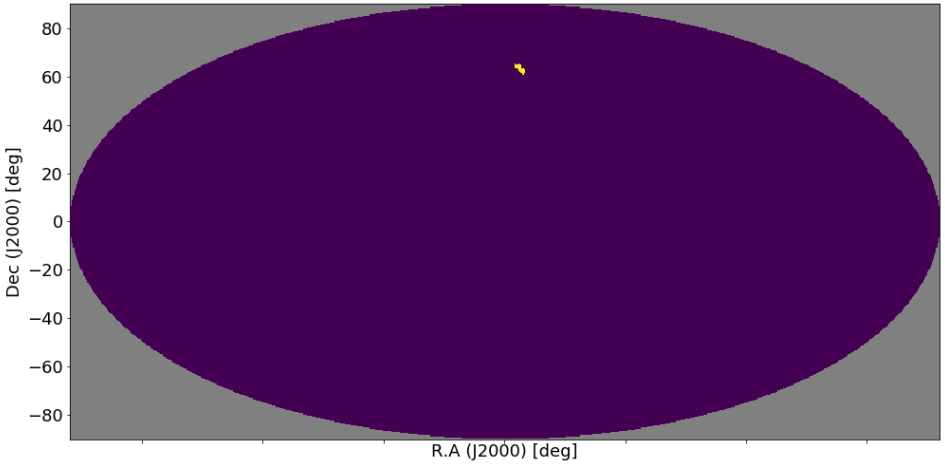
the cumulating probability <= 30%



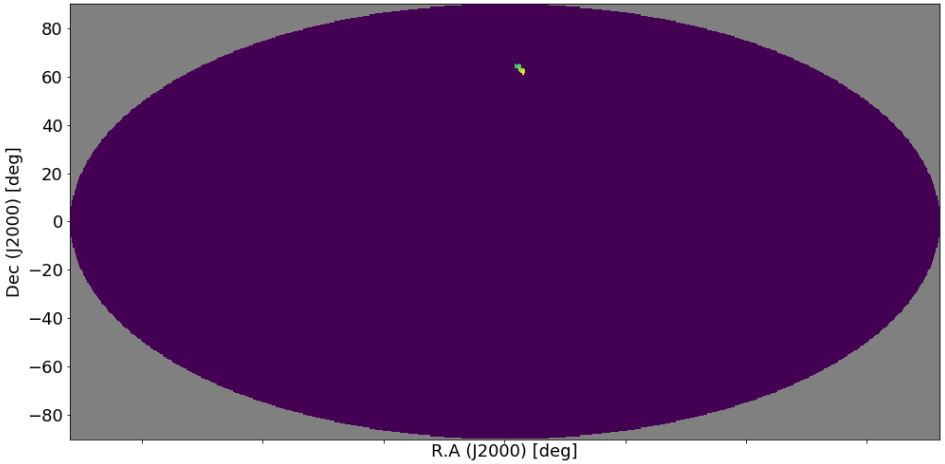
Masked exposure (> 30%)



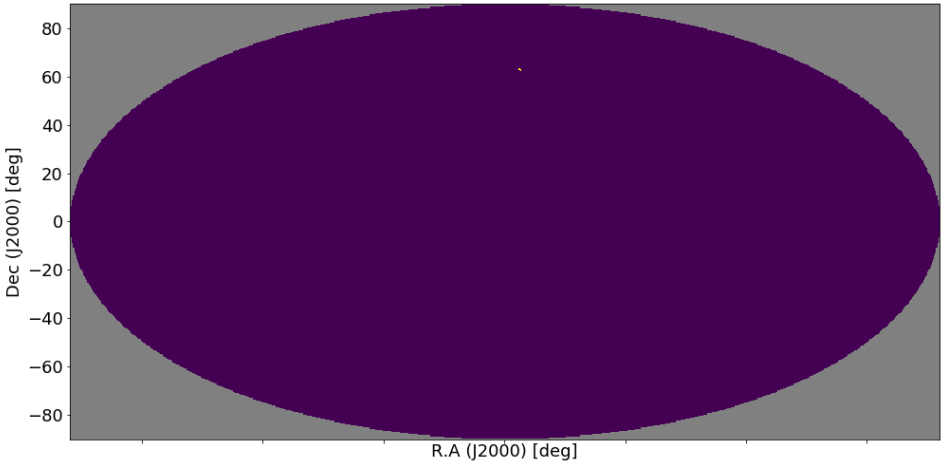
the cumulating probability <= 10%



Masked exposure (> 10%)



the cumulating probability <= 1%



Masked exposure (> 1%)