Gamma ray analysis and GW follow-up observations

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for the CALET collaboration

CALET TIM at CNR-IFAC, Florence, February 04-06-27, 2020
Gamma Ray Event Selection

= Electron Selection Cut + Gamma-ray ID Cut w/ Lower Energy Extension

100 GeV Event Examples

gamma-ray  electron  proton

Charge Z=0  Charge Z=1

Electromagnetic Shower
well contained, constant shower development

Hadron Shower
larger spread
Gamma-ray skymap

LE-γ mode, from 2015 November to 2018 May
(Contours show relative exposures)
Gamma-ray spectra

"On-plane": $|l| < 80^\circ$ & $|b| < 8^\circ$, "Off-plane": $|b| > 8^\circ$

Mori, Asaoka et al., ICRC2019+

On plane:
- This work

Off plane:
- This work

Averaged Fermi data

Preliminary
**CTA 102 (AGN) light curve**

Red: CALET signal, Hatched: CALET upper limit ($<10^{-7}\text{cm}^{-2}\text{s}^{-1}$)

Blue: Fermi-LAT

**LE trig (> 1 GeV)**

By Zenita
CTA 102 (AGN) light curve

[Flare period]

Red: CALET signal, Hatched: CALET upper limit (<10^{-7} cm^{-2}s^{-1})
Blue: Fermi-LAT

Modified Julian Day

LE trig (> 1 GeV)

By Zenita
Toward higher energies
- Gamma-ray line? -

No result yet...
Gamma-ray lines from DM annihilation

Neutralino

Kaluza-Klein

Bringmann and Calor 2013

Tsuchida and Mori 2017

$M = 800\text{GeV}$

(loop suppressed – low branching ratio)
Limits by indirect searches


\[ \chi \chi \rightarrow \nu_\alpha \bar{\nu}_\alpha \]
\[ \alpha = e, \mu, \tau \]
130 GeV line at the Galactic center?

Fig. 18.— Spectrum of emission within $4^\circ$ of the cusp center $(\ell, b) = (-1.5, 0)$, excluding $|b| < 0.5^\circ$. High-incidence angle events (upper panel) have a factor of $\sim 2$ better energy resolution than those that enter the LAT close to normal incidence (middle panel) or the whole sample (lower panel). All three spectra have been smoothed by a Gaussian of 0.06 FWHM in $\Delta E/E$, similar to the expected resolution of the upper panel. The continuum model is $dN/dE \sim E^{-2.6}$, normalized at $20 < E < 50$ GeV (blue dashed).
130 GeV line at the Galactic center?

FIG. 3: Spectral fits to the GC, inner Galactic plane, and Earth limb samples. The green line shows the null model (a power-law), whereas the red line shows the alternative power-law + line fit; the dotted blue lines are the two components of the alternative model. The red (black) dotted lines indicate 129 GeV (13.6% FWHM around 129 GeV). Note that the significance found in the GC region does not represent the full significance of the putative signal.

$TS=18.8 \leftrightarrow 4\sigma$
FIG. 8 (color online). 95% C.L. \(\langle \sigma v \rangle_{\tau} \) upper limits for each DM profile considered in the corresponding optimized ROI. The upper left panel is for the NFWc \(\gamma = 1.3\) DM profile in the R3 ROI. The discontinuity in the expected and observed limit in this ROI around 1 GeV is the result of using only PSF3-type events. See Sec. III for more information. The upper right panel is for the Einasto profile in the R16 ROI. The lower left panel is the NFW DM profile in the R41 ROI, and finally the lower right panel is the isothermal DM profile in the R90 ROI. Yellow (green) bands show the 68% (95%) expected containments derived from 1000 no-DM MC simulations (see Sec. V B). The black dashed lines show the median expected limits from those simulations. Also shown are the limits obtained in our 3.7-year line search [19] and our 5.2-year line search [22] when the assumed DM profiles were the same.
CALET gamma-ray spectrum
Effective area

CALET LE $\gamma$
(Cannady+, 2018)

Fermi LAT
https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
Energy resolution

CALET electron (Asaoka+ 2017)

Fermi LAT

https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

$\Delta E/E (\text{68\% containment})$ %

$E$ [GeV]

$\Delta E/E (\text{68\% containment})$ %

$E$ [$10^6$ MeV]

$2.5\% @ 100$ GeV

$7.5\% @ 100$ GeV
Angular resolution

$C_{68} \text{[deg]}$

CALET LE $\gamma$
(Cannady+, 2018)

$\rightarrow 0.6^\circ @ 100 \text{ GeV}$

$\rightarrow 0.13^\circ @ 100 \text{ GeV}$

Fermi LAT

https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

$\rightarrow 0.1^\circ @ 100 \text{ GeV}$
Point spread function: CALET vs LAT
Effective area at high energies

Gamma ray, LE trig

Electron, HE trig

100 GeV

Cannady+, 2018

Decreasing...

→ How to recover?

Adriani+, 2019
Efficiency in each step

By Zenita
GW counterpart search
LIGO-VIRGO observation 3

LIGO-VIRGO Joint Run Planning Committee

**Working schedule for O3**
(Public document G1801056-v4, based on G1800889-v7)

<table>
<thead>
<tr>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep</td>
<td>Oct</td>
</tr>
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</table>

- **LIGO**
  - **H1**: Commissioning
  - **L1**: Commissioning
- **VIRGO**: Commissioning

**GEO**: ~70% observing mode

- **Detector operational, commissioning mode** (small fraction of observing mode time)
- **Detector in observing mode for a fraction of the time during Engineering Runs (ERs)**, possible GW alerts with human vetting
- **Detector not producing data** (downtime)
- **24/7 observing mode** (Observing Run, Open Public Alerts in low-latency)
Energy flux limit map for S190408an

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.
CAL limits on electromagnetic emission from gravitational wave events

(LIGO/Virgo O3)

Table 1: Summary of CALET/CAL gamma-ray observations on gravitational event candidates in the LIGO/Virgo third observing run reported in GCN circulars [1]. Upper limits (U.L.) are given in unit of erg cm$^{-2}$s$^{-1}$ for the energy range 10–100 GeV except for those marked with † which are for 1–10 GeV, which corresponds to the HE and the LE-γ 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 $T_0$.

<table>
<thead>
<tr>
<th>GCN No.</th>
<th>LIGO/Virgo trigger</th>
<th>Trigger time $T_0$ (2019)</th>
<th>Events $T_0 \pm 60$ s</th>
<th>90% C.L. U.L.</th>
<th>Summed probability</th>
<th>CAL $\alpha$ (°)</th>
<th>CAL $\delta$ (°)</th>
<th>Comments</th>
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<td>24088</td>
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<td>04-08 18:18:02.288 UTC</td>
<td>0</td>
<td>$2.3 \times 10^{-6}$†</td>
<td>80%</td>
<td>352.9</td>
<td>8.3</td>
<td>BBH (99%)</td>
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<td>04-25 08:18:05.017 UTC</td>
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<td>-43.6</td>
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<td>-50.9</td>
<td>BNS (49%)</td>
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<td>05-03 18:54:04.294 UTC</td>
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<td>169</td>
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<td>BBH (96%)</td>
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<td>No</td>
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<td>50.8</td>
<td>Terrestrial (58%)</td>
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<td>$1.9 \times 10^{-5}$</td>
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<td>37.7</td>
<td>BBH (99%)</td>
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<td>BBH (98%)</td>
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<td>05-19 15:35:44.398 UT</td>
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<td>243.1</td>
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<td>S190521g</td>
<td>05-21 03:02:29.447 UT</td>
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<td>06-02 17:59:27.089 UT</td>
<td>0</td>
<td>$2.9 \times 10^{-4}$</td>
<td>5%</td>
<td>127.5</td>
<td>45.1</td>
<td>BBH (99%)</td>
</tr>
</tbody>
</table>

†: LE-γ
GraceDB glossary

• **BBH** - Binary black hole
• **BNS** - Binary neutron star
• **NSBH** - Neutron star black hole, a binary system composed of one neutron star and one black hole
• **Terrestrial** - Classification for signals in gravitational-wave detectors that are of instrumental or environmental origin. Terrestrial signals are not astrophysical and not due to gravitational waves. Some examples of sources of terrestrial signals are statistical noise fluctuations, detector glitches, and ground motion.

• **MassGap** - Compact binary systems with at least one compact object whose mass is in the hypothetical “mass gap” between neutron stars and black holes, defined here as 3-5 solar masses

### Table 1: Summary of CALET/CAL gamma-ray observations on gravitational event candidates in the LIGO/Virgo third observing run reported in GCN circulars [1]. Upper limits (U.L.) are given in unit of erg cm$^{-2}$s$^{-1}$ for the energy range 10–100 GeV except for those marked with † which are for 1–10 GeV, which corresponds to the HE and the LE-γ 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 $T_0$.

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<th>GCN No.</th>
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<th>Trigger time $T_0$ (2019)</th>
<th>Events $T_0 \pm 60$ s</th>
<th>90% C.L. U.L.</th>
<th>Summed probability</th>
<th>CAL $\alpha$ (°)</th>
<th>CAL $\delta$ (°)</th>
<th>Comments</th>
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<td>0</td>
<td>$1.2 \times 10^{-5}$</td>
<td>25%</td>
<td>84.0</td>
<td>31.5</td>
<td>BBH (94%)</td>
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<td>24970</td>
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<td>07-01 20:33:06.578 UT</td>
<td>0</td>
<td>$-\dagger$</td>
<td>No</td>
<td>286.8</td>
<td>-1.6</td>
<td>BBH (93%)</td>
</tr>
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<td>25027</td>
<td>S190706ai</td>
<td>07-06 22:26:41.345 UT</td>
<td>0</td>
<td>$-$</td>
<td>No</td>
<td>210.4</td>
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<td>BBH (99%)</td>
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<tr>
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<td>07-07 09:33:26.181 UT</td>
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<td>$2.1 \times 10^{-6}$</td>
<td>20%</td>
<td>262.4</td>
<td>2.2</td>
<td>BBH (&gt;99%)</td>
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<td>5%</td>
<td>195.8</td>
<td>-11.1</td>
<td>Terrestrial (98%)</td>
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<td>25%</td>
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<td>BBH (99%)</td>
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<td>No</td>
<td>201.1</td>
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<td>49.5</td>
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<td>$-$</td>
<td>No</td>
<td>13.9</td>
<td>12.6</td>
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<td>S190828l</td>
<td>08-28 06:55:09.887 UT</td>
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<td>No</td>
<td>106.9</td>
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<td>5%</td>
<td>353.8</td>
<td>16.6</td>
<td>BNS (86%)</td>
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</tbody>
</table>

†: LE-γ
CAL limits on electromagnetic emission from gravitational wave events (LIGO/Virgo O3)

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<th>CAL $\delta$ (°)</th>
<th>Comments</th>
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<td>09-10 01:26:19 UT</td>
<td>0</td>
<td>$-\dagger$</td>
<td>No</td>
<td>100.8</td>
<td>22.9</td>
<td>NSBH (98%)</td>
</tr>
<tr>
<td>25735</td>
<td>S190910h</td>
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<td>84.4</td>
<td>45.9</td>
<td>MassGap (&gt;99%)</td>
</tr>
</tbody>
</table>

†: LE-γ
LIGO-VIRGO O3: Monthly variation

Searching transient events

- Gamma ray bursts, AGN flares, EM counterparts of GW, ...
- 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.

Judging ‘pairs’ using PSF

See also poster PS3-243 (Cannady et al.) for GRB search by CALET/CAL
Transient gamma-ray monitor system

- Running since 2018/08/20 at WCOC
- Parallel processing (60 threads) – 40 min for 1hr data

Divide into threads

Classification of threads:
- **HE**
  - Same direction?
- **LE**
  - Same direction?
- **CGBM $T_0 \pm 60s$**
  - Same direction?
WCOC DQC “GAM_PAIRS”

Pair event list

<table>
<thead>
<tr>
<th>EventID_1</th>
<th>EventID_2</th>
<th>Probability</th>
<th>(RA, Dec) [degree]</th>
<th>Opening angle [degree]</th>
<th>MDCTIME</th>
<th>UT [s]</th>
<th>Time difference [s]</th>
<th>Energy_1 [GeV]</th>
<th>Energy_2 [GeV]</th>
<th>(dir0_1, dir1_1)</th>
<th>(dir0_2, dir1_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31522</td>
<td>43347</td>
<td>0.136</td>
<td>(128.800, -45.093)</td>
<td>0.444</td>
<td>1261636038</td>
<td>2019/12/29 23:30:06:70.45266</td>
<td>289.191015</td>
<td>1.298</td>
<td>4.277</td>
<td>(-0.251, 0.561)</td>
<td>(-0.497, 0.543)</td>
</tr>
</tbody>
</table>

No pairs were found with try17.

Event display

Event display for EventID: 31522

Event display for EventID: 43347
Summary

• Gamma ray analysis is on-going.
• We have to recover efficiencies toward higher energies to have enough statistics. Some new idea is necessary.
• Dark matter line signal search could be sensitive thanks to our good energy resolution.
• GW counterpart search results are regularly reported in GCN circulars, but we have only upper limits up to now.
• Automated search for gamma-ray pairs are working at WCOC.
Backups
Gamma-ray spectra

“On-plane”: \(|l| < 80^\circ \) & \(|b| < 8^\circ\)

LE-\(\gamma\) mode from 2015 November to 2018 May

Mori, Asaoka et al., ICRC2019
Monitoring count rates of AGNs

- Search for flares of known AGNs
- Use events within 68% containment angles from AGNs listed in 3FGL (Fermi-LAT 4-year catalog)
- Calculate count rates based on 28-day exposures assuming $E^{-2}$ spectra

Exposures for CTA102 (2015/11-2018/09)

Count rates for CTA102 (2015/11-2018/09)
Monitoring count rates of AGNs

- Search for flares of known AGNs
- Use events within 68% containment angles from AGNs listed in 3FGL (Fermi-LAT 4-year catalog)
- Calculate count rates based on 28-day exposures assuming $E^{-2}$ spectra

Fermi-LAT count rates for CTA102

Count rates for CTA102 (2015/11-2018/09)
Summary for part B

• Selection algorithm for transient gamma-ray events has been developed with FOV cut and direction consistency. It could identify point sources.

• 503 CGBM triggers are analyzed \((T_0 \pm 60\text{s})\) but no pairs were found.

• Monitoring method for count rates of AGNs has been developed. It could identify CTA102 flare (2017/01).

• Transient gamma-ray monitor system is running since 2018/08. It can detect transient events within 2hr from CGBM triggers by parallel processing.
Analysis of TXS 0506+056/IceCube-170922A

- 2015/10/13-2018/05/31, LE\(\gamma\) run, FOV cut (fixed structure & robot arm)

**Light curve**
(1day/bin, 2months/tic)

**Countmap**
(within 2\(\degree\))

+ : TXS 0506+056
Analysis of TXS 0506+056/IceCube-170922A

EM track

Integrated Exposure

CC track

Integrated Exposure

Integrated Flux

Integrated Flux (1.0-10.0 GeV) [cm^-2 s^-1]
Analysis of TXS 0506+056/IceCube-170922A

Cf. Fermi-LAT: $3.6 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$ (0.1-300 GeV, Sep.15-27 2017; Atel #10791)

$\to$ dN/dE = $3.6 \times 10^{-8}$ (E/GeV)$^{-2}$ cm$^{-2}$ s$^{-1}$ GeV$^{-1}$
Effective Area and Sensitivity

Effective area is estimated as a function of incident angle (dx/dz, dy/dz) and energy. Maximum effective area is achieved at around 5 GeV, but lower energy is more important for steep spectrum like $E^{-2}$.

3-10 GeV average

Mostly axially symmetric except for FOV cut

Effective area as a function of energy. Four representing zenith angle ranges are shown.

LE-γ trigger: > 1 GeV
HE trigger: > 10 GeV

CC Track

→ Talk by Fujita (25pK202-10)
CALET Collaboration


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2) CRESST/NASA/GSFC and Universities Space Research Association, USA
3) CRESST/NASA/GSFC and University of Maryland, USA
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5) Ibaraki National College of Technology, Japan
6) Ibaraki University, Japan
7) ICRR, University of Tokyo, Japan
8) ISAS/JAXA Japan
9) JAXA, Japan
10) Kanagawa University, Japan
11) Kavli IPMU, University of Tokyo, Japan
12) Louisiana State University, USA
13) Nagoya University, Japan
14) NASA/GSFC, USA
15) National Inst. of Radiological Sciences, Japan
16) National Institute of Polar Research, Japan
17) Nihon University, Japan
18) Osaka City University, Japan
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25) University of Florence, IFAC (CNR) and INFN, Italy
26) University of Padova and INFN, Italy
27) University of Pisa and INFN, Italy
28) University of Rome Tor Vergata and INFN, Italy
29) University of Siena and INFN, Italy
30) University of Tokyo, Japan
31) Waseda University, Japan
32) Washington University-St. Louis, USA
33) Yokohama National University, Japan
34) Yukawa Institute for Theoretical Physics, Kyoto University, Japan
CALET-CAL Detector

Fully active thick calorimeter (30X₀) optimized for electron spectrum measurements well into TeV region

1TeV electron shower is fully contained in TASC

Charge Detector (CHD): plastic scintillator hodoscope, absolute charge measurement (including charge zero)

Imaging Calorimeter (IMC): SciFi + tungsten plate (3X0), reconstruction of arrival direction and initial shower development

Total Absorption Calorimeter (TASC): PWO hodoscope (27X0), energy measurements and particle identification
Gamma Ray Event Selection

= Electron Selection Cut + Gamma-ray ID Cut w/ Lower Energy Extension

1. Geometry Condition
   - CHD-Top to TASC
     1st layer (2cm margin)

2. Pre selection
   - Offline trigger
   - Shower concentration
   - Shower starting point

3. Track quality cut
   - Track hits >2
   - matching w/ TASC

4. Electromagnetic shower selection
   - shower shape

5. Gamma-ray ID
   - CHD/IMC-veto
     (combination of loose cuts)

6. FOV cut

An example of gamma-ray event candidate in flight data (reconstructed primary energy ~5GeV)
Gamma Ray Event Selection

= Electron Selection Cut + Gamma-ray ID Cut w/ Lower Energy Extension

1. Geometry Condition
   - CHD-Top to TASC
     1st layer (2cm margin)

2. Pre selection
   - Offline trigger
   - Shower concentration
   - Shower starting point

3. Track quality cut
   - Track hits >2
   - matching w/ TASC

4. Electromagnetic shower selection
   - shower shape

5. Gamma-ray ID
   - CHD/IMC-veto
     (combination of loose cuts)

6. FOV cut

To maximize the field of view (FOV), the requirements on acceptance condition was loosened as much as possible compared to electron analysis. However, penetration of CHD paddle by shower axis is required to ensure charge zero selection.
Gamma Ray Event Selection

= Electron Selection Cut + Gamma-ray ID Cut w/ Lower Energy Extension

1. Geometry Condition
   - CHD-Top to TASC
     1st layer (2cm margin)

2. Pre selection
   - Offline trigger
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   - Track hits >2
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4. Electromagnetic shower selection
   - shower shape

5. Gamma-ray ID
   - CHD/IMC-veto
     (combination of loose cuts)

6. FOV cut

“K-cut”

\[ K = \log_{10}(F_E) + \frac{1}{2} R_E \]

\( F_E \): fractional energy deposit of TASC-Y6 relative to total TASC deposit
\( R_E \): Second moment of lateral energy deposit distribution relative to shower axis [cm]

FIG. 2. An example of K-estimator distribution in the 300 < \( E \) < 378 GeV bin. The reduced chi-square of the fit in the K-estimator range from -3 to 1 is 0.83.

O. Adriani et al., PRL 119, 181101 (2017) supplemental material
Gamma Ray Event Selection

= Electron Selection Cut + Gamma-ray ID Cut w/ Lower Energy Extension

1. Geometry Condition
   - CHD-Top to TASC
   1st layer (2cm margin)

2. Pre selection
   - Offline trigger
   - Shower concentration
   - Shower starting point

3. Track quality cut
   - Track hits >2
   - matching w/ TASC

4. Electromagnetic shower selection
   - shower shape

5. Gamma-ray ID
   - CHD/IMC-veto
   (combination of loose cuts)

6. FOV cut
Gamma Ray Event Selection

= Electron Selection Cut + Gamma-ray ID Cut w/ Lower Energy Extension

It was found that secondary gamma-ray produced in ISS structures are dominant source of background.

1. Geometry Condition
   - CHD-Top to TASC
     1st layer (2cm margin)

2. Pre selection
   - Offline trigger
   - Shower concentration
   - Shower starting point

3. Track quality cut
   - Track hits >2
   - matching w/ TASC

4. Electromagnetic shower selection
   - shower shape

5. Gamma-ray ID
   - CHD-veto

6. FOV cut

By removing Black parts, it is possible to reject majority of such background. More sophisticated rejection method is under development.
EM Track vs CC Track: Effective area

Figure 3. Effect of various selection cuts in zenith-pointing effective area. Grey shaded regions demonstrate the limits of applicability for each track due to background contamination with poor agreement between flight data and simulation.
EM Track vs CC Track : PSF

Figure 6. Composite PSF for EM and CC tracks. In each plot, the core contribution and tail contribution are represented by the red and green curves, respectively.
The observed point source spectra are well consistent with Fermi-LAT’s parameterizations. Therefore, it was found that current selection criteria has a validated sensitivity and can be used to set limit on GW counterpart flux.
Fermi LAT performance

https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
GRB analysis following a CGBM trigger: an example

GRB 180126A: triggered by CGBM at $T_0=2018/1/26/2:16:38$ UTC → No gamma ray candidates within $T_0 \pm 60$s

Exposure Map [LE Trigger] $T_0=1516932999$ -60~59 sec

Upper limits on energy flux (0 event)

Upper limits are calculated assuming number of events $N_0$ corresponding to 90% C.L.

- 0 event → $N_0 = 2.44$
- 1 event → $N_0 = 4.36$
- 2 events, not a pair → $N_0 = 4.38/0.68$

90% Confidence Limit Map [LE Trigger] $T_0=1516932999$ -60~59 sec

Upper limits on energy flux (2 events, not a pair)