CALETによる高エネルギーガンマ線観測

森　正樹

立命館大学理工学部物理科学科

For the CALET collaboration

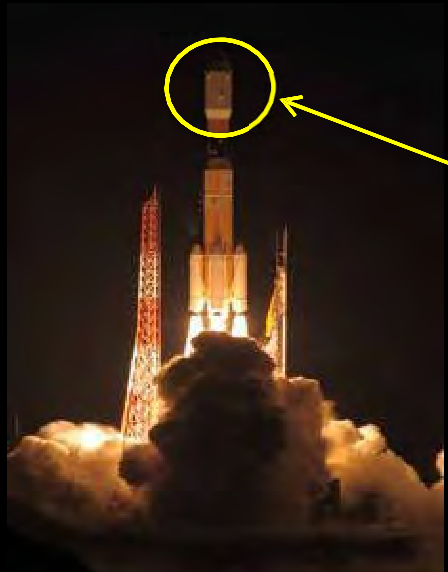
高エネルギー宇宙物理連絡会　研究会　2020/03/02-03

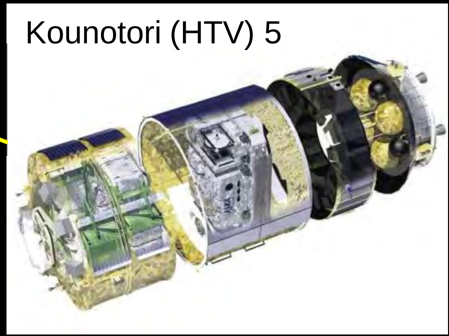
The CALET collaboration

O. Adriani[25], Y. Akaike[2], K. Asano[7], Y. Asaoka[9,31], M.G. Bagliesi[29], E. Berti[25], G. Bigongiari[29], W.R. Binns[32], M. Bongi[25], P. Brogi[29], A. Bruno[15], J.H. Buckley[32], N. Cannady[3], G. Castellini[25], C. Checchia[26], M.L. Cherry[13], G. Collazuol[26], K. Ebisawa[8], H. Fuke[8], T.G. Guzik[13], T. Hams[3], K. Hibino[10], M. Ichimura[4], K. Ioka[34], W. Ishizaki[7], M.H. Israel[32], K. Kasahara[31], J. Kataoka[31], R. Kataoka[17], Y. Katayose[33], C. Kato[23], Y.Kawakubo[13], N. Kawanaka[30], K. Kohri [12], H.S. Krawczynski[32], J.F. Krizmanic[2], J. Link[2], P. Maestro[29], P.S. Marrocchesi[29], A.M. Messineo[27], J.W. Mitchell[15], S. Miyake[5], A.A. Moiseev[3], M. Mori[20], N. Mori[25], H.M. Motz[31], K. Munakata[23], H. Murakami[31], S. Nakahira[9], J. Nishimura[8], G.A De Nolfo[15], S. Okuno[10], J.F. Ormes[25], N. Ospina[26], S. Ozawa[31], L. Pacini[25], F. Palma[28], V. Pal'shin[34], P. Papini[25], B.F. Rauch[32], S.B. Ricciarini[25], K. Sakai[3], T. Sakamoto[1], M. Sasaki[3], Y. Shimizu[10], A. Shiomi[18], R. Sparvoli[28], P. Spillantini[25], F. Stolzi[29], S. Sugita[34], J.E. Suh[29], A. Sulaj[29], I. Takahashi[11], M. Takita[7], T. Tamura[10], T. Terasawa[7], S. Torii[9,31], Y. Tsunesada[19], Y. Uchihori[16], E. Vannuccini[25], J.P. Wefel[13], K. Yamaoka[14], S. Yanagita[6], A. Yoshida[1], and K. Yoshida[22]

1) Aoyama Gakuin University, Japan
2) CRESST/NASA/GSFC and Universities Space Research Association, USA
3) CRESST/NASA/GSFC and University of Maryland, USA
4) Hirosaki University, Japan
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) KEK, Japan
13) Louisiana State University, USA
14) Nagoya University, Japan
15) NASA/GSFC, USA
16) National Inst. of Radiological Sciences, Japan
17) National Institute of Polar Research, Japan
18) Nihon University, Japan
19) Osaka City University, Japan
20) Ritsumeikan University, Japan
21) Saitama University, Japan
22) Shibaura Institute of Technology, Japan
23) Shinshu University, Japan
24) University of Denver, USA
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) Kyoto University, Japan

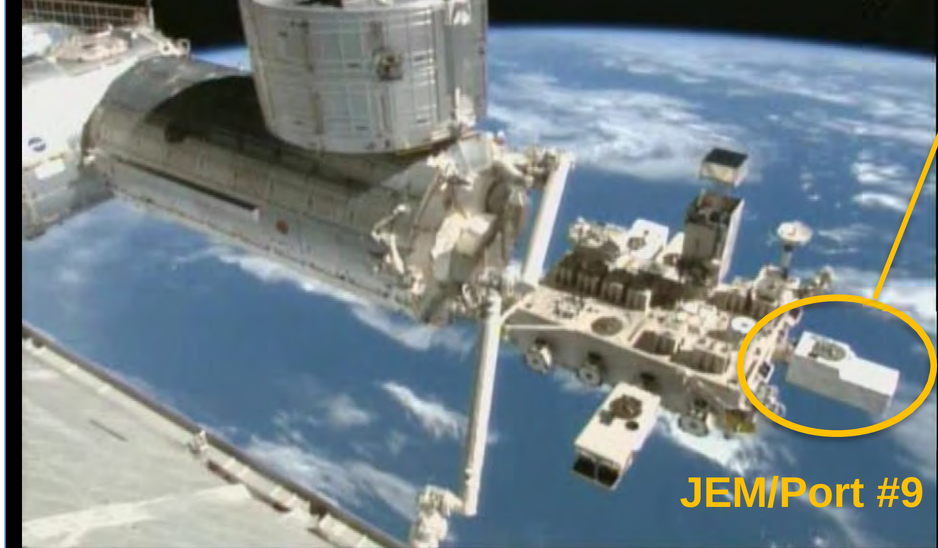
CALET Payload

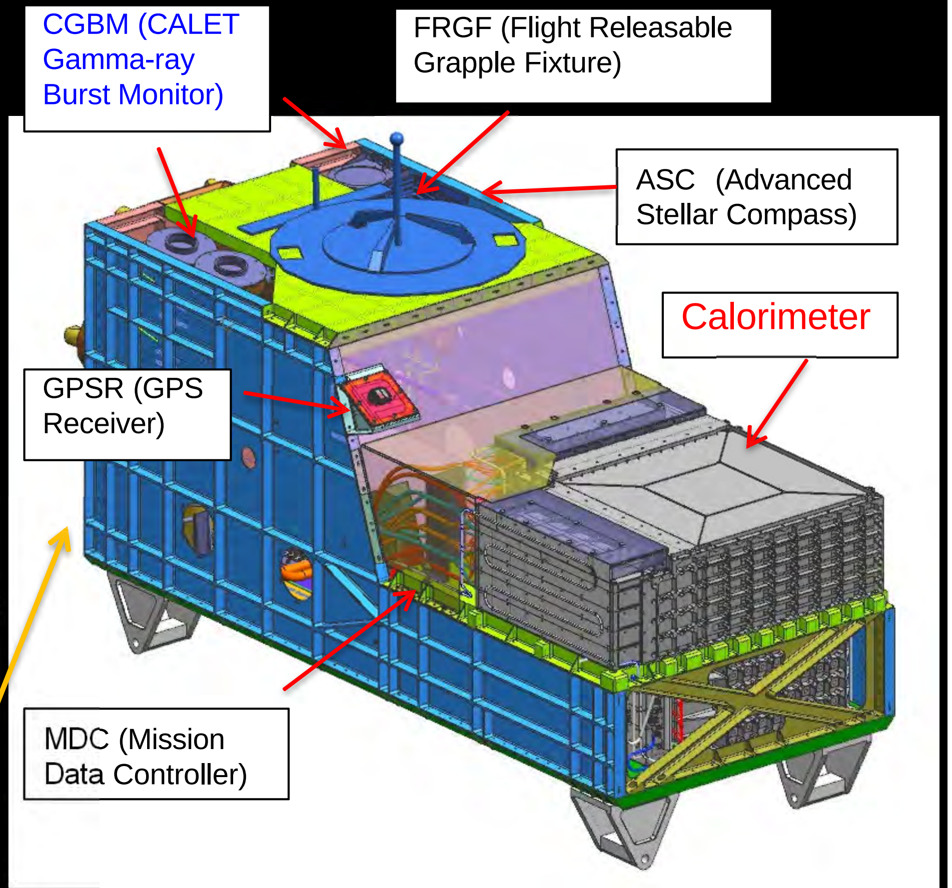




Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

Emplaced on JEM-EF port #9 on Aug. 25th, 2015 (JEM-EF: Japanese Experiment Module-Exposed Facility)

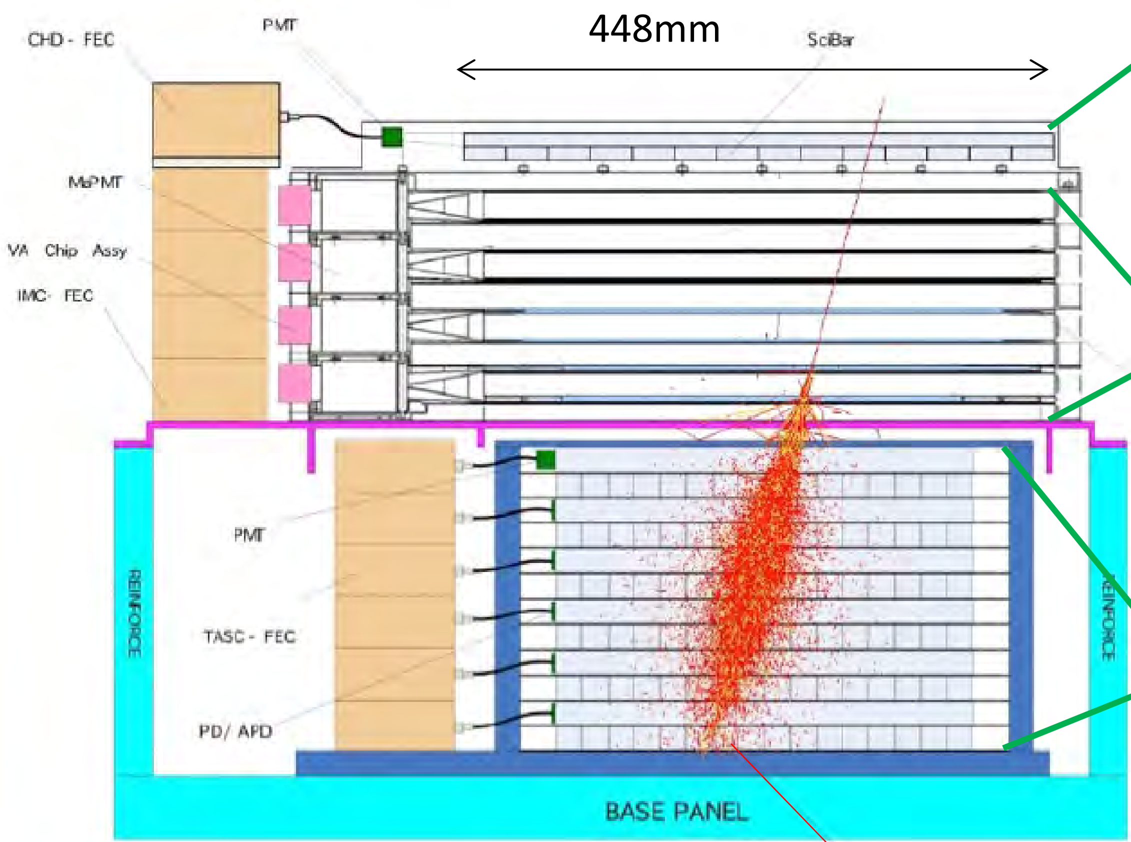




- **Mass: 612.8 kg**
- **JEM Standard Payload Size: 1850mm(L) × 800mm(W) × 1000mm(H)**
- **Power Consumption: 507 W (max)**
- **Telemetry: Medium 600 kbps (6.5GB/day) / Low 50 kbps**

CALET/CAL Detector

Fully active thick calorimeter ($30X_0$) 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 ($3X_0$), reconstruction of arrival direction and initial shower development

Total Absorption Calorimeter **TASC**

PWO hodoscope ($27X_0$), energy measurements and particle identification

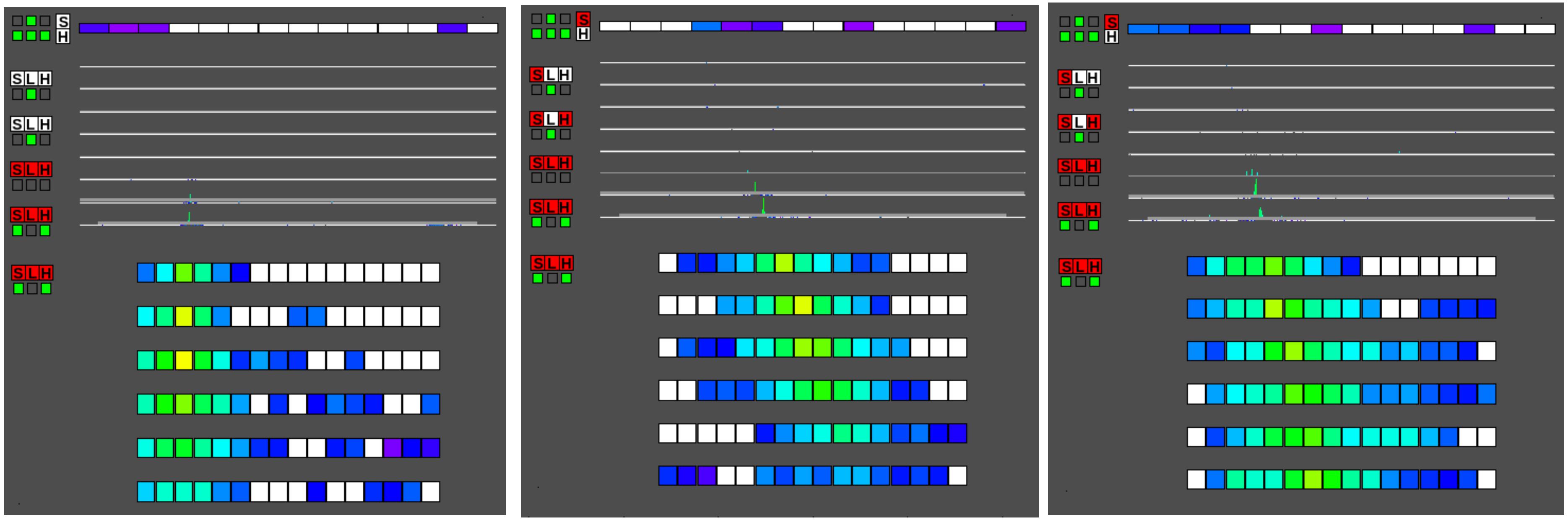
Cannady et al., ApJS 238:5 (2018)

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		Hadron Shower
well contained, constant shower development		larger spread

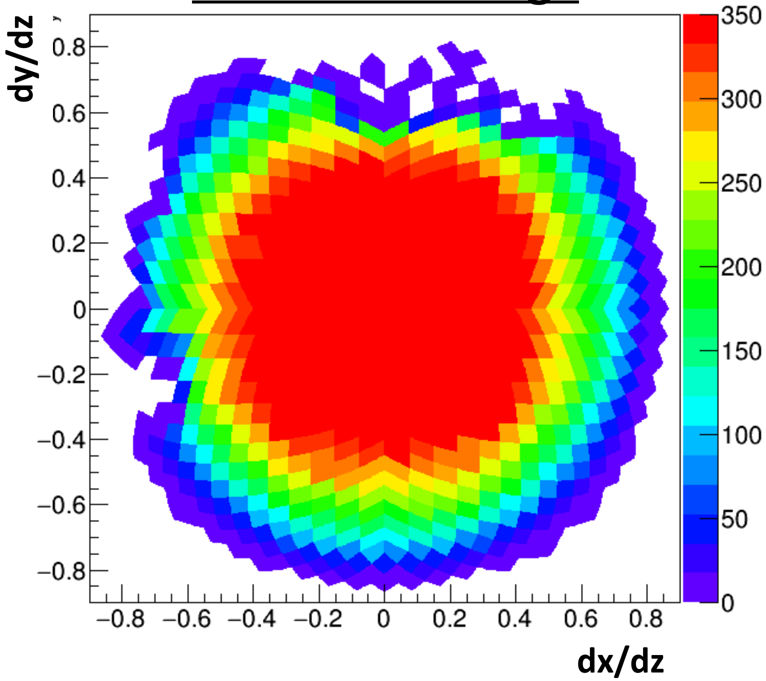
Effective Area and Sensitivity

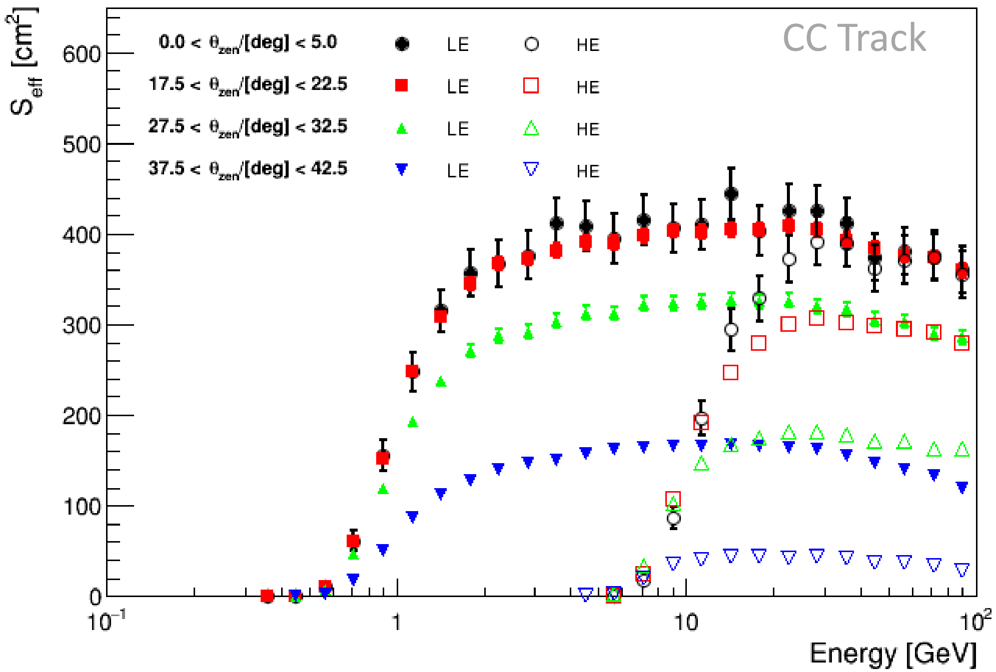
Cannady et al., ApJS 238:5 (2018)

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}.

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

3-10GeV average





Mostly axially symmetric except for FOV cut

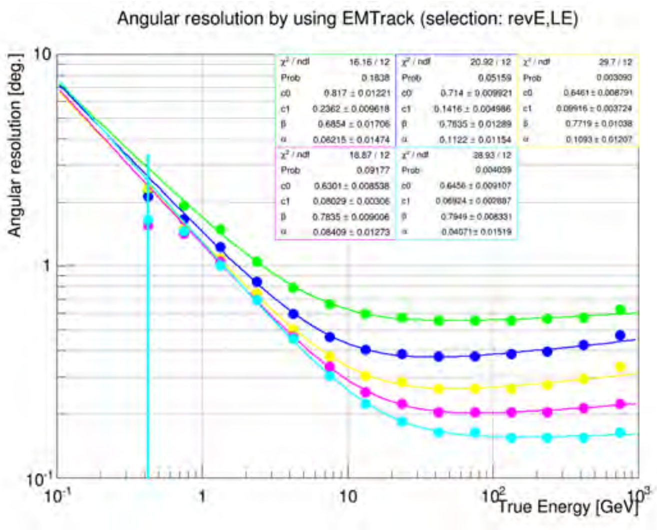
Effective area as a function of energy. Four representing zenith angle ranges are shown.

* LE-γ mode is activated when the geomagnetic latitude is below 20° and following a CALET Gamma-ray Burst Monitor (CGBM) burst trigger

Cannady et al., ApJS 238:5 (2018)

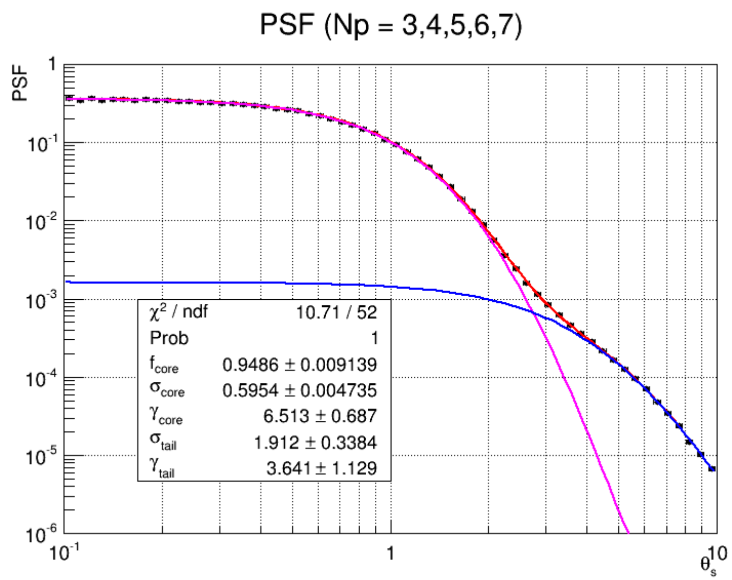
Point spread function (PSF)

$$P(\theta_s) = f_{core}K(\theta_s, \sigma_{core}, \gamma_{core}) + (1 - f_{core})K(\theta_s, \sigma_{tail}, \gamma_{tail}) \qquad K(\theta_s, \sigma, \gamma) = \frac{1}{2\pi\sigma^2}\left(1 - \frac{1}{\gamma}\right)\left[1 + \frac{1}{2\gamma}\frac{\theta_s^2}{\sigma^2}\right]^{-\gamma}$$



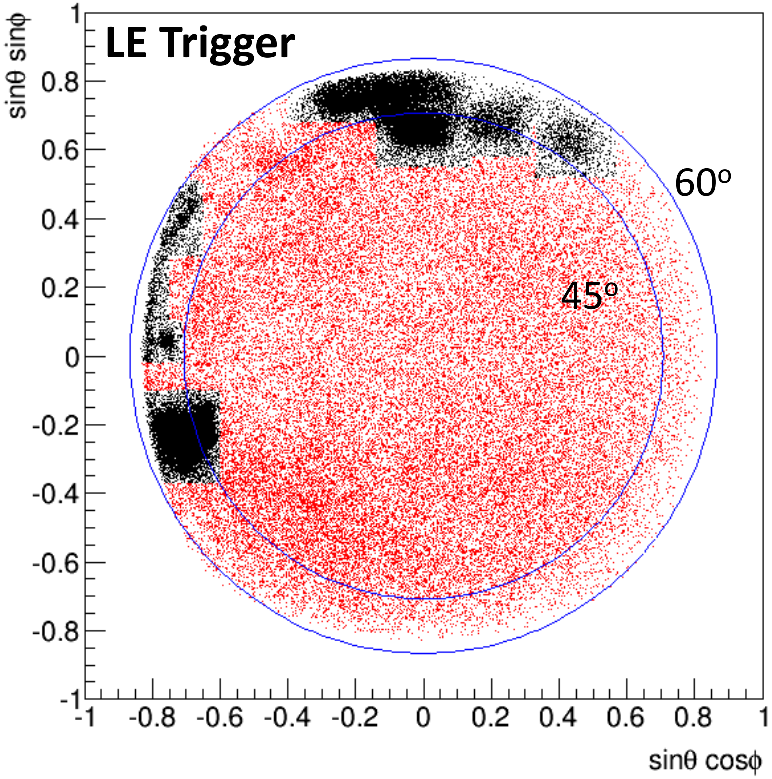
N_p : number of track points used for reconstruction

Np=3 Np=4 Np=5 Np=6 Np=7



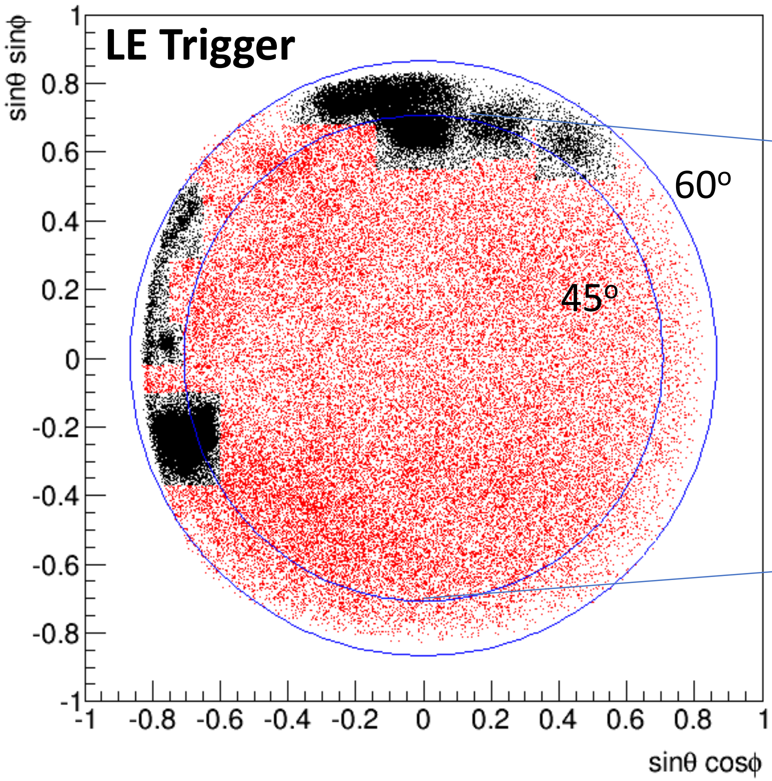
core
tail
core + tail

Gamma-ray candidates in CALET FOV

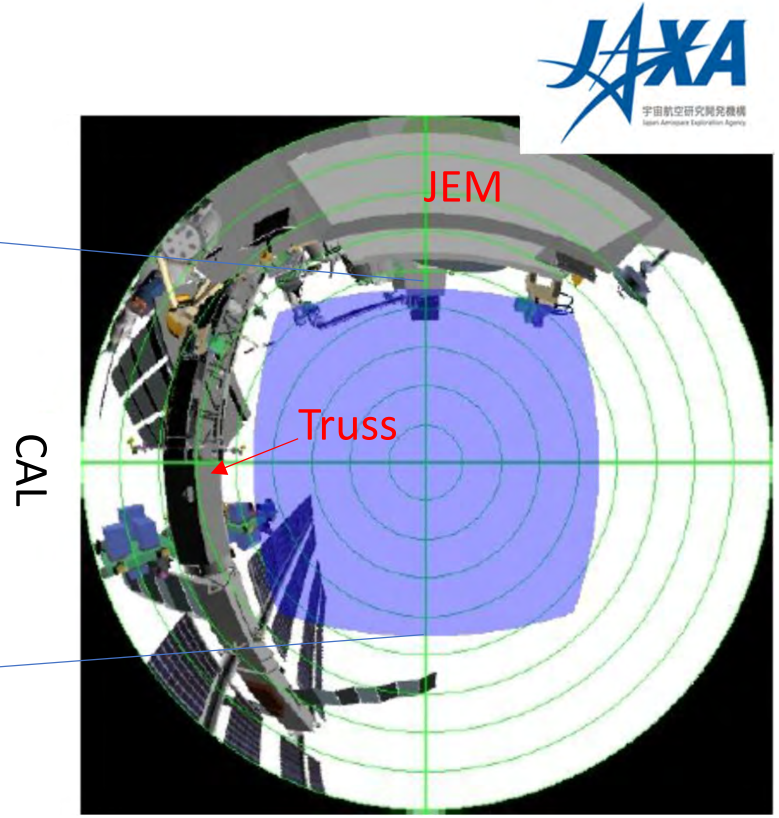


Gamma-ray candidates
in CALET FOV

Gamma-ray candidates in CALET FOV



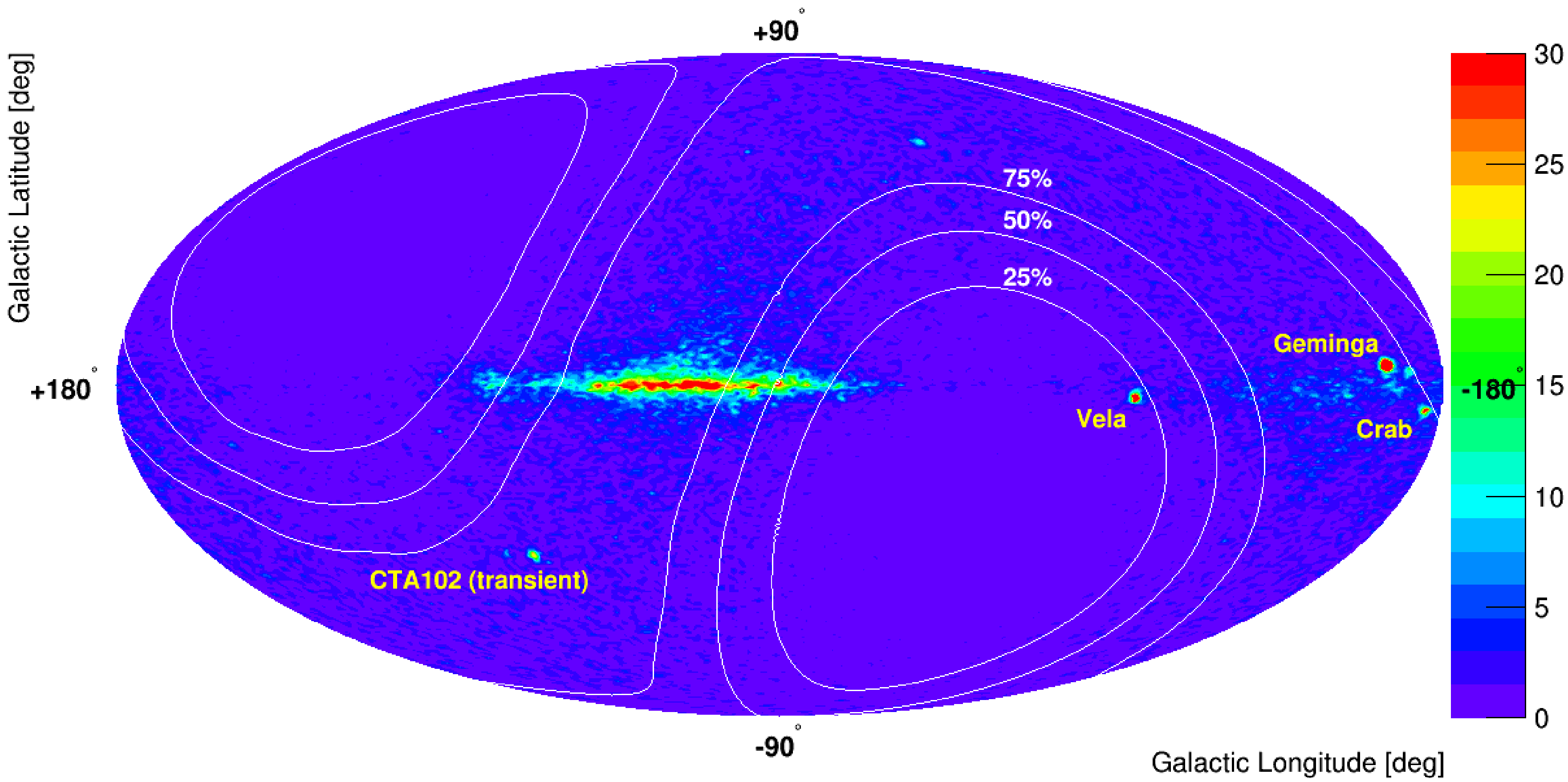
Gamma-ray candidates
in CALET FOV



Fish-eye view of CALET FOV

Mori, Asaoka et al., ICRC2019

Gamma-ray skymap



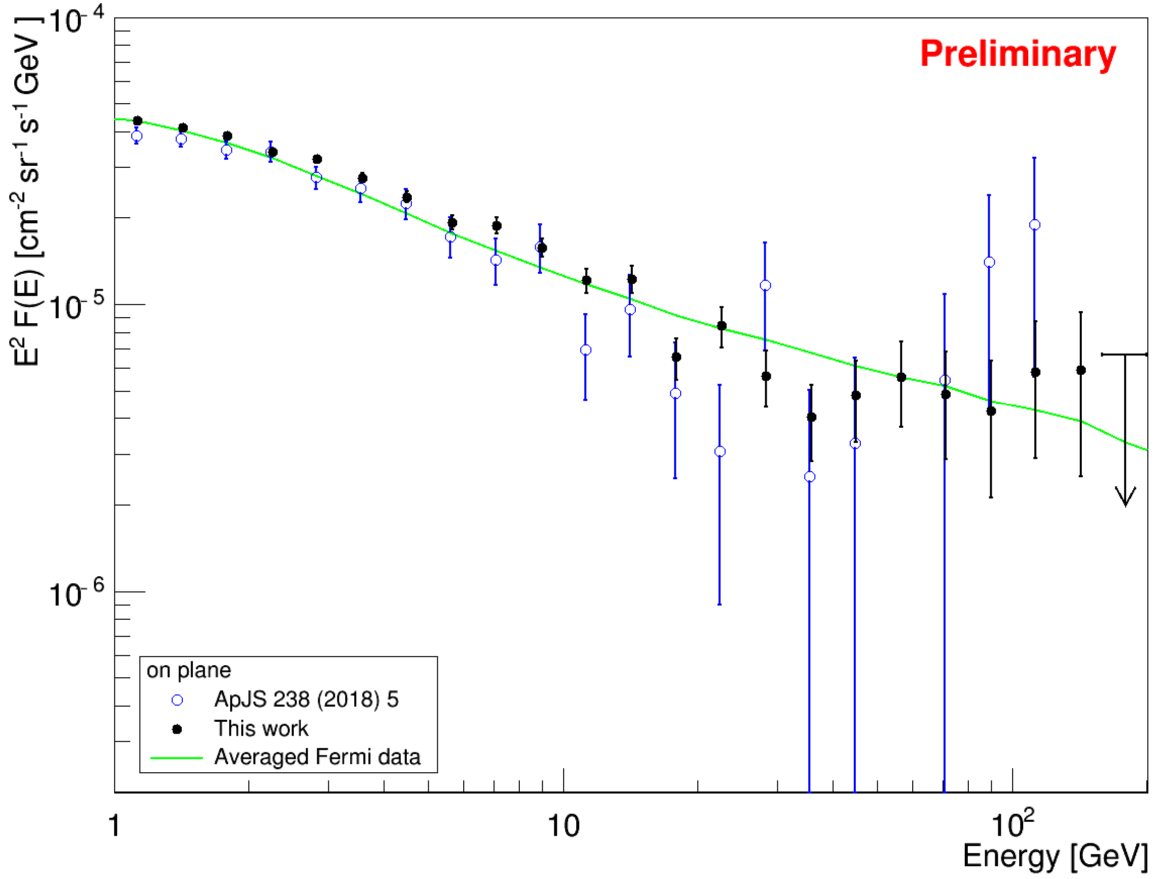
LE-γ mode, from 2015 November to 2018 May
(Contours show relative exposures)

Mori, Asaoka et al., ICRC2019

Gamma-ray spectra

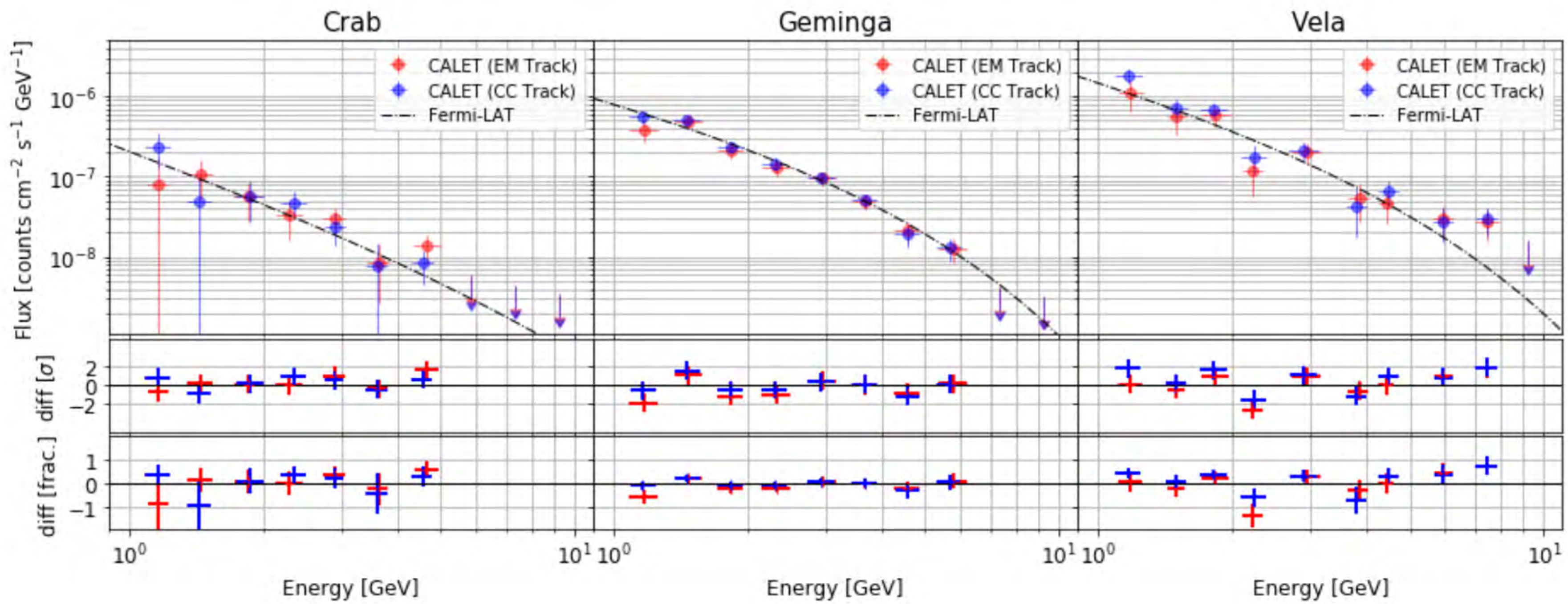
LE-γ mode
from 2015 November to 2018 May

“On-plane”: $|l| < 80°$ & $|b| < 8°$



Point Source Spectra: Sensitivity Validation

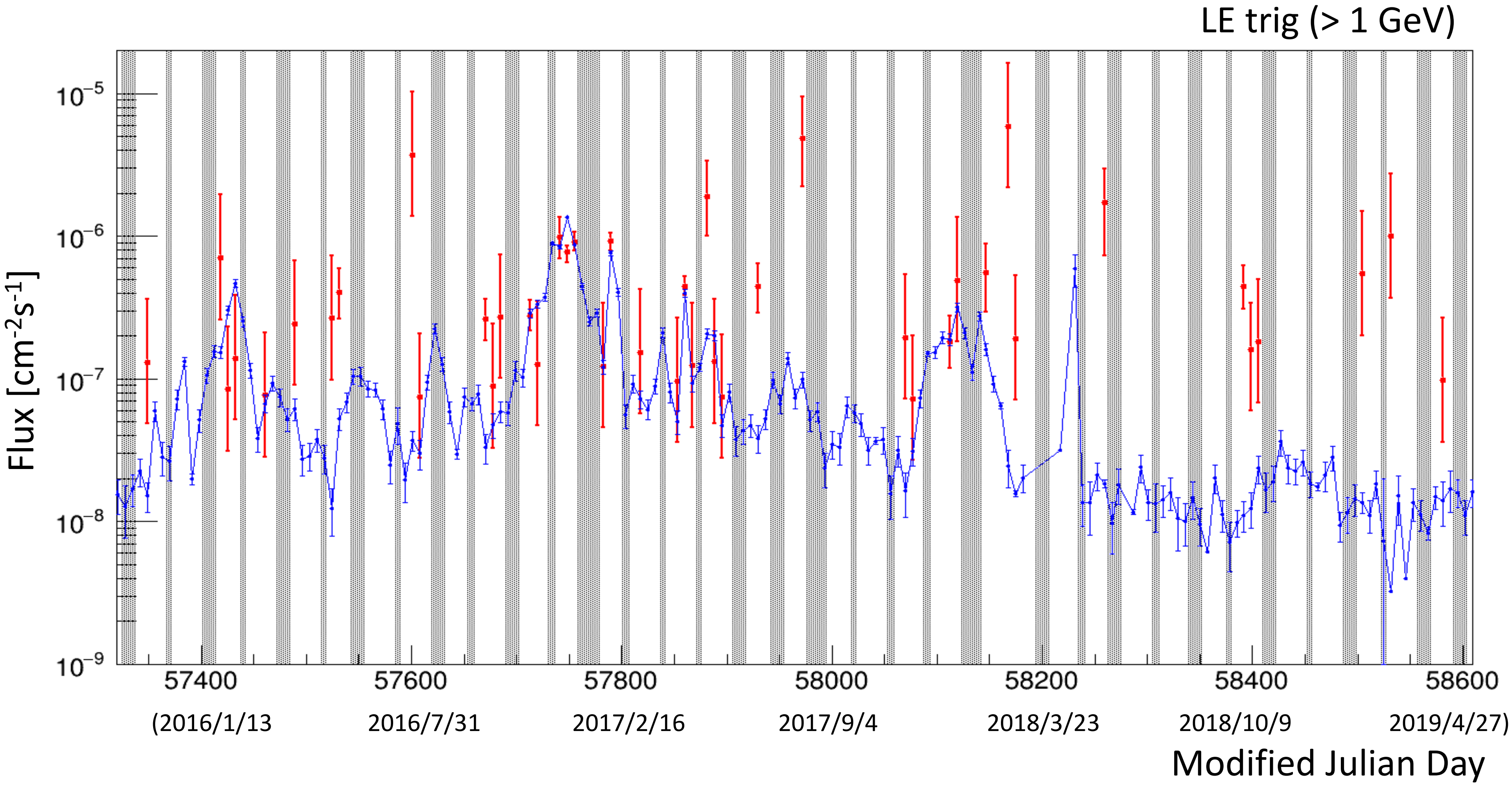
CALET Preliminary



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.

CTA 102 (AGN) light curve

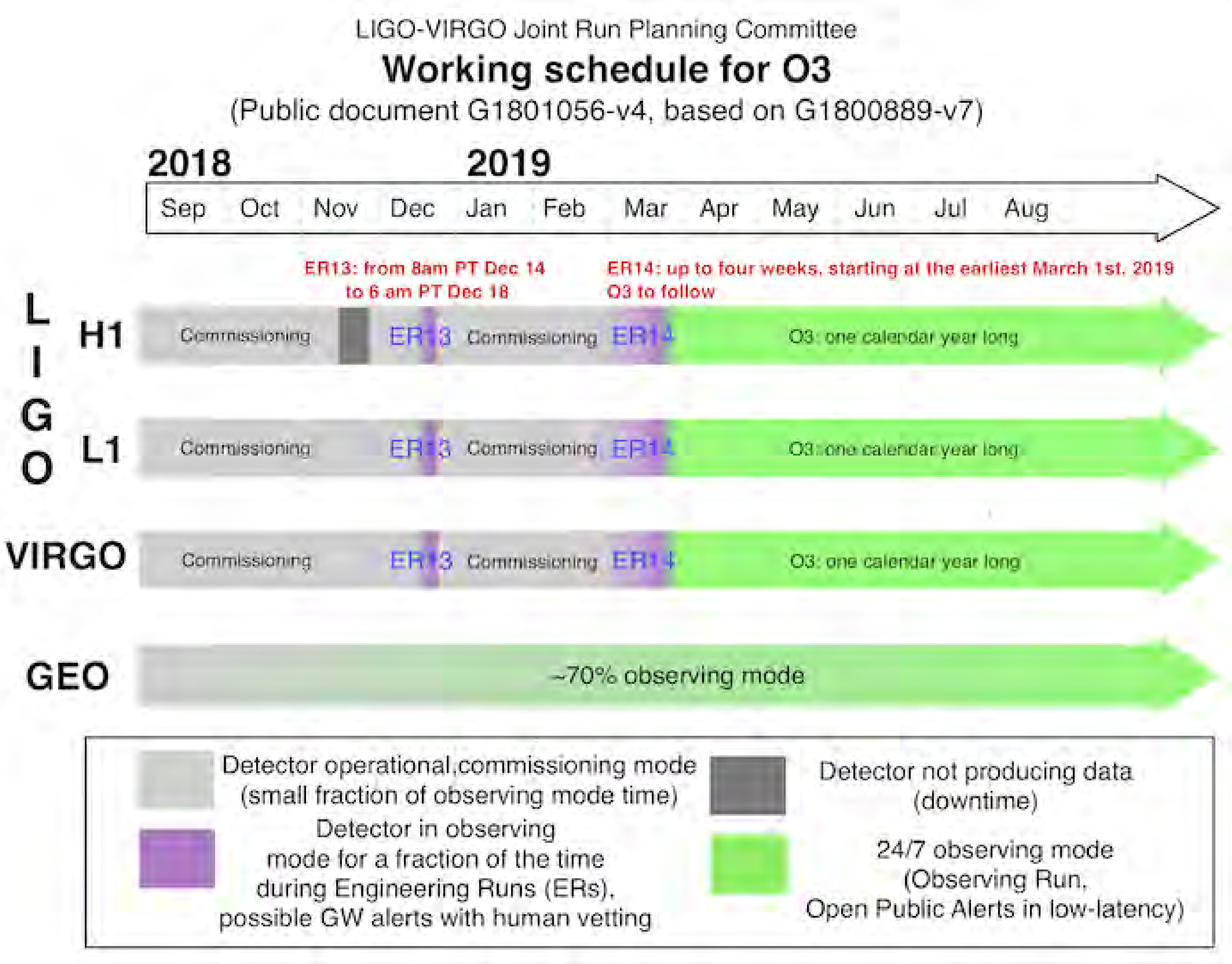
Preliminary



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

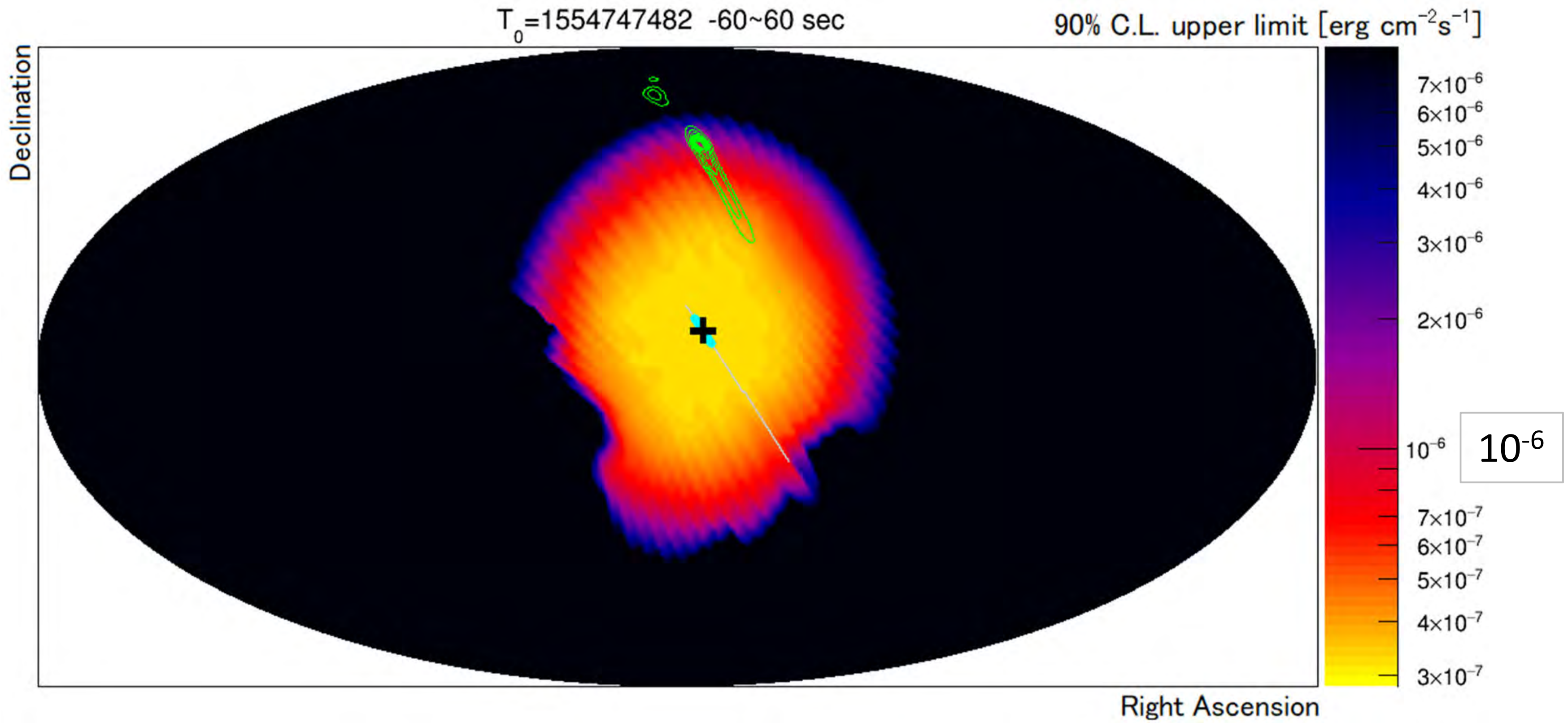
Blue: Fermi-LAT

LIGO-VIRGO observation 3



April 30, 2020

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_0-60s, T_0+60 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.

Mori, Asaoka et al., ICRC2019

CAL limits on electromagnetic emission from gravitational wave events

(LIGO/Virgo O3)

GCN No.	LIGO/Virgo trigger	Trigger time T_0 (2019)	Events $T_0 \pm 60$ s	90% C.L. U.L.	Summed probability	CAL α (°)	CAL δ (°)	Comments New!
24088	S190408an	04-08 18:18:02.288 UTC	0	2.3×10^{-6}†	80%	352.9	8.3	BBH (>99%)
24218	S190425z	04-25 08:18:05.017 UTC	0	1.0×10^{-4}	5%	131.3	-43.6	BNS (>99%)
24276	S190426c	04-26 15:21:55.337 UTC	0	2.5×10^{-5}	10%	183	-50.9	BNS (49%)
24403	S190503bf	05-03 18:54:04.294 UTC	0	4.2×10^{-5}	10%	169	-45.5	BBH (96%)
24495	S190510g	05-10 02:59:39.292 UT	0	–	No	295.7	50.8	Terrestrial (58%)
24531	S190512at	05-12 18:07:14.422 UT	0	1.9×10^{-5}	10%	214.9	37.7	BBH (99%)
24548	S190513bm	05-13 20:54:28.747 UT	0	6.0×10^{-5}†	5%	348	4.4	BBH (94%)
24593	S190517h	05-17 05:51:01.831 UT	0	–	No	126.2	-31.9	BBH (98%)
24617	S190519bj	05-19 15:35:44.398 UT	0	–	No	243.1	51.1	BBH (96%)
24648	S190521g	05-21 03:02:29.447 UT	0	6.0×10^{-6}	30%	205.7	49.2	BBH (97%)
24649	S190521r	05-21 07:43:59.463 UT	0	–	No	225.3	51.4	BBH (>99%)
24735	S190602aq	06-02 17:59:27.089 UT	0	2.9×10^{-4}	5%	127.5	45.1	BBH (99%)

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.

†: LE-γ

Extended to 12-SEP-2019

CAL limits on electromagnetic emission from gravitational wave events (LIGO/Virgo O3)

GCN No.	LIGO/Virgo trigger	Trigger time T_0 (2019)	Events $T_0 \pm 60$ s	90% C.L. U.L.	Summed probability	CAL α (°)	CAL δ (°)	Comments
24960	S190630ag	06-30 18:52:05.180 UT	0	1.2×10^{-5}	25%	84.0	31.5	BBH (94%)
24970	S190701ah	07-01 20:33:06.578 UT	0	–†	No	286.8	−1.6	BBH (93%)
25027	S190706ai	07-06 22:26:41.345 UT	0	–	No	210.4	−45.4	BBH (99%)
25033	S190707q	07-07 09:33:26.181 UT	0	2.1×10^{-6}†	20%	262.4	2.2	BBH (>99%)
25099	S190718y	07-18 14:35:12.068 UT	0	1.7×10^{-6}†	5%	195.8	−11.1	Terrestrial (98%)
25134	S190720a	07-20 00:08:36.704 UT	0	3.0×10^{-5}	25%	49.7	−32.1	BBH (99%)
25184	S190727h	07-27 06:03:33.986 UT	0	–	No	201.1	38.2	BBH (92%)
25214	S190728q	07-28 06:45:10.529 UT	0	–†	No	184.8	30.3	BBH (95%)
25390	S190814bv	08-14 21:10:39.013 UT	0	–	No	181.3	49.5	NSBH (>99%)
25536	S190828j	08-28 06:34:05.756 UT	0	–	No	13.9	12.6	BBH (>99%)
25537	S190828l	08-28 06:55:09.887 UT	0	–	No	106.9	51.0	BBH (>99%)
25647	S190901ap	09-01 23:31:01.838 UT	0	6.3×10^{-5}†	5%	353.8	16.6	BNS (86%)

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.

†: LE-γ

Summary

- CALET cosmic ray detector onboard the ISS has been monitoring cosmic gamma-rays above 1 GeV since 2015 October.
- We have developed cuts to reduce secondary gamma-ray background produced in the various ISS structures, which increase our event statistics significantly.
- Quality of gamma-ray data has been checked by skymaps, galactic plane spectra, and point sources.
- Searches for electromagnetic counterparts of gravitational events upon triggers supplied by LIGO/Virgo interferometers during their third observing run yielded upper limits on gamma-ray emission.
- We continue observation at least until 2021, hoping for a further extension.