Search for GeV-energy Gamma-ray Burst Counterparts with the CALET Calorimeter

Nicholas W. Cannady for the CALET Collaboration
CRESST II / University of Maryland, Baltimore County / NASA GSFC

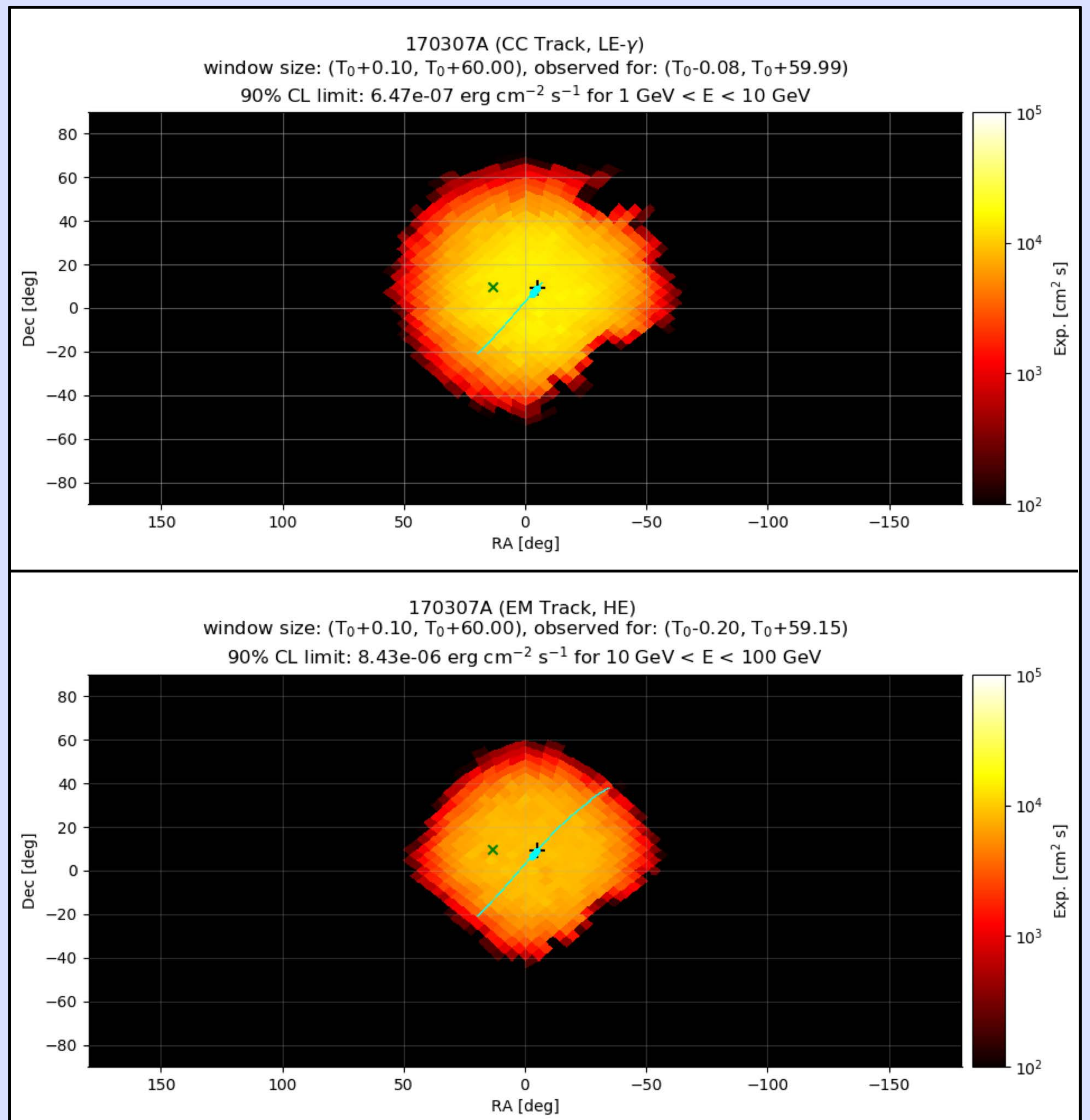

Figure 3: Example data analysis products for a CAL follow-up search to a Swift trigger. The upper and lower frames correspond to observations with the LE-γ and HE triggers, respectively. The thin cyan line shows the path of the zenith pointing while the trigger was active near the trigger time. The thicker cyan region shows the time over which the exposure is accumulated in the follow-up. The black + is the pointing at the trigger time, and the green ✕ indicates the position determined by the external instrument, which is Swift BAT in this case.

Search for GRBs in CAL triggered events

With the reconstructed photon dataset, we search for counterparts to transient events reported by instruments with localization capability. In this case, Swift and Fermi-GBM trigger catalogs starting with the beginning of CALET operations including a total of 204 and 584 events, respectively, were included in the search. Optimal observation involves the trigger occurring when the LE-γ mode is active due to the significantly decreased energy threshold (1 GeV vs. 10 GeV) and the expanded field-of-view (FOV) afforded by the wider acceptance conditions for low-energy events [6]. Of the checked events, 34 and 86 events from the respective catalogs were in the CAL FOV during LE-γ observations. No reconstructed photon events were found to be spatially consistent with the source position reported in the source catalogs. Upper limits on the flux are calculated assuming E^{-2} spectra considering the exposure at the source position in the 1 GeV – 10 GeV (LE-γ) band if available and in the 10 GeV – 100 GeV range (HE trigger). Figure 3 demonstrates observations of an event in both triggers. The upper limits, times considered, and trigger information are reported in the headers to the images. The wider coverage and deeper exposure of the LE-γ frame demonstrates the value of observations when this trigger is active.

In addition, we also search for counterparts to non-localized triggers from CGBM. Since the source position is unknown, we require multiple spatially coincident photons to consider a signal to be a counterpart candidate. Although there are photons seen in the observation windows around CGBM events, no credible counterparts are found satisfying this spatial consistency requirement. This includes a total of 22 GRBs from the CGBM on-board trigger list when LE-γ observations were active that are not included in either of the catalogs with localization listed above.

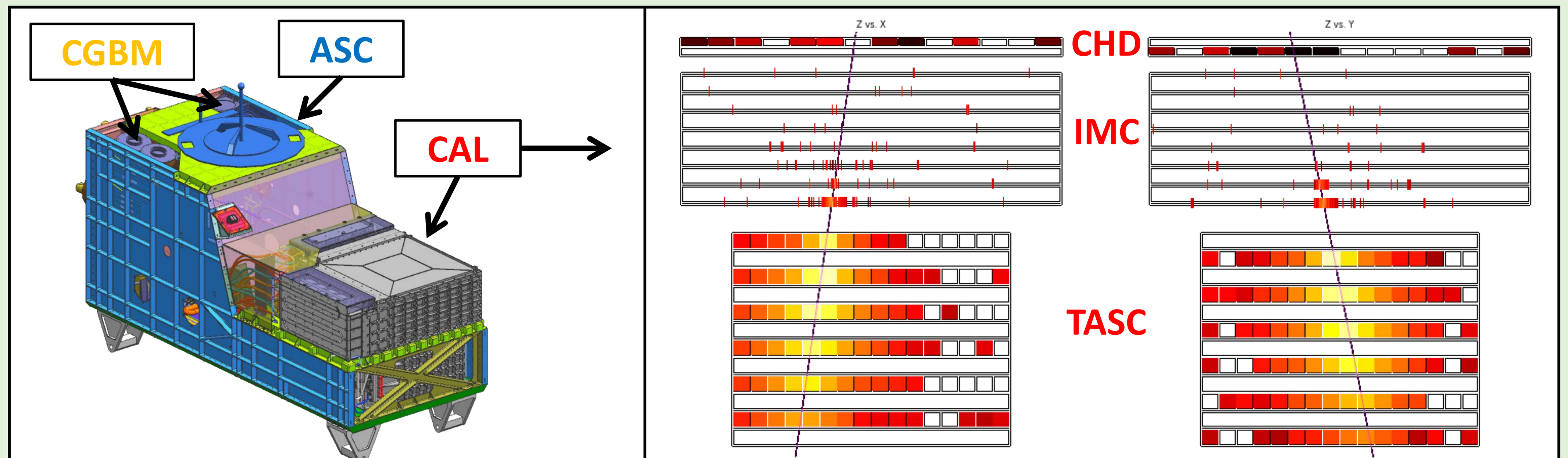

Figure 1: CALET structure. *left:* Full CALET payload, with CGBM, ASC, and CAL indicated. *right:* Event view of flight data gamma-ray candidate (~450 GeV) showing CAL subdectectors.

CHD	IMC	TASC
Plastic scintillating paddles 14 paddles x 2 layers (X, Y) = 28 paddles Each paddle: 32 x 10 x 450 mm^3	Plastic scintillating fibers & tungsten plates 448 fibers x 16 layers (8X, 8Y) = 7168 fibers Each fiber: 1 x 1 x 448 mm^3 7 W layers: (5 x 0.2 X_0) + (2 x 1 X_0) = 3 X_0	Lead tungstate ($PbWO_4$; PWO) logs 16 logs x 12 layers (6X, 6Y) = 192 logs Each log: 19 x 20 x 326 mm^3 Total thickness: 27 X_0, ~1.2 λ_I
Charge measurement Z = 1 - 40	Particle tracking Particle identification	Energy reconstruction e/p separation
PMT + CSA readout	64-anode PMT + ASIC	APD / PD + CSA PMT + CSA on top layer (for trigger)

Table 1: Physical description, purpose, and readout electronics specifications of the three CALET CAL subdetectors.

The Calorimetric Electron Telescope (CALET)

CALET [1] was launched in August 2015 to the International Space Station (ISS) Japanese Experiment Module Exposed Facility (JEM-EF) for the primary purpose of directly measuring the cosmic-ray electron spectrum up to energies of tens of TeV [2]. The payload schematic is shown in the left panel of Figure 1. The CALET calorimeter (CAL) has a normal-incidence depth of 30 radiation lengths (X_0) and comprises three submodules as detailed in Table 1. The right panel of Figure 1 demonstrates the structure and function of the CHD, IMC, and the TASC. The tungsten plates in the IMC stimulate early shower development, which is imaged by the scintillating plastic fibers. The majority of the shower energy is deposited in the TASC, which is able to fully contain electromagnetic showers up to TeV energies. The calorimeter was calibrated through lab testing on the ground and is updated regularly on orbit using signals from penetrating particles [3].

The payload also contains the CALET Gamma-ray Burst Monitor (CGBM) [4], a collection of $LaBr_3$ and BGO scintillators covering energies 7 keV – 20 MeV. Triggers in CGBM activate in the CAL the Low-Energy Gamma (LE-γ) trigger [5] to enable searches for counterpart emission. Finally, the Advanced Stellar Compass (ASC) takes images twice per second and correlates with star maps to enable arcminute pointing accuracy [6].

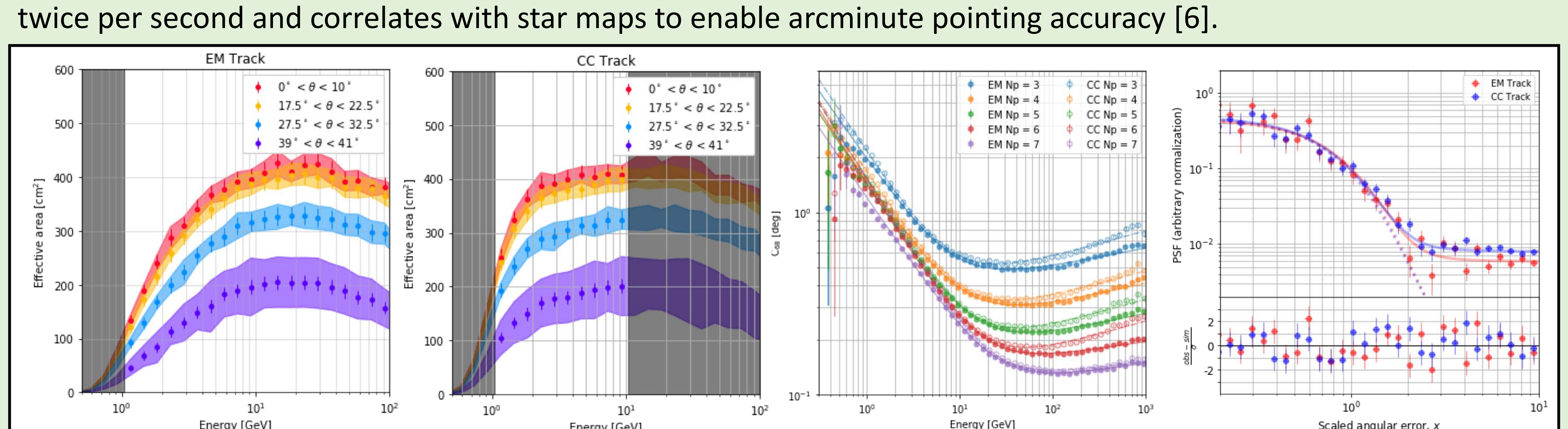

Figure 2: Instrument performance characteristics for the CAL gamma-ray analysis [6]. *left to right:* Effective area as a function of energy for the (1) EM Track and (2) CC Track algorithms, (3) the angular resolution as a function of energy and number of IMC layers used for tracking, and (4) a comparison of EPICS simulation-derived point-spread function with an added constant background and the distribution of events from the Geminga pulsar in flight data.

The performance of the CAL for gamma-ray analysis is established for the range 1 GeV – 1 TeV [6]. Figure 2 demonstrates the instrument response functions derived from simulations and a validation of the angular response with the on-orbit measurements of the Geminga pulsar. These demonstrate that the use of the CC Track reconstruction at low energies and the EM Track reconstruction at high energies balance the sensitivity of the CAL to photon events and the background of charged particles in the sample. For E > 2 GeV, the effective area is ~400 cm^2 up to hundreds of GeV (Figure 2 left panels). The angular resolution (Figure 2 third panel) is characterized as a function of energy and pair conversion depth in the IMC and is generally better than 2° for E > 1 GeV and better than 0.5° for E = 10 GeV – 100 GeV. After the instrument characterization, extensive work has been done to handle the presence of a secondary photon background due to ISS structures in the field of view. More details of the methodology and improvements are given in [7].

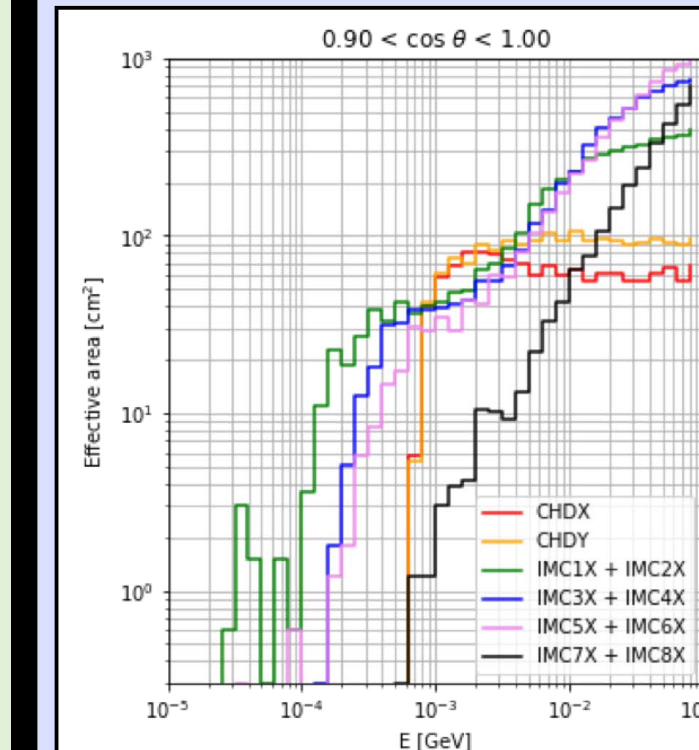

Figure 4: Effective area as a function of energy for individual trigger layers of the CAL for low energy photon injected at near-normal incidence (θ < 26°) assuming the Low-Energy Gamma trigger mode.

Trigger layer rates

Each CHD layer and pairs of IMC layers (IMC 1x + IMC 2x) according to MaPMT are used in the trigger logic. These "trigger layers" each have an associated counter for the number of times above threshold, even if the full trigger is not satisfied. These counters can be used to probe transient events that are not energetic enough to trigger the CAL readout. Similar analysis has been applied to Relativistic Electron Precipitation [8] and is currently used to analyze the September 2017 Solar Energetic Particle events [9].

Figure 4 shows the effective area for the individual trigger layers based on simulations assuming the LE-γ trigger is active. The proportional response in the layers changes as a function of energy. Although there is a degeneracy in that the response also changes as a function of incident angle, the potential for exploiting this effect to deduce features of the emitted spectrum are being investigated.

Figure 5 shows an example of a long GRB observed in the CAL count rates. GRB 190411A triggered CGBM with signals in both the SGM and HXM. The signal is seen most strongly in IMC 1/2 and IMC 3/4, with clear signals in the CHD and in IMC 5/6 as well. The emission shows a clear two-peaked structure. No corresponding signal in triggered photon events in the CAL is detected. A comprehensive follow-up search is being performed for on-board and external GRB triggers.

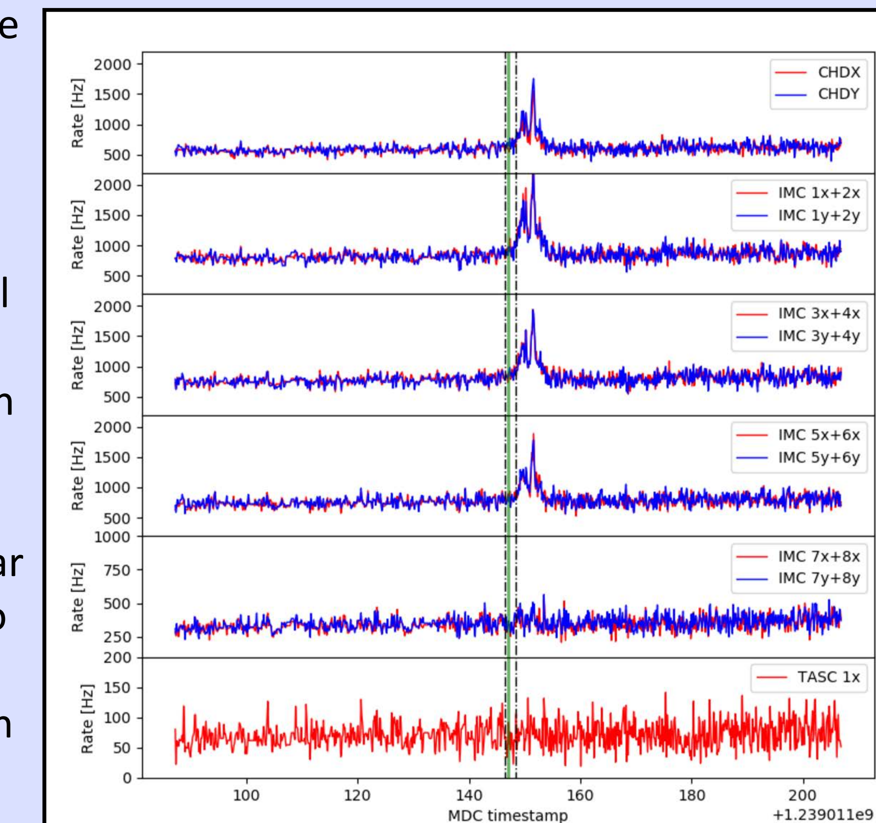

Figure 5: CALET structure. *left:* Full CALET payload, with CGBM, ASC, and CAL indicated. *right:* Event view of flight data gamma-ray candidate (~450 GeV) showing CAL subdectectors.

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