Search for GeV Gamma-Ray Counterparts of Gravitational Wave Events with CALET/CAL

# CALET/CALによる重力波イベントのガンマ線対応天体探索

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# CALET Collaboration

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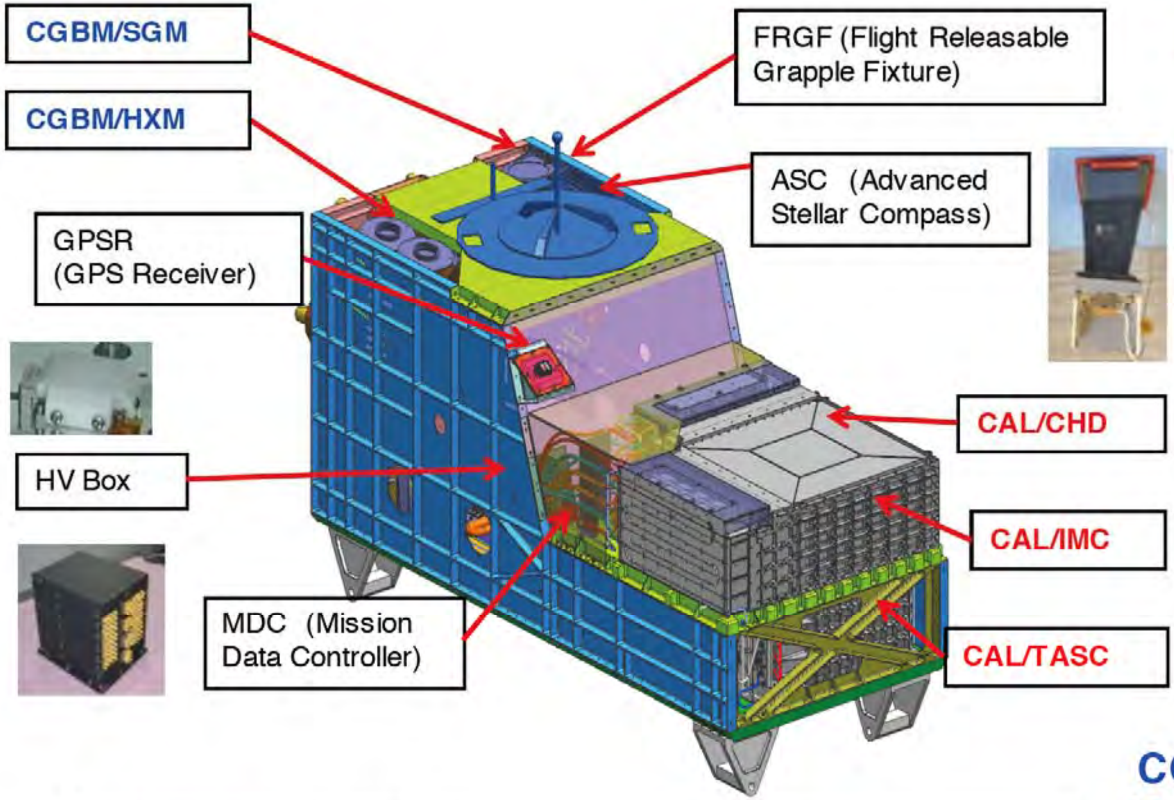
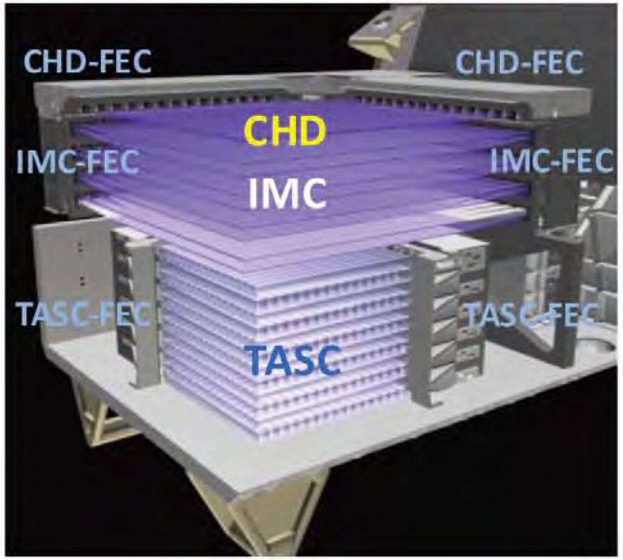
# CALET System Overview

Launched Aug.2015



## CALORIMETER (CAL)



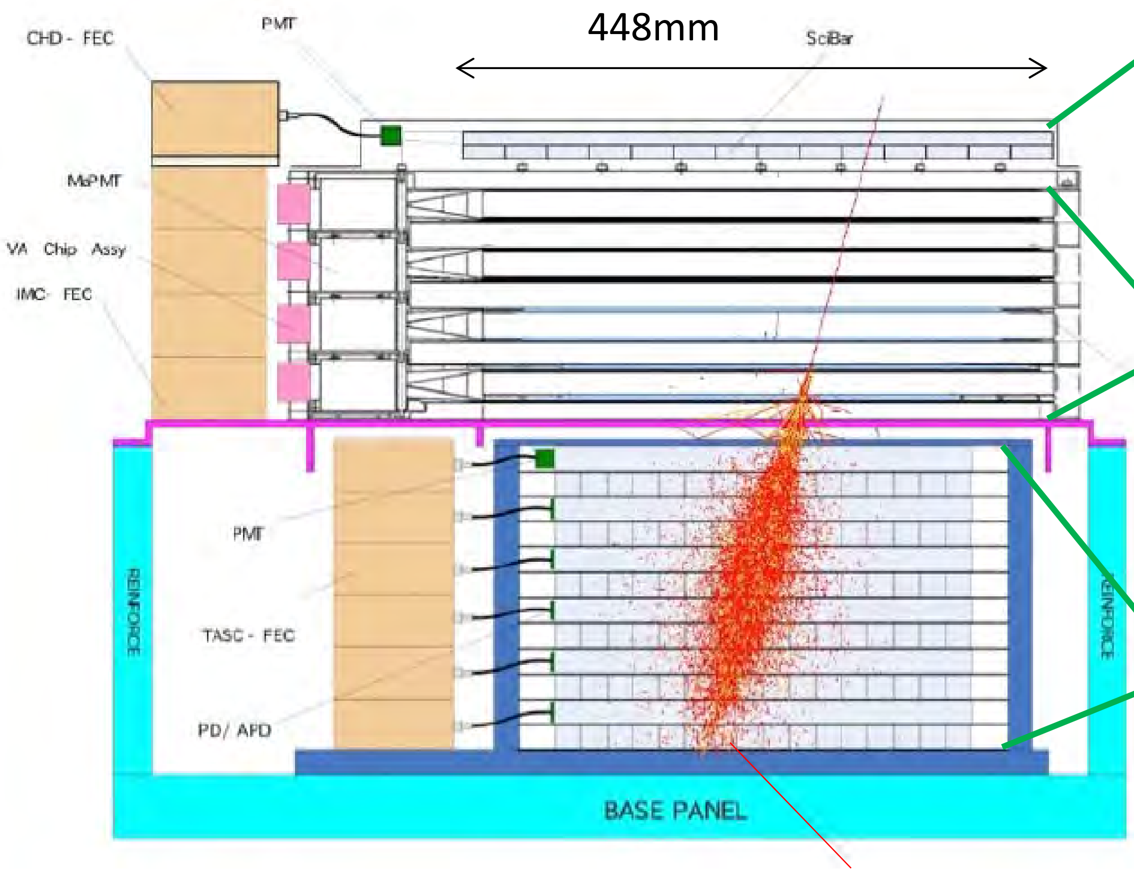
- Mass: 612.8 kg
- JEM Standard Payload Size
1850mm(L) × 800mm(W) × 1000mm(H)
- Power Consumption: 507 W(max)
- Telemetry:
Medium 600 kbps (6.5GB/day) / Low 50 kbps

(*) JEM stands for Japan Experiment Module

**CGBM (CALET Gamma-ray Burst Monitor)**

# 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)

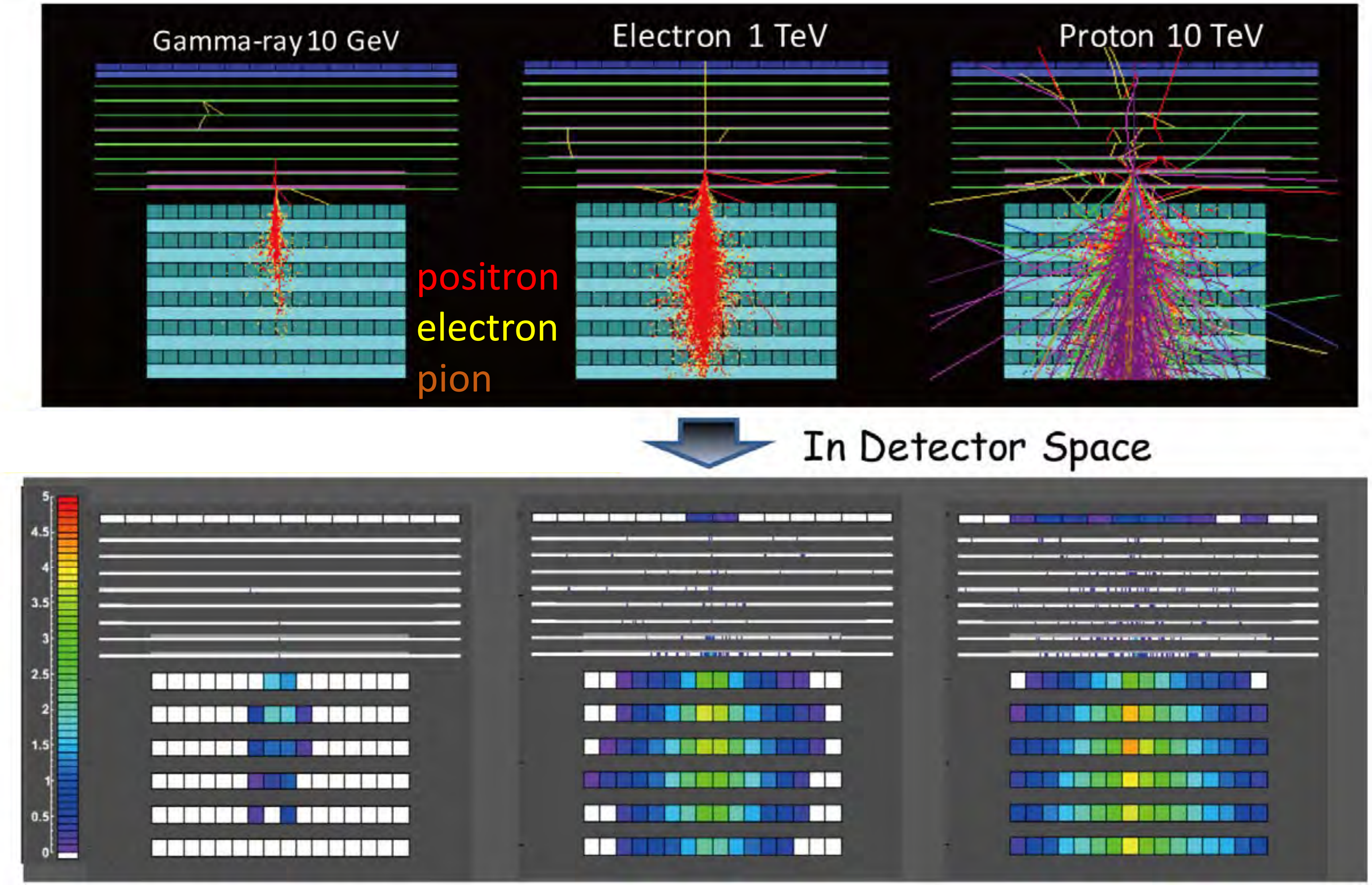
**Imaging Calorimeter** **IMC**

**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

# CALET-CAL Shower Imaging Capability (MC)



- Proton rejection power of $10^5$ can be achieved by taking advantage of shower imaging capability of IMC and TASC
- Angular resolution of ~0.2° for 10GeV gamma rays

# Overview of CALET Trigger System

Y. Asaoka et al., Astroparticle Phys. 100, 29 (2018)

**High Energy Shower Trigger (HE)**

- High energy electrons (10GeV ～20TeV)
- High energy gamma rays (10GeV ～10TeV)
- Nuclei (a few10GeV～1000TeV)

**Low Energy Shower Trigger (LE)**

- Low energy electron at high latitude (1GeV ～10GeV)
- GeV gamma- rays originated from GRB (1GeV ～)
- Ultra heavy nuclei (combined with heavy mode)

**Single Trigger (Single)**

- For detector calibration : penetrating particles (mainly non-interacting protons and heliums)

(*) In addition to above 3 trigger modes, heavy modes are defined for each of the above trigger mode. They are omitted here for simple explanation.

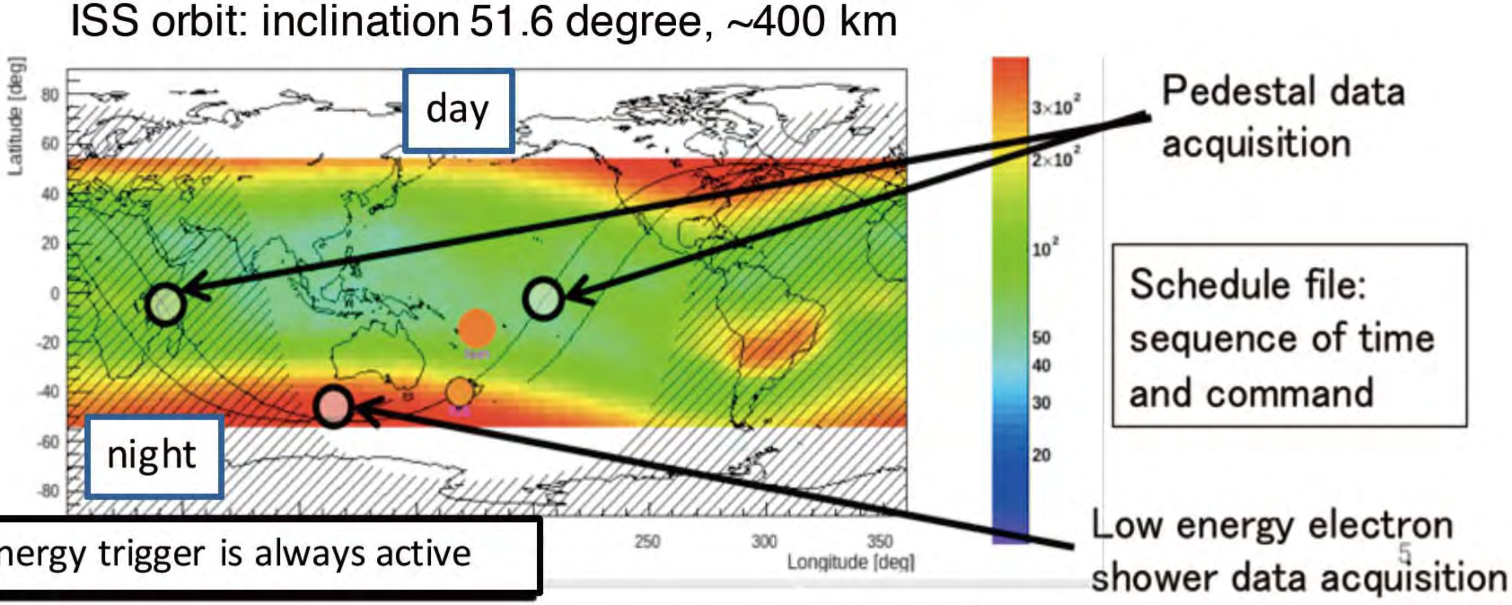
**Auto Trigger (Pedestal/Test Pulse)**

- For calibration:
  - ADC offset measurement (Pedestal)
  - FEC's response measurement (Test pulse)

# ISS Orbit and CALET Operations

Y. Asaoka et al., Astroparticle Phys. 100, 29 (2018)

**Concept of on-orbit operations**



ISS orbit: inclination 51.6 degree, ~400 km

day

night

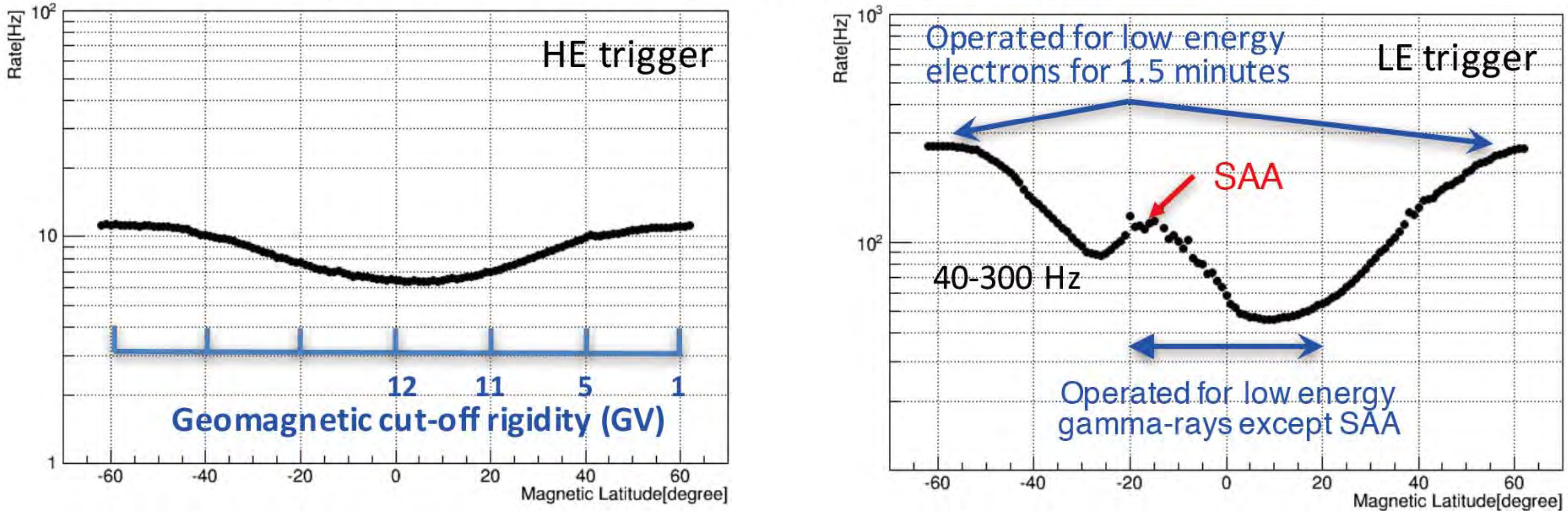
Pedestal data acquisition

Schedule file: sequence of time and command

Low energy electron shower data acquisition

High energy trigger is always active

## Dependence of the count rate on geomagnetic latitude



Geomagnetic cut-off rigidity (GV)

Operated for low energy electrons for 1.5 minutes

Operated for low energy gamma-rays except SAA

# CAL Limit Calculation Procedure

Gamma-ray Event Selection

Effective Area Calculation

Exposure Calculation

Upper Limit Calculation

Check Overlap with LIGO Localization Map

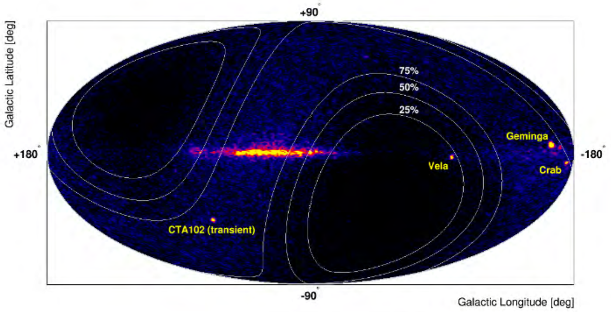
Lower energy is important

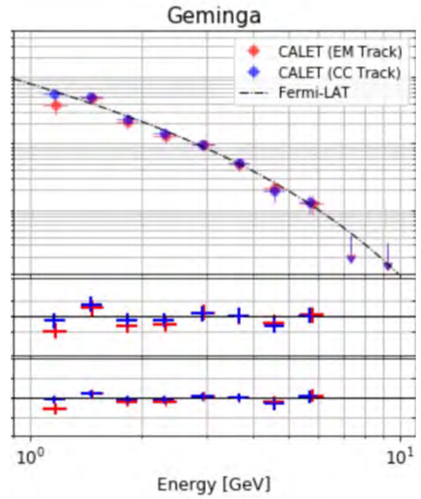
$S_{\mathrm{eff}}$ as a function of zenith and azimuth

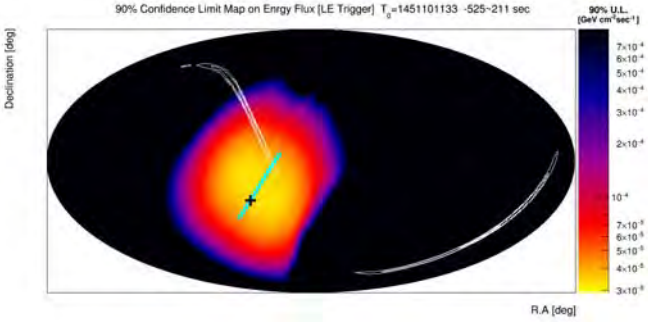
$S_{\mathrm{eff}}(\mathrm{zen,azi})\ T_{\mathrm{live}}$ projected to sky event by event along the ISS (CALET) orbit

**If no gamma-rays are observed**

Validation of Sensitivity with Observation of Diffuse/Point Sources







# Gamma Ray Event Selection

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

100 GeV Event Examples

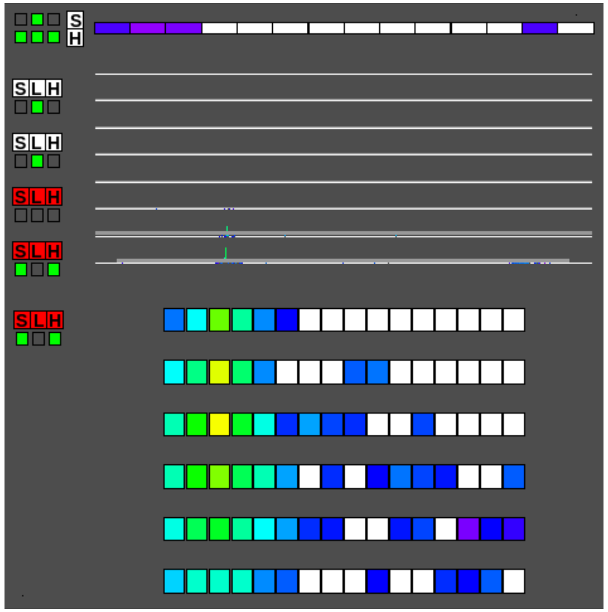
gamma-ray

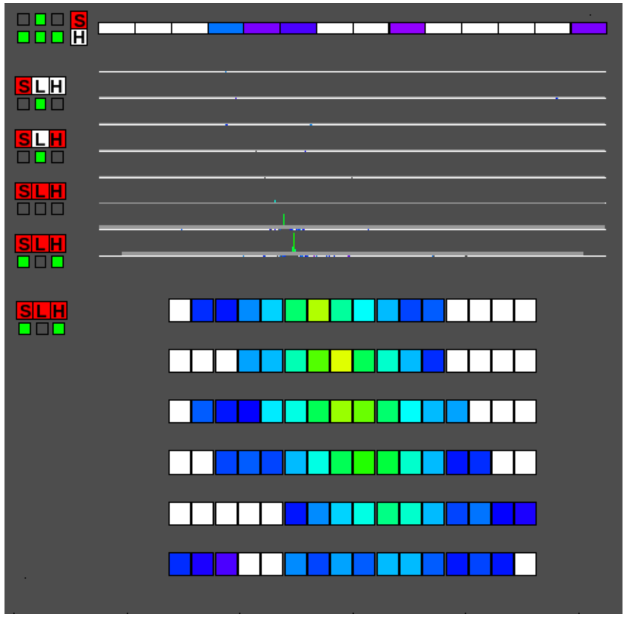
electron

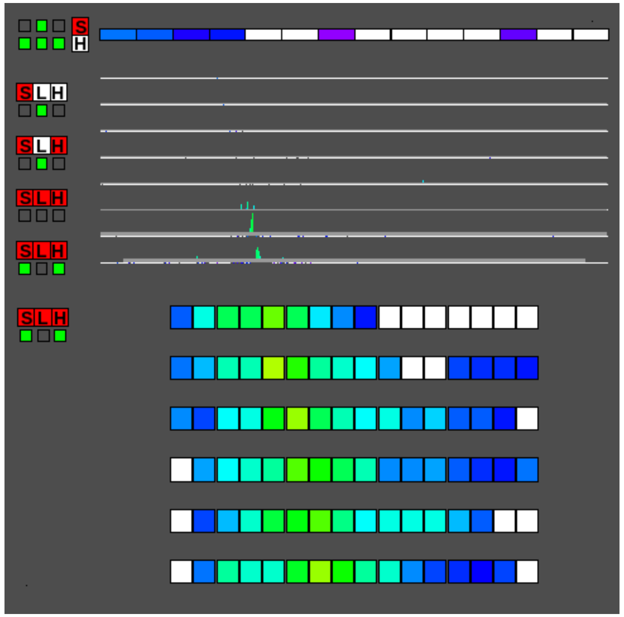
proton

Charge Z=0

Charge Z=1







Electromagnetic Shower

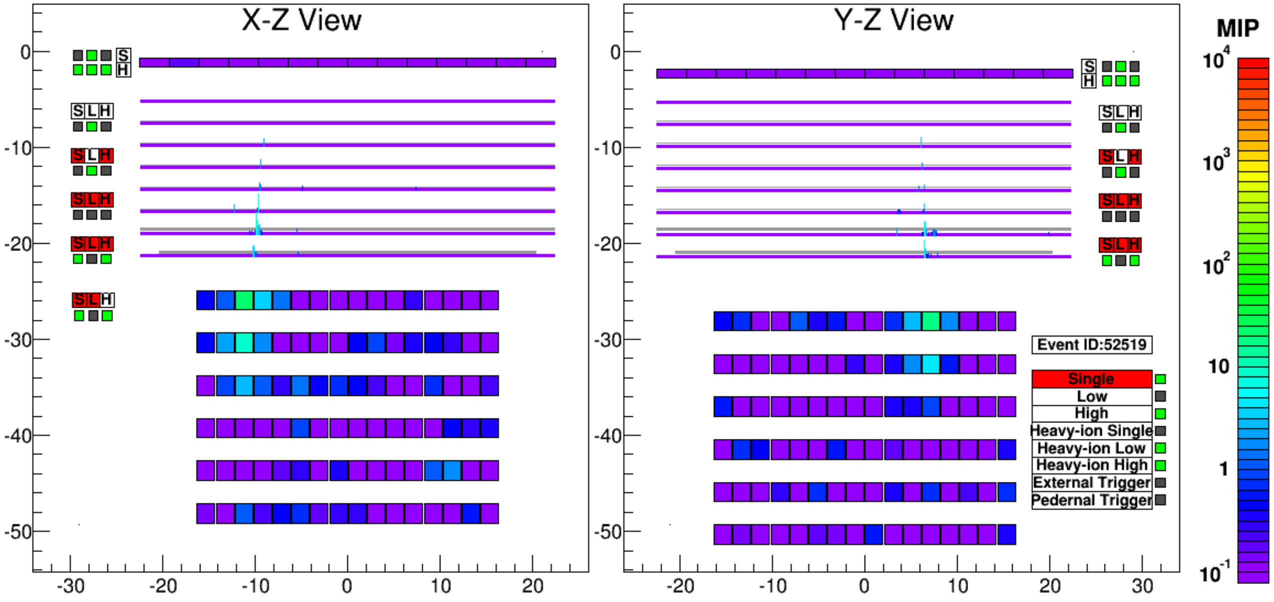
Hadron Shower

well contained, constant shower development

larger spread

# Gamma Ray Event Selection

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

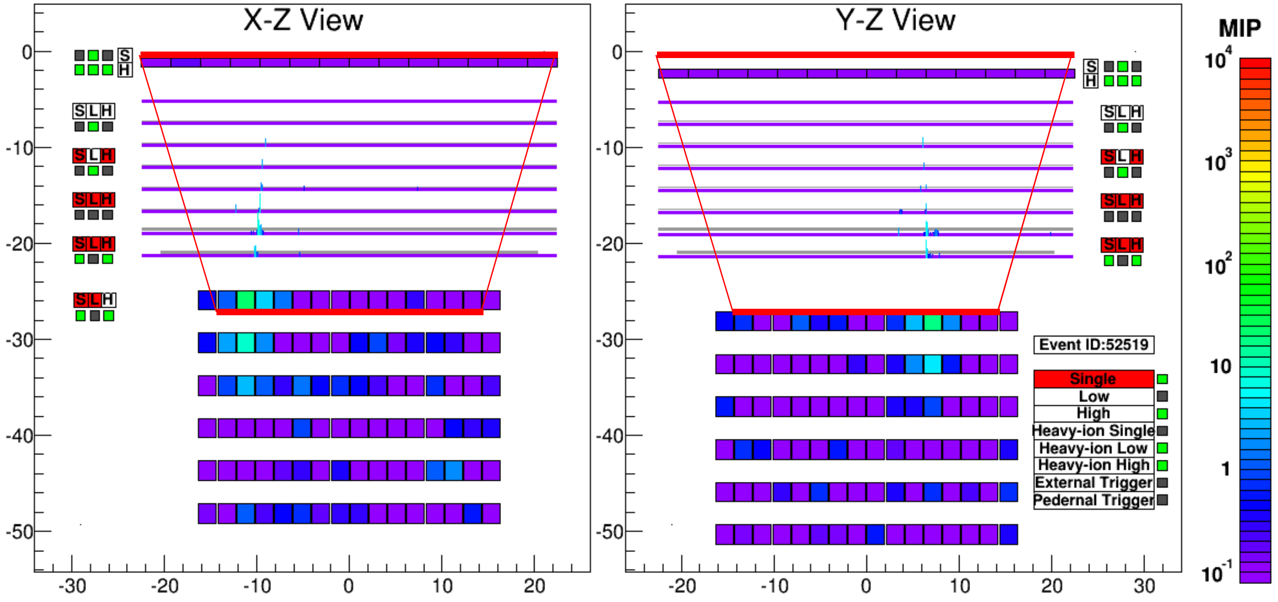


An example of gamma-ray event candidate in flight data
(reconstructed primary energy ~5GeV)

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**



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.

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)
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# Gamma Ray Event Selection

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

**“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]

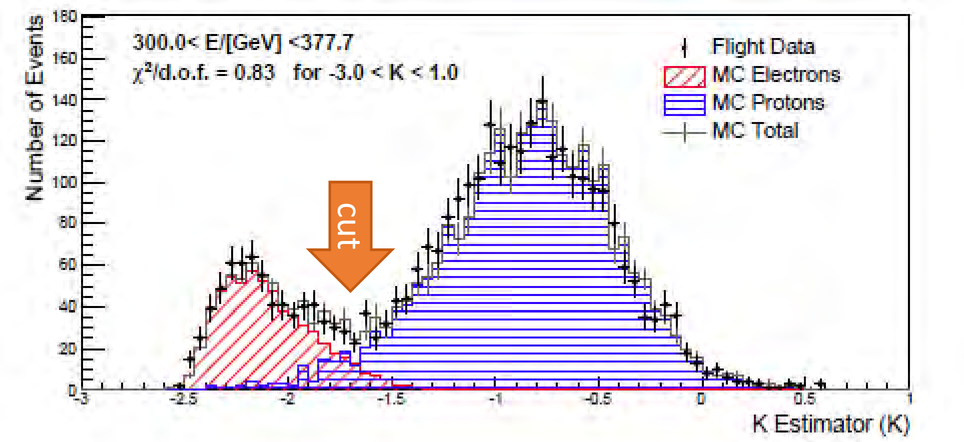


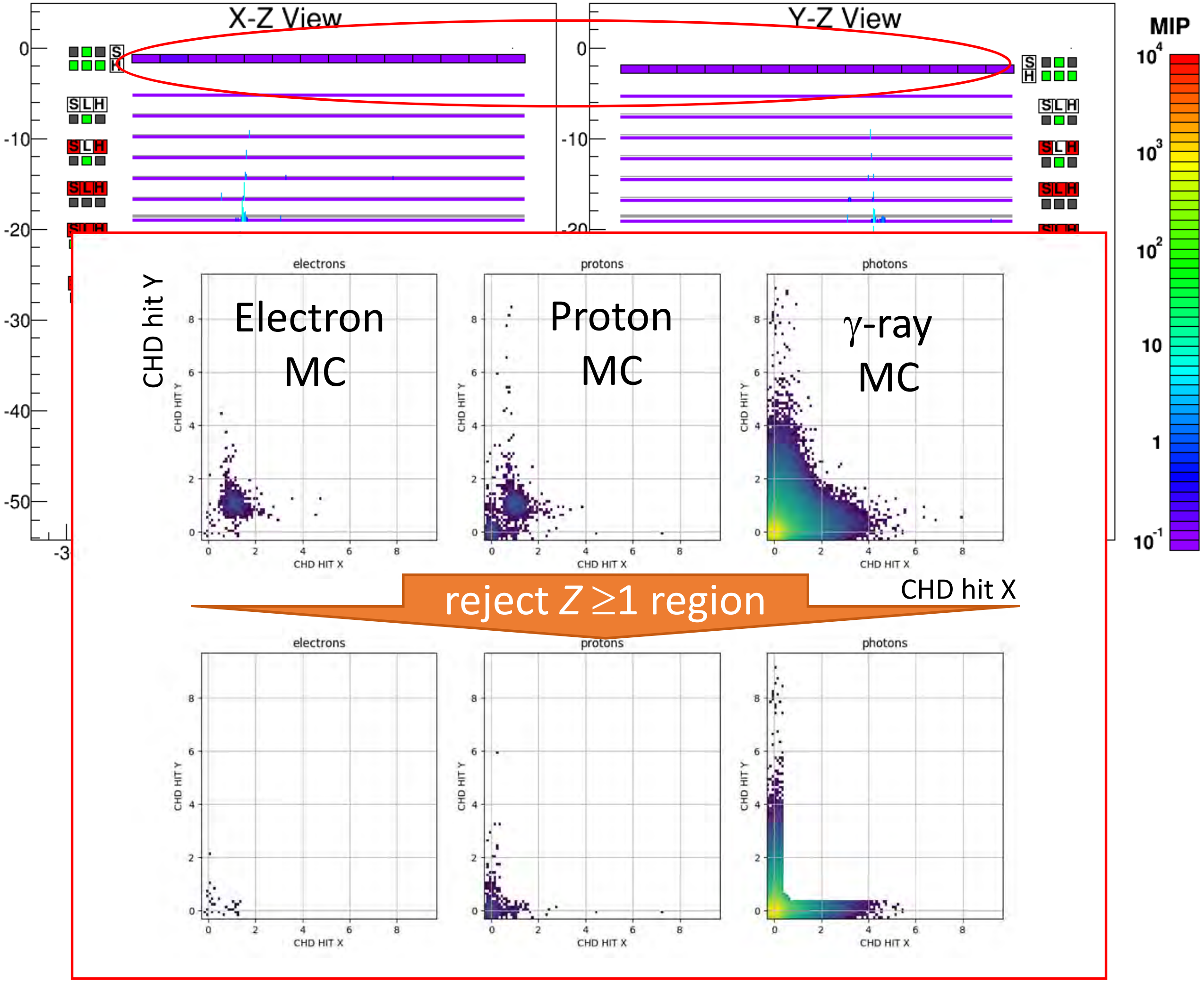
FIG. 2. An example of K-estimator distribution in the 300 < $E$ < 378 GeV bin. The reduced chi-square of the fit in the K-estimator range from -3 to 1 is 0.83.

*O. Adriani et al., PRL 119, 181101 (2017) supplemental material*

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**

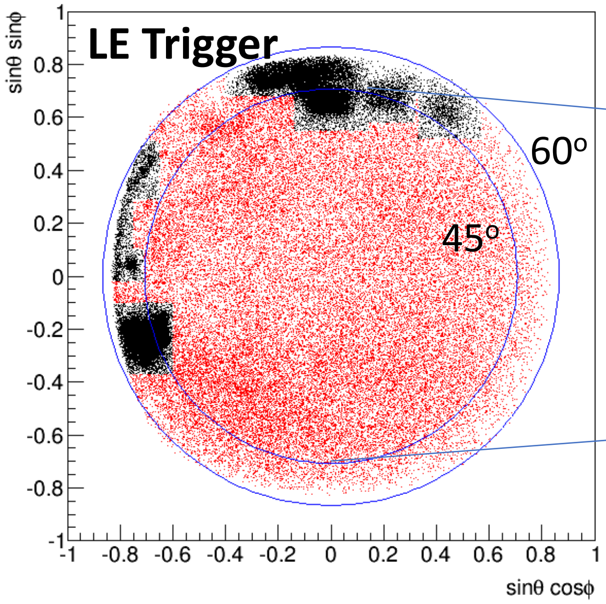


1. Geometry Condition
   - CHD-Top to TASC 1st layer (2cm margin)
2. Pre selection
   - Offline trigger
   - Shower concentration
   - Shower starting point
3. Track quality cut
   - Track hits >2
   - matching w/ TASC
4. Electromagnetic shower selection
   - shower shape
5. **Gamma-ray ID**
   - **CHD/IMC-veto (combination of loose cuts)**
6. FOV cut

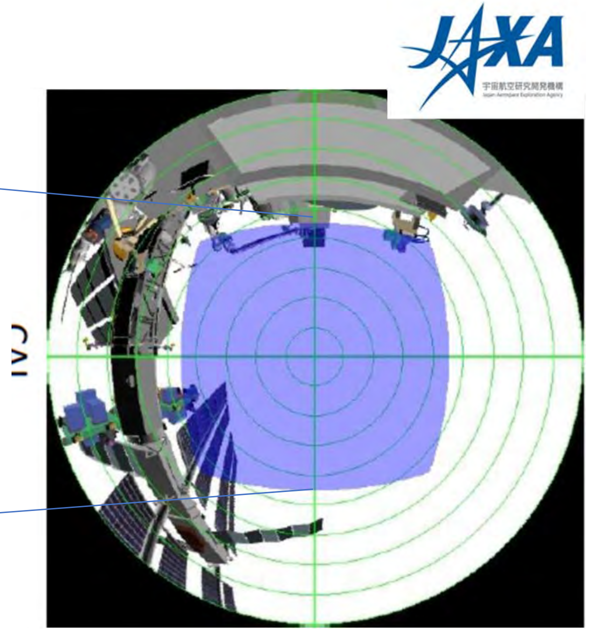
# Gamma Ray Event Selection

**= 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



Gamma-ray candidates in CALET FOV



Fish-eye view of CALET FOV

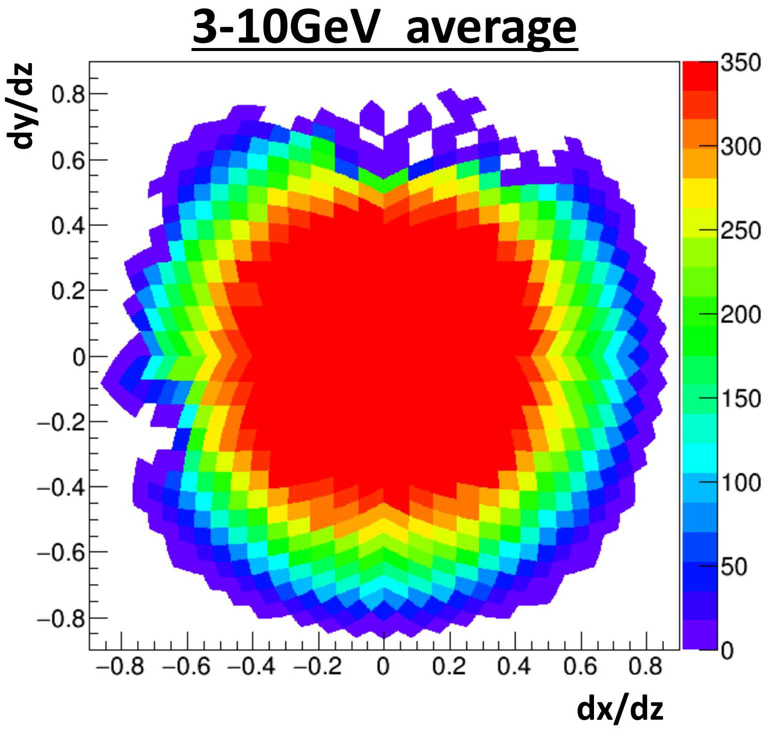
By removing Black parts, it is possible to reject majority of such background. More sophisticated rejection method is under development.

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

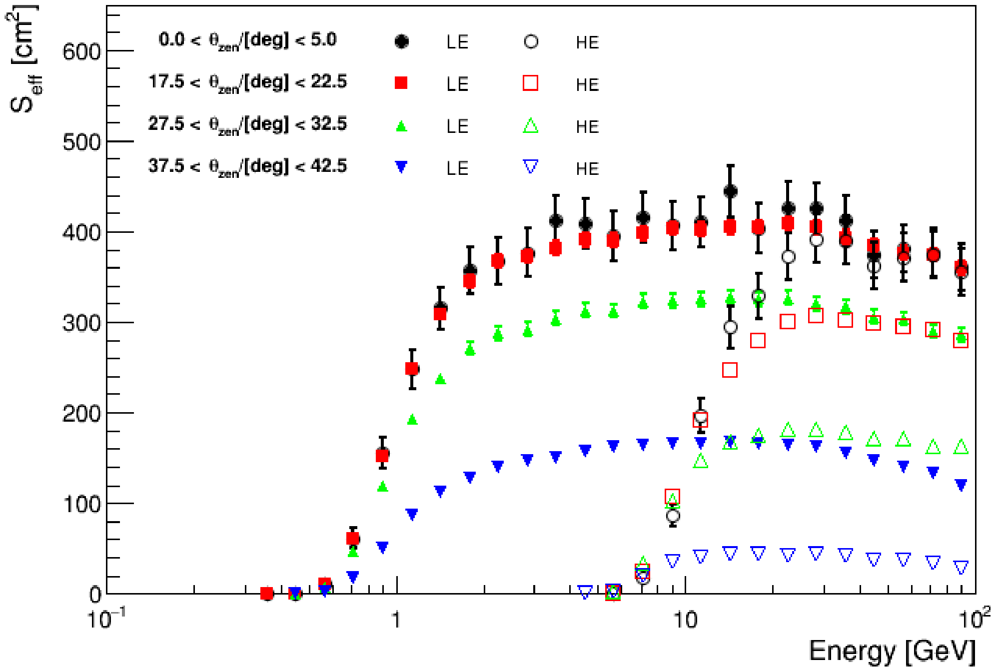
# Effective Area and Sensitivity

Preliminary
O. Adriani et al., in prep.

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$^{-2}$.



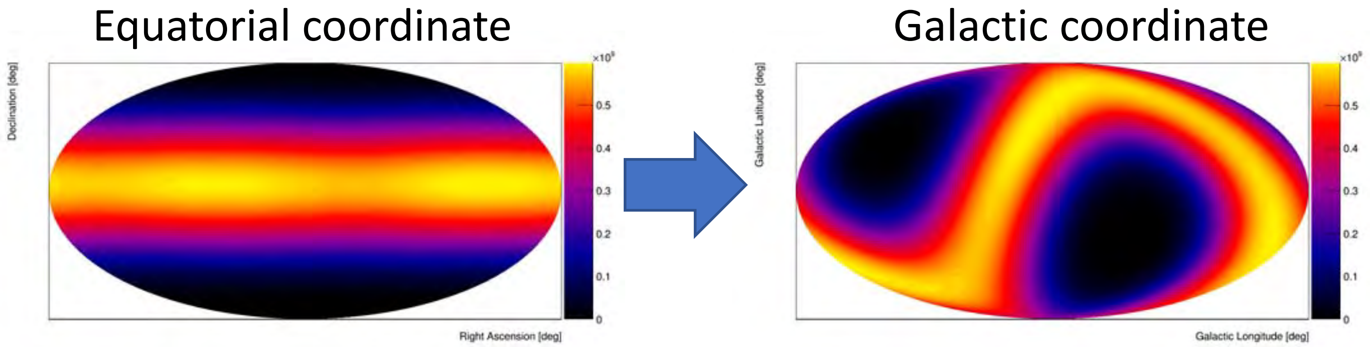
Mostly axially symmetric except for FOV cut



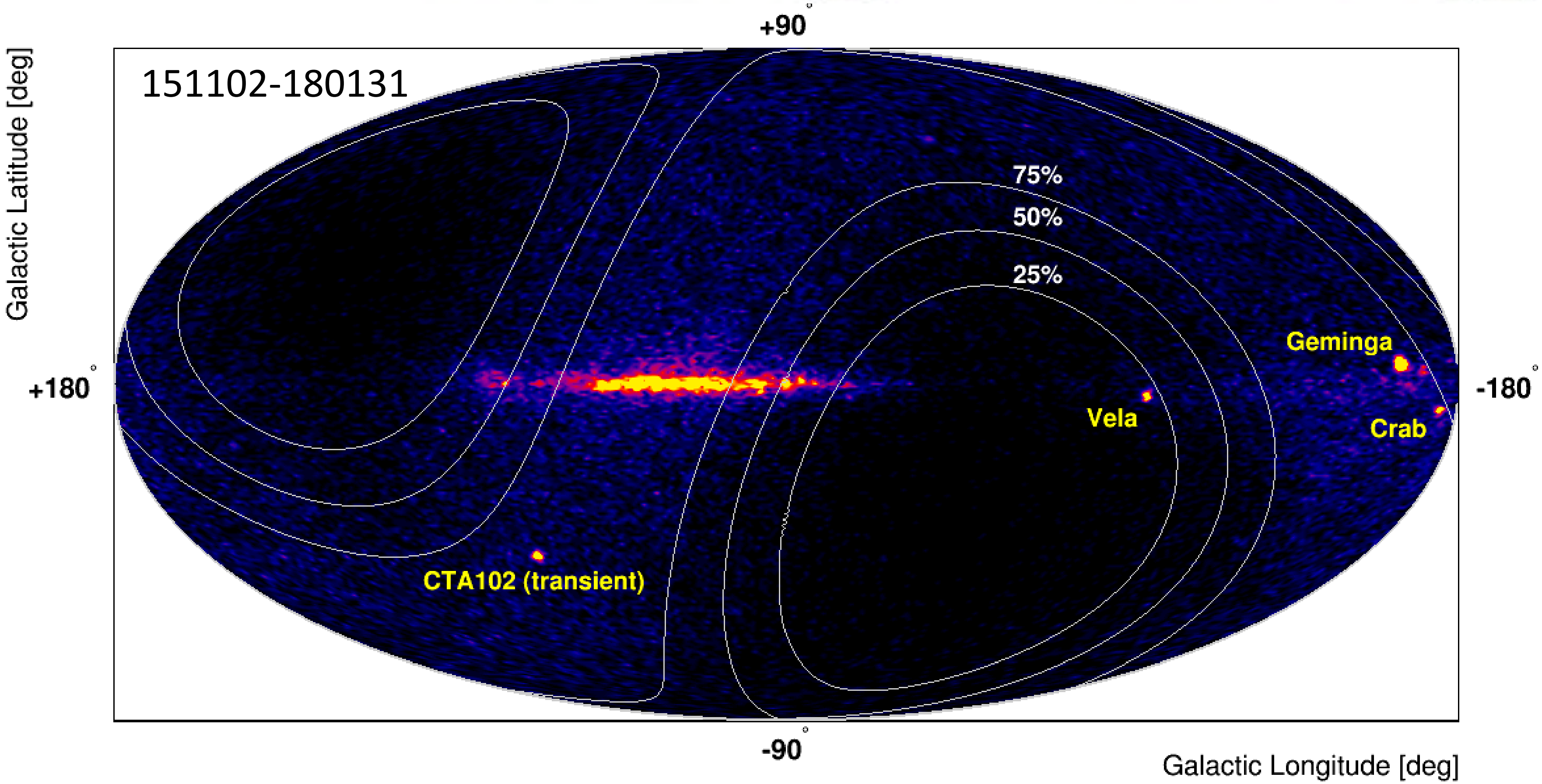
Effective area as a function of energy. Four representing zenith angle ranges are shown.

# CALET Sky Map w/ LE-$\gamma$ Trigger ($E$>1GeV)

While exposure is not uniform, we have clearly identified the galactic plane and bright GeV sources.


Equatorial coordinate

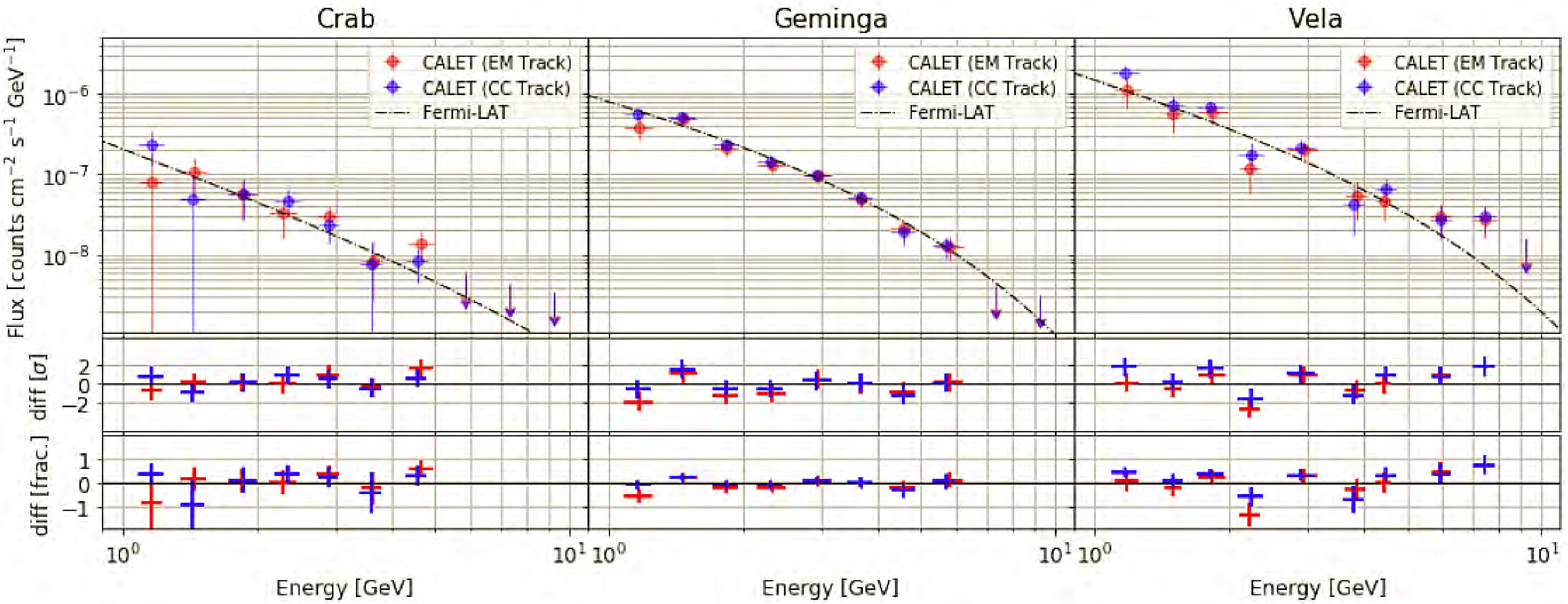
Galactic coordinate



# Point Source Spectra: Sensitivity Validation

<u>CALET Preliminary</u>

N. Cannady et al., in prep.

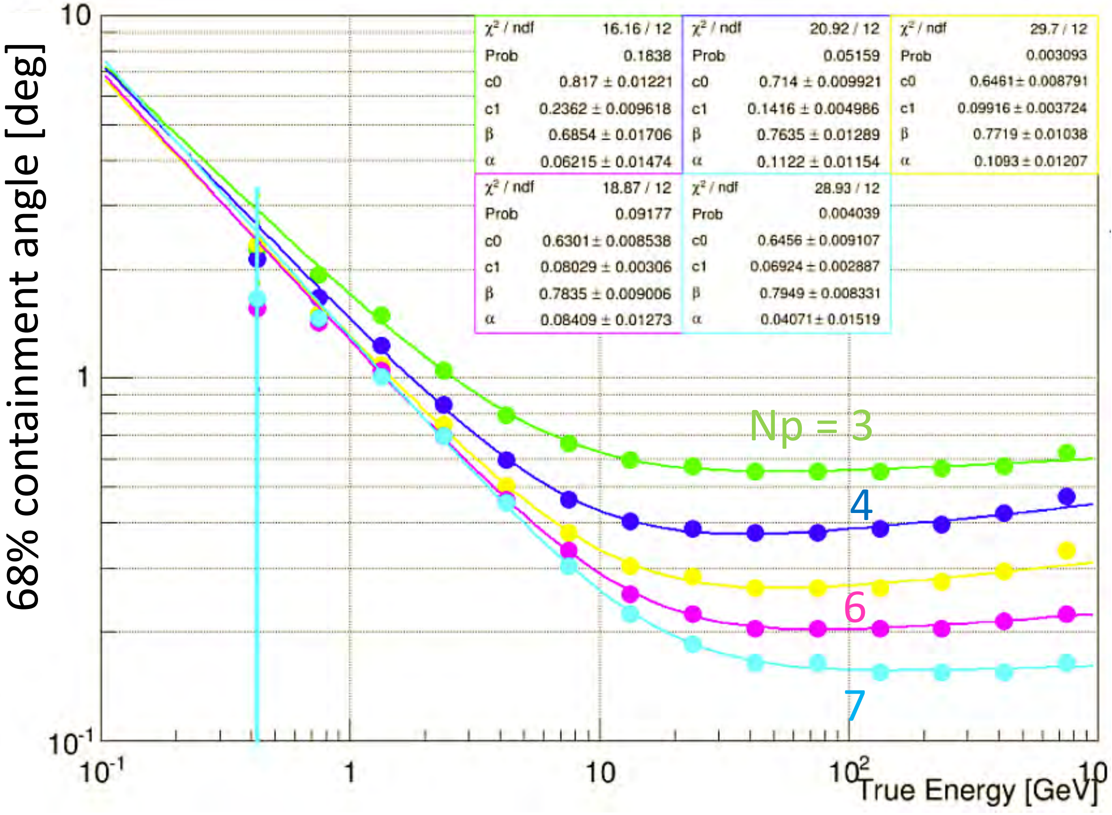


Fermi-LAT’s parameterizations. Therefore, it was found that current selection criteria has a validated sensitivity and can be used to set limit on GW counterpart flux.

N. Cannady et al., in prep.

# Angular resolution

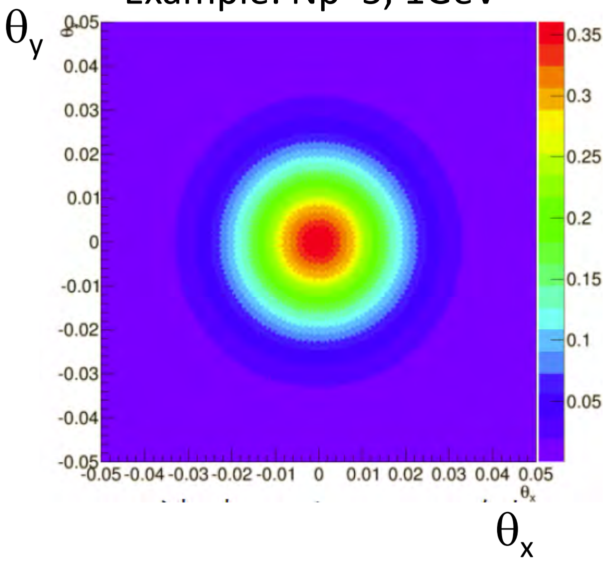
- Containment angles by Monte Carlo simulation



$$S_p(E, N_p) = \sqrt{\left(c_0 E^{-\beta}\right)^2 + c_1^2} \times \left(1 + E^{\delta}\right)$$

Np : number of points used for track reconstruction

Example: Np=5, 1GeV



# Gravitational-wave events by LIGO/Virgo

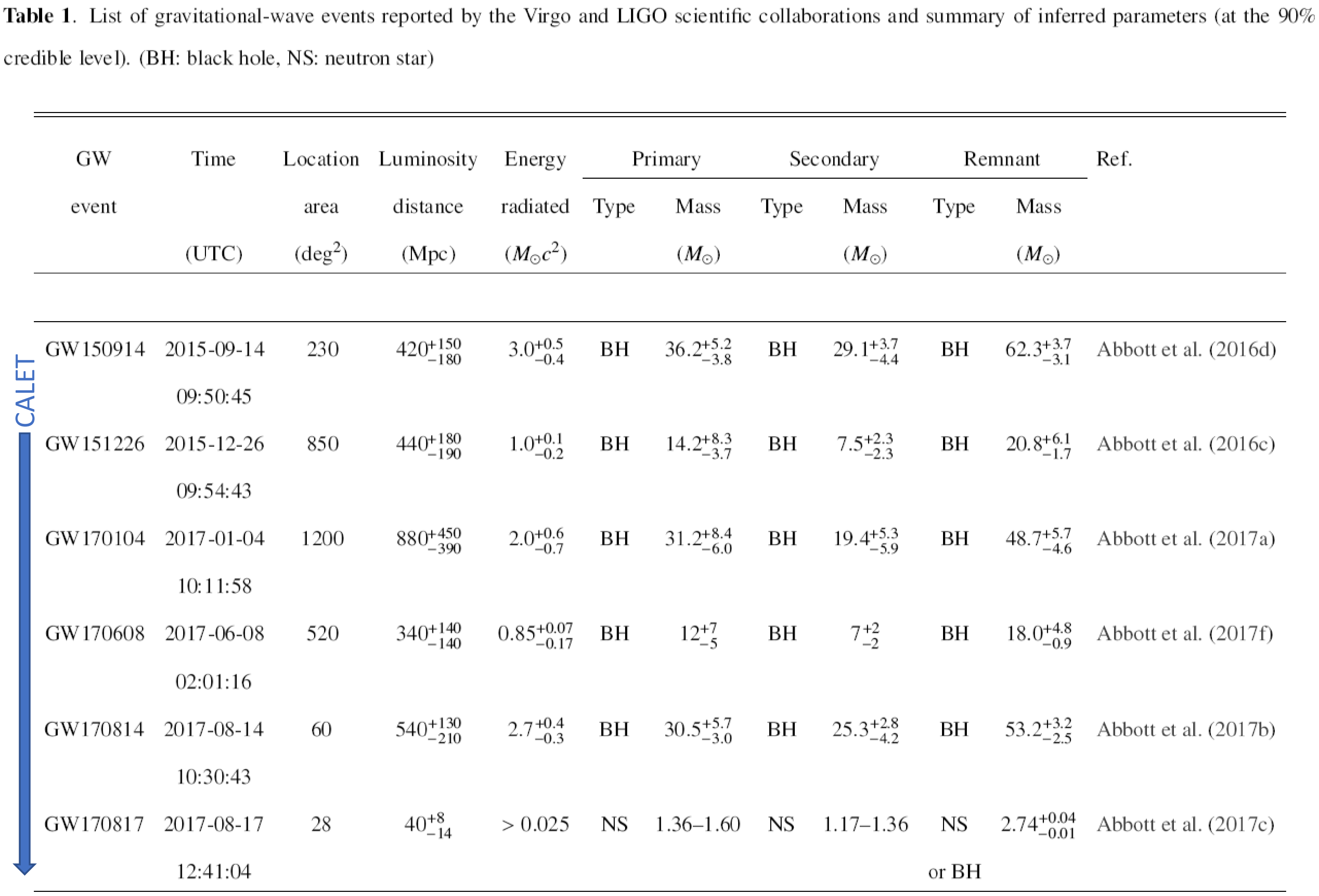
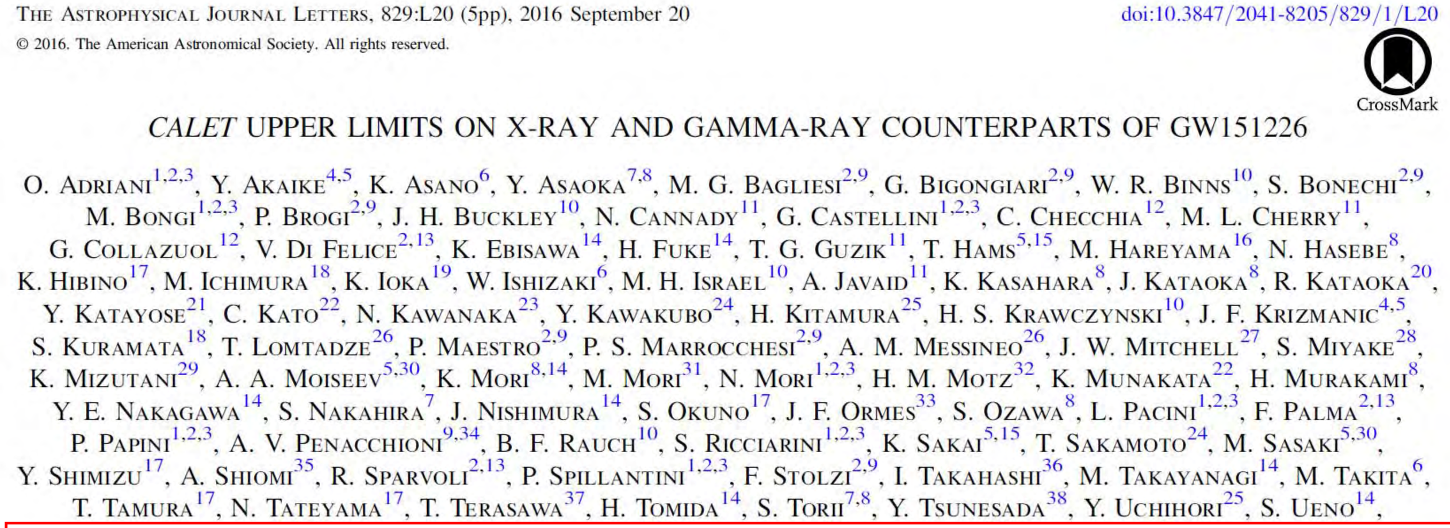


**Table 1.** List of gravitational-wave events reported by the Virgo and LIGO scientific collaborations and summary of inferred parameters (at the 90% credible level). (BH: black hole, NS: neutron star)

| GW event | Time (UTC) | Location area (deg$^2$) | Luminosity distance (Mpc) | Energy radiated ($M_\odot c^2$) | Primary | | Secondary | | Remnant | | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Type | Mass ($M_\odot$) | Type | Mass ($M_\odot$) | Type | Mass ($M_\odot$) | |
| GW150914 | 2015-09-14 09:50:45 | 230 | $420^{+150}_{-180}$ | $3.0^{+0.5}_{-0.4}$ | BH | $36.2^{+5.2}_{-3.8}$ | BH | $29.1^{+3.7}_{-4.4}$ | BH | $62.3^{+3.7}_{-3.1}$ | Abbott et al. (2016d) |
| GW151226 | 2015-12-26 09:54:43 | 850 | $440^{+180}_{-190}$ | $1.0^{+0.1}_{-0.2}$ | BH | $14.2^{+8.3}_{-3.7}$ | BH | $7.5^{+2.3}_{-2.3}$ | BH | $20.8^{+6.1}_{-1.7}$ | Abbott et al. (2016c) |
| GW170104 | 2017-01-04 10:11:58 | 1200 | $880^{+450}_{-390}$ | $2.0^{+0.6}_{-0.7}$ | BH | $31.2^{+8.4}_{-6.0}$ | BH | $19.4^{+5.3}_{-5.9}$ | BH | $48.7^{+5.7}_{-4.6}$ | Abbott et al. (2017a) |
| GW170608 | 2017-06-08 02:01:16 | 520 | $340^{+140}_{-140}$ | $0.85^{+0.07}_{-0.17}$ | BH | $12^{+7}_{-5}$ | BH | $7^{+2}_{-2}$ | BH | $18.0^{+4.8}_{-0.9}$ | Abbott et al. (2017f) |
| GW170814 | 2017-08-14 10:30:43 | 60 | $540^{+130}_{-210}$ | $2.7^{+0.4}_{-0.3}$ | BH | $30.5^{+5.7}_{-3.0}$ | BH | $25.3^{+2.8}_{-4.2}$ | BH | $53.2^{+3.2}_{-2.5}$ | Abbott et al. (2017b) |
| GW170817 | 2017-08-17 12:41:04 | 28 | $40^{+8}_{-14}$ | $> 0.025$ | NS | 1.36–1.60 | NS | 1.17–1.36 | NS or BH | $2.74^{+0.04}_{-0.01}$ | Abbott et al. (2017c) |

# GW Counterpart Search with CALET



The Astrophysical Journal Letters, 829:L20 (5pp), 2016 September 20
doi:10.3847/2041-8205/829/1/L20

*CALET* UPPER LIMITS ON X-RAY AND GAMMA-RAY COUNTERPARTS OF GW151226

O. Adriani[1,2,3], Y. Akaike[4,5], K. Asano[6], Y. Asaoka[7,8], M. G. Bagliesi[2,9], G. Bigongiari[2,9], W. R. Binns[10], S. Bonechi[2,9],
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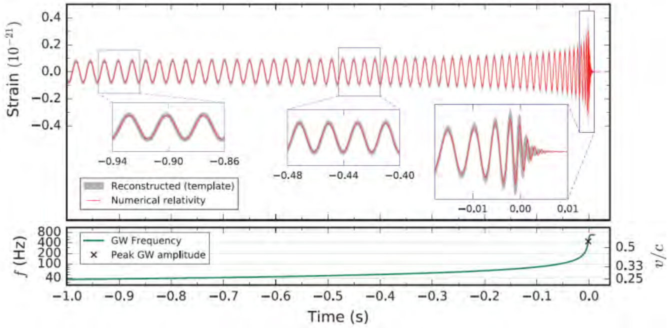
**Published in ApJ Letters**

## GW 151226 [B. P. Abbott *et al.*, PRL 116 (2016) 241103]

- GW trigger Time: 2015/12/26 3:38:53.647 UT
  - **gravitational-wave signal** produced by the coalescence of two stellar-mass black holes at a luminosity distance of ~440Mpc.



## CALET Observation

- CGBM HV-on (3:20 – 3:40 UT)
  - No on-board trigger
- CAL: low-energy gamma-ray mode (> 1GeV) 3:30-3:43UT

CALET Preliminary

N. Cannady et al., in prep.

# Analysis update

- EM Track … developed and used extensively for electron analysis
- CC Track … developed specifically for low energy gamma-rays

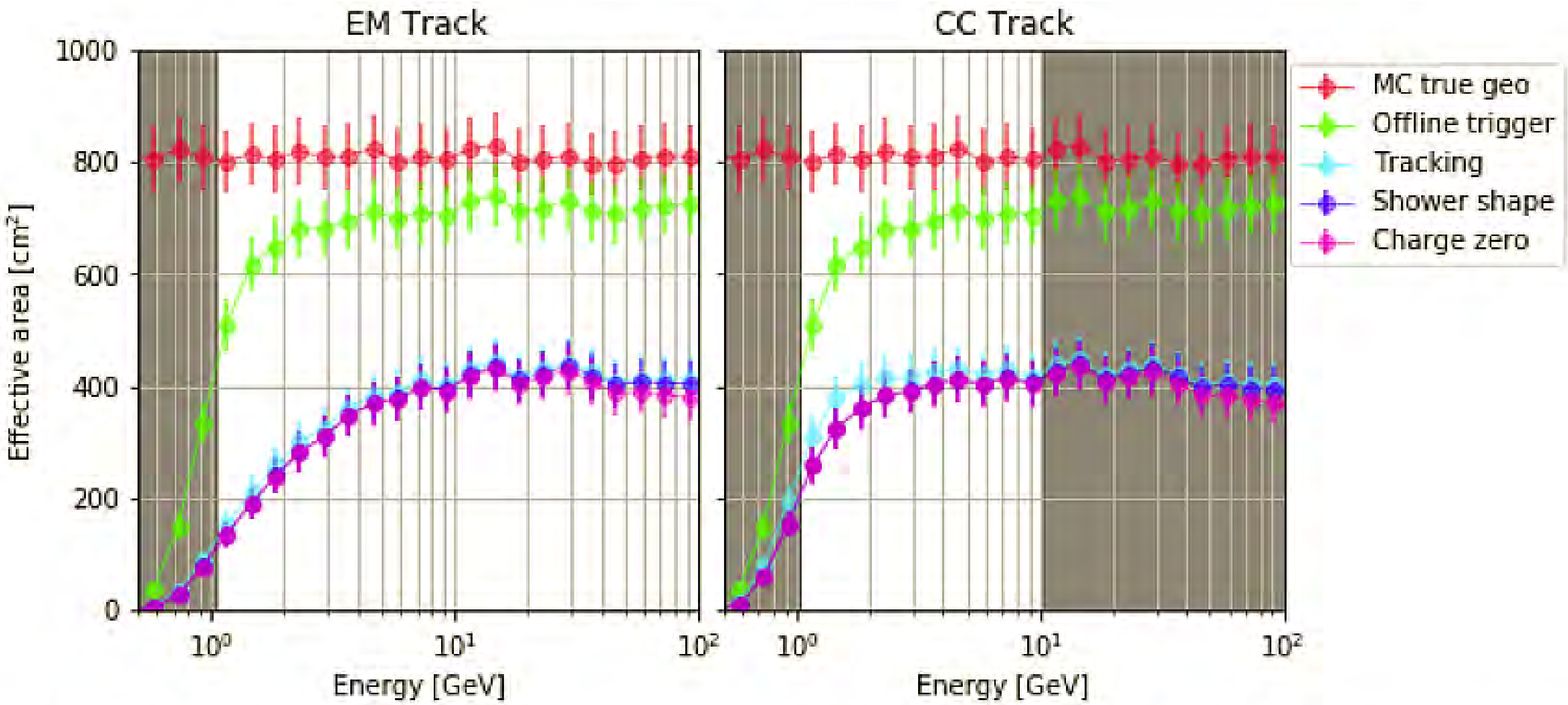
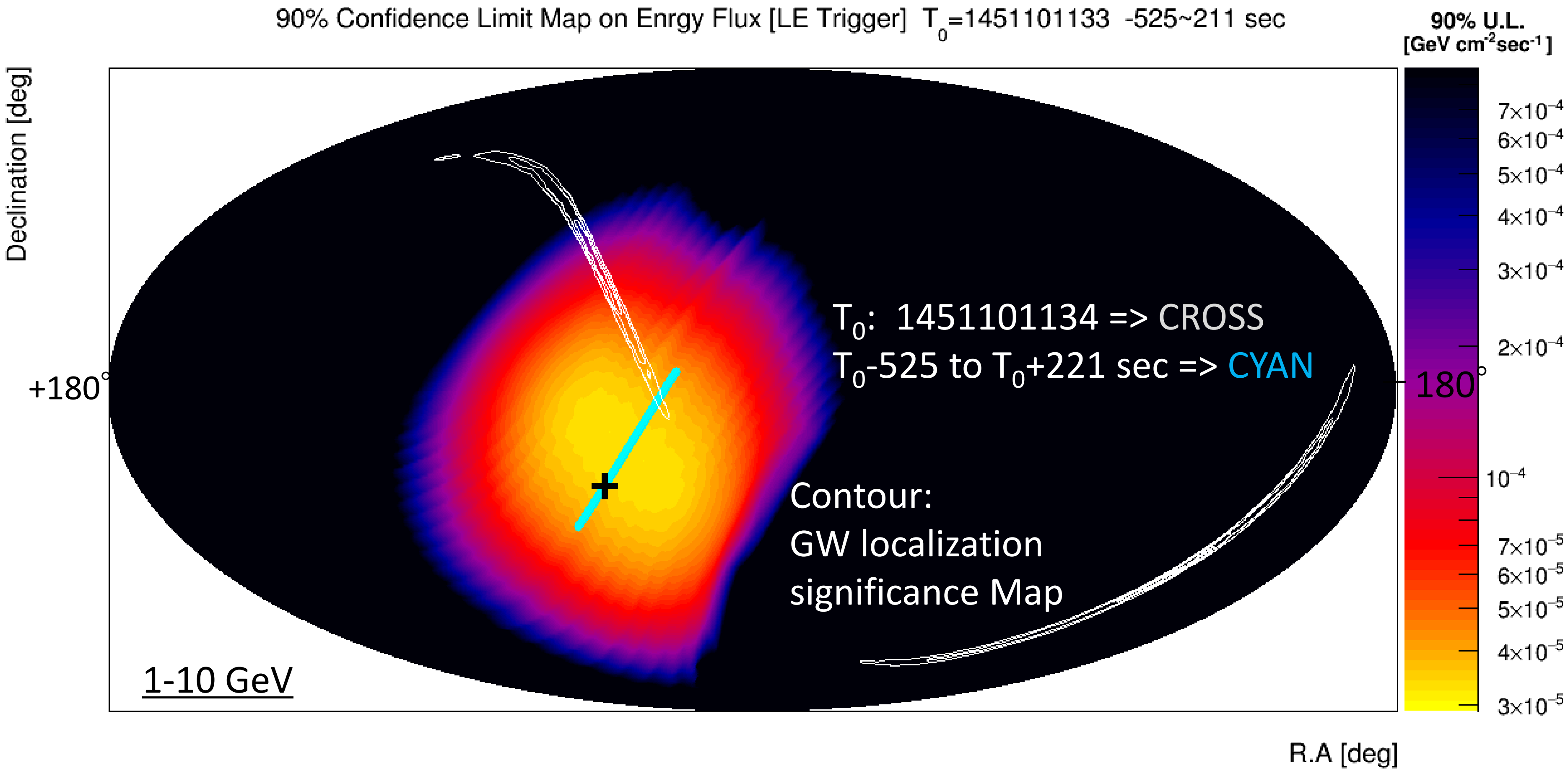


**Figure 3.** Effect of various selection cuts in zenith-pointing effective area. Grey shaded regions demonstrate the limits of applicability for each track due to background contamination with poor agreement between flight data and simulation.

# 90% CL Upper limit for GW151226 Counterpart Search

Preliminary
O. Adriani et al., in prep.

**NO event remained after applying all the selection criteria.**



$T_0$: 1451101134 => CROSS
$T_0$-525 to $T_0$+221 sec => CYAN

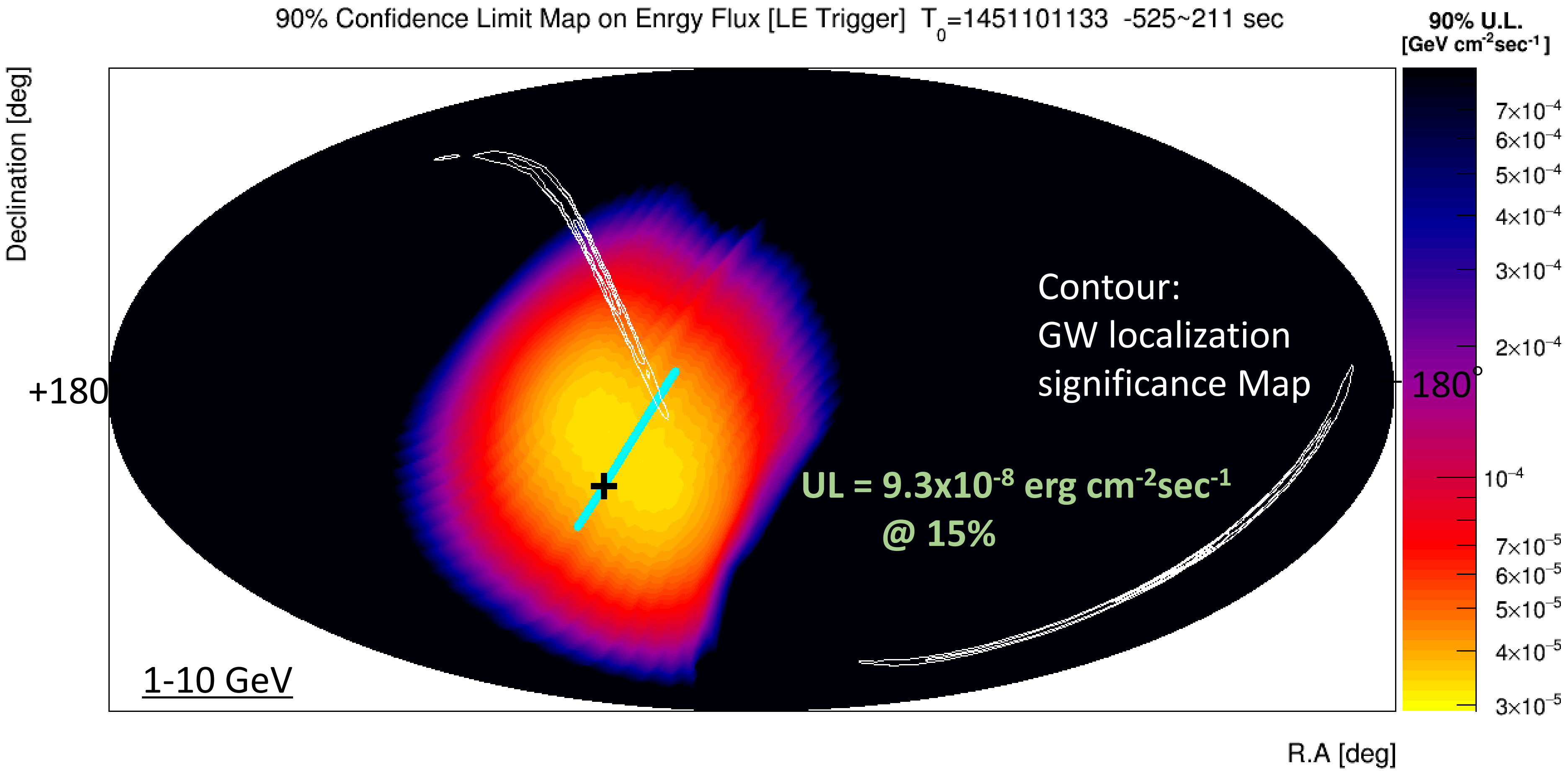
Contour:
GW localization
significance Map

1-10 GeV

**Background contamination is negligible in such a short time period.**

# 90% CL Upper limit for GW151226 counterpart search

Preliminary
O. Adriani et al., in prep.



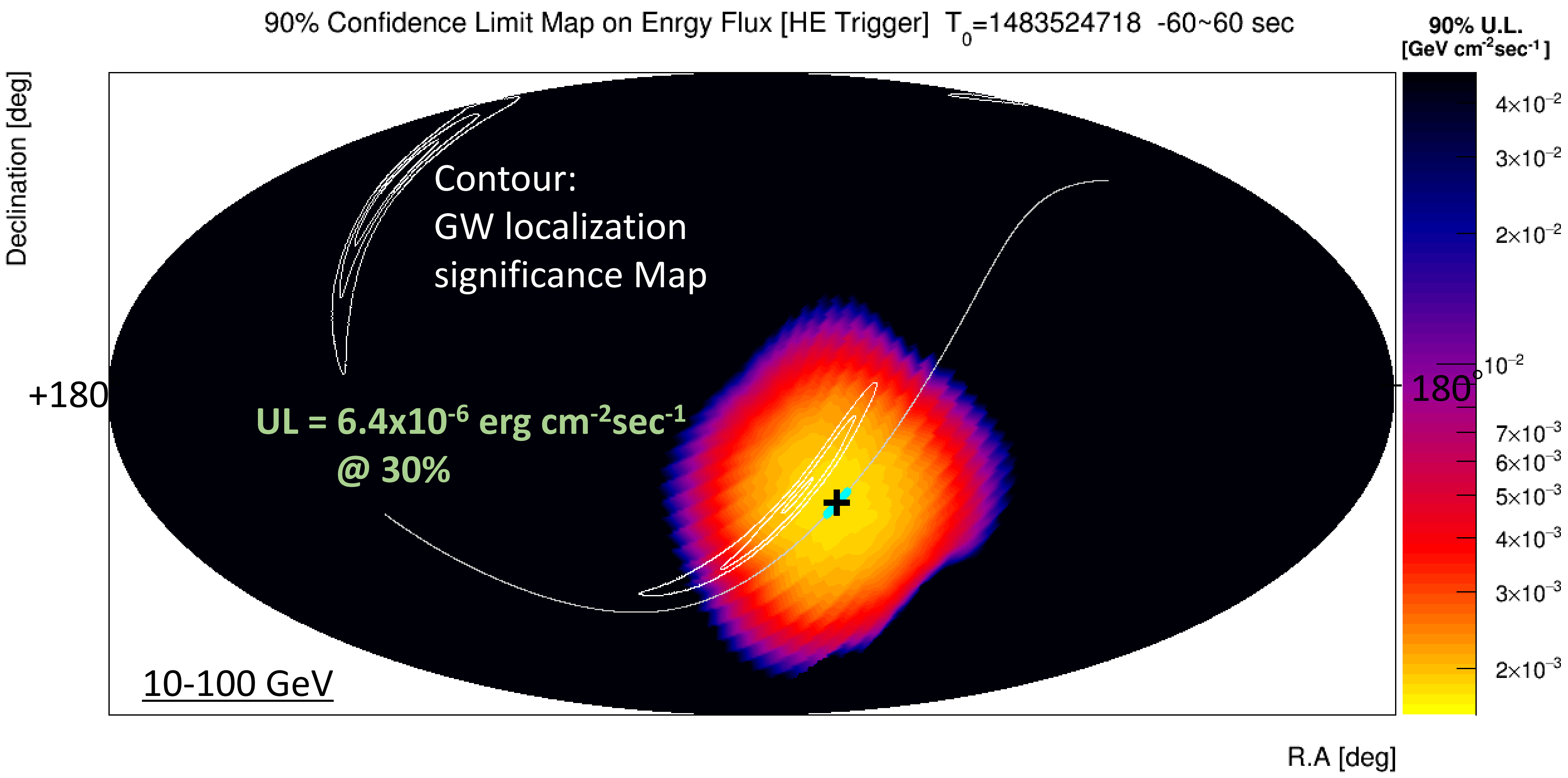
Contour:
GW localization
significance Map

**UL = $9.3 \times 10^{-8}$ erg $cm^{-2} sec^{-1}$**
**@ 15%**

CALET observation constrains at least some portion of LIGO probability.

# 90% CL Upper limit for GW170104 counterpart search

Preliminary
O. Adriani et al., in prep.



Contour:
GW localization
significance Map

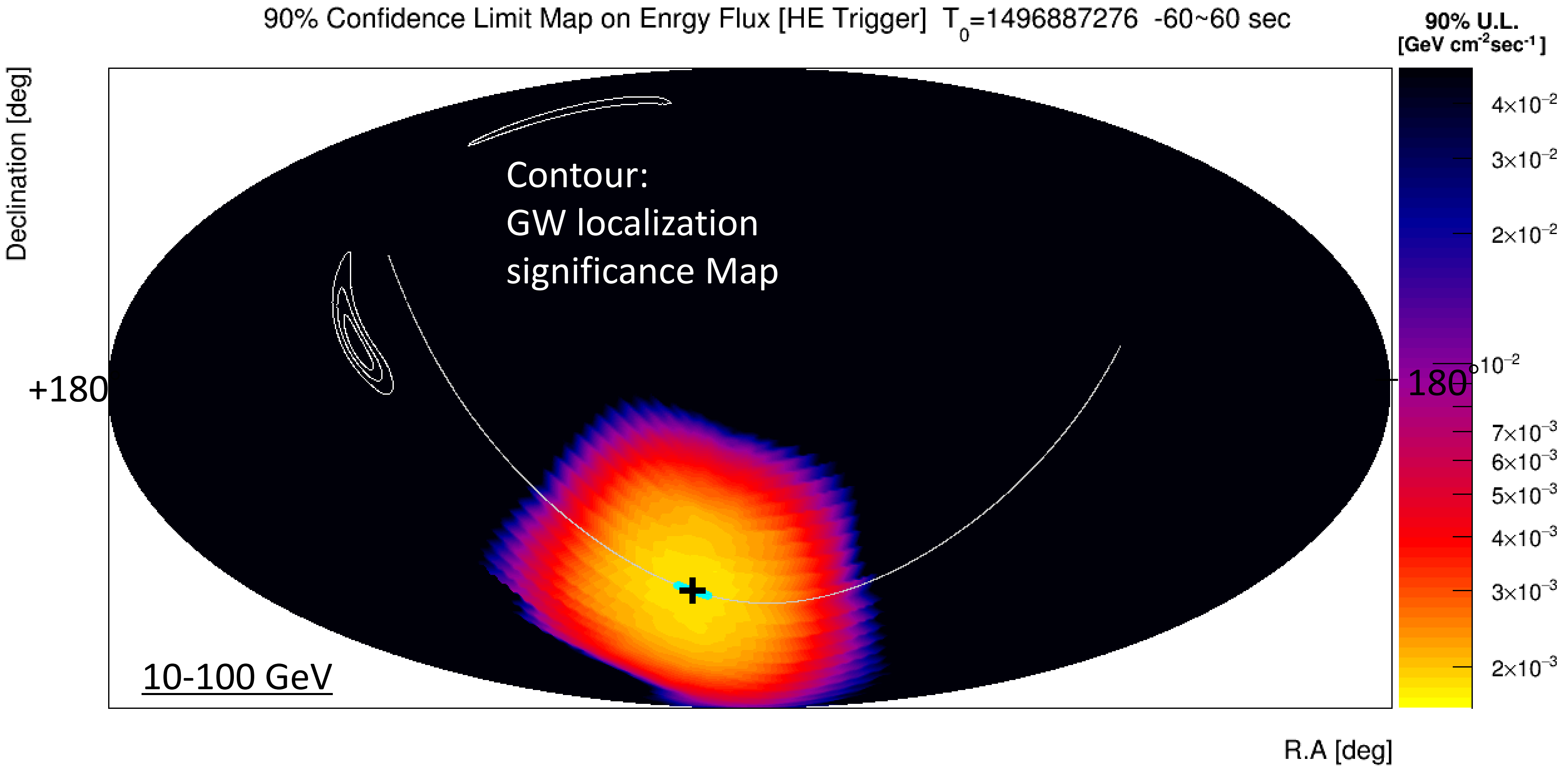
**UL = 6.4x10$^{-6}$ erg cm$^{-2}$sec$^{-1}$**
**@ 30%**

10-100 GeV

CALET observation constrains at least some portion of LIGO probability.

# 90% CL Upper limit for GW170608 counterpart search

Preliminary
O. Adriani et al., in prep.



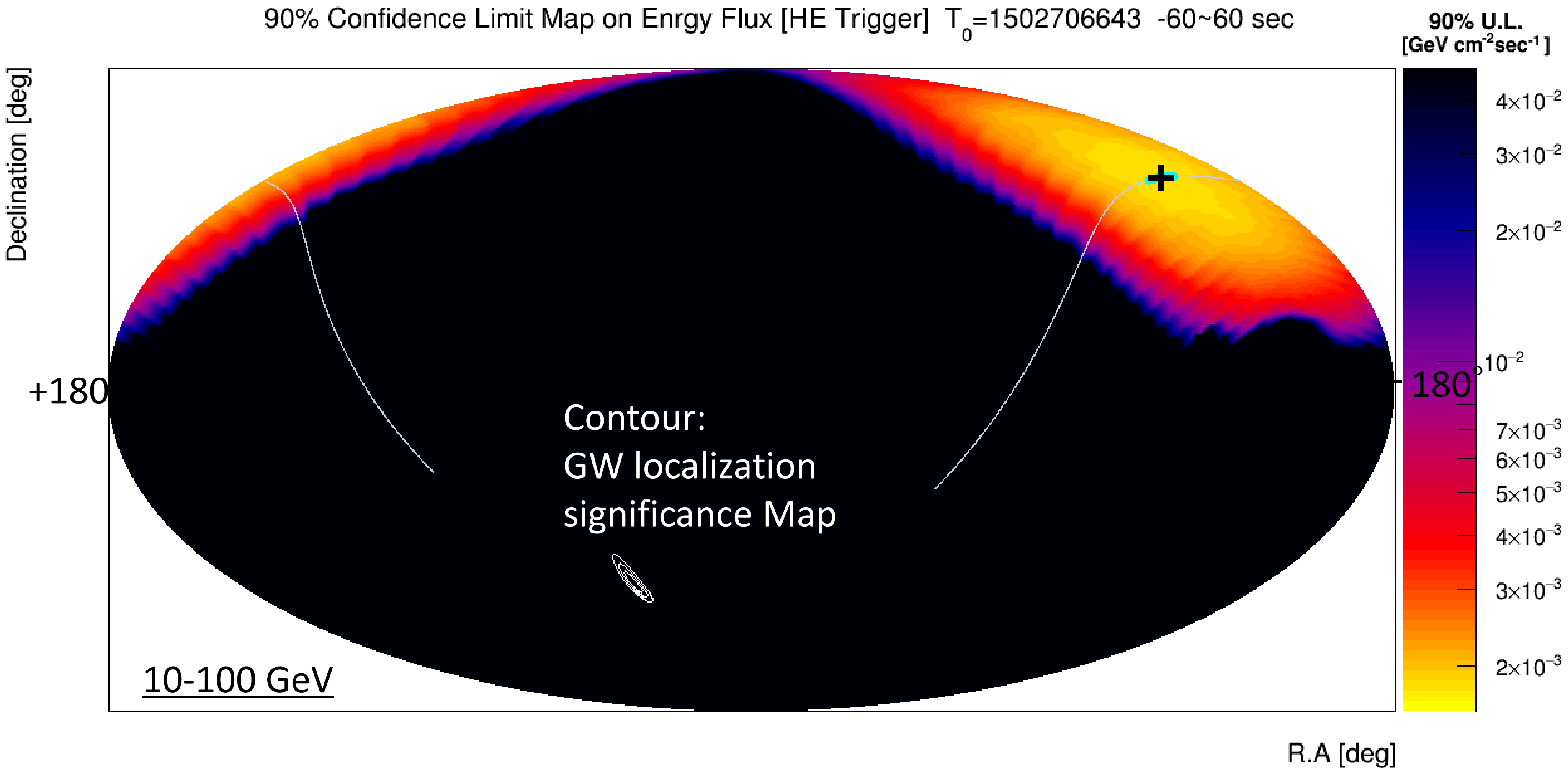
Contour:
GW localization
significance Map

10-100 GeV

CALET observation was out of localized region of LIGO event.

# 90% CL Upper limit for GW170814 counterpart search

Preliminary
O. Adriani et al., in prep.



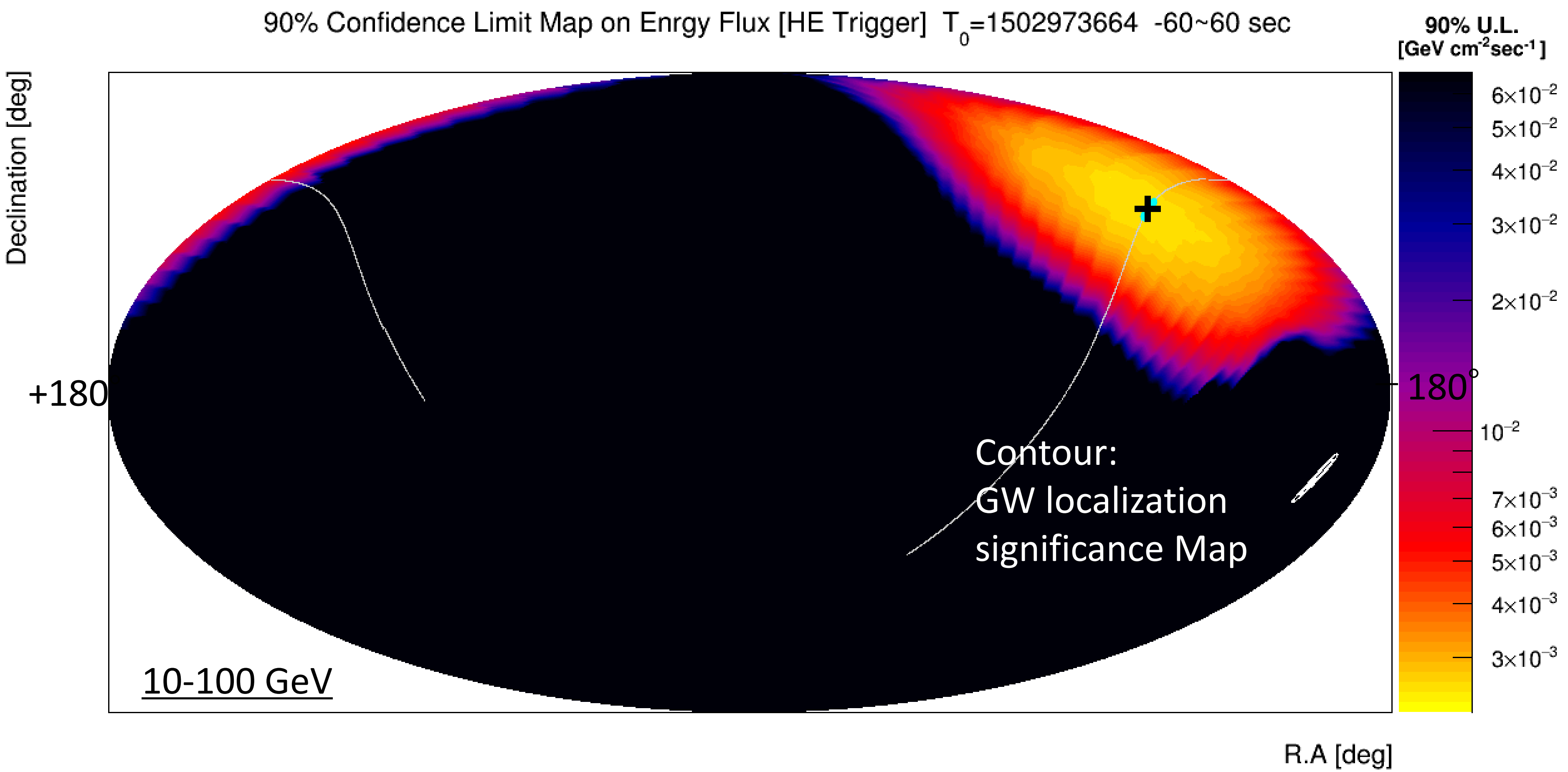
Contour:
GW localization
significance Map

10-100 GeV

CALET observation was out of localized region of LIGO event.

# 90% CL Upper limit for GW170817 counterpart search

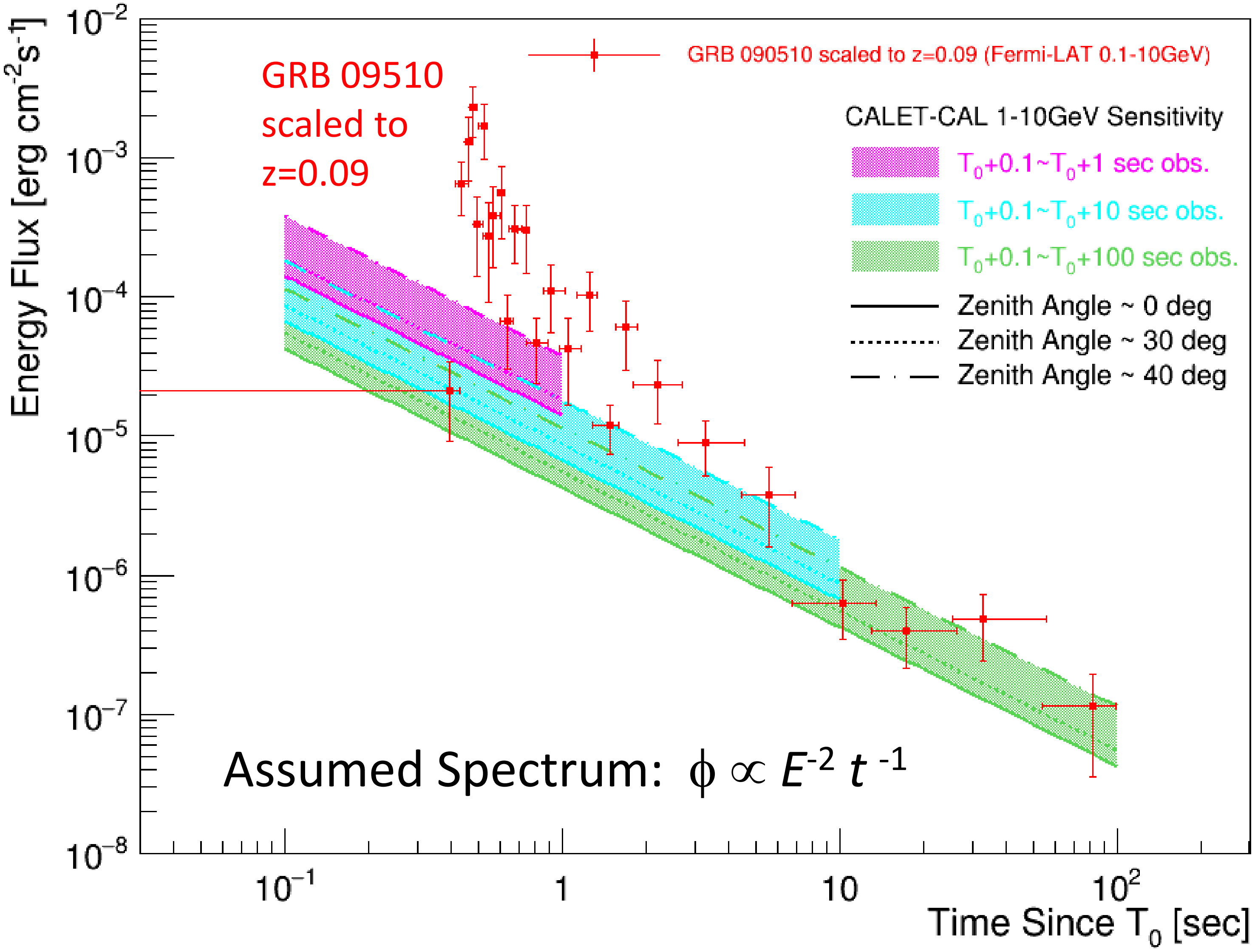
Preliminary
O. Adriani et al., in prep.



CALET observation was out of localized region of LIGO event.

# CALET Sensitivity to GeV Gamma-Rays

Short GRBs accompanied by GeV gamma-ray emissions could be detected by CALET-CAL given the closeness of GW candidates.



GRB 09510 scaled to z=0.09

Assumed Spectrum: $\phi \propto E^{-2}\, t^{-1}$

Preliminary: O. Adriani et al., in prep.

# Summary & Prospects

Preliminary
O. Adriani et al., in prep.

1. **CALET was successfully launched on Aug. 19, 2015, and the detector is being very stable for observation since Oct. 13, 2015.**
2. **As a result of GW151226 counterpart search in GeV gamma-rays, CALET-CAL observation constrains 15% of LIGO localization map by 90% upper limit flux of 9.3x10$^{-8}$ erg cm$^{-2}$sec$^{-1}$ (1-10GeV).**
3. **GeV gamma-ray counterpart of other GW events during O1&O2 have been performed and limits are set if there are overlap between our FOV and LIGO/Virgo localization map.**
4. **Its sensitivity was validated with diffuse and point-source observations.**
5. **Due to closeness of GW candidates, FOV coverage is more important than deepness of counterpart search assuming on-axis short GRBs as candidates.**
6. **Automated pipeline to search for gamma-ray transient was also developed and is being implemented.**

   **⇒Transient objects such as GW counterparts and GRBs, as well as flaring point sources will be monitored.**

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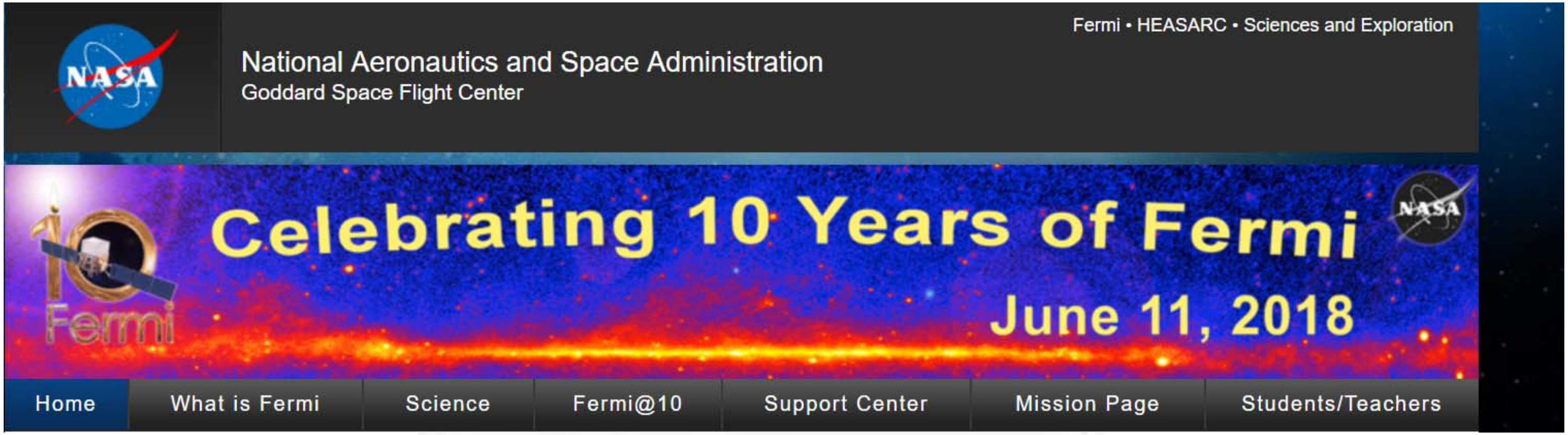
https://fermi.gsfc.nasa.gov/



## Latest News

**Mar 20, 2018**

**Fermi Spacecraft Operational Anomaly**

At 5:11 UT on March 16, Fermi encountered an issue with the solar array drive that caused the observatory to go into safe hold. In this mode, the instruments are powered off, and thus science data taking has stopped. Initial investigation suggests that one of the solar panels is stuck.

Investigation into the cause of the anomaly is ongoing and will continue for some time. We are exploring options to resume some science operations with a fixed solar panel which would run while the anomaly investigations are ongoing. The team is planning to start a return to science ops next week, to run in parallel with the ongoing engineering investigation.

GeV sky
- Agile
- CALET/CAL
- DAMPE (Wukong)