The CALorimetric Electron Telescope (CALET) on the ISS: Preliminary Results from the On-orbit Observations since October, 2015

Shoji Torii
for the CALET collaboration
Waseda University

ICRC2017
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The Astroparticle Physics Conference
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BEXCO, BUSAN, KOREA

Highlight Talk (CRD) 14 July, 2017

Outline

- Overview of CALET
- Science Targets
- Observation and calibration in orbit
- Preliminary results of the observations
  - protons, heavy nuclei, ultra heavy nuclei
  - electrons (+ positrons)
  - gamma-rays
- Extra observations
  - Follow-up observations of the GW events
  - Detection of relativistic electron precipitation (Space weather science)
- Summary and future prospects

CALET collaboration team

O. Adriani[25], Y. Akaike[2], K. Asano[7], Y. Asaoka[9,31], M.G. Bagliesi[29], G. Bigongiari[29], W.R. Binns[32], S. Bonechi[29], M. Bongi[25], P. Brogi[29], J.H. Buckley[32], N. Cannady[12], G. Castellini[25], C. Checchia[26], M.L. Cherry[12], G. Collazuol[26], V. Di Felice[28], K. Ebisawa[8], H. Fuke[8], G.A. de Nalfo[14], T.G. Guzik[12], T. Hams[3], M. Hareyama[23], N. Hasebe[31], K. Hibino[10], M. Ichimura[4], K. Ioka[34], W.Ishizaki[7], M.H. Israel[32], A. Javaid[12], K. Kasahara[31], J. Kataoka[31], R. Kataoka[16], Y. Katayose[33], C. Kato[22], Y.Kawakubo[1], N. Kawanaka[30], H. Kitamura[15], H.S. Krawczynski[32], J.F. Krizmanic[2], S. Kuramata[4], T. Lomtadze[27], P. Maestro[29], P.S. Marrocchesi[29], A.M. Messineo[27], J.W. Mitchell[14], S. Miyake[5], K. Mizutani[20], A.A. Moiseev[3], K. Mori[9,31], M. Mori[19], N. Mori[25], H.M. Motz[31], K. Munakata[22], H. Murakami[31], Y.E. Nakagawa[8], S. Nakahira[9], J. Nishimura[8], S. Okuno[10], J.F. Ormes[24], S. Ozawa[31], L. Pacini[25], F. Palma[28], P. Papini[25], A.V. Penacchioni[29], B.F. Rauch[32], S.B. Ricciarini[25], K. Sakai[3], T. Sakamoto[1], M. Sasaki[3], Y. Shimizu[10], A. Shiomi[17], R. Sparvoli[28], P. Spillantini[25], F. Stolzi[29], I. Takahashi[11], M. Takayanagi[8], M. Takita[7], T. Tamura[10], N. Tateyama[10], T. Terasawa[7], H. Tomida[8], S. Torii[9,31], Y. Tunesada[18], Y. Uchihori[15], S. Ueno[8], E. Vannuccini[25], J.P. Wefel[12], K. Yamaoka[13], S. Yanagita[6], A. Yoshida[1], K. Yoshida[21], and T. Yuda[7]

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) Louisiana State University, USA
13) Nagoya University, Japan
14) NASA/GSFC, USA
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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

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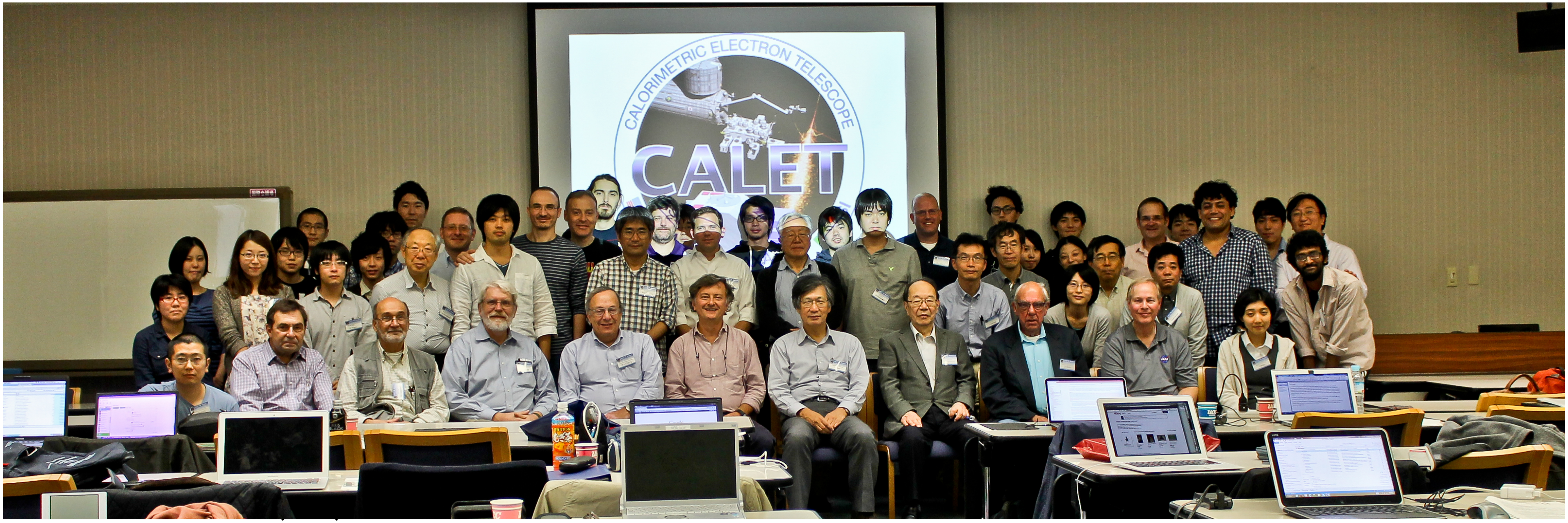
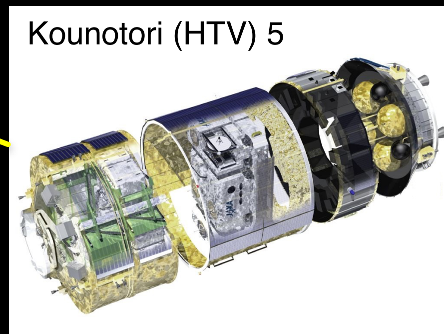
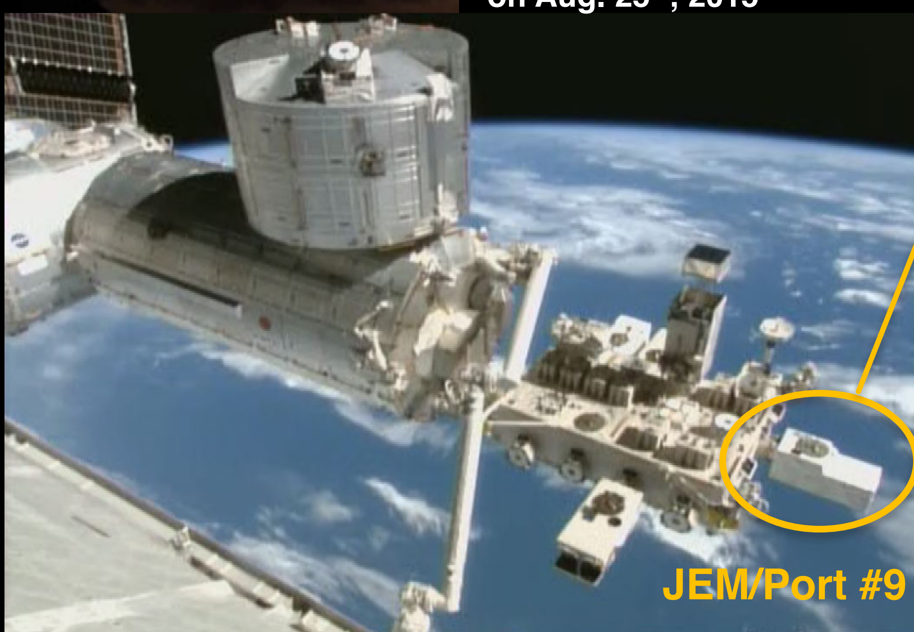


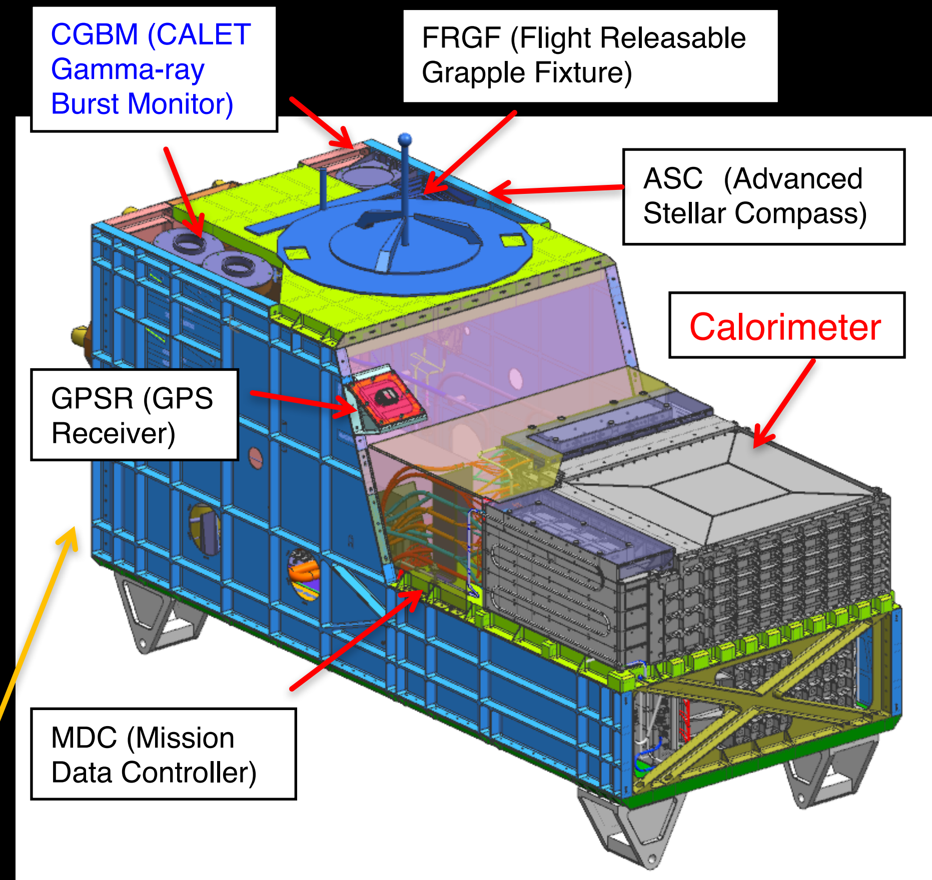
CALET Payload



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

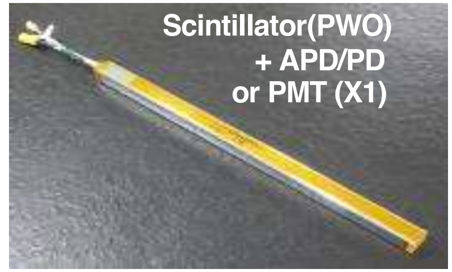
Emplaced on JEM-EF port #9 on Aug. 25th, 2015

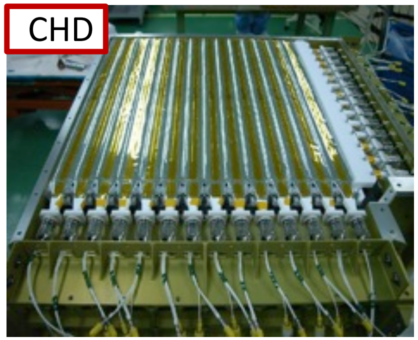


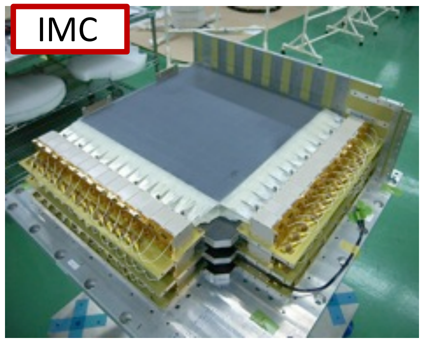


- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W (max)**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

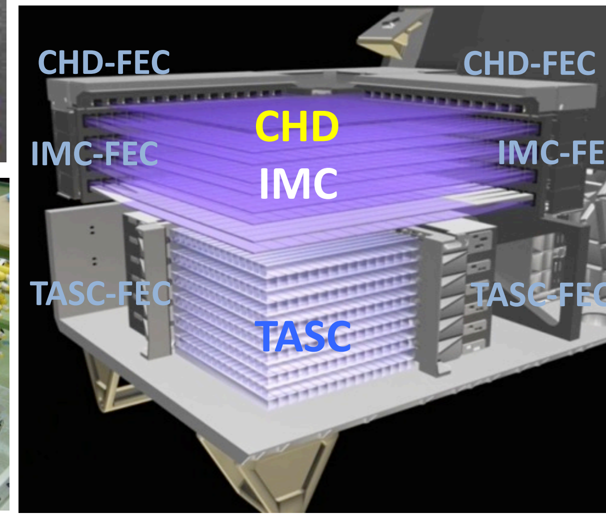
CALET Instrument







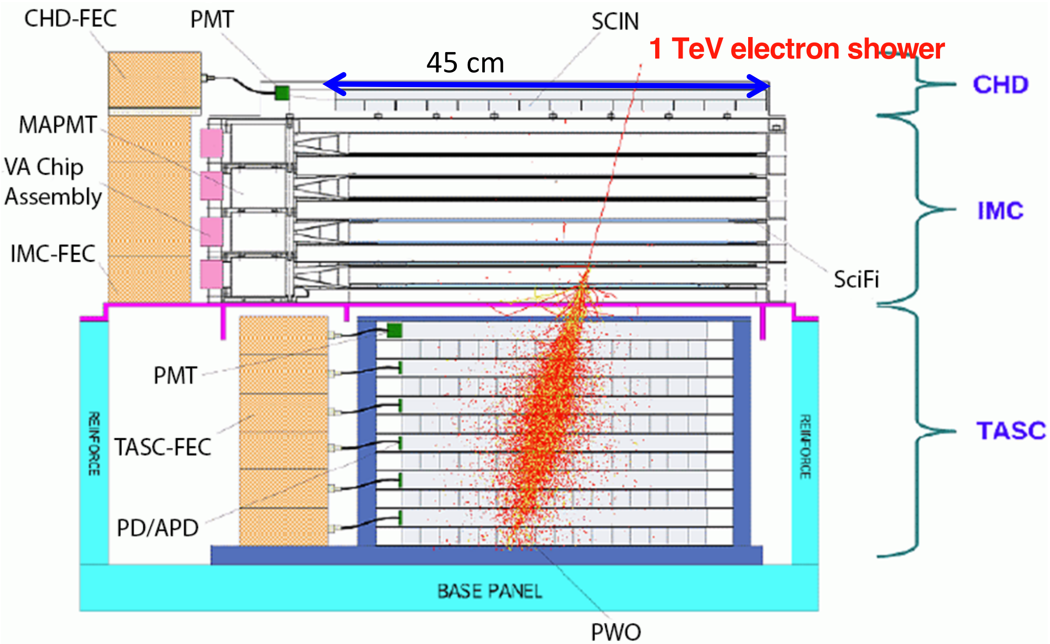
CALORIMETER



	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator** **14 paddles x 2 layers (X,Y): 28 paddles** **Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers (X,Y) : 7168 Scifi** **7 W layers ($3X_0$): $0.2X_0$ x 5 + $1X_0$ x2** **Scifi size : 1 x 1 x 448 mm^3**	**16 PWO logs x 12 layers (x,y): 192 logs** **log size: 19 x 20 x 326 mm^3** **Total Thickness : 27 X_0 , ~1.2 λ_I**
Readout	**PMT+CSA**	**64-anode PMT+ ASIC**	**APD/PD+CSA** **PMT+CSA (for Trigger)@top layer**

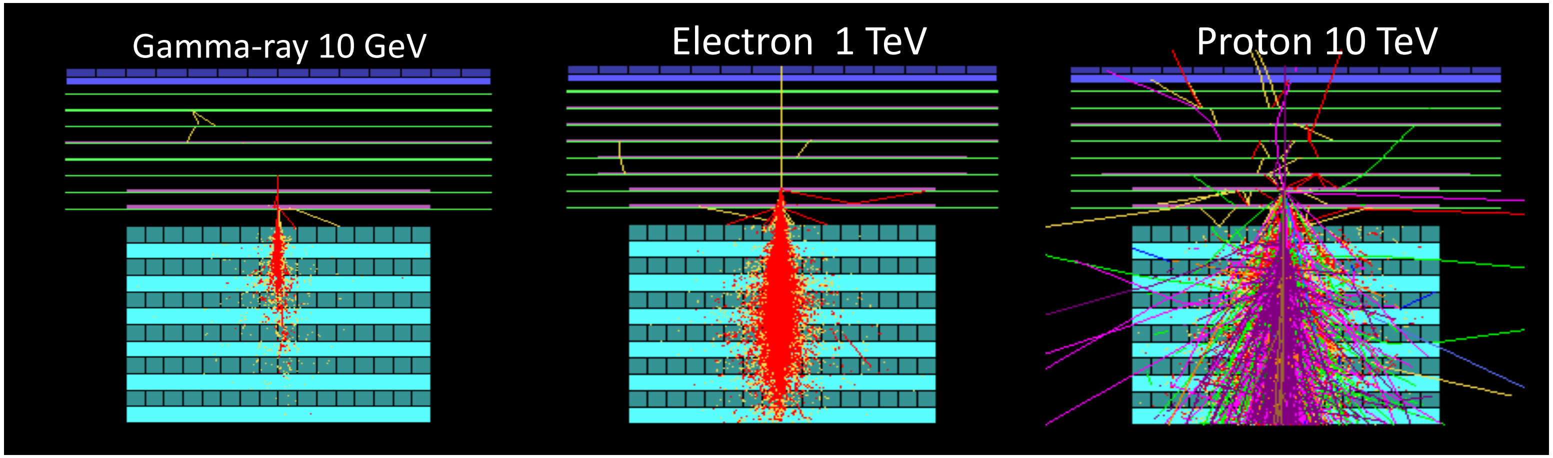
CALET Capability

Field of view: ~ 45 degrees (from the zenith)
Geometrical Factor: ~ 1,040 cm^2sr (for electrons)



Unique features of CALET

- A dedicated charge detector + multiple dE/dx track sampling in the IMC allow to identify individual nuclear species（Δz~0.15-0.3 e).
- Thick(~30 X_0), fully active calorimeter allows measurements well into the TeV energy region with excellent energy resolution (~2-3%)
- High granularity imaging pre-shower calorimeter accurately identify the arrival direction of incident particles (~0.2°) and the starting point of electro-magnetic showers.
- ➢ Combined, they powerfully separate electrons from the abundant protons: contamination is much less than 10 % up to the TeV region.

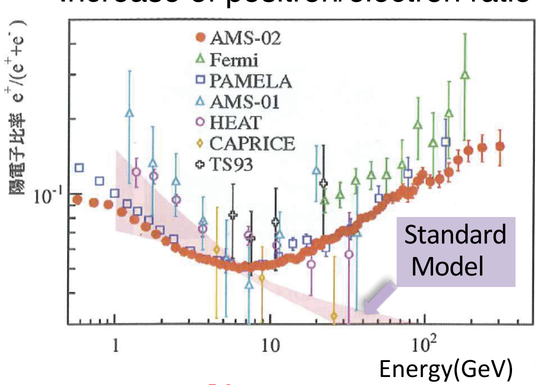


Scientific Targets

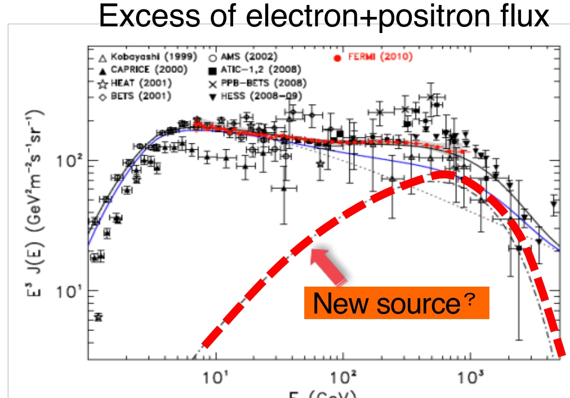
Scientific Objectives	Observation Targets	Energy Range
CR Origin and Acceleration	Electron spectrum p--Fe individual spectra Ultra Heavy Ions (26<Z≤40) Gamma-rays (Diffuse + Point sources)	1GeV - 20 TeV 10 GeV - 1000 TeV > 600 MeV/n 1 GeV - 1 TeV
Galactic CR Propagation	B/C and sub-Fe/Fe ratios	Up to some TeV/n
Nearby CR Sources	Electron spectrum	100 GeV - 20 TeV
Dark Matter	Signatures in electron/gamma-ray spectra	100 GeV - 20 TeV
Solar Physics	Electron flux	< 10 GeV
Gamma-ray Transients	Gamma-rays and X-rays	7 keV - 20 MeV

Respond to the unresolved questions from the results found by recent observations

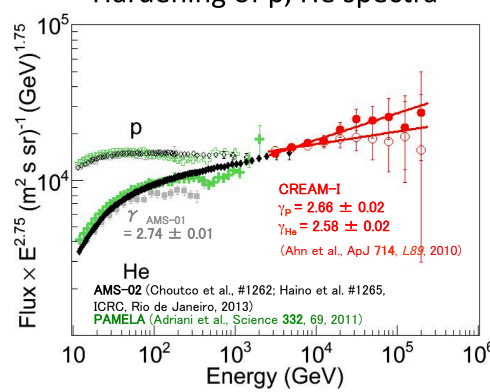
Increase of positron/electron ratio



Excess of electron+positron flux



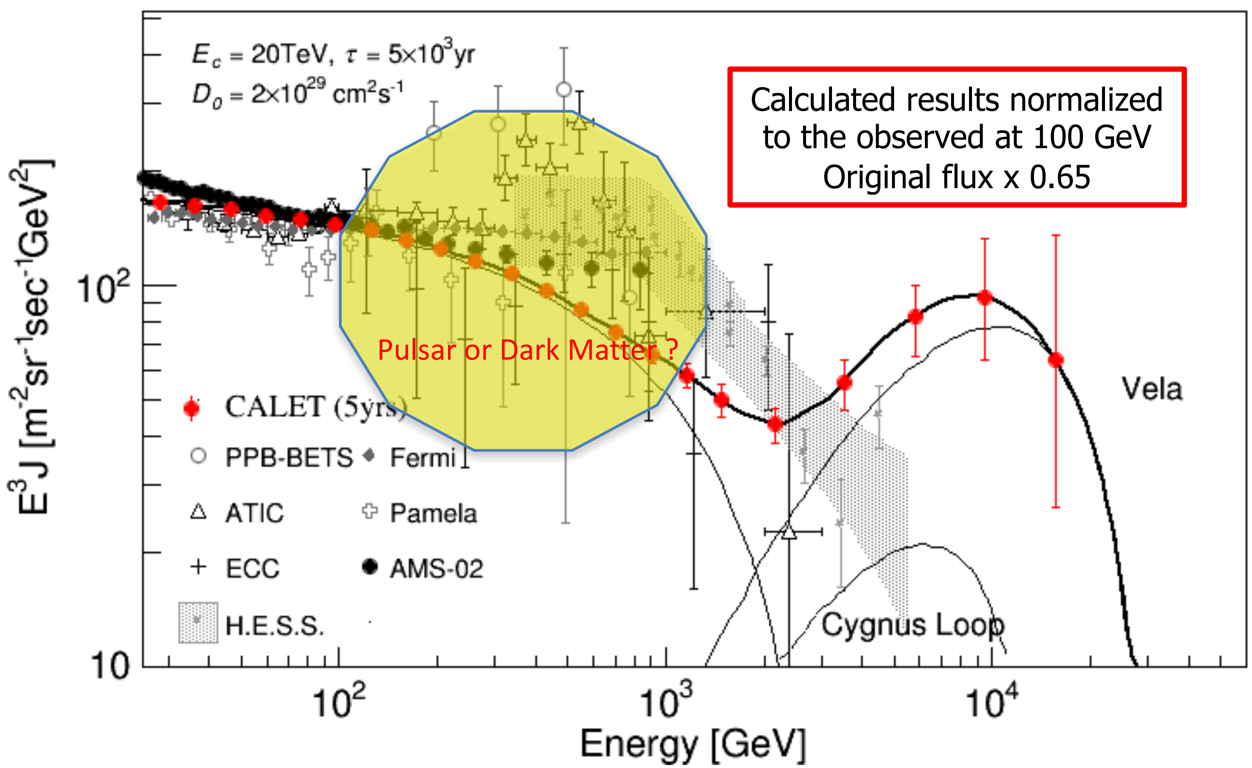
Hardening of p, He spectra



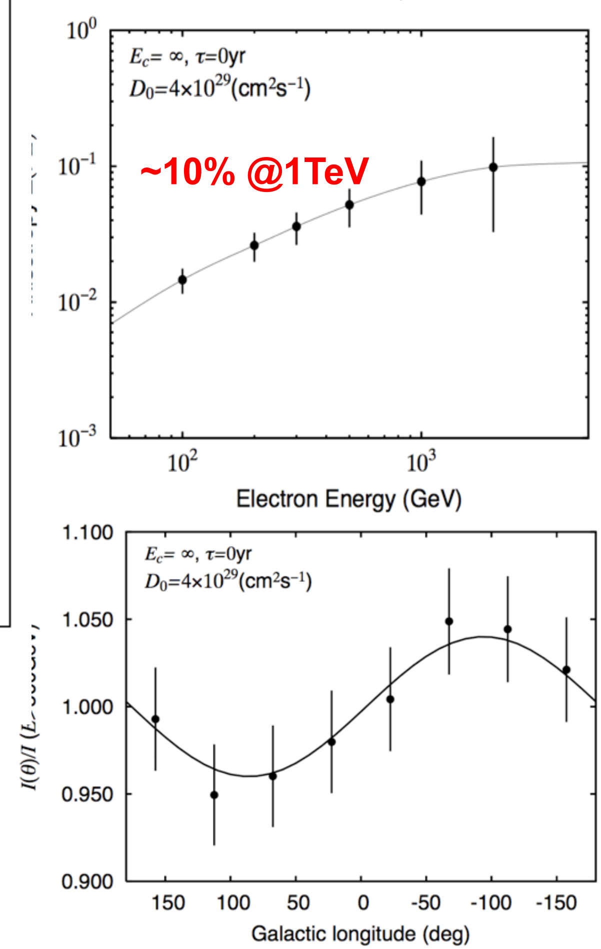
New source of electrons and positrons at 100 GeV ?

CALET Main Target: Identification of Electron Sources

Some nearby sources, e.g. Vela SNR, is likely to have unique signatures in the electron energy spectrum in the TeV region (Kobayashi et al. ApJ 2004)



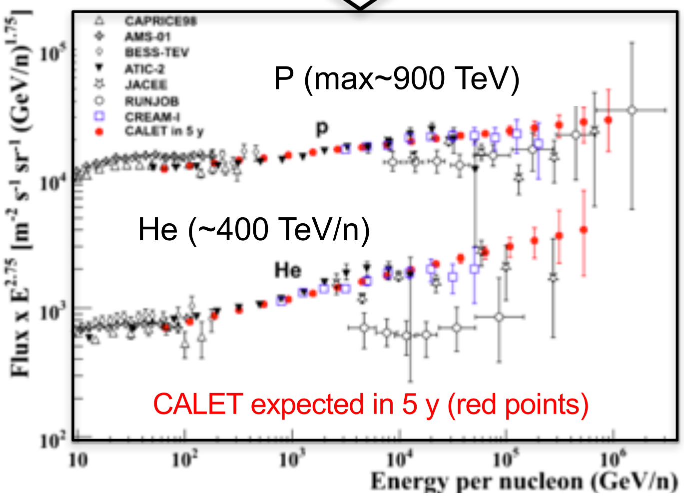
Expected Anisotropy from Vela



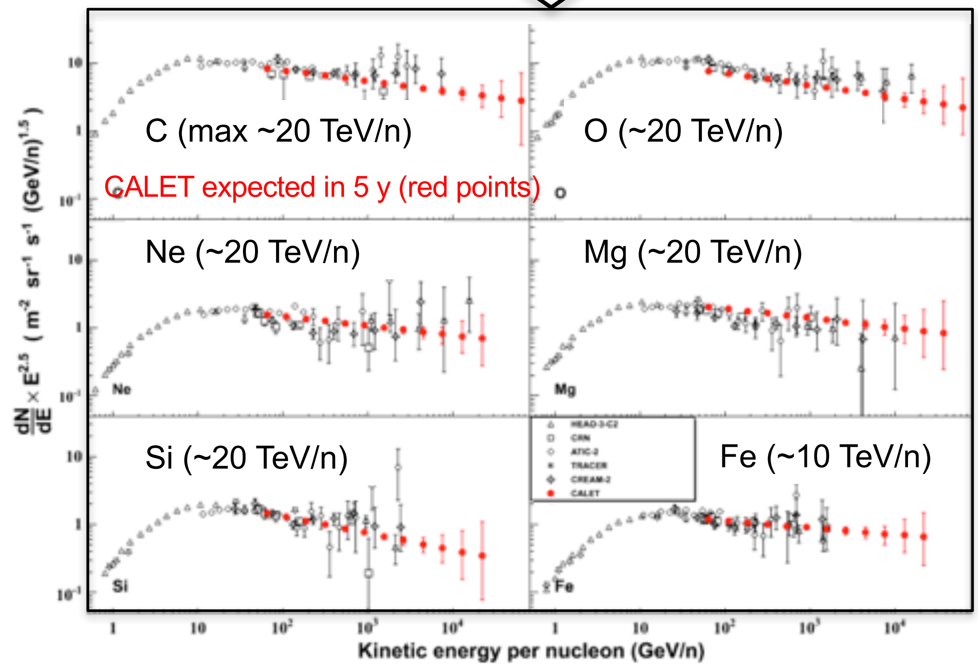
▶ Identification of the unique signature from nearby SRNs, such as Vela, in the electron spectrum by CALET in the TeV region

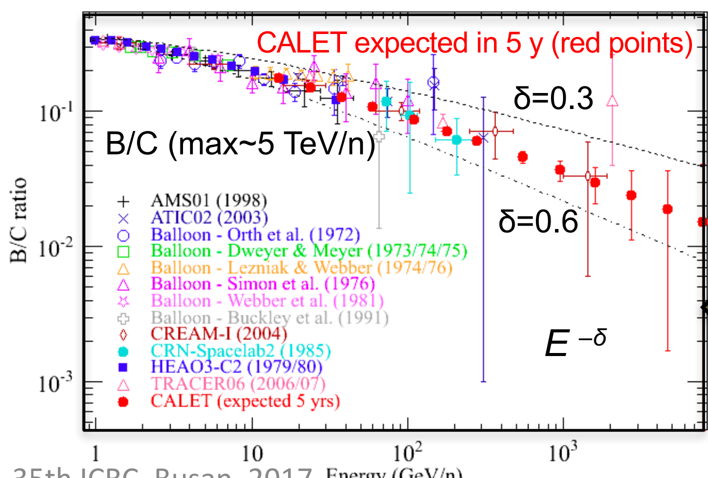
Measurements of Cosmic-Ray Nuclei Spectra with CALET

- **Hardening** in the p and He at 200 GV observed by PAMELA
- p and He spectra have **different slopes** in the multi TeV region (CREAM)
- **Acceleration limit** by SNR shock wave around 100 TeV/Z ?



- All primary heavy nuclei spectra well fitted to **single power-laws** with similar spectral index (CREAM, TRACER)
- However hint of a **hardening** from a combined fit to all nuclei spectra (CREAM)





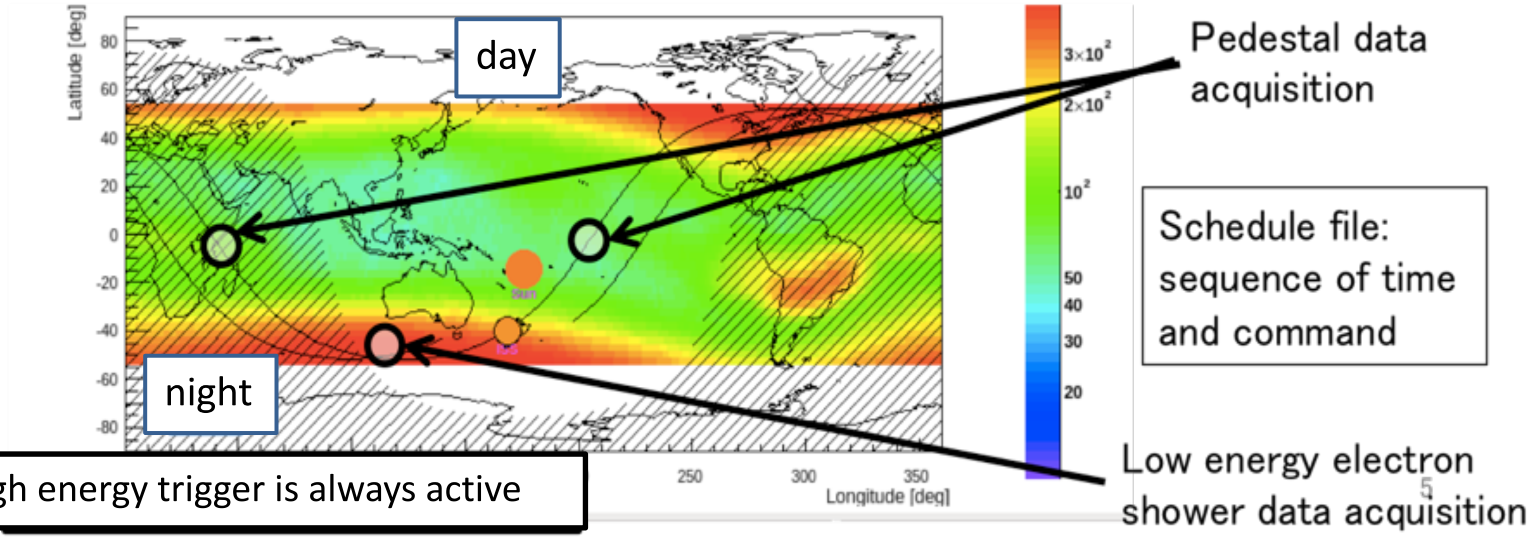
- At high energy (> 10 GeV/n) the B/C ratio measures the energy dependence of the escape path-length, $\sim E^{-\delta}$, of CRs from the Galaxy
- Data below 100 GeV/n indicate δ~0.6. At high energy the ratio is expected to flatten out.

ISS Orbit and CALET In-orbit Operations

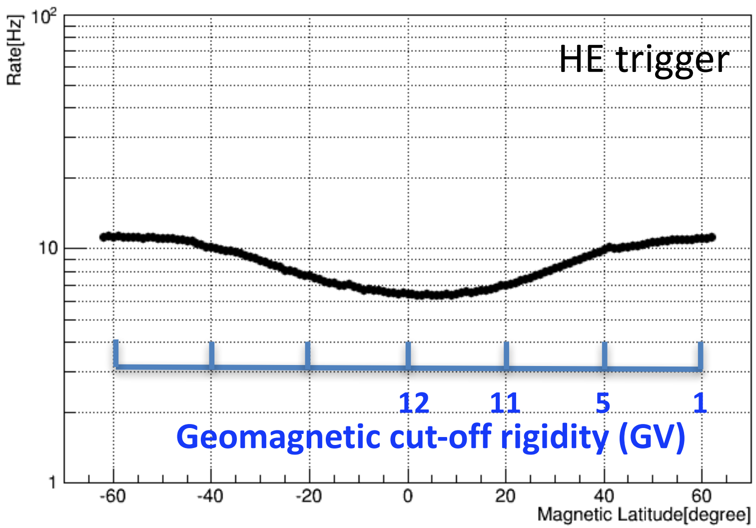
S.Ozawa et al.
ID165 (poster)

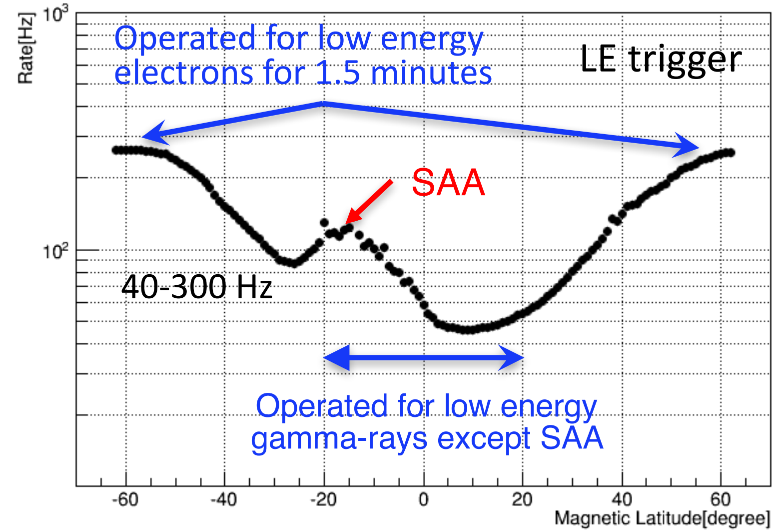
ISS orbit: inclination 51.6 degree, ~400 km

Concept of on-orbit operations



Dependence of the count rate on geomagnetic latitude



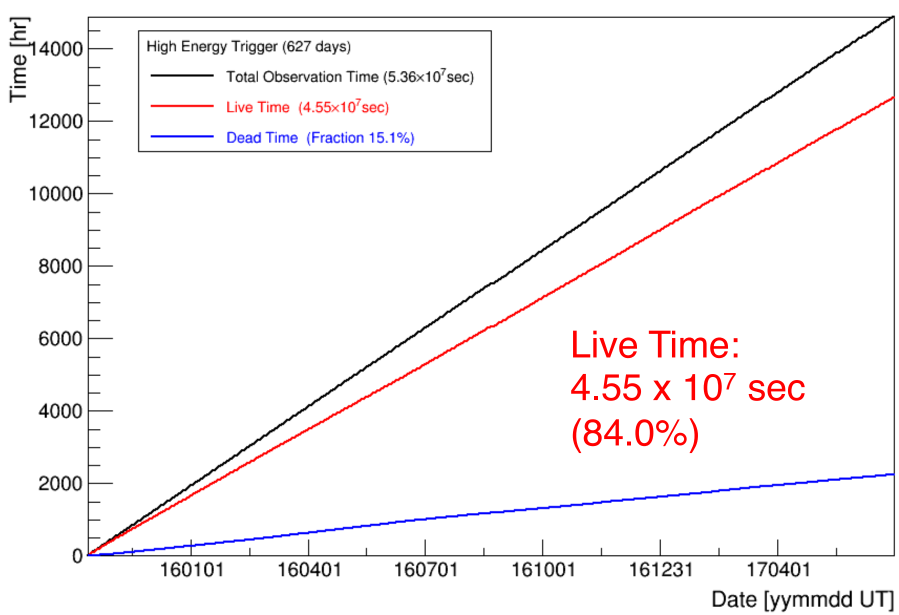


Observation by High Energy Trigger (>10GeV)

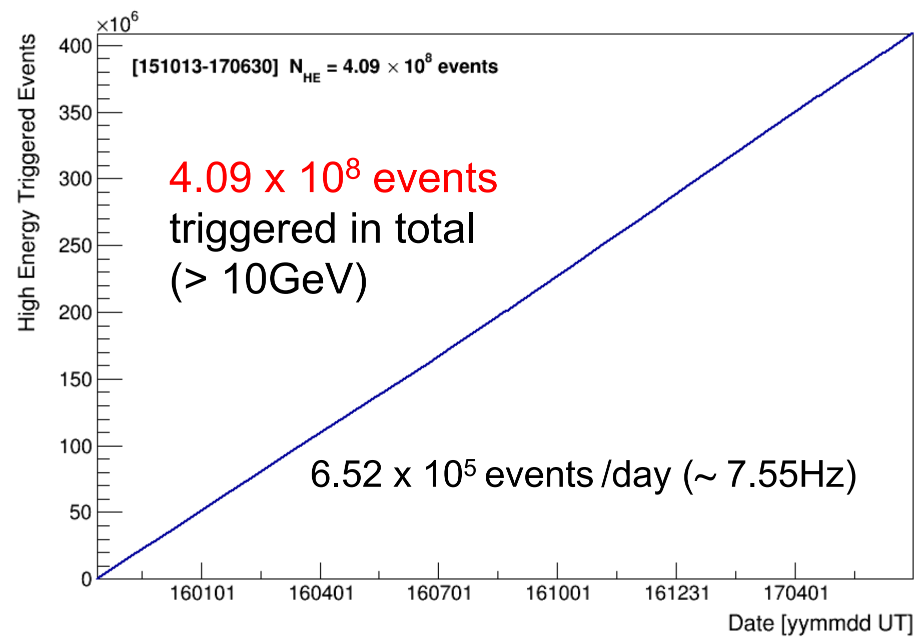
Observation by High Energy Trigger for 627 days :
Oct. 13, 2015 – Jun. 30, 2017

- The exposure, SΩT, has reached to ~55 m^2 sr day for electron observations by continuous and stable operations.
- Total number of the triggered events is ~ 409 million with a live time fraction of 84.0 %.

Accumulated observation time (live, dead)

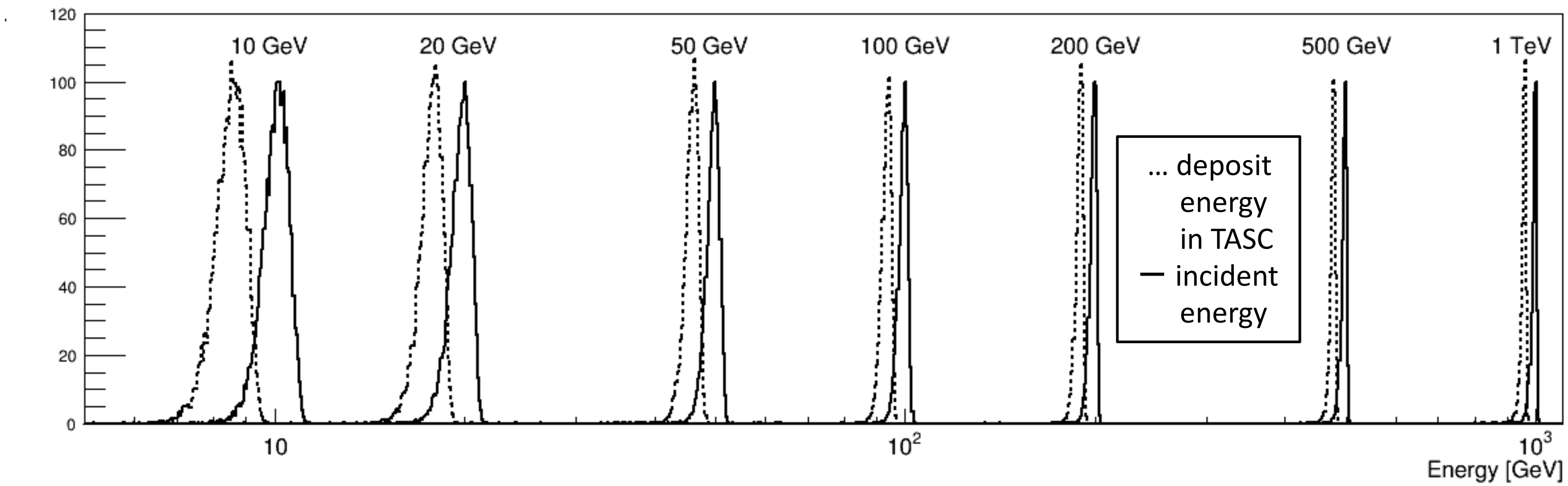


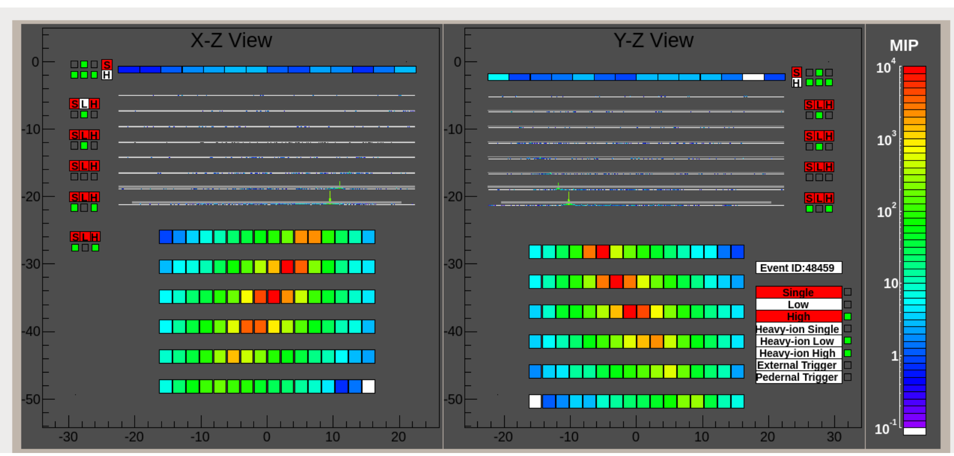
Accumulated triggered event number



Energy Reconstruction for Electromagnetic Showers

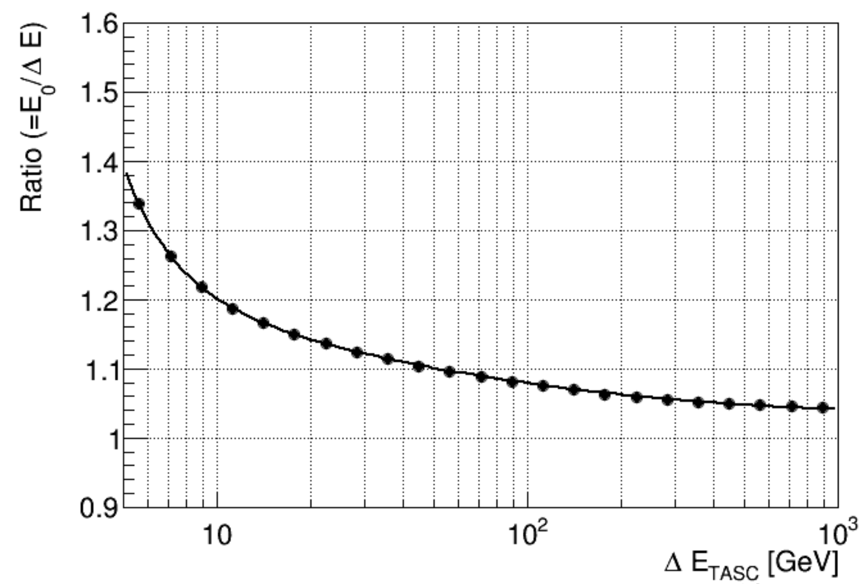
Simulation: Comparison of deposit energy in TASC (ΔE) with incident energy (E_0)





4 TeV electron candidate (well contained)
⇒ very small leakage (~ a few %)

Energy reconstruction factor vs. Energy



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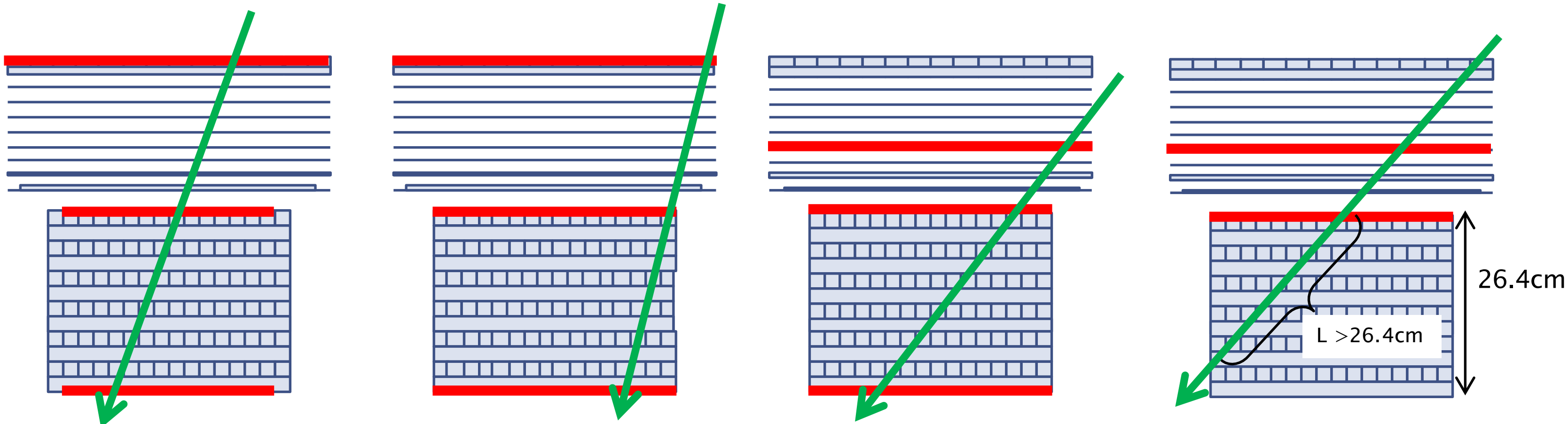
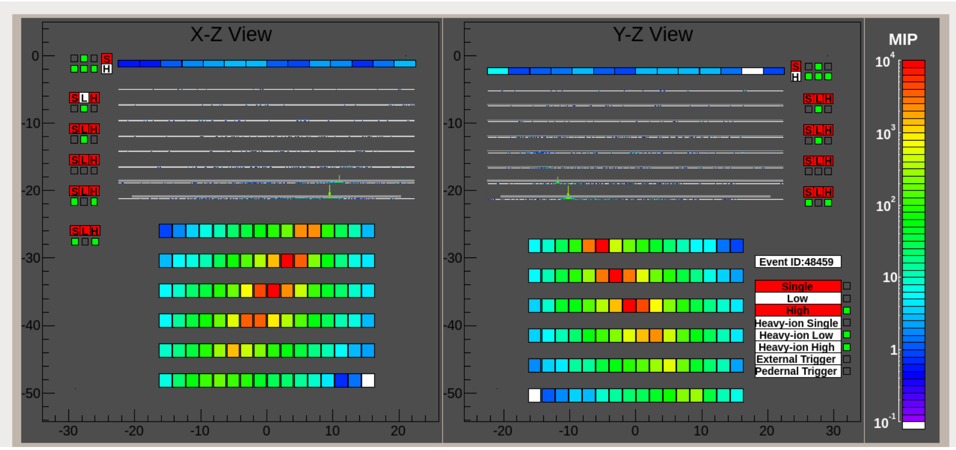


SΩ (cm^2sr) 416 A+B:570 All: 1040



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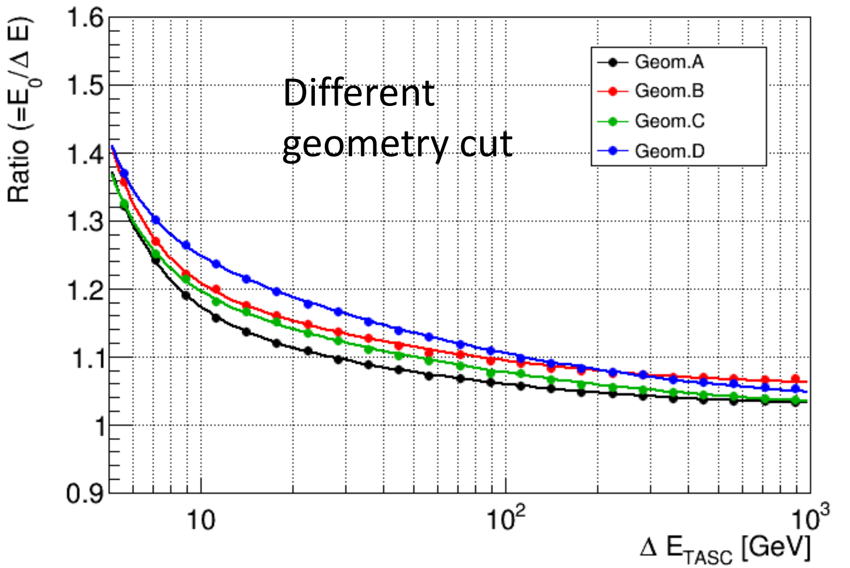
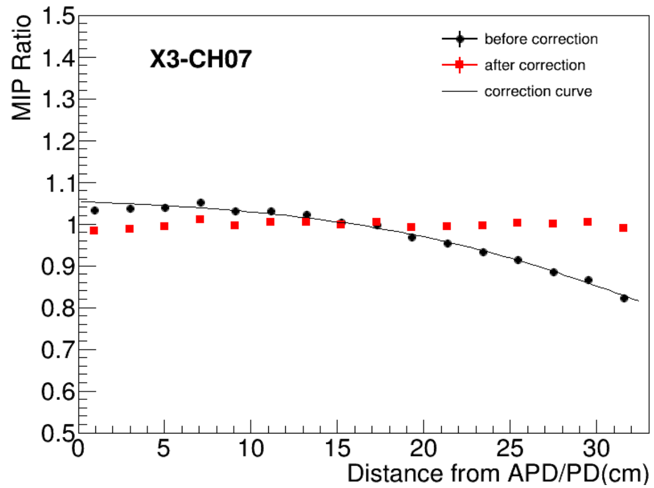
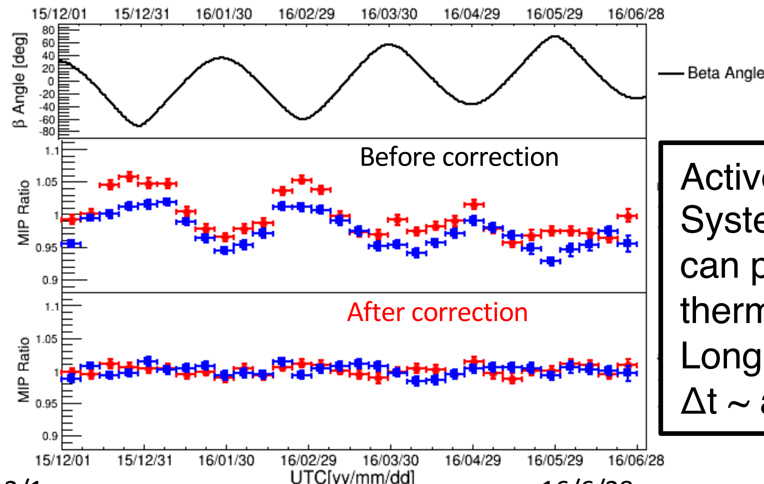


Position and Temperature Calibration, and Long-term Stability

Example of position dependence correction



Examples of temperature change correction

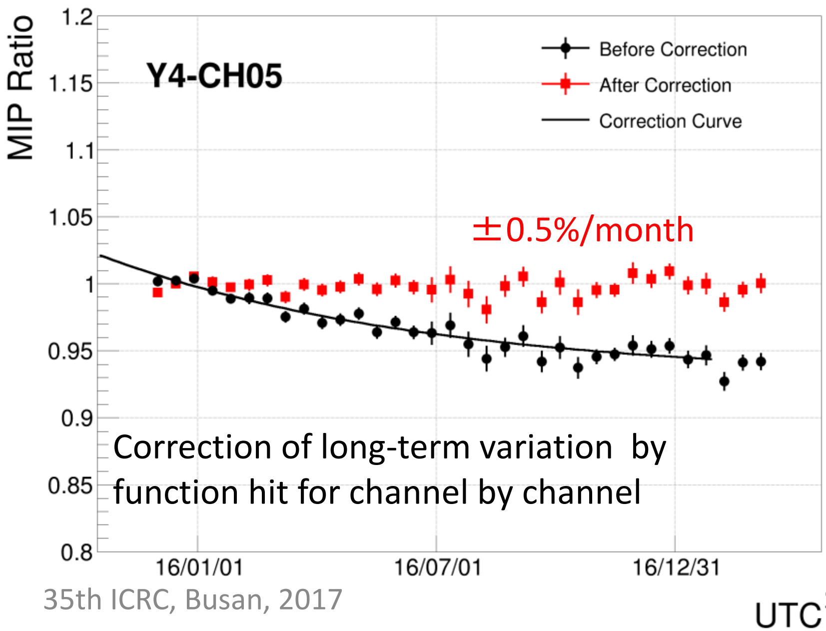


15/12/1 16/6/28

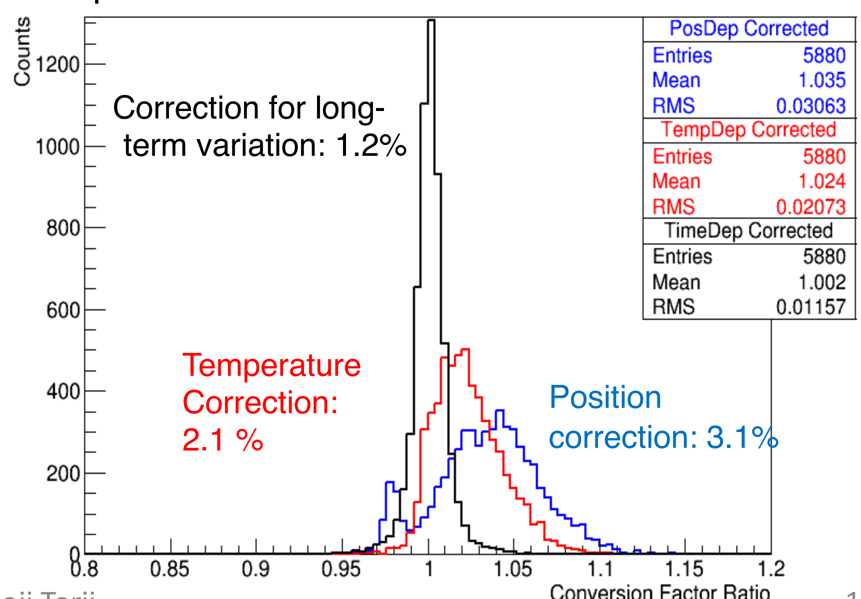
Y.Komiya et al. (poster) ID206

Active Thermal Control System (ATCS) on ISS can provide very stable thermal condition during Long-tem observations: Δt ~ a few degrees

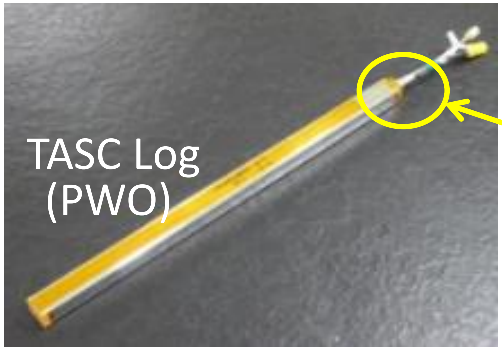
Example of long-term variation correction

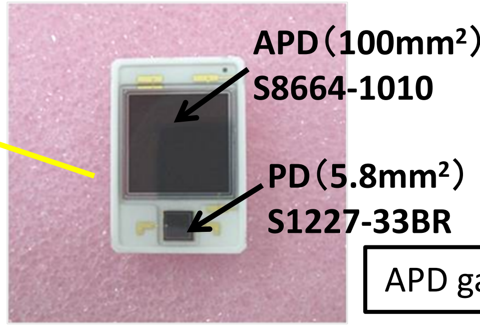


Distribution of MIPs for 192 ch x 16 segmented positions after each correction

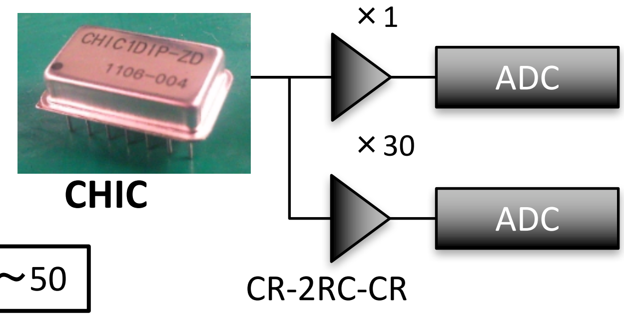


Energy Measurement in Dynamic Range of 1-10^6 MIP in TASC

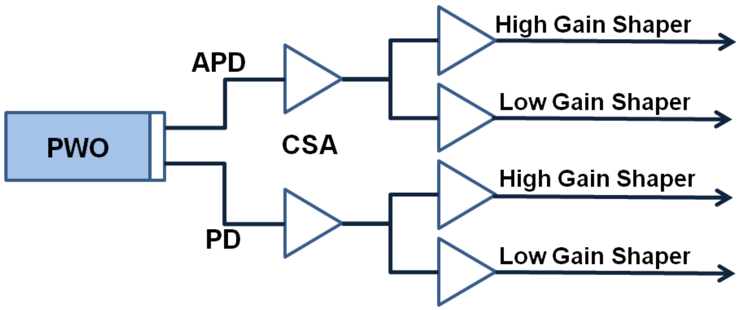




APD gain ～50



R.Miyata et al. (poster) ID207



The linearity was calibrated by using UV laser irradiation on ground :

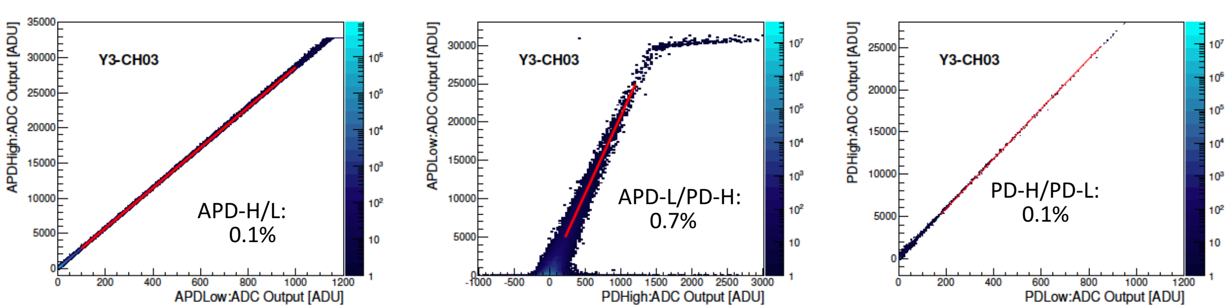
1) The linearity is confirmed in the range of 1.4-2.5 %.

2) The whole dynamic range is confirmed to cover from 1 MIP to 10^6 MIPs.

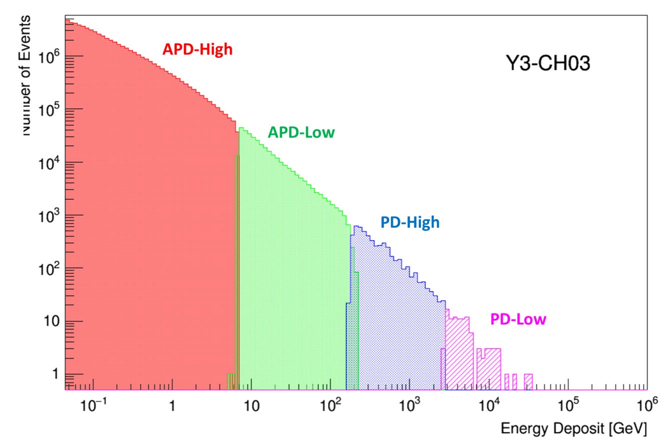
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel.

APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%

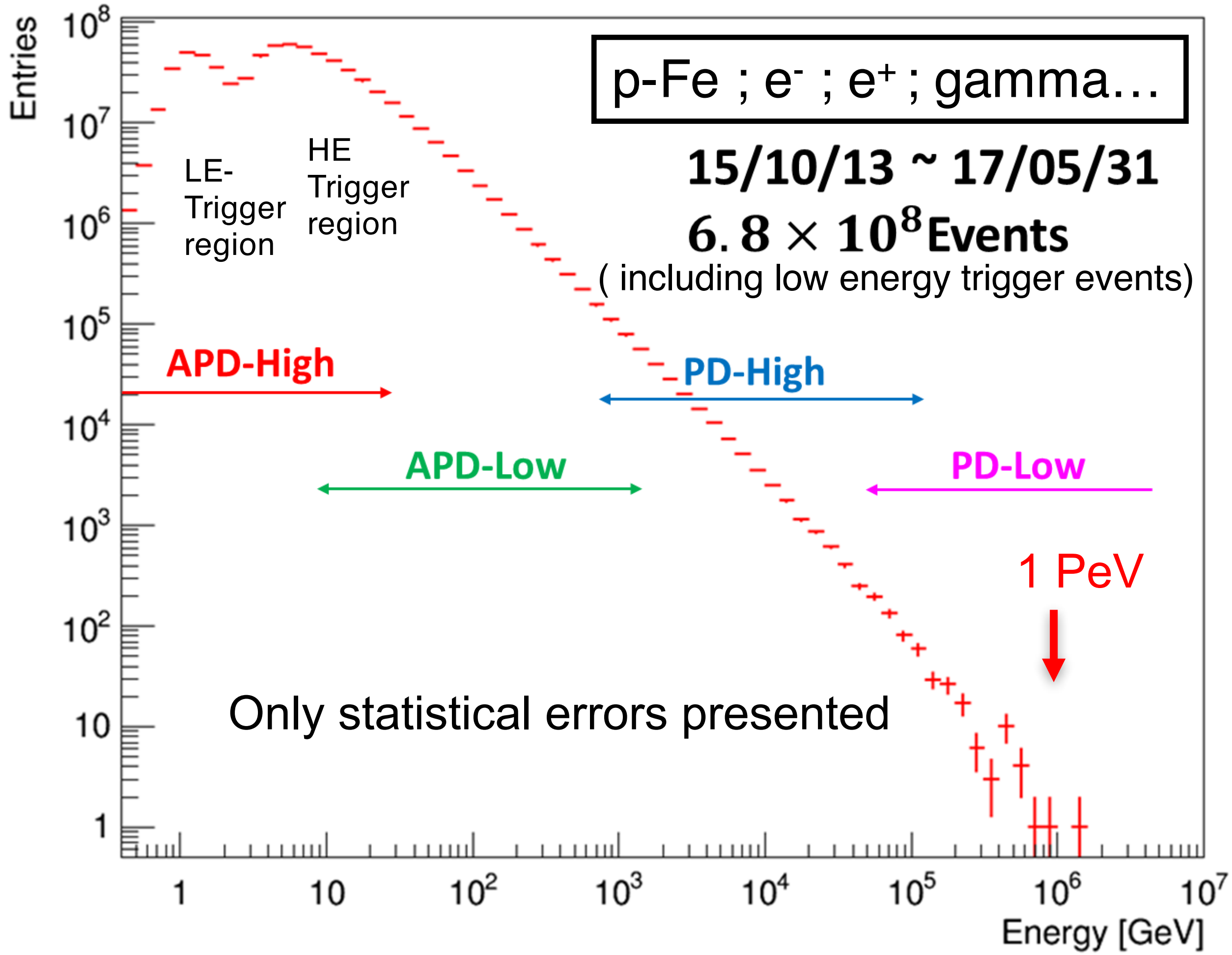


Example of energy distribution in one PWO log



Energy Deposit Distribution of All Triggered-Events by Observation for 597 days

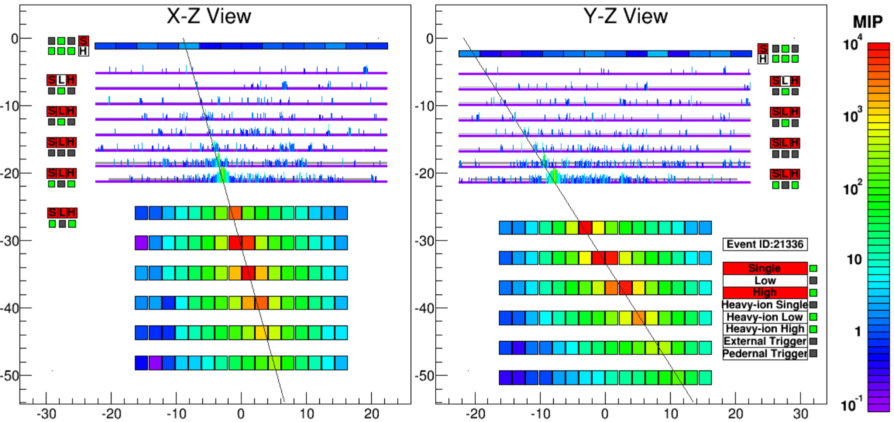
Distribution of deposit energies (ΔE) in TASC



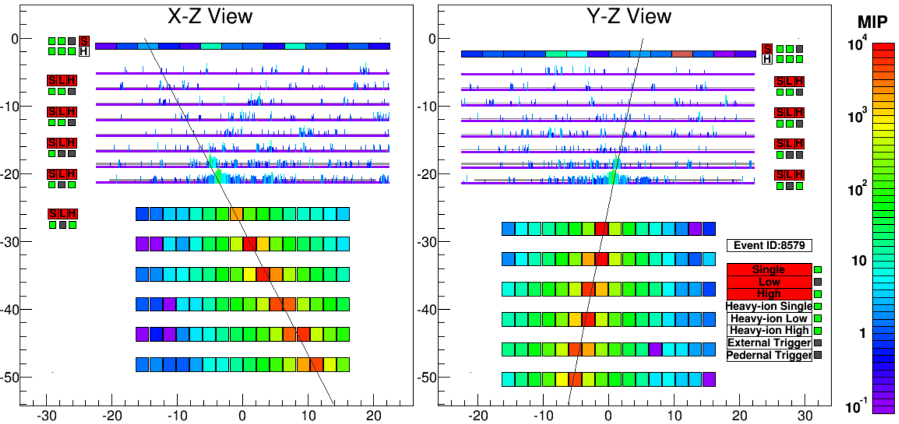
The TASC energy measurements have successfully been carried out in the dynamic range of 1 GeV – 1 PeV.

Examples of Event Display

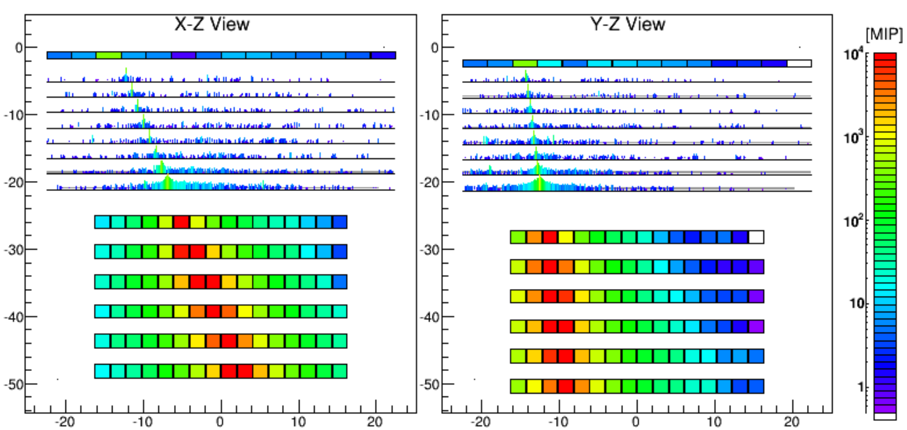
Electron, E=3.05 TeV



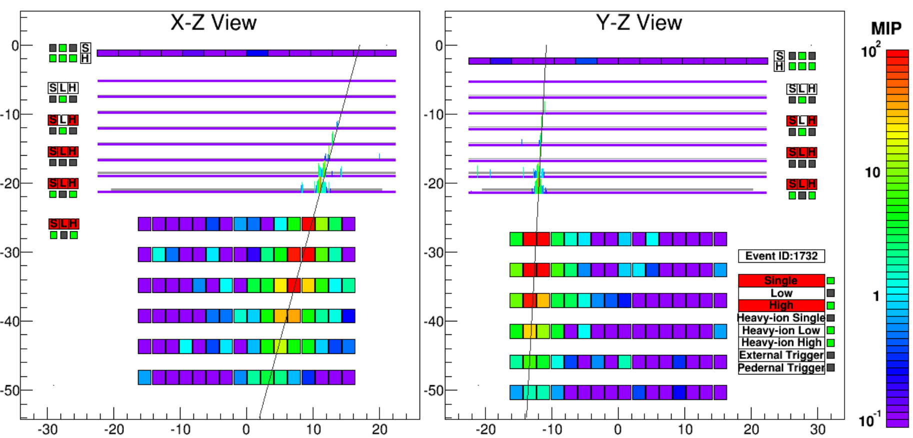
Proton, ΔE=2.89 TeV



Fe, ΔE=9.3 TeV



Gamma-ray, E=44.3 GeV

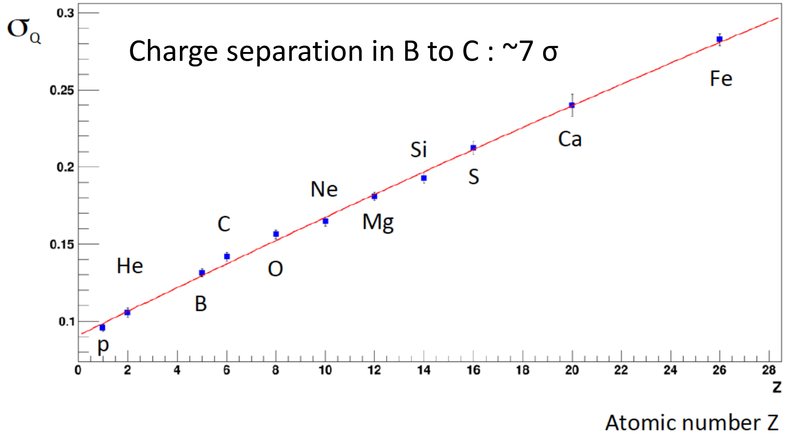


Unit in MIP

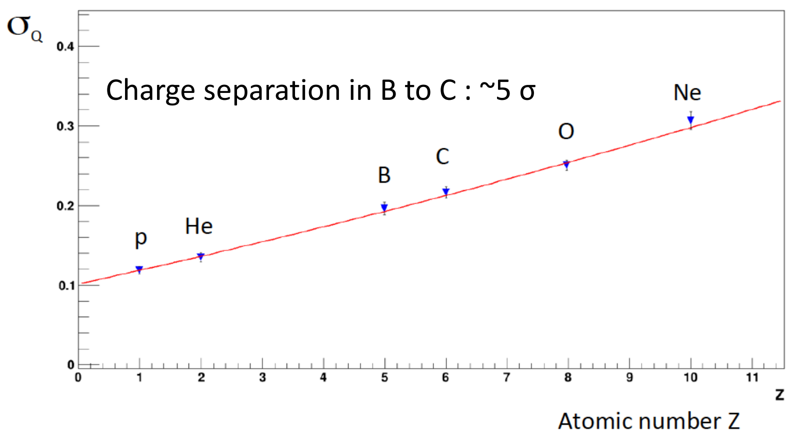
Preliminary Nuclei Measurements for Z=1-8

P.S.Marrocchesi et al. (oral) ID156

CHD charge resolution (2 layers combined) vs. Z

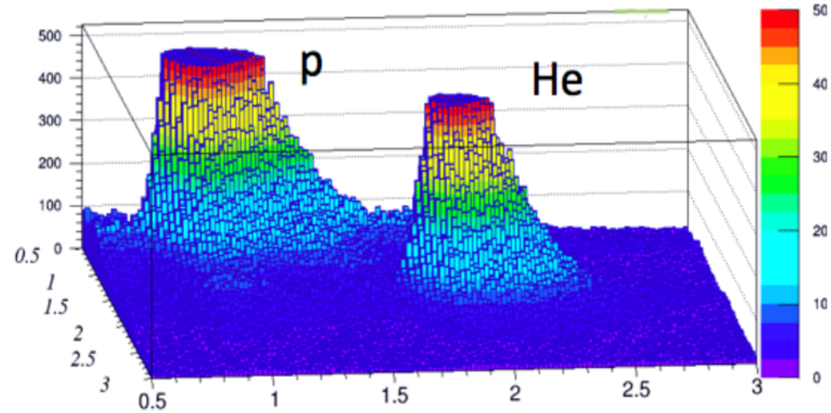


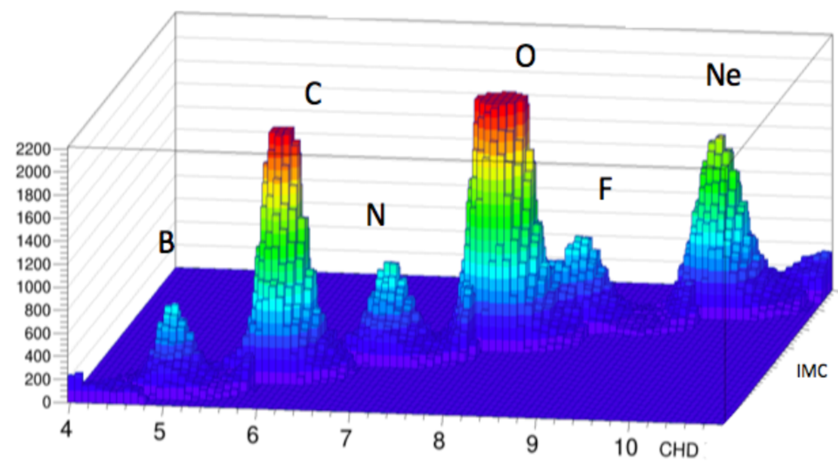
Charge resolution using multiple dE/dx measurements from the IMC scintillating fibers.



Non-linear response to Z^2 is corrected both in CHD and IMC using a model.

Charge resolution combined CHD+IMC



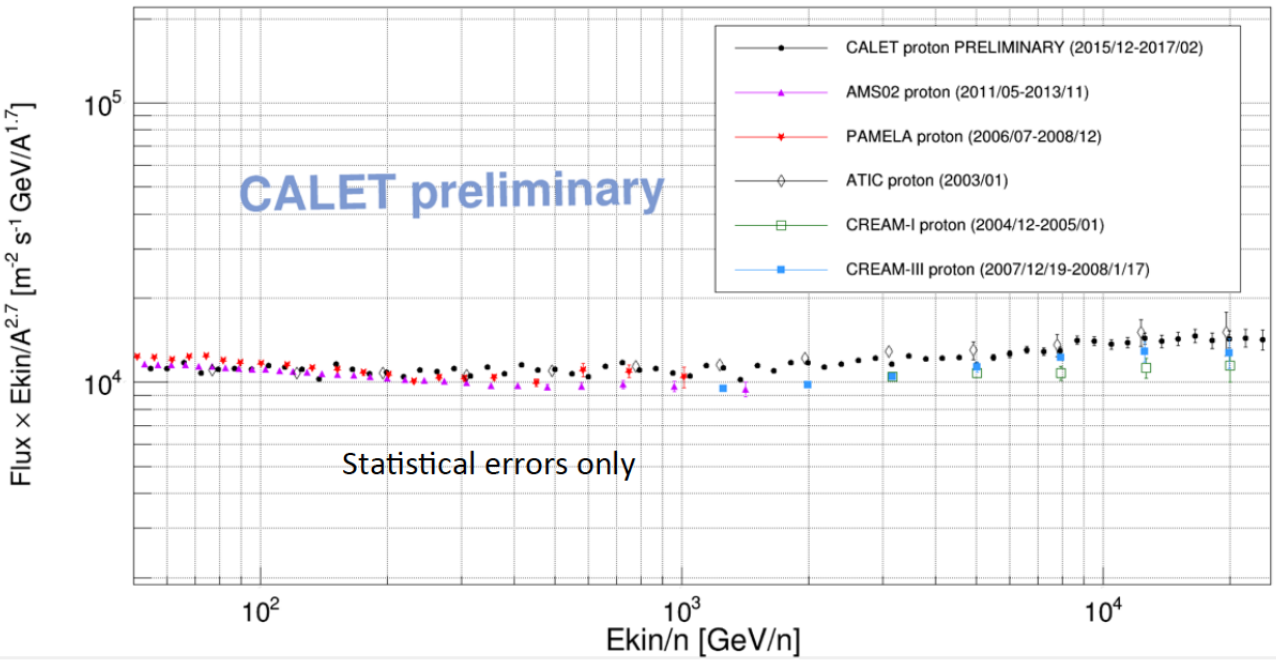


*) Plots are truncated to clearly present the separation.

A clear separation between p, He, ~ Z=8, can be seen from CHD+IMC data analysis.

Preliminary Proton Energy Spectrum

Preliminary proton flux $E^{2.7}$ from 50 GeV to 22 TeV



- 15 months of observation from December 1st , 2015 to February 28th, 2017
- subset of total acceptance: acceptance A (fiducial) with SΩ = 416 cm² sr
- Assessment of the systematic errors: IN PROGRESS

Data Analysis

☐ Proton Event Selection

1) Fully-contained (Acceptance A) event in geometry
2) Good tracking (KF)
3) High Energy Trigger
4) Charge selection Z=1
5) Helium rejection cuts
6) Electron rejection cuts

☐ Energy Unfolding by an ***energy overlap matrix*** from MC data

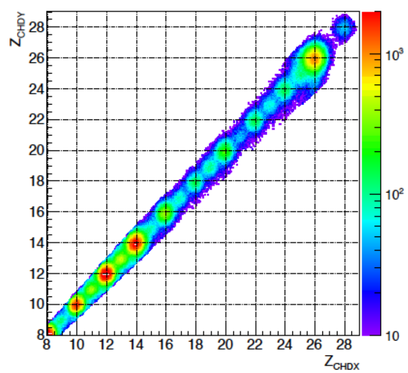
Preliminary Nuclei Measurements for Z= 8~26

Y.Akaike et al. (oral) ID181

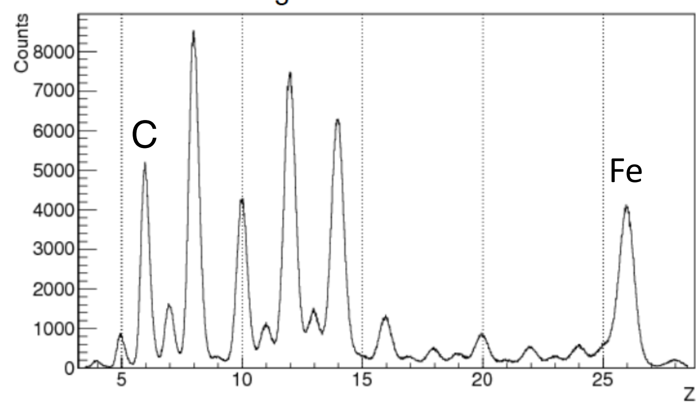
Independent analysis is carried out for heavy nuclei in Z=8-26.

- Charge identification using correlation of CHD-X and CHD-Y:
  - require the charge consistency in CHD and IMC
  - efficiency of the consistency cuts is 65-70% for heavy nuclei (Z > 8)
- Quite similar charge resolutions were obtained by the different two analysis methods.

Charge correlation in CHD



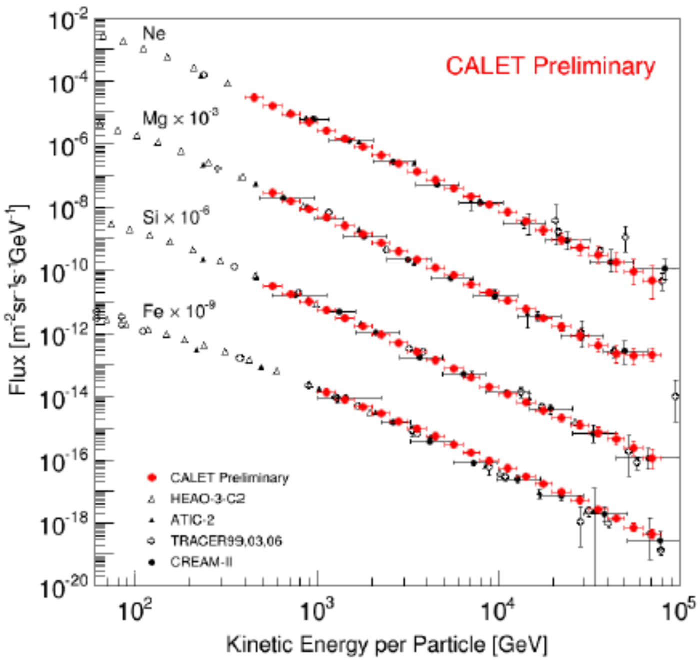
Charge distribution with CHD



Flux measurement:

$$\Phi(E) = \frac{N(E)}{S\Omega\varepsilon(E)T\Delta E}$$

$N(E)$	Events in unfolded energy bin
$S\Omega$	Geometrical acceptance (416 cm^2sr)
T	Live time (39 million seconds) (Oct.13 2015 – Mar.31 2017)
$\varepsilon(E)$	Efficiency of trigger and track reconstruction (>96%)
ΔE	Bin width



Data Analysis Method
(except similar way with light nuclei)

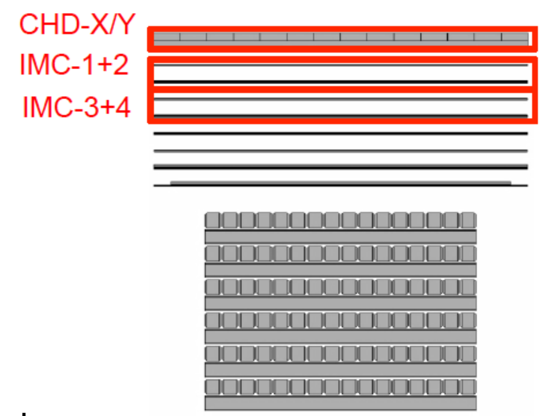
- Unfolding procedure based on ***Bayes' theorem*** is applied with response function from MC data.
- Charge selection efficiencies and contaminations from neighboring charged nuclei are also taken into account in the unfolding procedure.

Preliminary Ultra Heavy Nuclei Measurements for $26 < Z \leq 40$

B.Rauch, Y.Aakike et al. (poster) ID180

- CALET measures the relative abundances of ultra heavy nuclei through ${}_{40}$Zr
- Trigger for ultra heavy nuclei:
  - signals of only CHD, IMC1+2 and IMC3+4 are required
  - ➡ an expanded geometrical acceptance (4000 cm²sr)
- Energy threshold depends on the geomagnetic cutoff rigidity

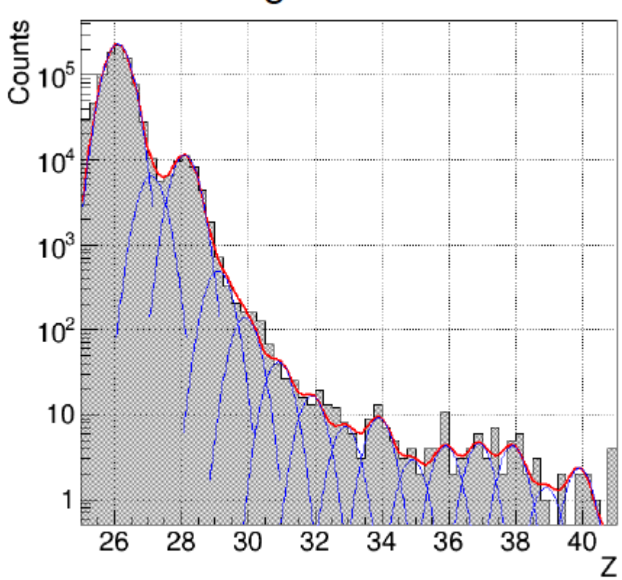
Onboard trigger for UH events



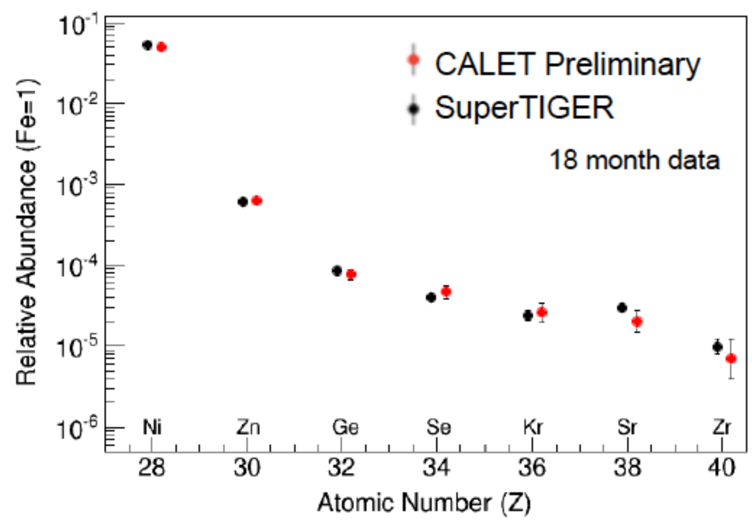
<u>Data analysis</u>

- ☐ Event Selection: Vertical cutoff rigidity > 4GV & Zenith Angle < 60 degrees
- ☐ Contamination from neighboring charge are determined by multiple-Gaussian function

Charge distribution



Relative abundance (Fe=1)



Electron Identification

Y.Asaoka et al. (oral) ID205
L.Pacini, Y.Akaike et al. (poster) ID163

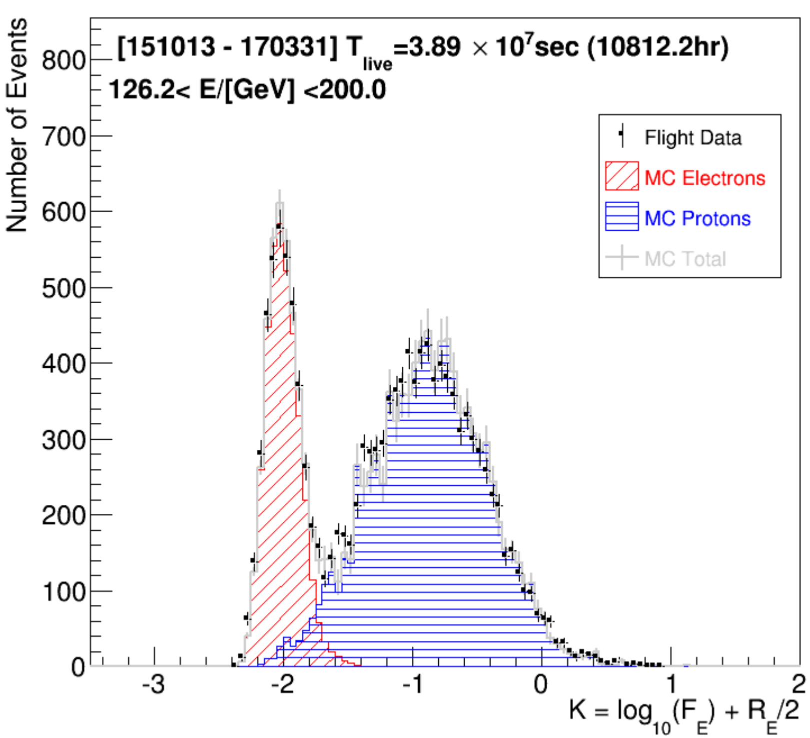
Simple Two Parameter Cut

F_E: Energy fraction of the bottom layer sum to the whole energy deposit sum in TASC

R_E: Lateral spread of energy deposit in TASC-X1

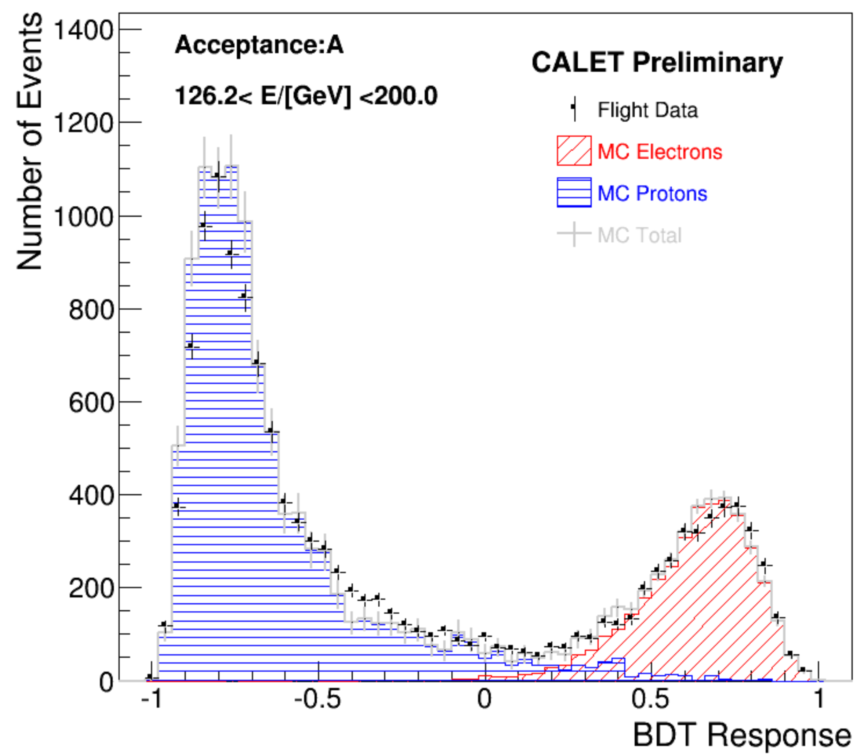
Cut Parameter K is defined as follows:

$$K = \log_{10}(F_E) + 0.5\, R_E\ (/\mathrm{cm})$$



Boosted Decision Trees (BDT)

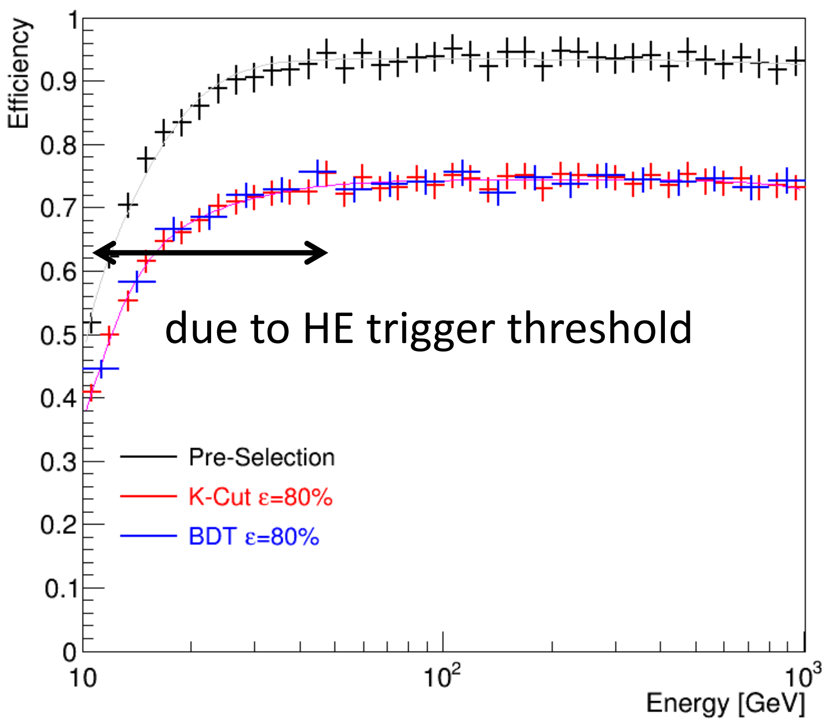
In addition to the two parameters in the left, TASC and IMC shower profile fits are used as discriminating variables.



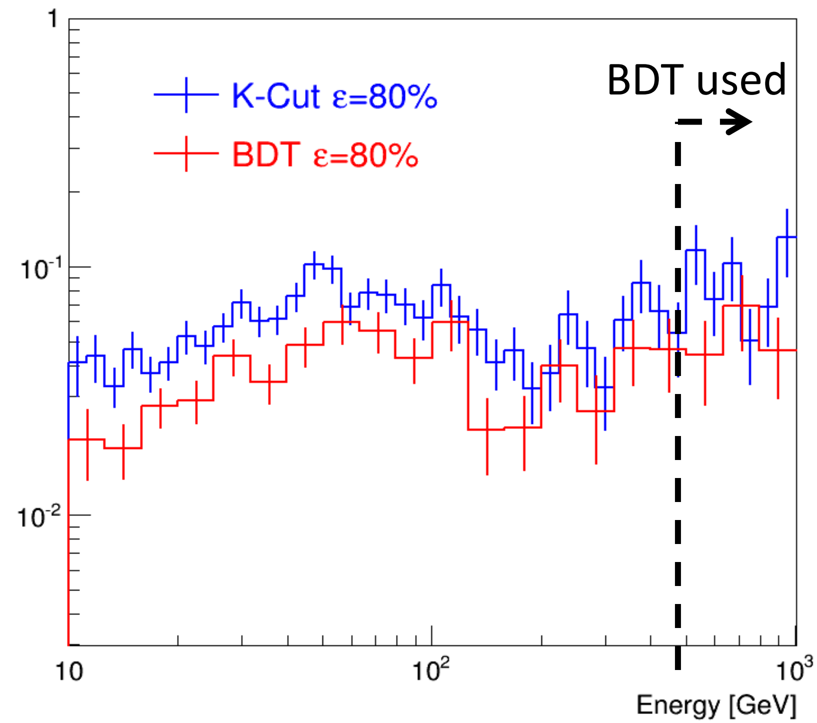
Electron Efficiency and Subtraction of Proton Contamination

- Constant and high efficiency is the key point in our analysis.
- Simple two parameter cut is used in the low energy region while the difference in resultant spectrum are taken into account in the systematic uncertainty.

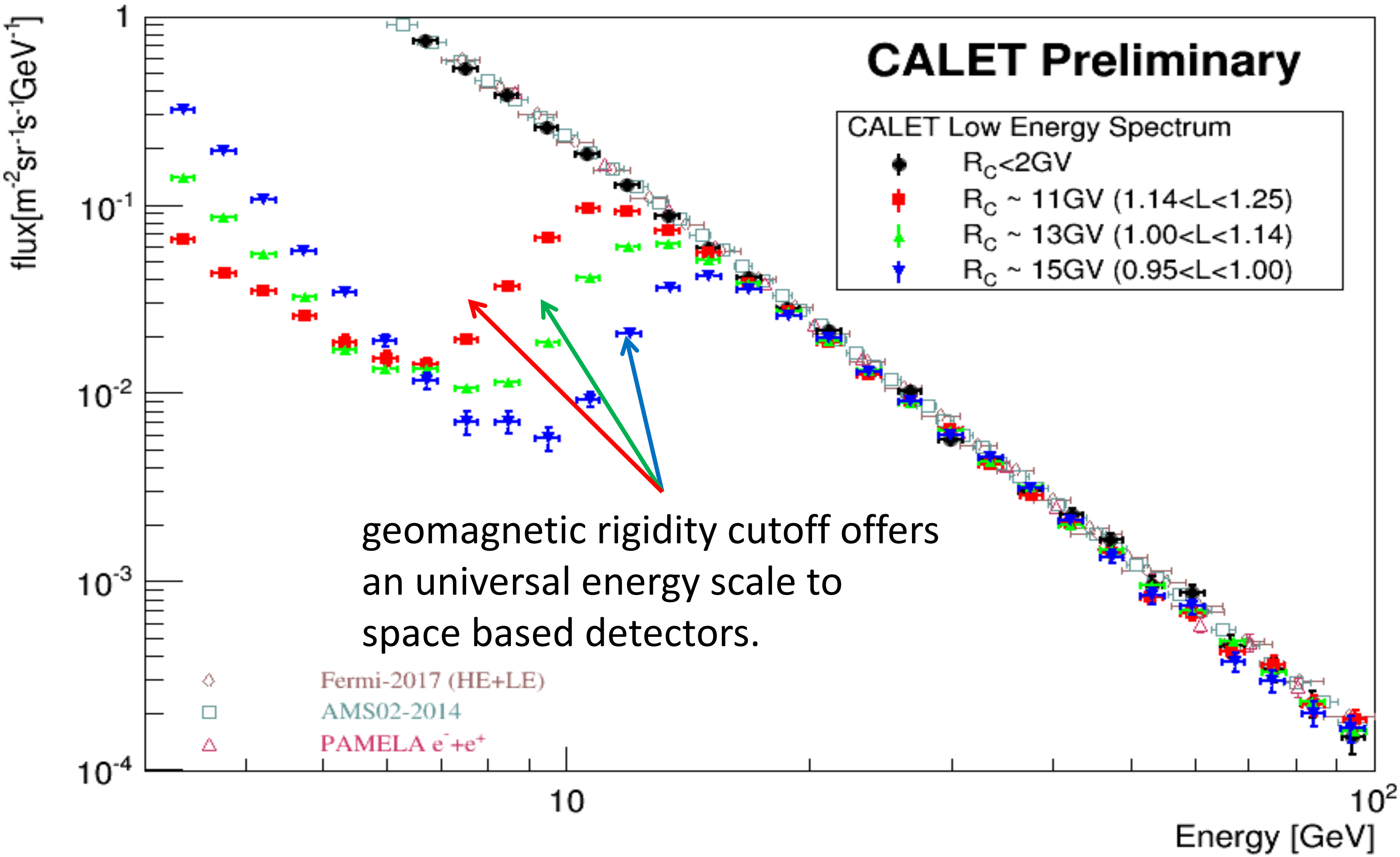
Energy vs Efficiency by Cut



Energy vs Proton Contamination



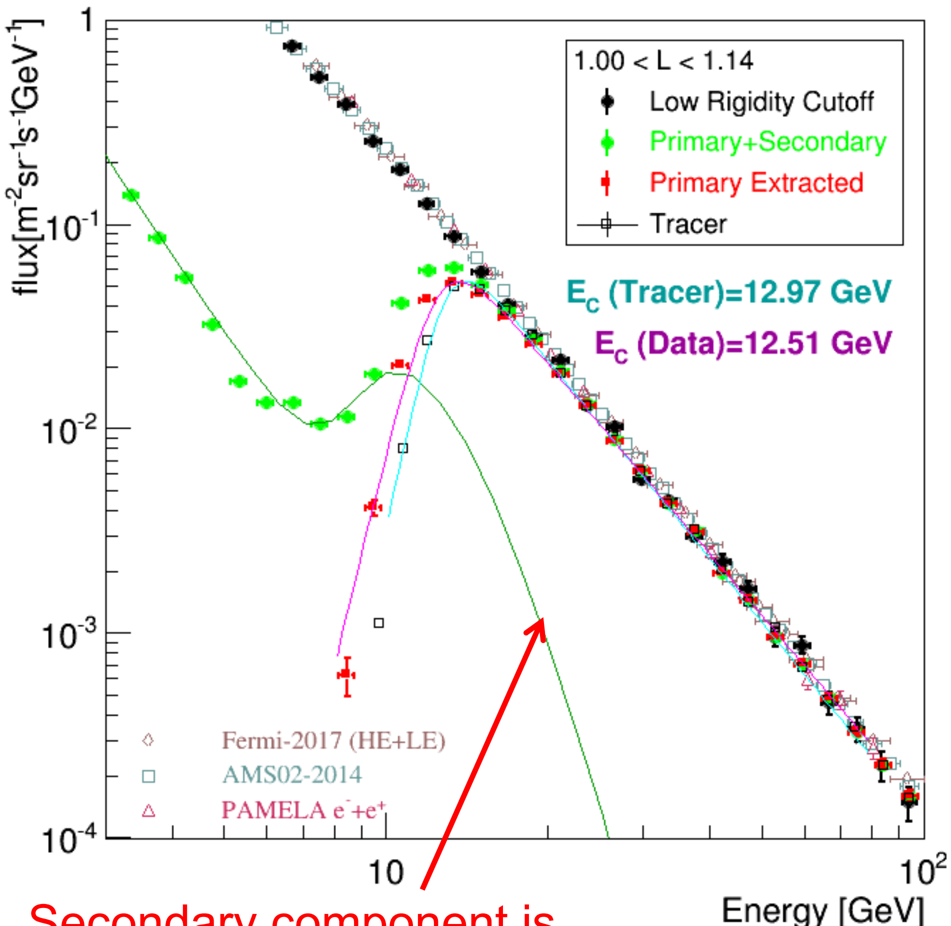
Calibration of Absolute Energy Scale Using Geomagnetic Rigidity Cutoff Energy



geomagnetic rigidity cutoff offers an universal energy scale to space based detectors.

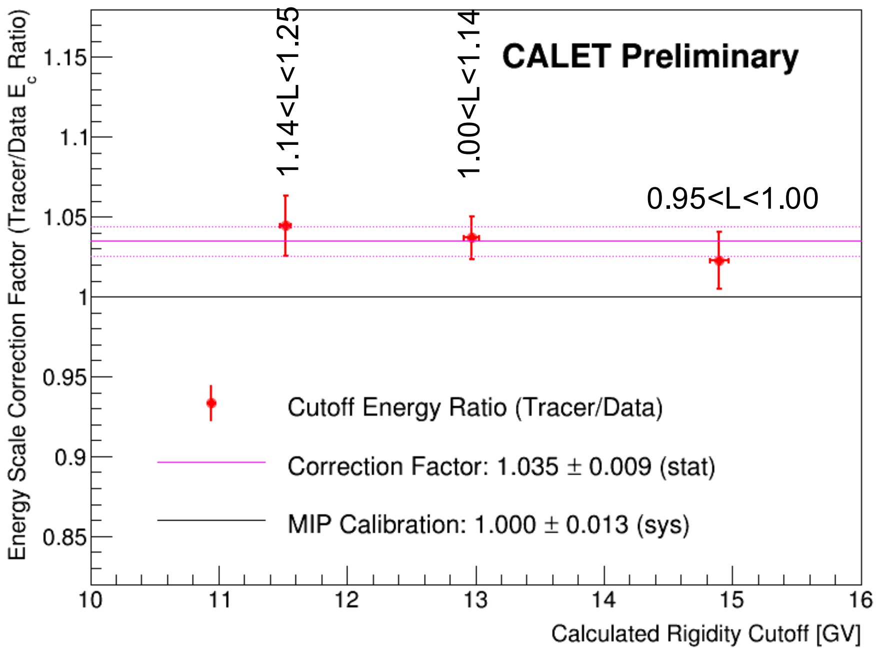
Cutoff Rigidity Measurements and Comparison with Calculation

BEFORE CORRECTION



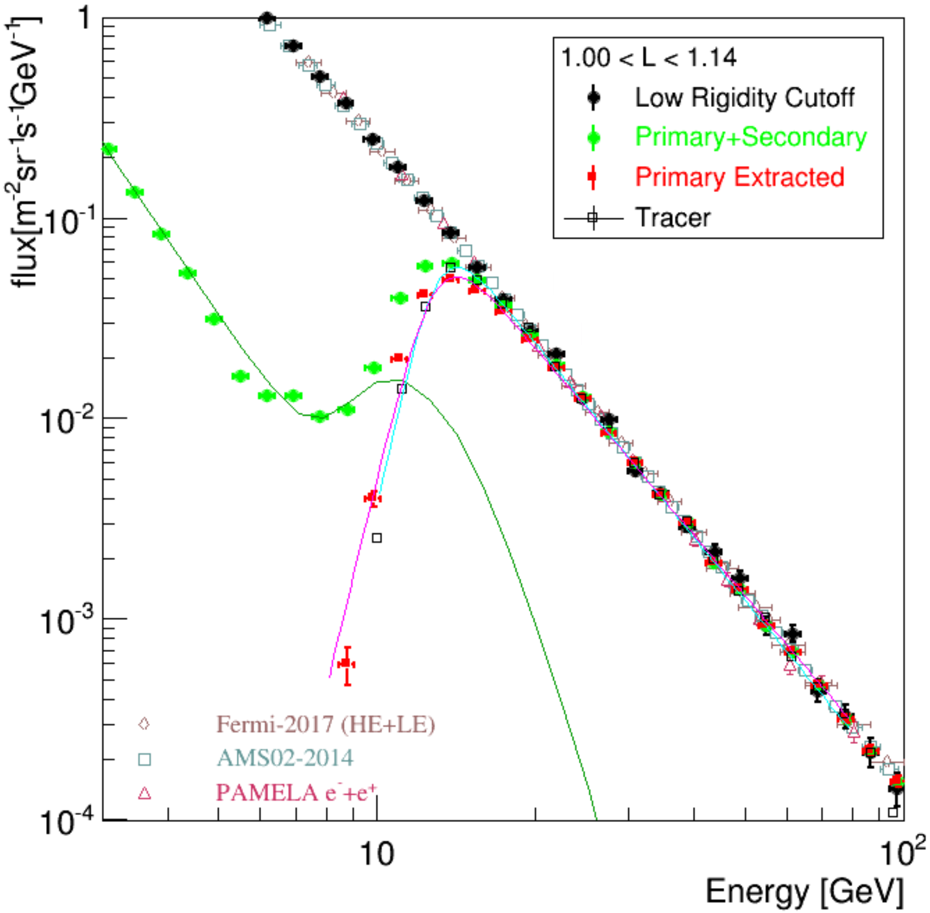
Secondary component is estimated using azimuthal distributions

- Performed in three different cutoff rigidity regions.
- Correction factor was found to be **1.035** compared to MIP calibration.

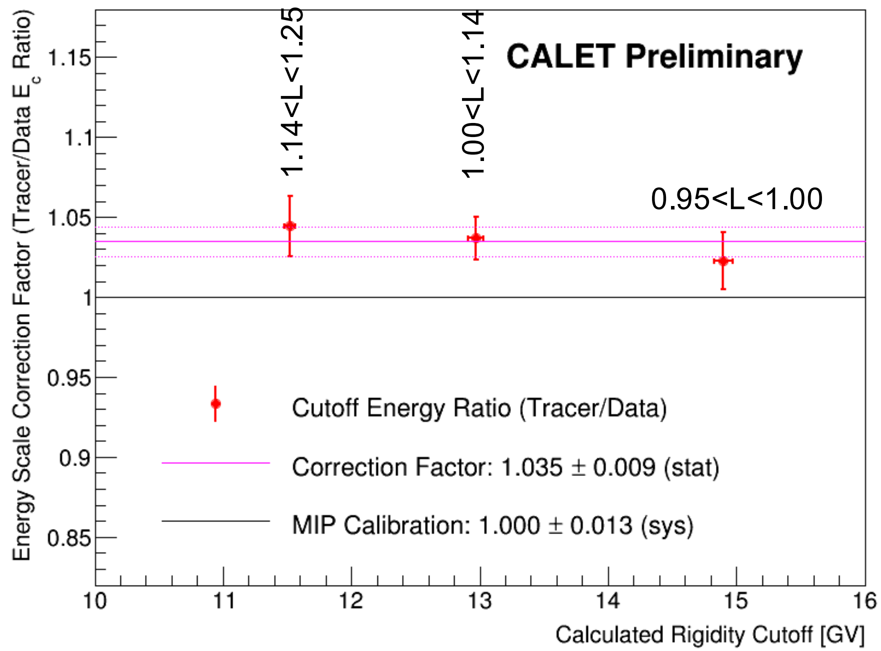


Cutoff Rigidity Measurements and Comparison with Calculation

AFTER CORRECTION



- Performed in three different cutoff rigidity regions.
- Correction factor was found to be **1.035** compared to MIP calibration.

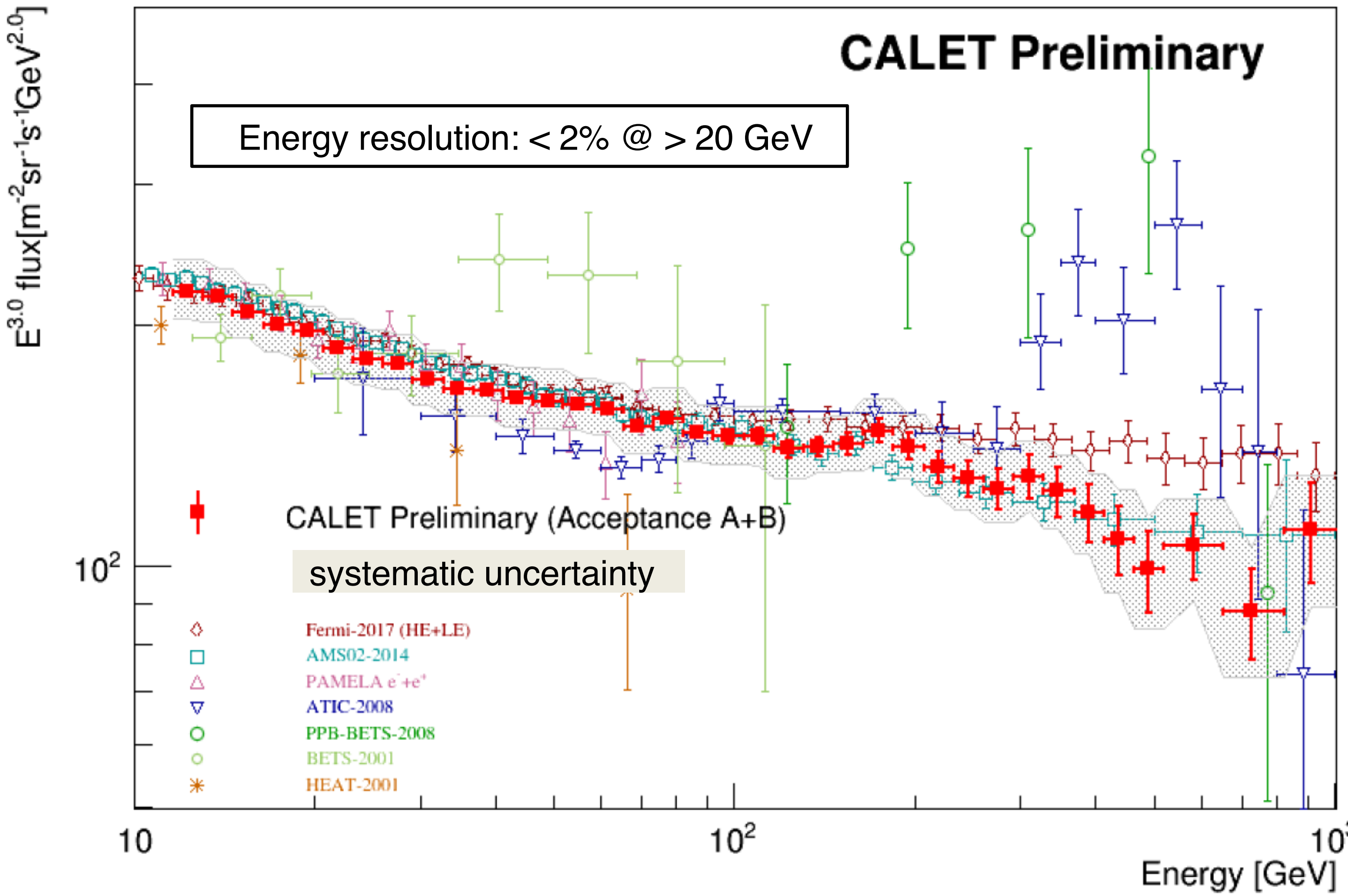


Since universal energy-scale calibration between different instruments is very important, we adopt the energy scale determined by rigidity cutoff to derive our spectrum.

Total Electron Energy Spectrum in 10 GeV～1TeV

Y.Asaoka et al.
(oral) ID205

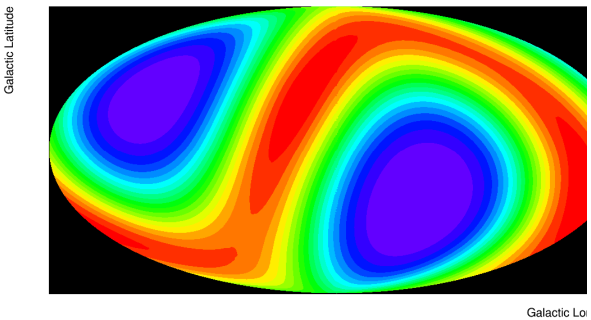
- Geometry Condition: SΩ= 570.3 cm^2sr (A+B: 55% for all acceptance)
- Live Time: 2015/10/13—2017/03/31 (x 0.85) => T= 3.89 x 10^7 sec
- Exposure: SΩT = 2.24 x 10^6 m^2 sr sec ~1/7 of full analysis for 5 years



CALET γ–ray Sky in LE (>1GeV) Trigger

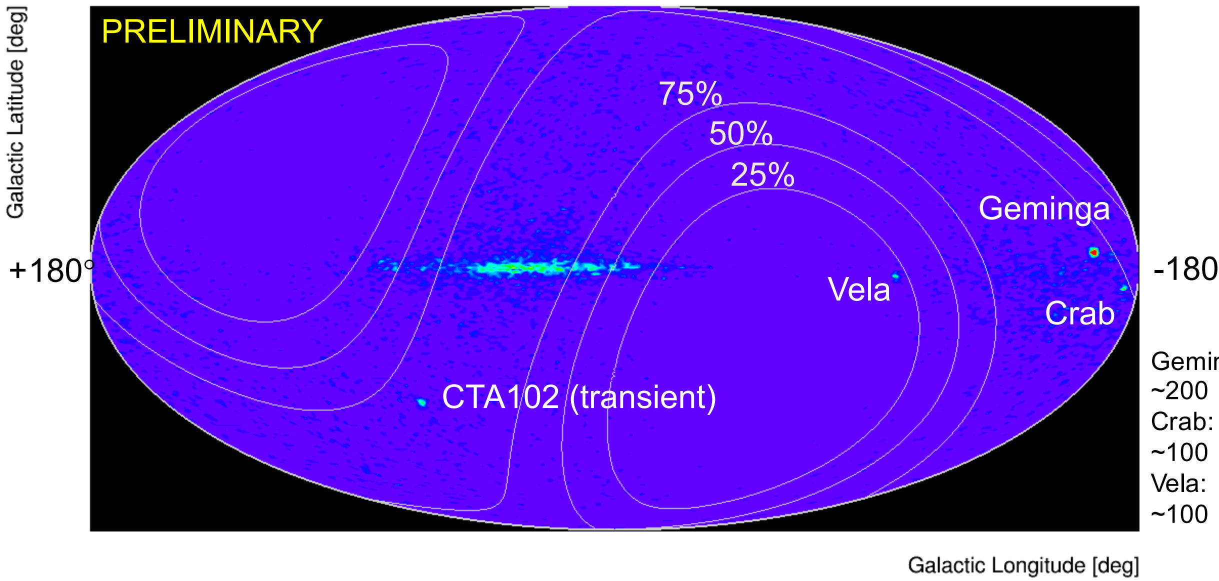
N.Cannady et al. (oral) ID720

Exposure



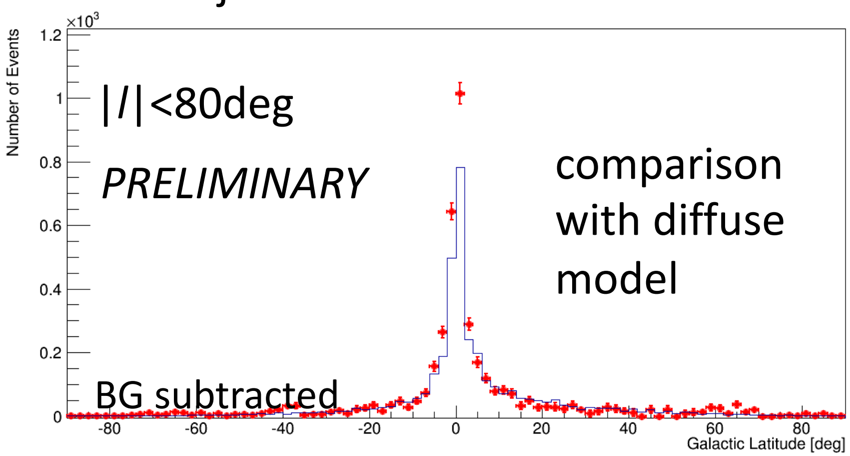
Exposure is limited to low latitude region
=> ldeclinationl > 60 deg is hardly seen in LE gamma-ray trigger mode.

151013—170228 E>1GeV Galactic Coordinate

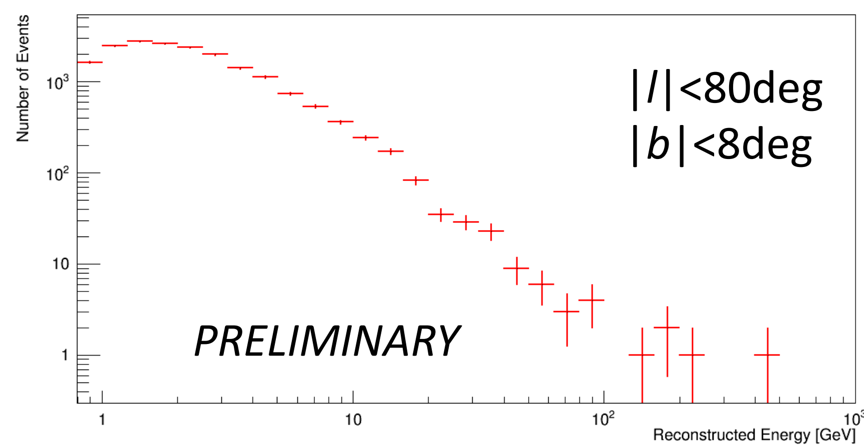


Geminga: ~200
Crab: ~100
Vela: ~100

Projection to Galactic Latitude



Galactic Diffuse Spectrum

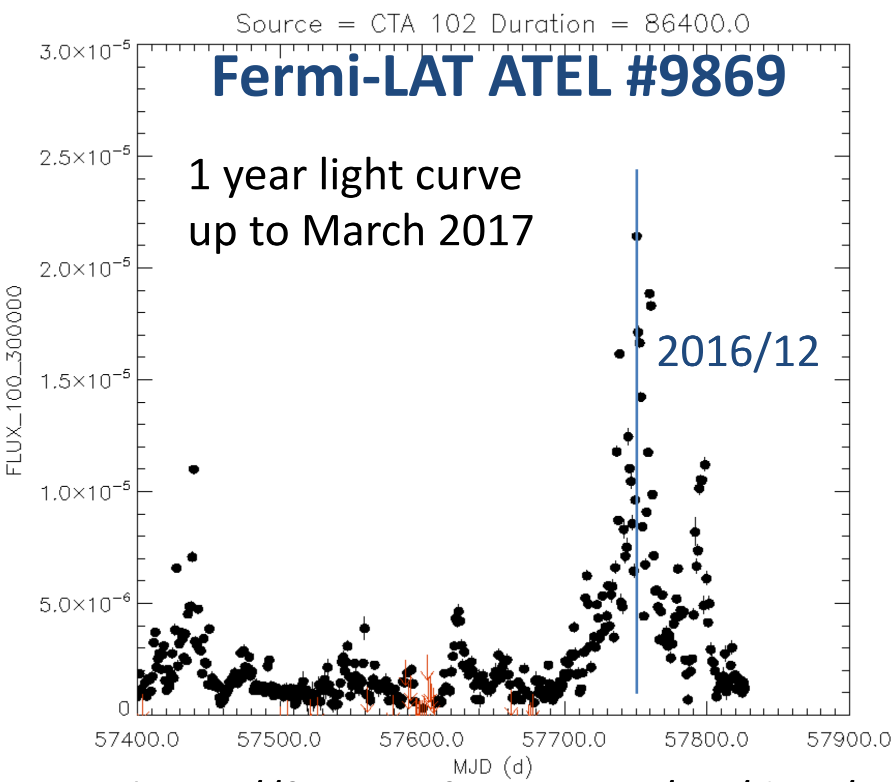


*) Contribution from point sources is not included in the model

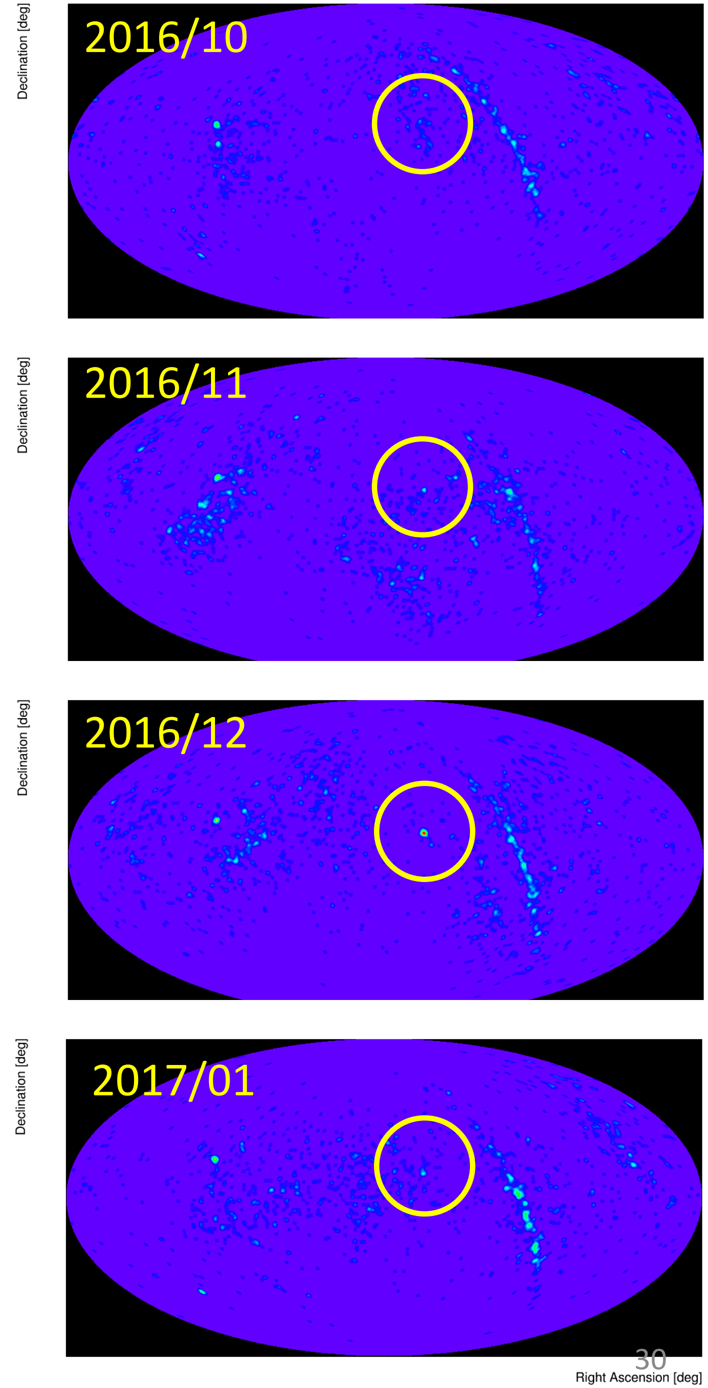
Strong GeV Gamma-ray Activity from Blazar CTA 102

Reported to ATEL by AGILE, Fermi, DAMPE in GeV

⇒ Also detected by CALET

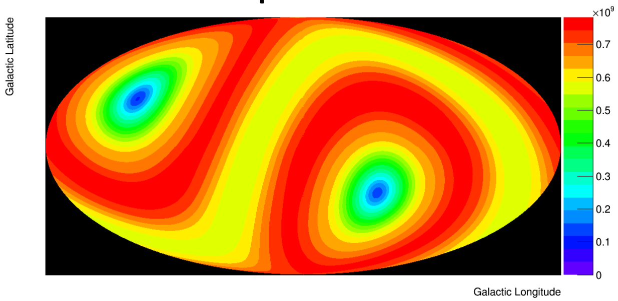


https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/source/CTA_102



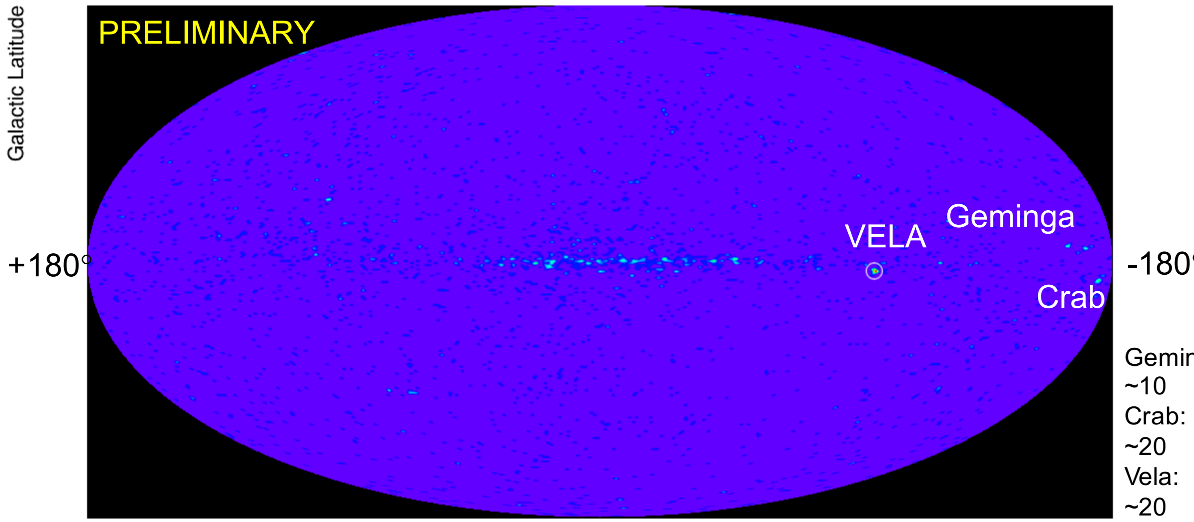
CALET γ–ray Sky in HE (>10GeV) Trigger

Exposure



HE trigger is always ON
=> Exposure determined by the ISS orbit and FOV is more uniform than LE trigger.

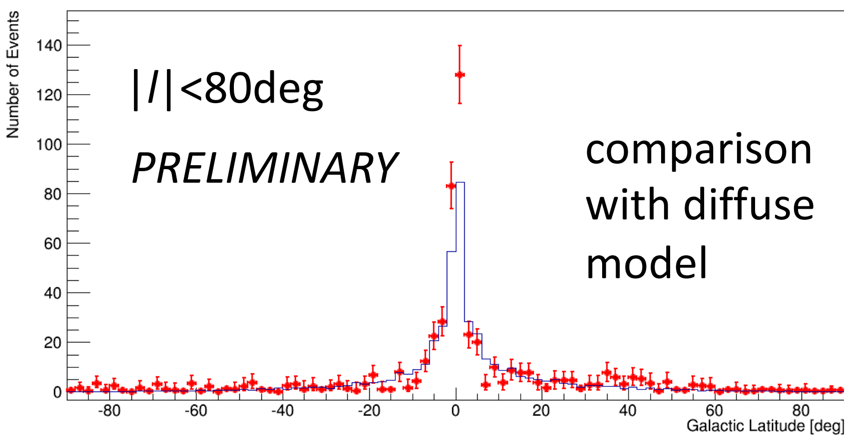
151013—170228 E>10GeV Galactic Coordinate



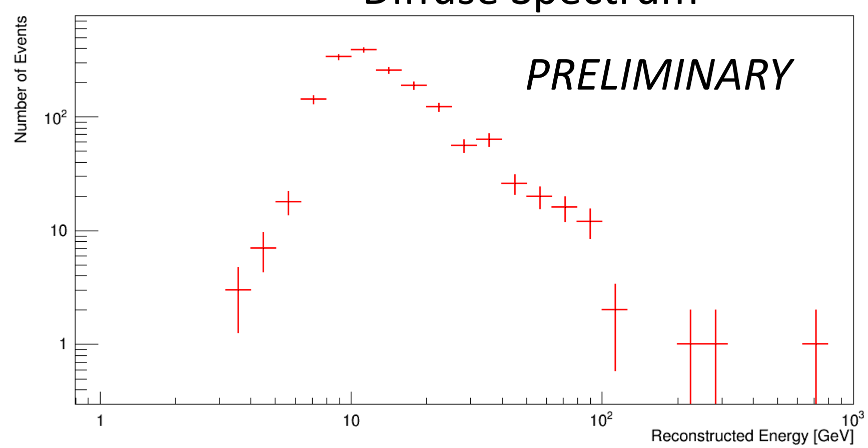
Geminga: ~10
Crab: ~20
Vela: ~20

Vela, Crab and Geminga are identified.

Projection to Galactic Latitude



Diffuse Spectrum



contribution from point sources is not included in the model

CALET UPPER LIMITS ON X-RAY AND GAMMA-RAY COUNTERPARTS OF GW 151226

Astrophysical Journal Letters 829:L20(5pp), 2016 September 20

The CGBM covered 32.5% and 49.1% of the GW 151226 sky localization probability in the 7 keV - 1 MeV and 40 keV - 20 MeV bands respectively. We place a 90% upper limit of 2×10^{-7} erg cm^{-2} s^{-1} in the 1 - 100 GeV band where CAL reaches 15% of the integrated LIGO probability (~1.1 sr). The CGBM 7 σ upper limits are 1.0×10^{-6} erg cm^{-2} s^{-1} (7-500 keV) and 1.8×10^{-6} erg cm^{-2} s^{-1} (50-1000 keV) for one second exposure. Those upper limits correspond to the luminosity of 3-5 $\times 10^{49}$ erg s^{-1} which is significantly lower than typical short GRBs.

CGBM light curve at the moment of the GW151226 event

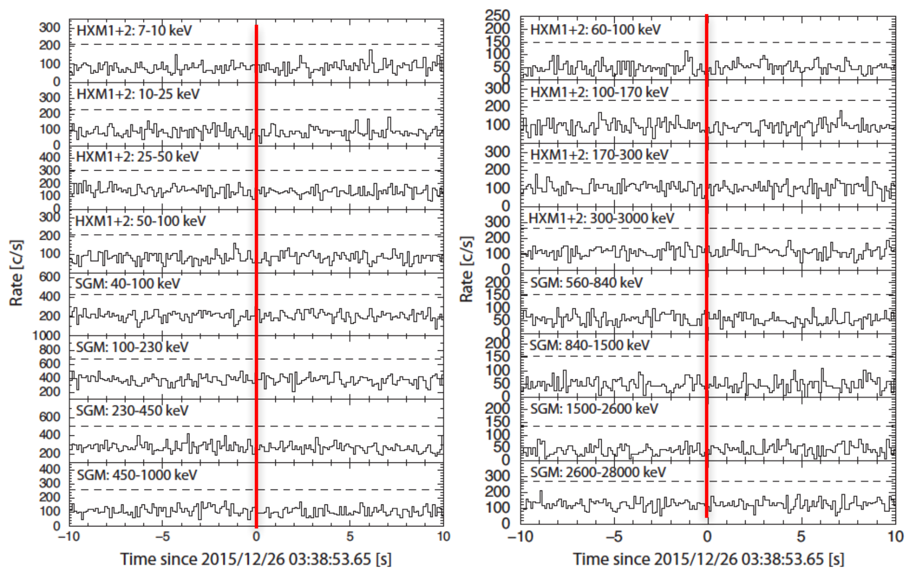


Figure 1. The CGBM light curves in 0.125 s time resolution for the high-gain data (left) and the low-gain data (right). The time is offset from the LIGO trigger time of GW 151226. The dashed-lines correspond to the 5 σ level from the mean count rate using the data of ±10 s.

Upper limit for gamma-ray burst monitors and Calorimeter

HXM: 7-500 keV

SGM: 50-1000 keV

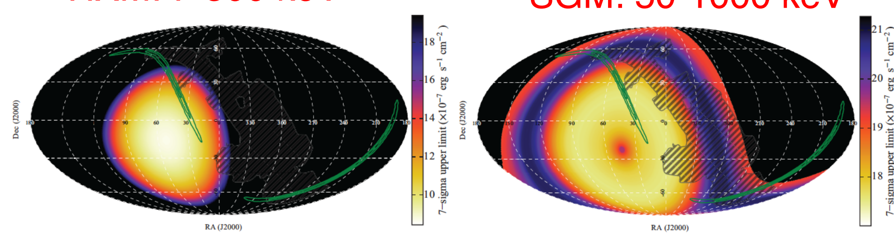


Figure 2. The sky maps of the 7 σ upper limit for HXM (left) and SGM (right). The assumed spectrum for estimating th upper limit is a typical BATSE S-GRBs (see text for details). The energy bands are 7-500 keV for HXM and 50-1000 keV fo SGM. The GW 151226 probability map is shown in green contours. The shadow of ISS is shown in black hatches.

Calorimeter: 1-100 GeV

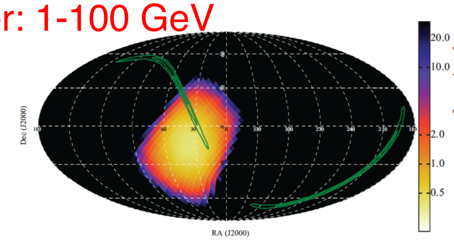


Figure 3. The sky map of the 90% upper limit for CAL in the 1-100 GeV band. A power-law model with a photon index of − is used to calculate the upper limit. The GW 151226 probability map is shown in green contours.

M.Mori et al. (poster) ID637
Revised analysis for Calorimeter

CALET's first publication NOT for Cosmic Rays

Accepted article online 25 APR 2016

Geophysical Research Letters

Relativistic electron precipitation at International Space Station: Space weather monitoring by Calorimetric Electron Telescope

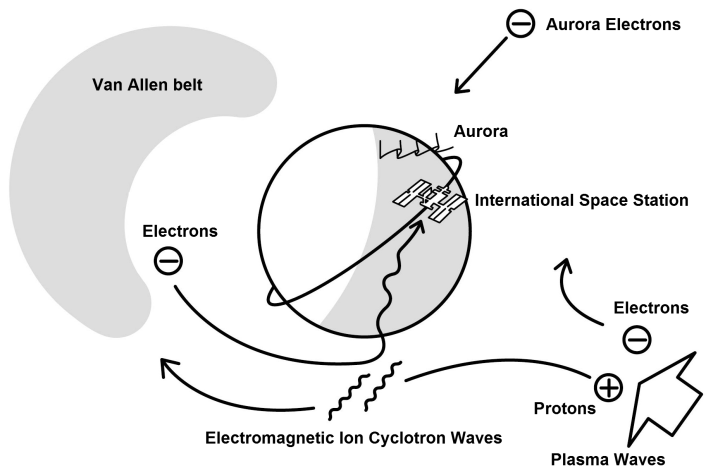
Ryuho Kataoka[1,2], Yoichi Asaoka[3], Shoji Torii[3,4], Toshio Terasawa[5], Shunsuke Ozawa[4], Tadahisa Tamura[6], Yuki Shimizu[6], Yosui Akaike[4], and Masaki Mori[7]

[1]Space and Upper Atmospheric Sciences Group, National Institute of Polar Research, Tachikawa, Japan, [2]Department of Polar Science, School of Multidisciplinary Sciences, SOKENDAI (Graduate University for Advanced Studies), Tachikawa, Japan, [3]Research Institute for Science and Engineering, Waseda University, Shinjuku, Japan, [4]Department of Physics, Waseda University, Shinjuku, Japan, [5]Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Japan, [6]Institute of Physics, Kanagawa University, Yokohama, Japan, [7]Department of Physical Sciences, Ritsumeikan University, Kusatsu, Japan

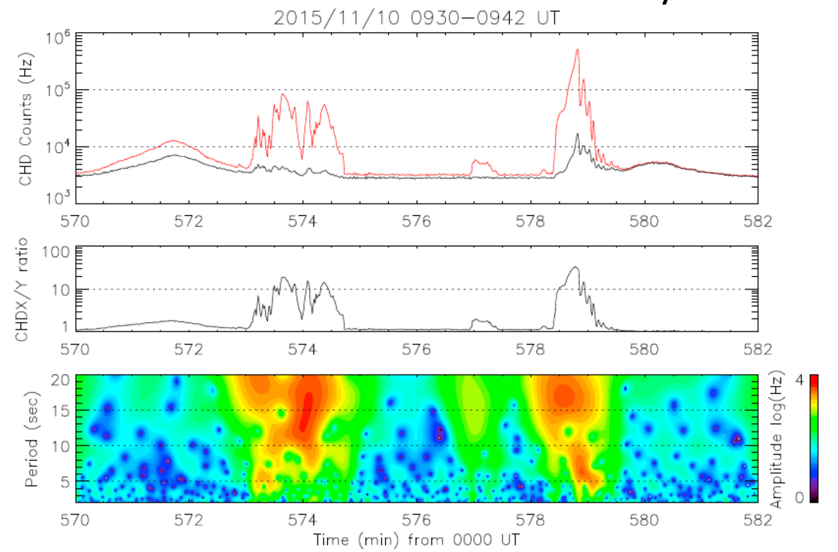
Abstract The charge detector (CHD) of the Calorimetric Electron Telescope (CALET) on board the International Space Station (ISS) has a huge geometric factor for detecting MeV electrons and is sensitive to relativistic electron precipitation (REP) events. During the first 4 months, CALET CHD observed REP events mainly at the dusk to midnight sector near the plasmapause, where the trapped radiation belt electrons can be efficiently scattered by electromagnetic ion cyclotron (EMIC) waves. Here we show that interesting 5–20 s periodicity regularly exists during the REP events at ISS, which is useful to diagnose the wave-particle interactions associated with the nonlinear wave growth of EMIC-triggered emissions.

Space Weather is now a new topic of the CALET science !!

Relativistic Electron Precipitation



CHD X and Y count rate increase by REP



Summary and Future Prospects

- CALET was successfully launched on Aug. 19th, 2015, and the detector is being very stable for observation since Oct. 13th, 2015.
- As of Jun. 30th, 2017, total observation time is 627 days with live time fraction to total time to close 84%. Nearly 409 million events are collected with high energy (>10 GeV) trigger.
- Careful calibrations have been adopted by using "MIP" signals of the non-interacting p & He events, and the linearity in the energy measurements up to 10^6 MIPs is established by using observed events.
- Preliminary analysis of nuclei, total elections and gamma-rays have successfully been carried out to obtain the energy spectra in the energy range;
  Protons: 55 GeV~22 TeV, Ne-Fe: 500 GeV~70 TeV, Total electrons: 10 GeV~1 TeV.
- Preliminary analysis of UH cosmic-ray flux are done up to Z=40.
- CALET's CGBM detected nearly 60 GRBs (~20 % short GRB among them) per year in the energy range of 7 keV-20 MeV, as expected. Follow-up observations of the GW events were carried out. (Not reported in this talk) See K Yamaoka et al. (poster) ID614
- The so far excellent performance of CALET and the outstanding quality of the data suggests that a 5-year observation period is likely to provide a wealth of new interesting results.

Presentations from CALET Collaboration

Analysis and Preliminary Results for the Cosmic Ray Electron Spectrum from CALET
-- Y.Asaoka (CR-D:Pos205) Oral
Observation of Protons and Light Nuclei with CALET: Analysis and Preliminary Results
-- P.S.Marrocchesi (CR-D: PoS 156) Oral
Measurements of heavy nuclei with the CALET experimentHeavy
-- Y.Akaike (CR-D: PoS 181) Oral
Status of the CALET Ultra Heavy Cosmic Ray Analysis
-- B.Rauch and Y.Akaike (CR-D: PoS 180) Poster
Particle tracking in the CALET experiment
-- P. Maestro and N.Mori (CR-D: PoS 208) Oral
Capability of electron identification for the CALET measurement.
-- L. Pacini + Y.Akaike (CR-D: PoS 163) Poster
CALET on-orbit operations and data analysis system at the Waseda CALET Operations Center (WCOC)
-- S.Ozawa (CR-D: PoS 165) Poster
Full Dynamic Range Energy Calibration of CALET onboard the International Space Station
-- R. MIyata (MC student in WU) (CR-D: PoS 207) Poster
MIP Calibration and the Long-term Stability of CALET onboard the International Space Station
-- Y.Komiya (MC student in WU) + G. Bigongiari (CR-D : PoS 206) Poster
High-Energy Gamma-ray Observations Using the CALorimetric Electron Telescope
-- N.Cannady (GA : PoS 720) Oral
Search for gamma-ray emission from electromagnetic counterparts of gravitational wave sources with the CALET calorimeter
-- M.Mori (GA: PoS 637) Poster
CALET GBM Observations of Gamma-ray Bursts and Gravitational Wave Sources
-- K.Yamaoka (GA: PoS 614) Poster