The Calorimetric Electron Telescope (CALET) on the International Space Station: Latest results from the first three-years on orbit

Yoichi Asaoka
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CALET Collaboration Team

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11) Kavli IPMU, University of Tokyo, Japan
12) KEK, Japan
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14) Nagoya University, Japan
15) NASA/GSFC, USA
16) National Inst. of Radiological Sciences, Japan
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26) University of Padova and INFN, Italy
27) University of Pisa and INFN, Italy
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Outline

1. Introduction
2. Calibration
3. Operations
4. Results
   - Electrons
   - Hadrons
   - Gamma-Rays
   - Space Weather
5. Summary

Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), Astropart. Phys. 91 (2017) 1.

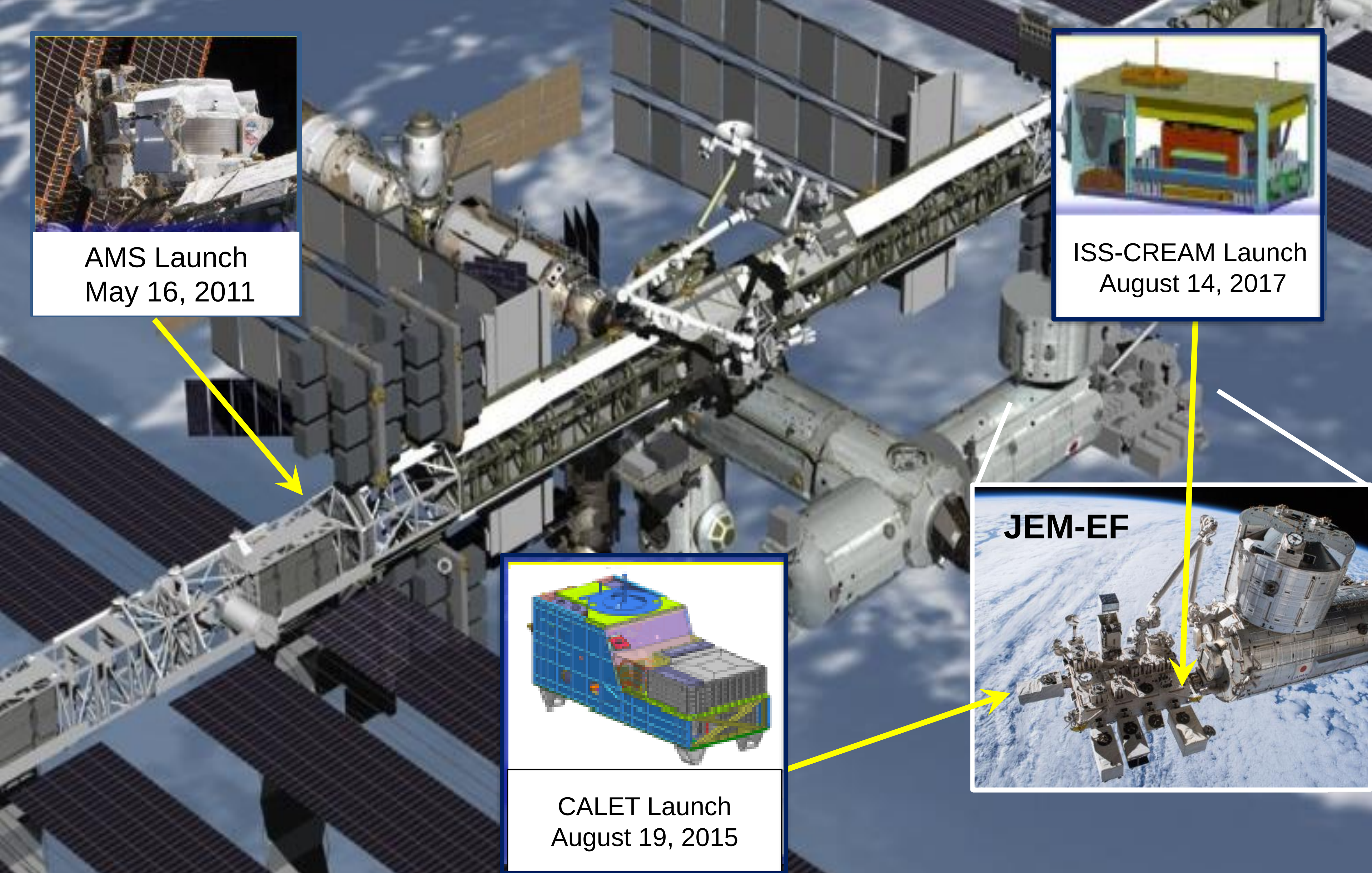
Y.Asaoka, S.Ozawa, S.Torii et al. (CALET Collaboration), Astropart. Phys. 100 (2018) 29.

Electrons:
O.Adriani et al. (CALET Collaboration), Phys.Rev.Lett. 119 (2017) 181101.
O.Adriani et al. (CALET Collaboration), Phys.Rev.Lett. 120 (2018) 261102.

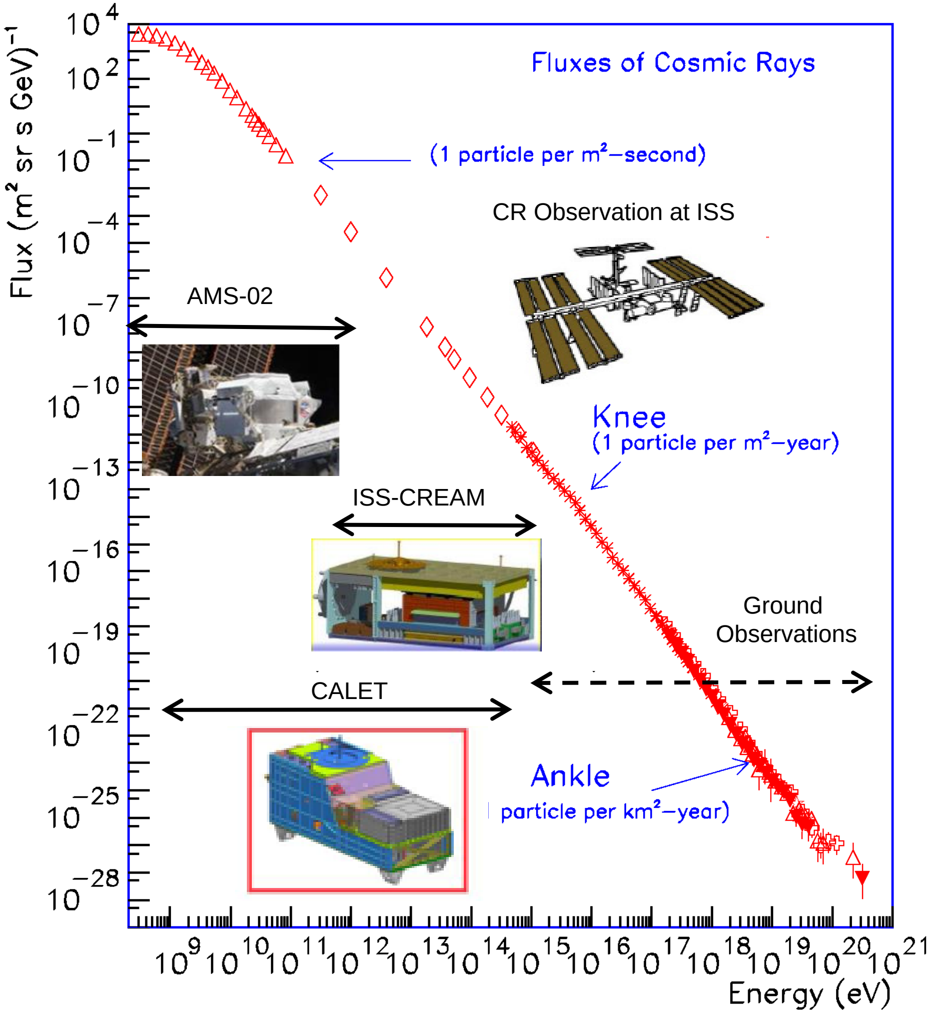
Gamma-Rays:
O.Adriani et al. (CALET Collab.), ApJL 829 (2016) L20.
O.Adriani et al. (CALET Collab.), ApJ 863 (2018) 160.
N.Cannady, Y.Asaoka et al. (CALET Collab.), ApJS in press.

Space Weather:
R.Kataoka et al., JGR, 10.1002/2016GL068930 (2016).

ISS as Cosmic Ray Observatory



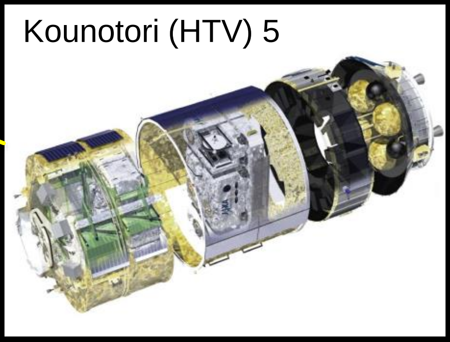
Cosmic Ray Observations at the ISS and CALET



Overview of CALET Observations

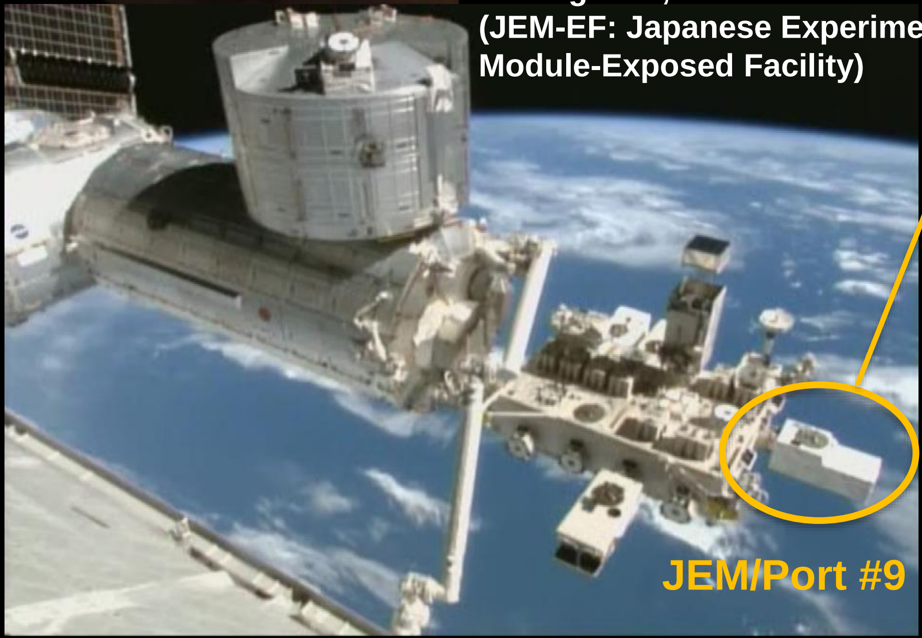
- Direct cosmic ray observations in space at the highest energy region by combining:
  - ✓ A large-size detector
  - ✓ Long-term observation onboard the ISS (5 years or more is expected)
- Electron observation in 1 GeV - 20 TeV will be achieved with high energy resolution due to optimization for electron detection
  ⇨ Search for Dark Matter and Nearby Sources
- Observation of cosmic-ray nuclei will be performed in energy region from 10 GeV to 1 PeV
  ⇨ Unravelling the CR acceleration and propagation mechanism
- Detection of transient phenomena is expected in space by long-term stable observations
  ⇨ EM radiation from GW sources, Gamma-ray burst, Solar flare, etc.

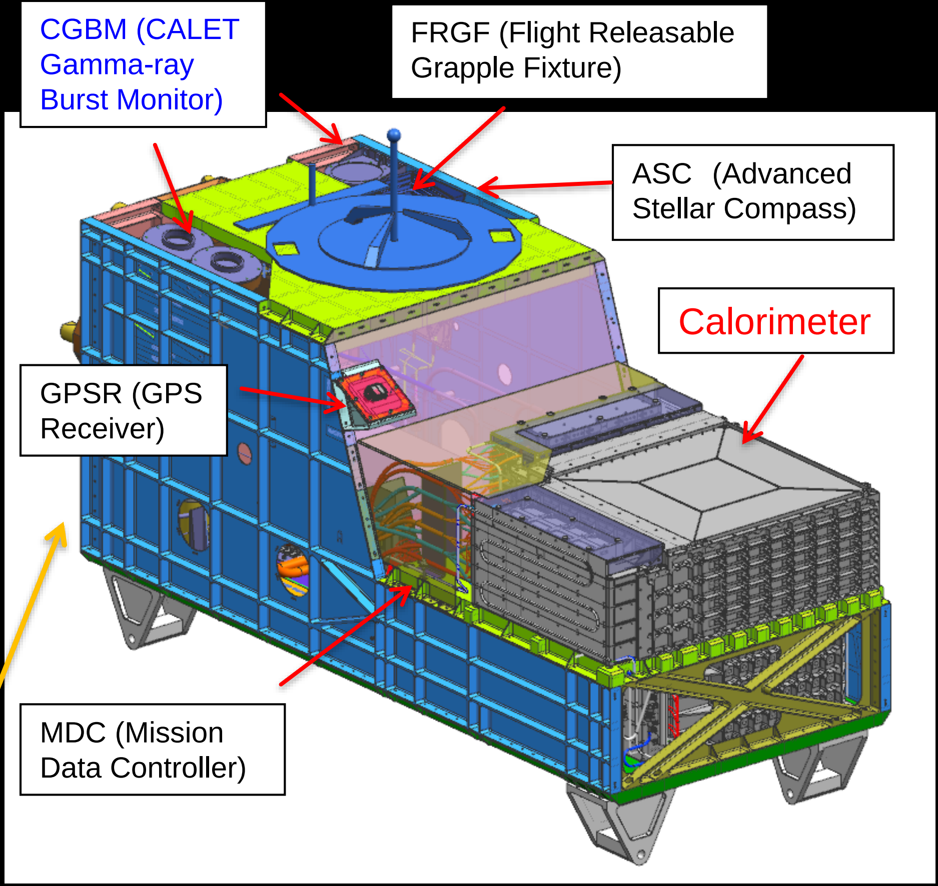
CALET Payload



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

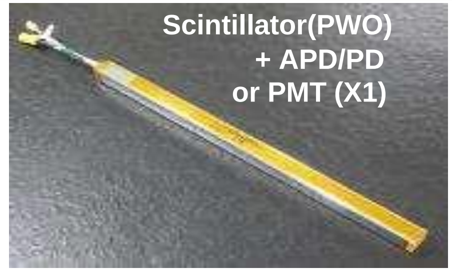
Emplaced on JEM-EF port #9 on Aug. 25th, 2015 (JEM-EF: Japanese Experiment Module-Exposed Facility)



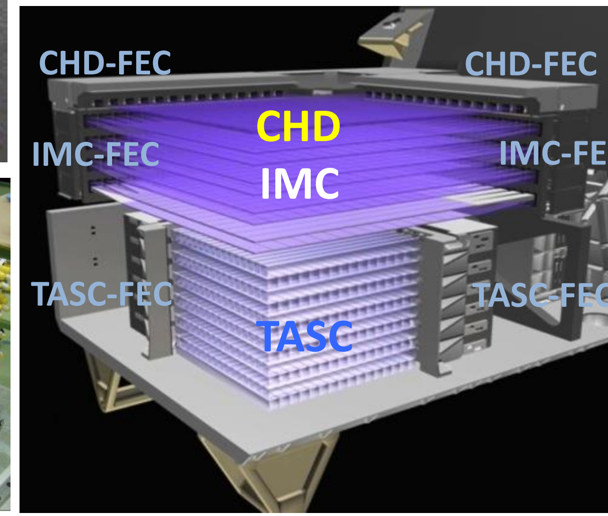


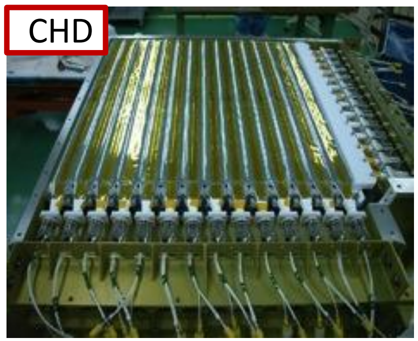
- **Mass: 612.8 kg**
- **JEM Standard Payload Size: 1850mm(L) × 800mm(W) × 1000mm(H)**
- **Power Consumption: 507 W（max）**
- **Telemetry: Medium 600 kbps (6.5GB/day) / Low 50 kbps**

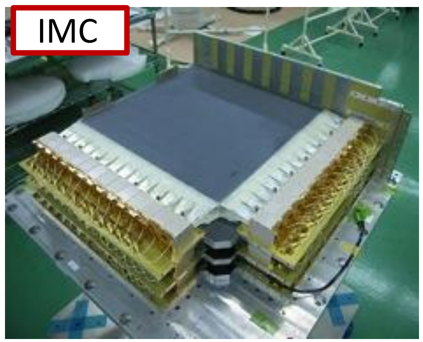
CALET Instrument



CALORIMETER



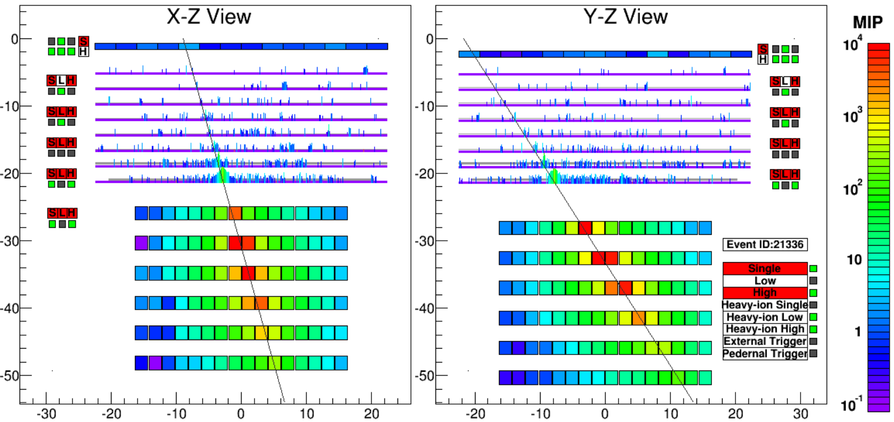




	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers (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**

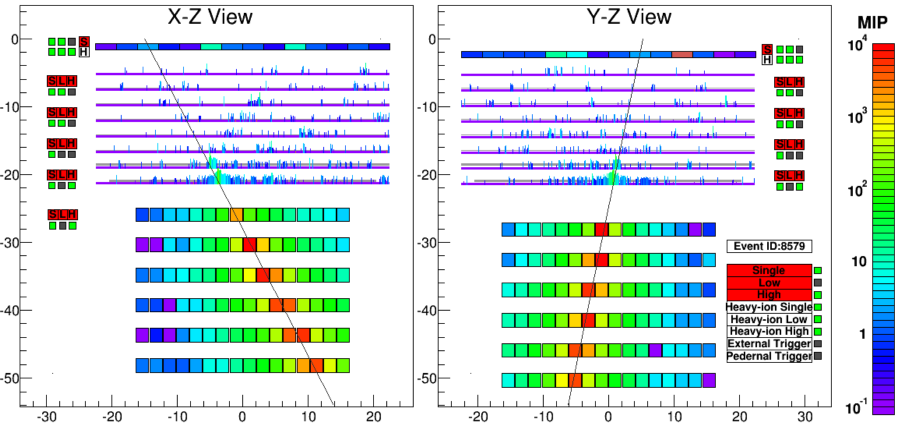
Event Examples of High-Energy Showers

Electron, E=3.05 TeV



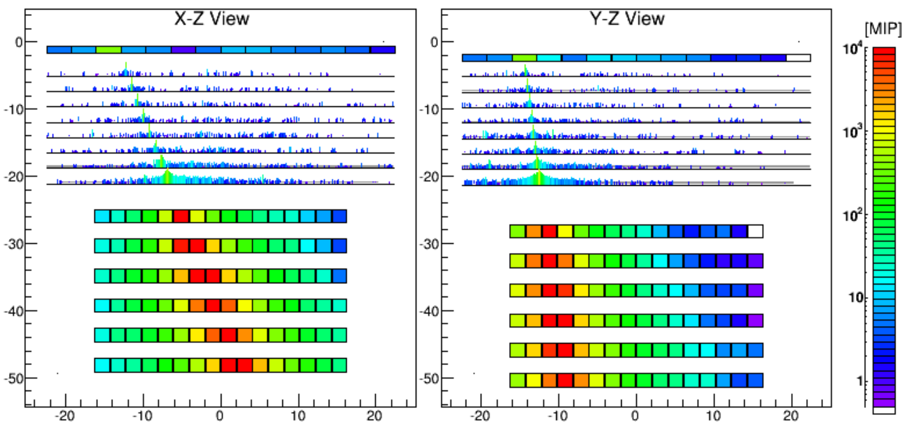
fully contained even at 3TeV

Proton, ΔE=2.89 TeV



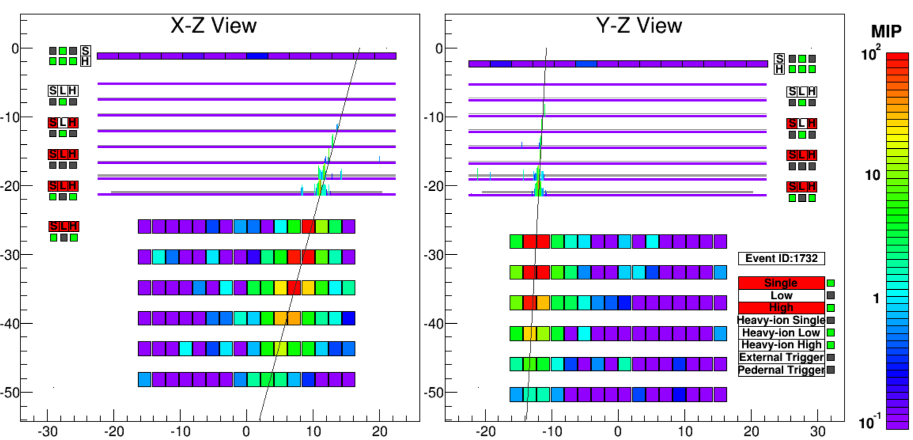
clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

Gamma-ray, E=44.3 GeV



no energy deposit before pair production

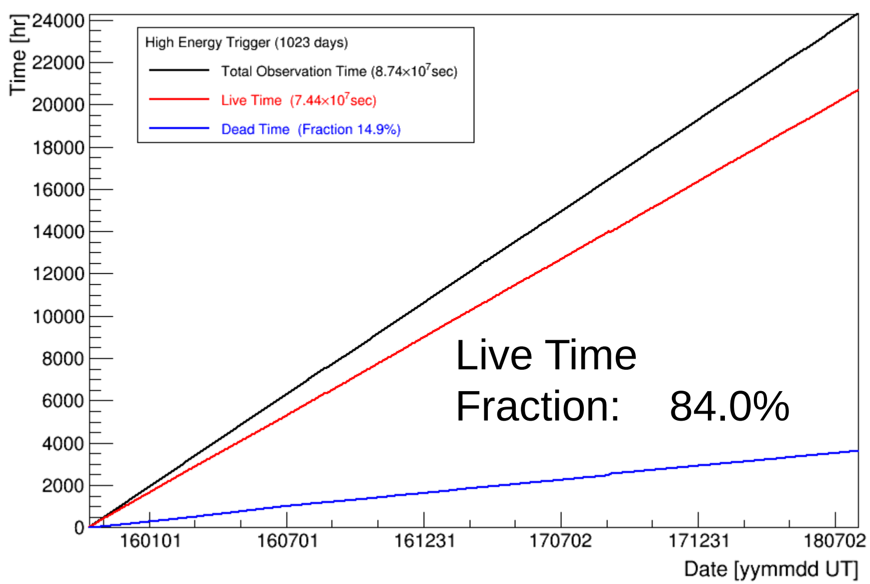
Observation with High Energy Trigger (>10GeV)

Y.Asaoka, S.Ozawa, S.Torii et al. (CALET Collaboration), Astropart. Phys. 100 (2018) 29.

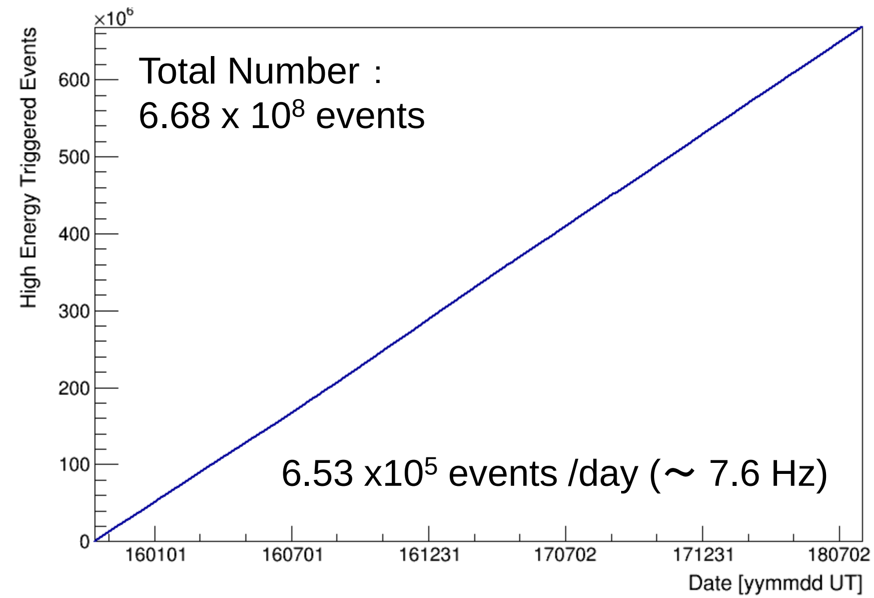
Observation by High Energy Trigger for 1023 days : Oct.13, 2015 – Jul. 31, 2018

- The exposure, SΩT, has reached to ~89.6 m^2 sr day for electron observations by continuous and stable operations.
- Total number of triggered events is ~670 million with a live time fraction of 84.0 %.

Accumulated observation time (live, dead)



Accumulated triggered event number

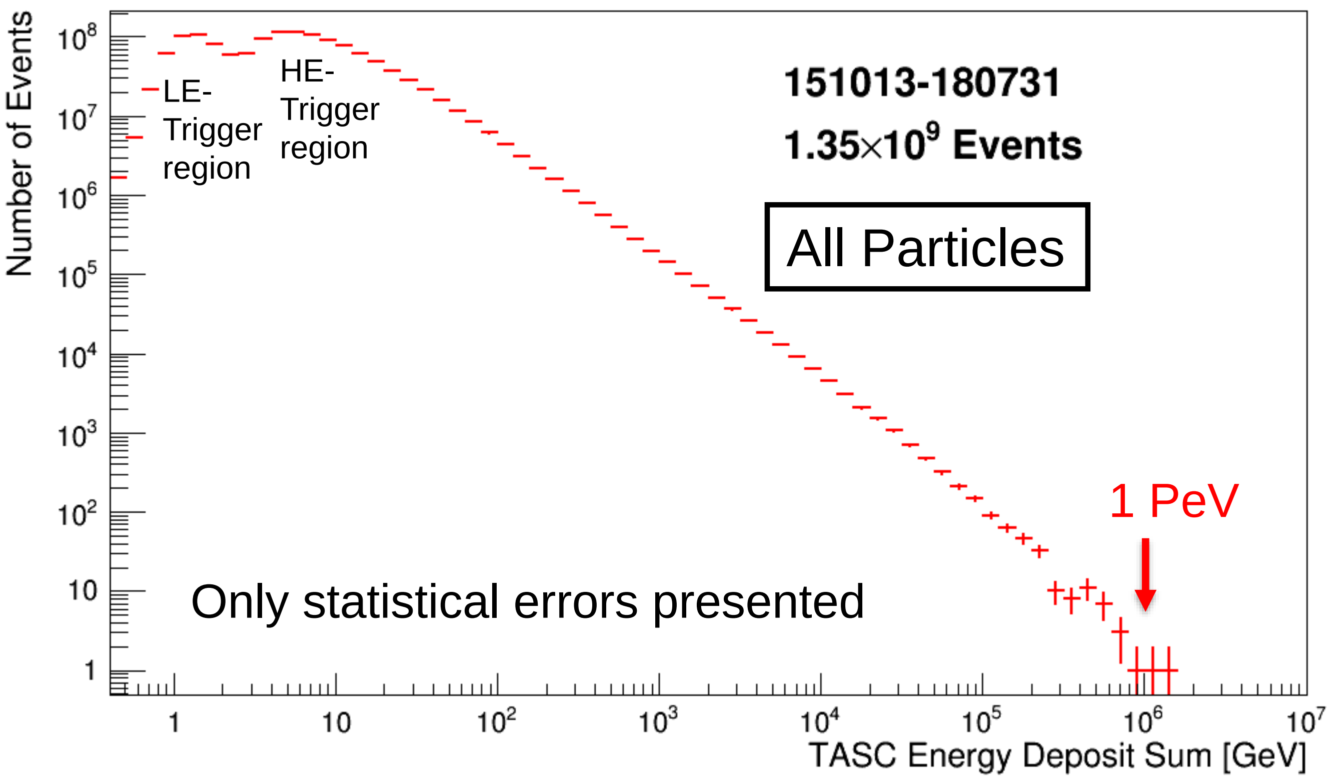


TASC Energy Deposit Distribution of All Triggered-Events by Observation for 1023 days

Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), Astropart. Phys. 91 (2017) 1.

Distribution of deposit energies in TASC observed in 2015.10.13—2018.7.31

➡ Energies are calibrated but non-reconstructed



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

All-Electron (e^++e^-)

O.Adriani et al. (CALET collaboration), Phys. Rev. Lett. 119 (2017) 181101

O.Adriani et al. (CALET collaboration), Phys. Rev. Lett. 120 (2018) 261102

Electron Identification

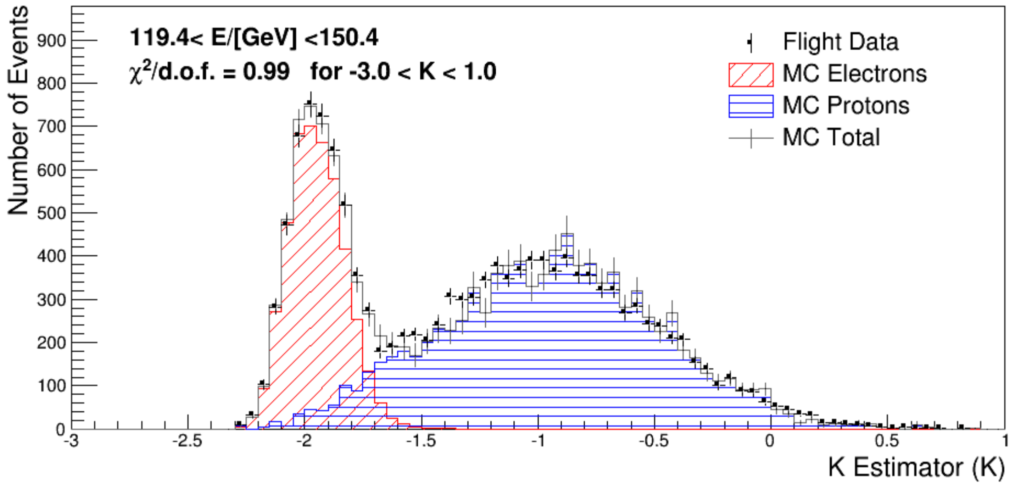
Simple Two Parameter Cut

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

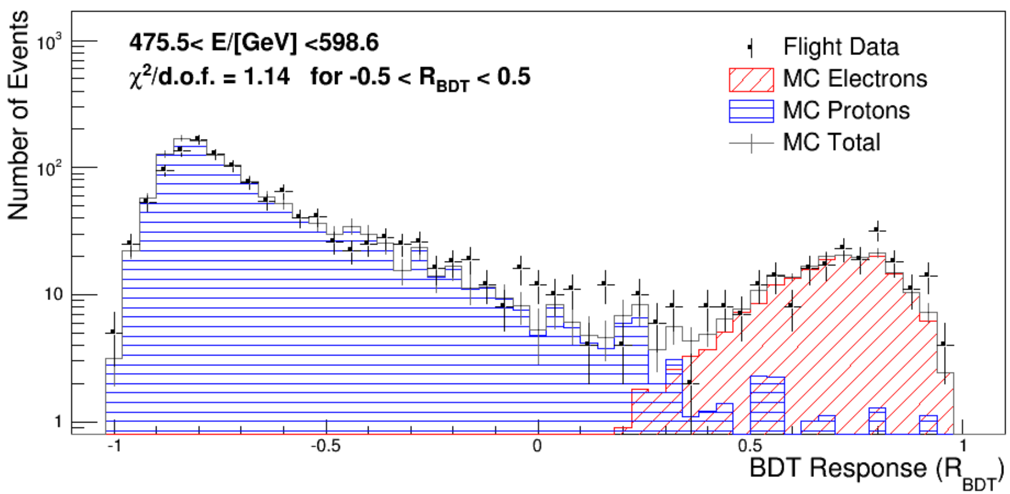
Separation Parameter K is defined as follows:

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



Boosted Decision Trees

In addition to the two parameters making up K, TASC and IMC shower profile fits are used as discriminating variables.



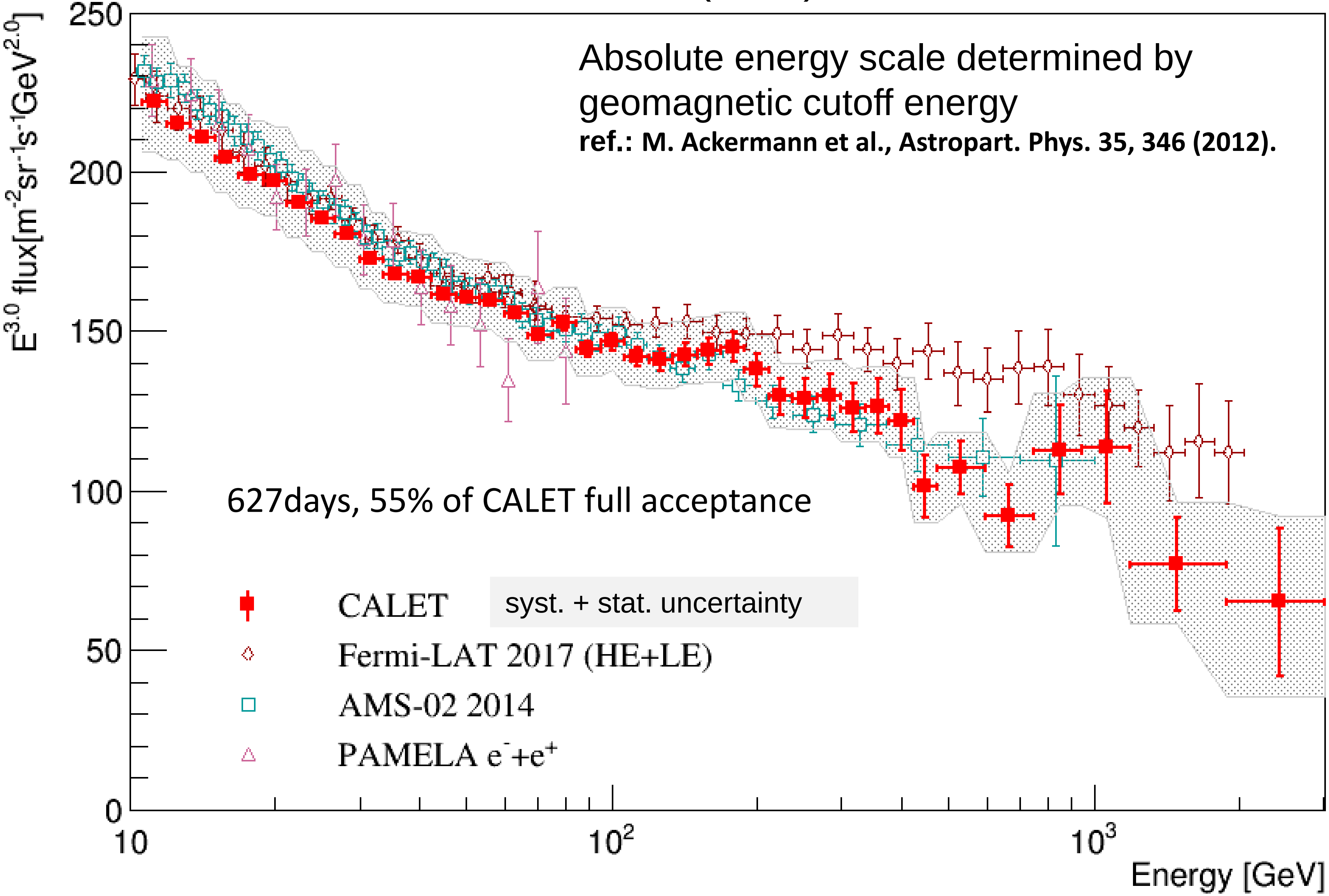
E<475GeV: Simple two parameter cut
E>475GeV: BDT cut

} the small difference in resultant spectrum between two methods are taken into account in the systematic error.

⇒ Contamination is ~5% up to 1TeV, and 10~15% in the 1—3 TeV region.

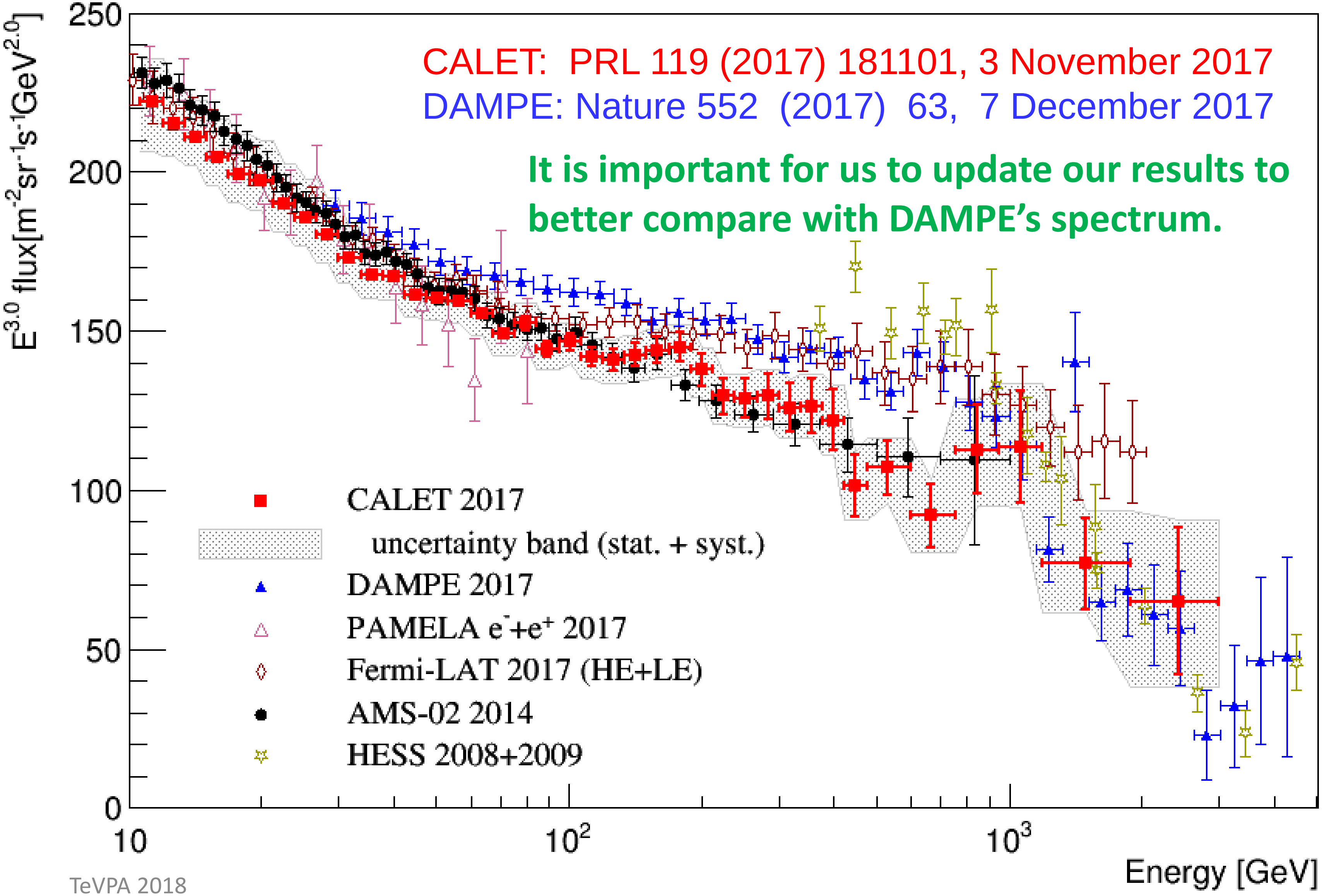
All-Electron Spectrum Measured with CALET from 10 GeV to 3 TeV

CALET: PRL 119 (2017) 181101, 3 November 2017



All-Electron Spectrum Comparison w/ DAMPE

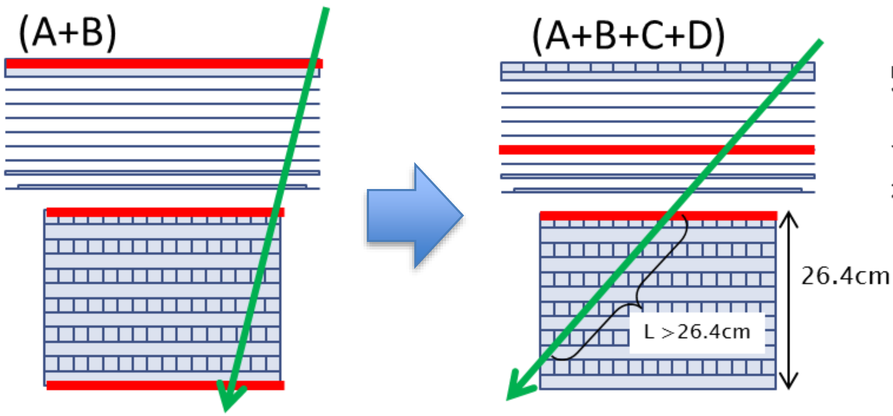
and other space based experiments

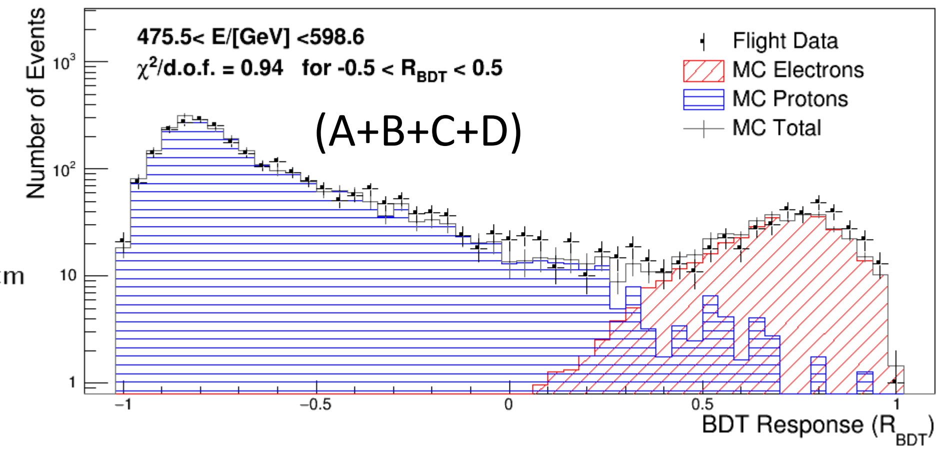


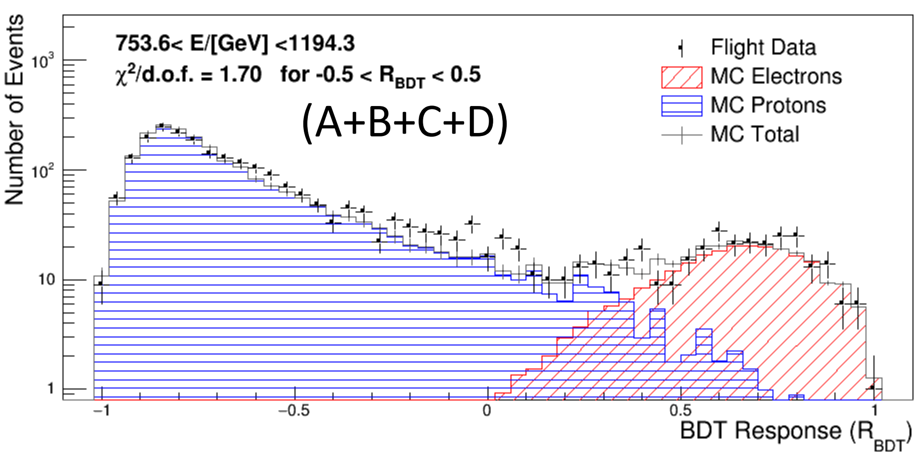
Extending the Analysis to Full Acceptance

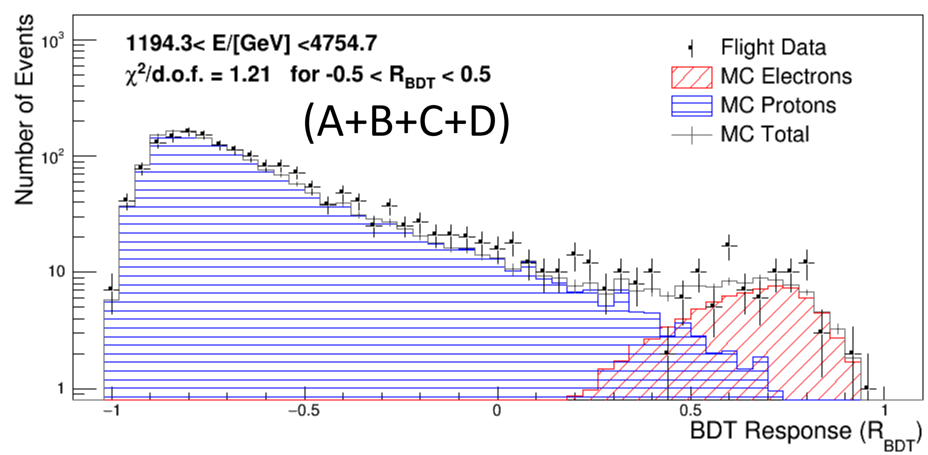
Analyzed Flight Data:

- 780 days (October 13, 2015 to November 30, 2017)
- Full CALET acceptance at the high energy region (Acceptance A+B+C+D; 1040cm^2sr). In the low energy region fully contained events are used (A+B; 550cm^2sr)









Systematic Uncertainties

(other than energy scale uncertainty)

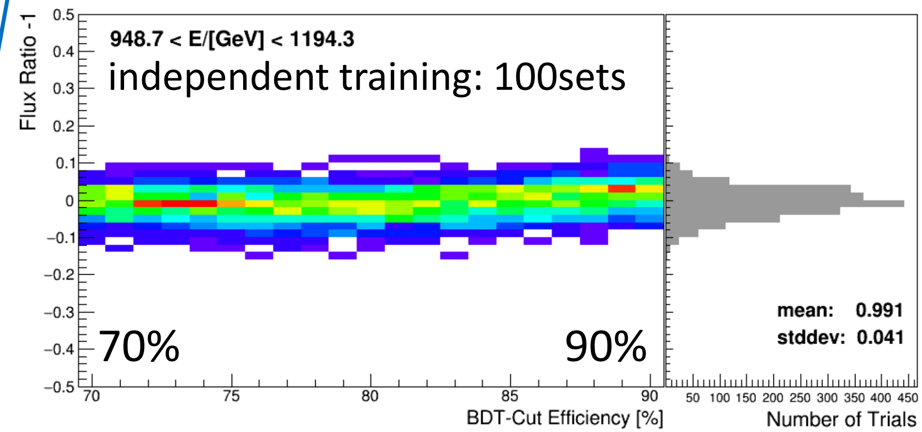
Stability of resultant flux are analyzed by scanning parameter space

Normalization:

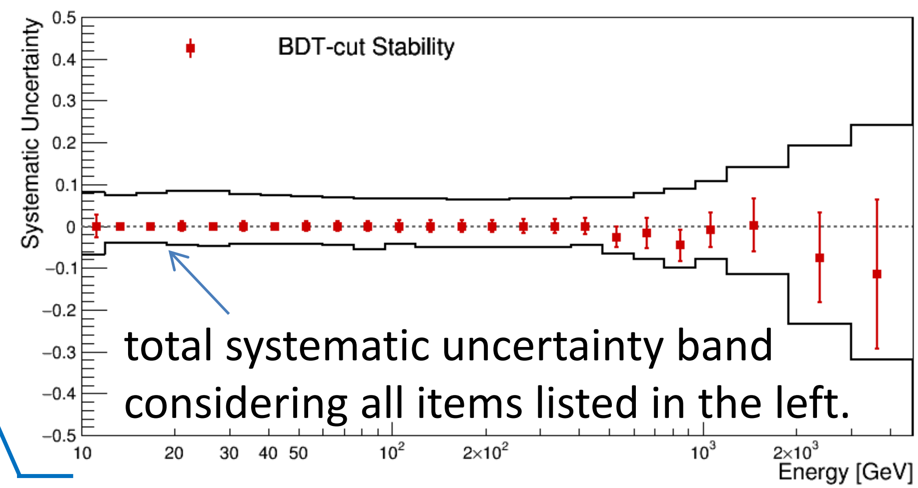
- Live time
- Radiation environment
- Long-term stability
- Quality cuts

- Energy dependent:
  - 2 independent tracking
  - charge ID
  - electron ID (K-Cut vs BDT)
  - **BDT stability** (vs efficiency & training)
  - MC model (EPICS vs Geant4)

Flux Ratio vs Efficiency for BDT @ 1TeV

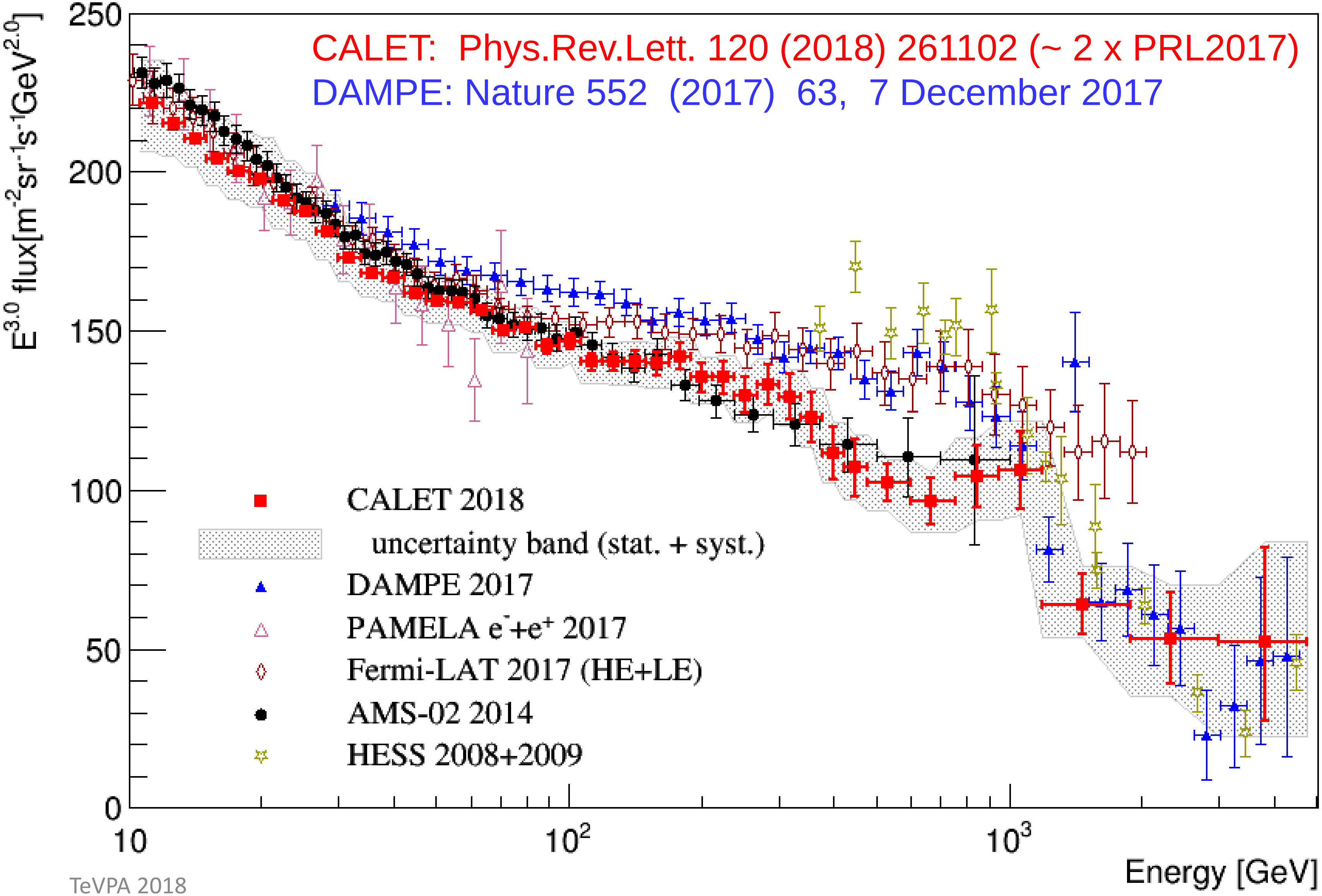


Energy Dependence of BDT stability



Extended Measurement by CALET

Approximately doubled statistics above 500GeV by using full acceptance of CALET



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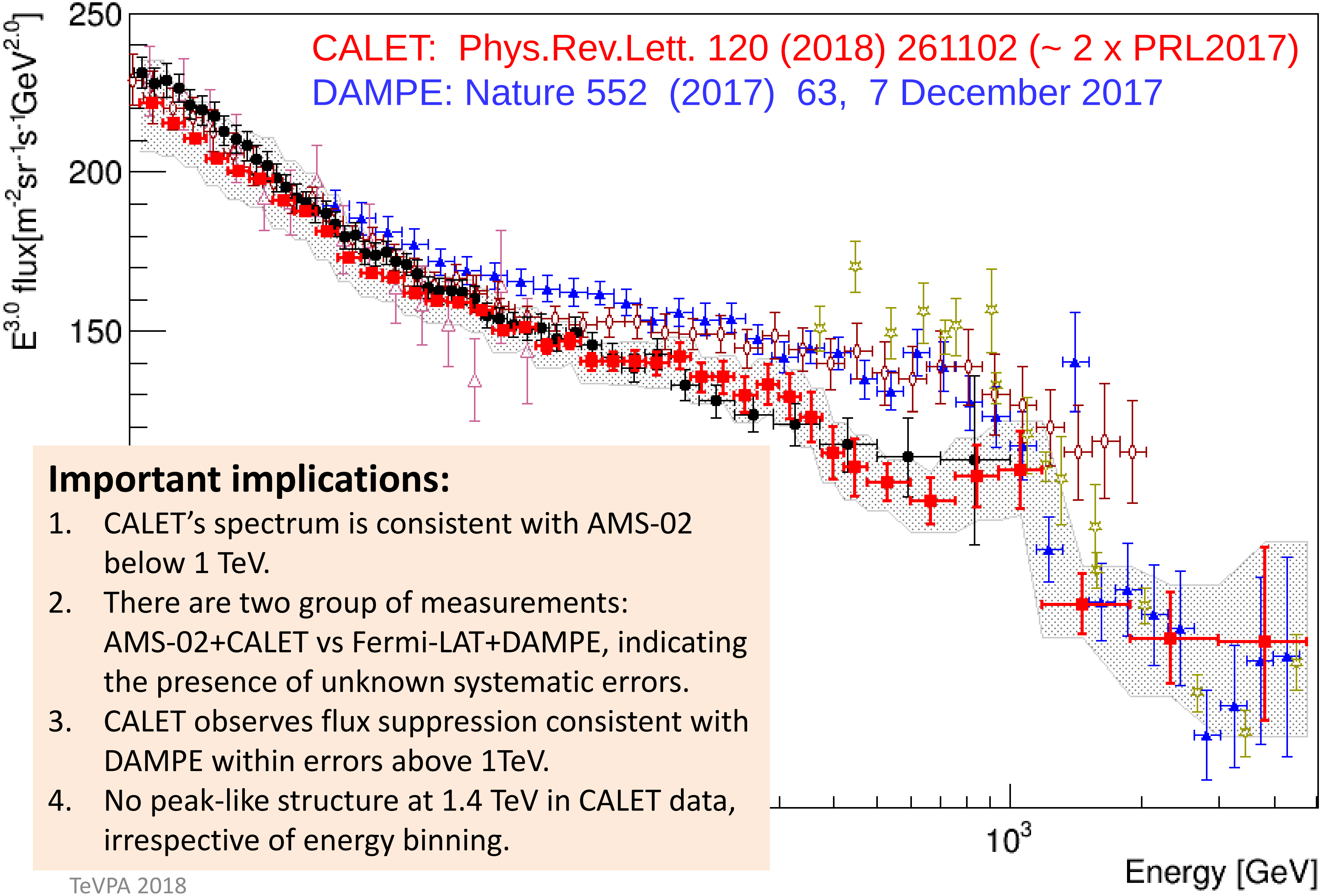
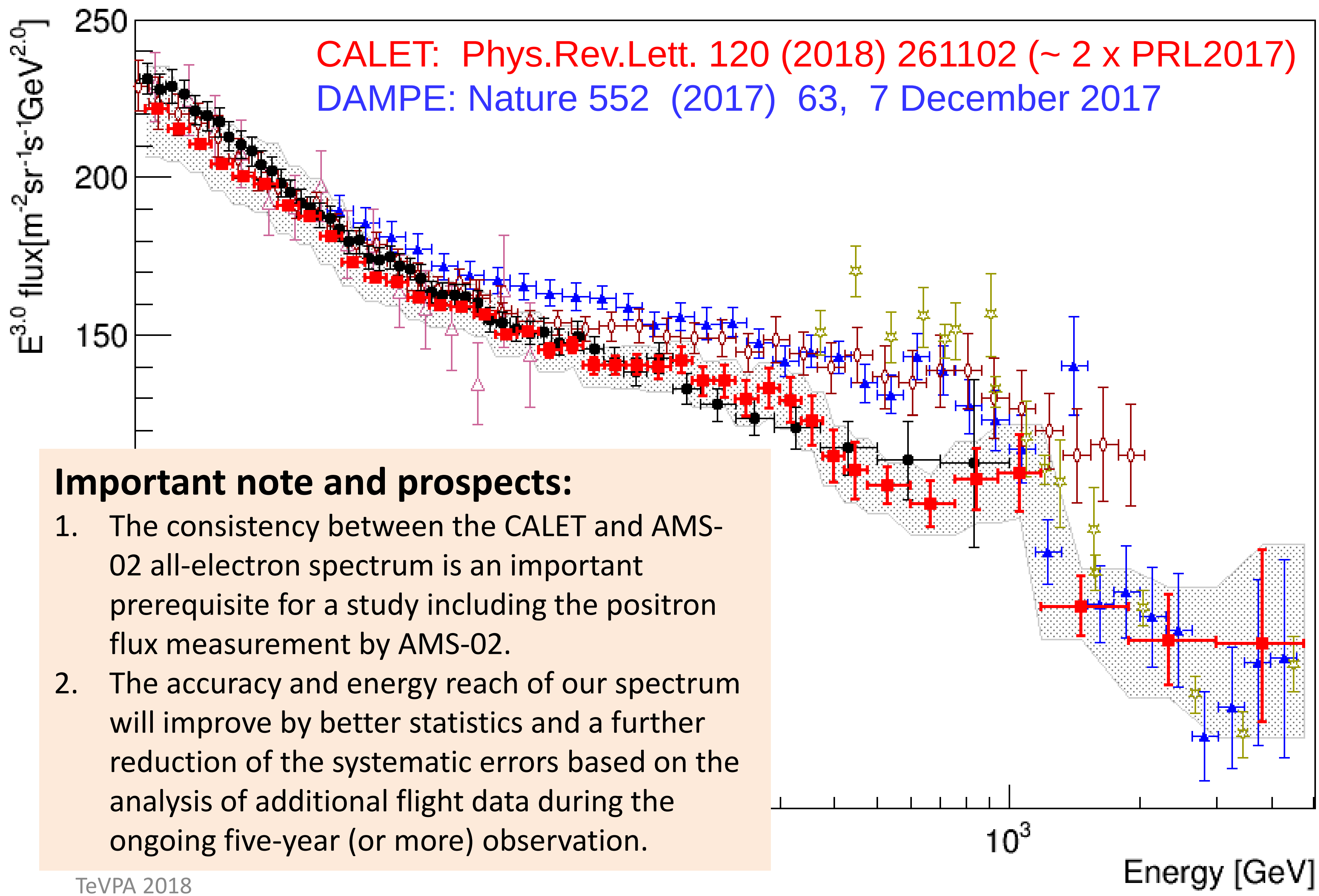


Important implications:

1. CALET's spectrum is consistent with AMS-02 below 1 TeV.
2. There are two group of measurements: AMS-02+CALET vs Fermi-LAT+DAMPE, indicating the presence of unknown systematic errors.
3. CALET observes flux suppression consistent with DAMPE within errors above 1TeV.
4. No peak-like structure at 1.4 TeV in CALET data, irrespective of energy binning.

Extended Measurement by CALET

Approximately doubled statistics above 500GeV by using full acceptance of CALET



Important note and prospects:

1. The consistency between the CALET and AMS-02 all-electron spectrum is an important prerequisite for a study including the positron flux measurement by AMS-02.
2. The accuracy and energy reach of our spectrum will improve by better statistics and a further reduction of the systematic errors based on the analysis of additional flight data during the ongoing five-year (or more) observation.

Hadrons & Gamma-Rays

O.Adriani et al. (CALET Collab.), ApJL 829 (2016) L20.
O.Adriani et al. (CALET Collab.), ApJ 863 (2018) 160.
N.Cannady, Y.Asaoka et al. (CALET Collab.),
ApJS in press.

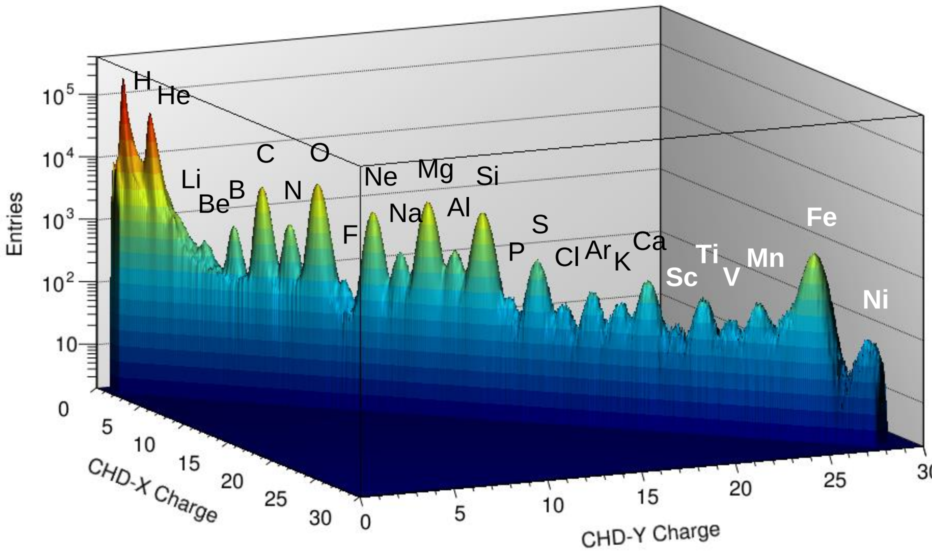
Preliminary Flux of Primary Components

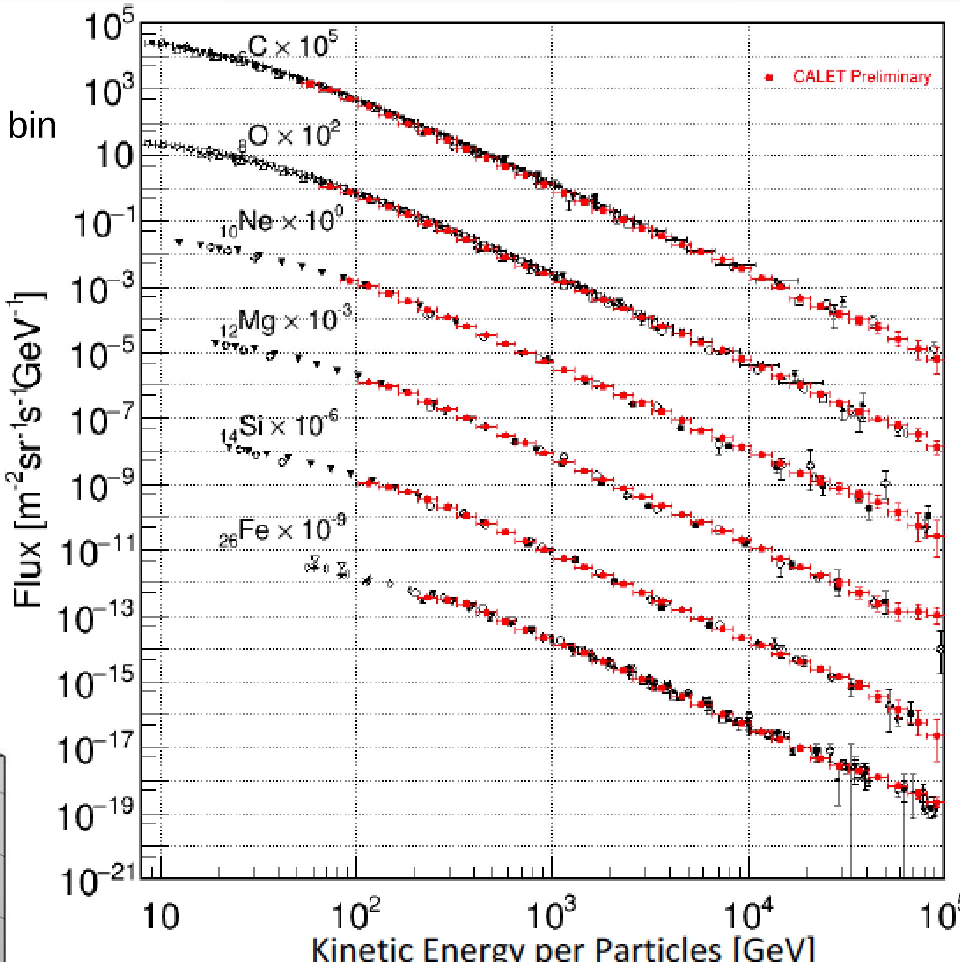
Flux measurement:

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

N(*E*): Events in unfolded energy bin
SΩ : Geometrical acceptance
T : Live time
ε(*E*) : Efficiency
ΔE : Energy bin width

Observation period:
2015.10.13 – 2017.10.31 (750 days)
Selected events: ~13 million



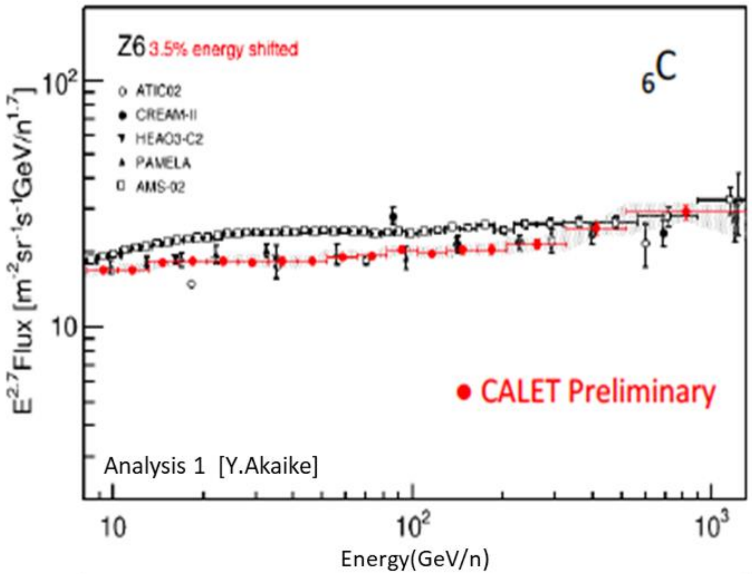


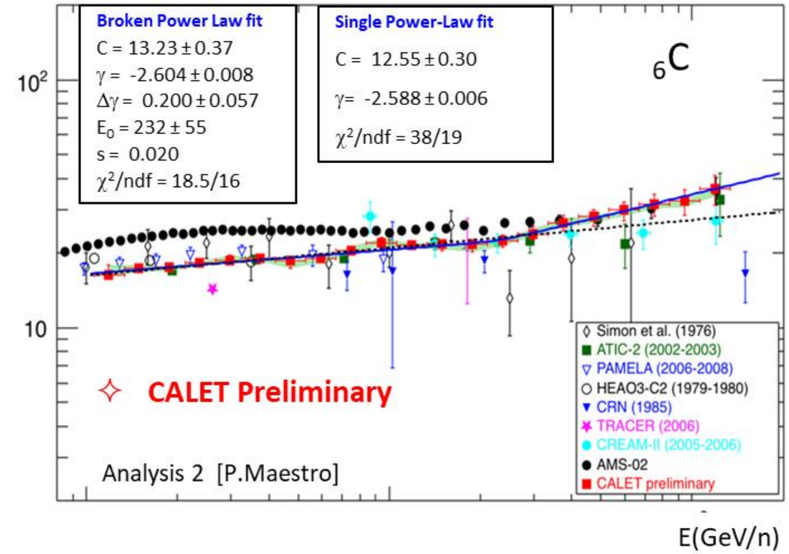
Charge Separation only with CHD

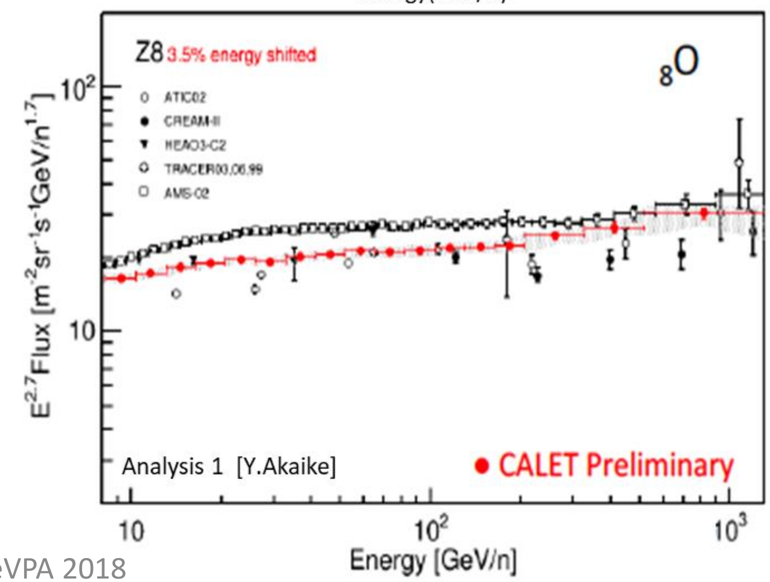
Clear separation of protons, helium to iron and nickel (up to Z=40).

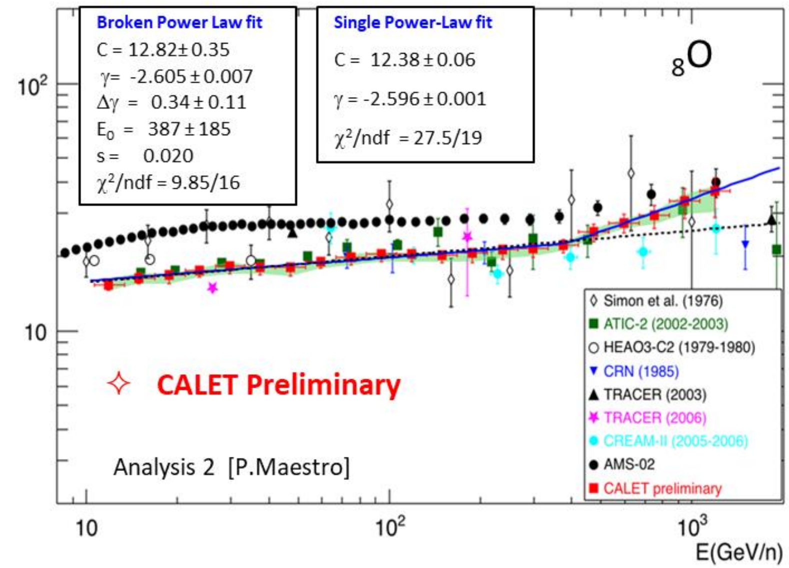
Preliminary Energy Spectra of Carbon and Oxygen

(2 independent CALET analyses)





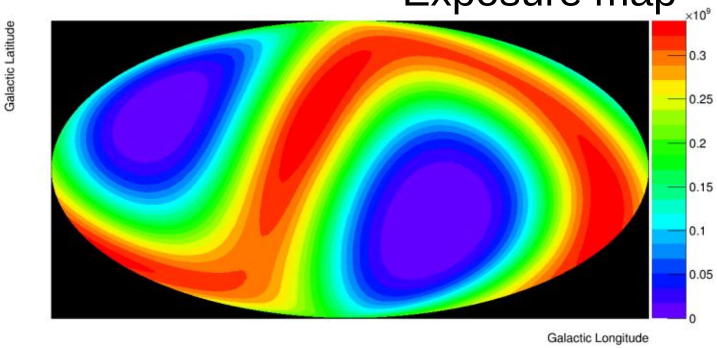




CALET γ–ray Sky in LE (>1GeV) Trigger

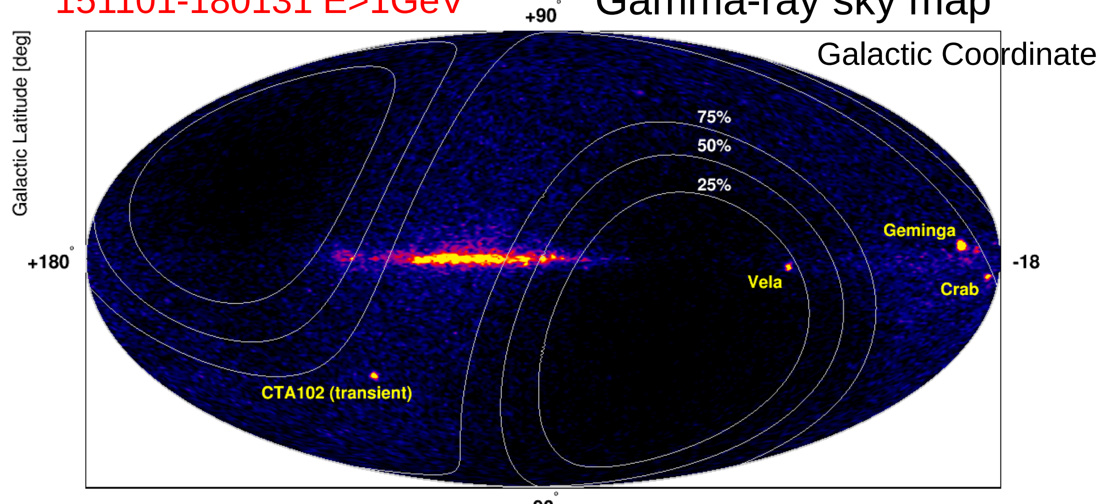
Analysis methodology:
N.Cannady, Y.Asaoka et al.
(CALET Collab.), ApJS in press.

Exposure map



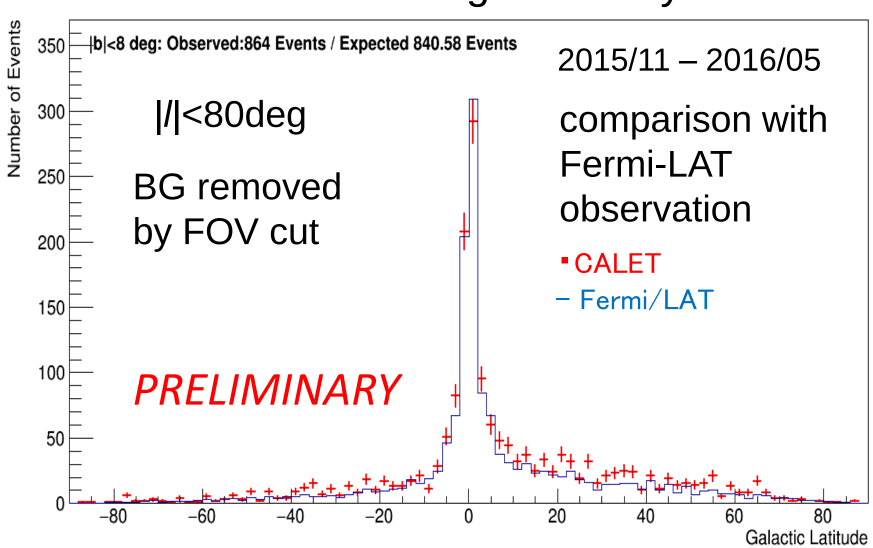
Gamma-ray sky map

151101-180131 E>1GeV

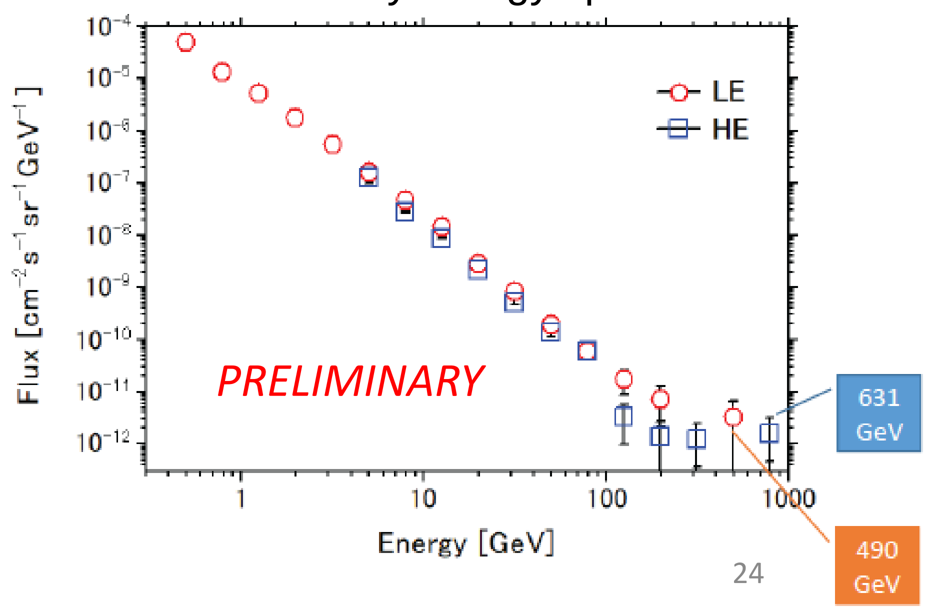


Geminga:432 Vela:138 Crab:150 All: 45740

Galactic diffuse gamma-rays



Gamma-ray energy spectrum



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

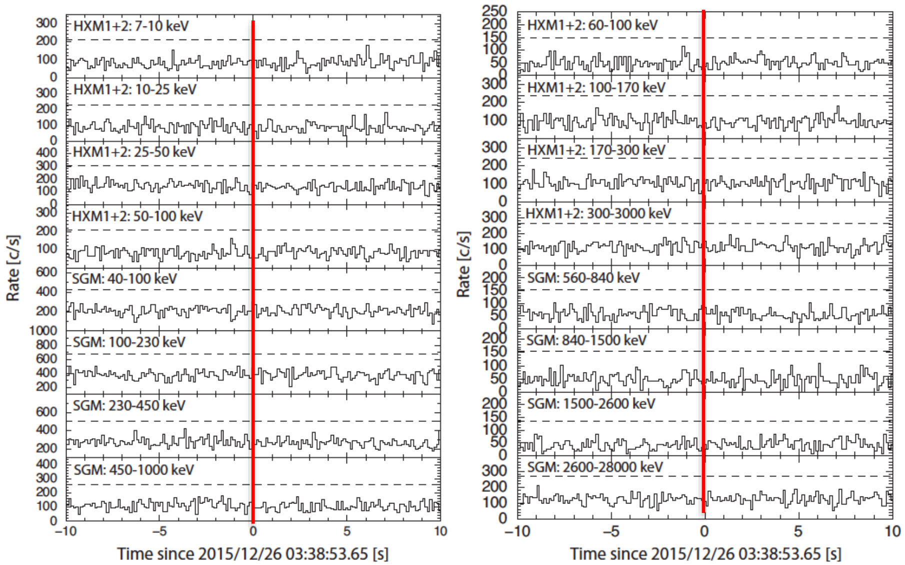


Figure 1. The CGBM light curves in 0.125 s time resolution for the high-gain data (left) and the low-gain data (right). The time is offset from the LIGO trigger time of GW 151226. The dashed-lines correspond to the 5 σ level from the mean count rate using the data of ±10 s.

Upper limit for gamma-ray burst monitors and Calorimeter

HXM: 7-500 keV

SGM: 50-1000 keV

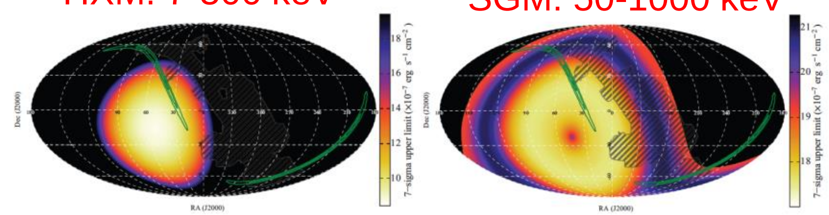


Figure 2. The sky maps of the 7 σ upper limit for HXM (left) and SGM (right). The assumed spectrum for estimating the upper limit is a typical BATSE S-GRBs (see text for details). The energy bands are 7-500 keV for HXM and 50-1000 keV for SGM. The GW 151226 probability map is shown in green contours.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

Calorimeter: 1-100 GeV

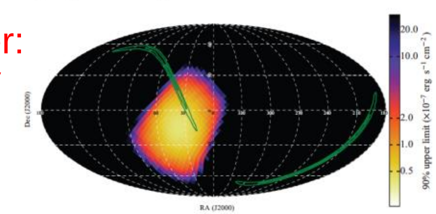


Figure 3. The sky map of the 90% upper limit for CAL in the 1-100 GeV band. A power-law model with a photon index of −2 is used to calculate the upper limit. The GW 151226 probability map is shown in green contours.

Updated analysis incl. all GW candidates in O2: O.Adriani et al. (CALET Collab.), ApJ 863 (2018) 160.

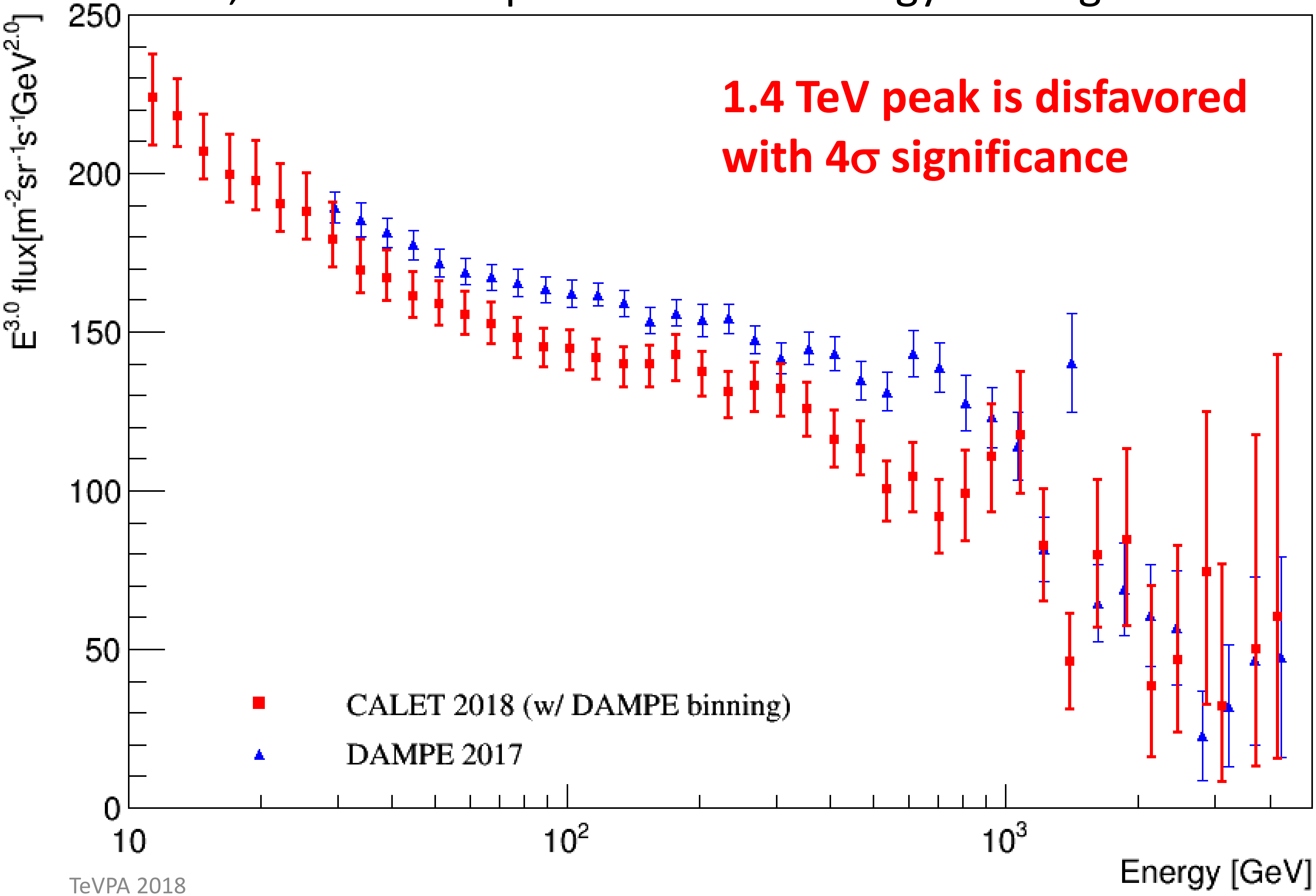
Summary and Future Prospects

- CALET was successfully launched on Aug. 19, 2015, and the detector is being very stable for observation since Oct. 13, 2015.
- As of July 31, 2018, total observation time is 1023 days with live time fraction to total time close to 84%. Nearly 670 million events are collected with high energy trigger (E>10 GeV)
- 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.
- All electron spectrum has been extended in statistics and in the energy range up to 4.8TeV. This result is published in PRL again on June 2018.
- Preliminary analysis of nuclei have successfully been carried out to obtain the energy spectra in the energy range: Protons in 55 GeV~22 TeV, Ne-Fe in 500 GeV~100 TeV.
- CALET's CGBM detected nearly 60 GRBs (~20 % short GRB among them) per year in the energy range of 7keV-20 MeV, as expected (not included in this talk). Follow-up observation of the GW events is carried out and published in ApJL.
- GW counterpart searches with CALET calorimeter were extended to cover the whole LIGO/Virgo O2 and published in ApJ. In addition, onboard performance of gamma-ray observation will be published in ApJS (currently in press).
- The so far excellent performance of CALET and the outstanding quality of the data suggest that a 5-year observation period is likely to provide a wealth of new interesting results.

Backup

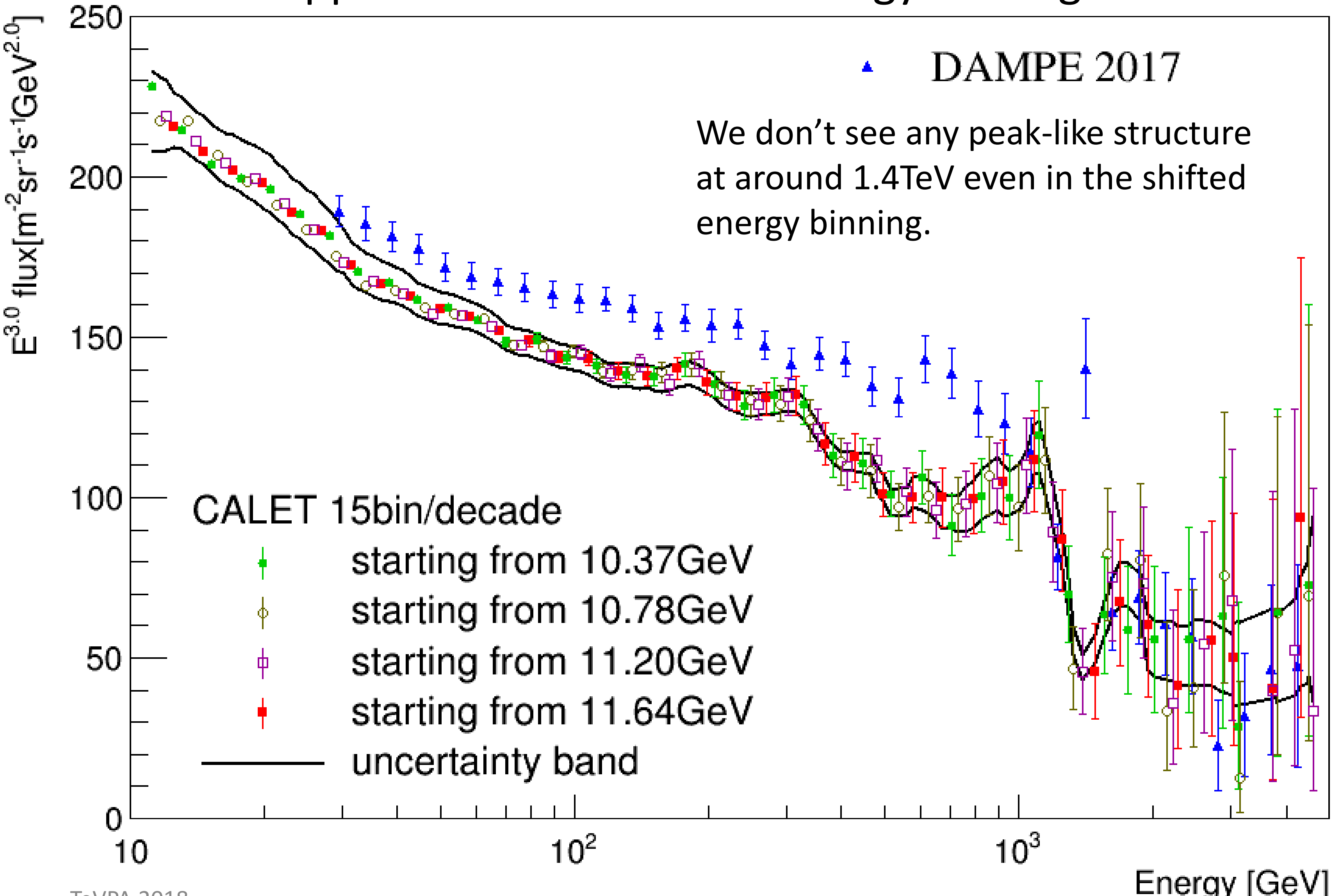
Comparison with DAMPE's result

Here, we have adopted the same energy binning as DAMPE.

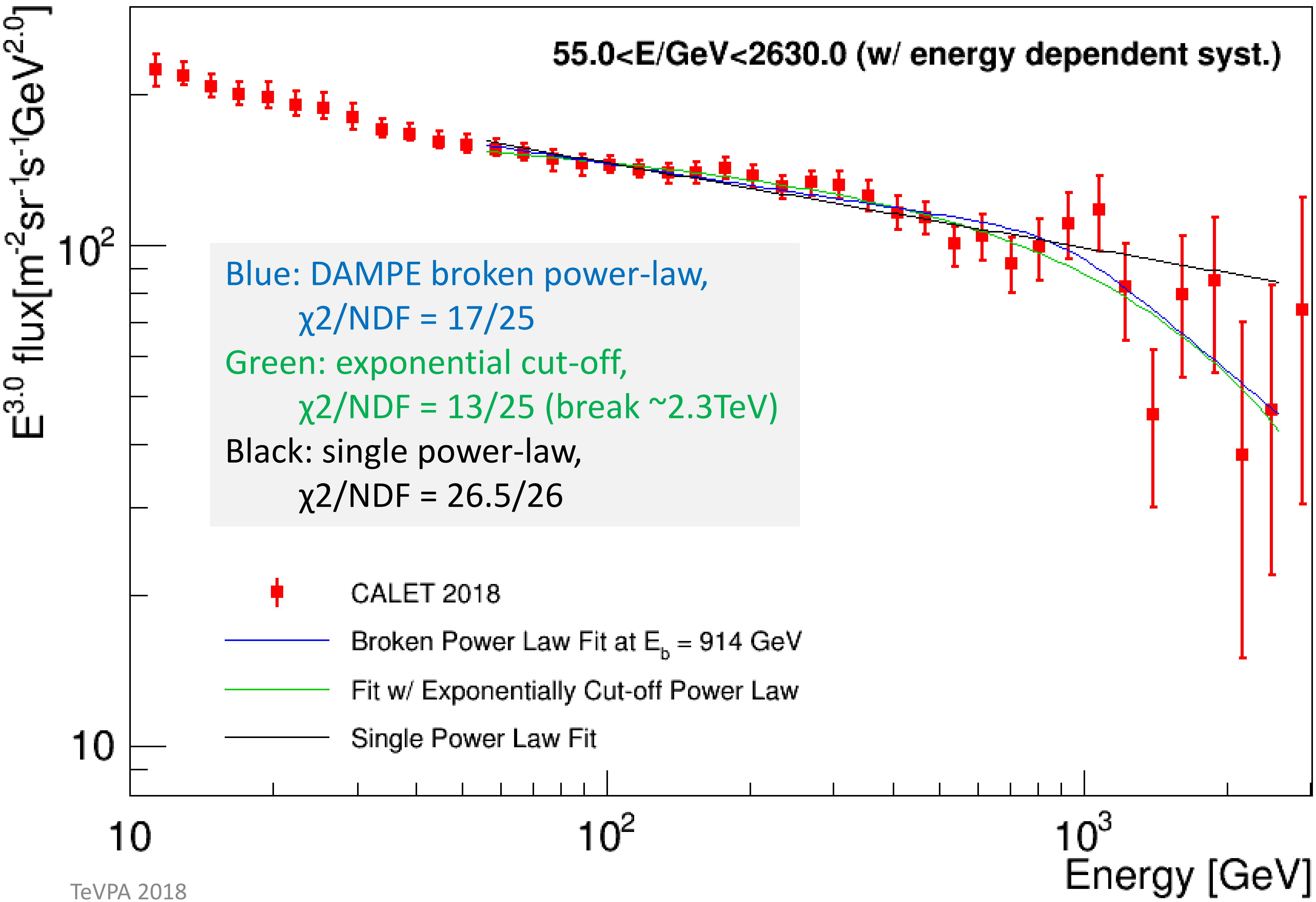


Comparison with DAMPE's result

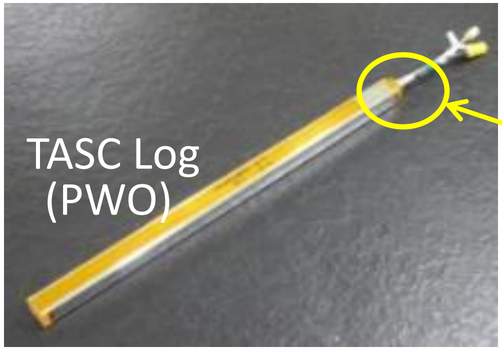
What happens if we shifted our energy binning…

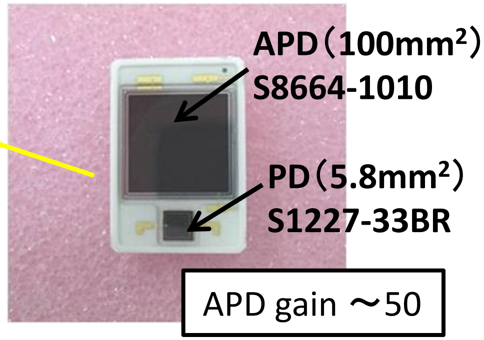


Spectral Analysis with Extended CALET Result

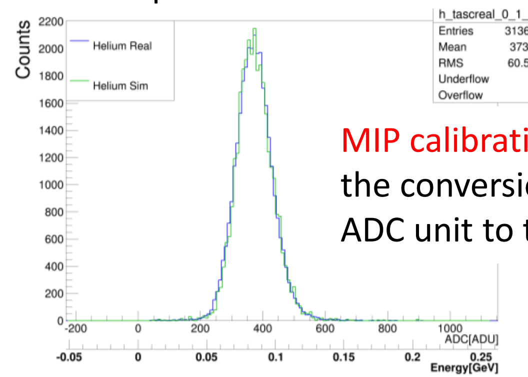


TASC Energy Measurement in Dynamic Range of 1-10^6 MIP

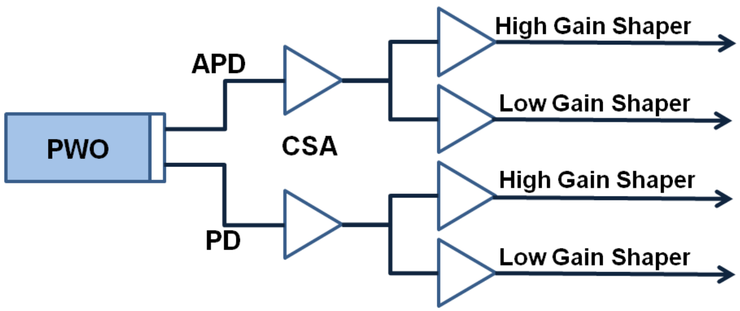




"MIP" peak in PWO: Obs. vs. MC



MIP calibration determines the conversion factor from ADC unit to the energy

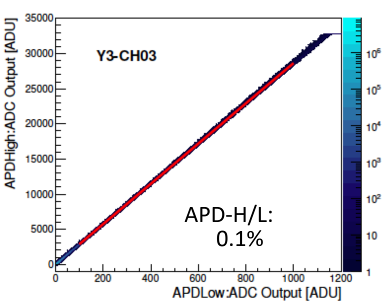


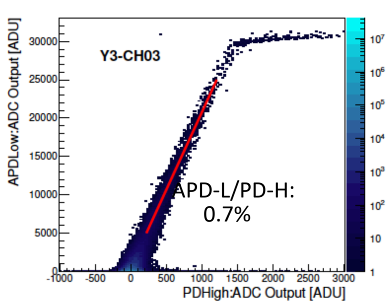
The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

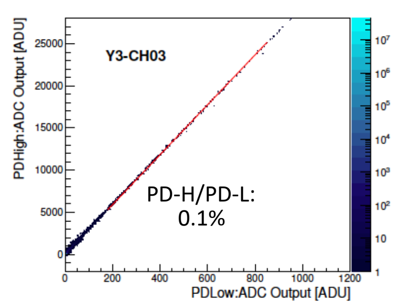
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

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

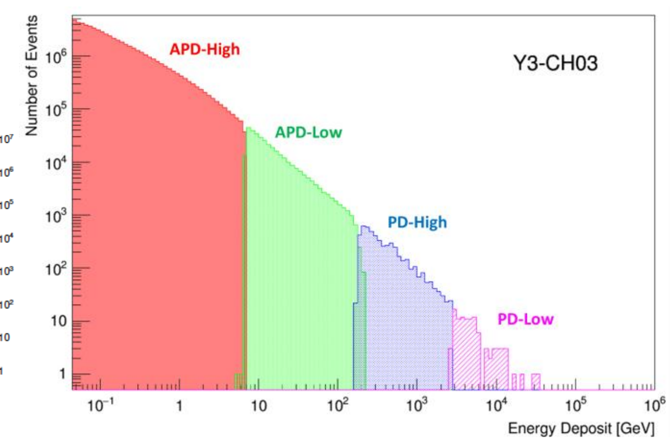
APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%



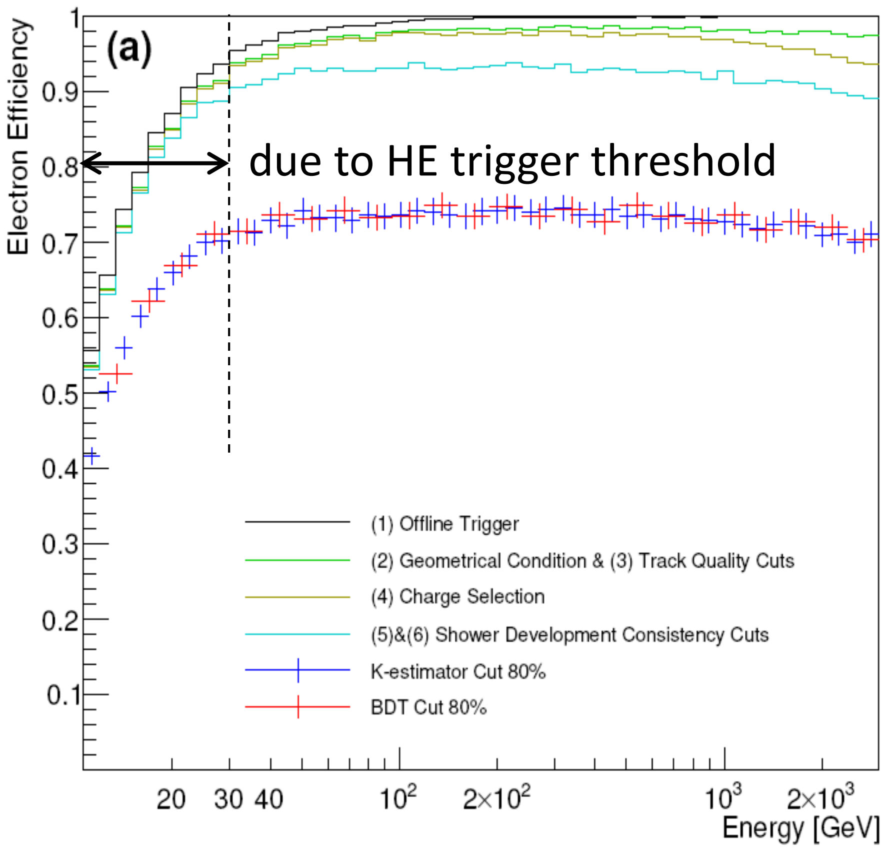


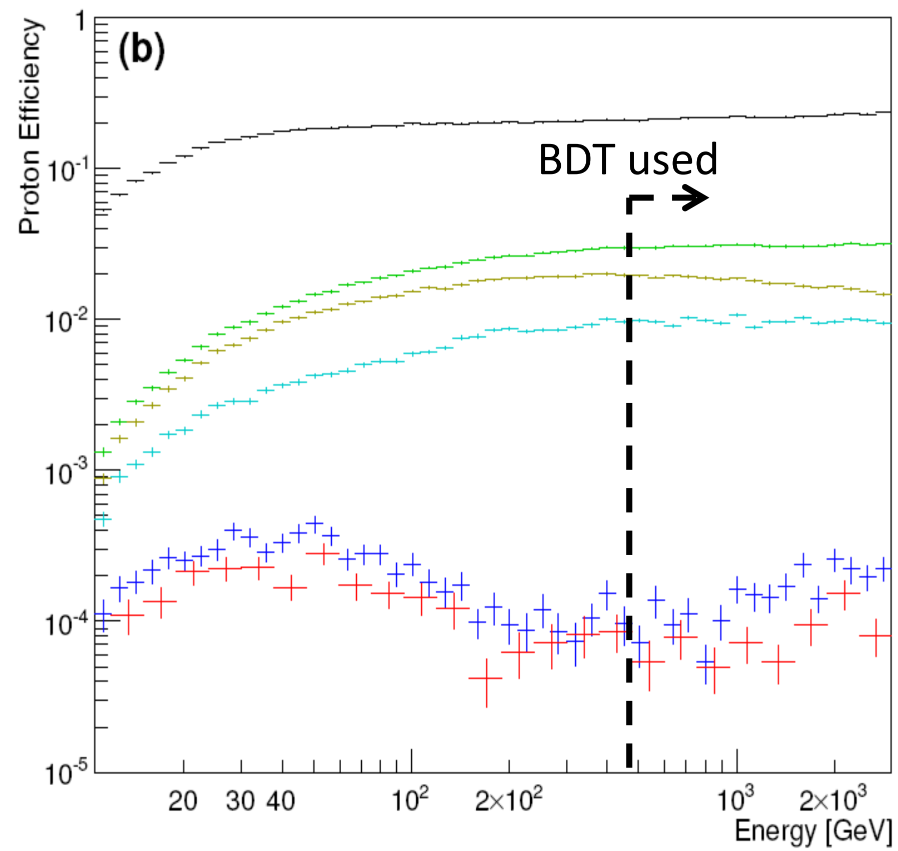


Example of energy distribution in one PWO log



Electron Efficiency and Proton Rejection



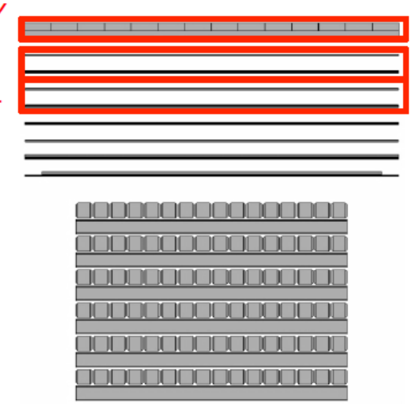


- Constant and high efficiency is the key point in our analysis.
- Simple two parameter (BDT) cut is used in the energy region E<475GeV (E>475GeV) while the small difference in resultant spectrum between two methods are taken into account in the systematic uncertainty.
- Contamination is ~5% up to 1TeV, and 10~15% in the 1—3 TeV region.

Preliminary Ultra Heavy Nuclei Measurements (26 < Z ≤ 40)

- 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 cm^2sr)
- Energy threshold depends on the geomagnetic cutoff rigidity

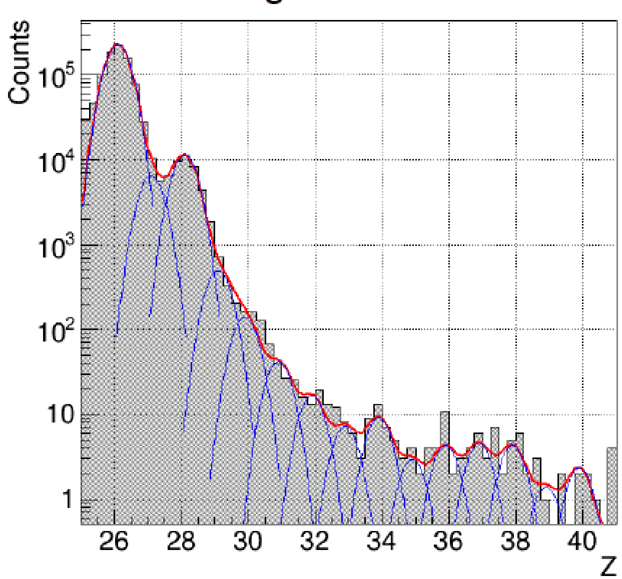
Onboard trigger for UH events



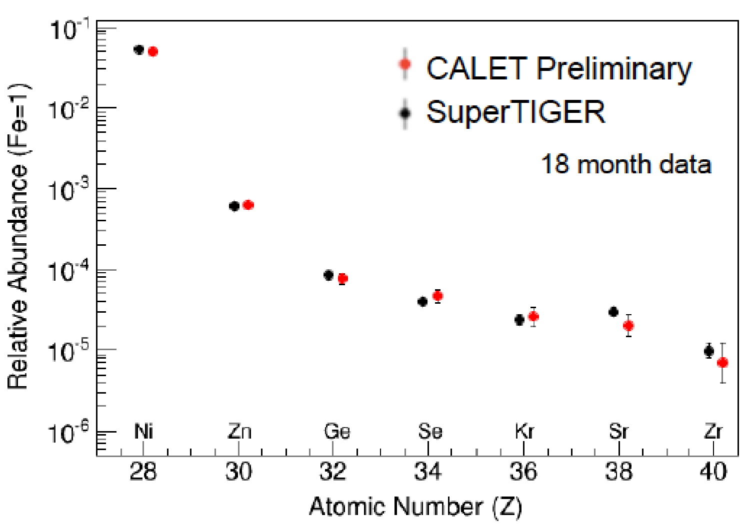
Data analysis

- ☐ 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)



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

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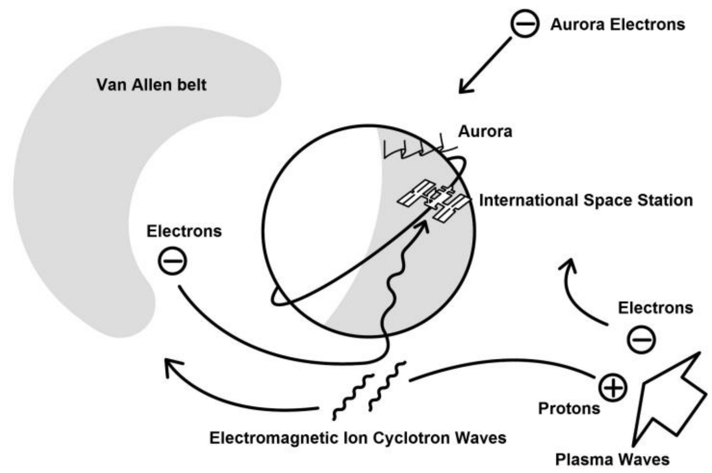
Abstract The charge detector (CHD) of the Calorimetric Electron Telescope (CALET) on board the International Space Station (ISS) has a huge geometric factor for detecting MeV electrons and is sensitive to relativistic electron precipitation (REP) events. During the first 4 months, CALET CHD observed 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