The CALorimetric Electron Telescope (CALET) on the International Space Station

– Results from the First Two Years of Operation –

Yoichi Asaoka
for the CALET collaboration
WISE, Waseda University

CALET Collaboration Team

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

1) Aoyama Gakuin University, Japan
2) CRESST/NASA/GSFC and Universities Space Research Association, USA
3) CRESST/NASA/GSFC and University of Maryland, USA
4) Hirosaki University, Japan
5) Ibaraki National College of Technology, Japan
6) Ibaraki University, Japan
7) ICRR, University of Tokyo, Japan
8) ISAS/JAXA Japan
9) JAXA, Japan
10) Kanagawa University, Japan
11) Kavli IPMU, University of Tokyo, Japan
12) KEK, Japan
13) Louisiana State University, USA
14) Nagoya University, Japan
15) NASA/GSFC, USA
16) National Inst. of Radiological Sciences, Japan
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22) Shibaura Institute of Technology, Japan
23) Shinshu University, Japan
24) University of Denver, USA
25) University of Florence, IFAC (CNR) and INFN, Italy
26) University of Padova and INFN, Italy
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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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O. Adriani[25], Y. Akaike[2], K. Asano[7], Y. Asaoka[9,31], M.G. Bagliesi[29], E. Berti[25], G. Bigongiari[29], W.R. Binns[32], S. Bonechi[29], M. Bongi[25], P. Brogi[29], A. Bruno[14], J.H. Buckley[32], N. Cannady[13], G. Castellini[25], C. Checchia[26],M.L. Cherry[13], G. Collazuol[26], V. Di Felice[28], K. Ebisawa[8], H. Fuke[8], T.G. Guzik[13], T. Hams[3], N. Hasebe[31], K. Hibino[10], M. Ichimura[4], K. Ioka[34], W. Ishizaki[7], M.H. Israel[32], K. Kasahara[31], J. Kataoka[31], R. Kataoka[17], Y. Katayose[33], C. Kato[23], Y.Kawakubo[1], N. Kawanaka[30], K. Kohri [12], H.S. Krawczynski[32], J.F. Krizmanic[2], T. Lomtadze[27], P. Maestro[29], P.S. Marrocchesi[29], A.M. Messineo[27], J.W. Mitchell[15], S. Miyake[5], A.A. Moiseev[3], K. Mori[9,31], M. Mori[20], N. Mori[25], H.M. Motz[31], K. Munakata[23], H. Murakami[31], S. Nakahira[9], J. Nishimura[8], G.A De Nolfo[15], S. Okuno[10], J.F. Ormes[25], S. Ozawa[31], L. Pacini[25], F. Palma[28], V. Pal'shin[1], 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[18], R. Sparvoli[28], P. Spillantini[25], F. Stolzi[29], S. Sugita[1], J.E. Suh[29], A. Sulaj[29], I. Takahashi[11], M. Takayanagi[8], M. Takita[7], T. Tamura[10], N. Tateyama[10], T. Terasawa[7], H. Tomida[8], S. Torii[31], Y. Tunesada[19], Y. Uchihori[16], S. Ueno[8], E. Vannuccini[25], J.P. Wefel[13], K. Yamaoka[14], S. Yanagita[6], A. Yoshida[1], and K. Yoshida[22]

Outline

1. Introduction
2. Calibration
3. Operations
4. Results
    1. Electrons
    2. Hadrons
    3. Gamma-Rays
    4. 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.

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

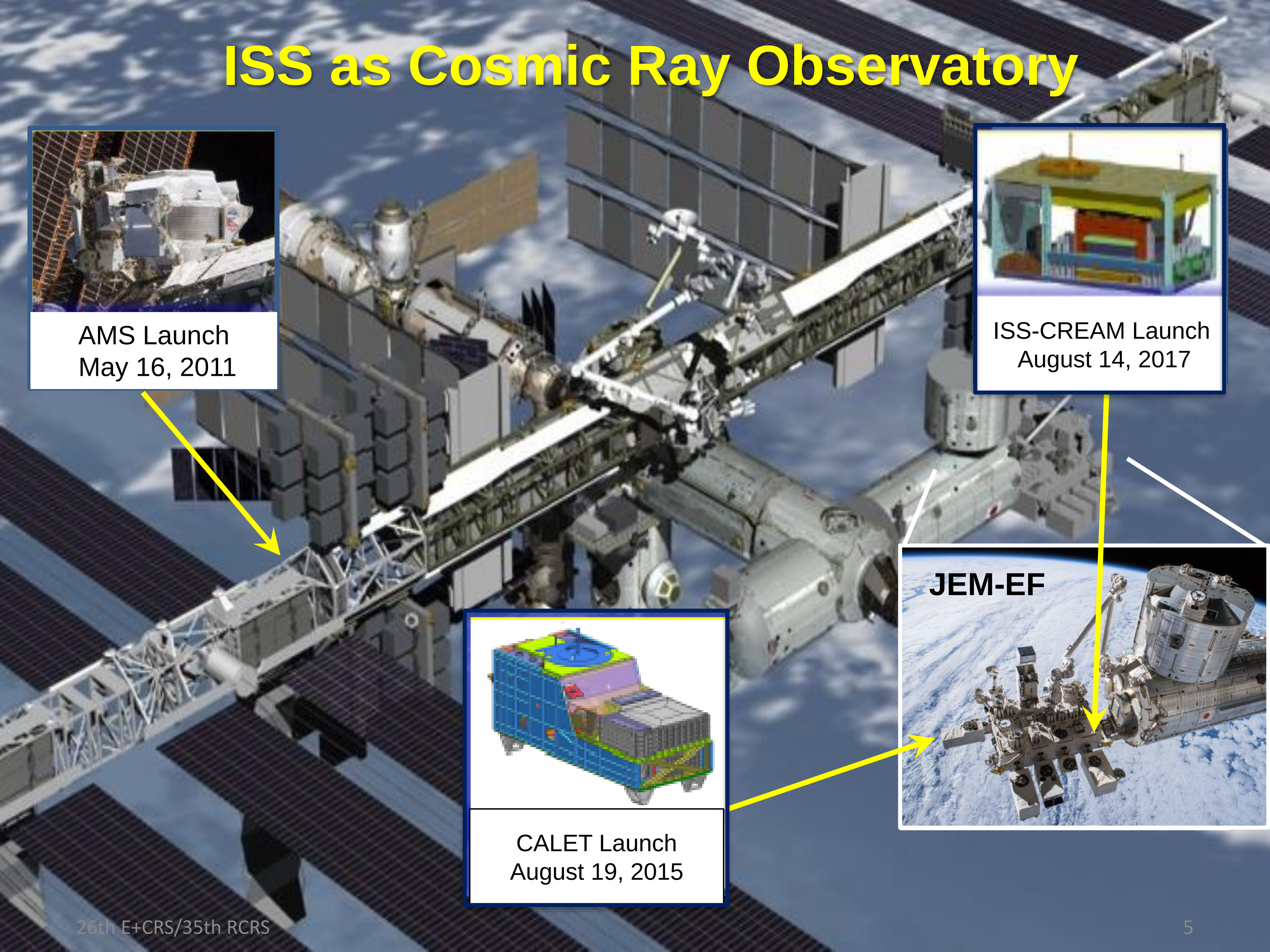
O.Adriani et al. (CALET Collaboration),
Phys.Rev.Lett. 120 (2018) 261102.

CRD July 7, 14:15-14:30 by Y. Akaike
@ Academic Council Conference Hall)

O.Adriani et al. (CALET Collaboration),
ApJL 829 (2016) L20.

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

ISS as Cosmic Ray Observatory



ISS as Cosmic Ray Observatory

AMS Launch
May 16, 2011

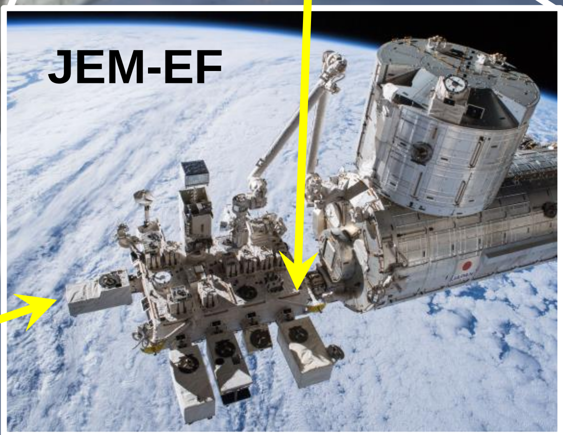
Magnet Spectrometer
- Various PID
- Anti-particles
- E ≤ TeV

Calorimeter
- Carbon target
- Hadrons
- Including TeV region

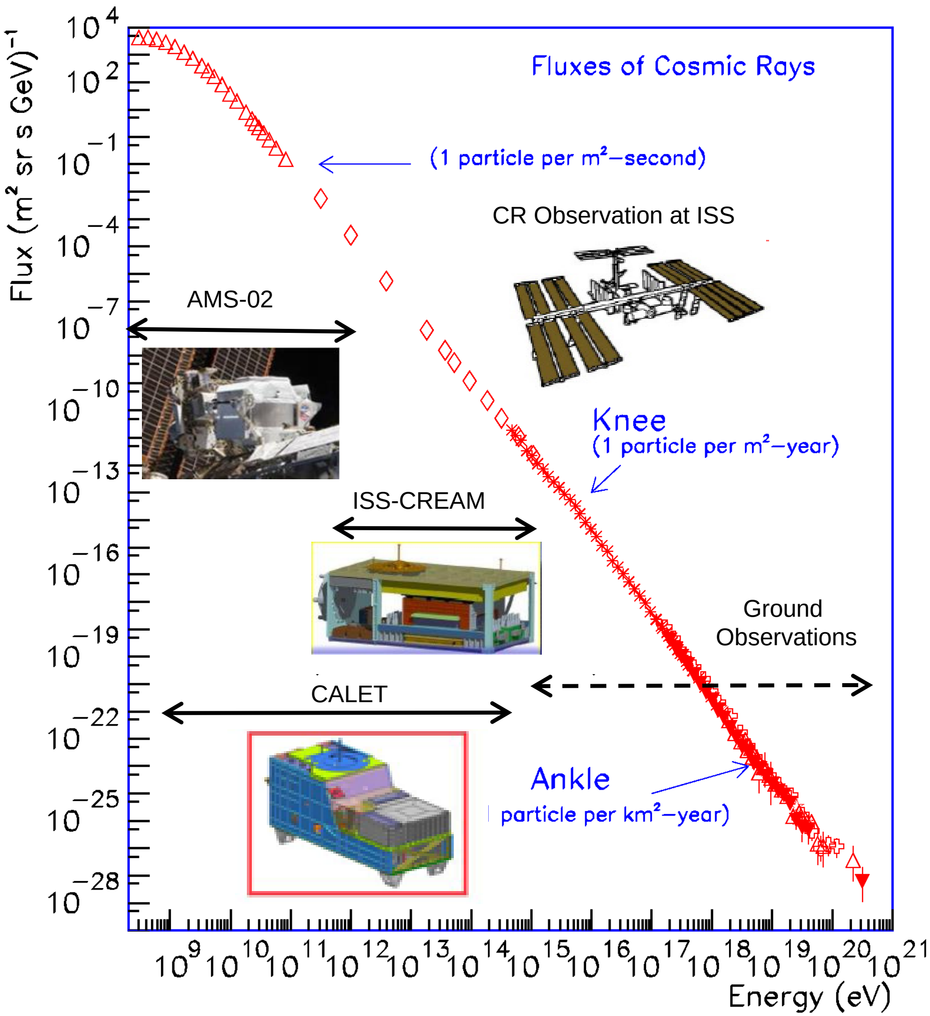
ISS-CREAM Launch
August 14, 2017

Calorimeter
- Fully active
- Electrons
- Including TeV region

CALET Launch
August 19, 2015



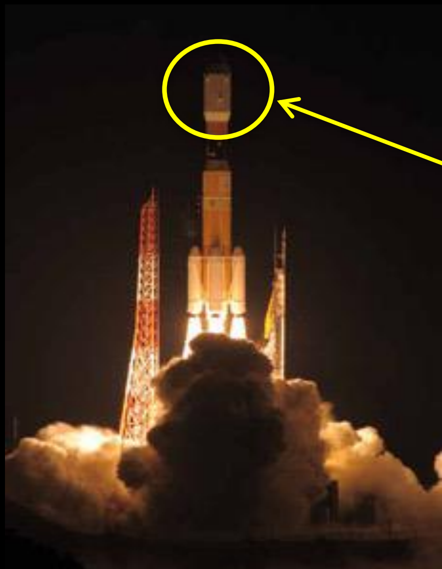
Cosmic Ray Observations at the ISS and CALET

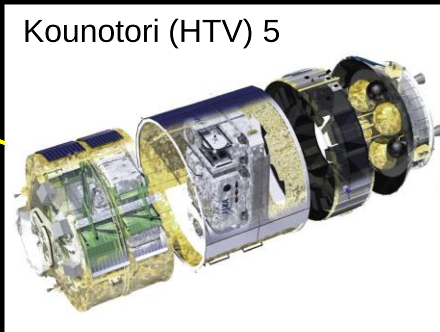


Overview of CALET Observations

- Direct cosmic ray observations in space at highest energy region
- Cosmic ray observation at world-record level using a large-scale detector at ISS for a long-term (5 years expected)
- Electron observation in 1 GeV - 20 TeV is 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 in space by stable observations
  - ⇨ Gamma-ray burst, Solar flare, Radiation from GW source etc.

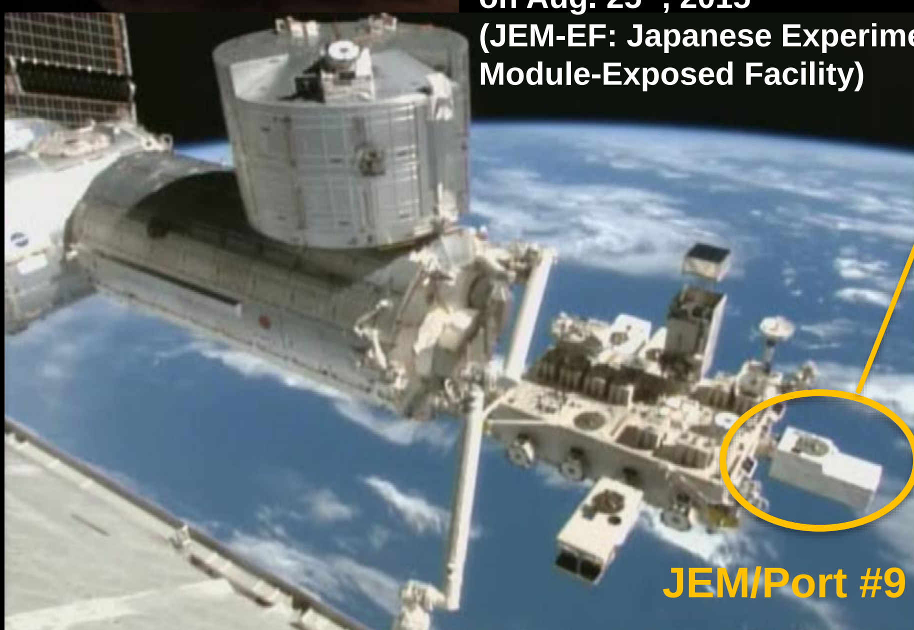
CALET Payload

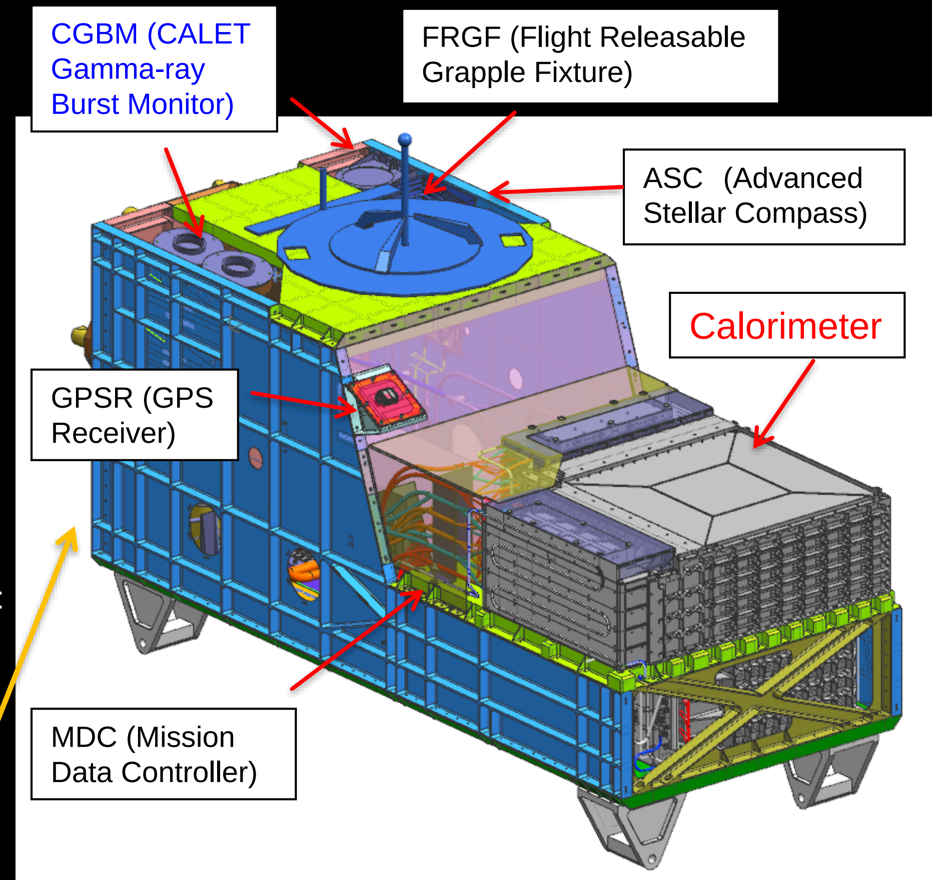




Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

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

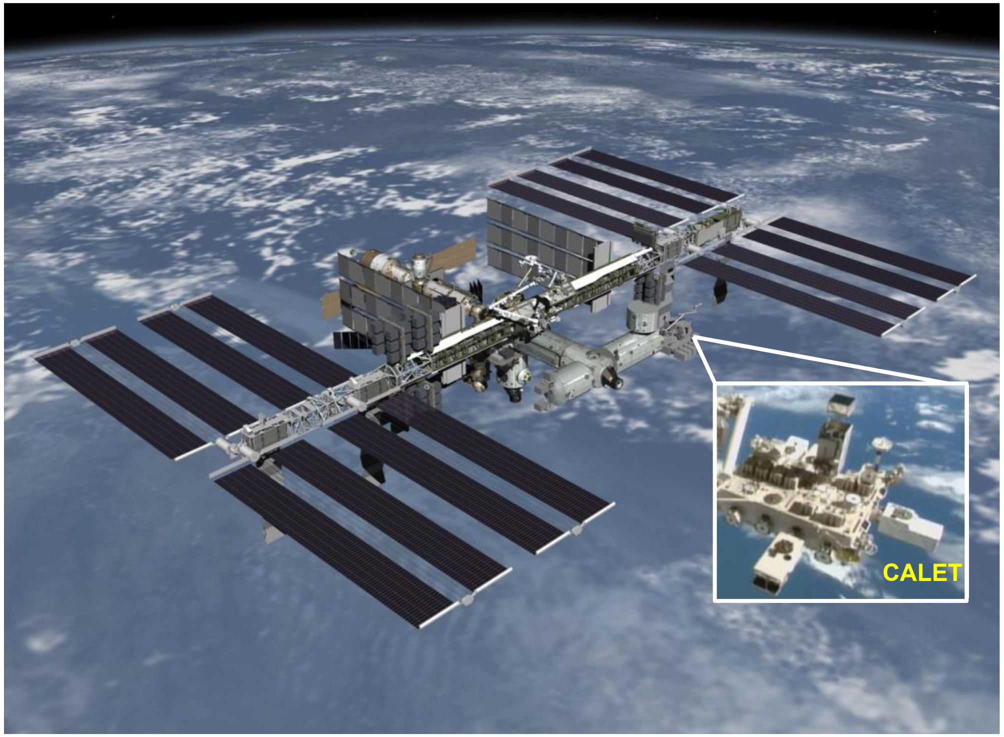




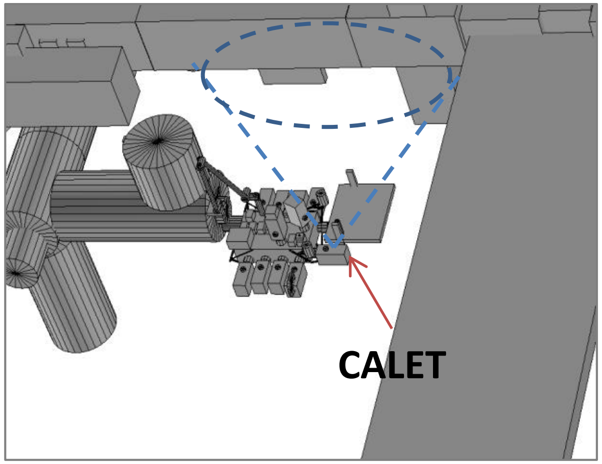
- **Mass: 612.8 kg**
- **JEM Standard Payload Size: 1850mm(L) × 800mm(W) × 1000mm(H)**
- **Power Consumption: 507 W（max）**
- **Telemetry: Medium 600 kbps (6.5GB/day) / Low 50 kbps**

Attached Location (JEM-EF Port No.9) and the FOV

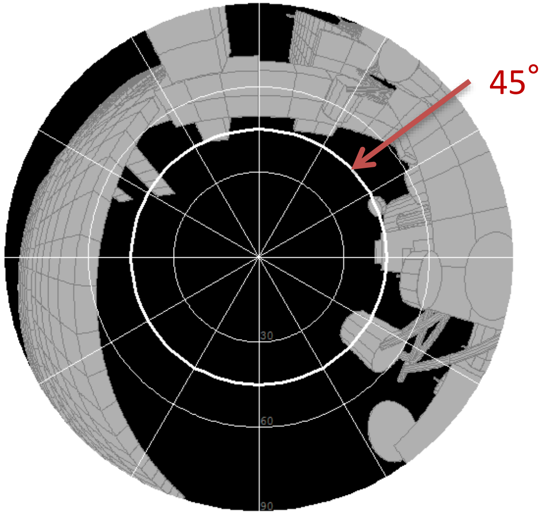
CALET has a Field-Of-View of 45º from its position at Port No.9. (A small part of the FOV is covered by thin structural material.



CALET located at the Port No.9
at the Japanese Experiment Module

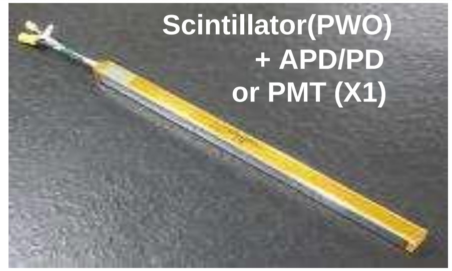


ISS simplified model

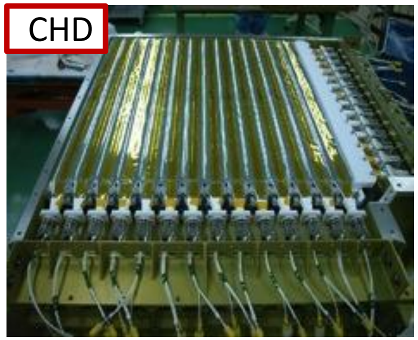


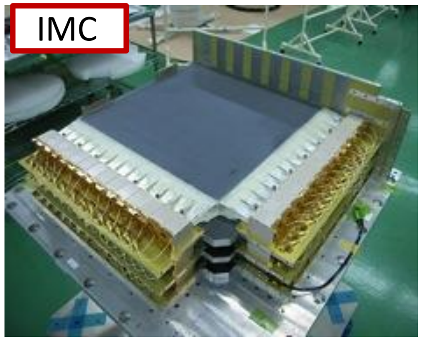
CALET FOV

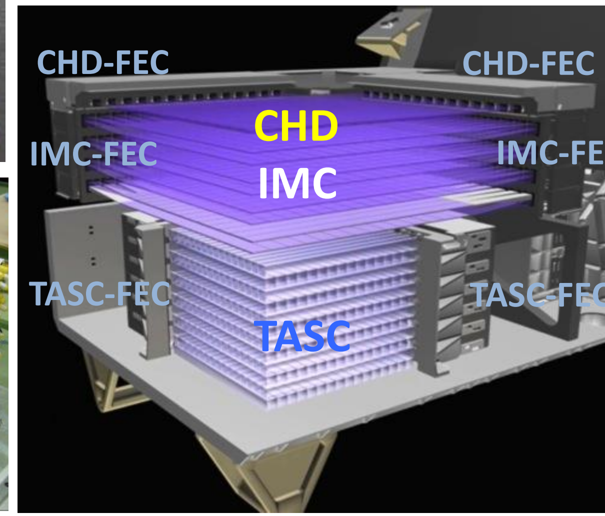
CALET Instrument



CALORIMETER

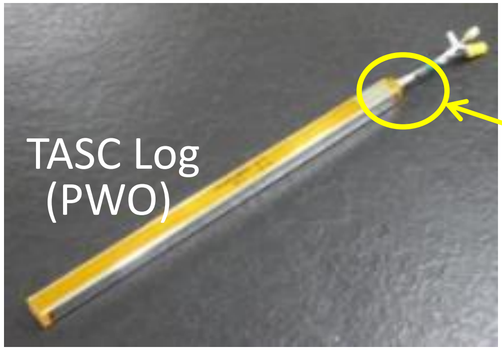


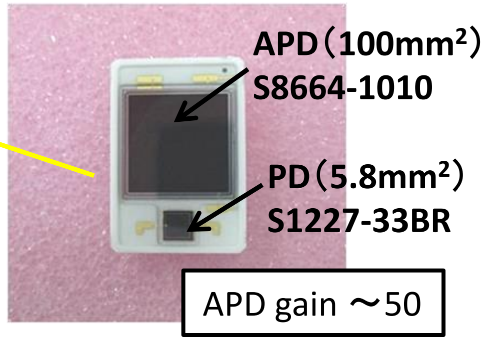




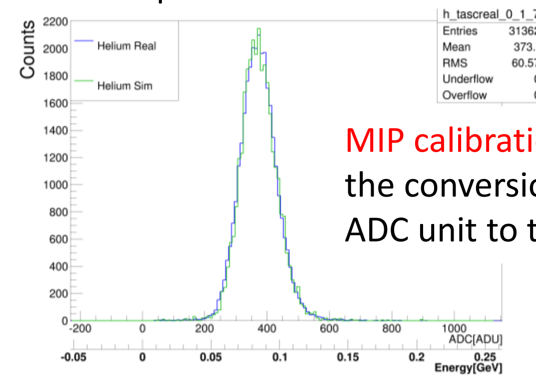
	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers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

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

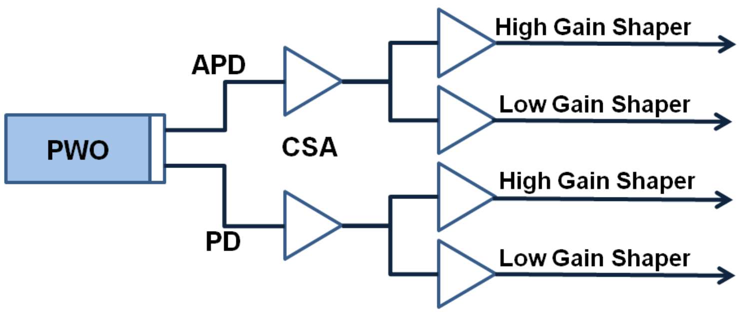




“MIP” peak in PWO: Obs. vs. MC



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



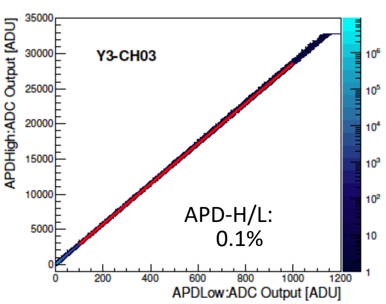
The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

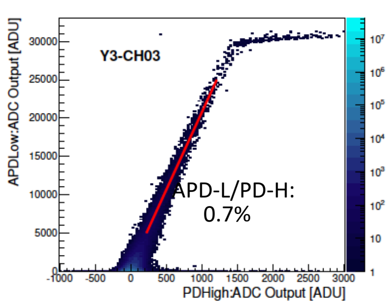
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

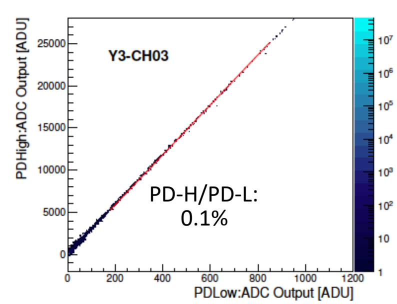
The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel.

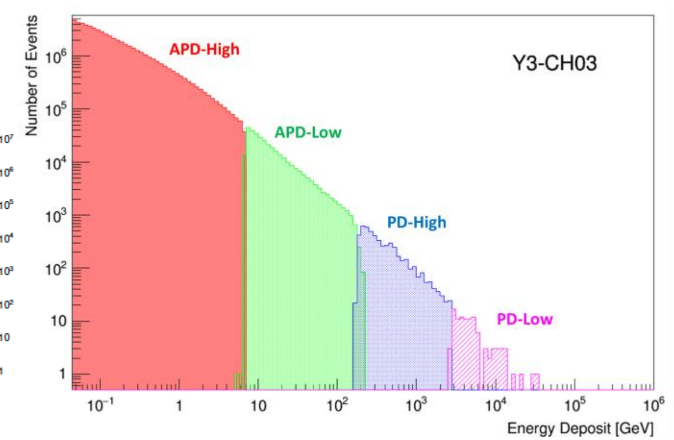
APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%

Example of energy distribution in one PWO log



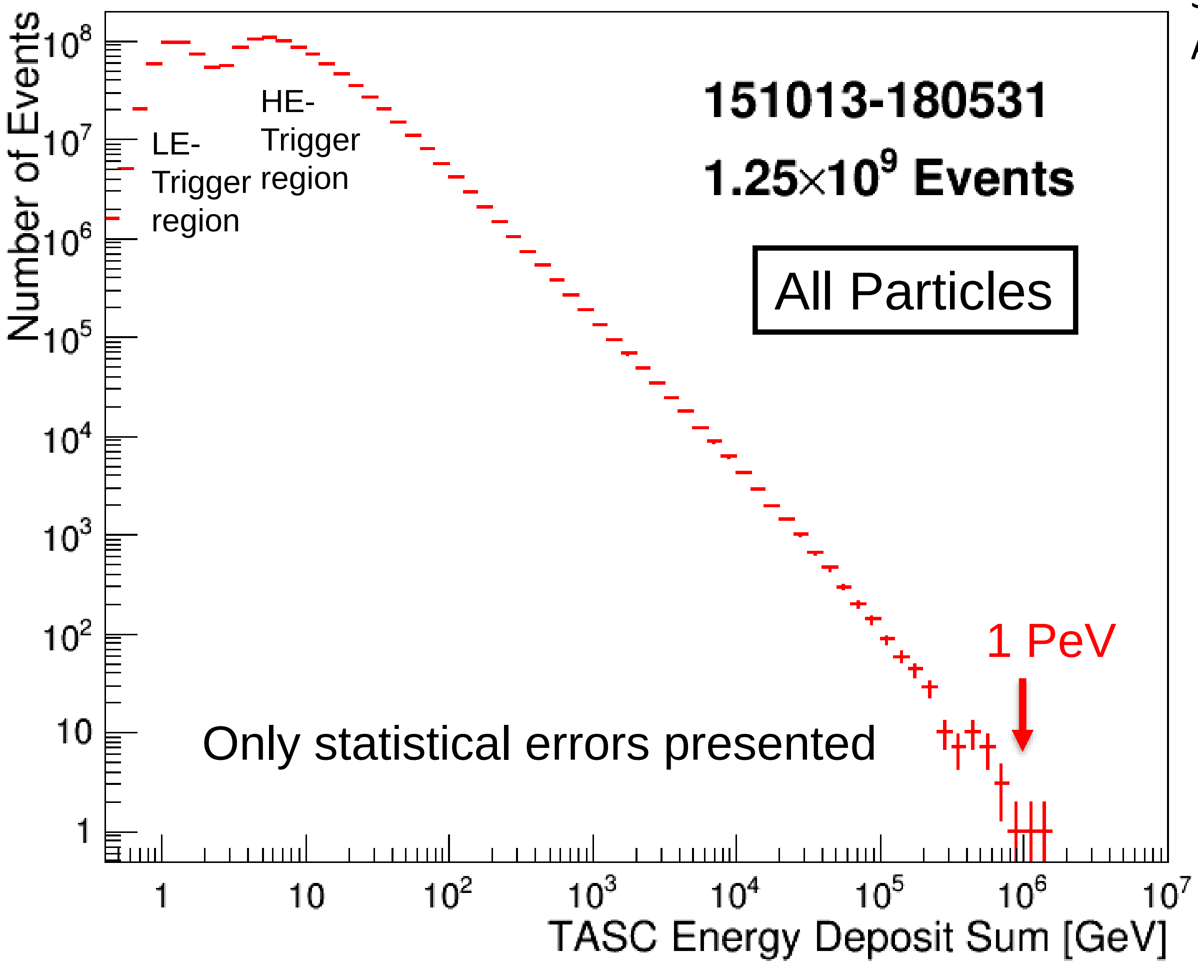






TASC Energy Deposit Distribution of All Triggered-Events by Observation for 962 days

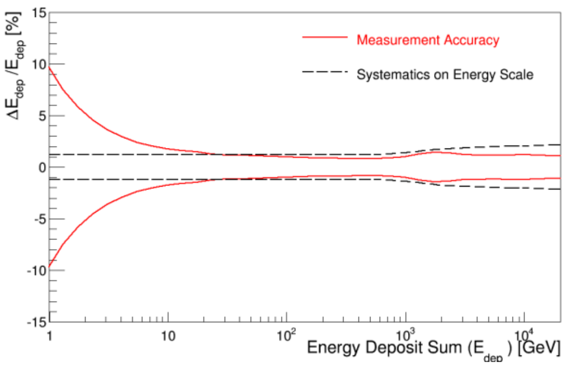
Distribution of deposit energies (ΔE) in TASC



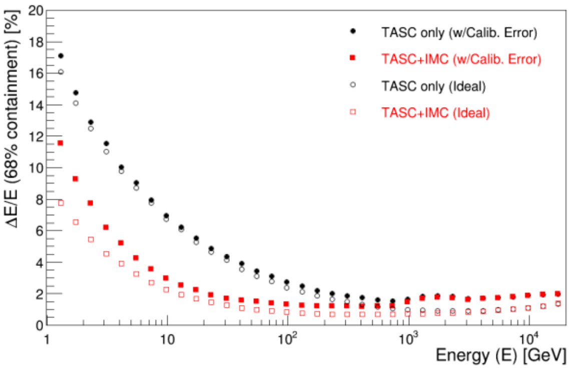
The TASC energy measurements have successfully been carried out in the dynamic range of 1 GeV – 1 PeV.

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

Performance of energy measurement in 1GeV-20TeV

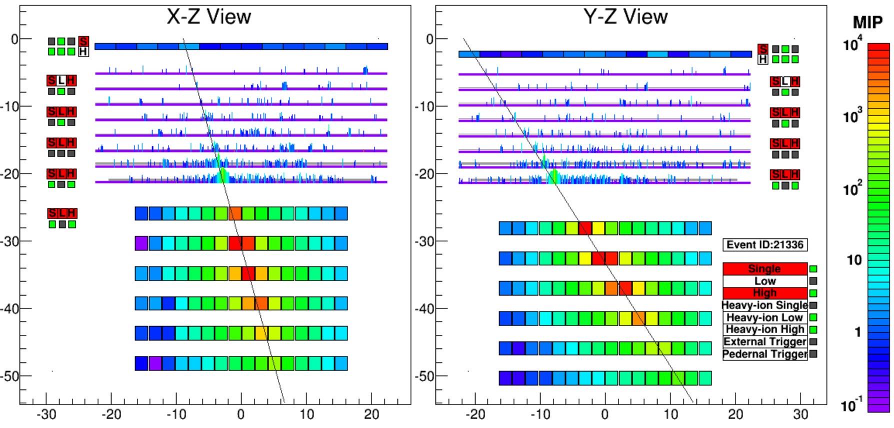


Energy resolution for electrons (TASC+IMC): < 3% over 10 GeV; <2% over 100GeV



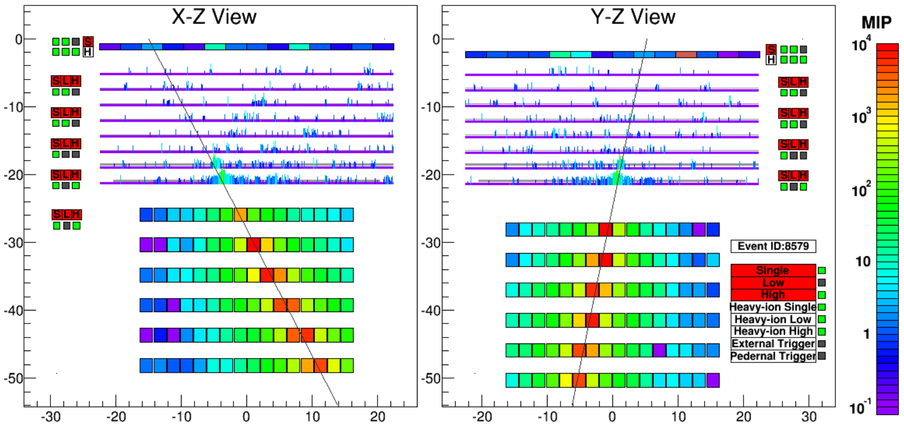
Event Examples of High-Energy Showers

Electron, E=3.05 TeV



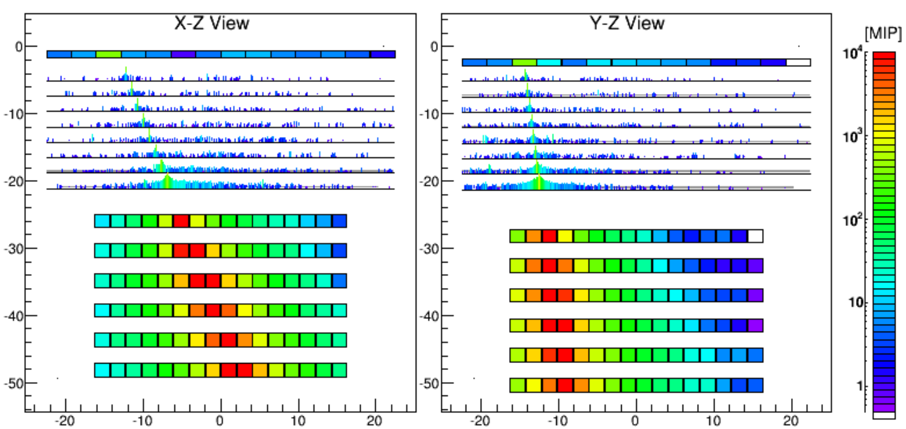
fully contained even at 3TeV

Proton, ΔE=2.89 TeV



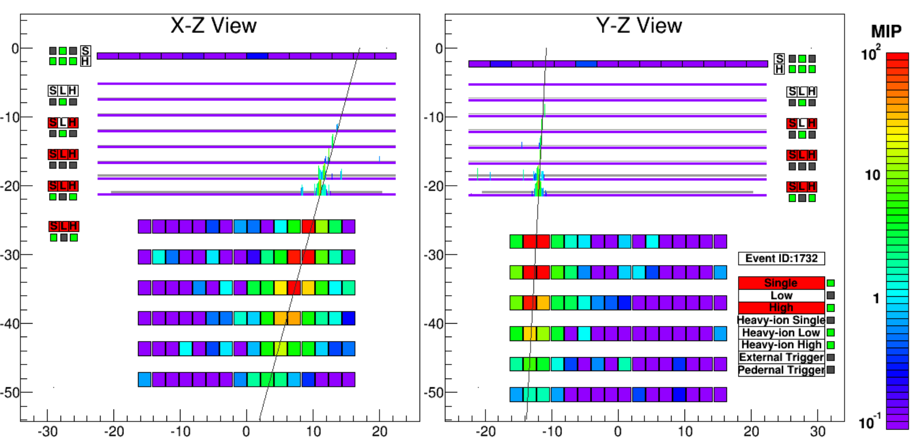
clear difference from electron shower

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

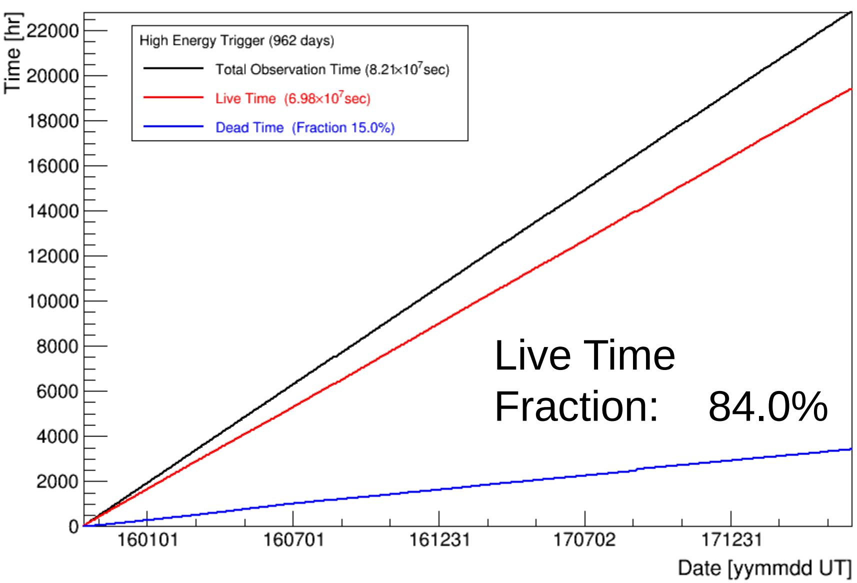
Observation with High Energy Trigger (>10GeV)

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

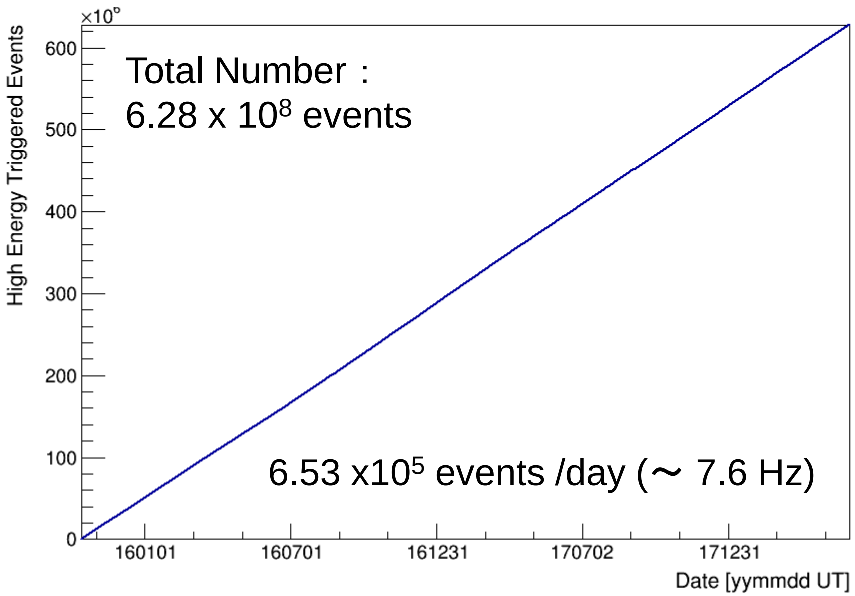
Observation by High Energy Trigger for 962 days : Oct.13, 2015 – May 31, 2018

- The exposure, SΩT, has reached to ~84.0 m^2 sr day for electron observations by continuous and stable operations.
- Total number of triggered events is ~630 million with a live time fraction of 84.0 %.

Accumulated observation time (live, dead)



Accumulated triggered event number



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

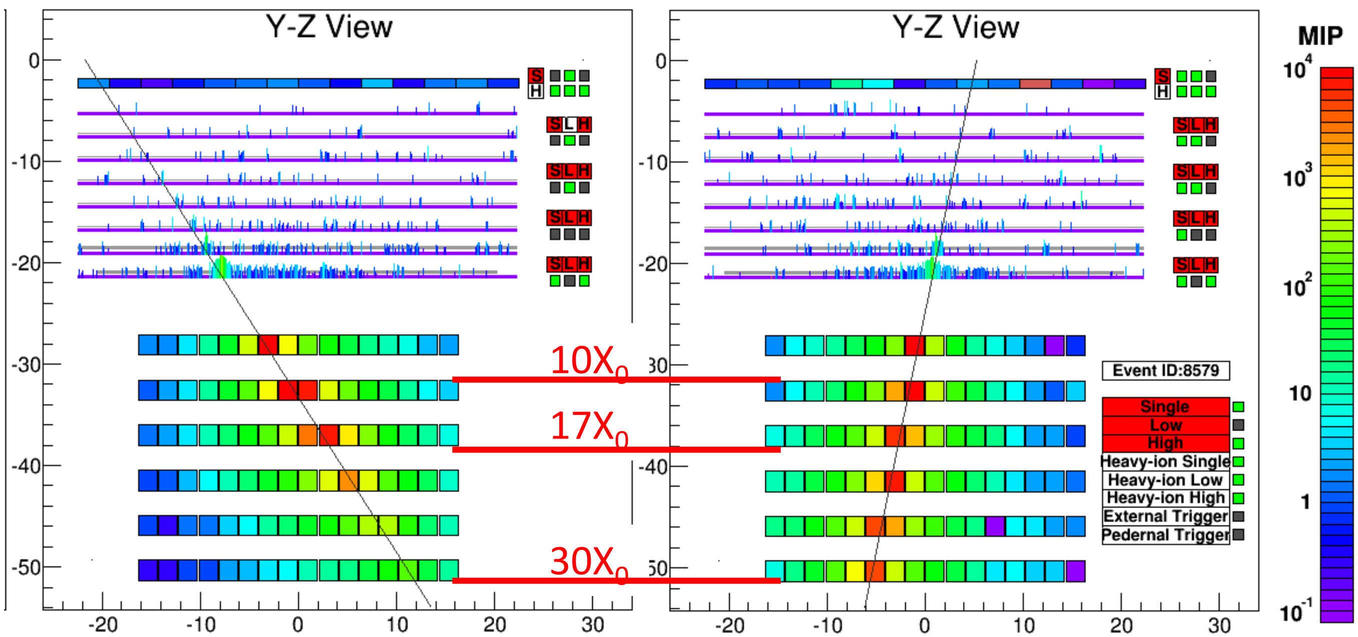
All-Electron (electron + positron) Analysis

CALET is an instrument optimized
for all-electron spectrum measurements.

⇒ CALET is best suited for observation of possible fine structures in the all-electron spectrum up to the trans-TeV region.

3TeV Electron Candidate

Corresponding Proton Background



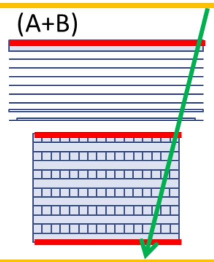
(Flight data; detector size in cm)

1. **Reliable tracking**
   well-developed shower core
2. **Fine energy resolution**
   full containment of TeV showers
3. **High-efficiency electron ID**
   $30X_0$ thickness

Event Selection

Analyzed Flight Data:

- 627 days (October 13, 2015 to June 30, 2017)
- 55% of full CALET acceptance (Acceptance A+B; 570cm^{2}sr)



1. Offline Trigger
2. Acceptance Cut
3. Single Charge Selection
4. Track Quality Cut
5. Shower Development Consistency
6. Electron Identification
    1. Simple two parameter cut
    2. Multivariate Analysis using Boosted Decision Trees (BDT)

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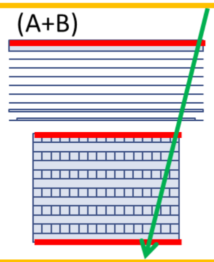

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Pre-selection:

- Select events with successful reconstructions
- Rejecting heavier particles
- Equivalent sample between flight and MC data

Electron Identification

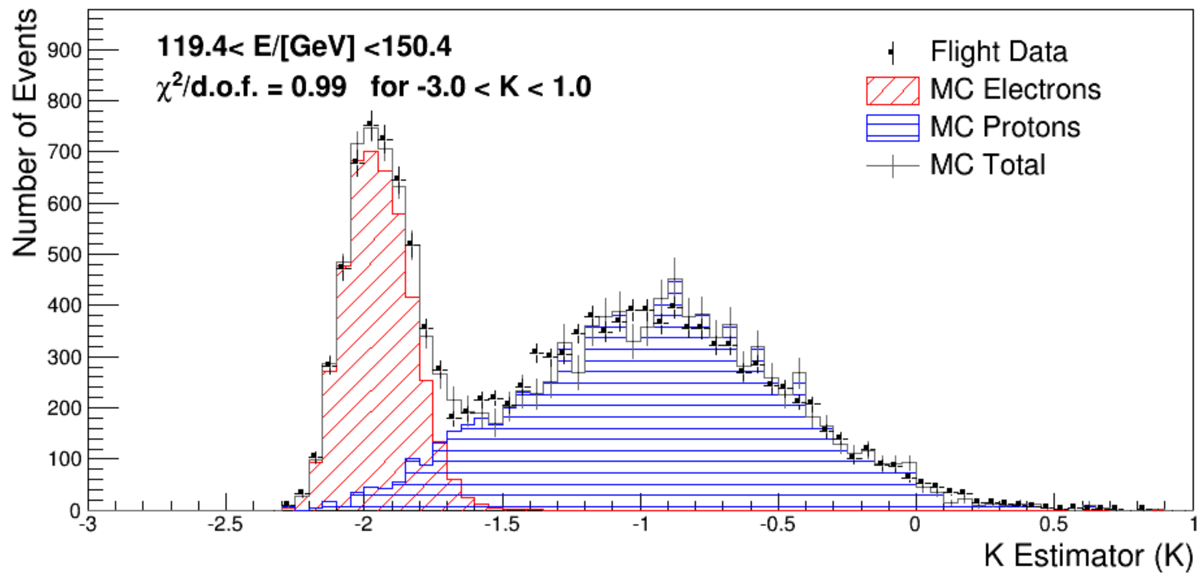
Simple Two Parameter Cut

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

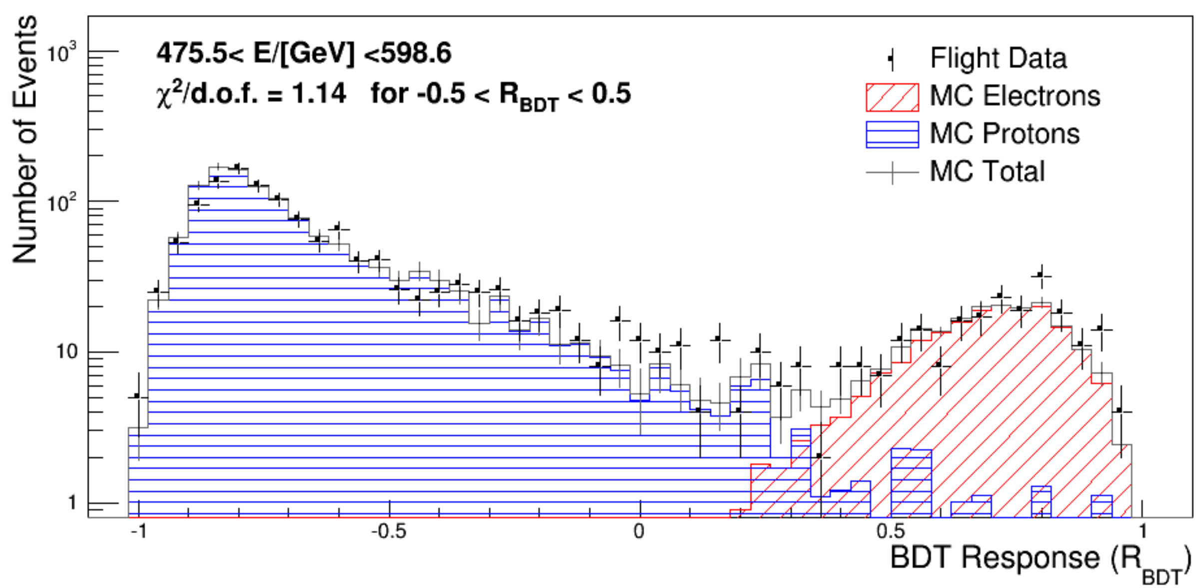
Separation Parameter K is defined as follows:

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

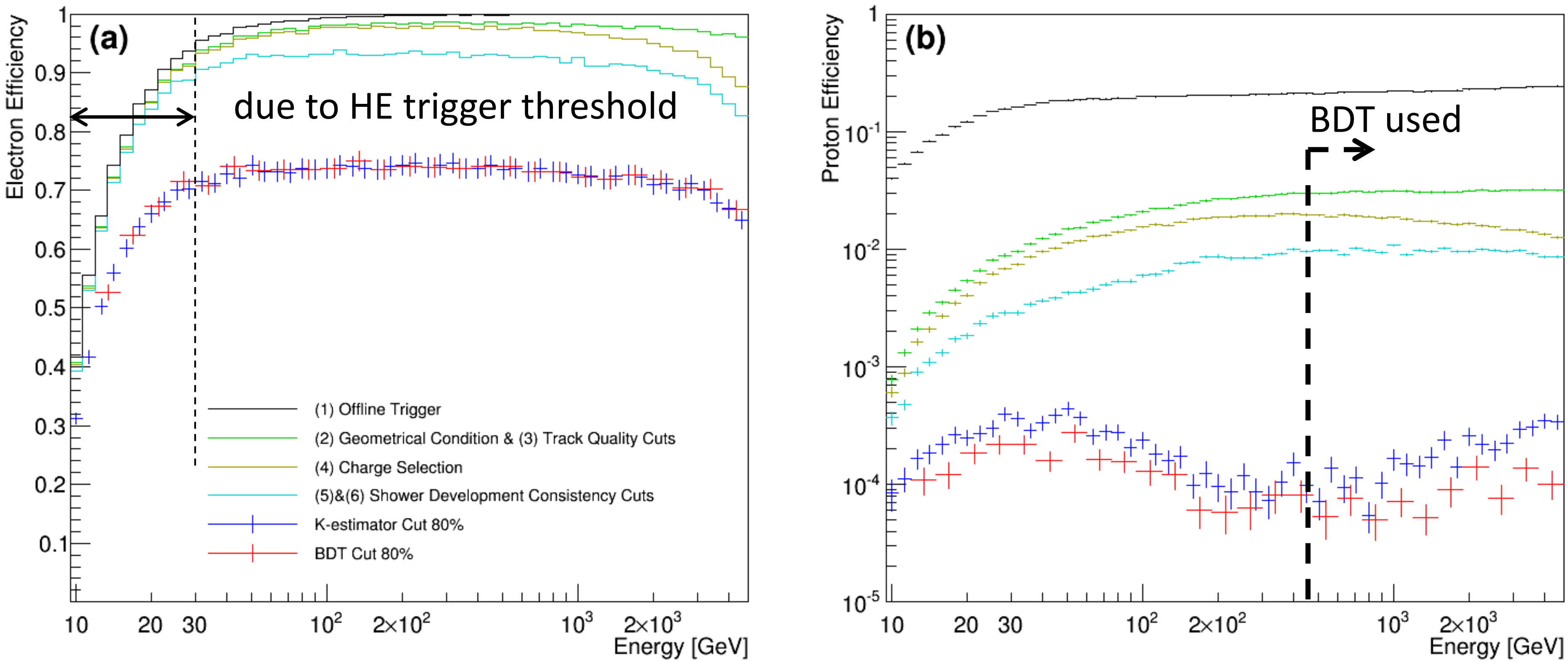


Boosted Decision Trees

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



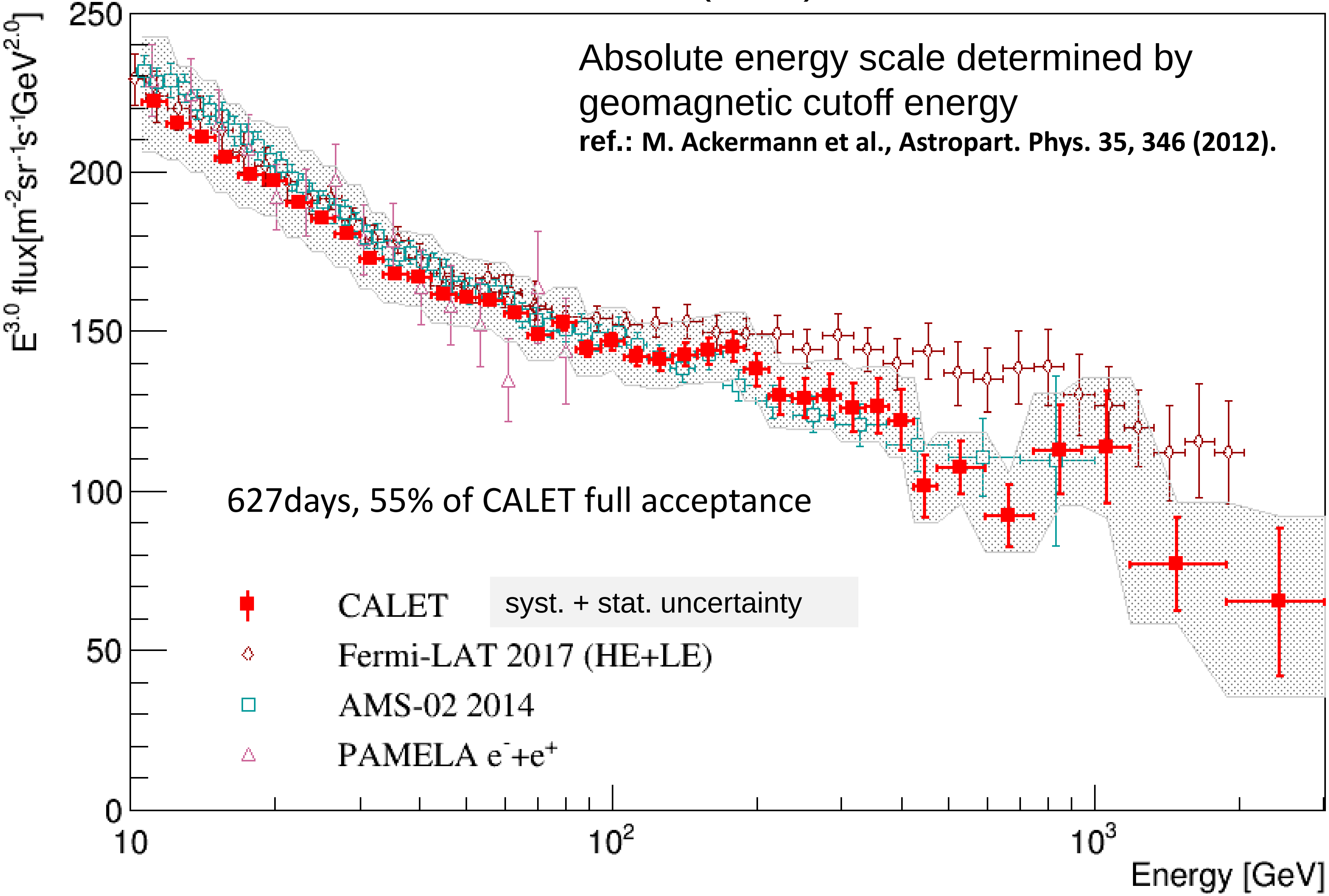
Electron Efficiency and Proton Rejection



- 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 10~20% in the 1—4.8 TeV region.

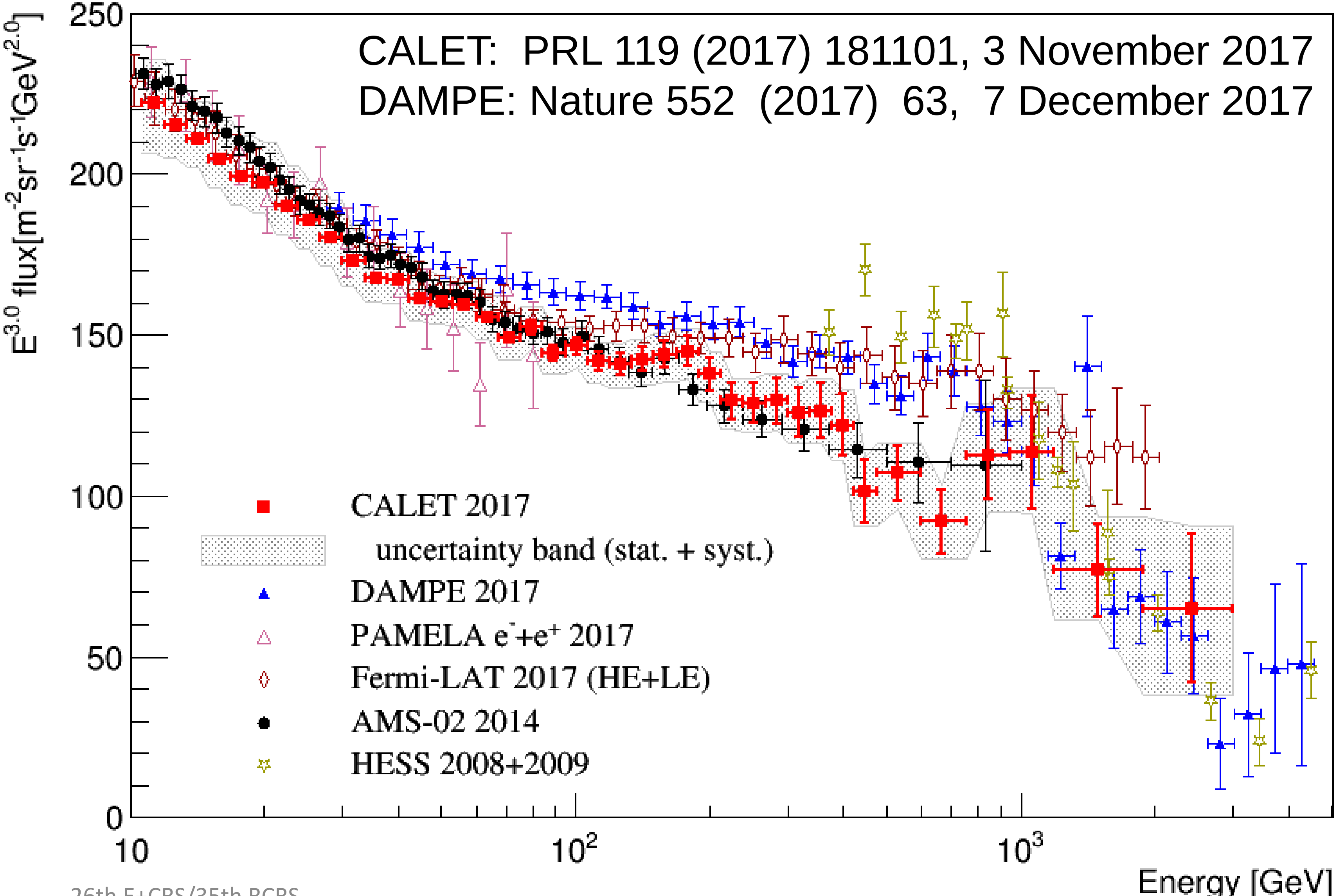
All-Electron Spectrum Measured with CALET from 10 GeV to 3 TeV

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



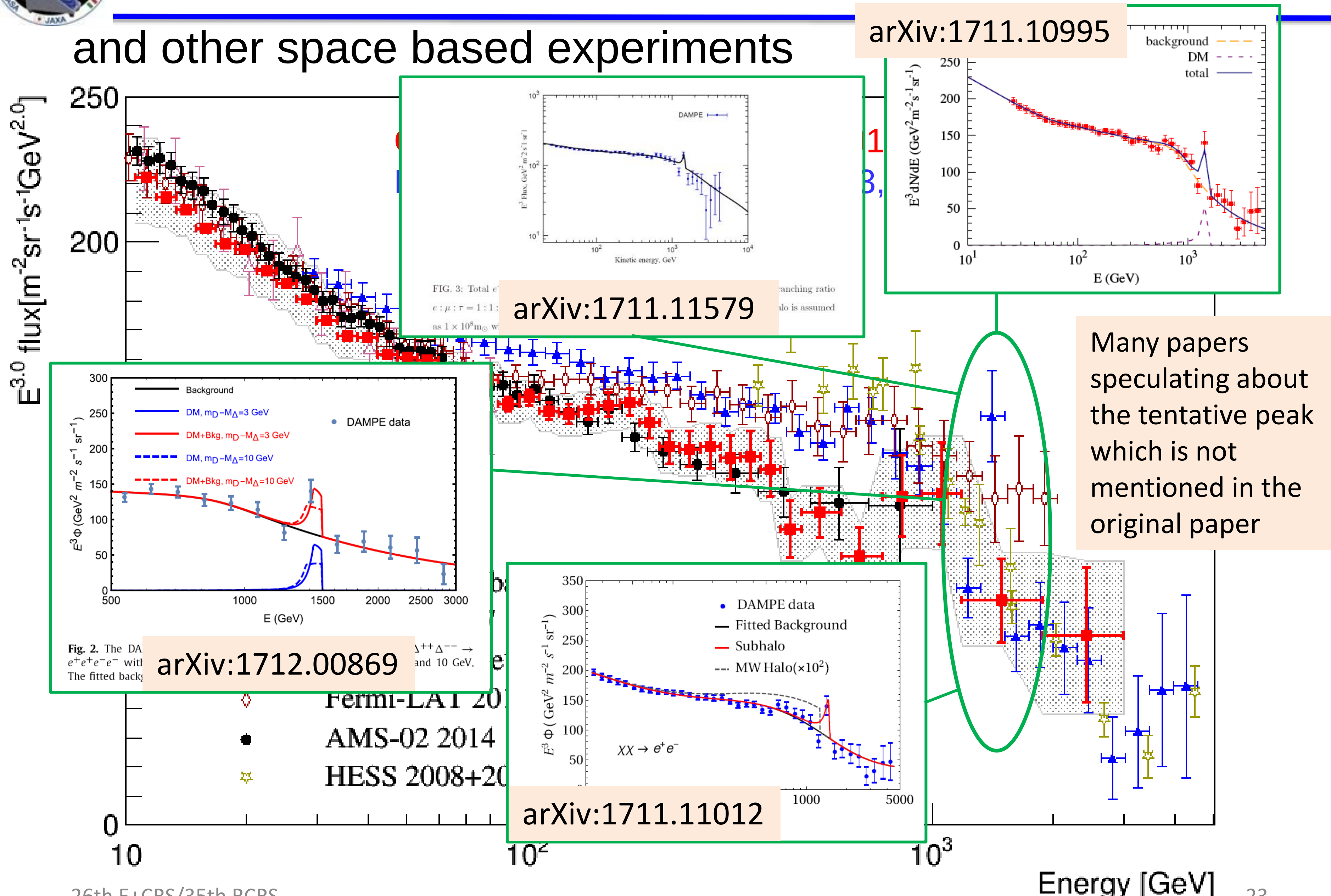
All-Electron Spectrum Comparison w/ DAMPE

and other space based experiments



All-Electron Spectrum Comparison w/ DAMPE

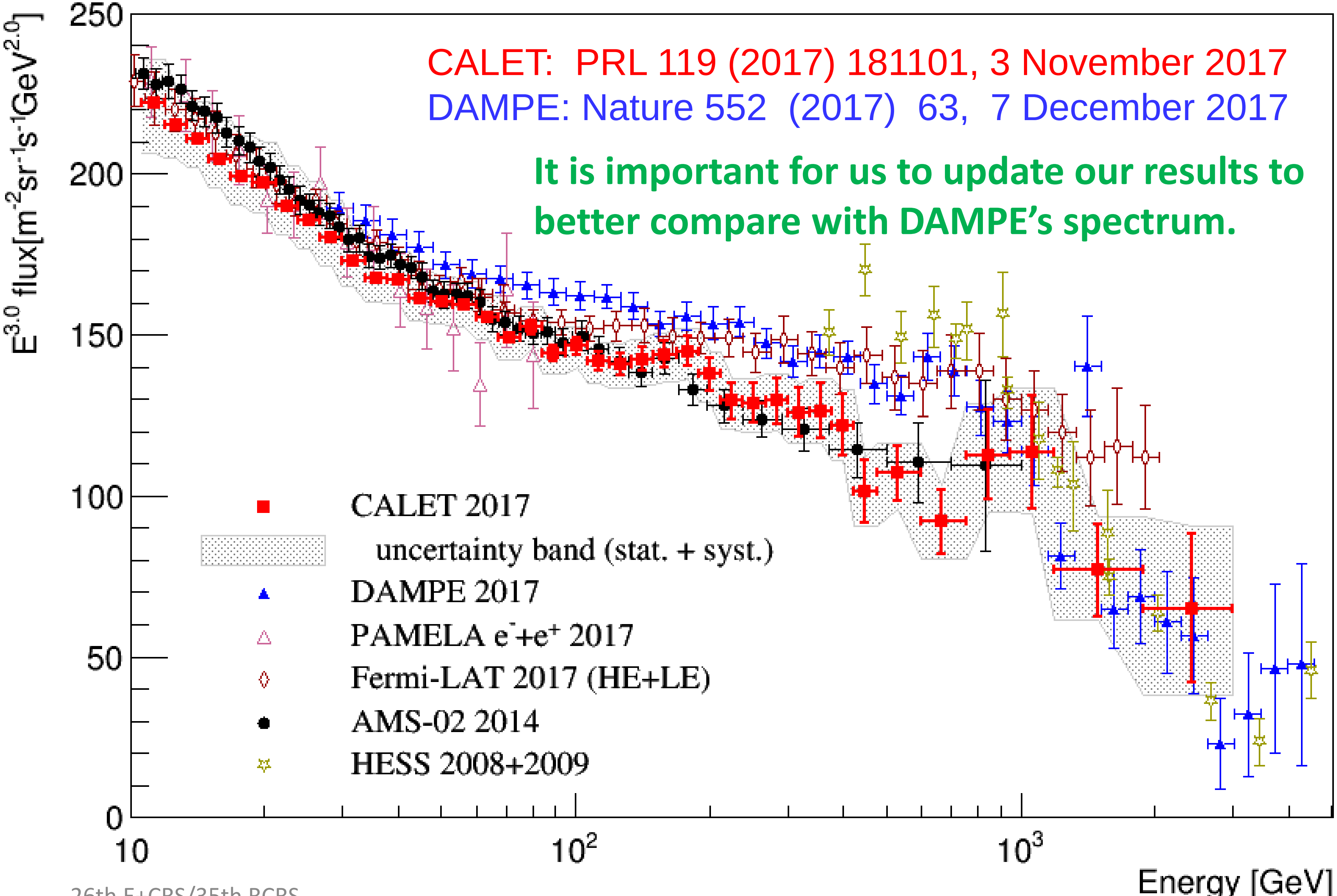
and other space based experiments



Many papers speculating about the tentative peak which is not mentioned in the original paper

All-Electron Spectrum Comparison w/ DAMPE

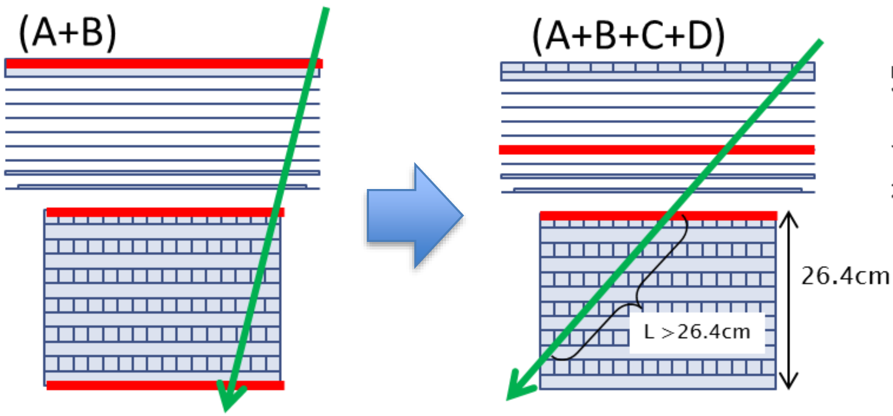
and other space based experiments

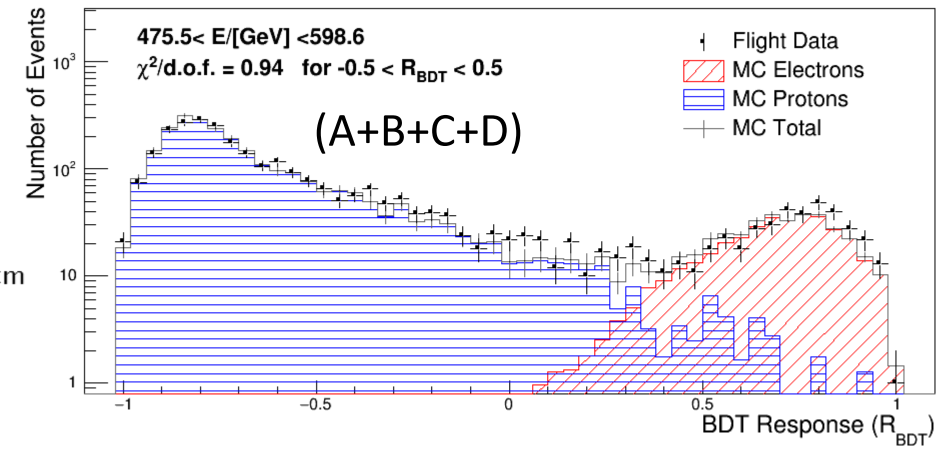


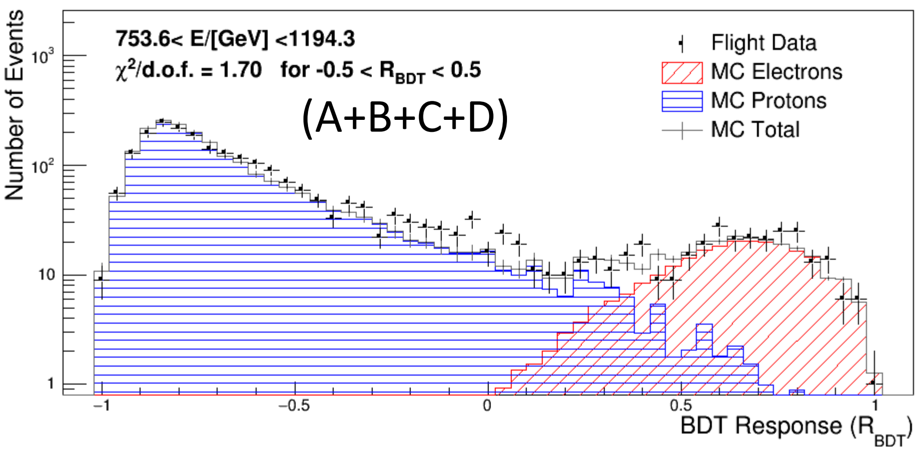
Extending the Analysis to Full Acceptance

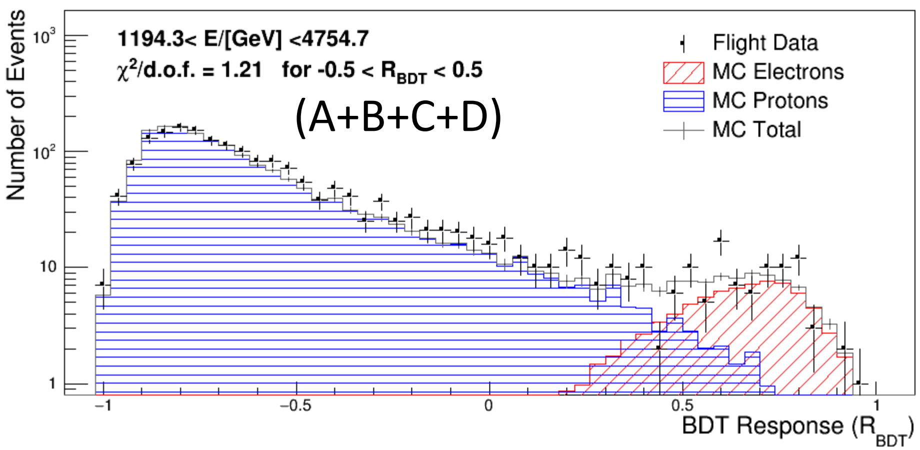
Analyzed Flight Data:

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









Systematic Uncertainties

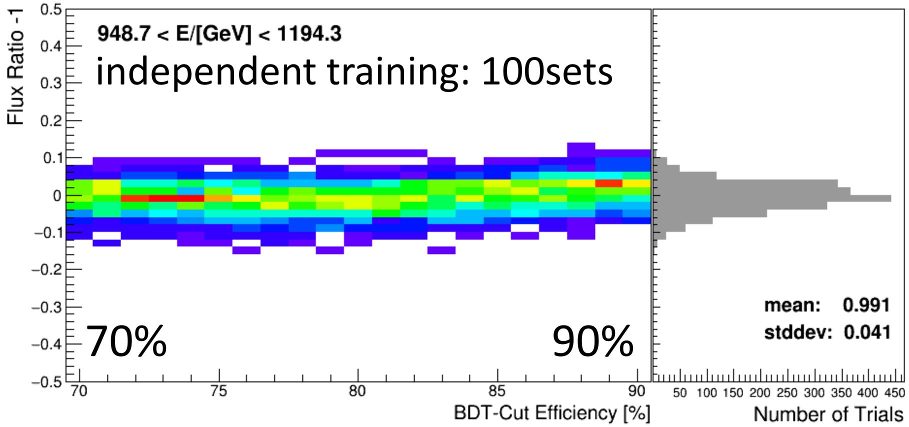
(other than energy scale uncertainty)

Stability of resultant flux are analyzed by scanning parameter space

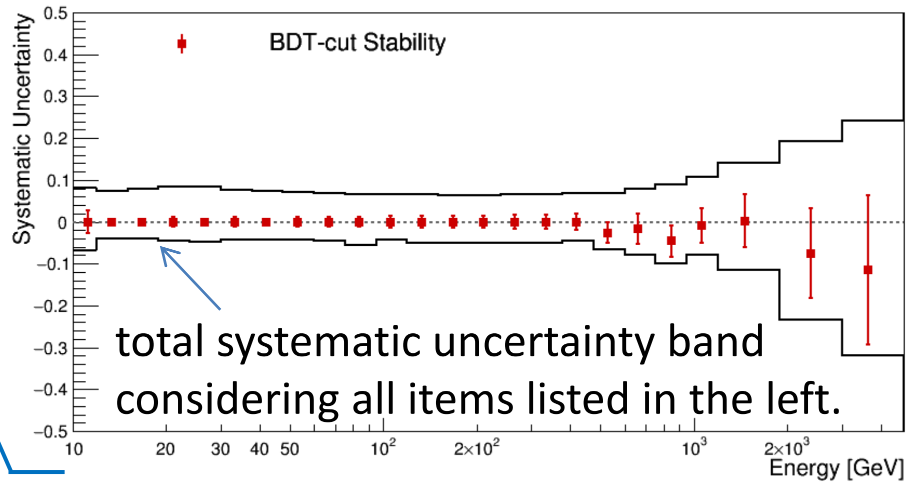
Normalization:
- Live time
- Radiation environment
- Long-term stability
- Quality cuts

- 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

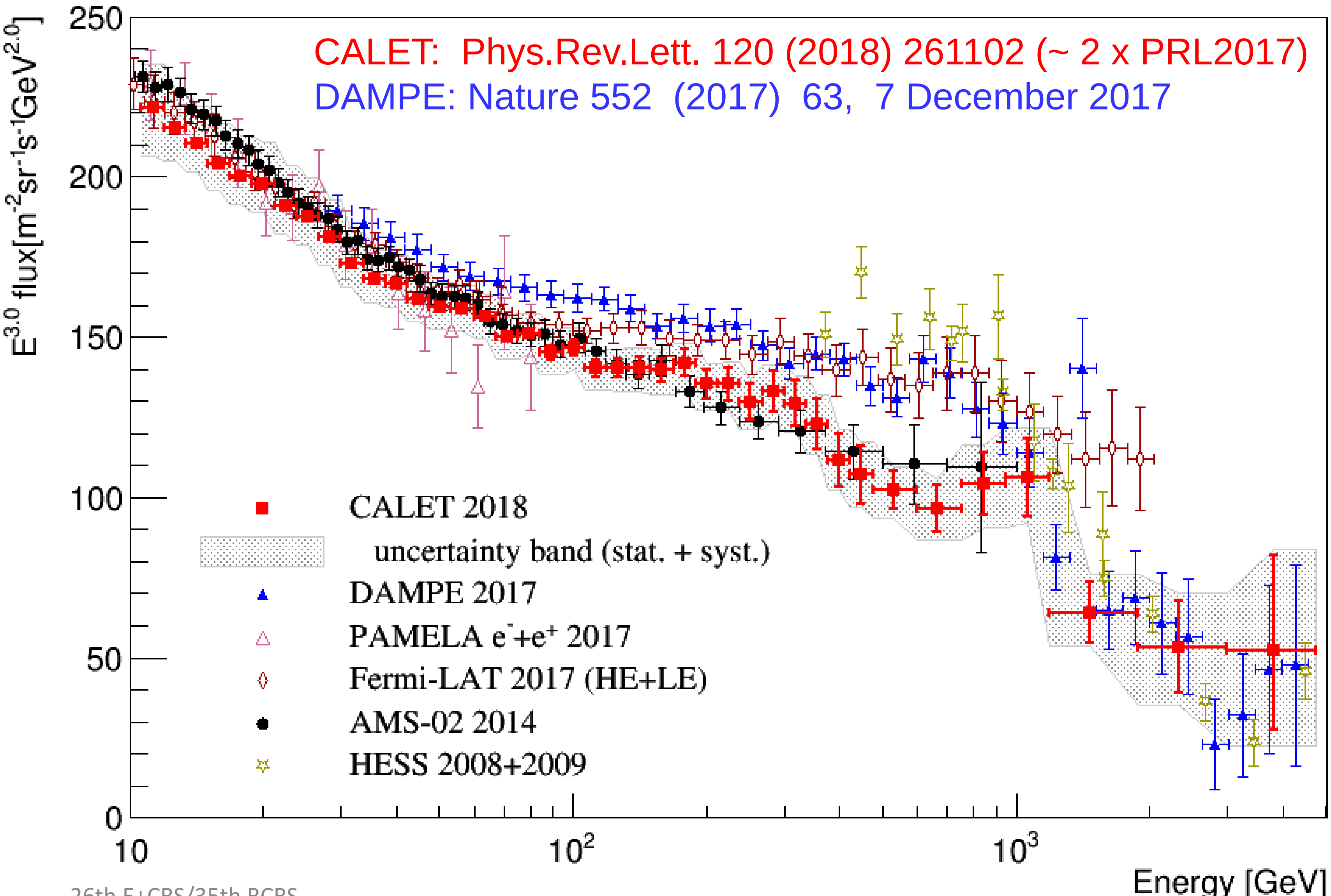


Energy Dependence of BDT stability



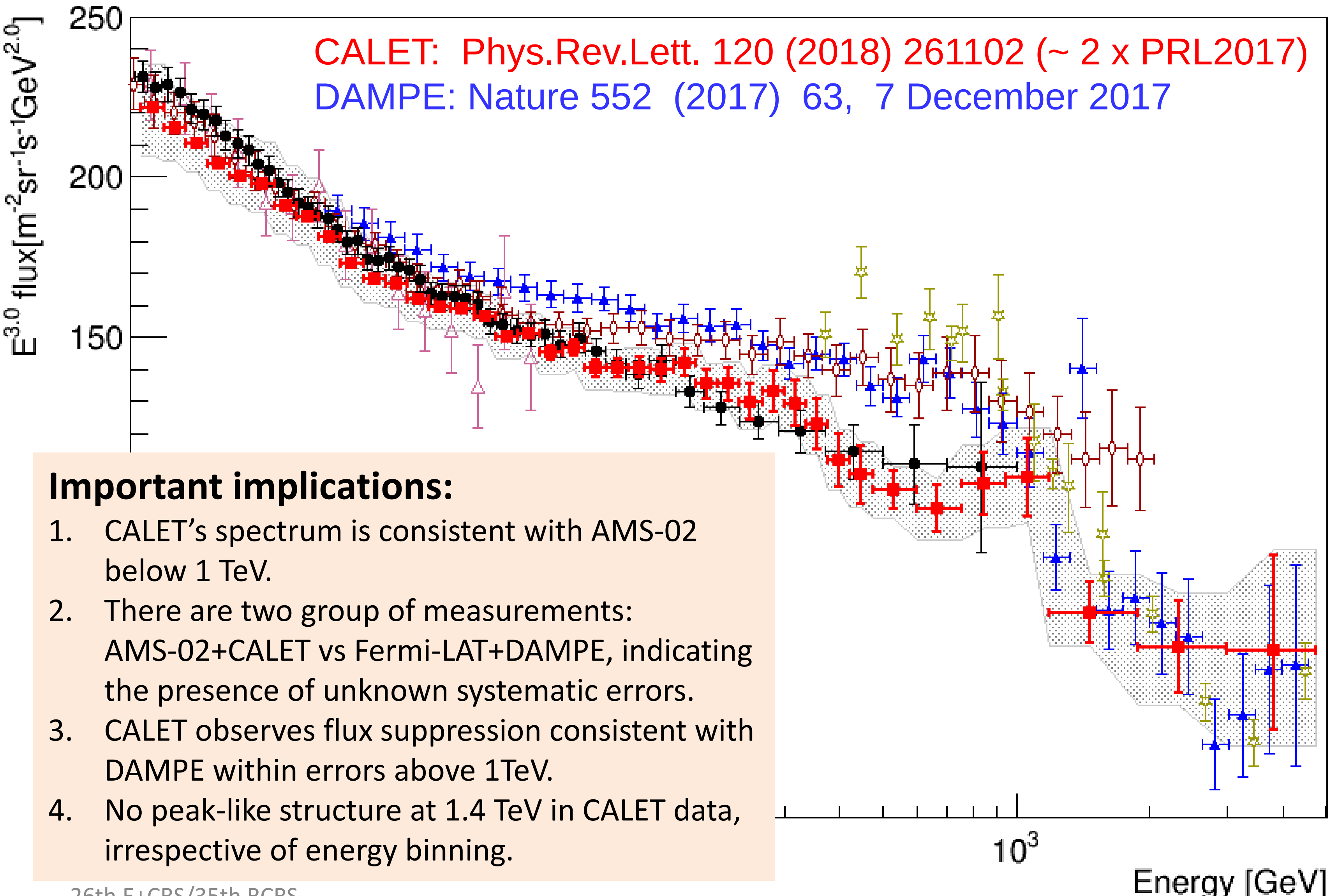
Extended Measurement by CALET

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



Extended Measurement by CALET

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

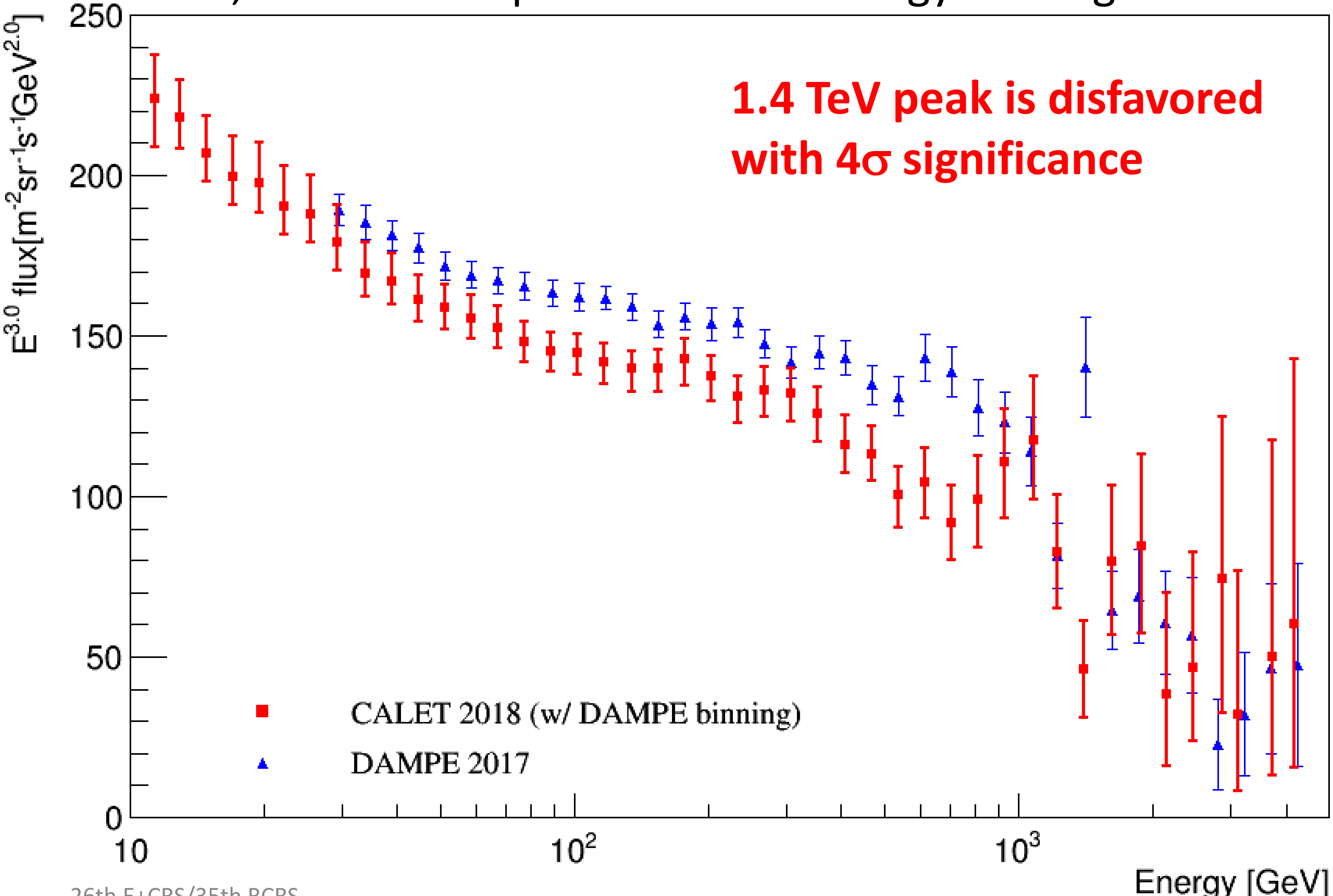


Important implications:

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.

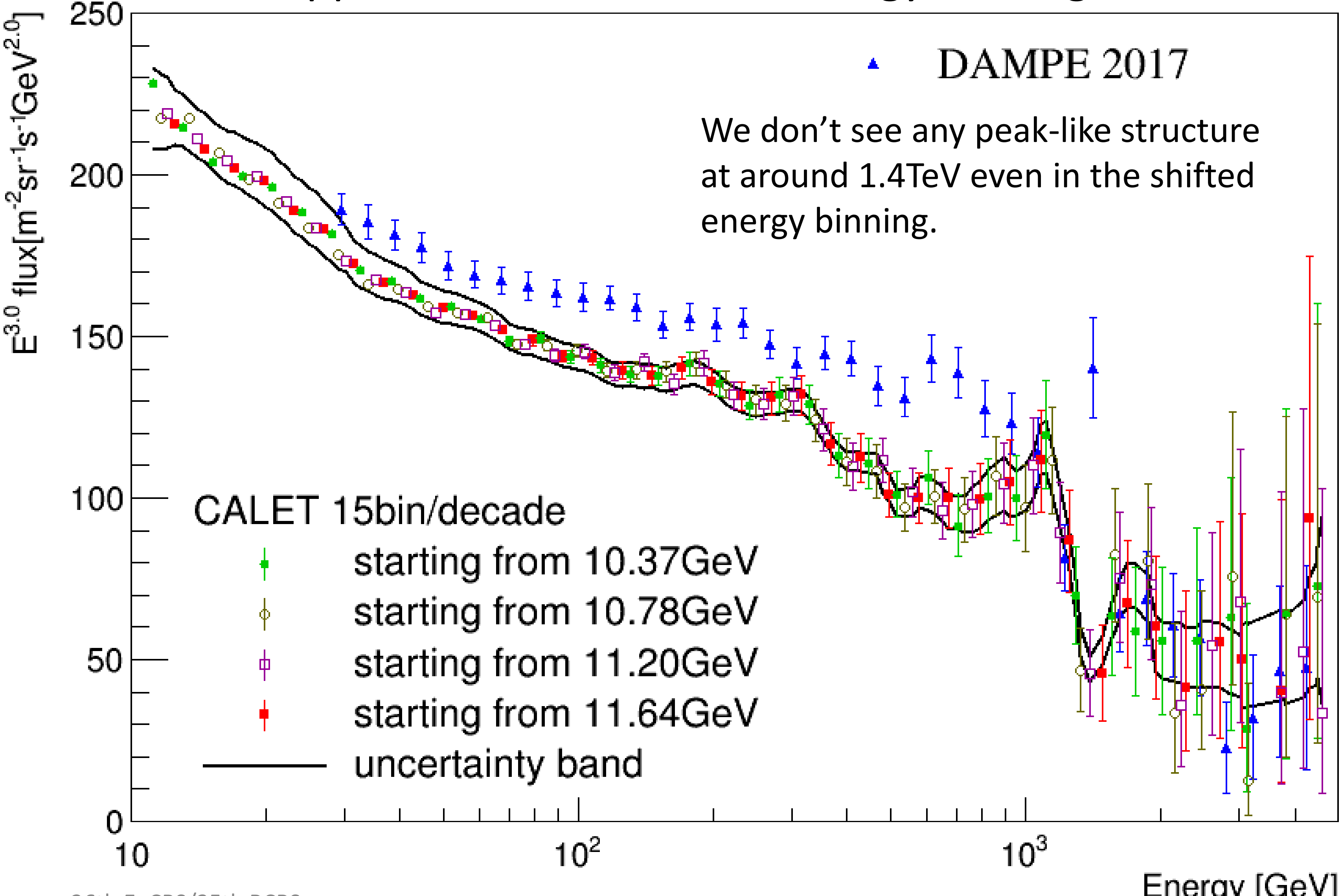
Comparison with DAMPE's result

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



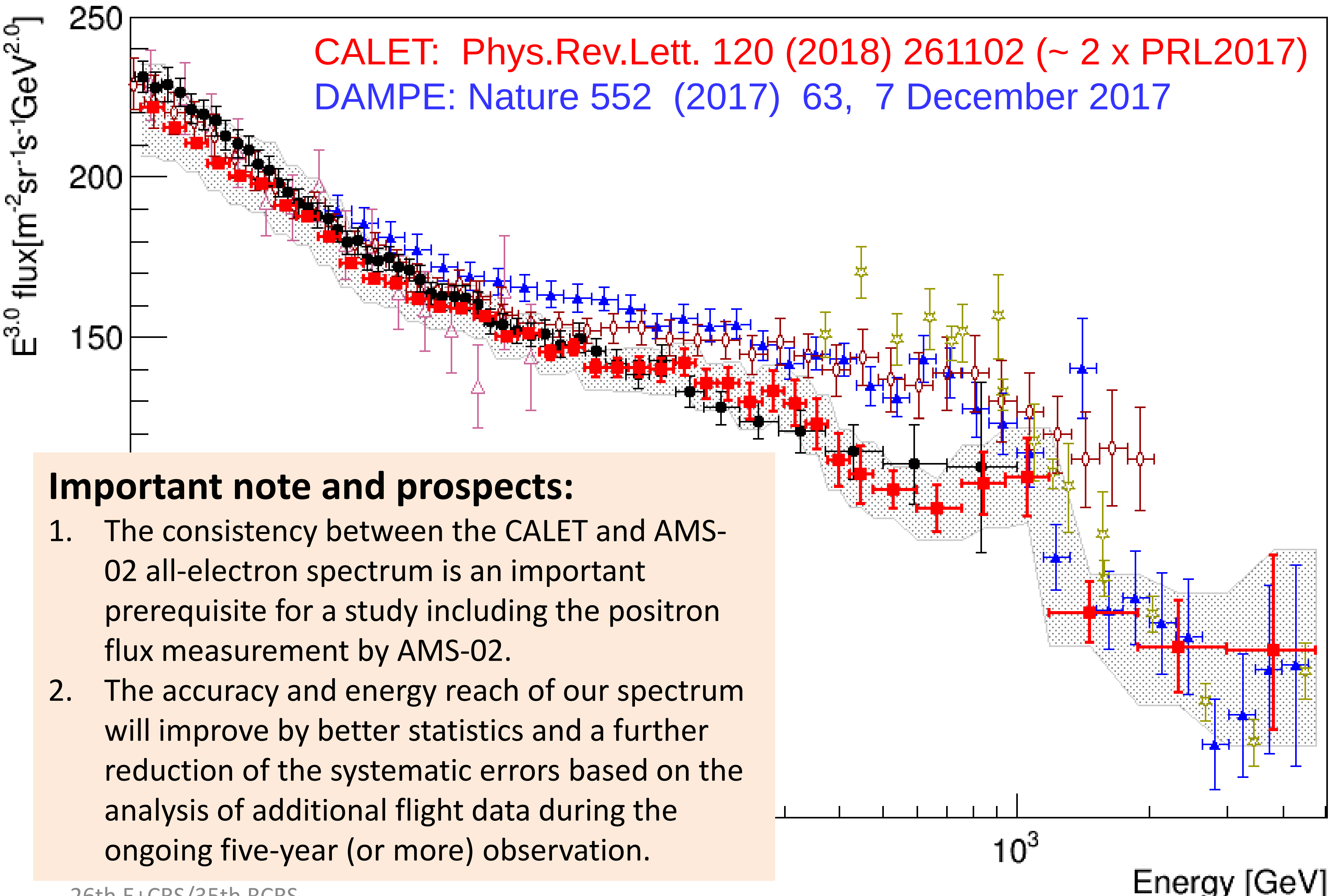
Comparison with DAMPE's result

What happens if we shifted our energy binning…



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 Collaboration), ApJL 829 (2016) L20.

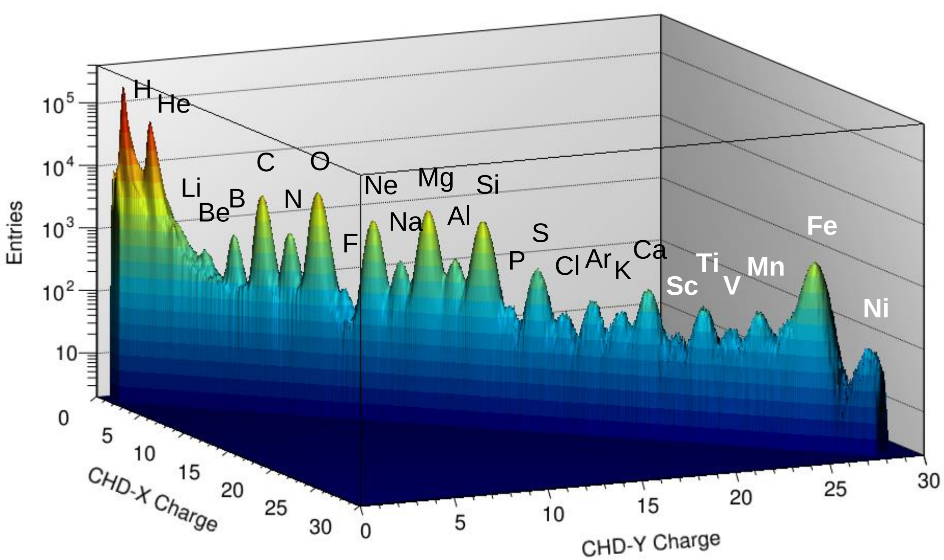
Preliminary Flux of Primary Components

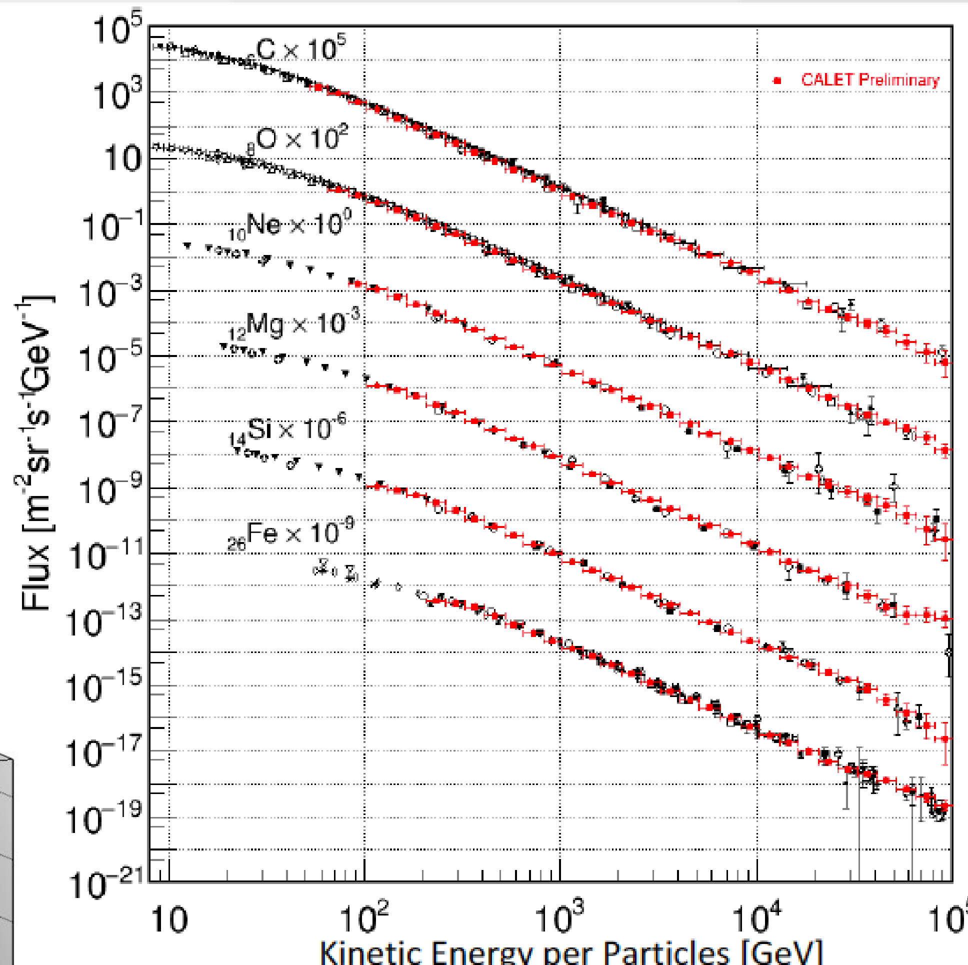
Flux measurement:

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

N(E): Events in unfolded er
$S\Omega$: Geometrical acceptar
T : Live time
ε(E) : Efficiency
ΔE : Energy bin width

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

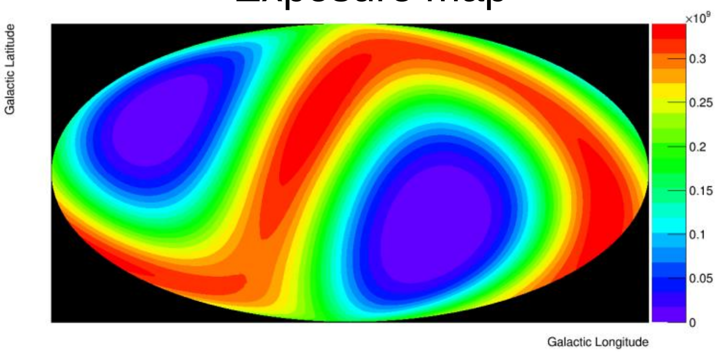




CRD July 7, 14:15-14:30 by Y. Akaike
@ Academic Council Conference Hall)

CALET γ–ray Sky in LE (>1GeV) Trigger

Exposure map

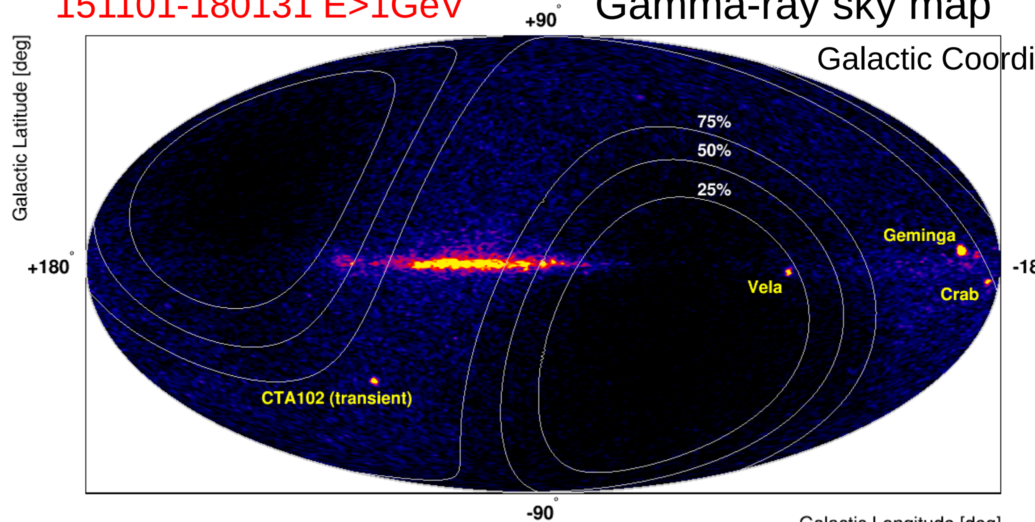


Exposure is limited to low latitude region
=> |declination| > 60 deg is hardly seen
in LE gamma-ray trigger mode.

151101-180131 E>1GeV

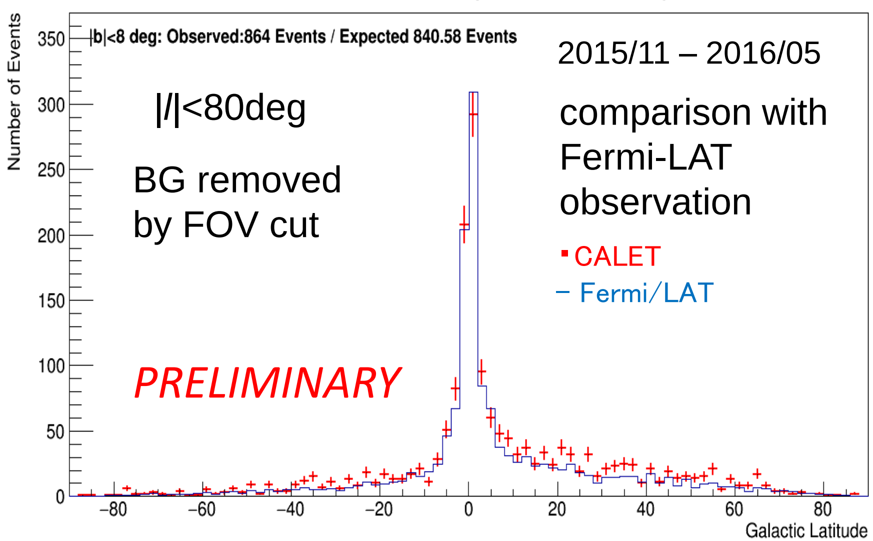
Gamma-ray sky map

Galactic Coordinate

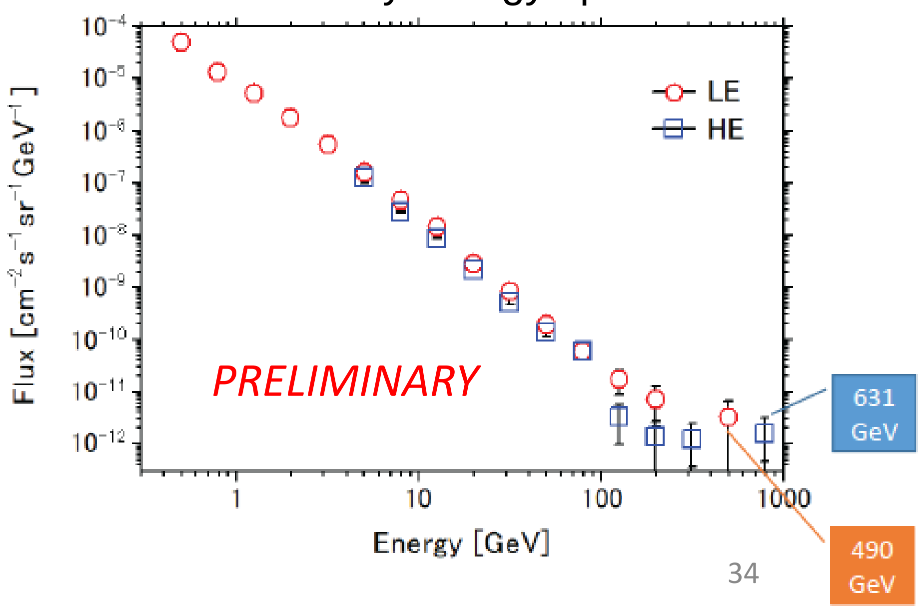


Geminga:432 Vela:138 Crab:150 All: 45740

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

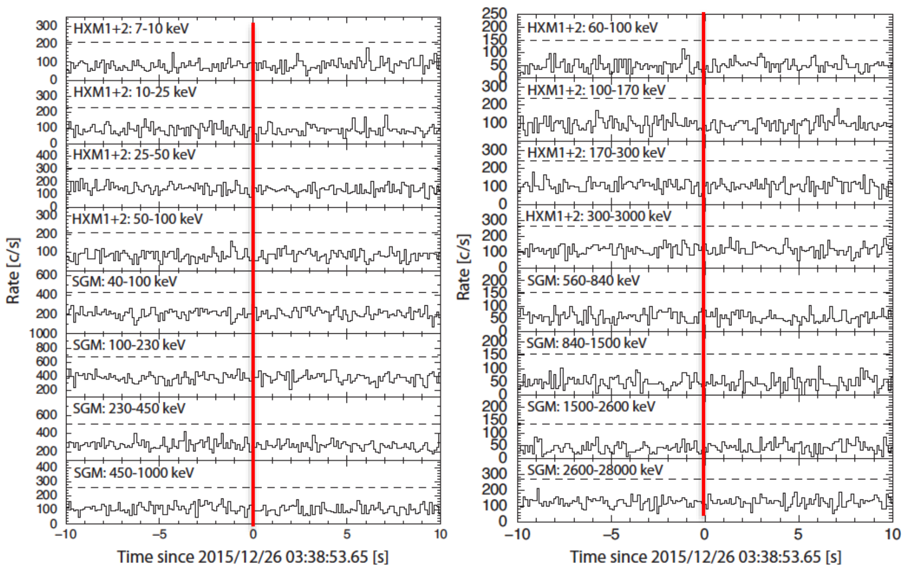


Figure 1. The CGBM light curves in 0.125 s time resolution for the high-gain data (left) and the low-gain data (right). The time is offset from the LIGO trigger time of GW 151226. The dashed-lines correspond to the 5 σ level from the mean count rate using the data of $\pm$10 s.

Upper limit for gamma-ray burst monitors and Calorimeter

HXM: 7-500 keV

SGM: 50-1000 keV

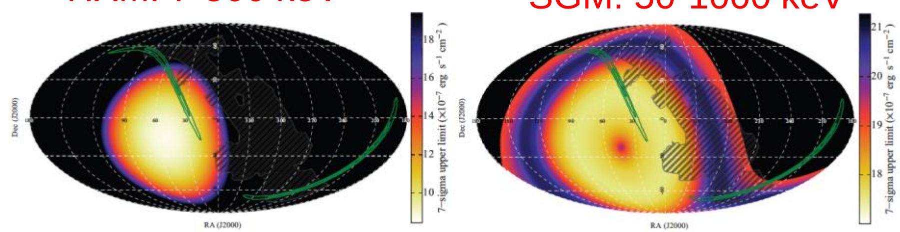


Figure 2. The sky maps of the 7 σ upper limit for HXM (left) and SGM (right). The assumed spectrum for estimating the upper limit is a typical BATSE S-GRBs (see text for details). The energy bands are 7-500 keV for HXM and 50-1000 keV for SGM. The GW 151226 probability map is shown in green contours.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

Calorimeter: 1-100 GeV

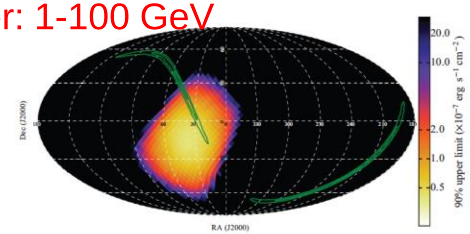


Figure 3. The sky map of the 90% upper limit for CAL in the 1-100 GeV band. A power-law model with a photon index of −2 is used to calculate the upper limit. The GW 151226 probability map is shown in green contours.

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 May 31, 2018, total observation time is 962 days with live time fraction to total time close to 84%. Nearly 630 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.
- All electron spectrum has been extended in statistics and in the energy range from 11 GeV to 4.8TeV. This result is published in PRL again on June 2018.
- Preliminary analysis of nuclei and gamma-rays 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~70 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.
- 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.