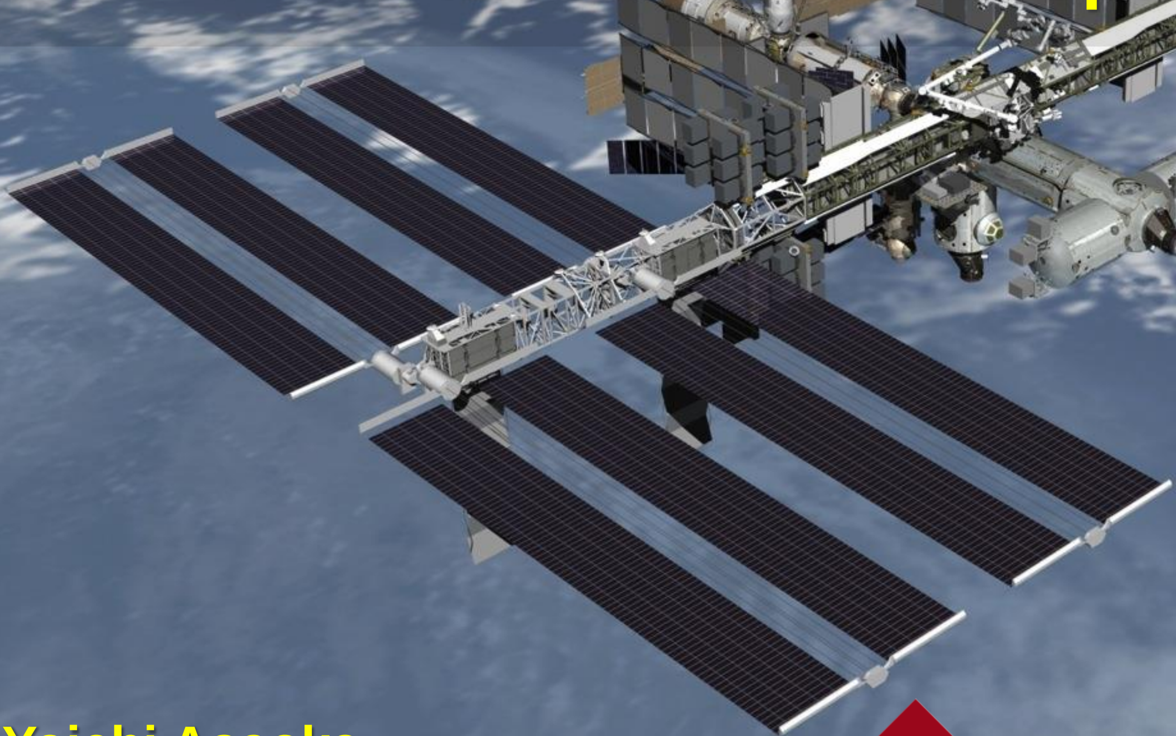
Recent Results from the CALorimetric Electron Telescope (CALET) on the International Space Station



Yoichi Asaoka
for the CALET collaboration
WISE, Waseda University

CALET Collaboration Team

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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
17) National Institute of Polar Research, Japan
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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.

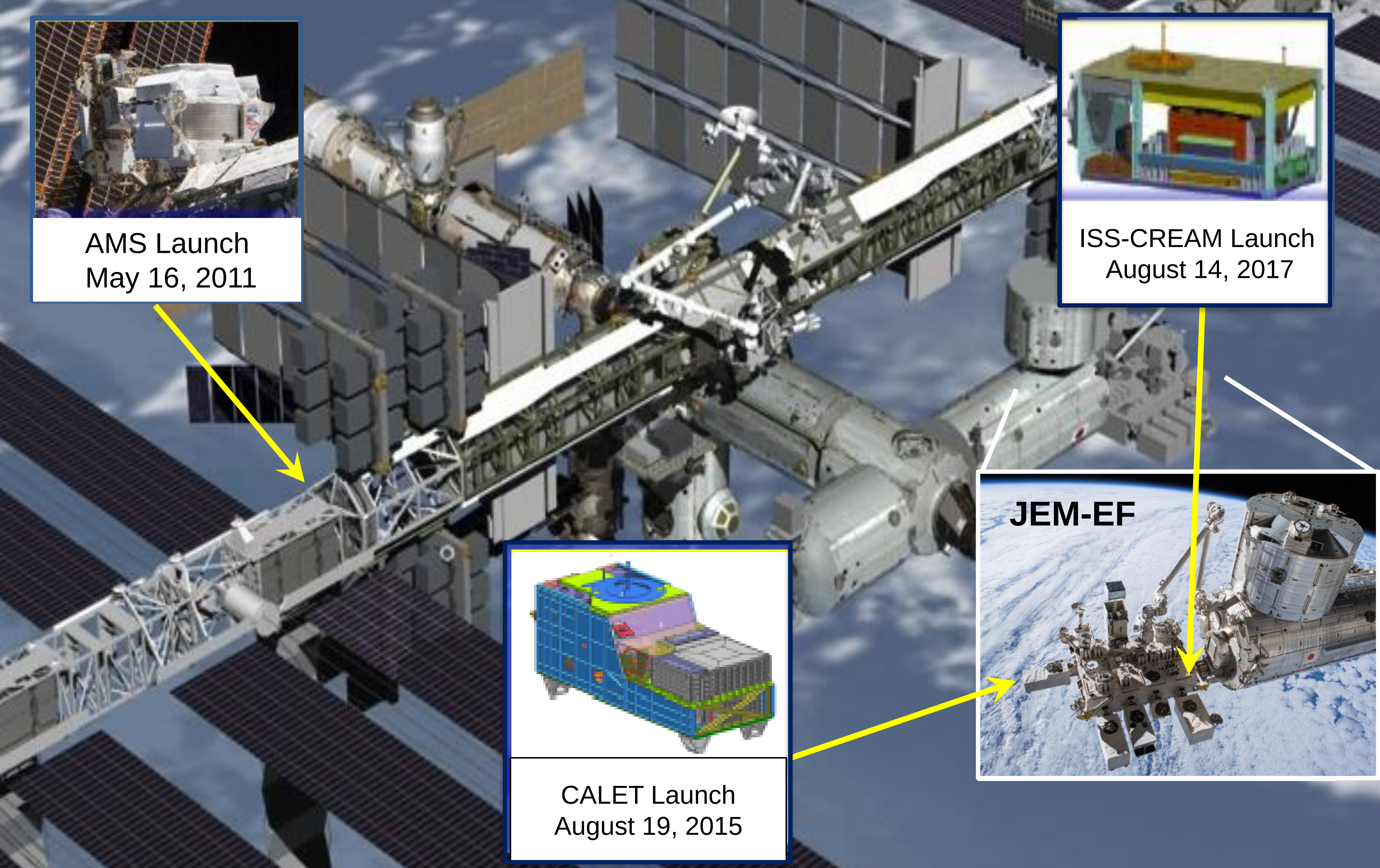
Y.Asaoka, S.Ozawa, S.Torii et al. (CALET Collaboration), Astropart. Phys. 100 (2018) 29.

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 238 (2018) 5.

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

ISS as Cosmic Ray Observatory



ISS as Cosmic Ray Observatory

AMS Launch
May 16, 2011

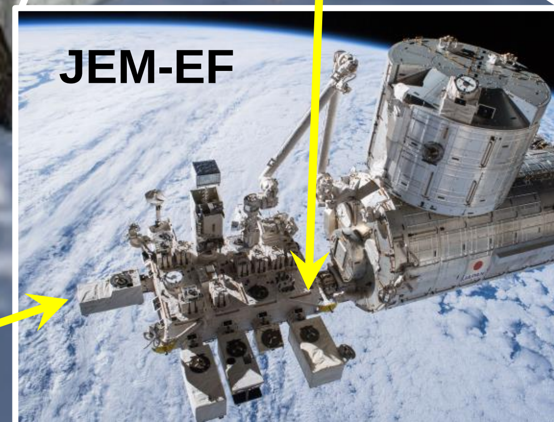
Magnet Spectrometer
- Various PID
- Anti-particles
- E ≤ TeV

Calorimeter
- Carbon target
- Hadrons
- Including TeV region

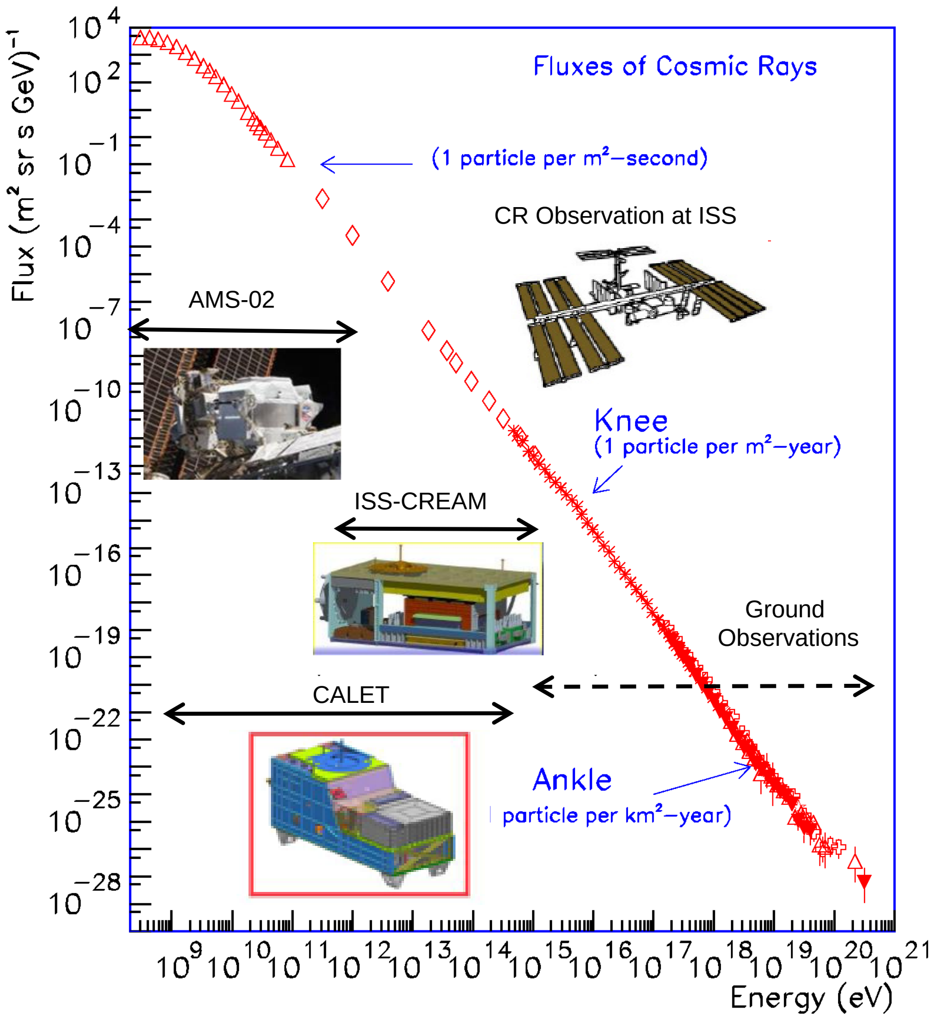
ISS-CREAM Launch
August 14, 2017

Calorimeter
- Fully active
- Electrons
- Including TeV region

CALET Launch
August 19, 2015



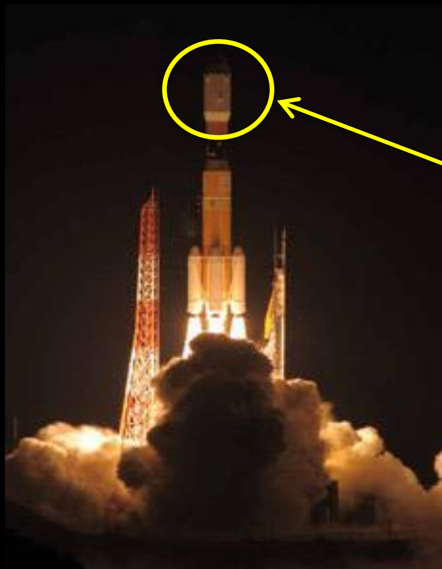
Cosmic Ray Observations at the ISS and CALET

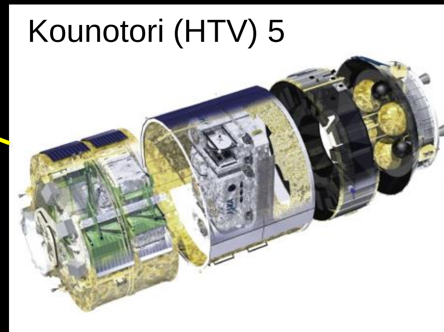


Overview of CALET Observations

- Direct cosmic ray observations in space at 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.

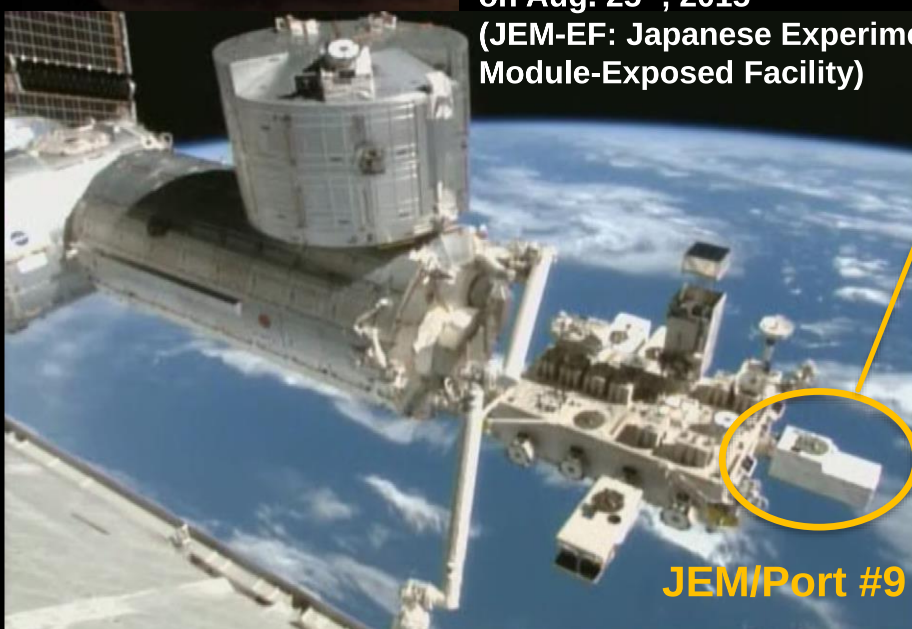
CALET Payload

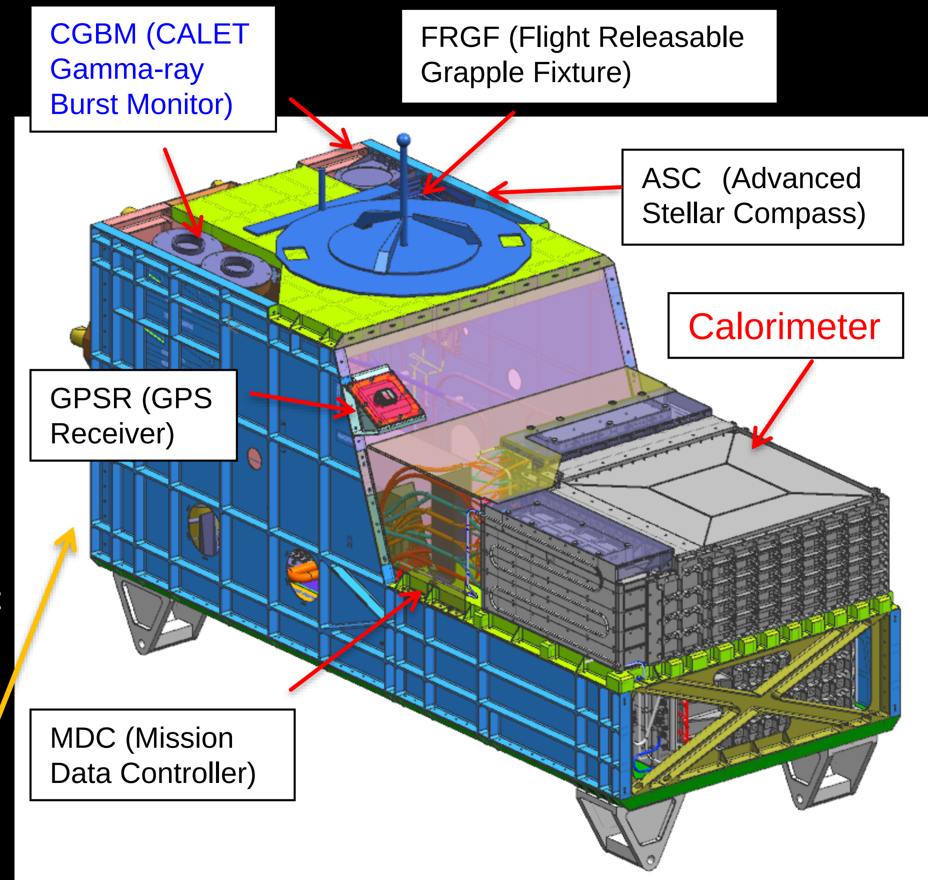




Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

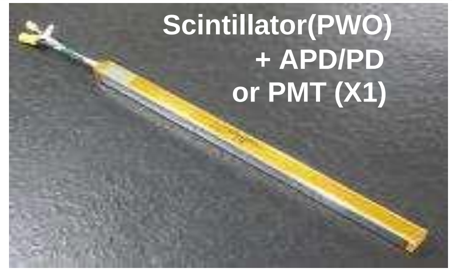
Emplaced on JEM-EF port #9 on Aug. 25th, 2015
(JEM-EF: Japanese Experiment Module-Exposed Facility)



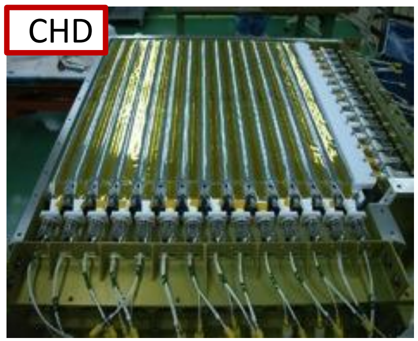


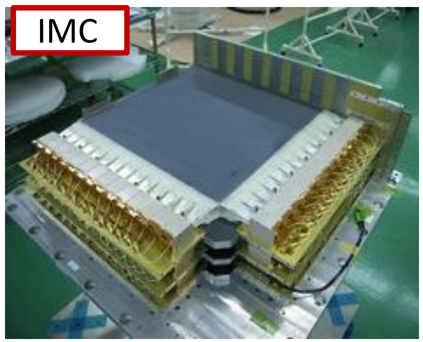
- Mass: 612.8 kg
- JEM Standard Payload Size:
  1850mm(L) × 800mm(W) × 1000mm(H)
- Power Consumption: 507 W（max）
- Telemetry:
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

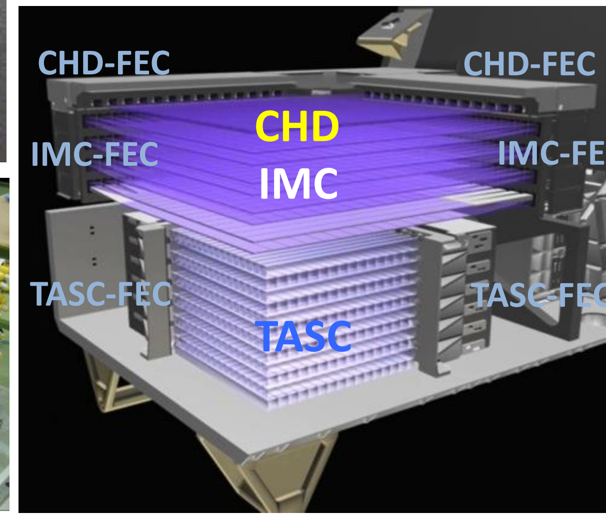
CALET Instrument



CALORIMETER



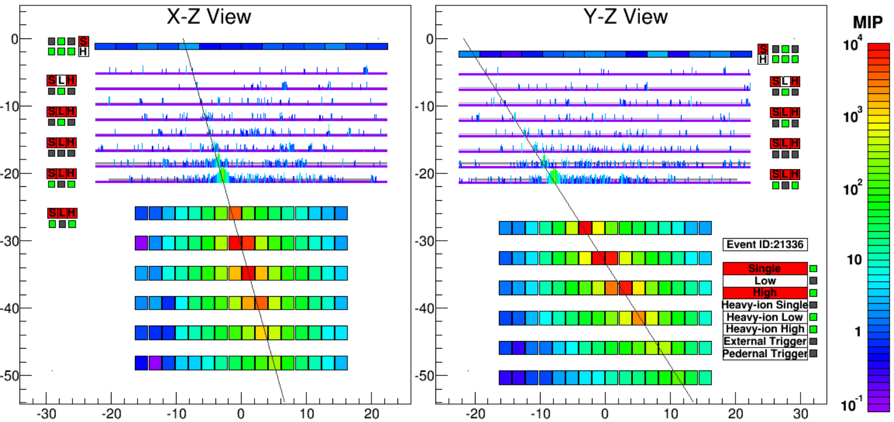




	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	Charge (Z=1-40)	Tracking , Particle ID	Energy, e/p Separation
Geometry (Material)	Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3	448 Scifi x 16 layers (X,Y) : 7168 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

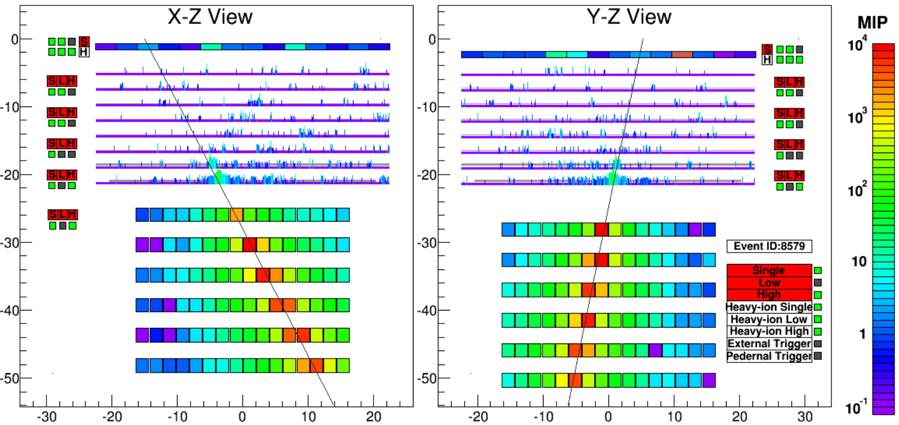
Event Examples of High-Energy Showers

Electron, E=3.05 TeV



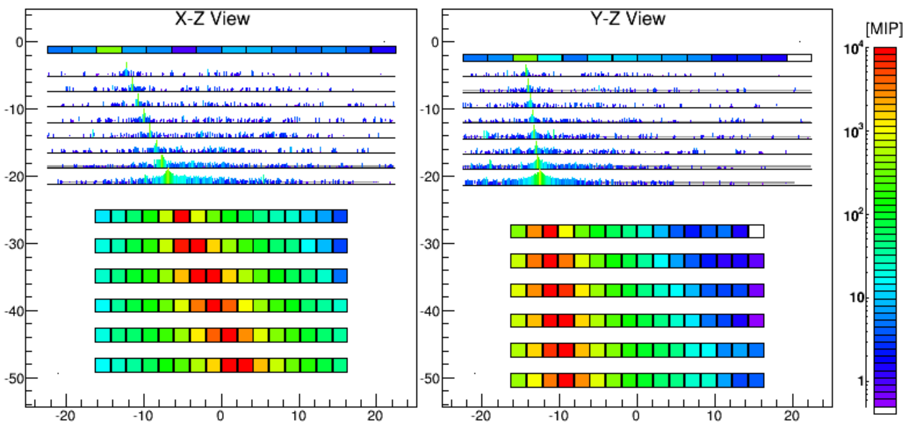
fully contained even at 3TeV

Proton, ΔE=2.89 TeV



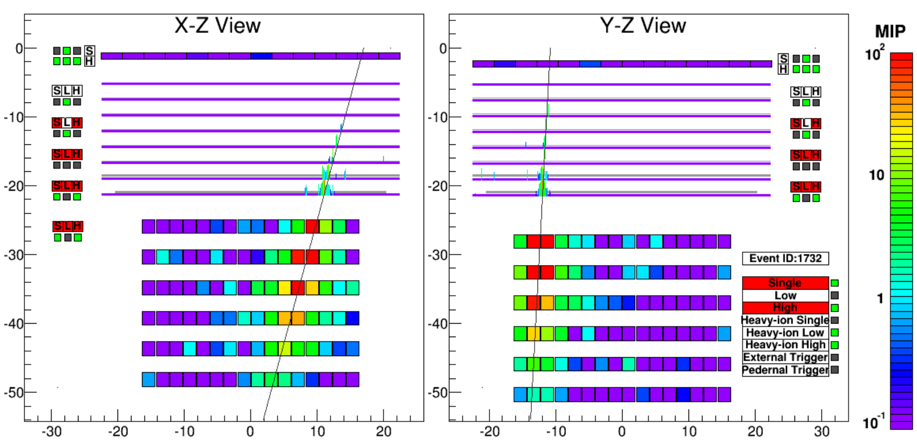
clear difference from electron shower

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

Energy Calibration Using “MIP” in Flight with Tests on Ground

Intrinsic Advantage of the Fully Active Total Absorption Calorimeter:

EM Shower Energy Measurement = Energy Deposit Sum × “Small” Correction

- Active and thick calorimeter absorbs most of the electromagnetic energy (~95%) up to the TeV region in the case of CALET instrument.
- In principle, energy measurement with small systematic error is possible.
- CALET Detector features:
  - Fine energy resolution of ~ 2 %
  - Wide dynamic range to measure shower energy from 1GeV to 1000 TeV.
- It requires to obtain the ADC unit to energy conversion factor and to calibrate the whole dynamic range channel by channel.

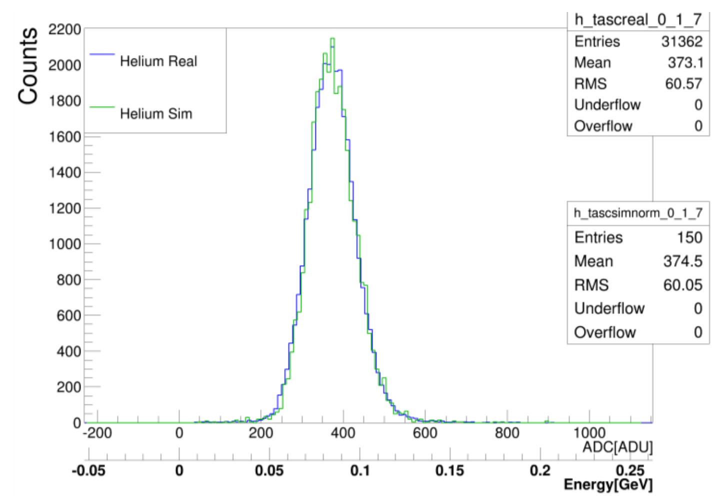
On orbit : Energy conversion factor using “MIP” of p or He

- Position and temperature dependence
- Latitude dependence due to rigidity cutoff

On ground: Linearity measurements for the whole dynamic range

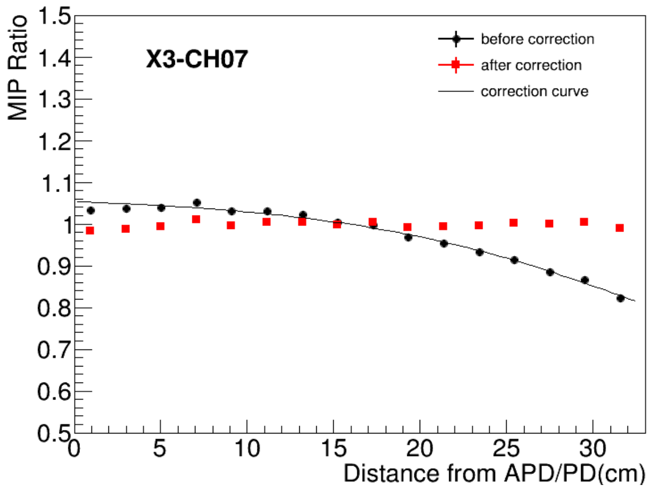
- CHD/IMC – Charge injection
- TASC – UV Laser irradiation (end-to-end)

“MIP” peak in PWO: Obs. vs. MC

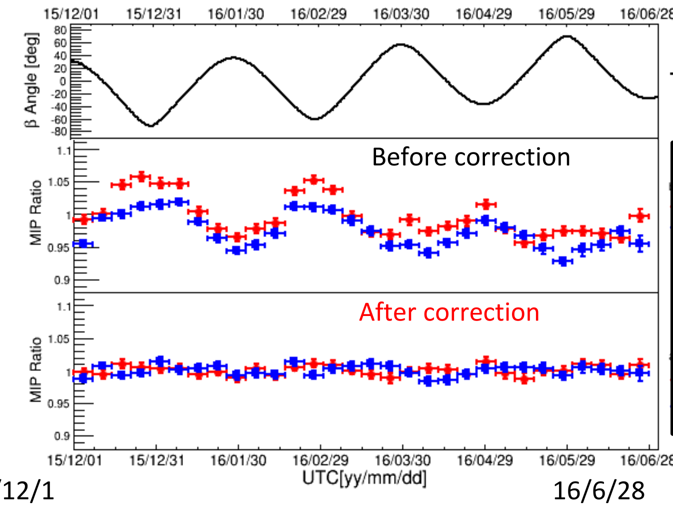


Position and Temperature Calibration, and Long-term Stability

Example of position dependence correction

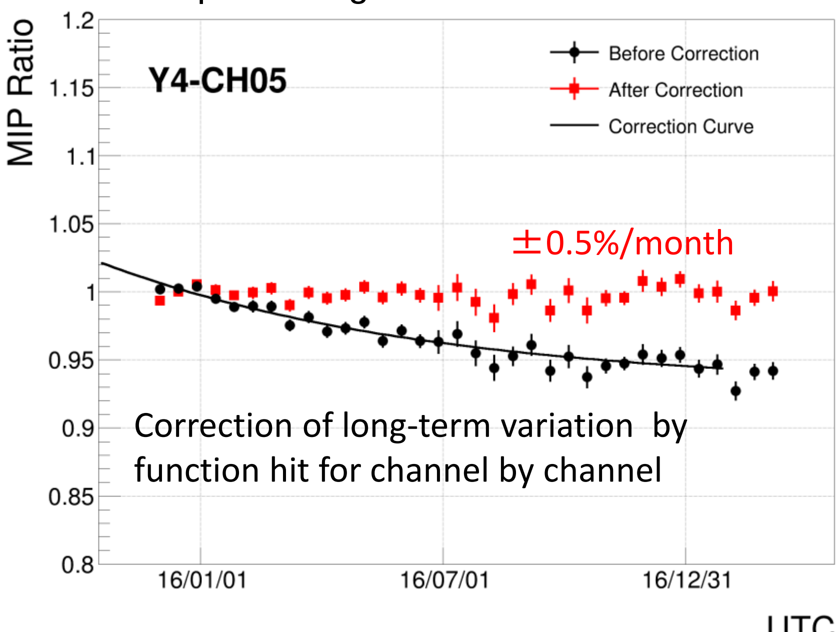


Examples of temperature change correction

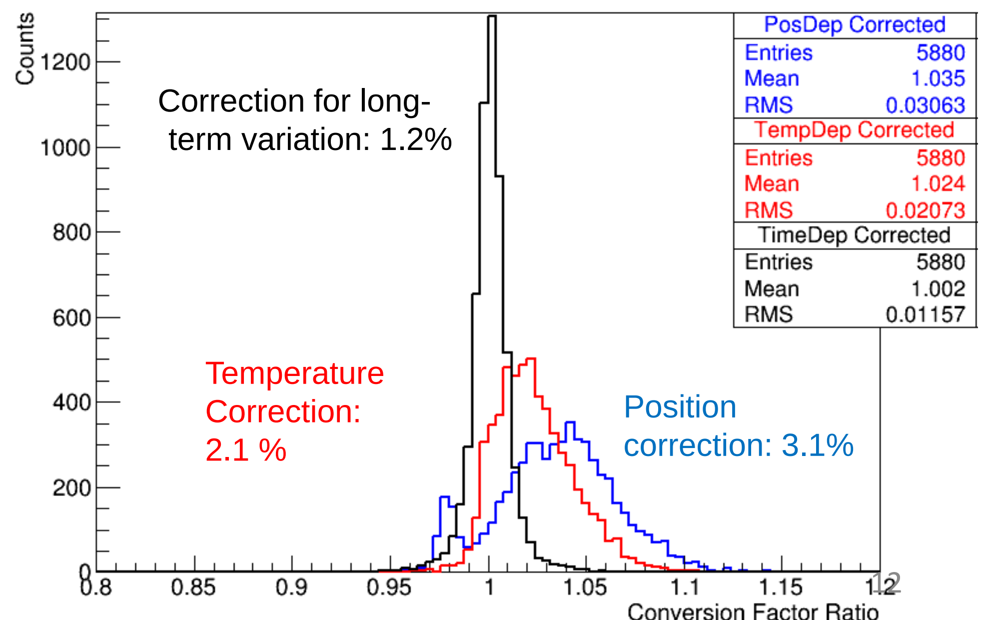


Active Thermal Control System (ATCS) on ISS can provide very stable thermal condition during observations:
Δt ~ a few degrees

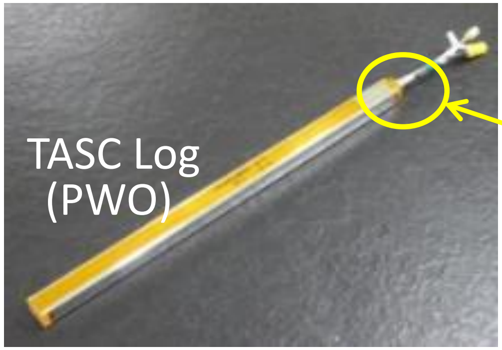
Example of long-tem variation correction

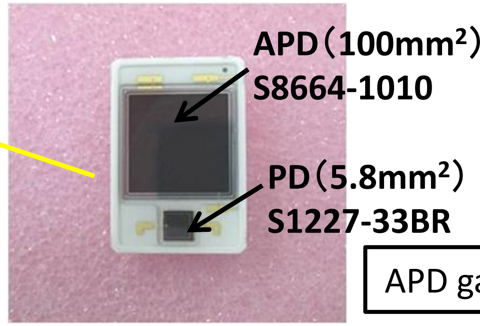


Distribution of MIPs for 192 ch x 16 segmented positions after each correction

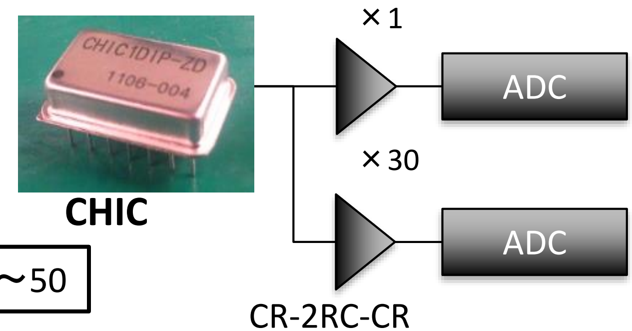


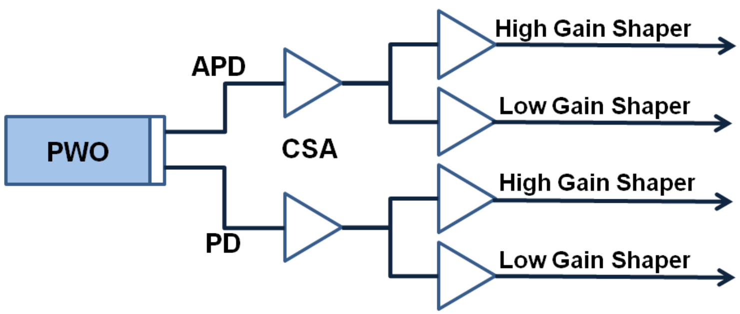
Energy Measurement in Dynamic Range of 1-10^6 MIP in TASC





APD gain ～50





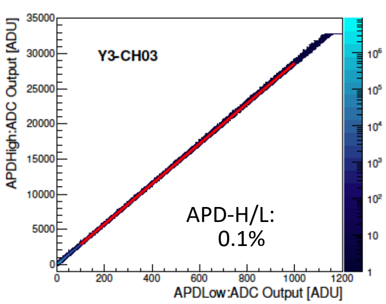
The linearity was calibrated by using UV laser irradiation on ground :
1) The linearity is confirmed in the range of 1.4-2.5 %.
2) The whole dynamic range is confirmed to cover from 1 MIP to 10^6 MIPs.

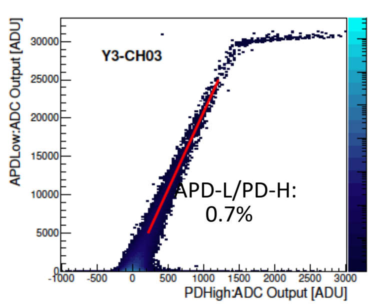
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

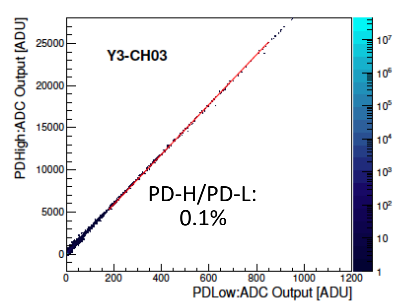
The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel.

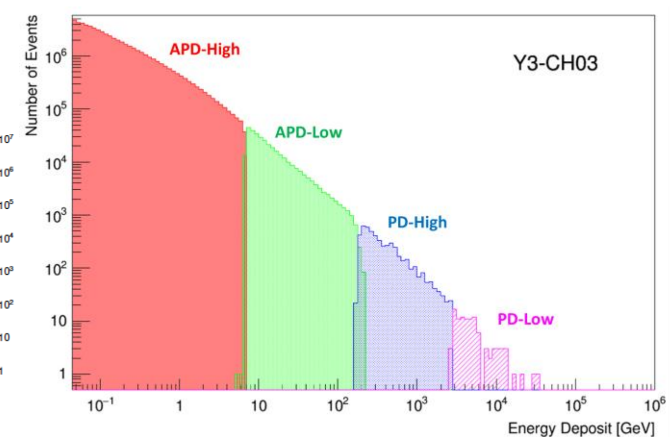
APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%

Example of energy distribution in one PWO log



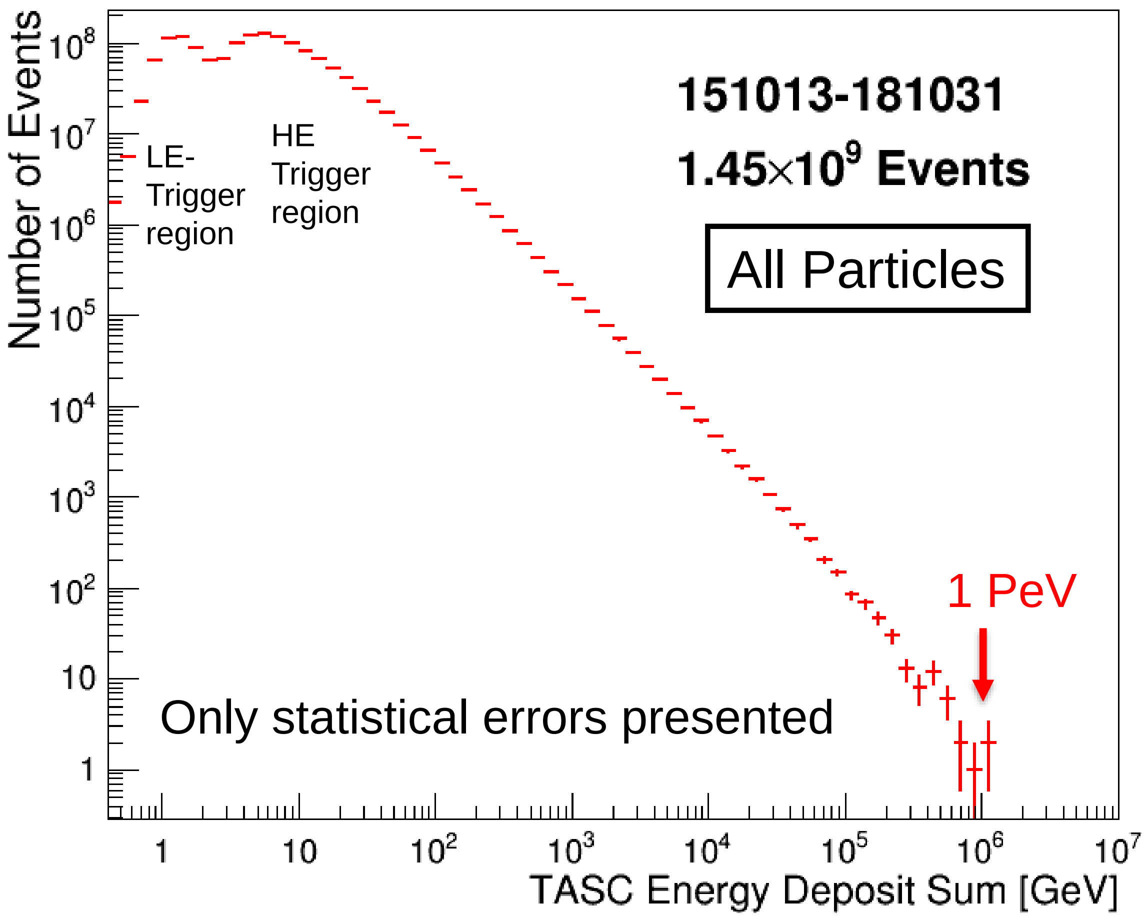




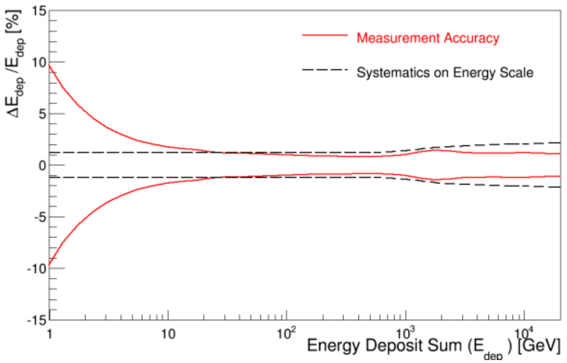


Energy Deposit Distribution of All Triggered-Events

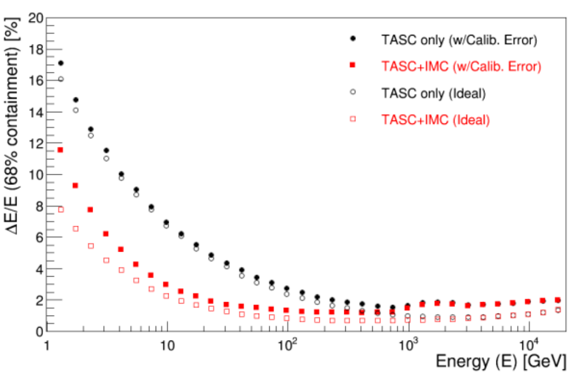
Distribution of deposit energies (ΔE) in TASC



Performance of energy measurement in 1GeV-20TeV



Energy resolution for electrons (TASC+IMC): < 3% over 10 GeV; <2% over 20GeV

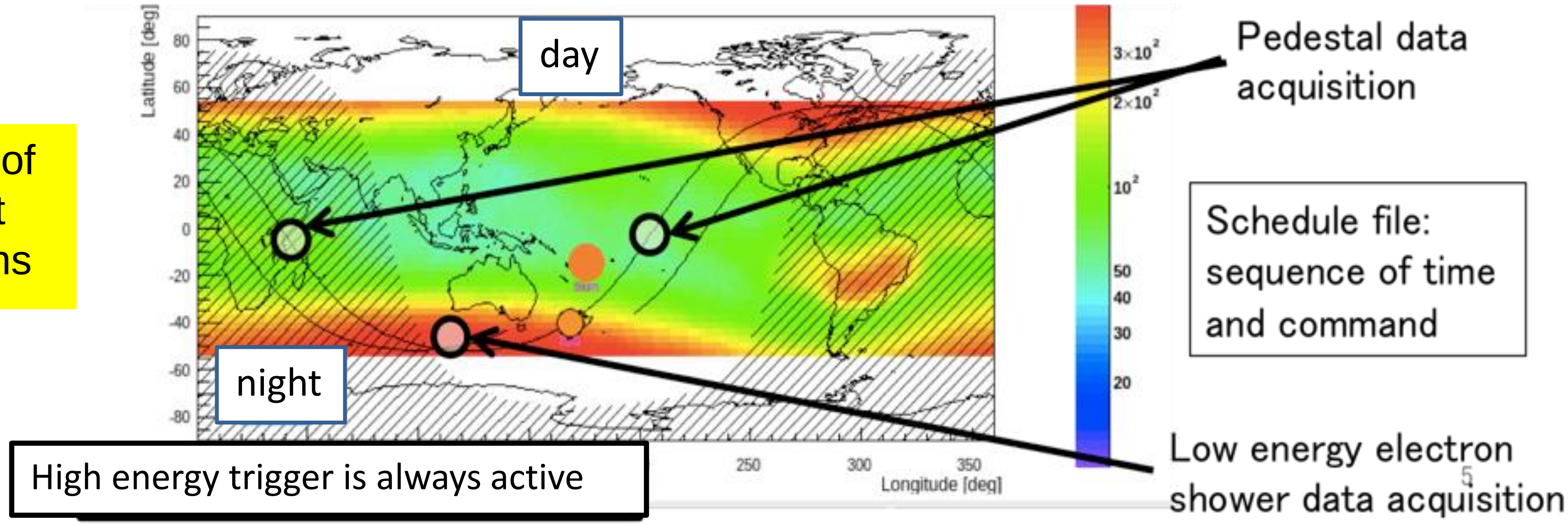


The TASC energy measurements have successfully been carried out in the dynamic range of 1 GeV – 1 PeV.

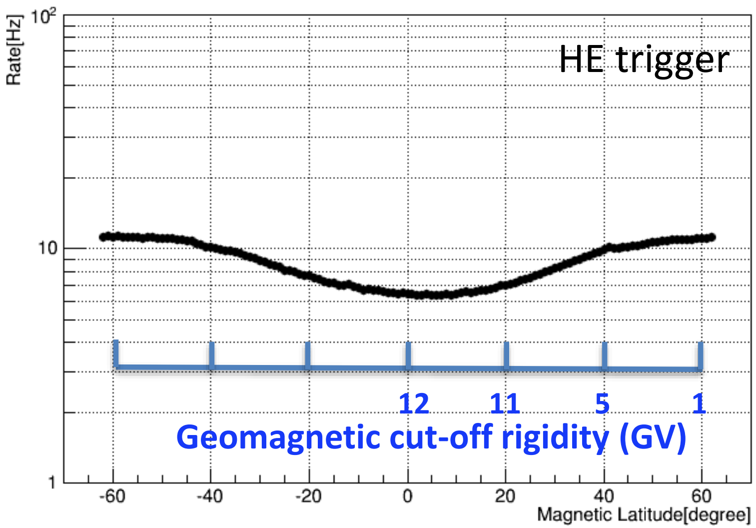
ISS Orbit and CALET On-orbit Operations

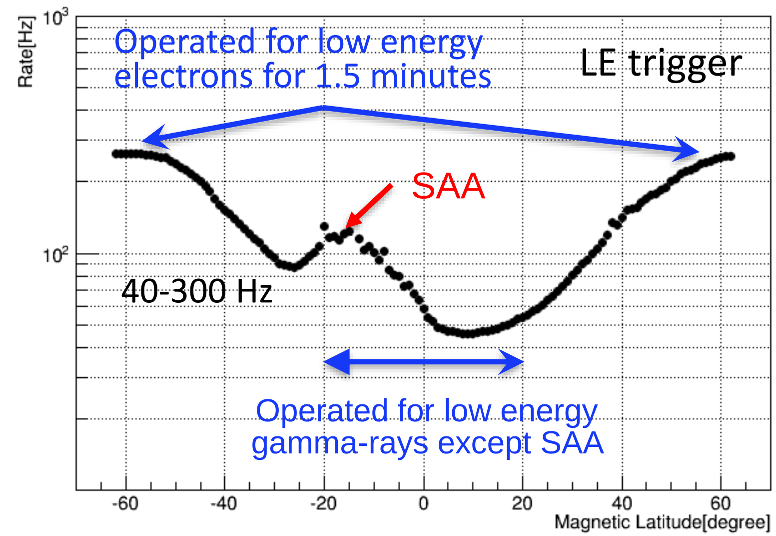
ISS orbit: inclination 51.6 degree, ~400 km

Concept of on-orbit operations



Dependence of the count rate on geomagnetic latitude

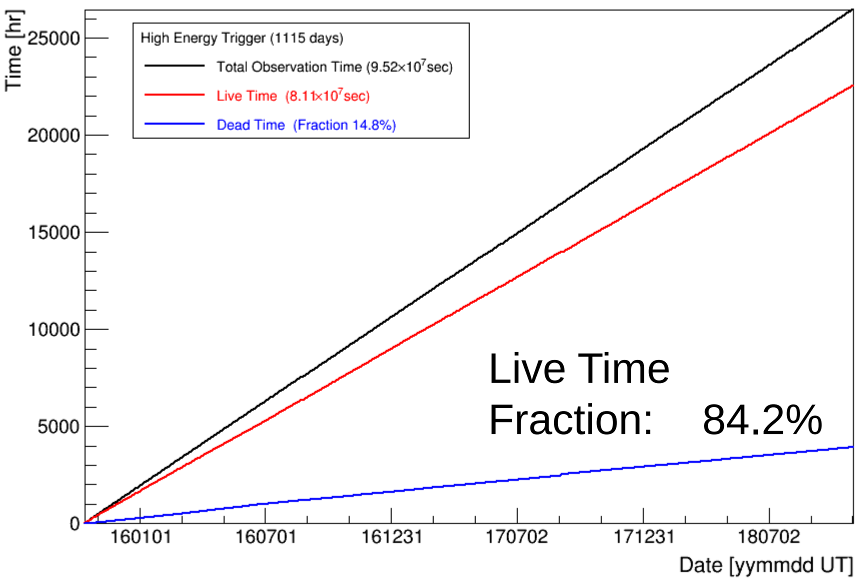




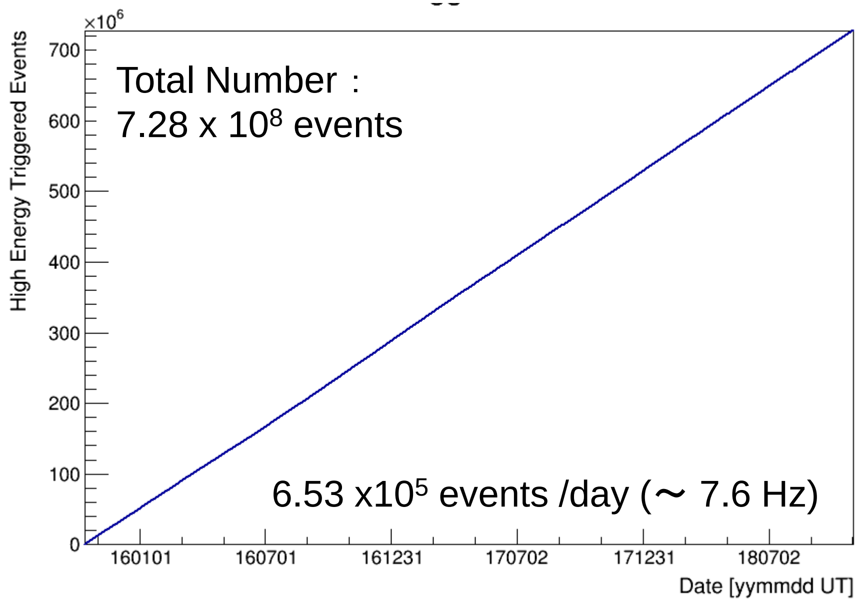
Observation with High Energy Trigger (>10GeV)

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

Accumulated observation time (live, dead)



Accumulated triggered event number



Observation by High Energy Trigger for 1115 days : Oct.13, 2015 – Oct. 31, 2018

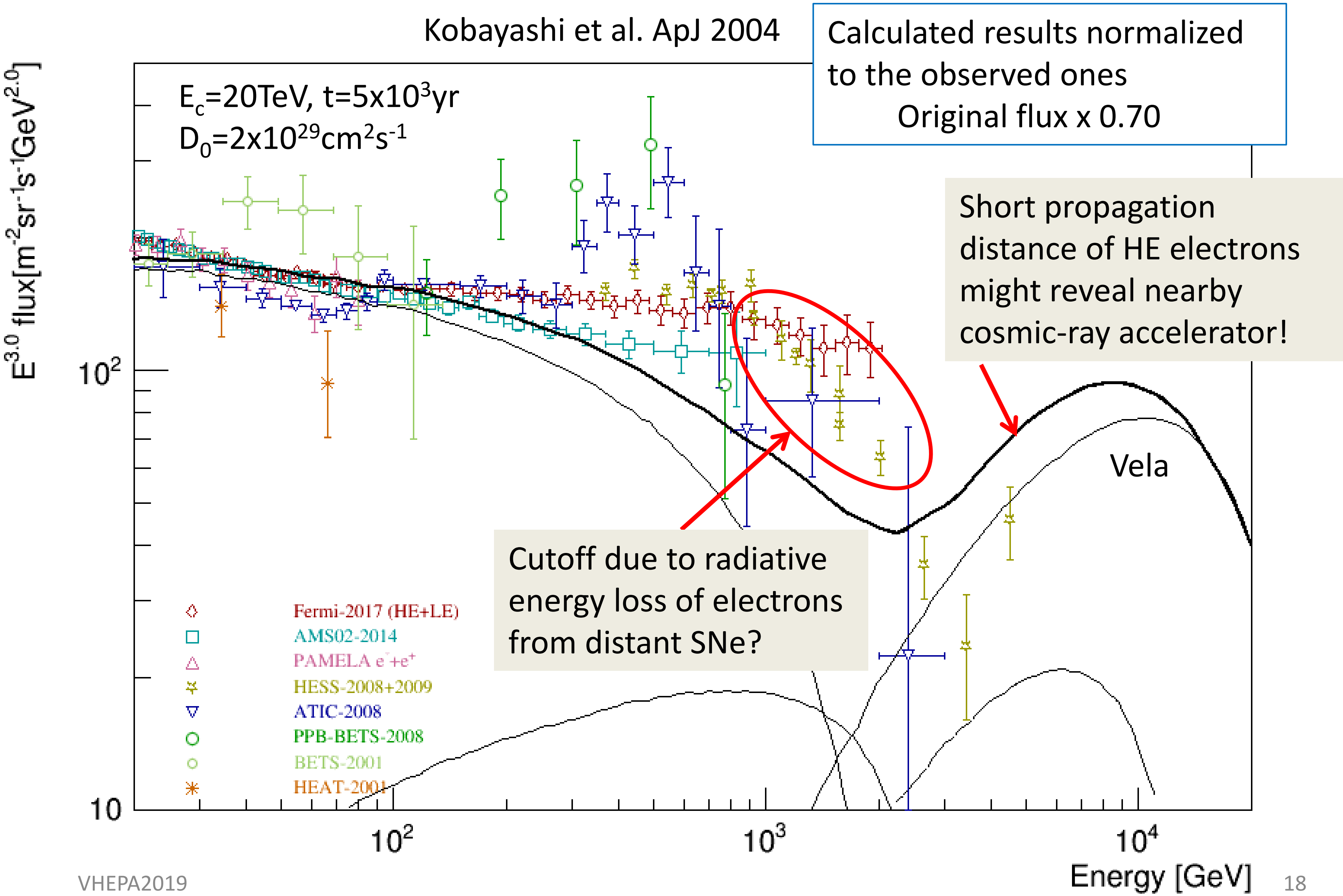
- The exposure, SΩT, has reached to ~97.6 m^2 sr day for electron observations by continuous and stable operations.
- Total number of triggered events is ~730 million with a live time fraction of 84.2 %.

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

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

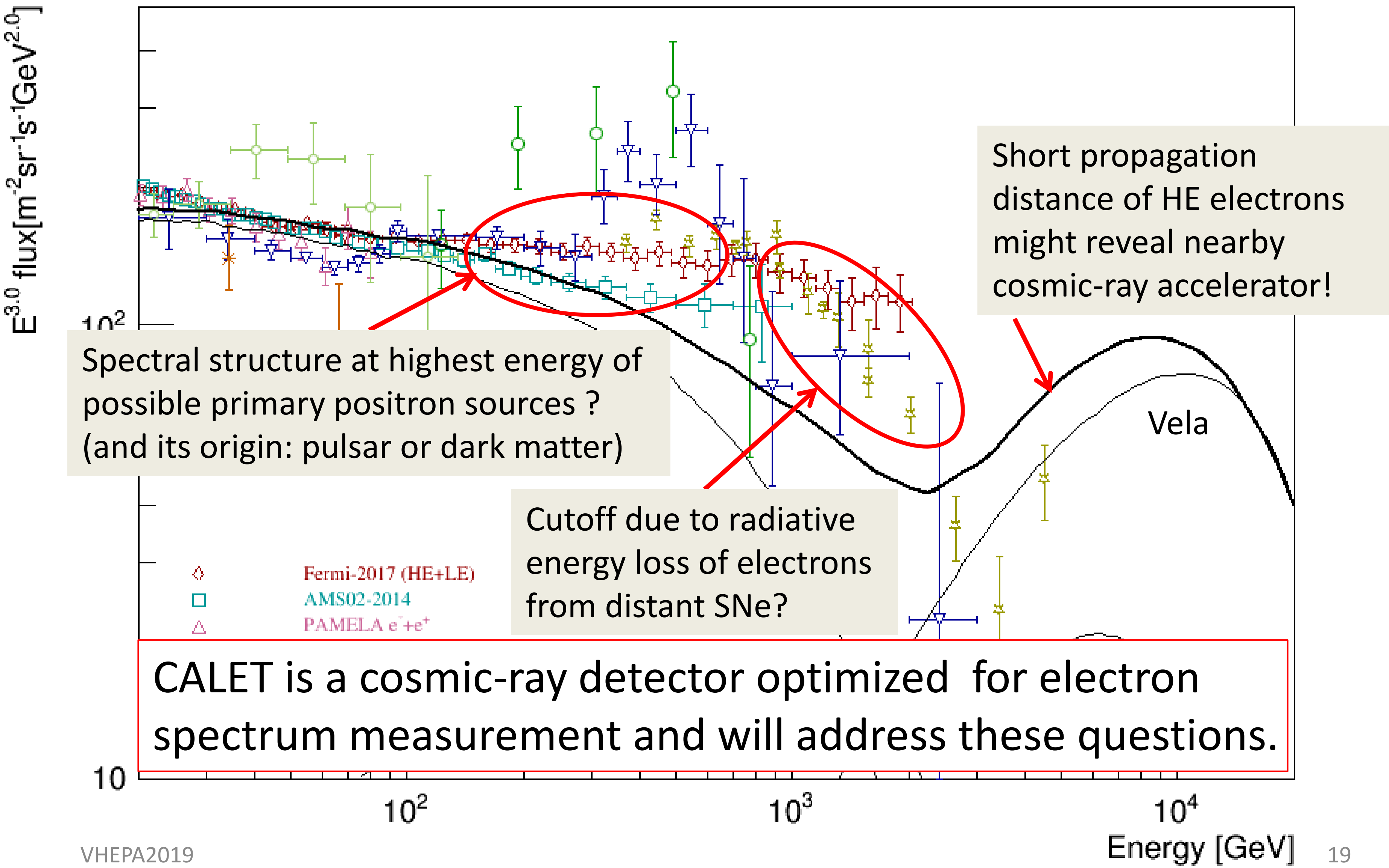
O.Adriani et al. (CALET collaboration), Phys. Rev. Lett. 120 (2018) 261102

Cosmic-Ray All-Electron Spectrum ($e^{+}+e^{-}$)



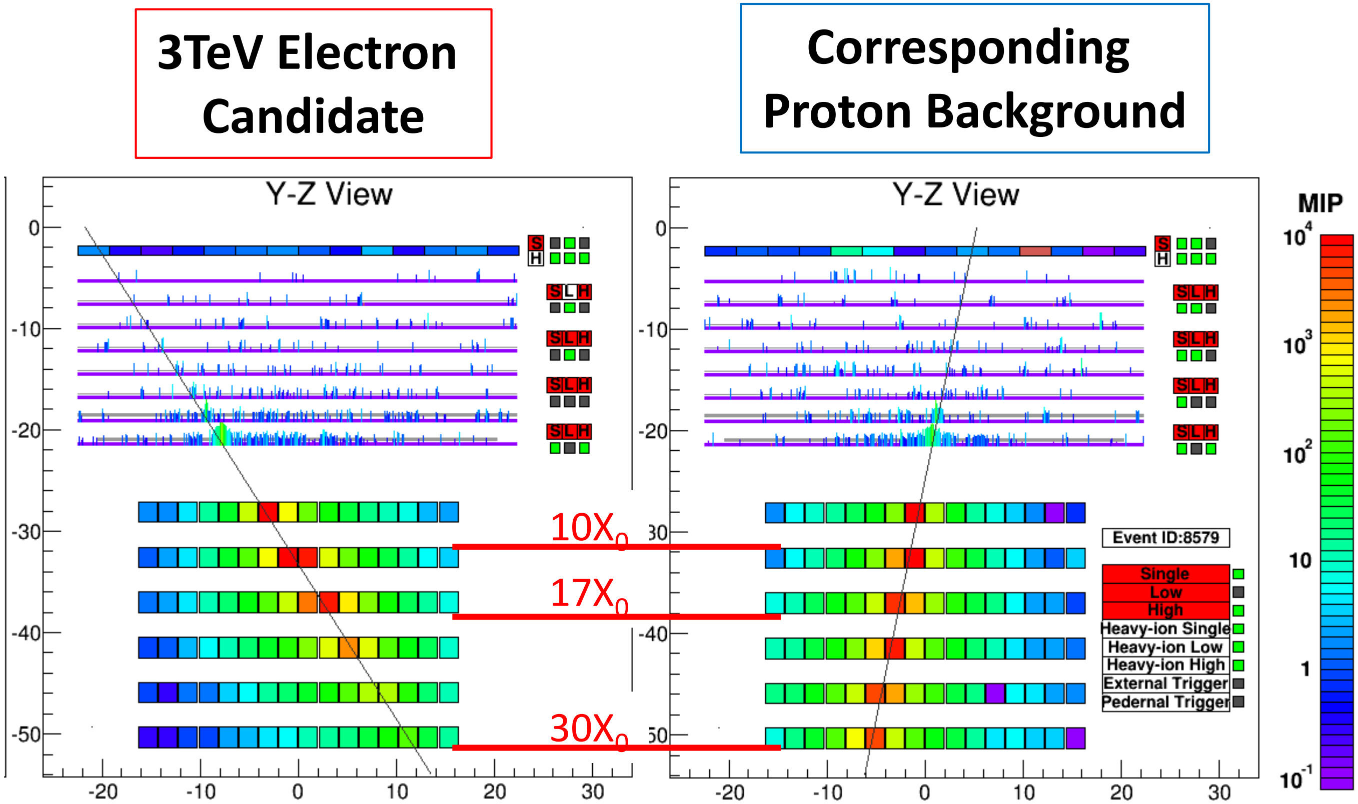
Cosmic-Ray All-Electron Spectrum ($e^+ + e^-$)

Possible fine structures in all-electron (electron + positron) spectrum



CALET is a cosmic-ray detector optimized for electron spectrum measurement and will address these questions.

All-Electron (electron + positron) Analysis



(Flight data; detector size in cm)

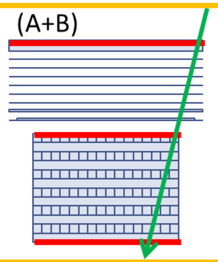
1. **Reliable tracking**
   well-developed shower core
2. **Fine energy resolution**
   full containment of TeV showers
3. **High-efficiency electron ID**
   $30X_0$ thickness, closely packed logs

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

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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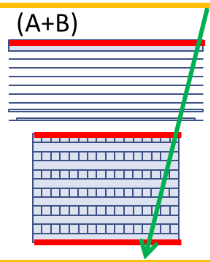

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3. Single Charge Selection
4. Track Quality Cut
5. Shower Development Consistency
6. Electron Identification
    1. Simple two parameter cut
    2. Multivariate Analysis using Boosted Decision Trees (BDT)

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

Electron Identification

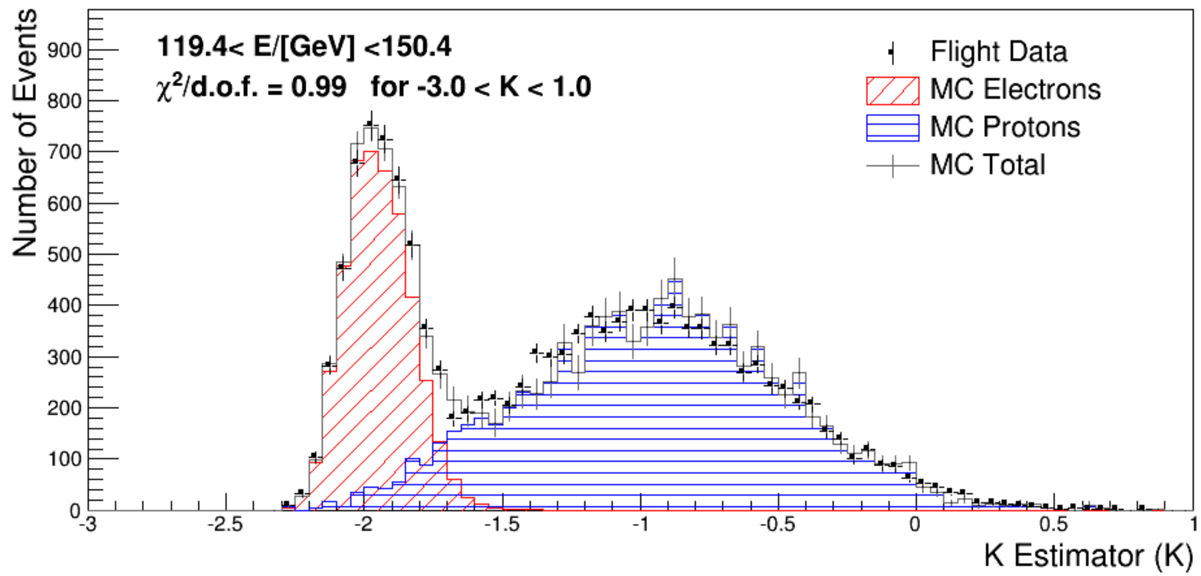
Simple Two Parameter Cut

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

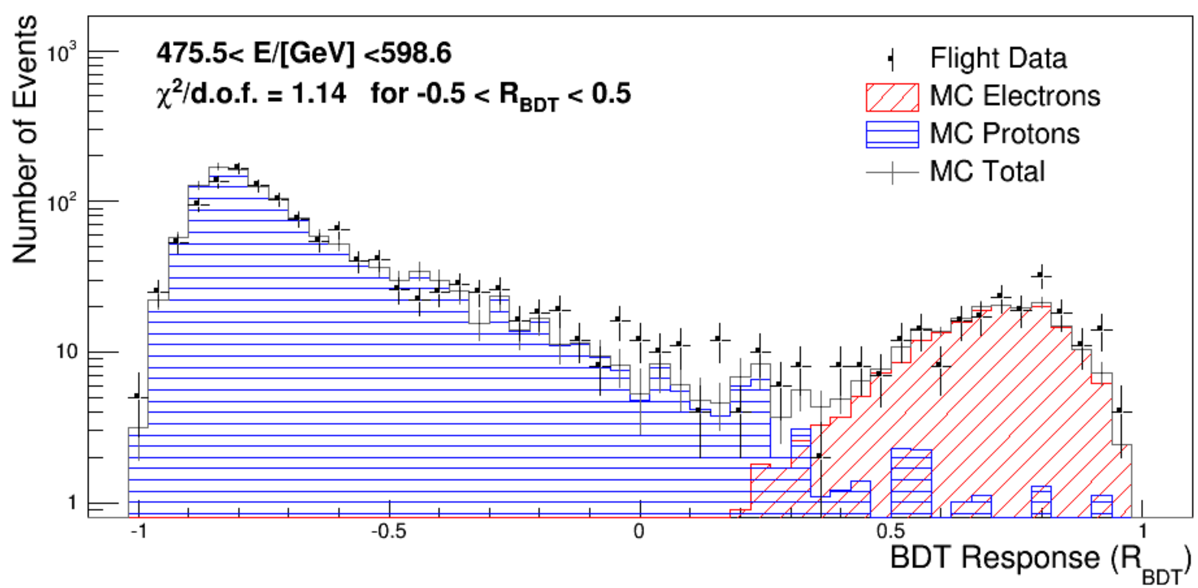
Separation Parameter K is defined as follows:

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

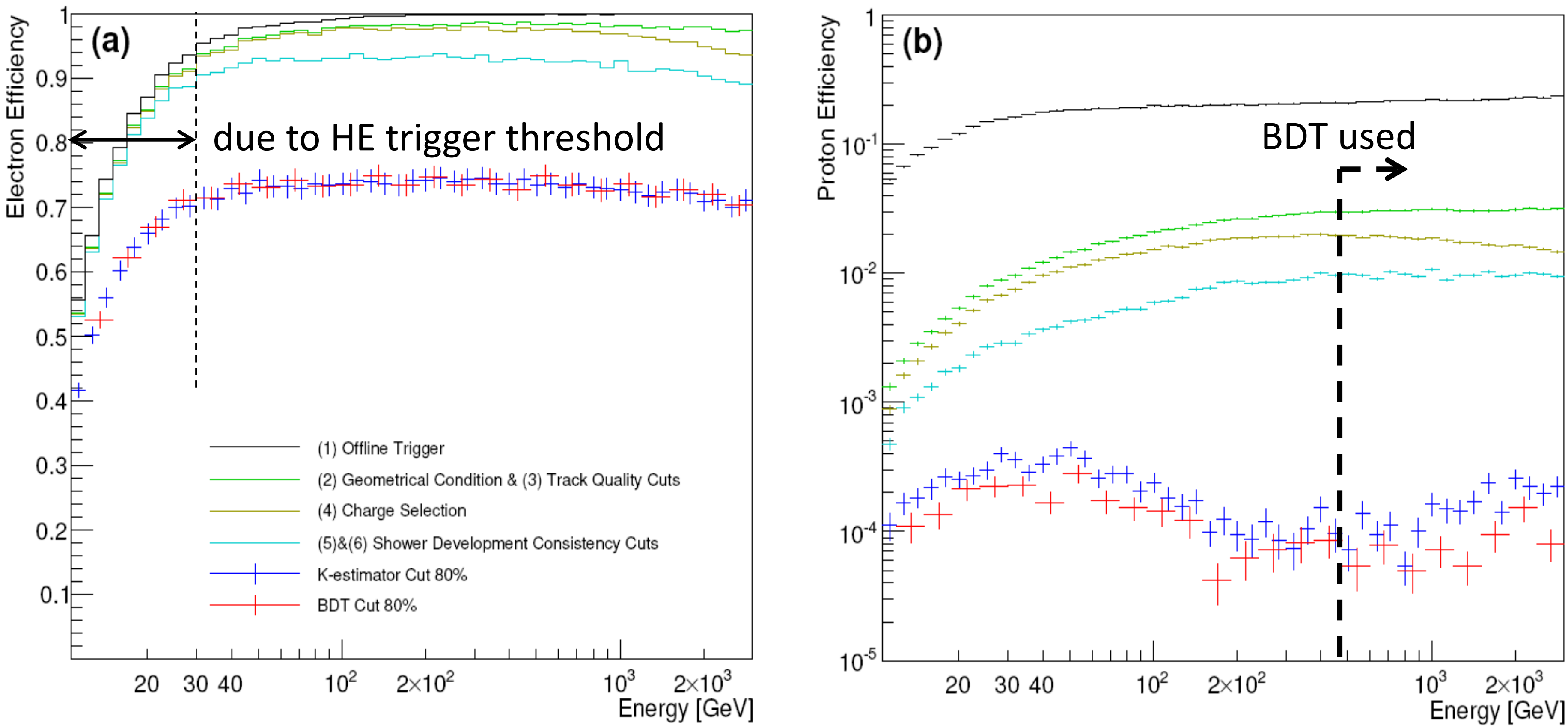


Boosted Decision Trees

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

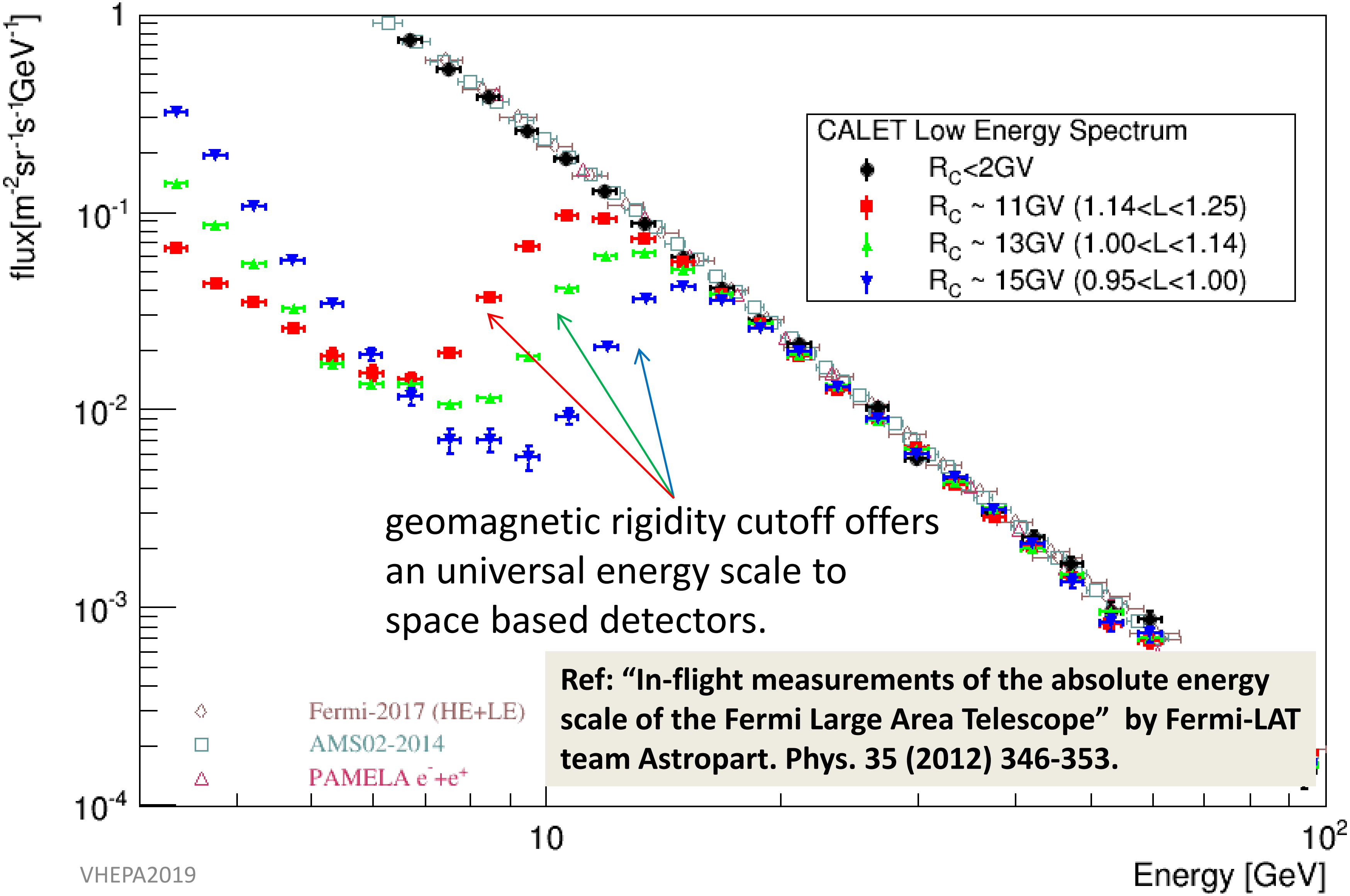


Electron Efficiency and Proton Rejection



- 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 <15% in the 1—3 TeV region.

Absolute Calibration of Energy Scale using Geomagnetic Rigidity Cutoff

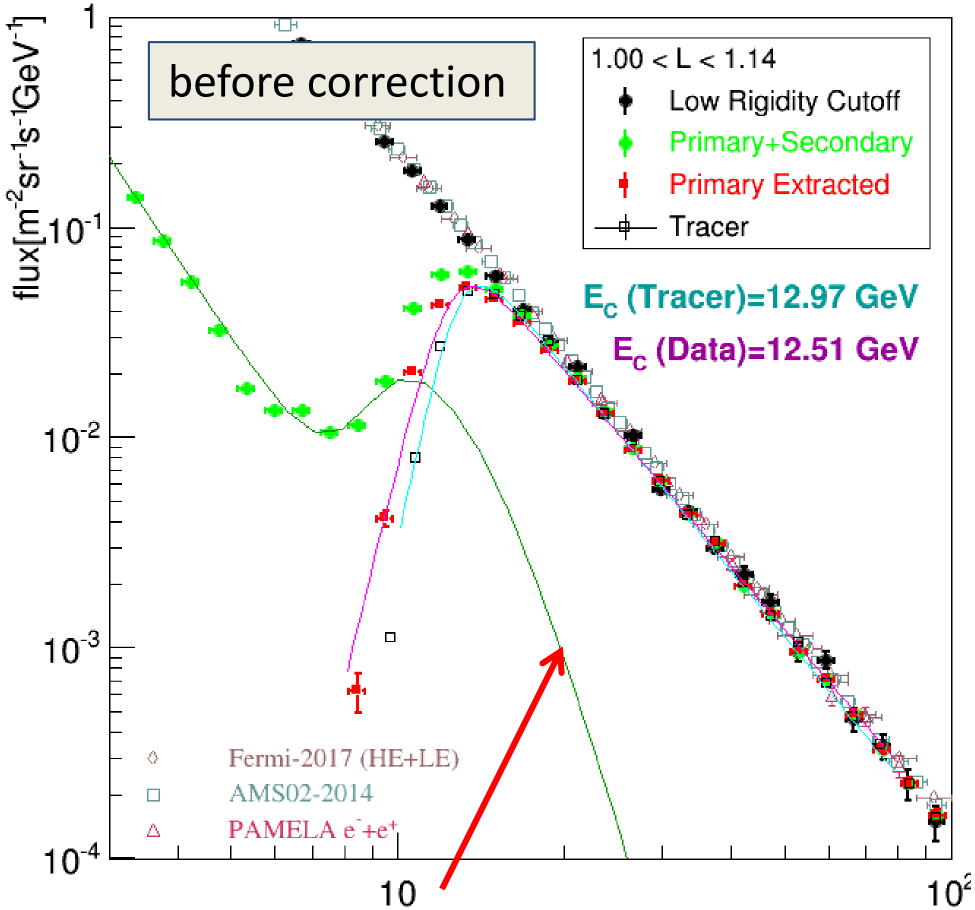


geomagnetic rigidity cutoff offers an universal energy scale to space based detectors.

Ref: "In-flight measurements of the absolute energy scale of the Fermi Large Area Telescope" by Fermi-LAT team Astropart. Phys. 35 (2012) 346-353.

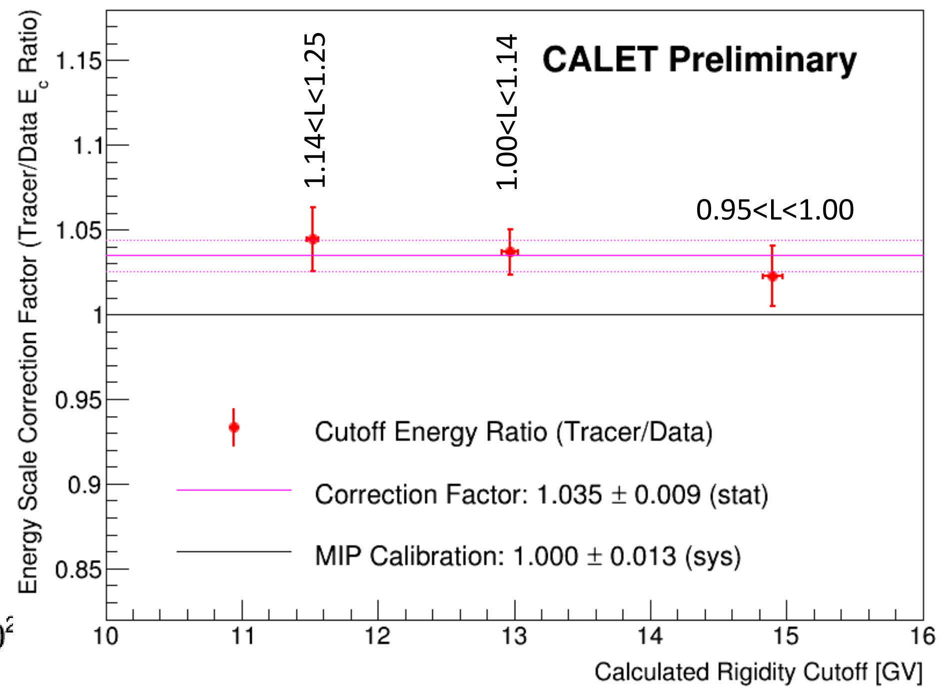
Cutoff Rigidity Measurements and Comparison with Calculation

Measured cutoff rigidity is compared with calculated one (denoted as Tracer) which trace particle in earth's magnetic field (IGRF12).



Secondary component is estimated using azimuthal distributions

- Same analysis performed in 3 different rigidity cutoff regions.



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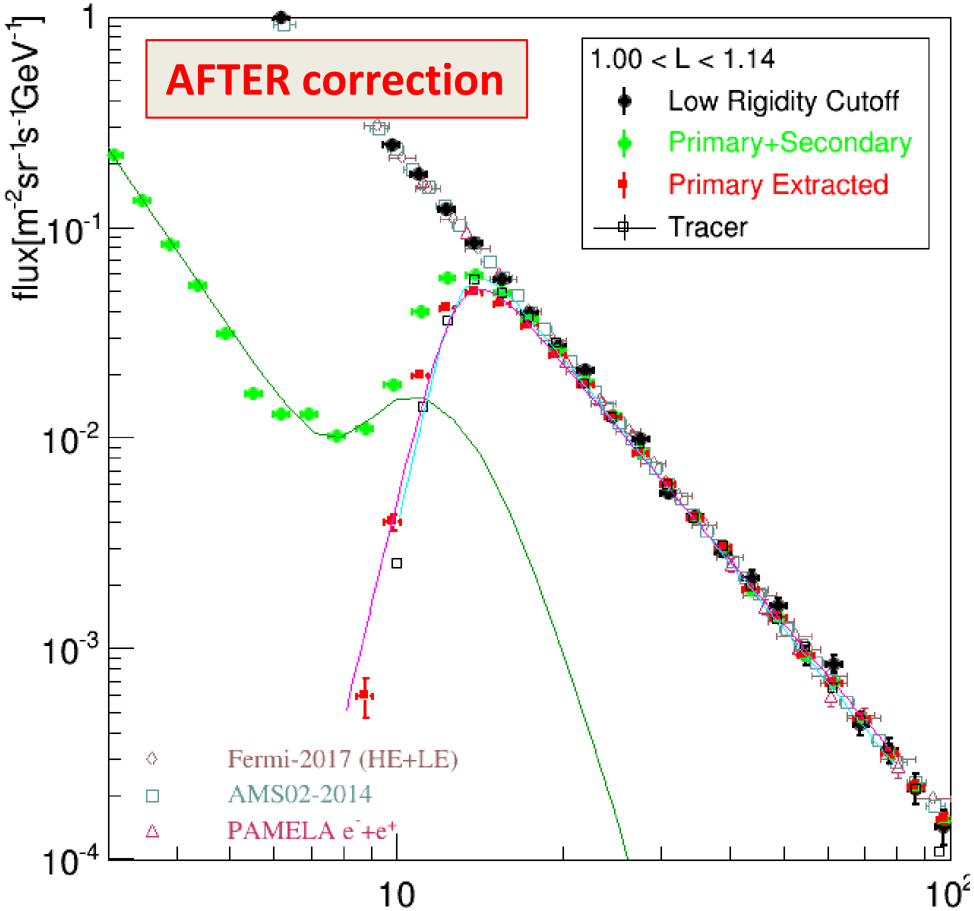
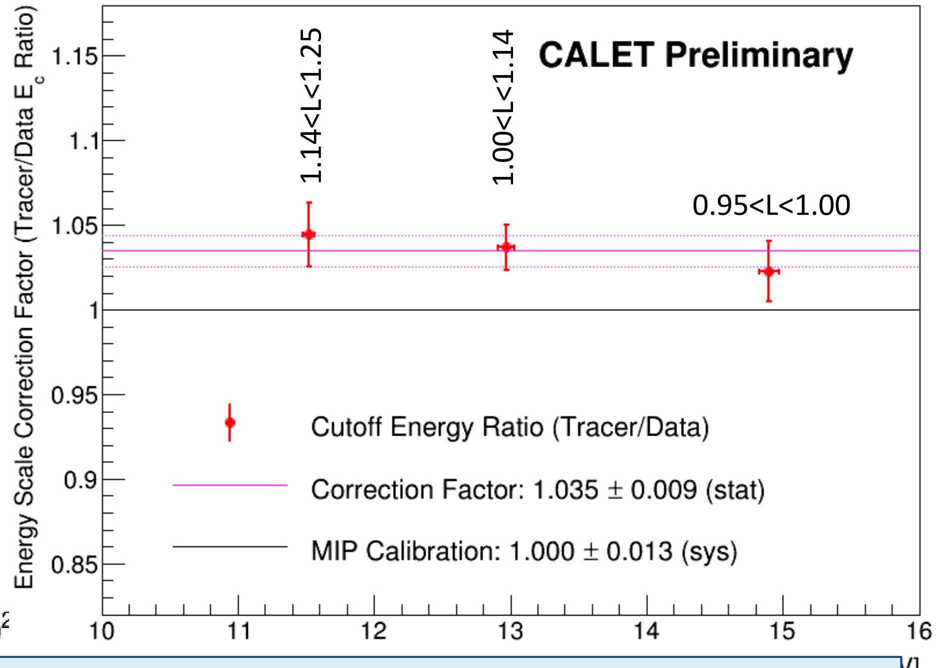


- Same analysis performed in 3 different rigidity cutoff regions.

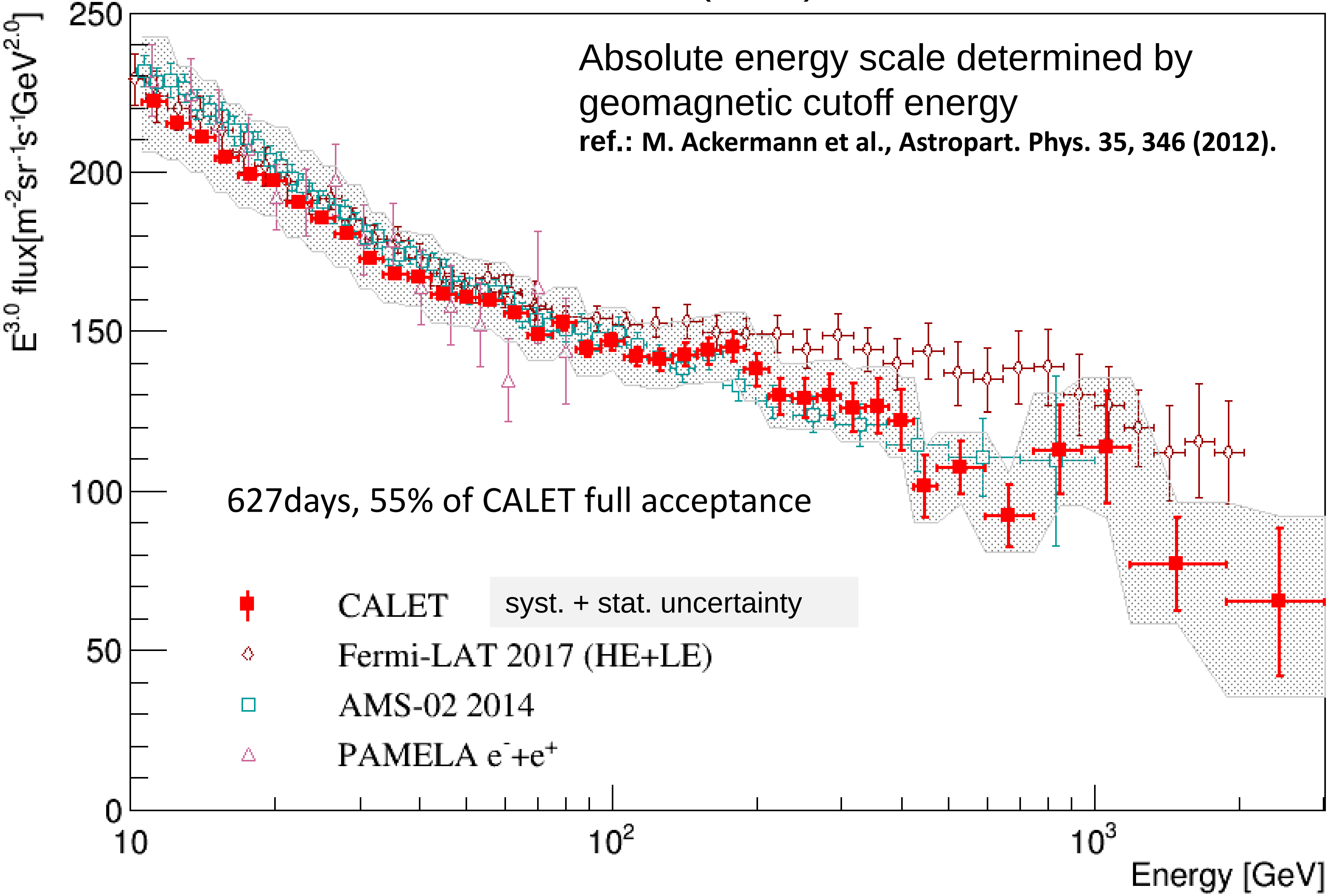
⇒ Correction factor was found to be **1.035** compared to MIP calibration.



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

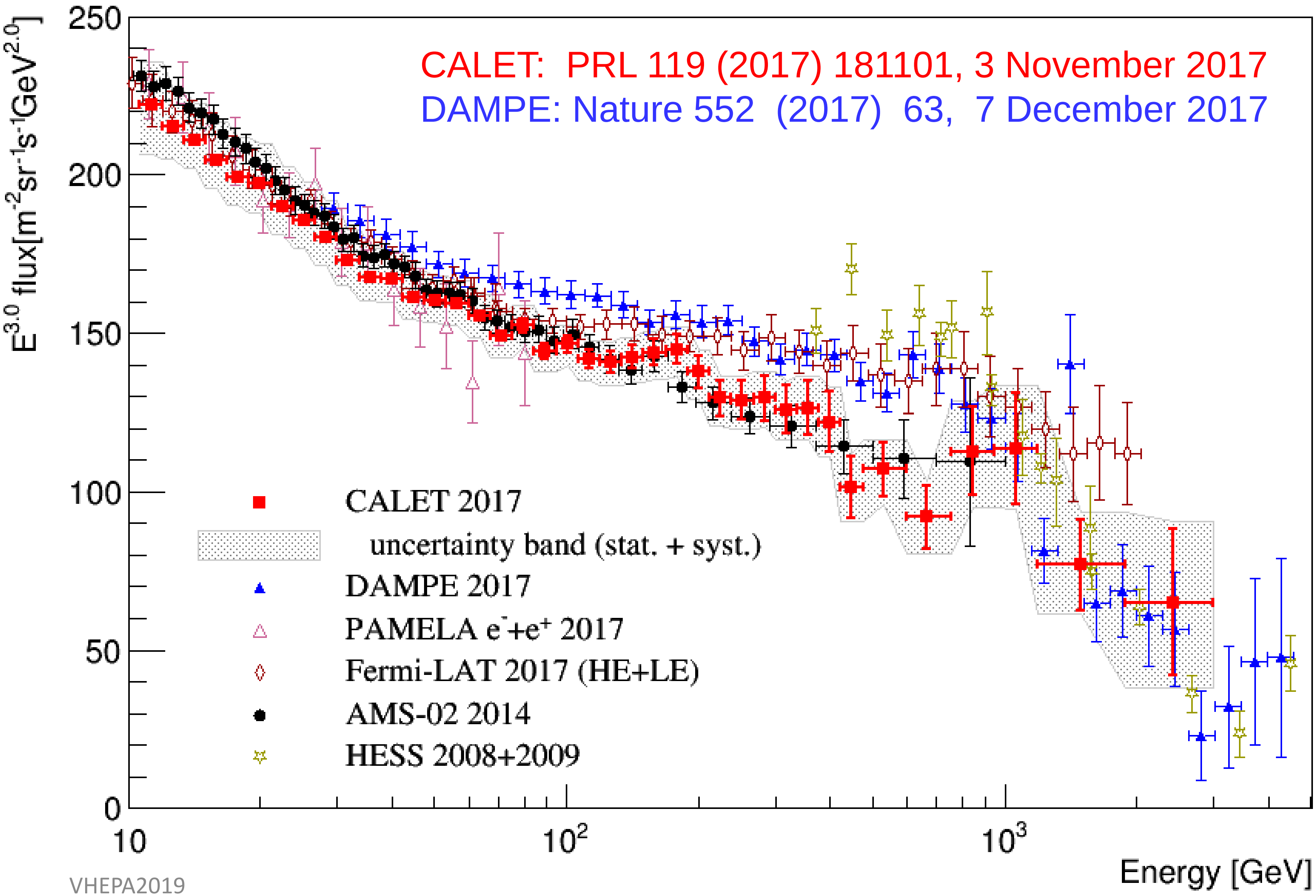
All-Electron Spectrum Measured with CALET from 10 GeV to 3 TeV

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



All-Electron Spectrum Comparison w/ DAMPE

and other space based experiments



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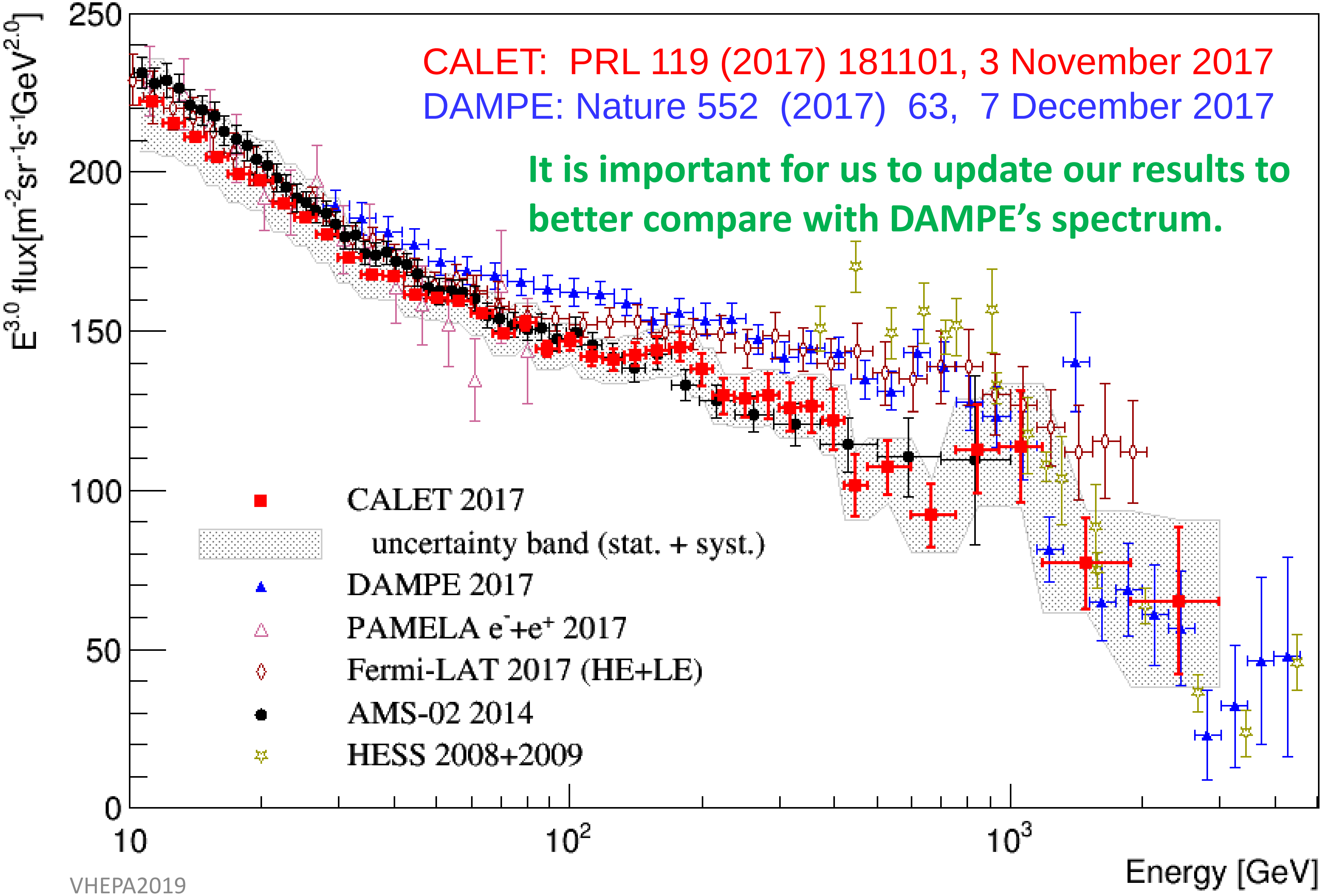
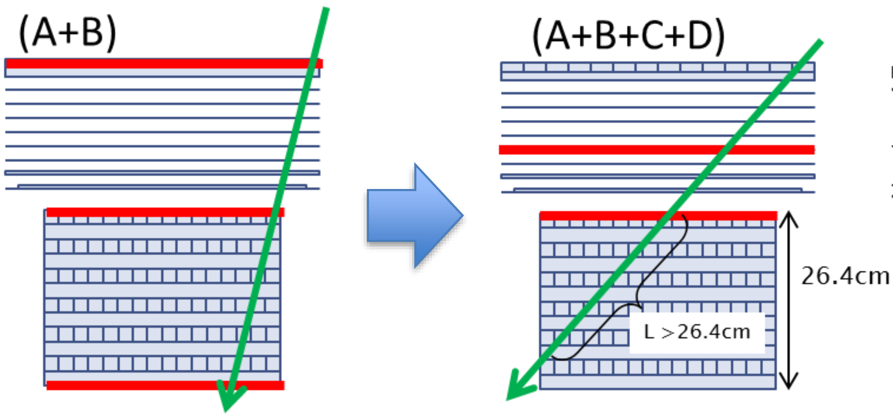
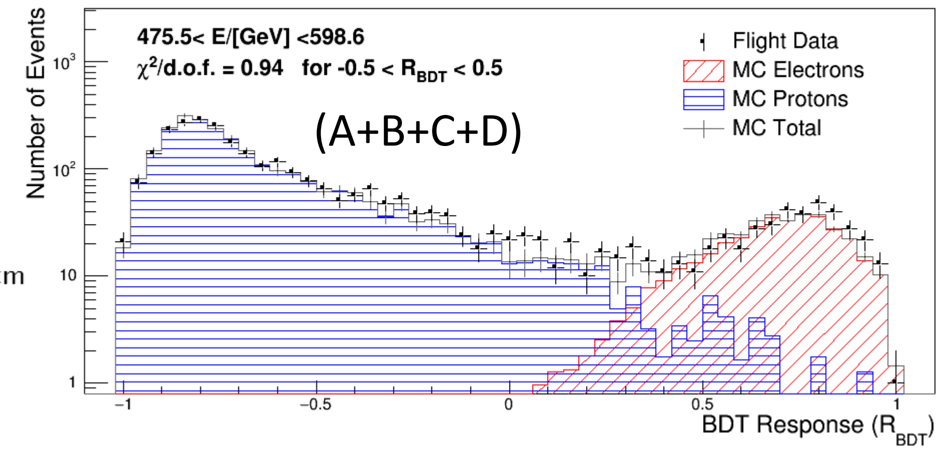


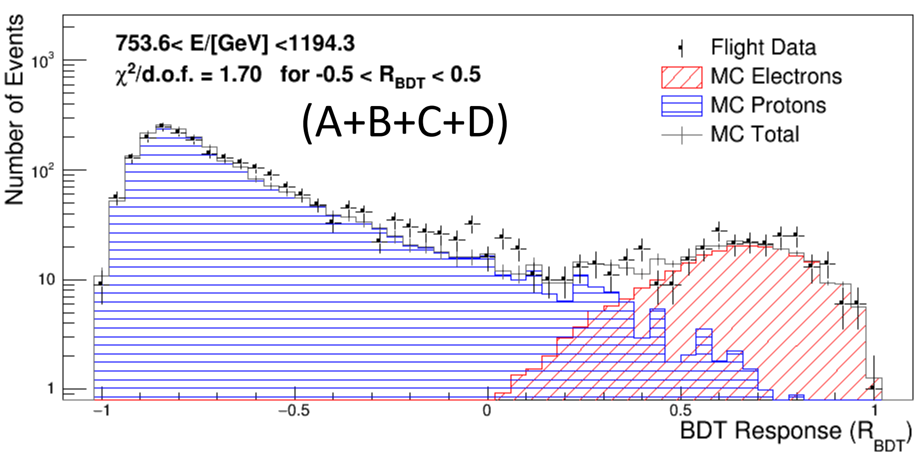
Extending the Analysis to Full Acceptance

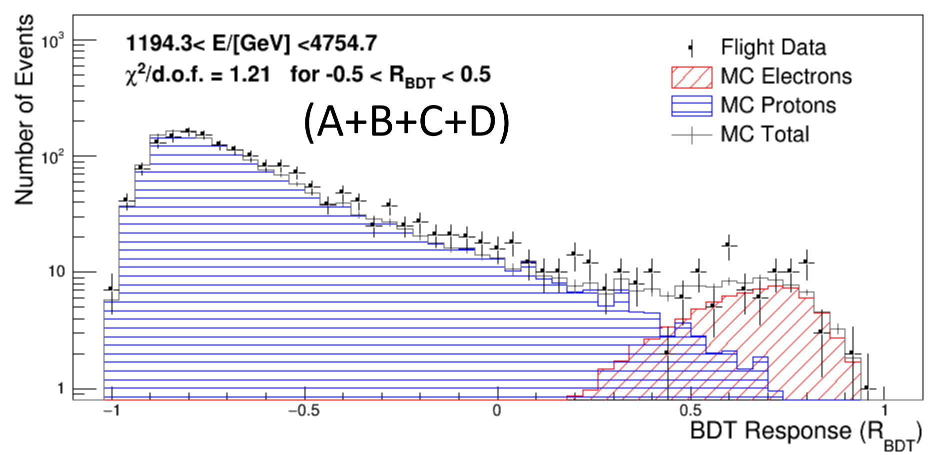
Analyzed Flight Data:

- 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)









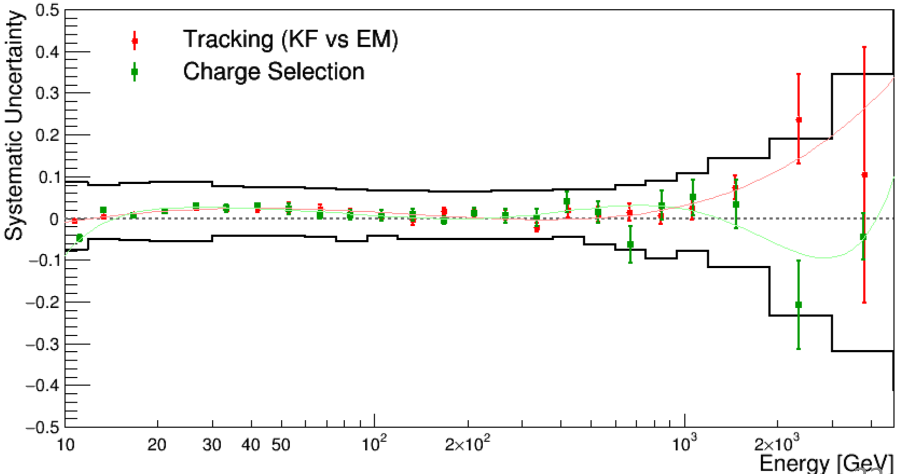
Systematic Uncertainties

(other than energy scale uncertainty)

The energy scale uncertainty does not have energy dependence, because of the full containment of the EM showers well into the TeV region. Errors due to calibration of lower gain ranges are found to be negligible.

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)



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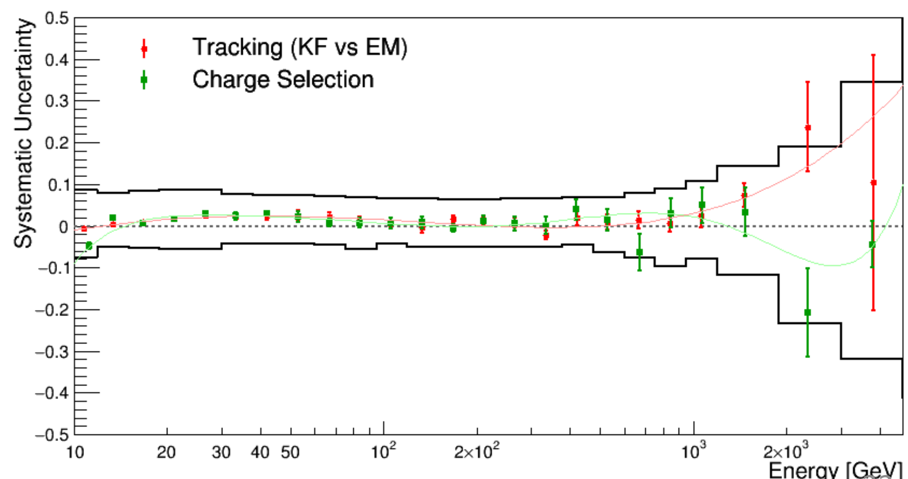
1. Divided into 4 sub-periods (195days each)
2. spectrum in each sub-period is compared with the one from the whole period.
3. standard deviation of the relative difference distribution is taken as systematic uncertainty (1.4%)



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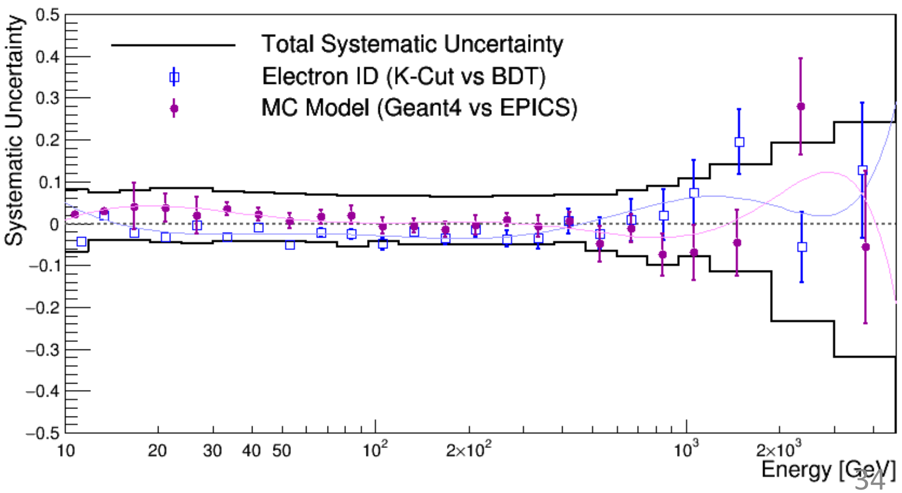

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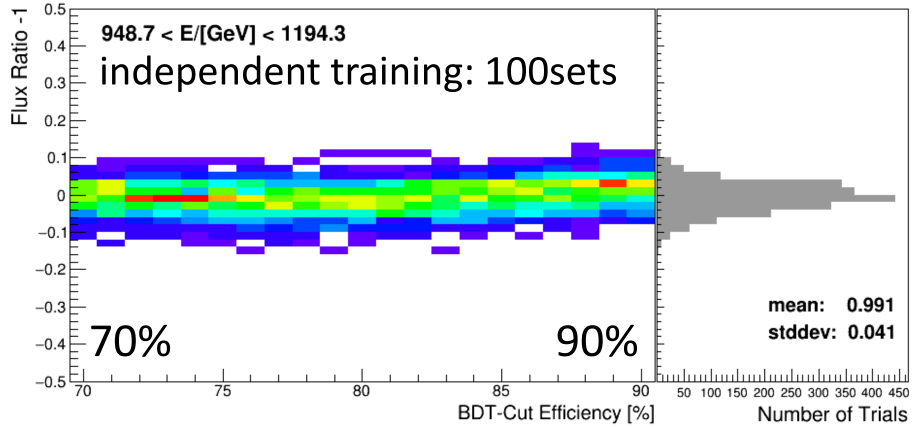
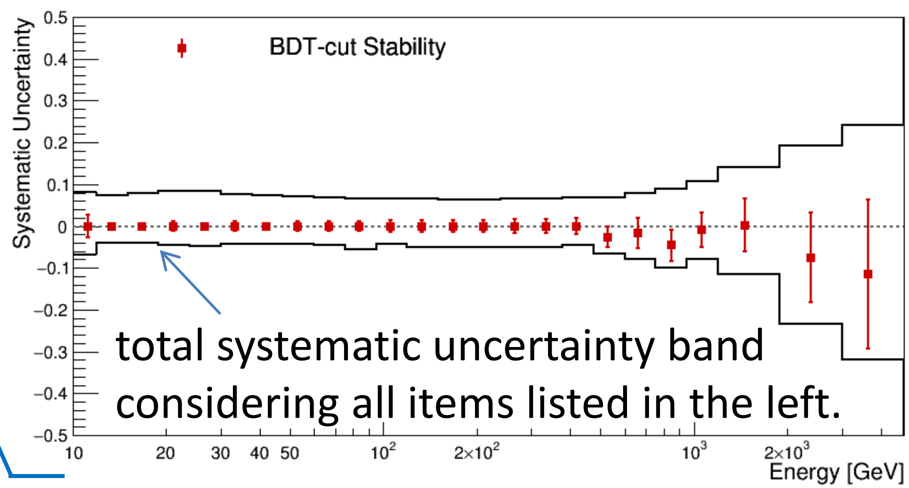
Flux Ratio vs Efficiency for BDT @ 1TeV

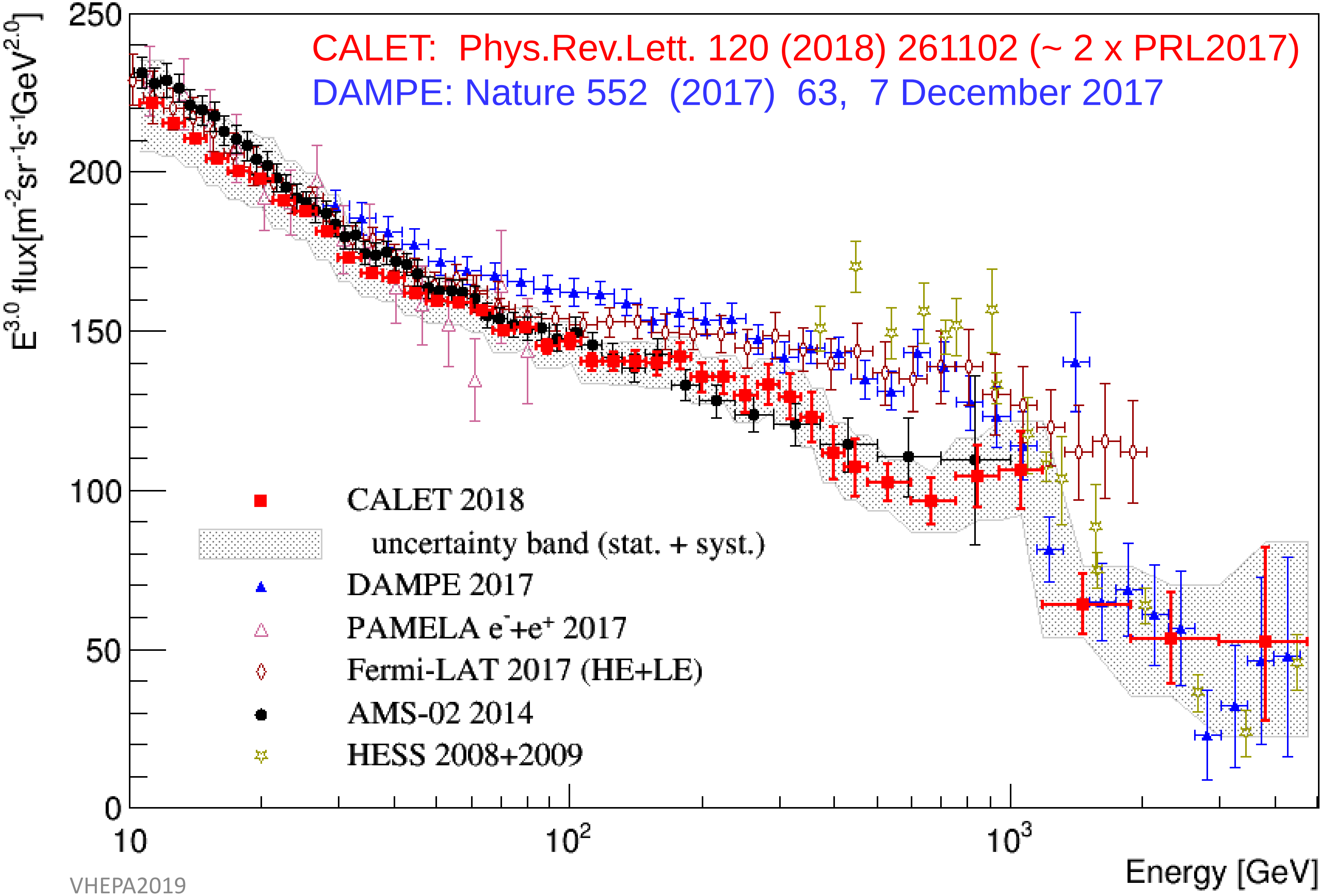


Energy Dependence of BDT stability



Extended Measurement by CALET

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



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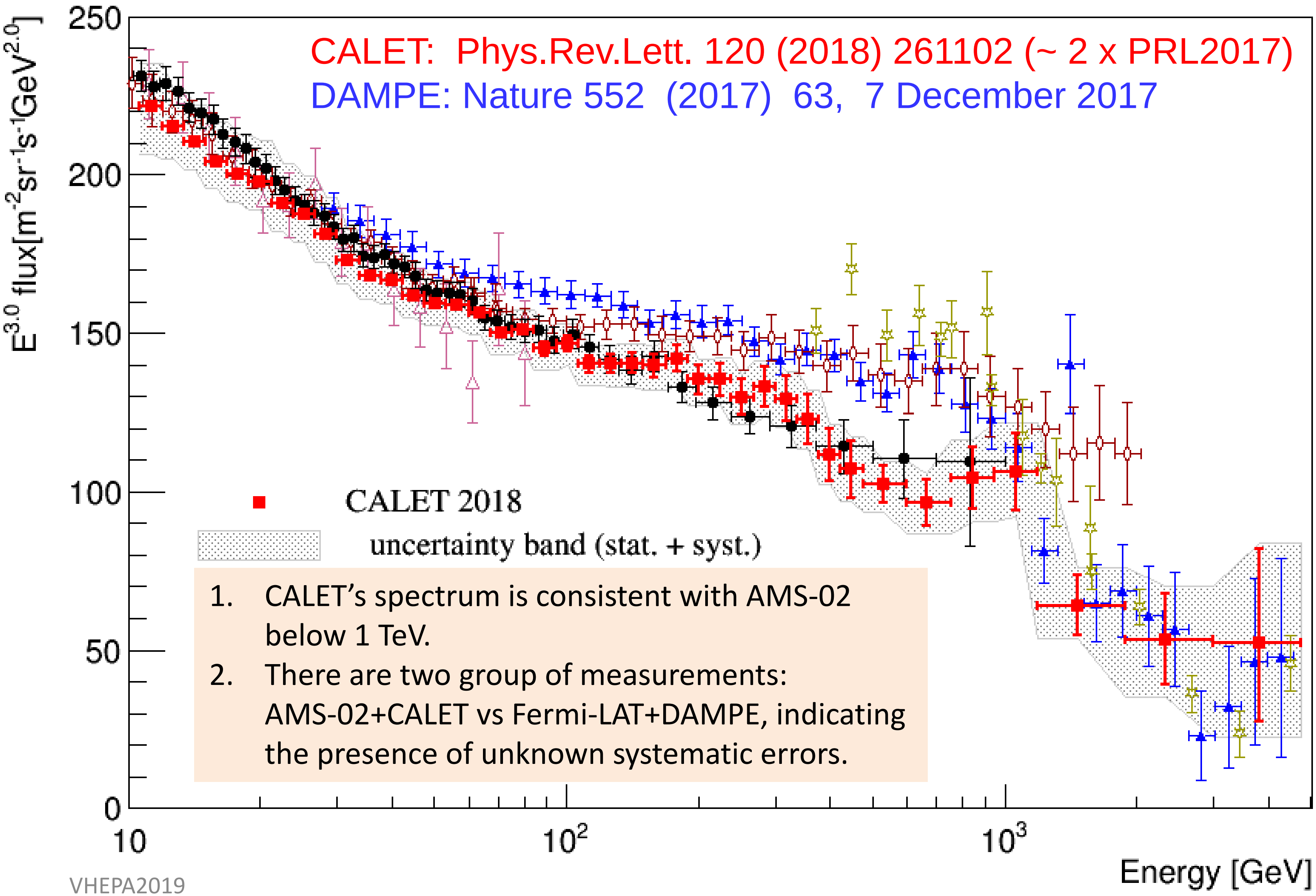

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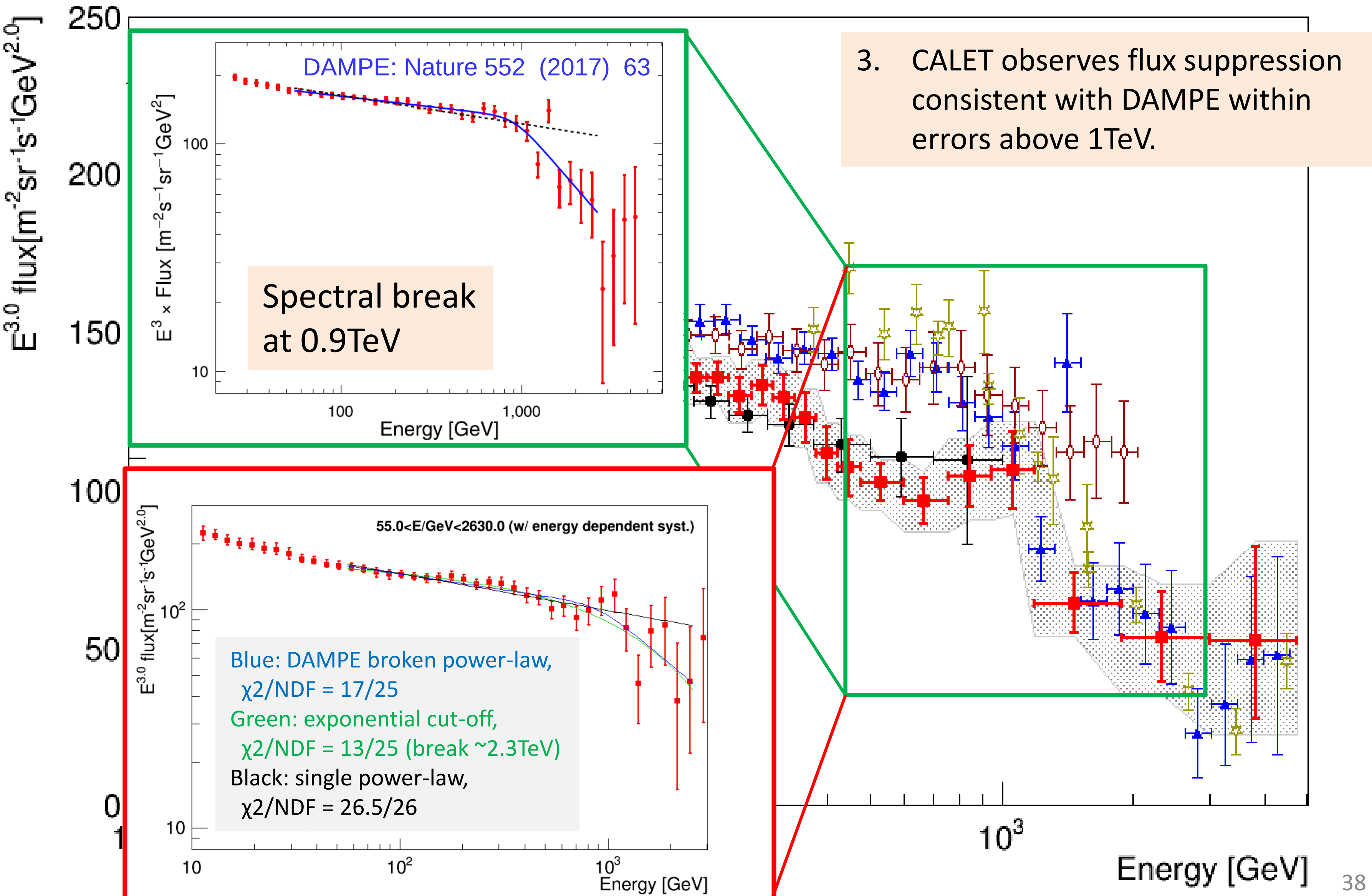
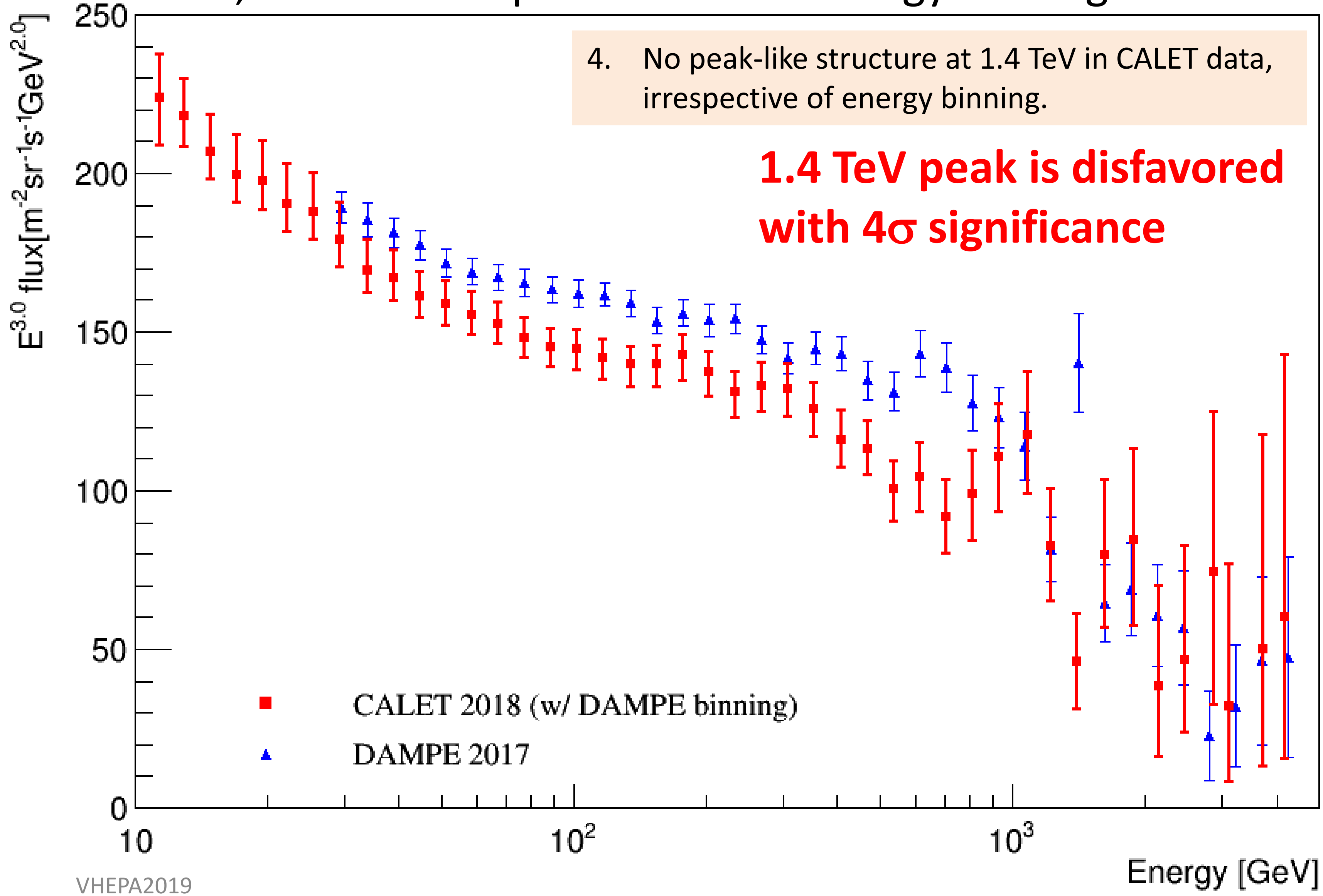


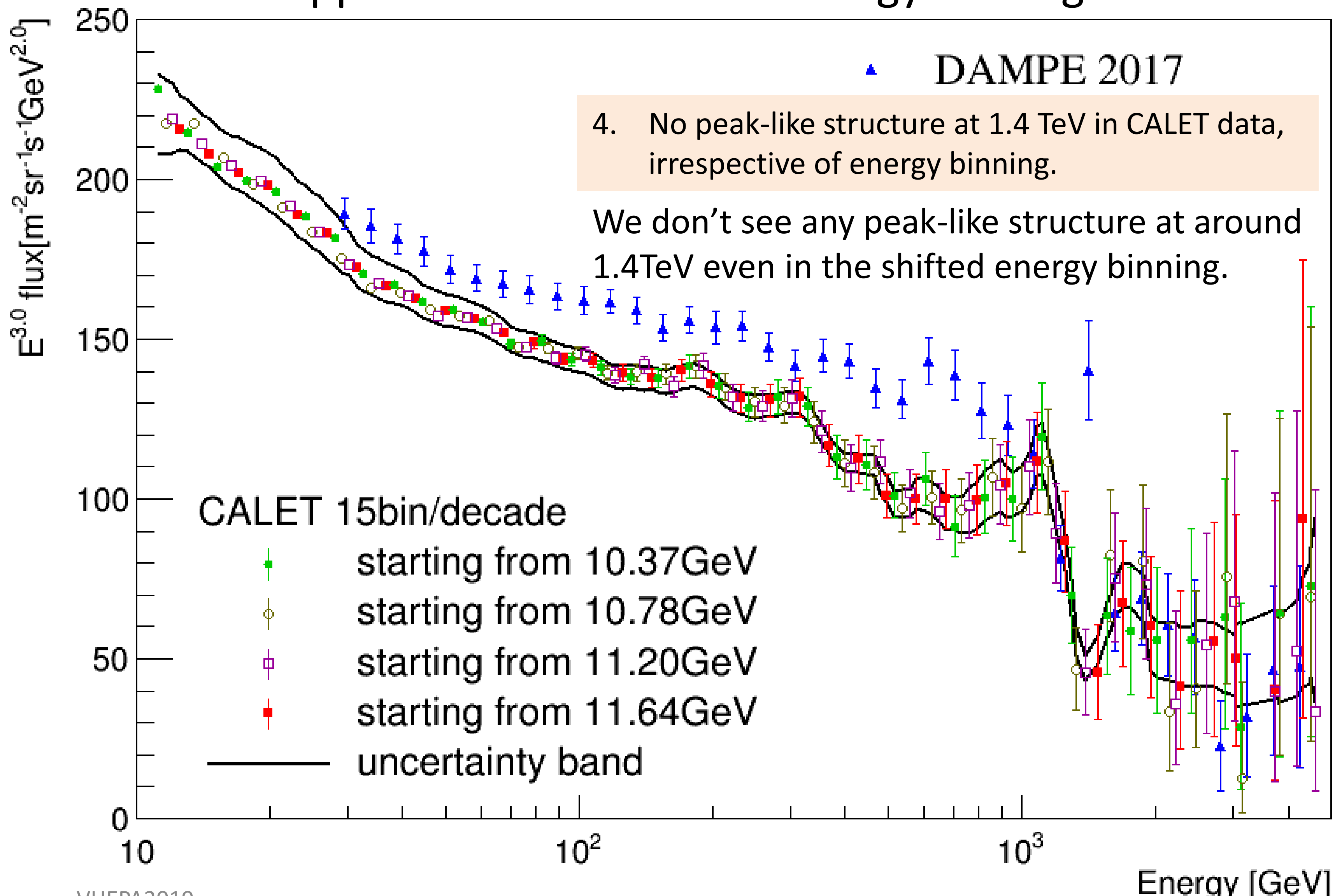
Comparison with DAMPE's result

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



Comparison with DAMPE's result

What happens if we shifted our energy binning…



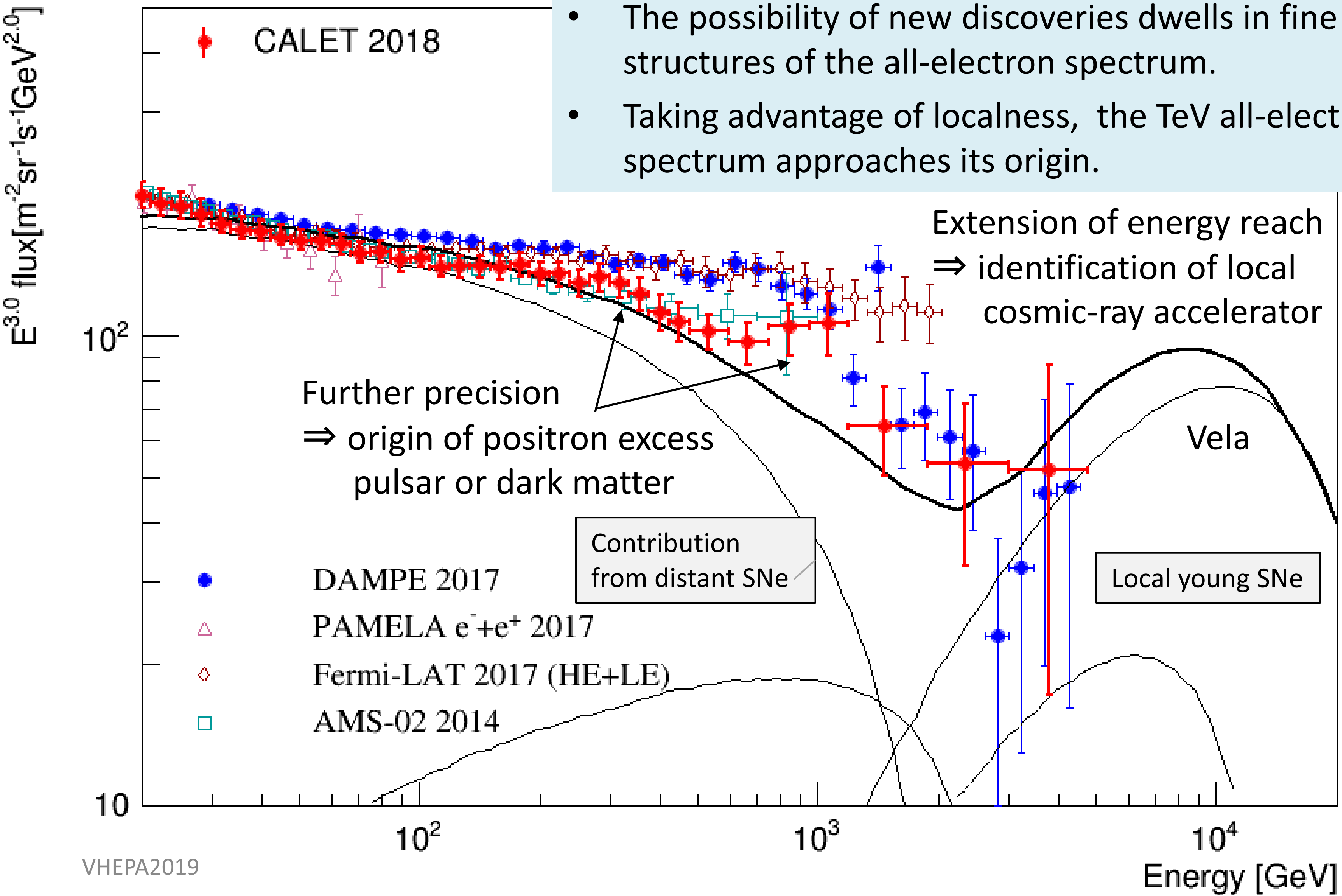
4. No peak-like structure at 1.4 TeV in CALET data, irrespective of energy binning.

We don't see any peak-like structure at around 1.4TeV even in the shifted energy binning.

Prospects for CALET All-Electron Spectrum

Five years or more observations ⇒ 3 times more statistics, reduction of systematic errors

- The possibility of new discoveries dwells in fine structures of the all-electron spectrum.
- Taking advantage of localness, the TeV all-electron spectrum approaches its origin.

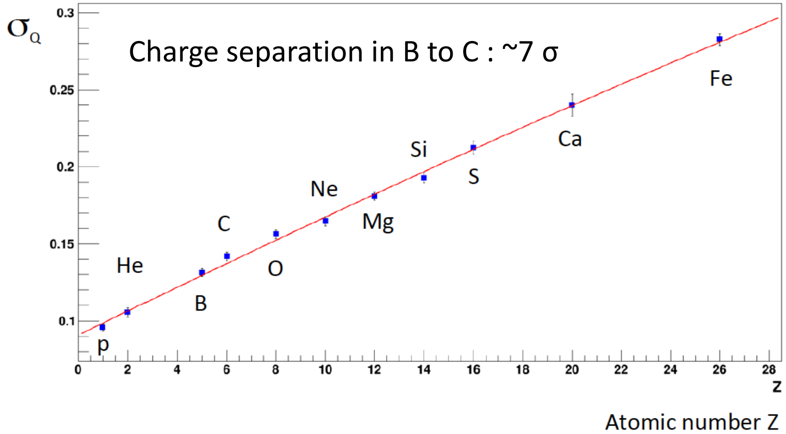


Hadrons

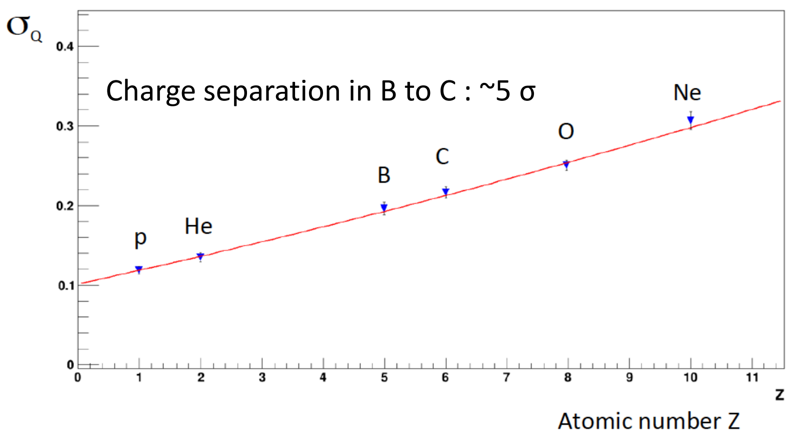
Preliminary Nuclei Measurements (p, He, Z ≤ 8)

P.S.Marrocchesi et al., ICRC 2017, PoS 205.

CHD charge resolution (2 layers combined) vs. Z

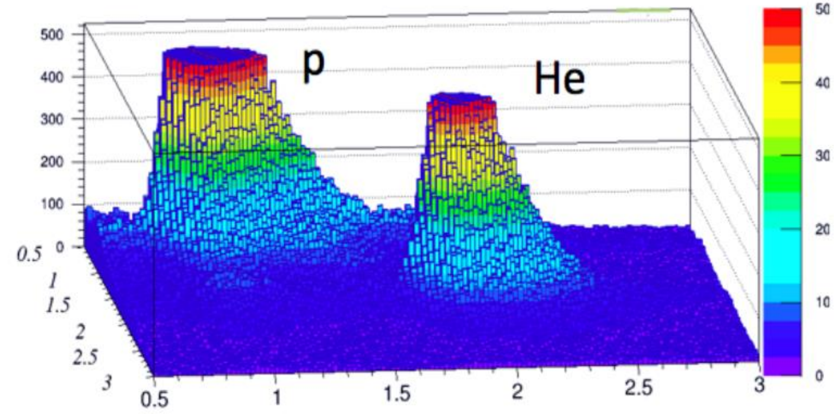


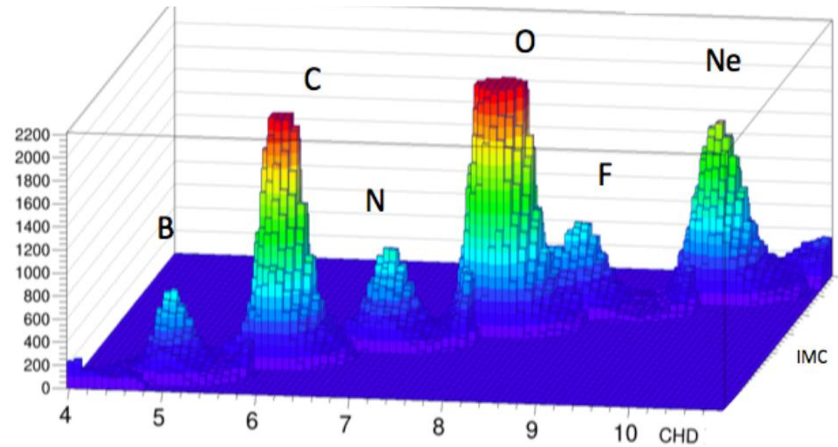
Charge resolution using multiple dE/dx measurements from the IMC scintillating fibers



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, up to Z=8, can be seen from CHD+IMC data analysis.

Preliminary Flux of Primary Components

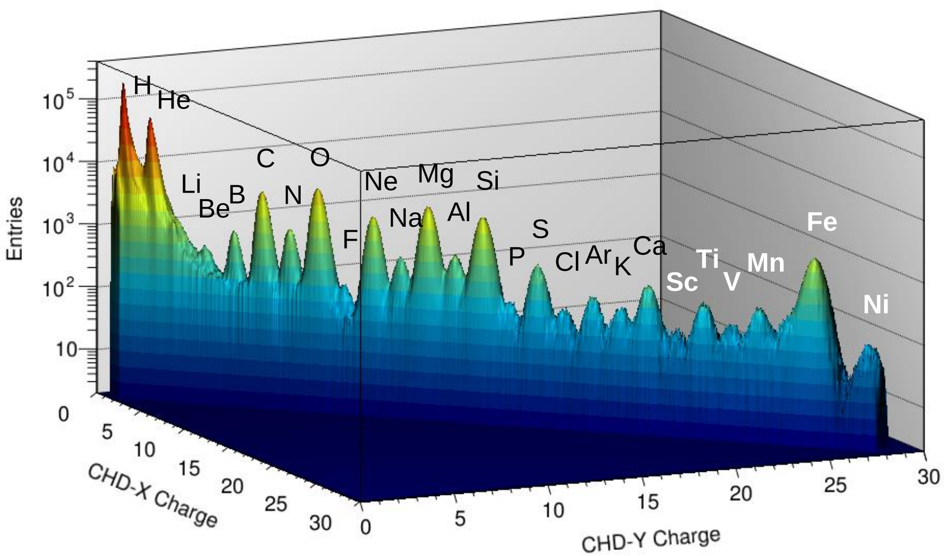
Y. Akaike et al., E+CRS 2018

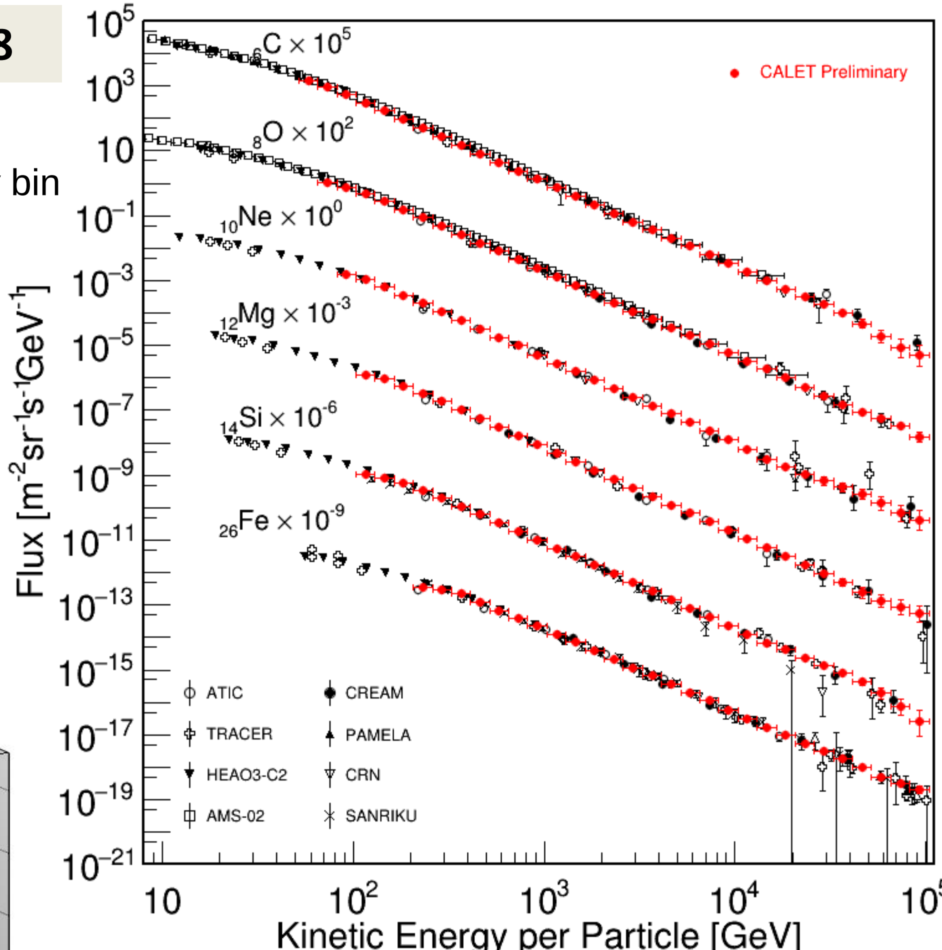
Flux measurement:

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

$N(E)$: Events in unfolded energy bin
$S\Omega$: Geometrical acceptance
T : Live time
$\varepsilon(E)$: Efficiency
ΔE : Energy bin width

Observation period:
2015.10.13 – 2018.5.31 (962 days)
Selected events: ~5.6 million for C-Fe





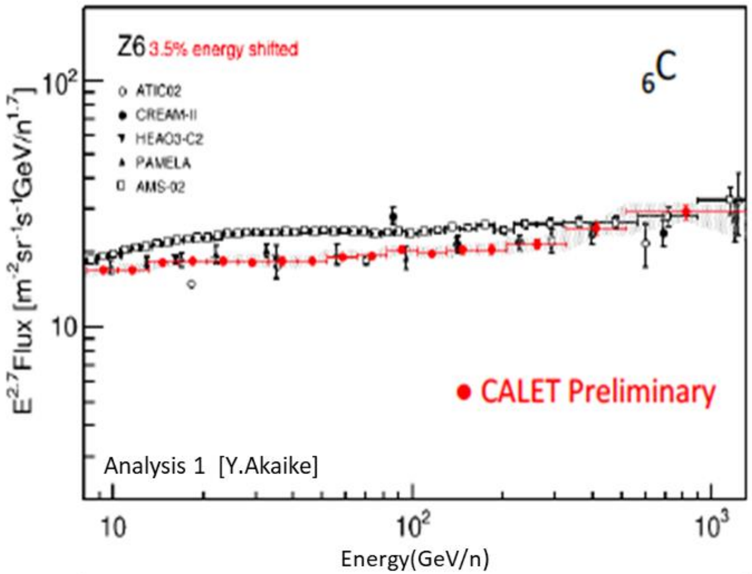
<u>Charge Separation only with CHD</u>

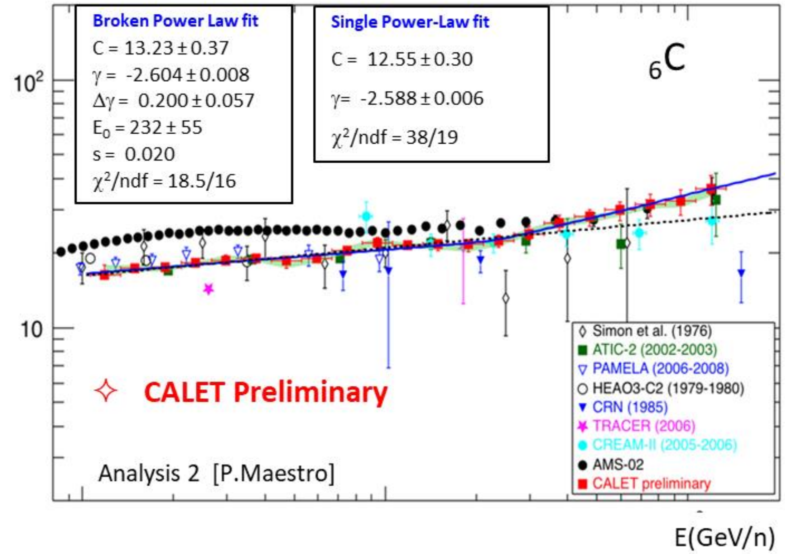
Clear separation of protons, helium to iron and nickel (up to Z=40).

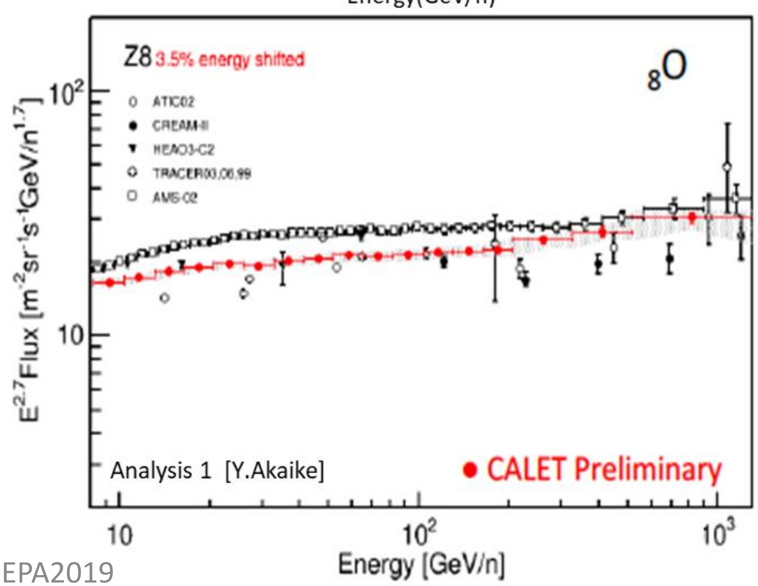
Preliminary Energy Spectra of Carbon and Oxygen

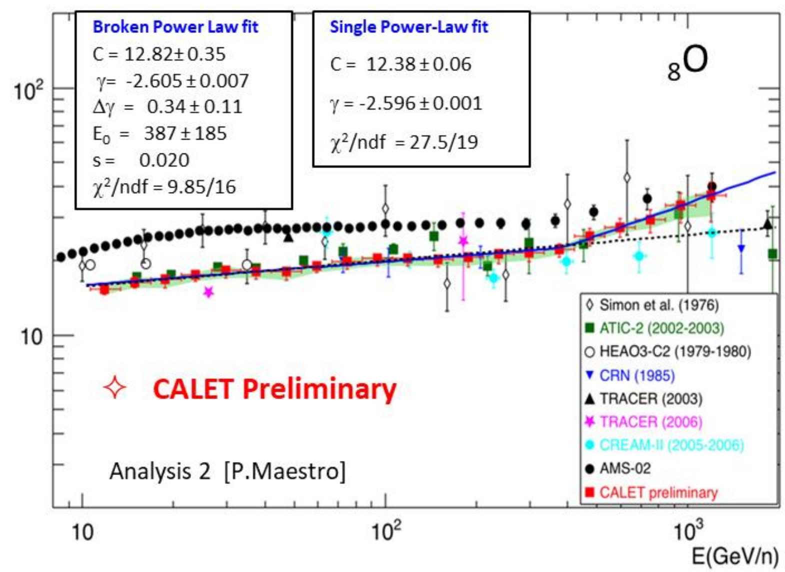
(2 independent CALET analyses)

P. Maestro et al., COSPAR2018









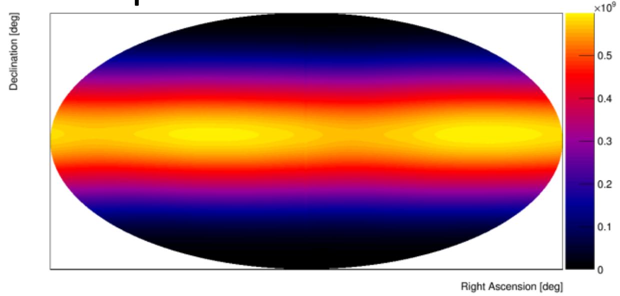
Gamma-Rays

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 238 (2018) 5.

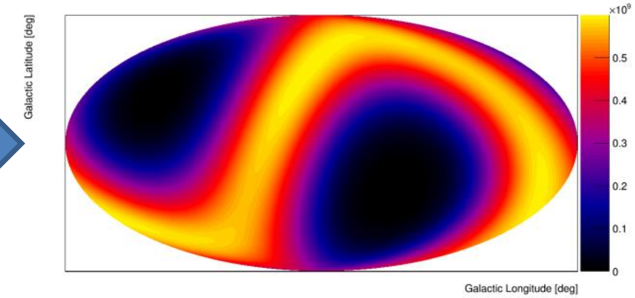
CALET Sky Map w/ LE-γ Trigger (E>1GeV)

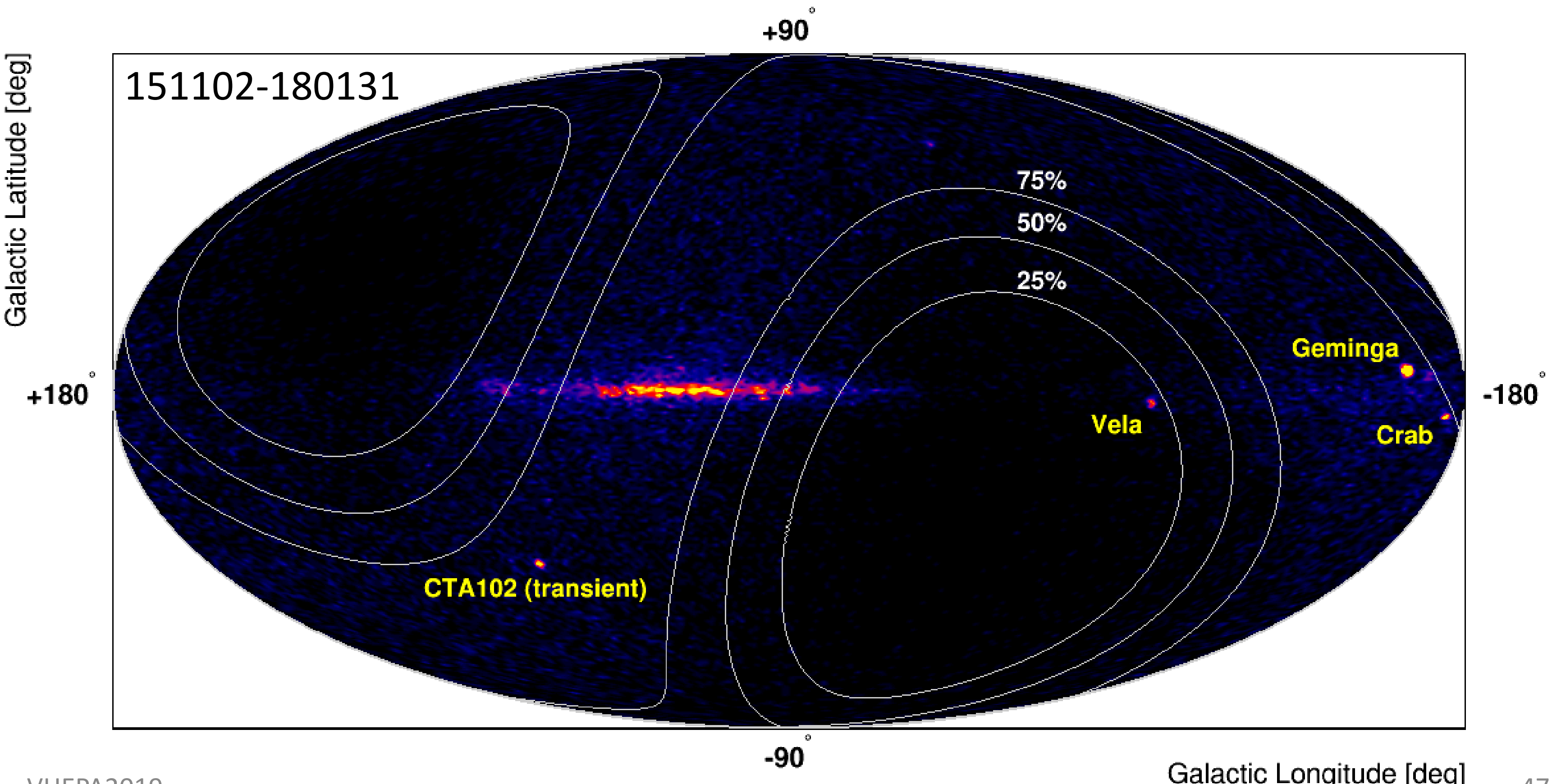
While exposure is not uniform, we have clearly identified the galactic plane and bright GeV sources.

Equatorial coordinate

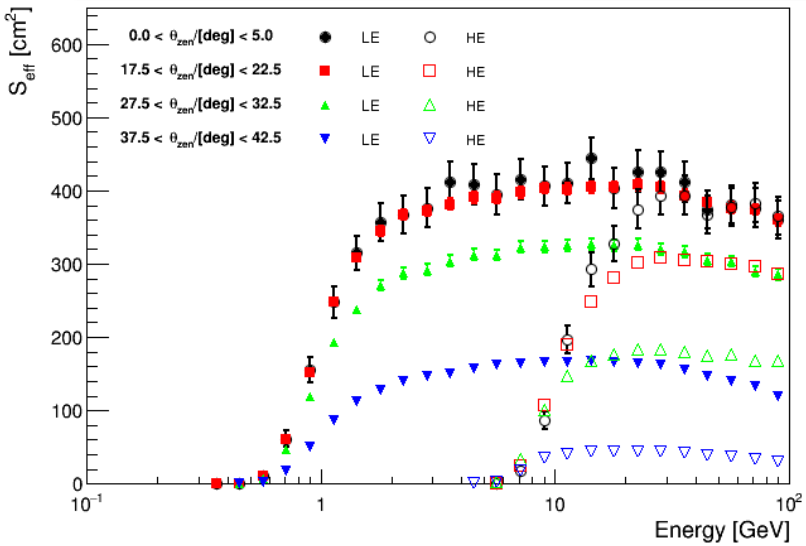


Galactic coordinate

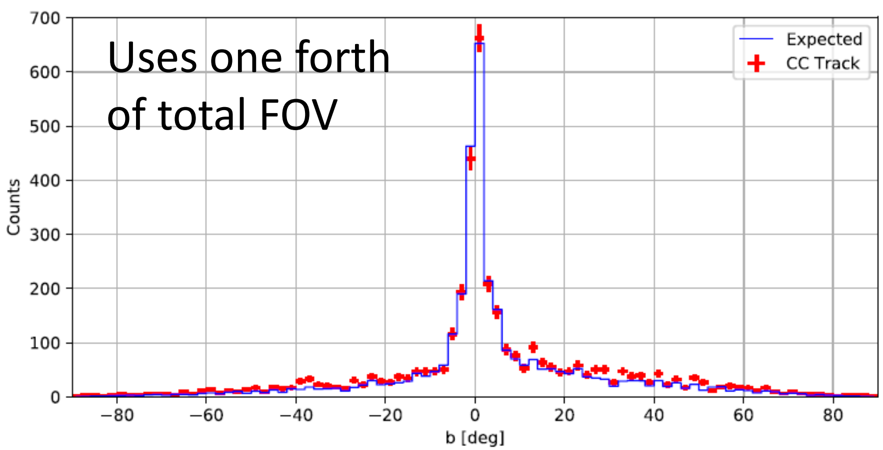




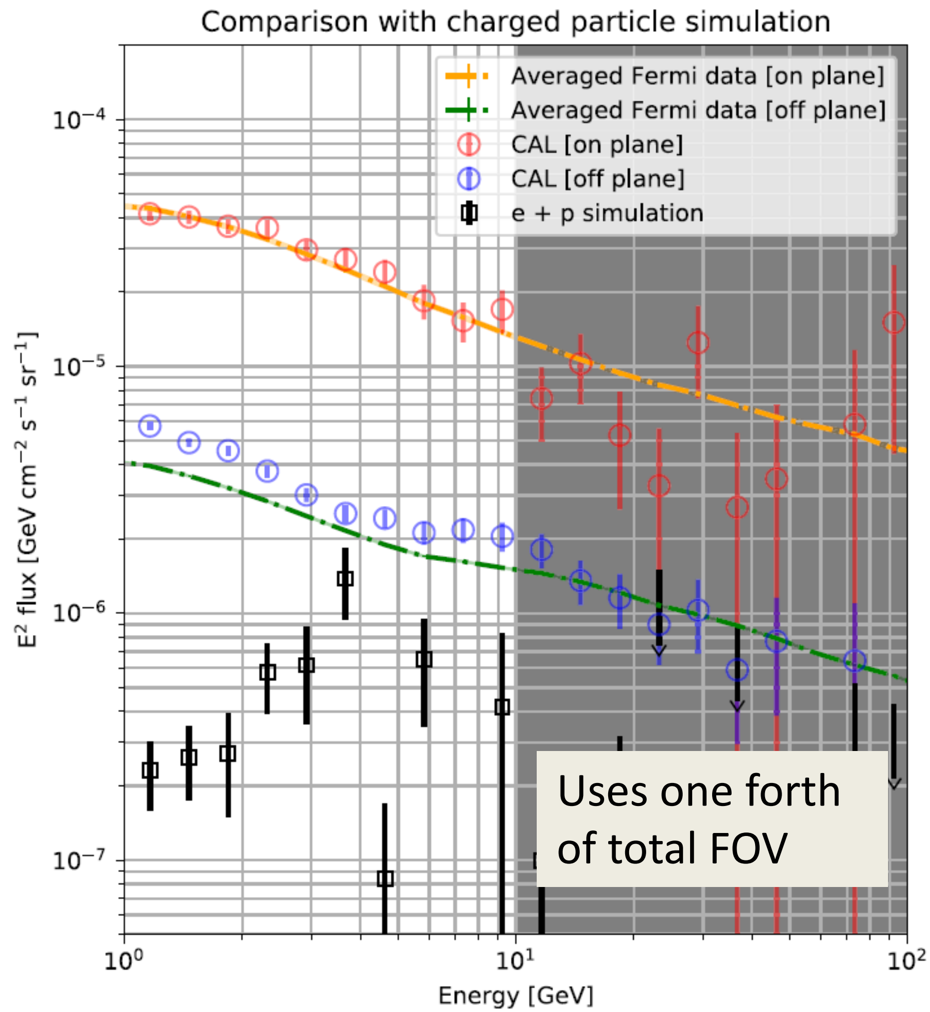
Effective Area and γ -ray Flux from On/Off Plane



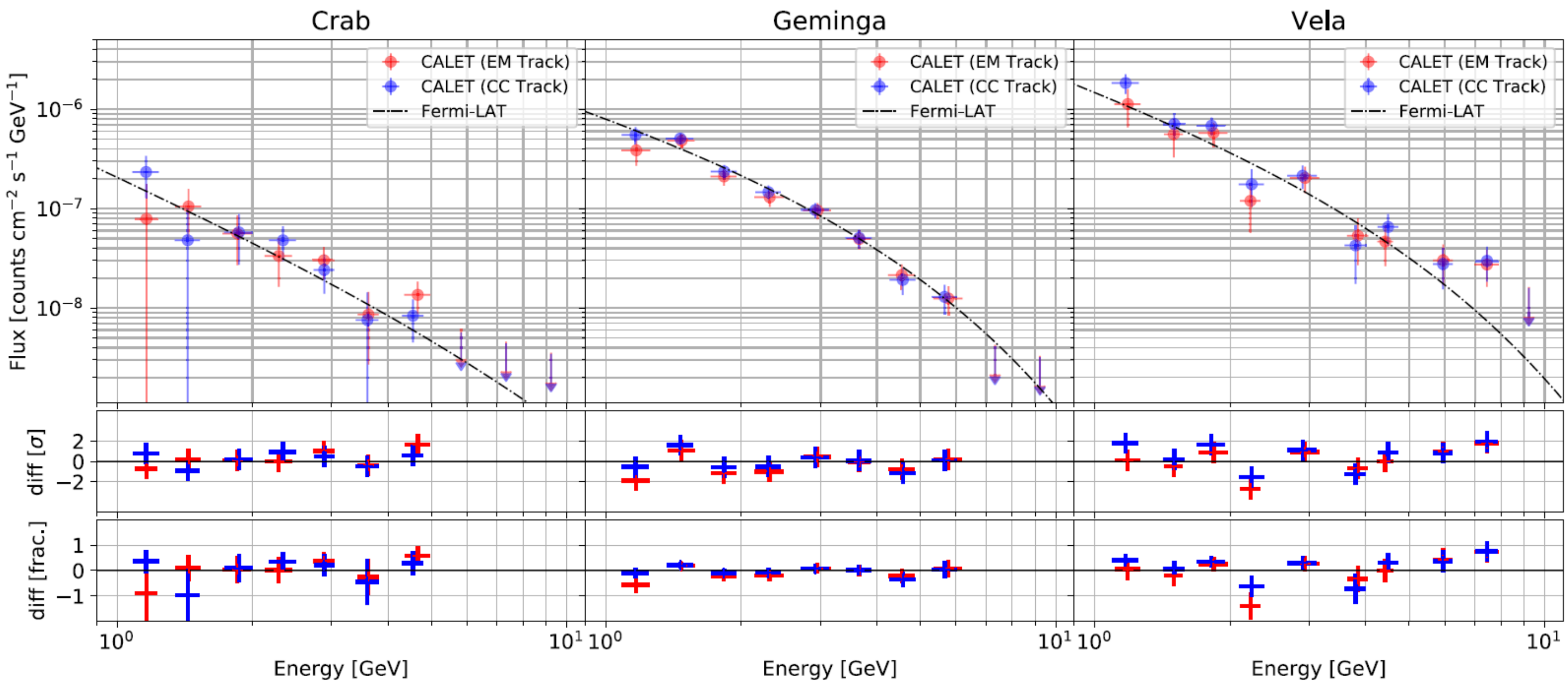
Effective area as a function of energy. Four representing zenith angle ranges are shown.



Analysis methodology, performance: N.Cannady, Y.Asaoka et al. (CALET Collab.), ApJS 238 (2018) 5.



Bright Point-Source Spectra



- The observed point source spectra are well consistent with Fermi-LAT's parameterizations.
- Point Spread Function (PSF) and absolute pointing accuracy (~0.1deg) were validated, too, using bright point source data.

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

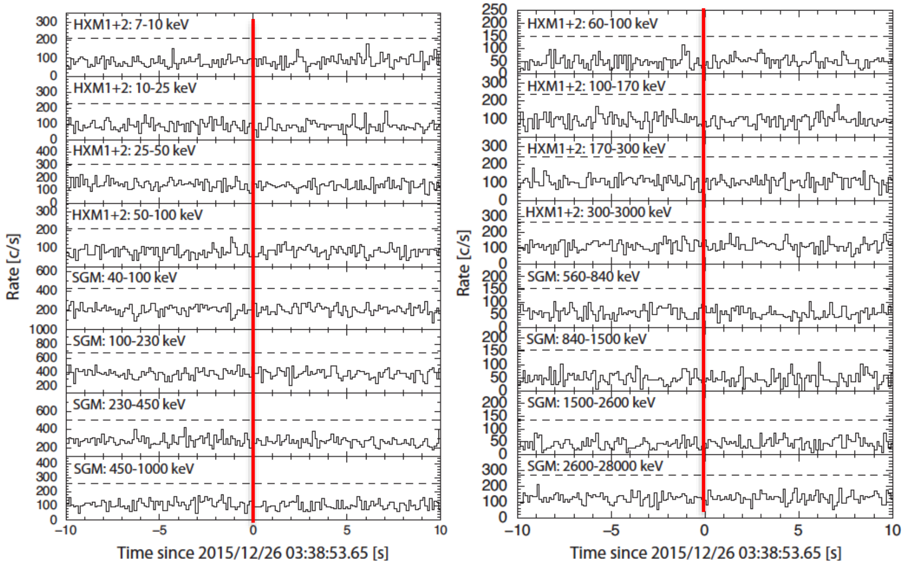


Figure 1. The CGBM light curves in 0.125 s time resolution for the high-gain data (left) and the low-gain data (right). The time is offset from the LIGO trigger time of GW 151226. The dashed-lines correspond to the 5 σ level from the mean count rate using the data of ±10 s.

Upper limit for gamma-ray burst monitors and Calorimeter

HXM: 7-500 keV

SGM: 50-1000 keV

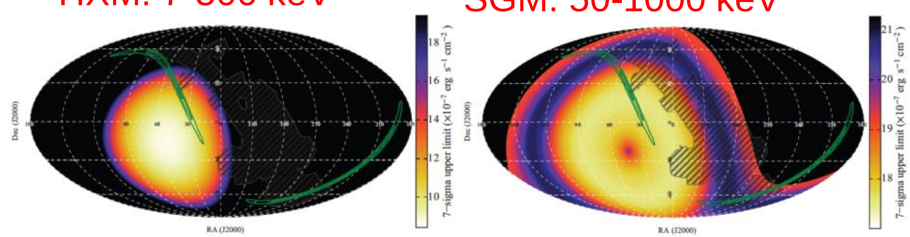


Figure 2. The sky maps of the 7 σ upper limit for HXM (left) and SGM (right). The assumed spectrum for estimating the upper limit is a typical BATSE S-GRBs (see text for details). The energy bands are 7-500 keV for HXM and 50-1000 keV for SGM. The GW 151226 probability map is shown in green contours.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

Calorimeter:
1-100 GeV

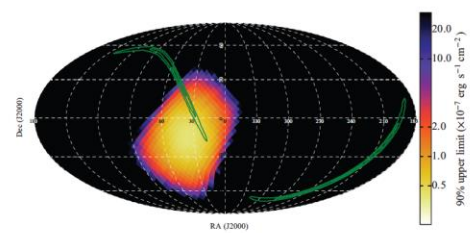


Figure 3. The sky map of the 90% upper limit for CAL in the 1-100 GeV band. A power-law model with a photon index of −2 is used to calculate the upper limit. The GW 151226 probability map is shown in green contours.

Complete Search Results for GW Events during O1&O2

O.Adriani et al. (CALET Collabolation), ApJ 863 (2018) 160.

- CALET was not operational, yet, at the time of GW150914.
- For GW151226, we set 90% C.L. limit of 9.3 x 10^{-8} erg cm^{-2} s^{-1} (1-10GeV) covering 15% of the summed LIGO probabilities in the time window [T0-525s, T0+211s] (LE trigger).
- For GW170104, we set 90% C.L. limit of 8.3 x 10^{-6} erg cm^{-2} s^{-1} (10-100GeV) covering 30% of the summed LIGO probabilities in the time window [T0-60s,T0+60s] (HE trigger).
- Unfortunately, other GW events (GW170608, GW170814, GW170817) occurred during O2 are all out of the CALET-CAL FOV.

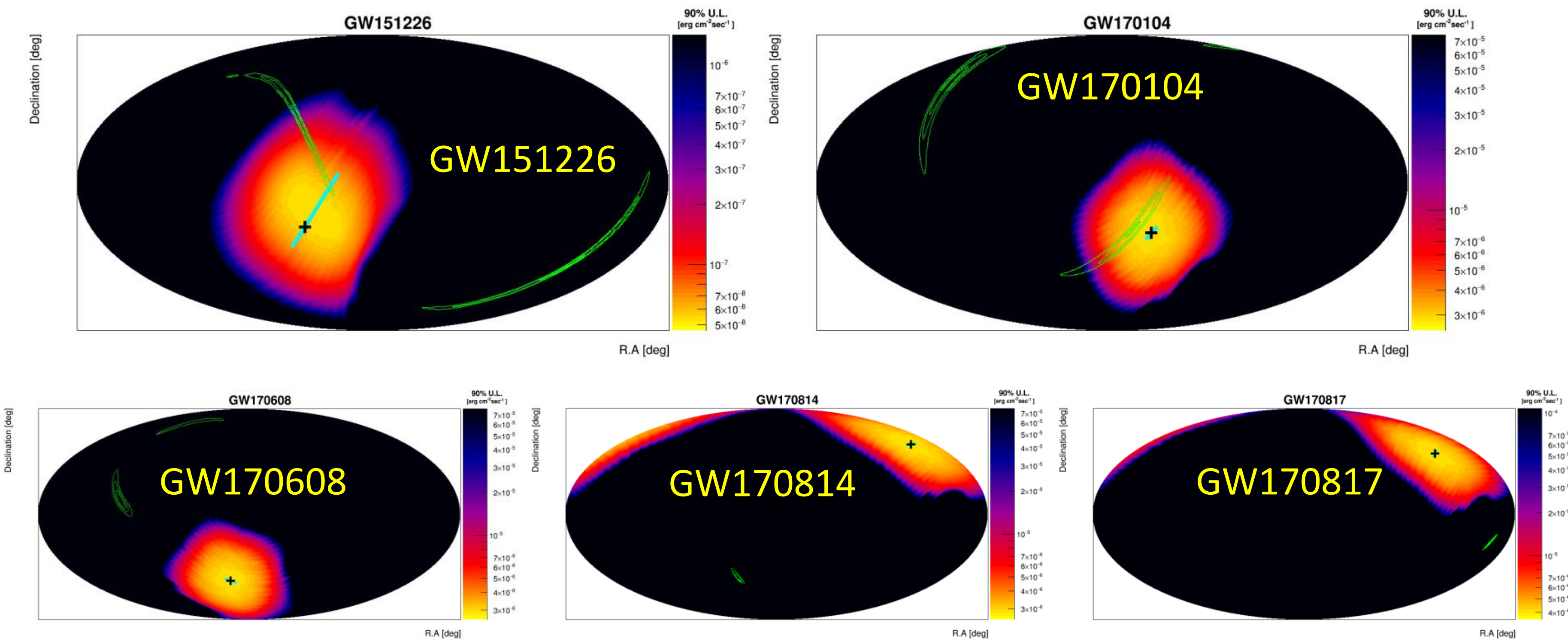


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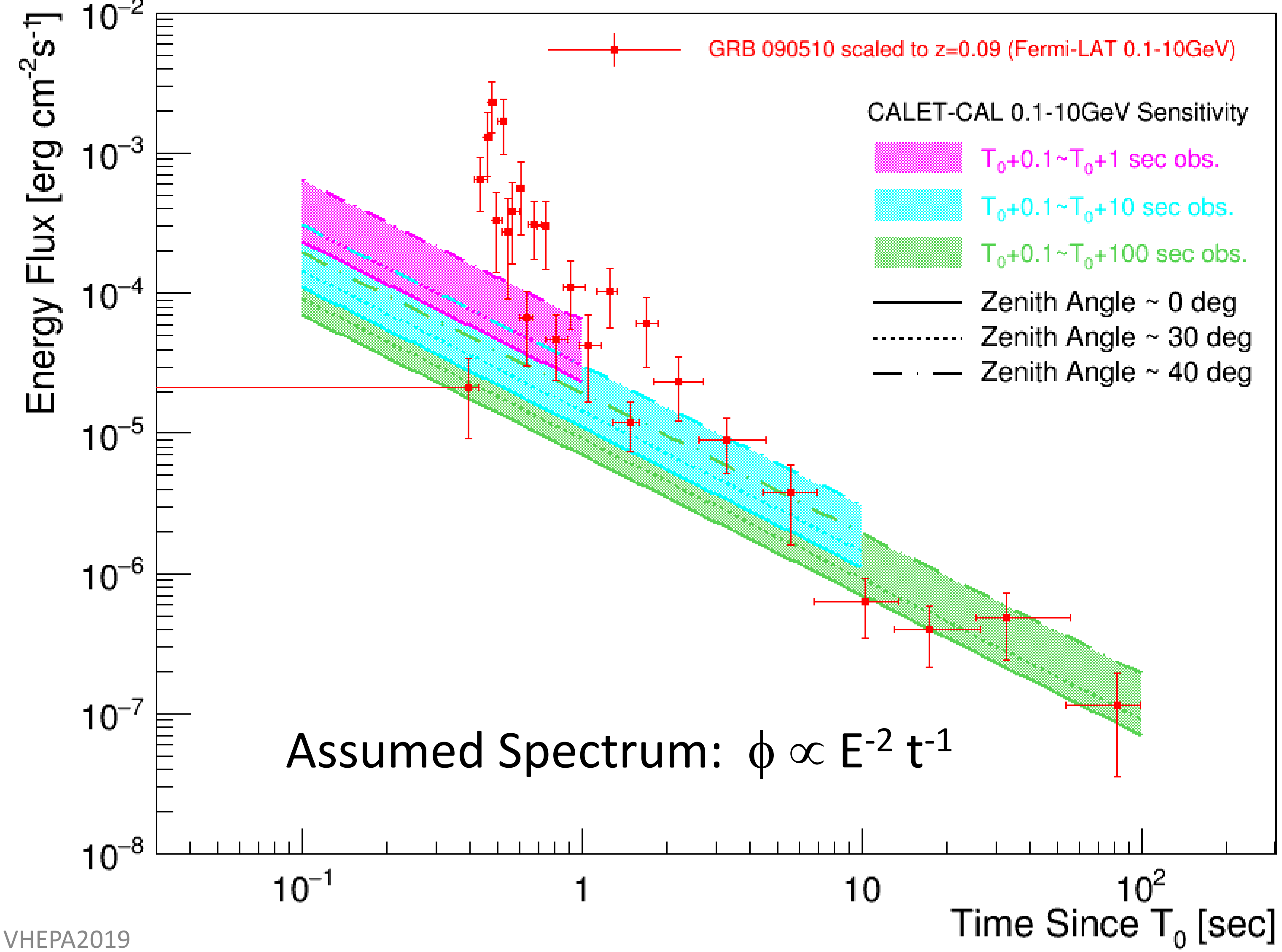
Table 1

Summary of *CALET* Observations of Gravitational Events Reported by the Virgo and LIGO Scientific Collaborations (BH: black hole, NS: Neutron Star) and Representative Results from *CALET* Observation (See the Text for Other Time Windows)

GW event	Time T_0 (UTC)	Location area (deg^2)	Luminosity distance (Mpc)	Event Type	References	*CALET* Results [Time Window]			
						Mode	Summed LIGO probability	Upper Limits (90% C.L.)	
								Energy Flux (erg cm^{-2} s^{-1})	Luminosity (erg s^{-1})
GW150914	2015 Sep 14 09:50:45	600	440^{+160}_{-180}	BH–BH	(a)			Before operation	
GW151226	2015 Dec 26 03:38:53	850	440^{+180}_{-190}	BH–BH	(b)	LE	15%	$[T_0 - 525$ s, $T_0 + 211$ s] 9.3×10^{-8}	2.3×10^{48}
GW170104	2017 Jan 04 10:11:58	1200	880^{+450}_{-390}	BH–BH	(c)	HE	30%	$[T_0 - 60$ s, $T_0 + 60$ s] 6.4×10^{-6}	6.2×10^{50}
GW170608	2017 Jun 08 02:01:16	520	340^{+140}_{-140}	BH–BH	(d)	HE		$[T_0 - 60$ s, $T_0 + 60$ s] Out of FOV	
GW170814	2017 Aug 14 10:30:43	60	540^{+130}_{-210}	BH–BH	(e)	HE		$[T_0 - 60$ s, $T_0 + 60$ s] Out of FOV	
GW170817	2017 Aug 17 12:41:04	28	40^{+8}_{-14}	NS–NS	(f)	HE		$[T_0 - 60$ s, $T_0 + 60$ s] Out of FOV	

CALET Sensitivity to GeV Gamma-Rays

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



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 October 31, 2018, total observation time is 1115 days with live time fraction to total time close to 84%. Nearly 730 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 (August 2018). In addition, onboard performance of gamma-ray observation is published in ApJS (September 2018).
- 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.