# Calorimetric Electron Telescope (CALET) on the International Space Station

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for the CALET Collaboration
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# CALET Collaboration Team

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# Outline

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3. Operations
4. Results
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    2. Hadrons
    3. Gamma-Rays
    4. Space Weather
    5. Gamma-ray Burst
       + GW events
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.

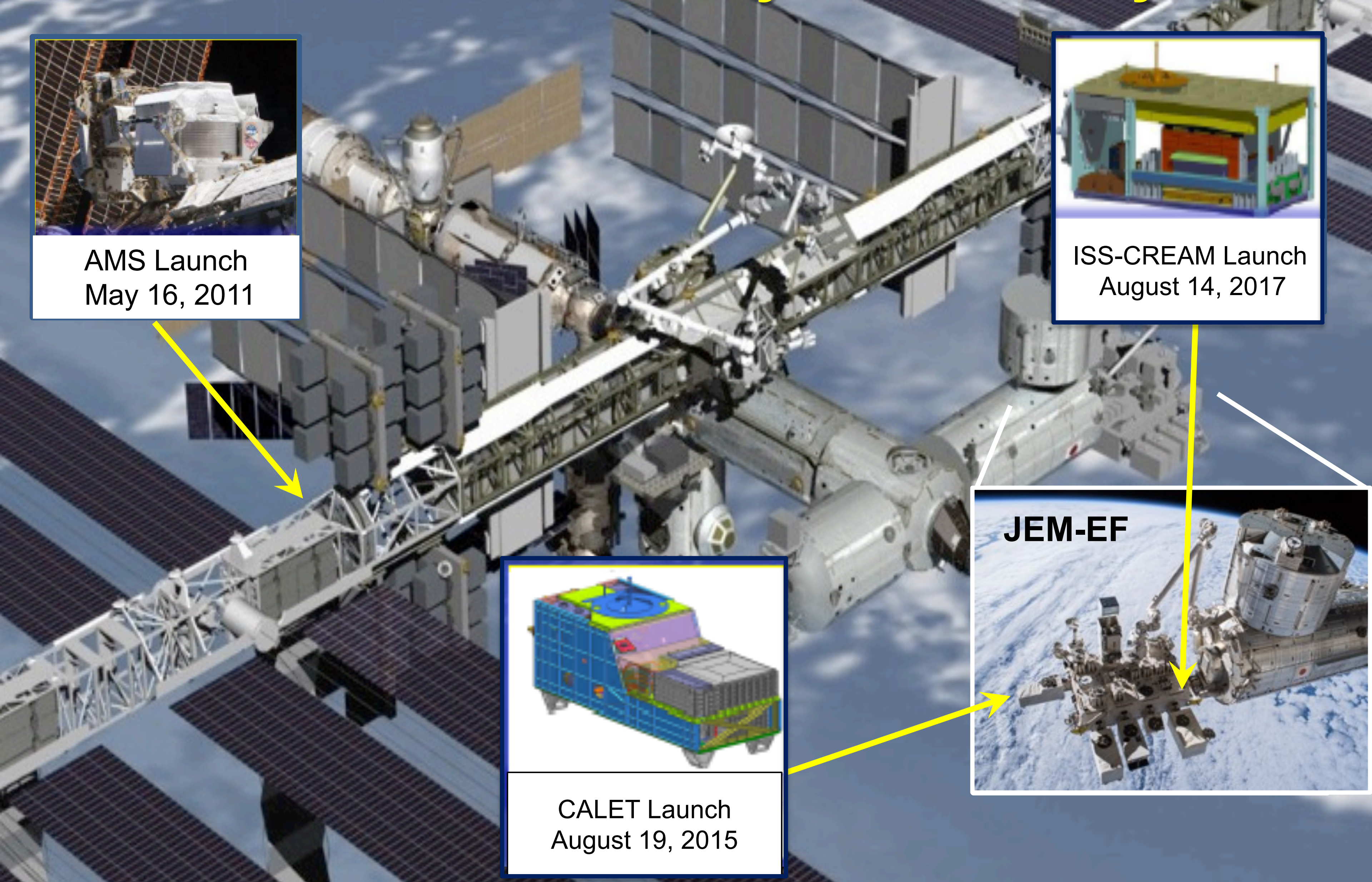
O.Adriani et al. (CALET Collaboration), Phys.Rev.Lett. 119 (2017) 181101.

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

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

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

# ISS as Cosmic Ray Observatory

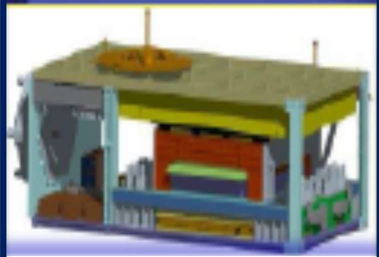


# ISS as Cosmic Ray Observatory

AMS Launch
May 16, 2011

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

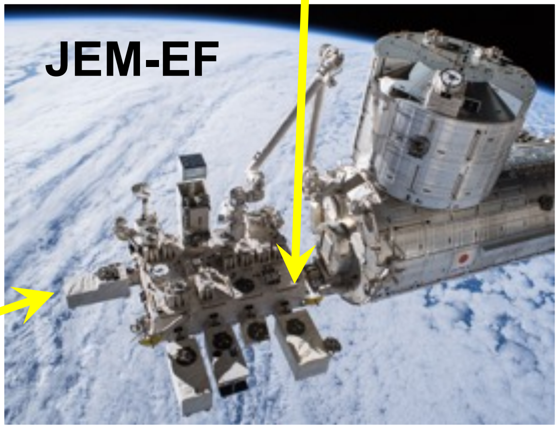
Calorimeter
- Carbon target
- Hadrons
- Including TeV region



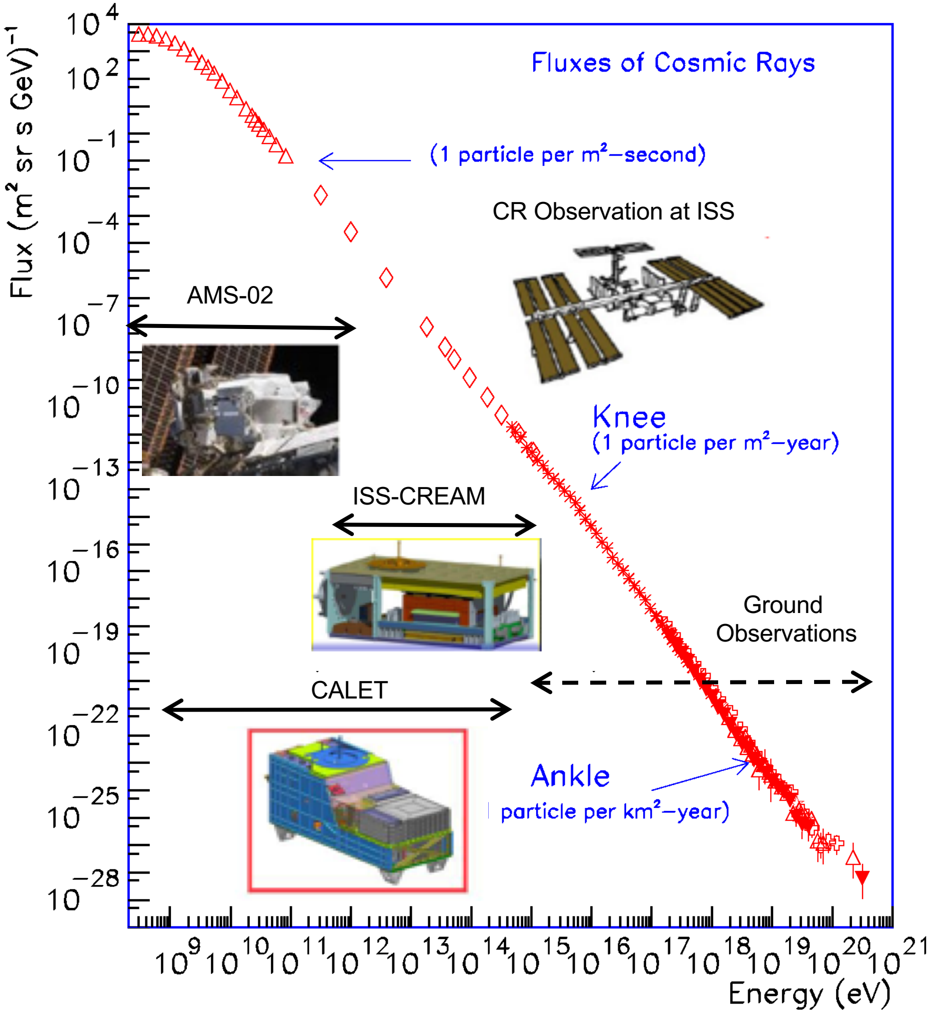
ISS-CREAM Launch
August 14, 2017

Calorimeter
- Fully active
- Electrons
- Including TeV region

CALET Launch
August 19, 2015



# Cosmic Ray Observations at the ISS and CALET




## Overview of CALET Observations

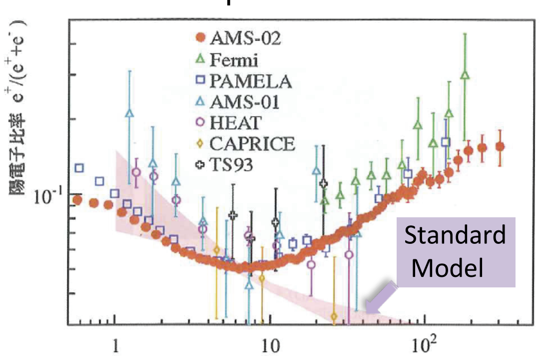
- Direct cosmic ray observations in space at the highest energy region by combining:
  - ✓ A large-size detector
  - ✓ Long-term observation onboard the ISS (5 years or more is expected)
- Electron observation in 1 GeV - 20 TeV will be achieved with high energy resolution due to optimization for electron 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.

# Scientific Targets

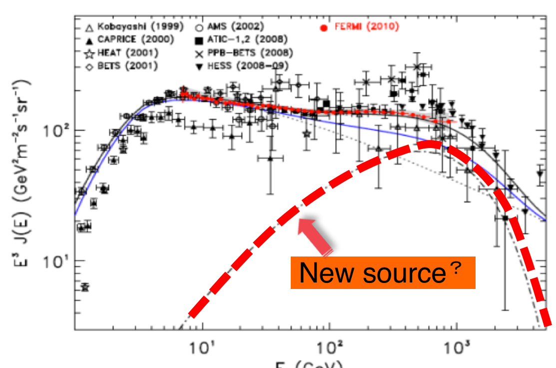
| Scientific Objectives | Observation Targets | Energy Range |
|---|---|---|
| CR Origin and Acceleration | Electron spectrum<br>p--Fe individual spectra<br>Ultra Heavy Ions (26<Z≤40)<br>Gamma-rays (Diffuse + Point sources) | 1GeV - 20 TeV<br>10 GeV - 1000 TeV<br>> 600 MeV/n<br>1 GeV - 1 TeV |
| Galactic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

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

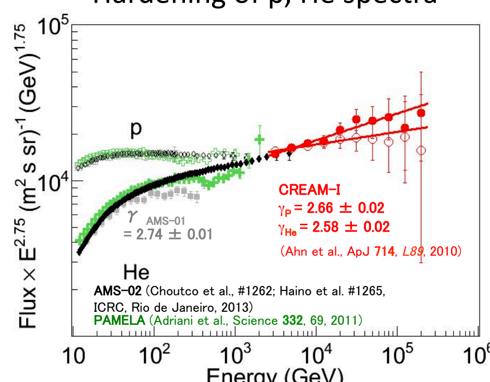
Increase of positron/electron ratio




Excess of electron+positron flux

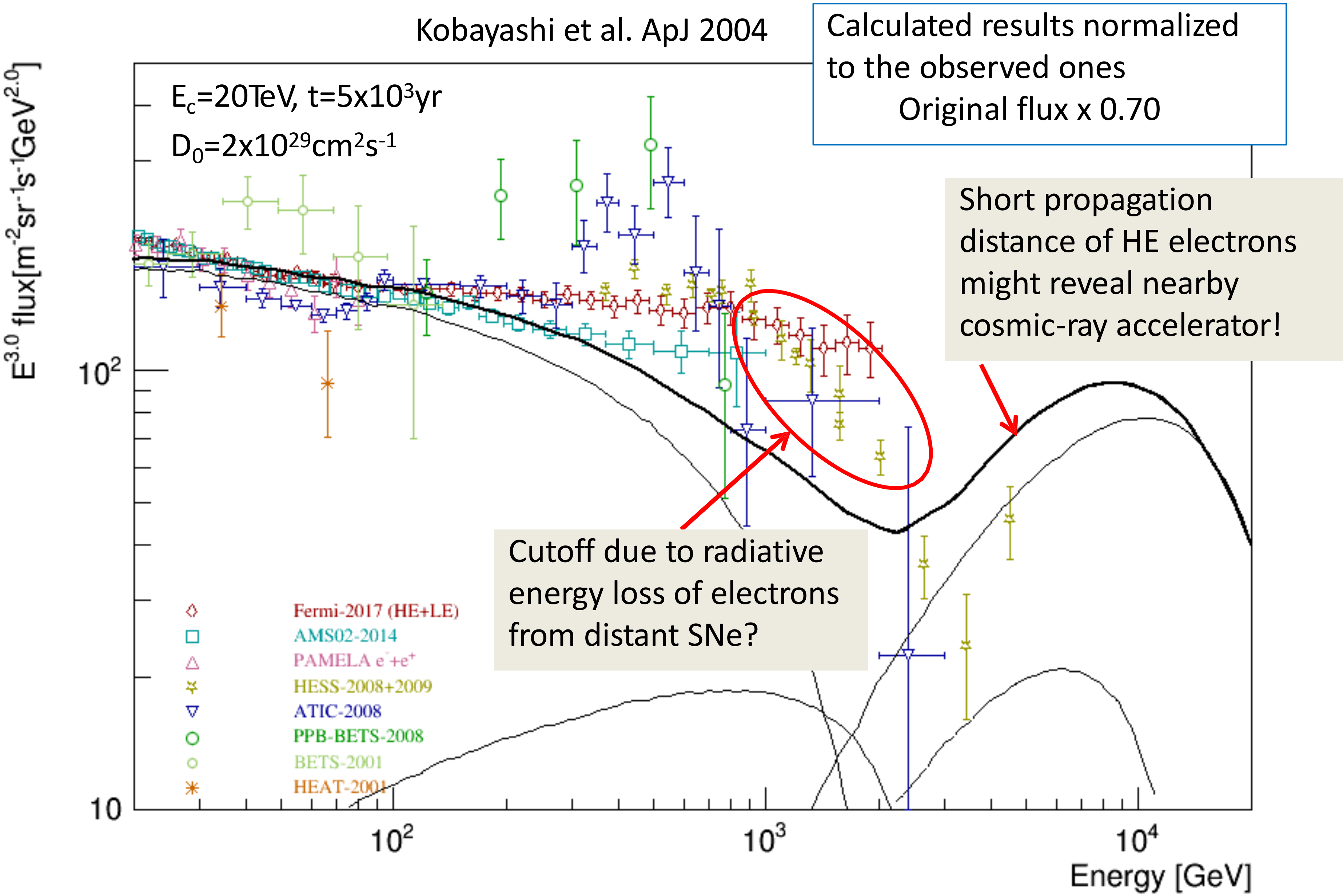



Hardening of p, He spectra



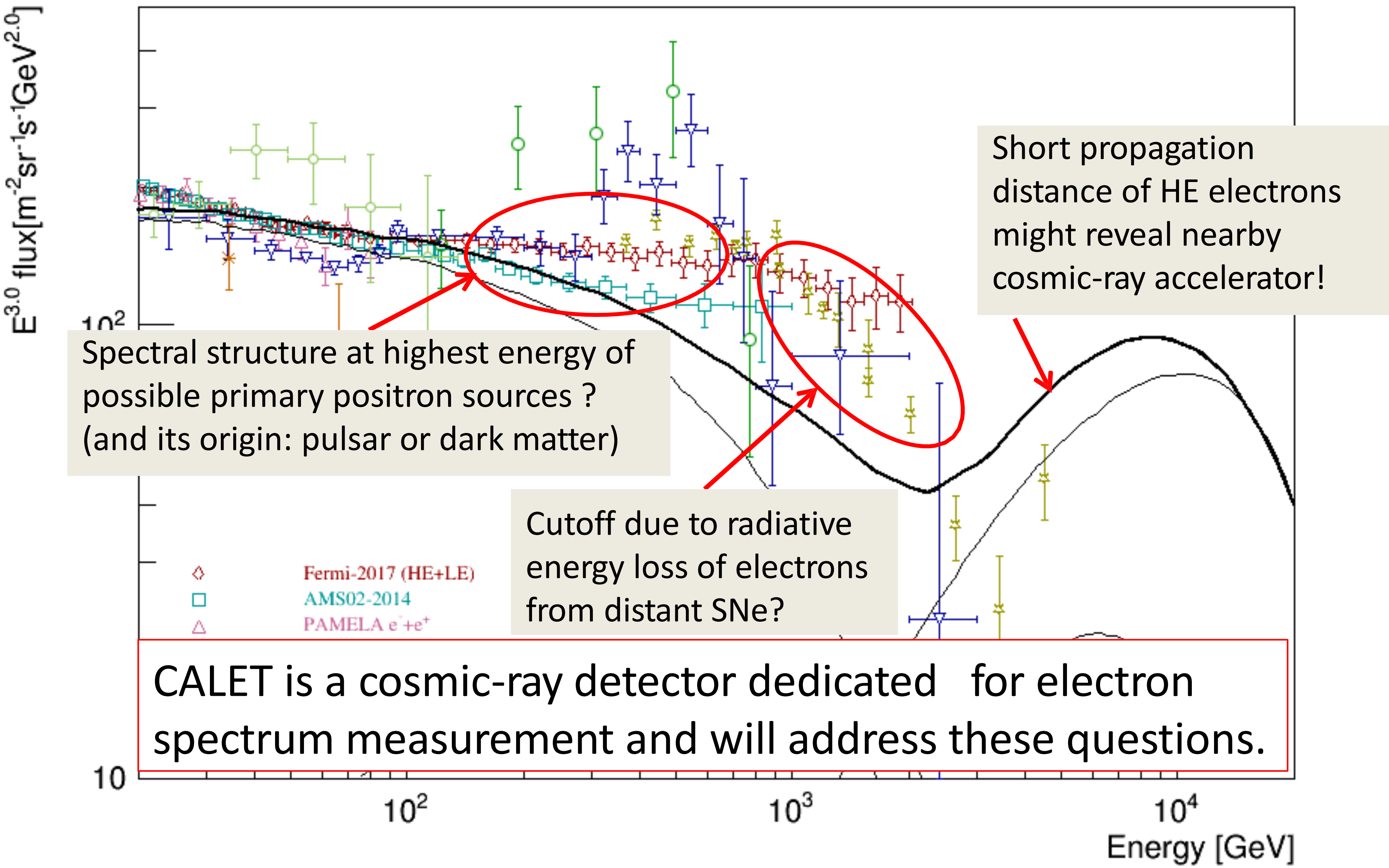

New source of electrons and positrons at 100 GeV region ?

# CALET Main Target: Cosmic-Ray All-Electron Spectrum ($e^{+}+e^{-}$)



# CALET Main Target: Cosmic-Ray All-Electron Spectrum ($e^{+}$+$e^{-}$)

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

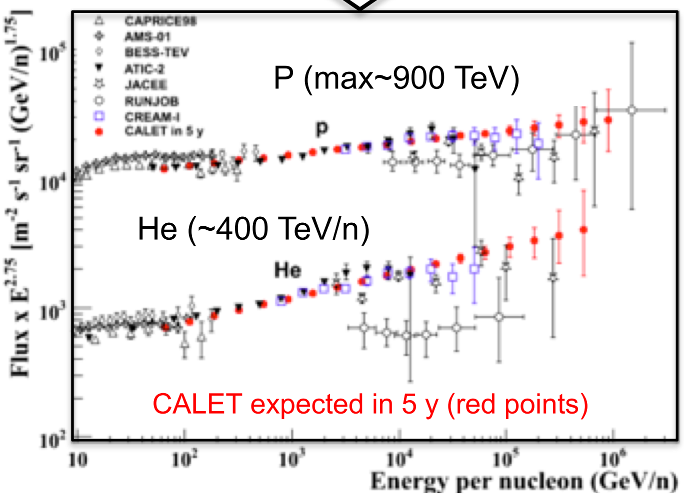


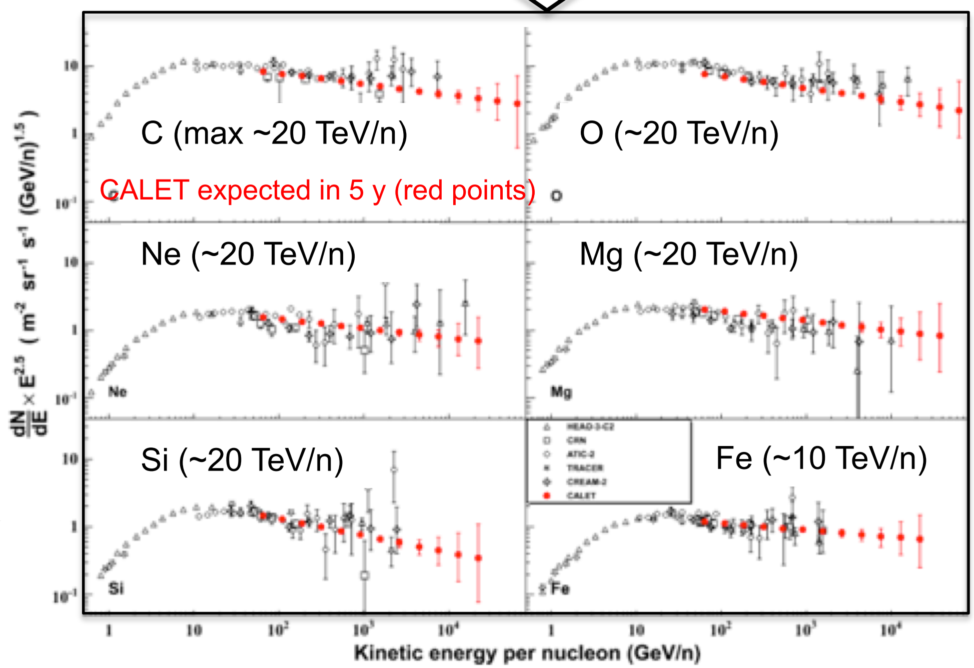

CALET is a cosmic-ray detector dedicated for electron spectrum measurement and will address these questions.

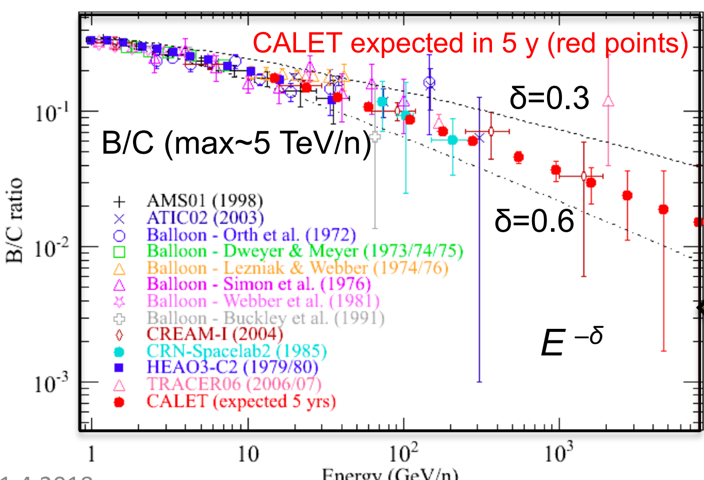
# Measurements of Cosmic-Ray Nuclei Spectra with CALET

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

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

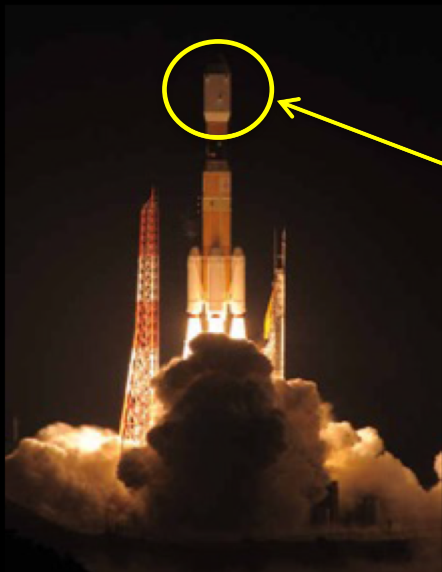


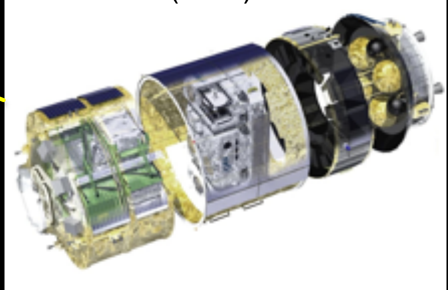




- At high energy (> 10 GeV/n) the B/C ratio measures the energy dependence of the escape path-length, $\sim E^{-\delta}$, of CRs from the Galaxy
- Data around 100 GeV/n indicate δ~1/3. At highest energy the ratio is expected to flatten out by residual material.

# CALET Payload

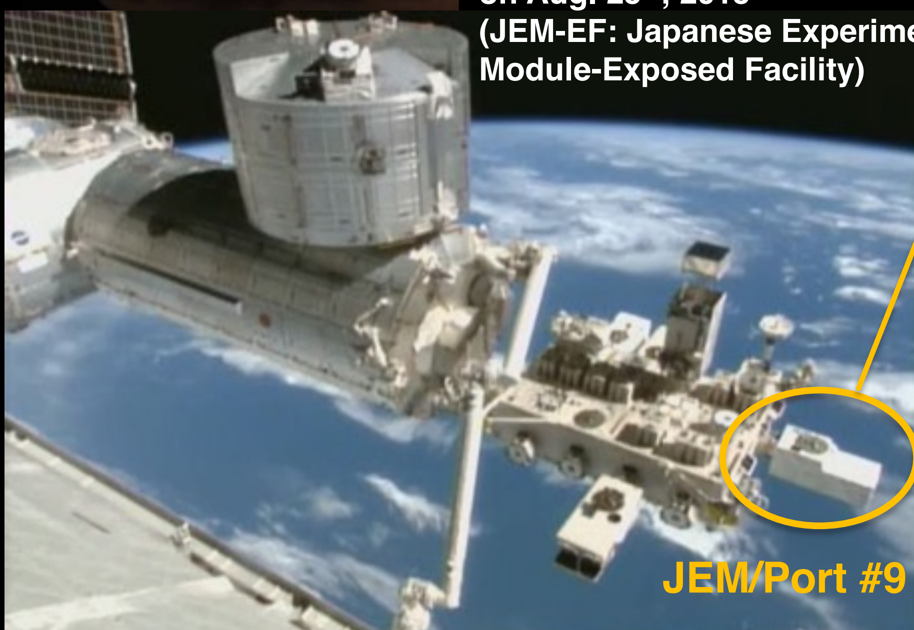


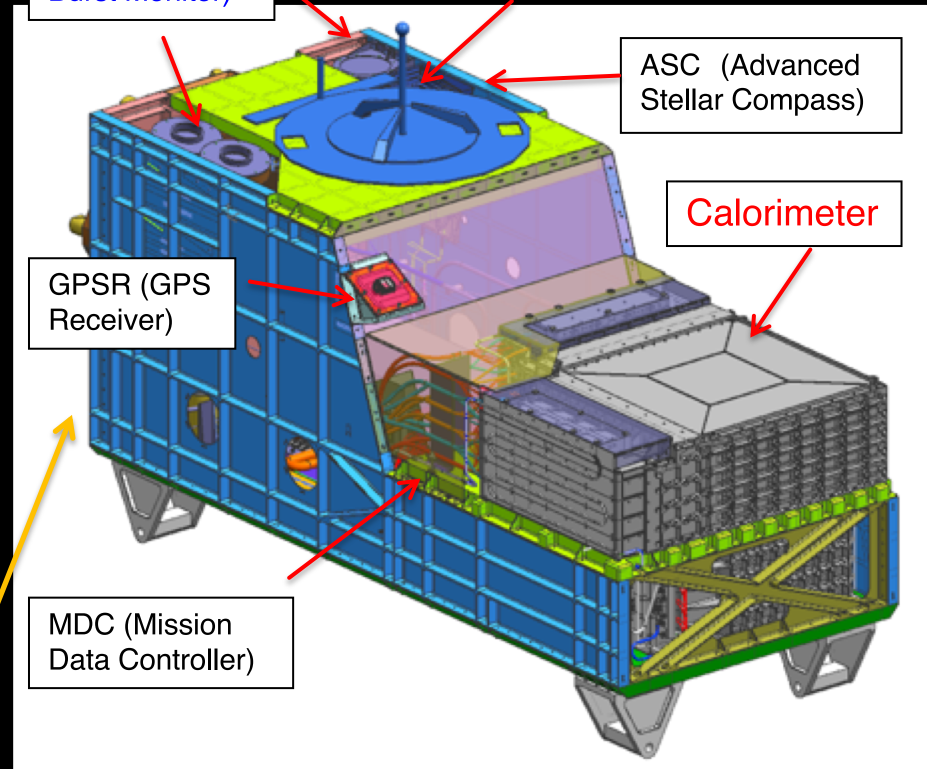
Kounotori (HTV) 5



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

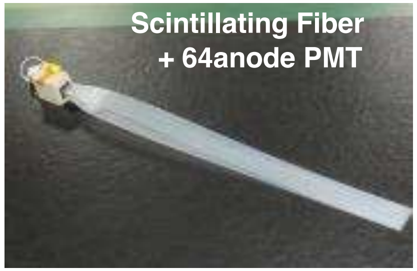
**Emplaced on JEM-EF port #9 on Aug. 25th, 2015 (JEM-EF: Japanese Experiment Module-Exposed Facility)**

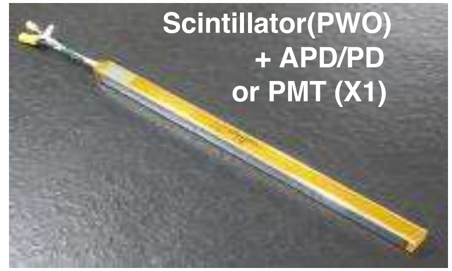


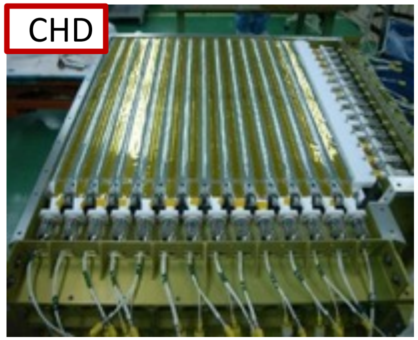



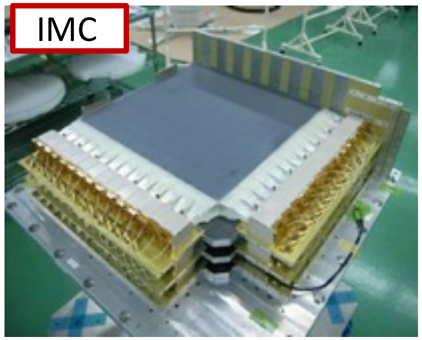

- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  **1850mm(L) × 800mm(W) × 1000mm(H)**
- **Power Consumption: 507 W （max）**
- **Telemetry:**
  **Medium 600 kbps (6.5GB/day) / Low 50 kbps**

# CALET Instrument

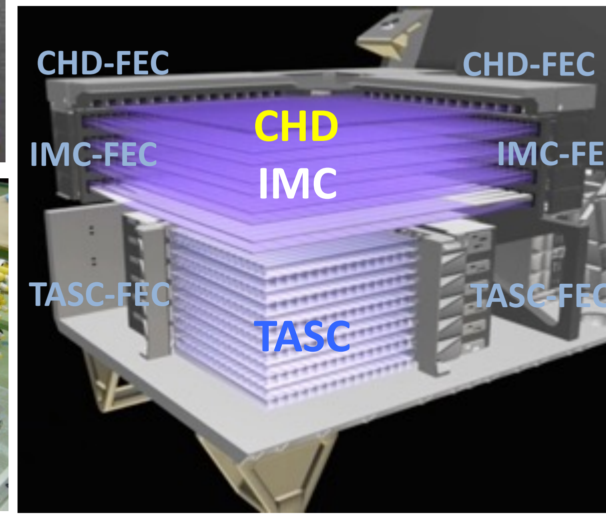





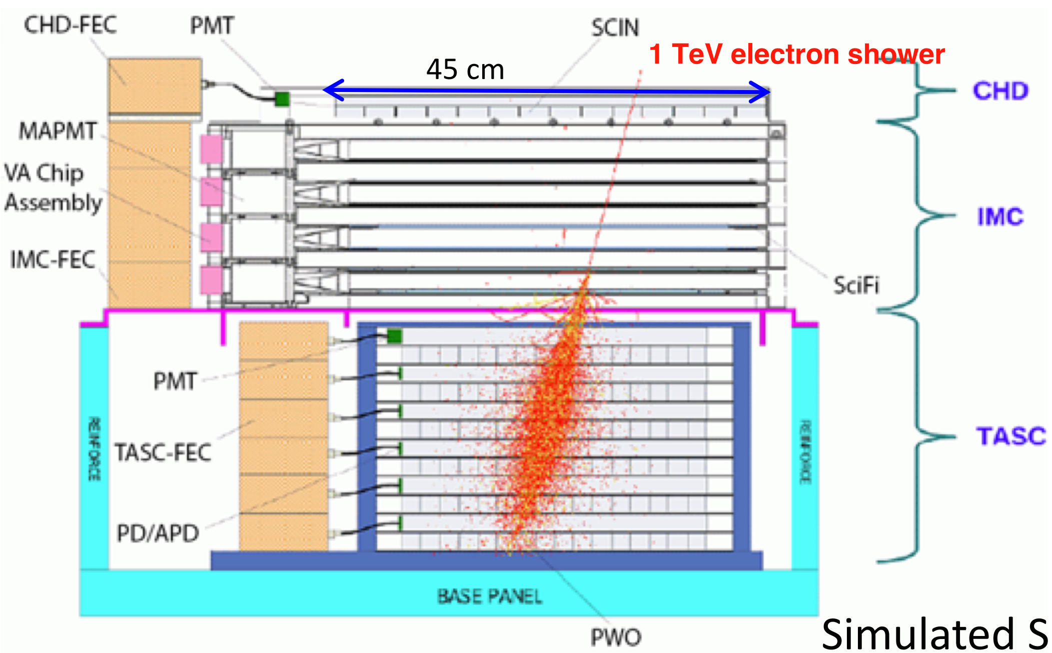
CALORIMETER




| | 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<br>14 paddles x 2 layers (X,Y): 28 paddles<br>Paddle Size: 32 x 10 x 450 $mm^3$ | 448 Scifi x 16 layers (X,Y) : 7168 Scifi<br>7 W layers ($3X_0$): $0.2X_0$ x 5 + $1X_0$ x2<br>Scifi size : 1 x 1 x 448 $mm^3$ | 16 PWO logs x 12 layers (x,y): 192 logs<br>log size: 19 x 20 x 326 $mm^3$<br>Total Thickness : 27 $X_0$ , ~1.2 $\lambda_I$ |
| Readout | PMT+CSA | 64-anode PMT+ ASIC | APD/PD+CSA<br>PMT+CSA (for Trigger)@top layer |

# CALET Capability

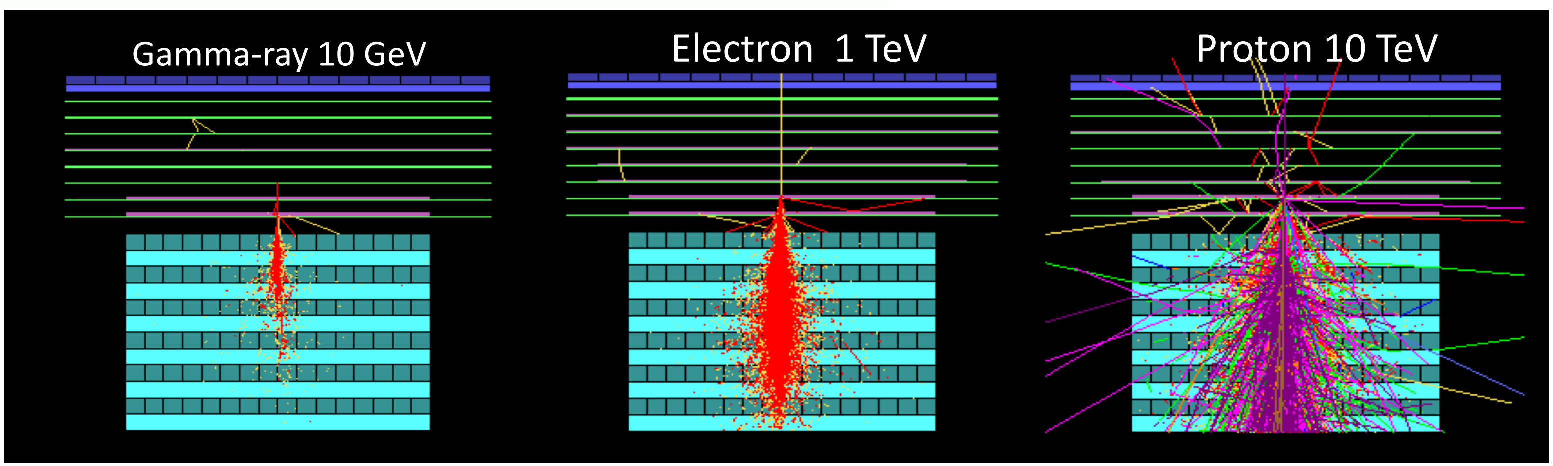
Geometrical Factor: ~ 1,040 $cm^2sr$ (for electrons)




## Unique features of CALET

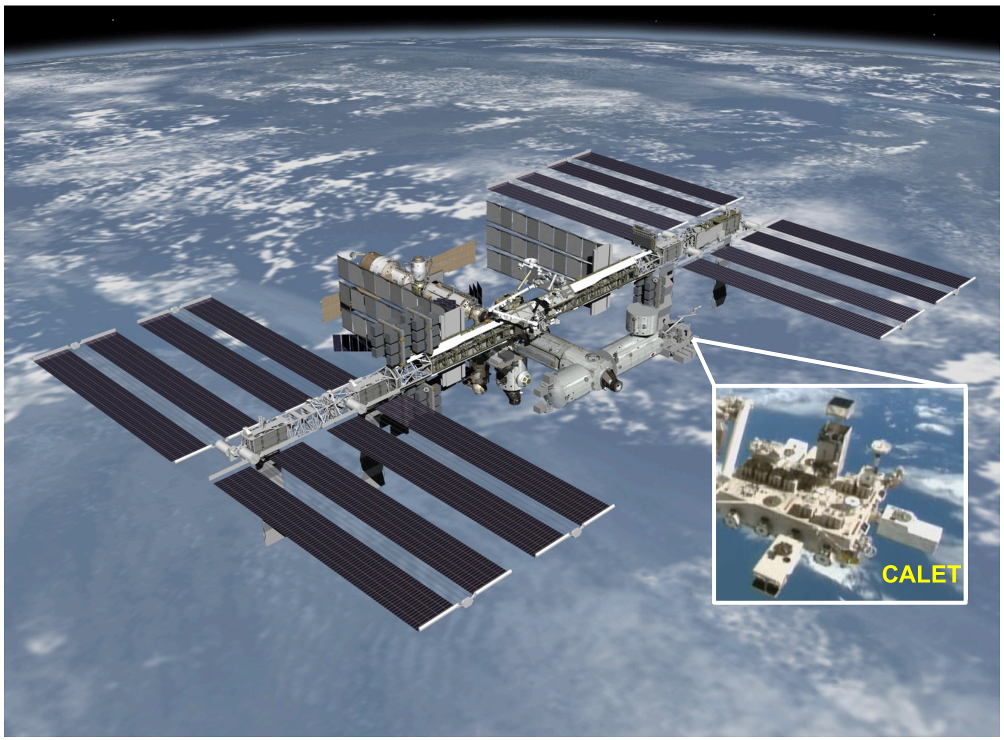
- **A dedicated charge detector + multiple dE/dx track sampling in the IMC allow to identify individual nuclear species (Δz~0.15-0.3 e).**
- **High granularity imaging pre-shower calorimeter accurately identify the arrival direction of incident particles ( ~0.1°) and the starting point of electro-magnetic showers.**
- **Thick(~30 $X_0$), fully active calorimeter allows measurements well into the TeV energy region with excellent energy resolution ( ~2%)**
- **Combined, they powerfully separate electrons from the abundant protons: contamination is much less than 10 % up to the TeV region.**

Simulated Shower Profile

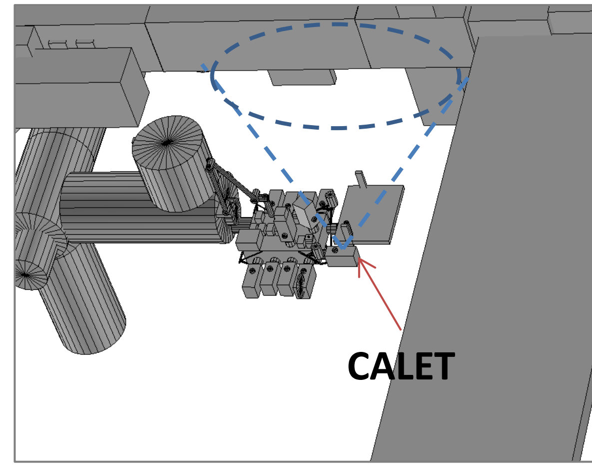


# Attached Location (JEM-EF Port No.9) and the FOV

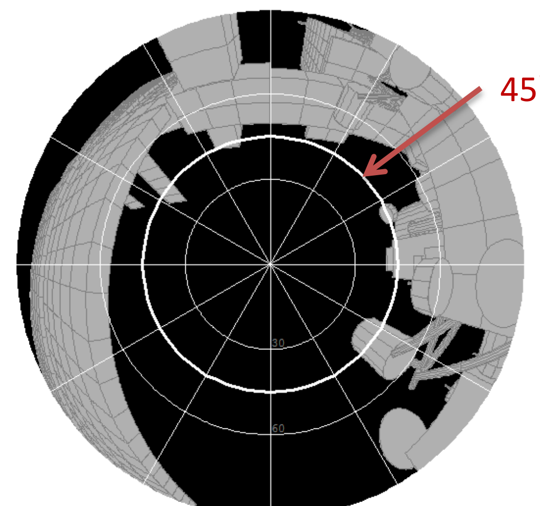
CALET has a Field-Of-View of 45$^{o}$ from its position at Port No.9. (A small part of the FOV is covered by thin structural material.




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

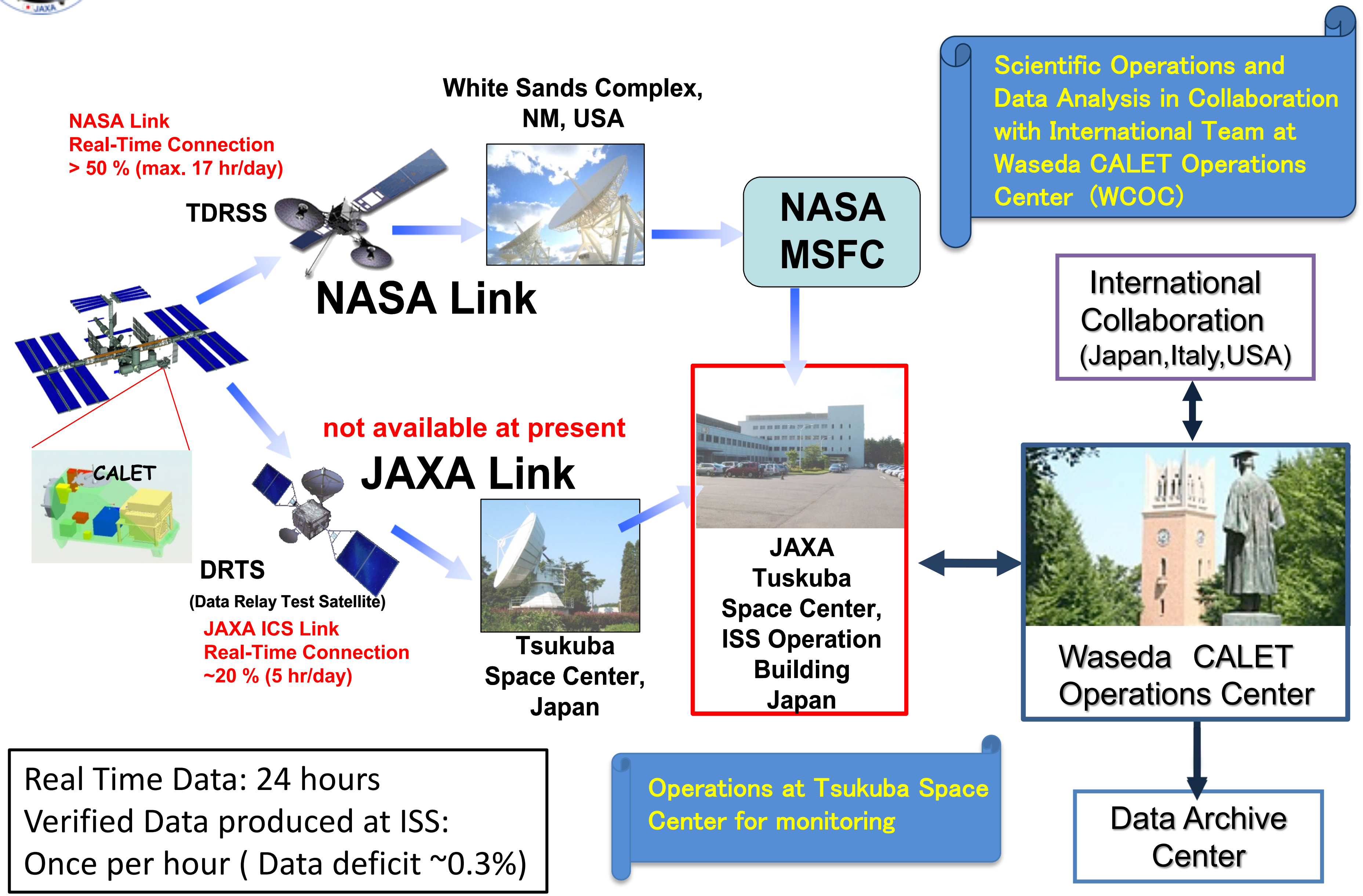



**ISS simplified model**



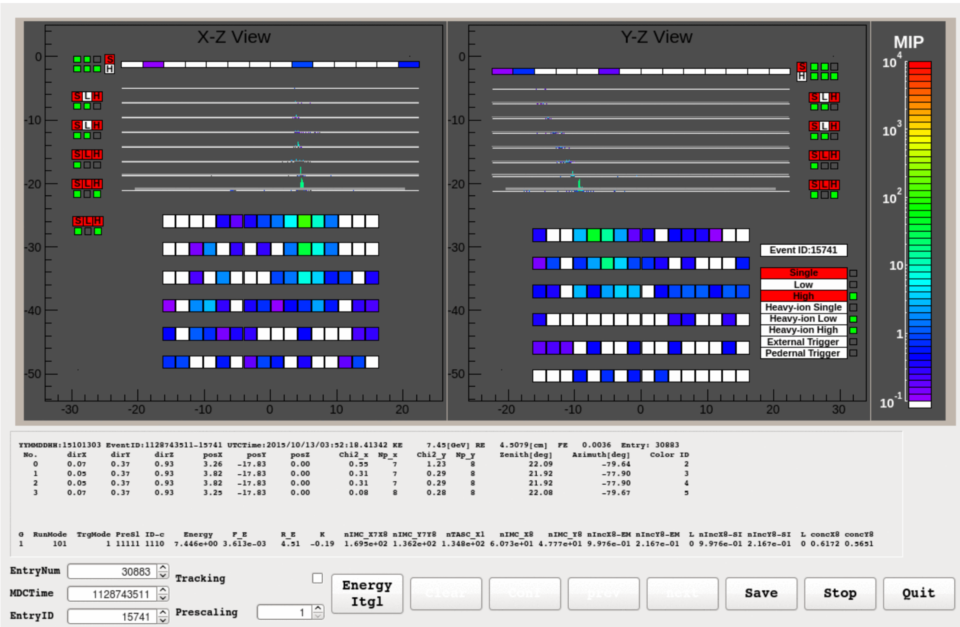

**CALET FOV**

# Data Downlink to Waseda COC via TDRS

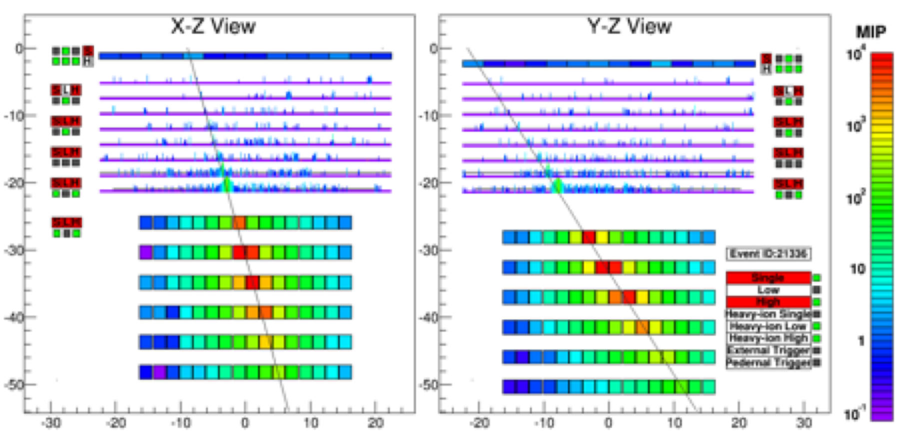


# Examples of Observed Events

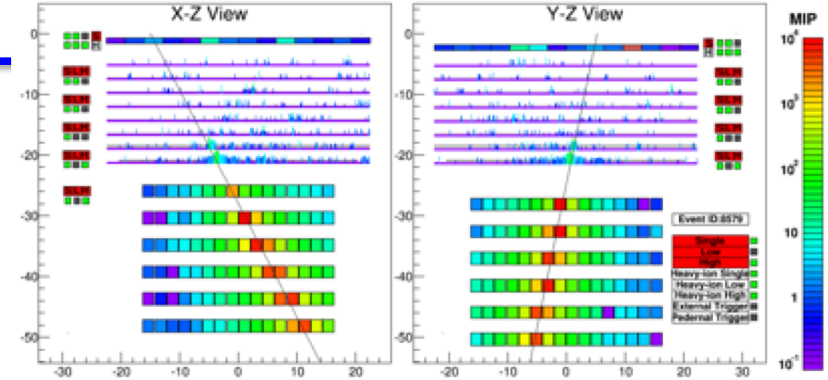
## Event Display: Electron Candidate (>100 GeV)



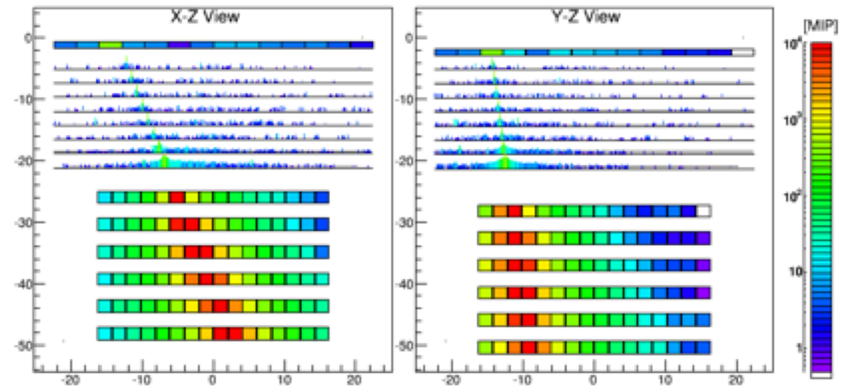

## Electron, E=3.05 TeV



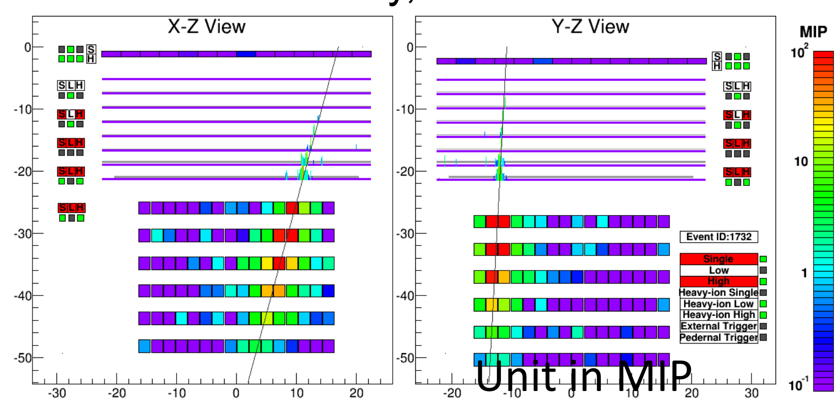

## Proton, ΔE=2.89 TeV




## Fe, ΔE=9.3 TeV




## Gamma-ray, E=44.3 GeV




Unit in MIP

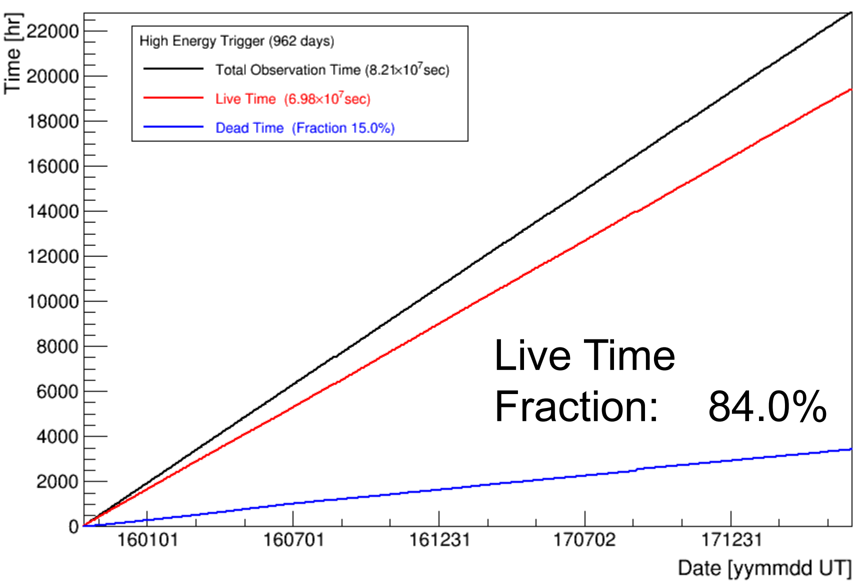
# Observation with High Energy Trigger (>10GeV)

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

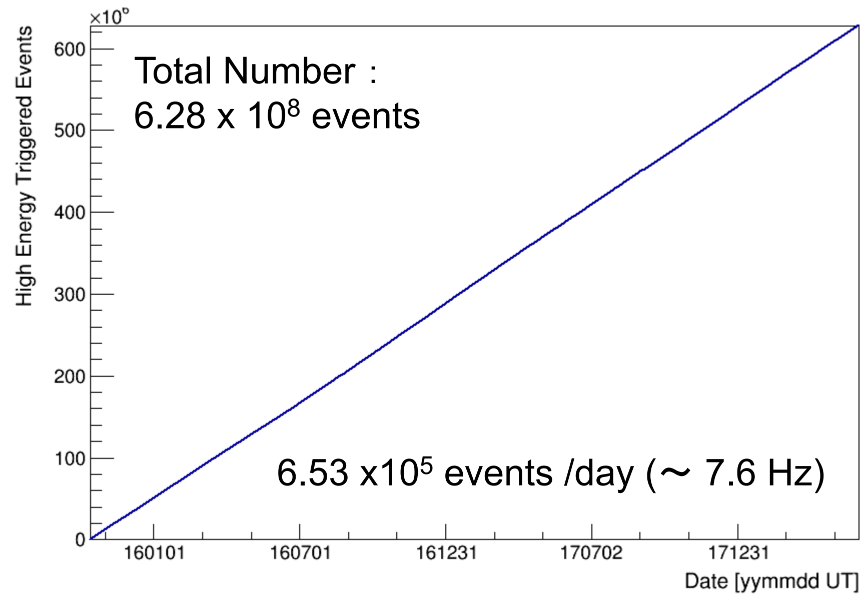
Observation by High Energy Trigger for 962 days : Oct.13, 2015 – May 31, 2018

- 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)

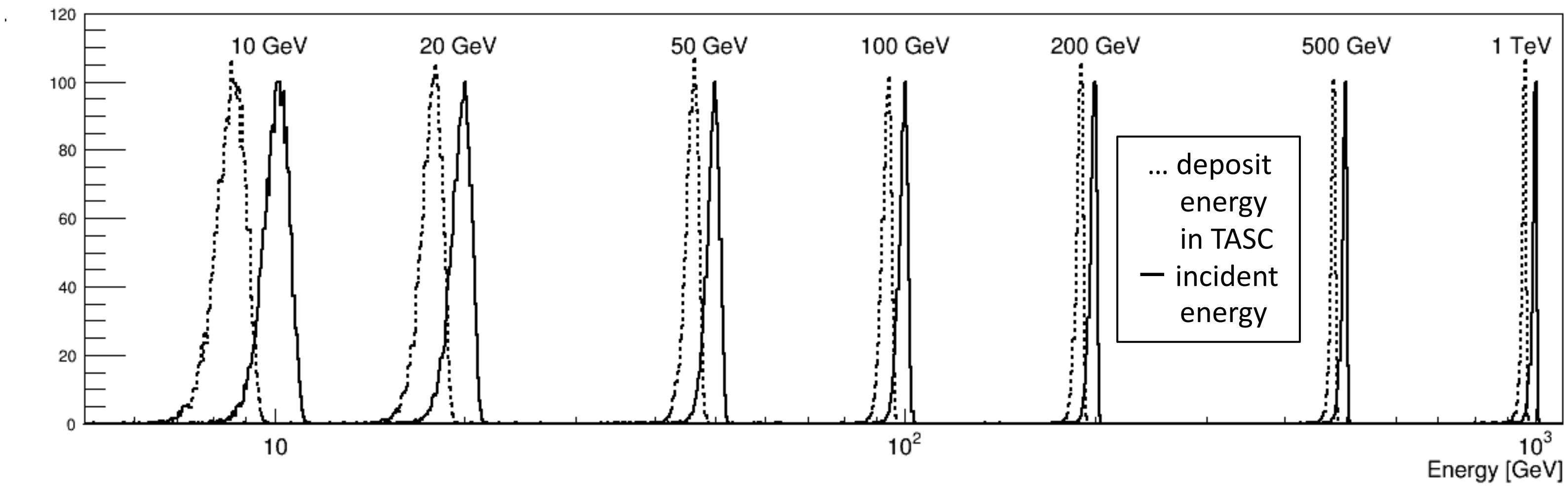


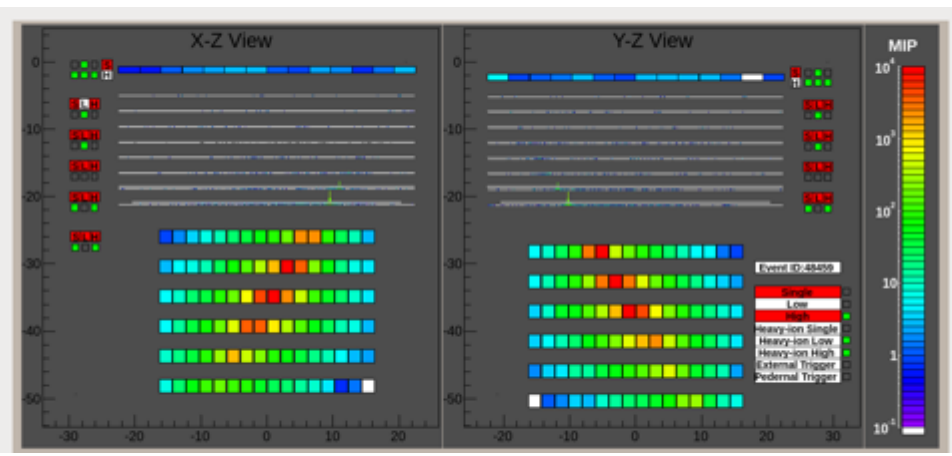

Accumulated triggered event number



# Energy Reconstruction for Electromagnetic Showers

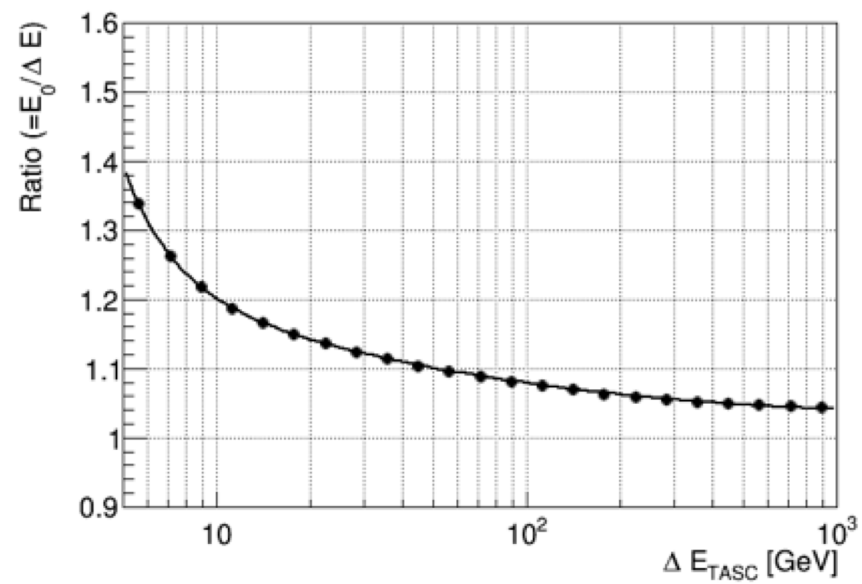
Simulation: Comparison of deposit energy in TASC ($\Delta E$) with incident energy ($E_0$)



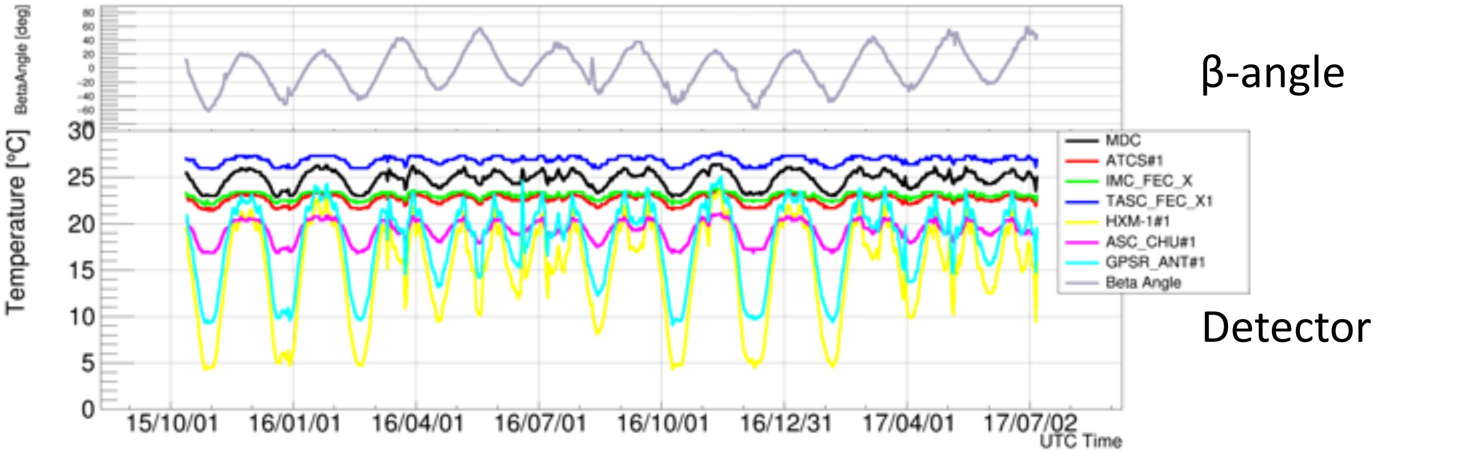

4 TeV electron candidate (well contained)
⇒ very small leakage (~ a few %)

Energy reconstruction factor vs. Energy

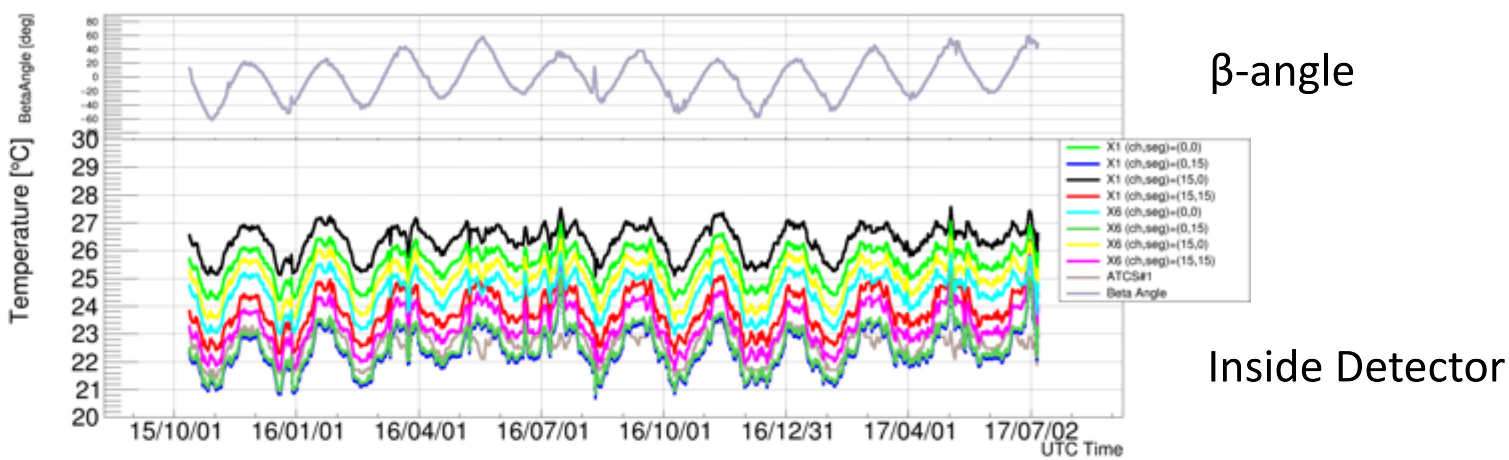


# Temperature Variation

- Period: 2015/10/13 – 2017/06/30
- Daily averaged temperatures and solar beta angle are plotted as a function of time.



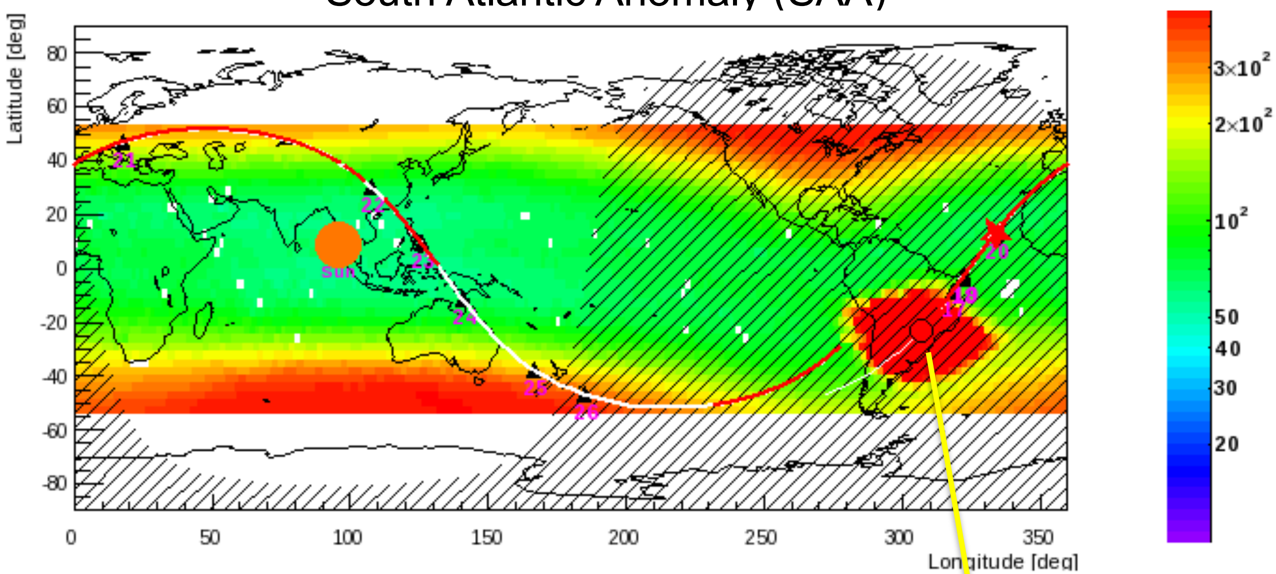

While rather large temperature variations are observed for exposed sensors (GPSR, ASC,HXM), the variations are much smaller for sensors attached to the calorimeter (IMC,TASC,MDC) due to the Active Thermal Control System (ATCS) . The temperature variation has clear correlation with solar beta angle.




The temperature variations inside the detector are kept within a few degrees by using the ATCS.

# ISS Radiation Environment

South Atlantic Anomaly (SAA)

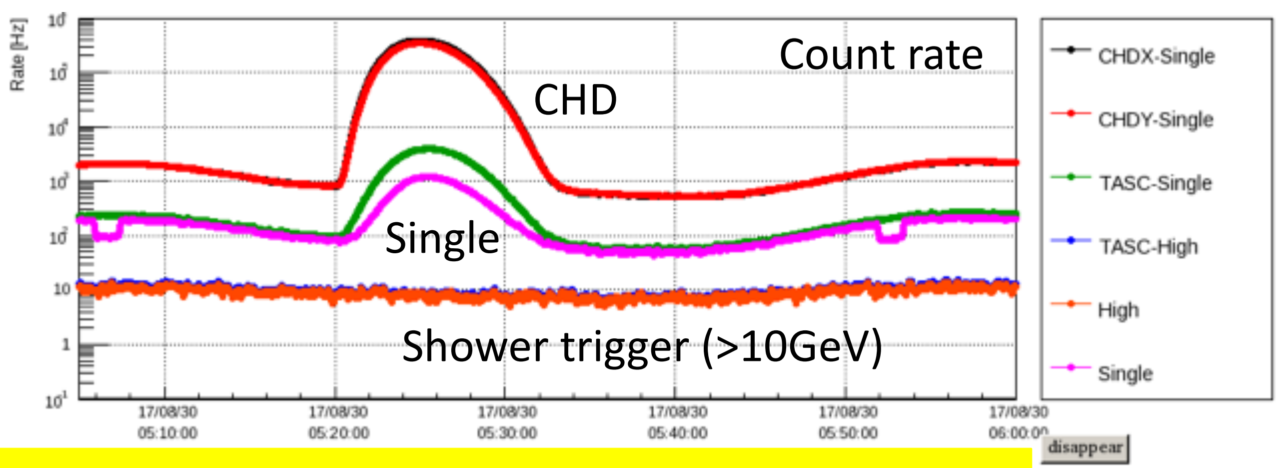



<u>ISS orbit</u>
<u>@ 2017/08/29 5:25UT</u>
ISS ran through SAA.

CHD count rate jumped up to ~3x$10^5$ Hz from $10^3$ Hz, but the HE trigger rate remained stable.

<u>Trigger/Count Rate</u>
<u>@ 2017/08/29</u>

HE trigger was not affected by SAA thanks to high energy threshold (>10 GeV).
(Energies of the trapped particles are too low to make a trigger for the observations.)

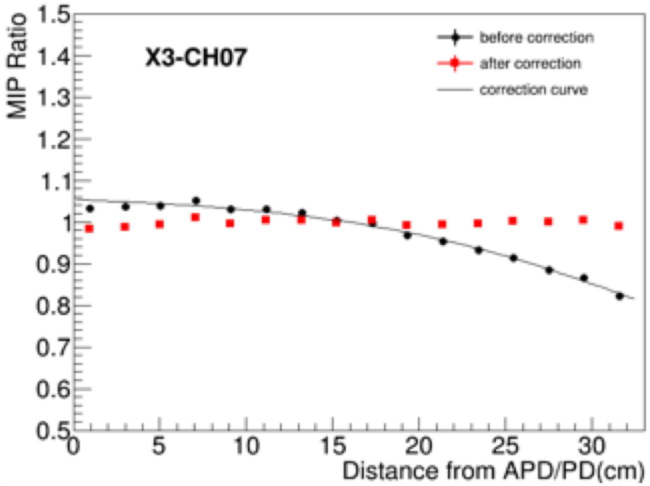



**⇒ Observation is continuously carried out even at SAA!**

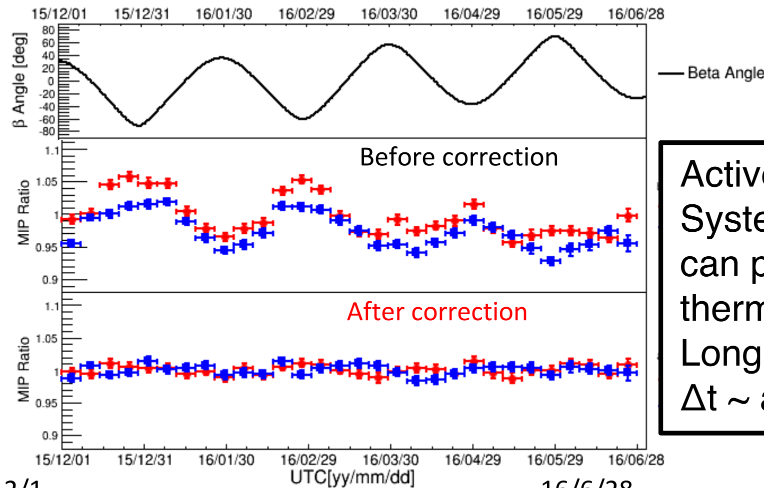
# Position and Temperature Calibration and Long-term Stability

## TASC

Example of position dependence correction

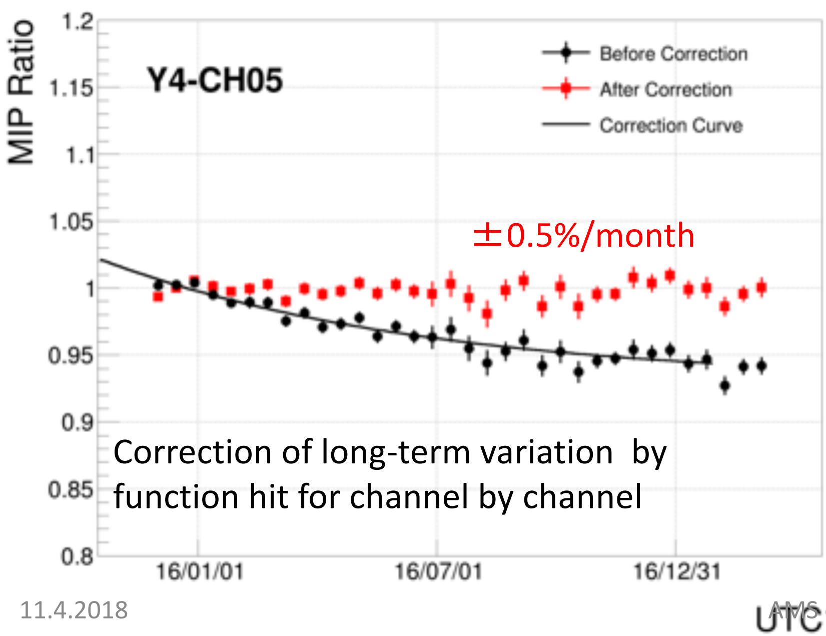



Examples of temperature change correction

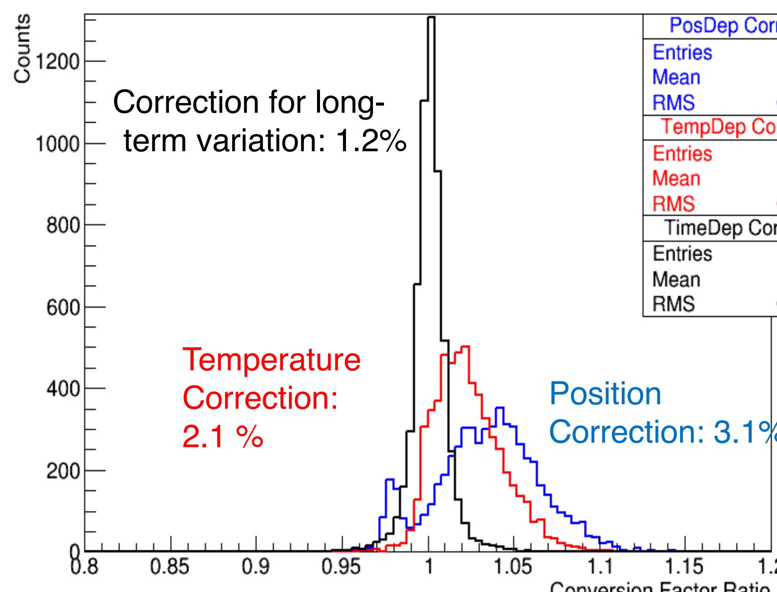



Active Thermal Control System (ATCS) on ISS can provide very stable thermal condition during Long-tem observations: Δt ~ a few degrees

Example of long-term variation correction

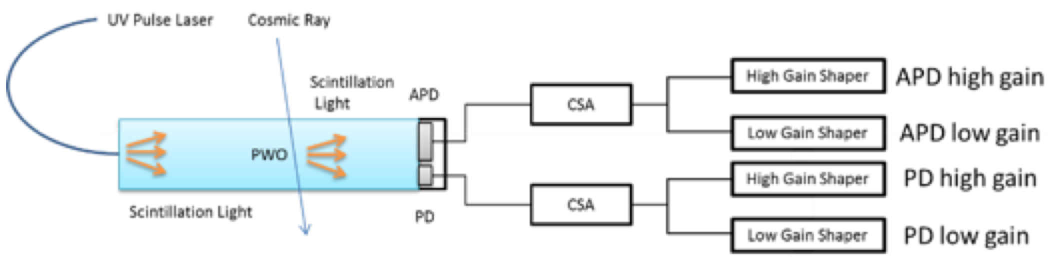


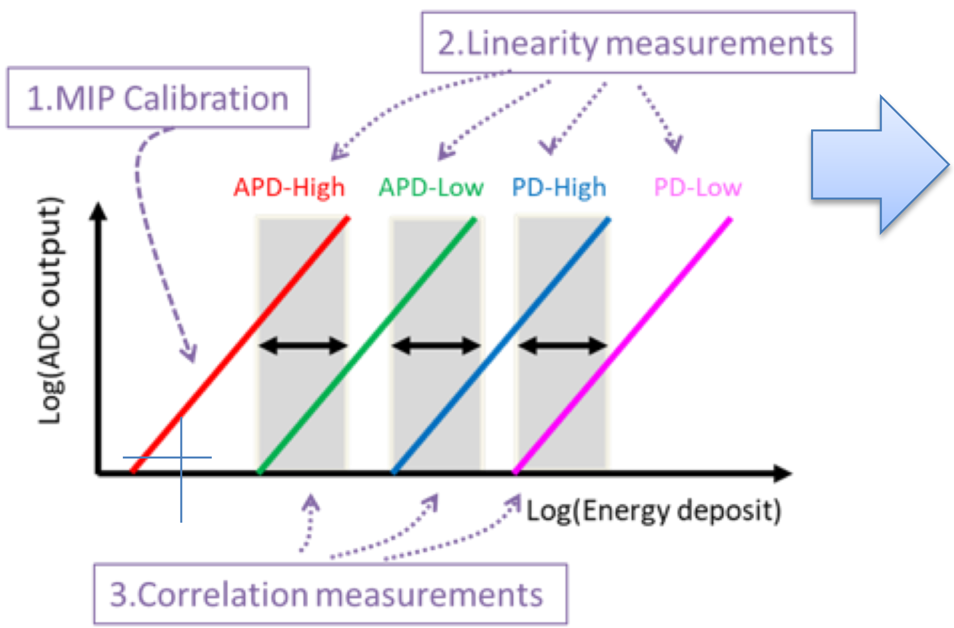

Distribution of MIPs for 192 ch x 16 segmented positions after each correction

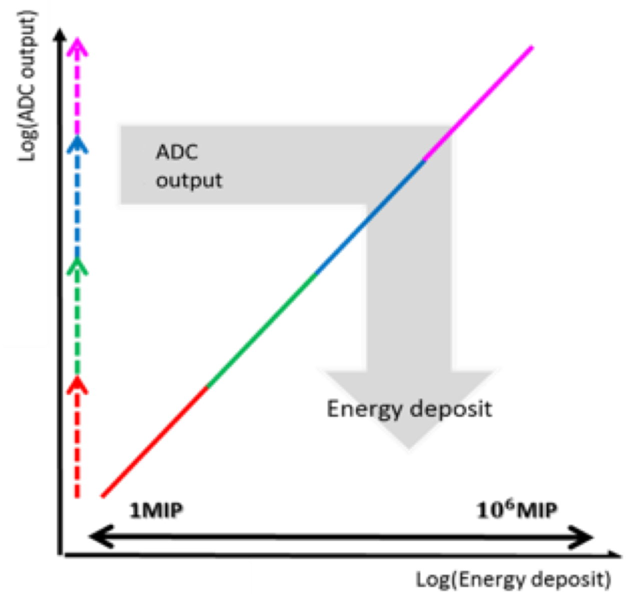


# Energy Measurement Using TASC in Range up to $10^6$ MIPs

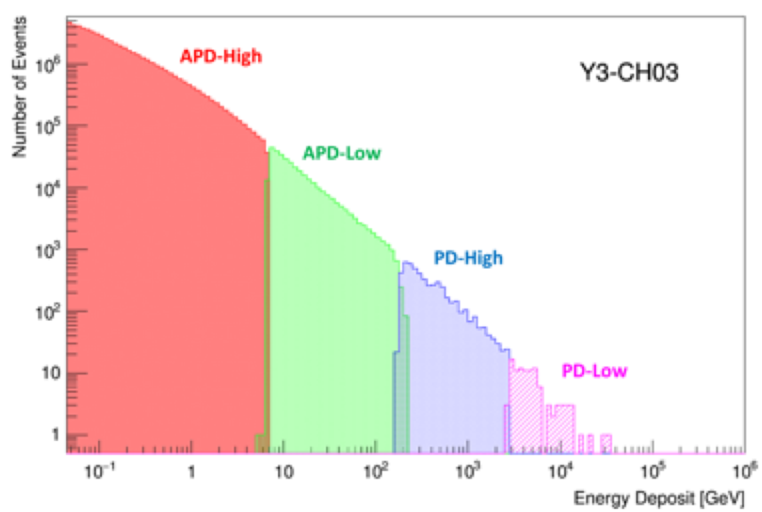
Calibration done by UV pulse laser



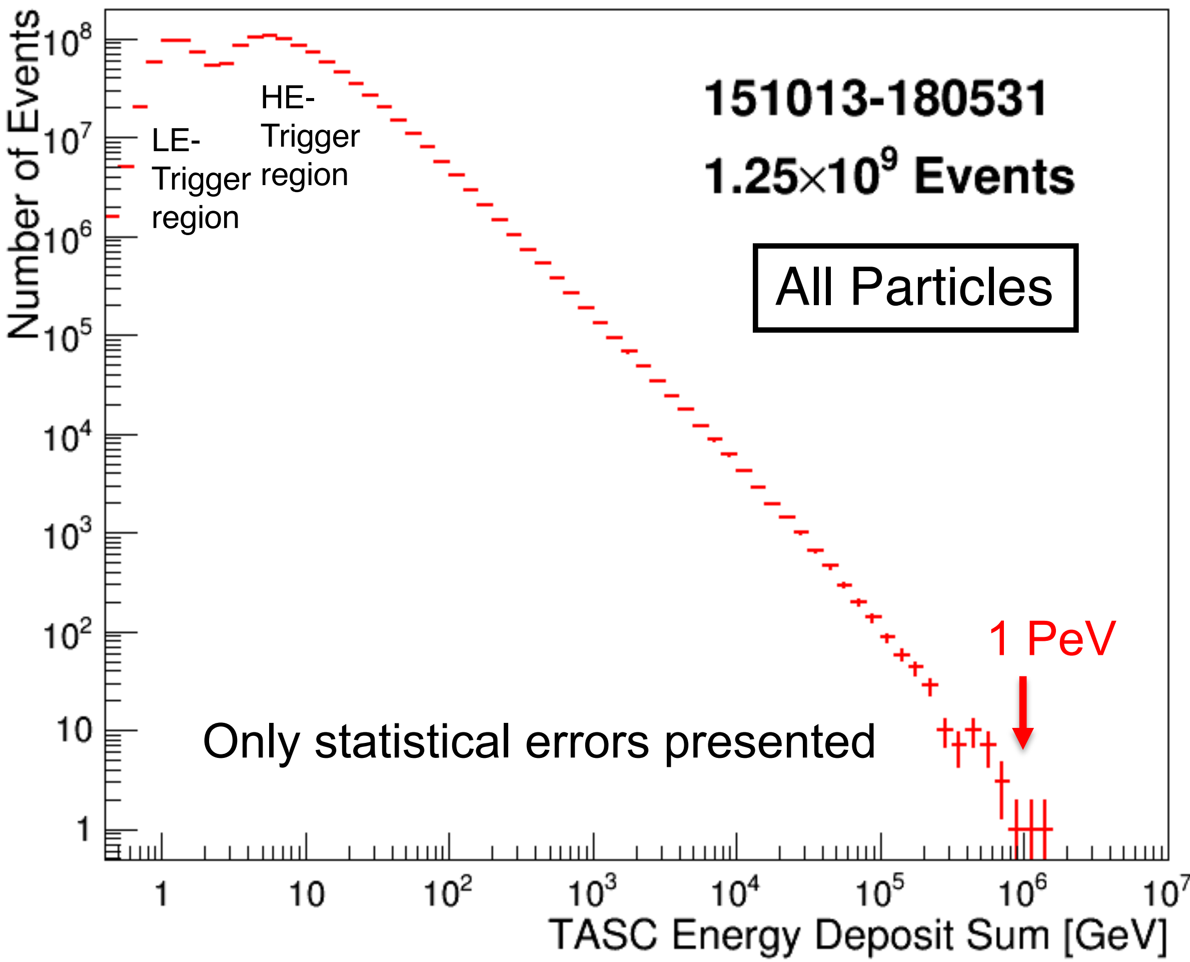

Example of energy measurement in one log of TASC




Details of our energy calibration can be found at:
Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al., Astropart. Phys. 91 (2017) 1.

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

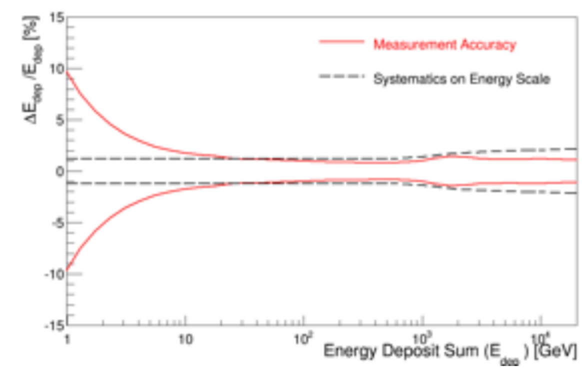
Distribution of deposit energies (ΔE) in TASC



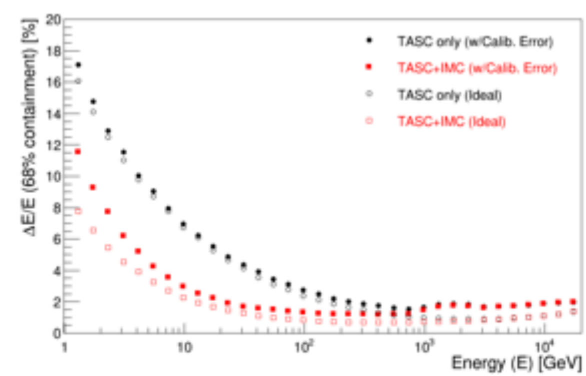

The TASC energy measurements have successfully been carried out in the dynamic range of 1 GeV – 1 PeV.

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 20GeV



# 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

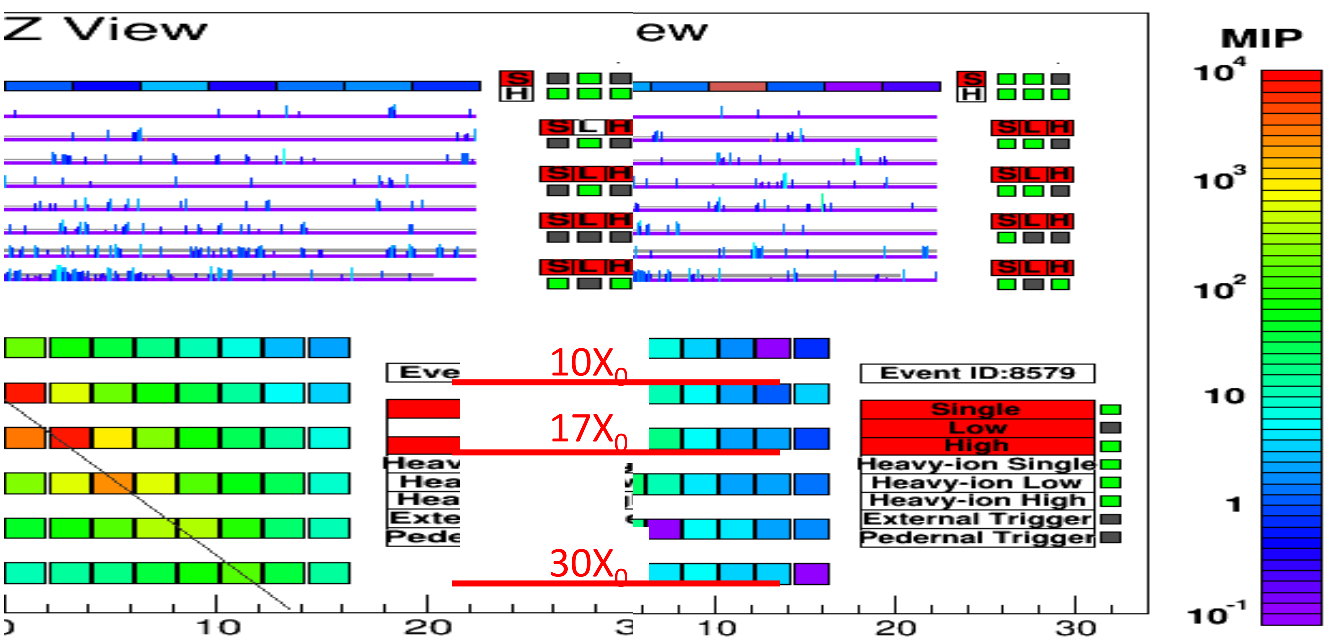
# All-Electron (electron + positron) Analysis

## 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**



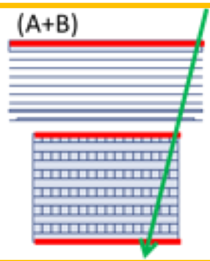

(Flight data; detector size in cm)

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

# Event Selection

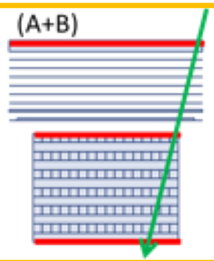
**Analyzed Flight Data:**

- 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)

# Event Selection




**Analyzed Flight Data:**

- 627 days (October 13, 2015 to June 30, 2017)
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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)

**Pre-selection:**

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

# Electron Identification

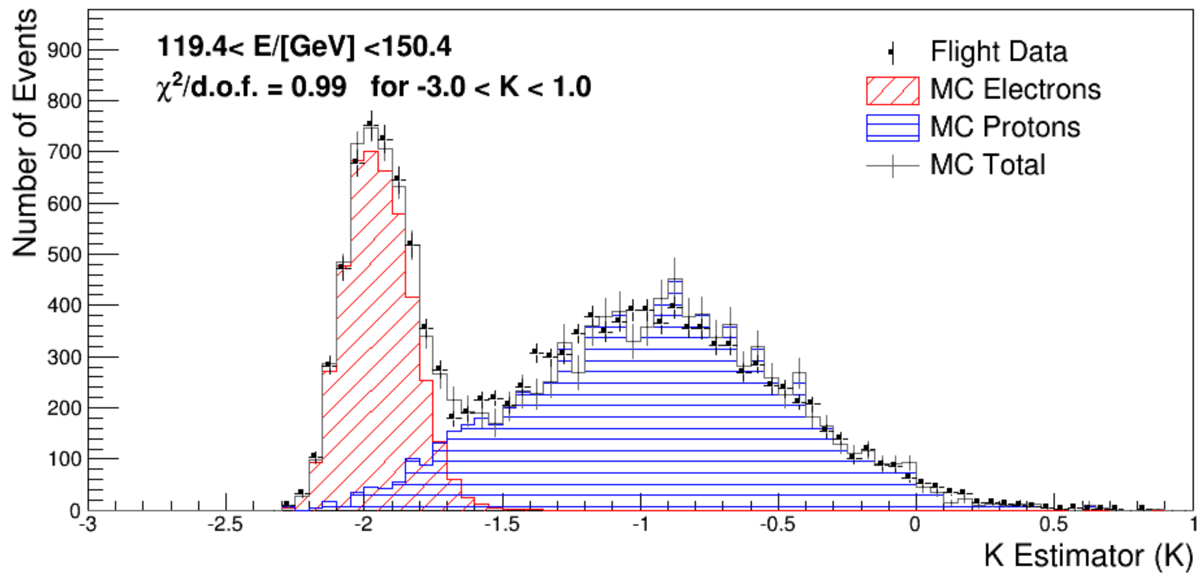
## Simple Two Parameter Cut

$F_E$: 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

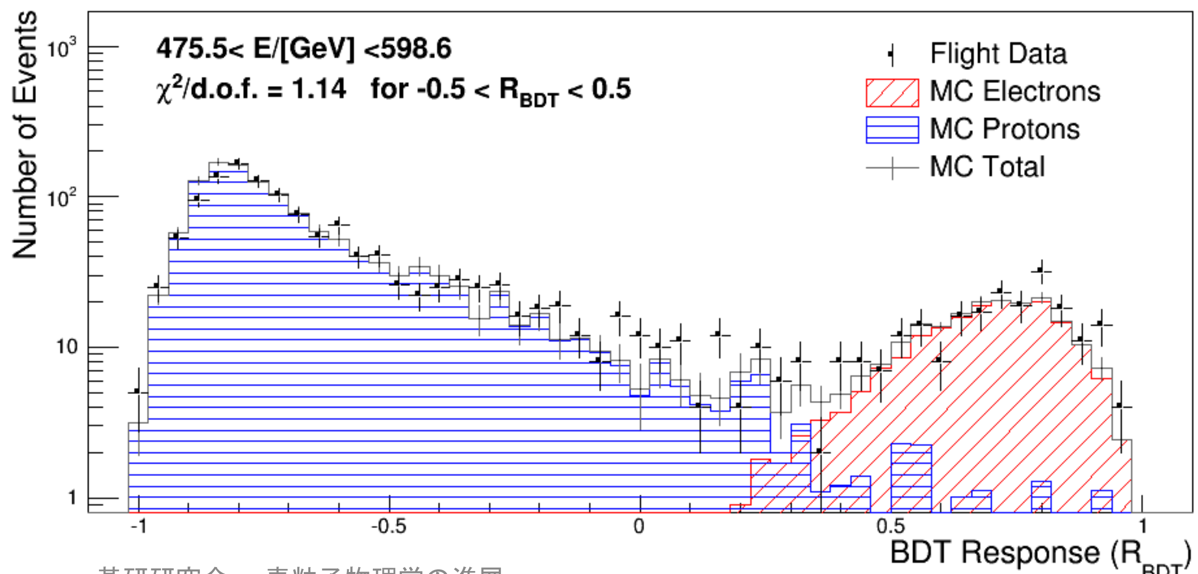
Separation Parameter K is defined as follows:

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

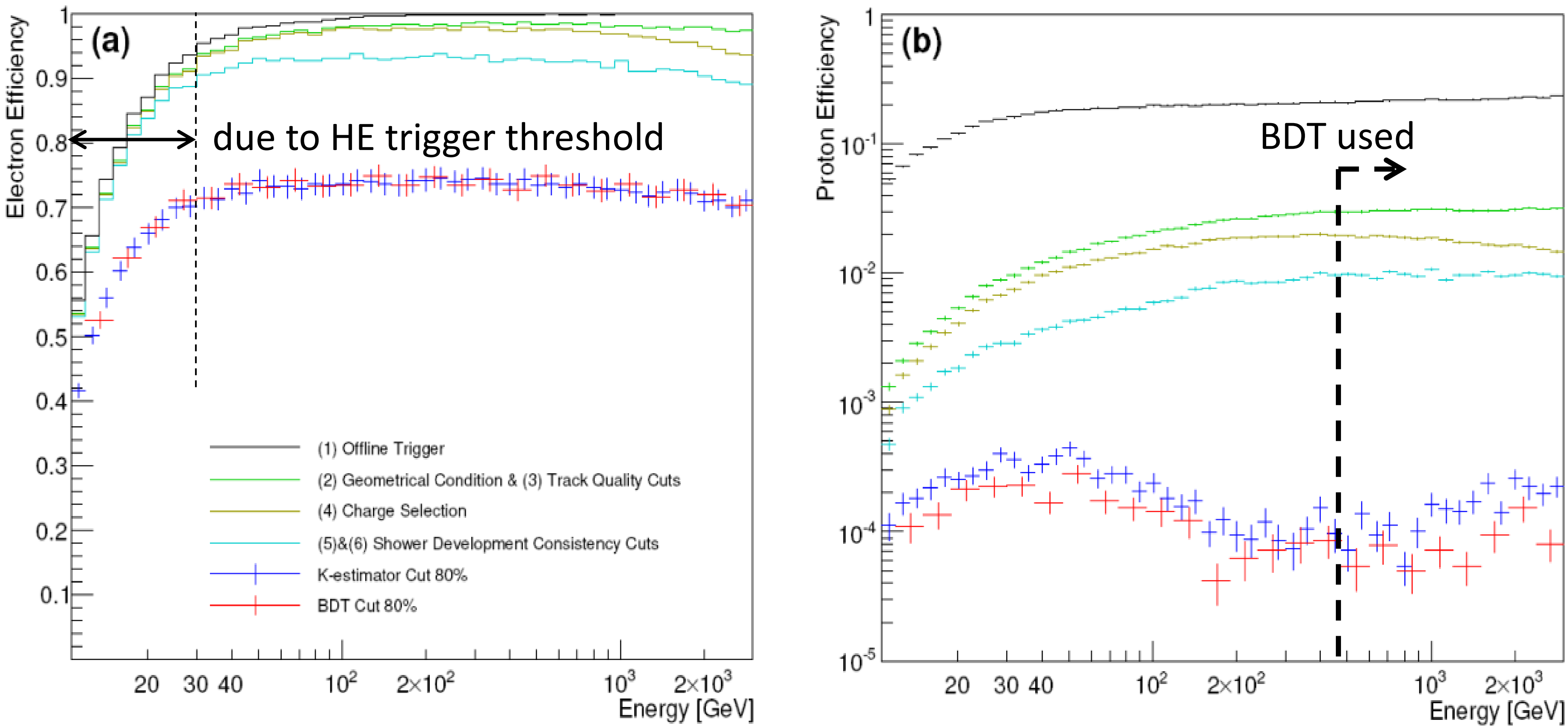



## Boosted Decision Trees

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



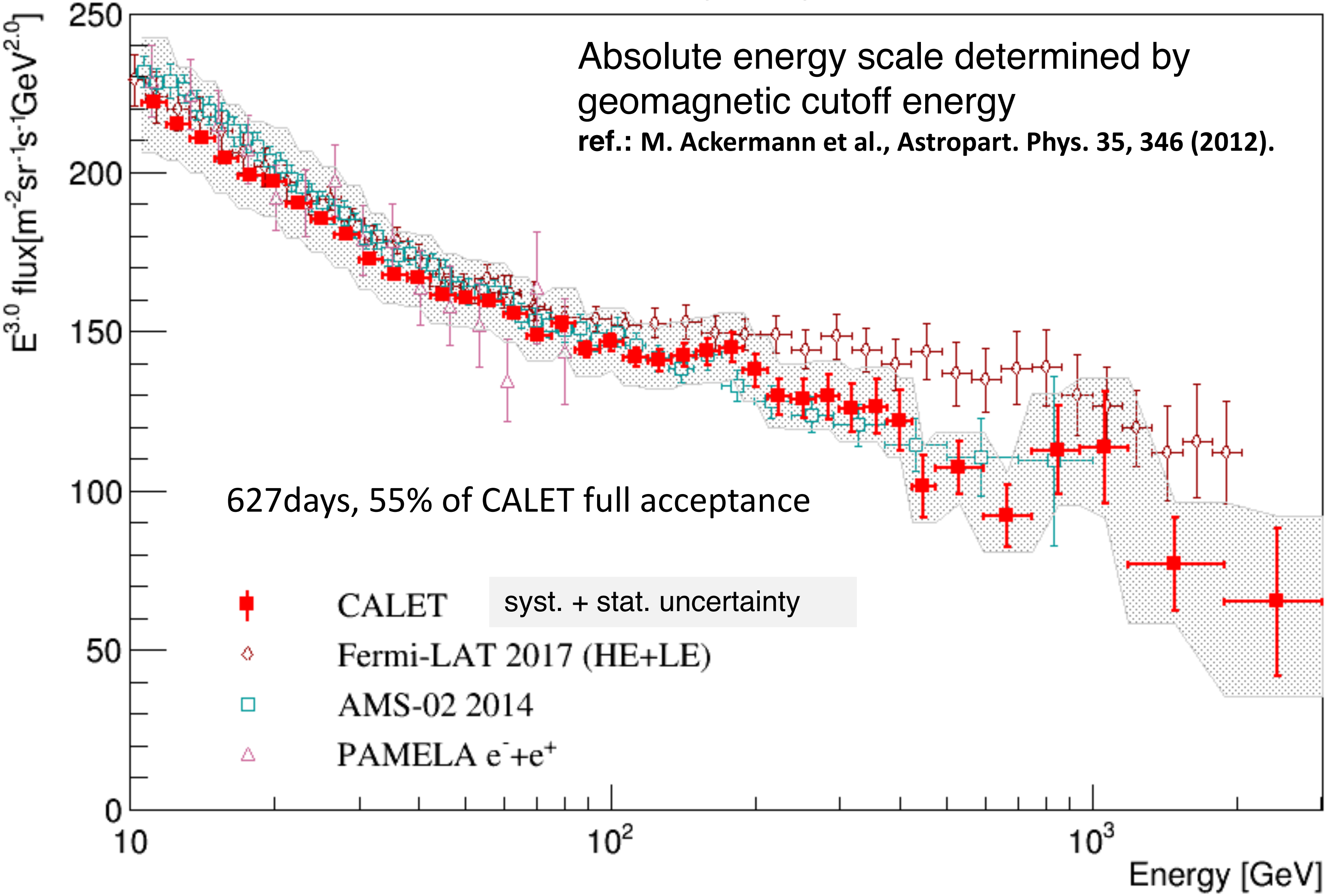
# Electron Efficiency and Proton Rejection




- 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 % in the 1—4.8 TeV region.

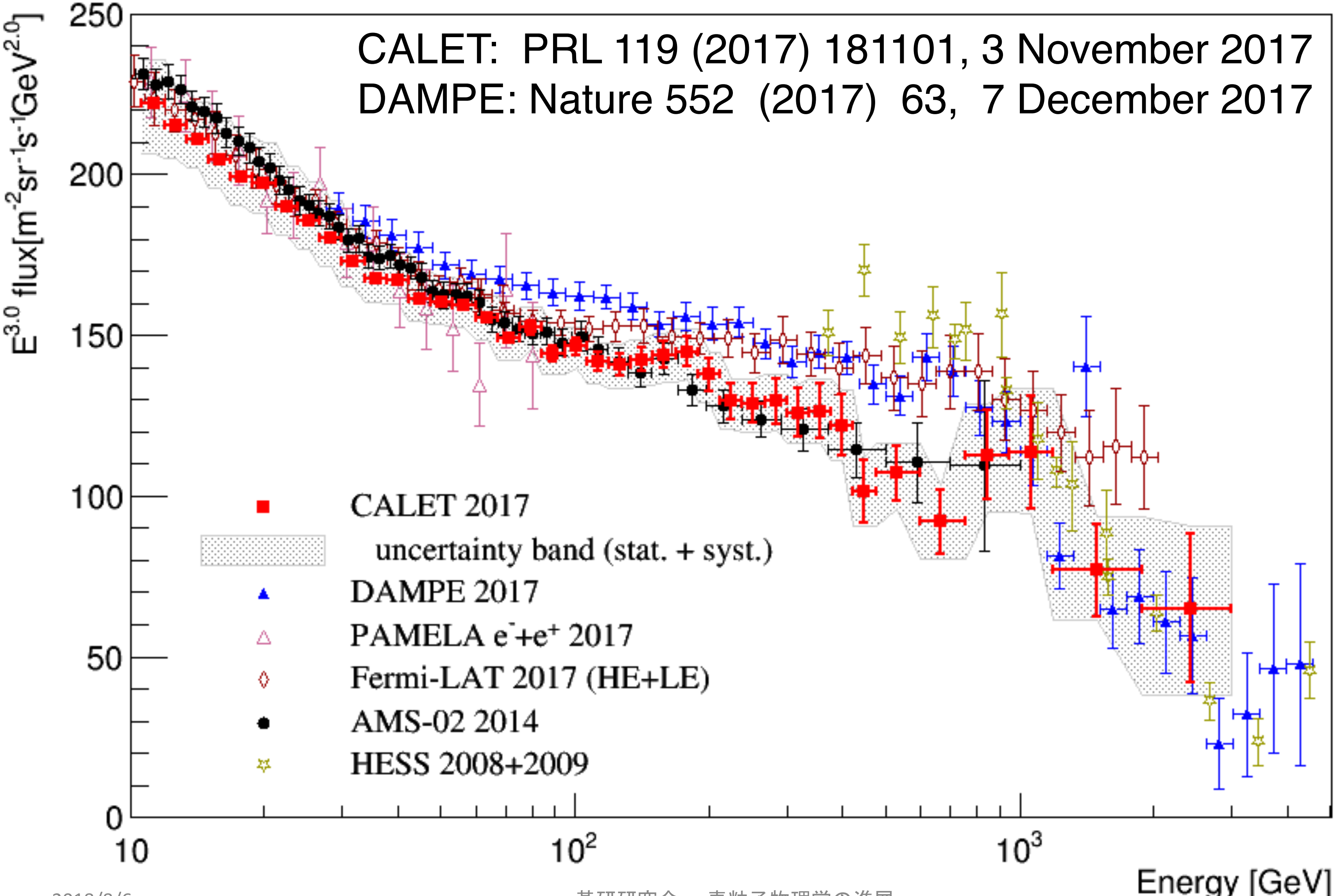
# All-Electron Spectrum Measured with CALET from 10 GeV to 3 TeV

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



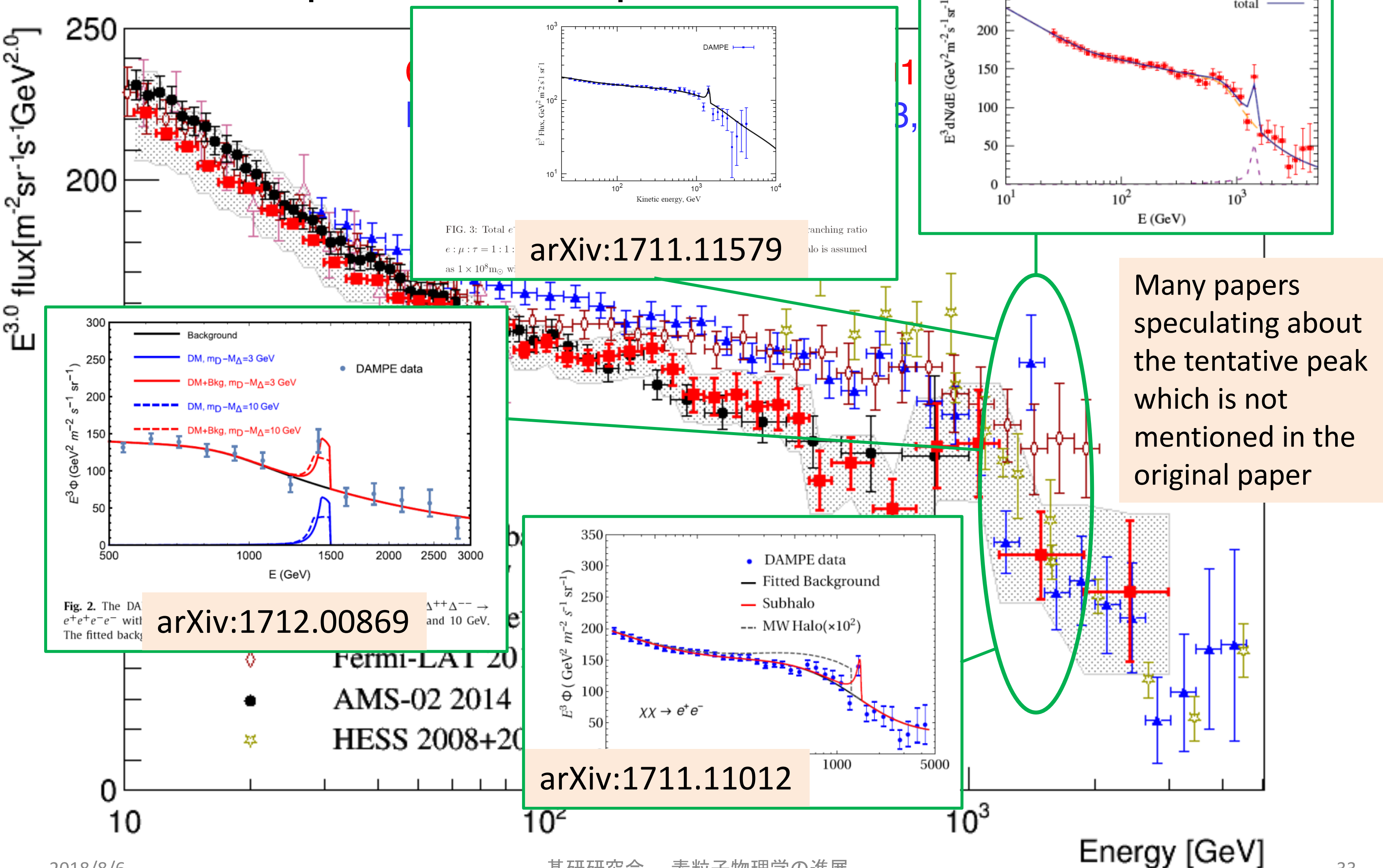
# All-Electron Spectrum Comparison w/ DAMPE

and other space based experiments



# All-Electron Spectrum Comparison w/ DAMPE

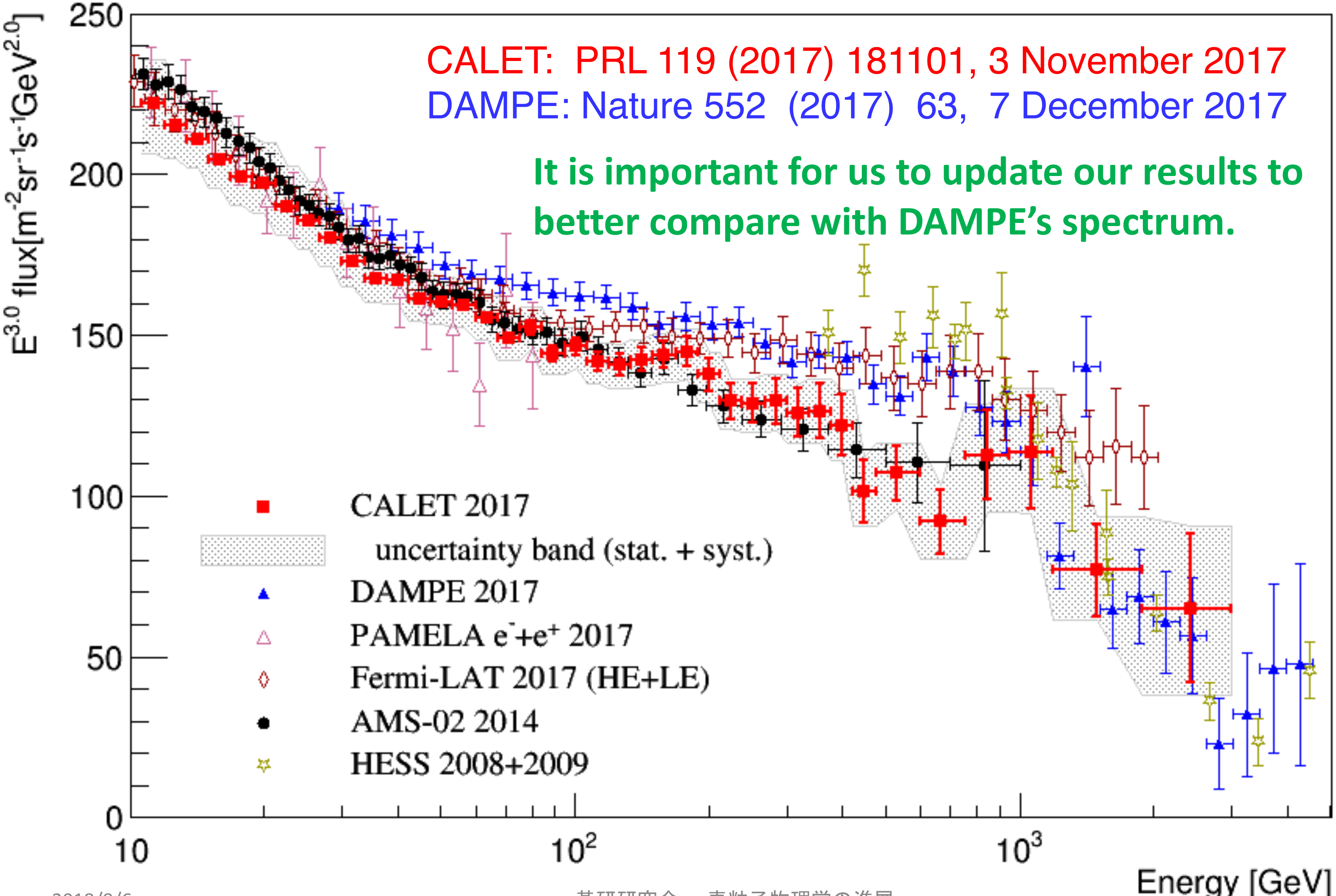
and other space based experiments




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

# All-Electron Spectrum Comparison w/ DAMPE

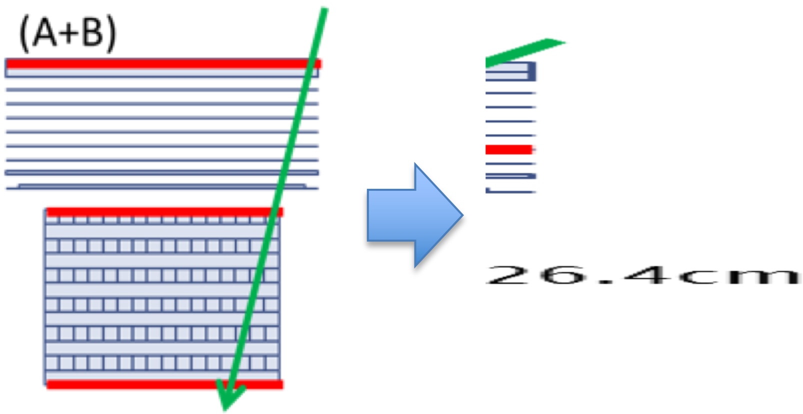
and other space based experiments

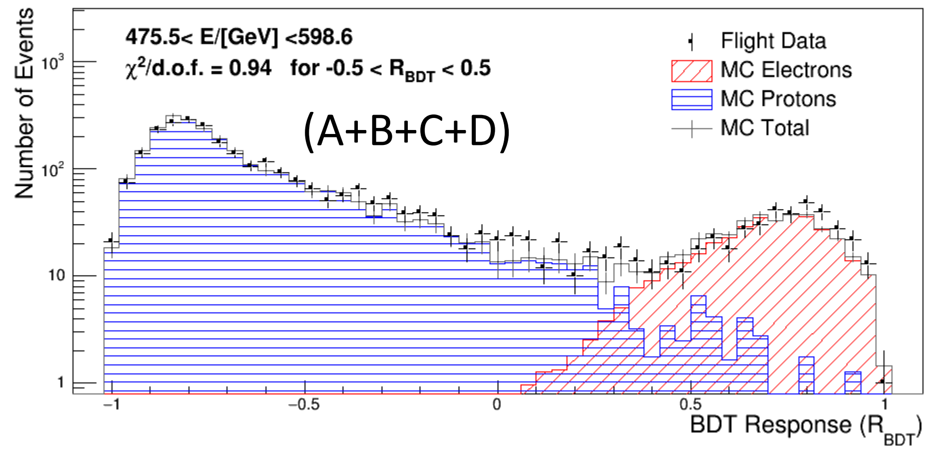


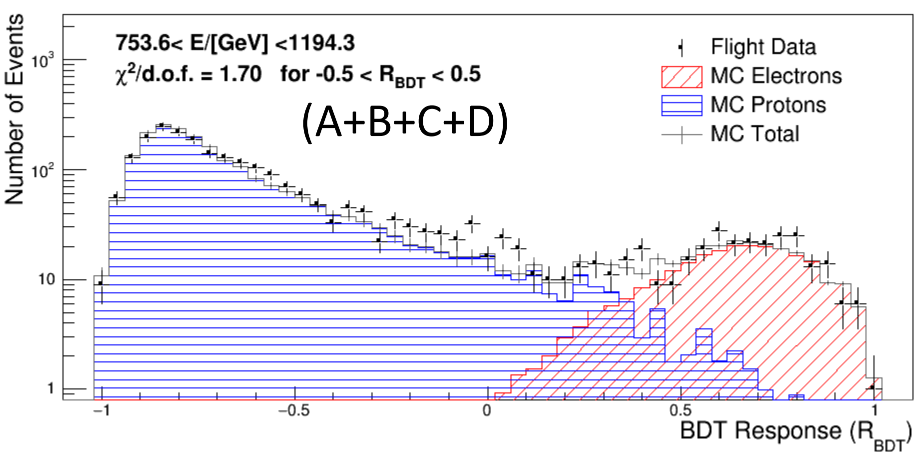
# Extending the Analysis to Full Acceptance

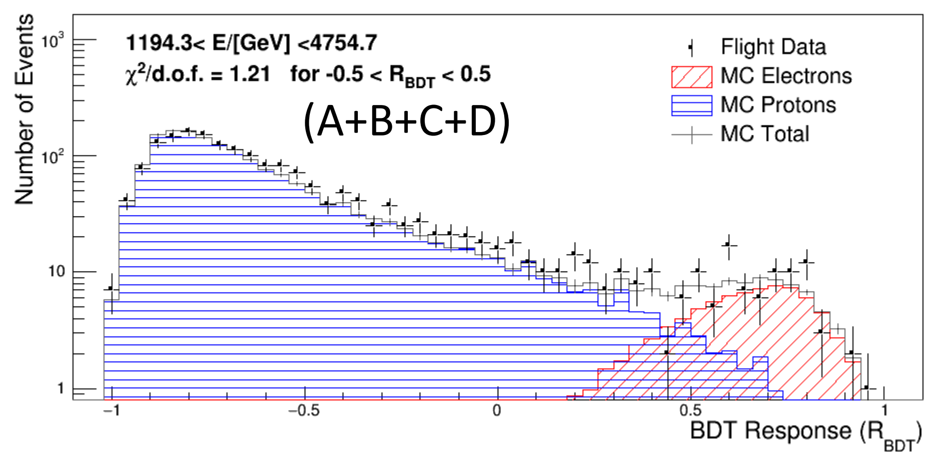
**Analyzed Flight Data:**

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



# Systematic Uncertainties

(other than energy scale uncertainty)

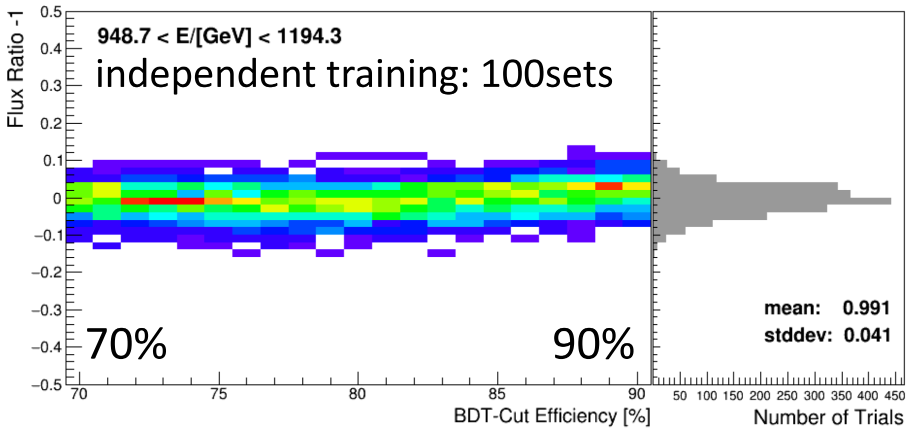
**Stability of resultant flux are analyzed by scanning parameter space**

Normalization:

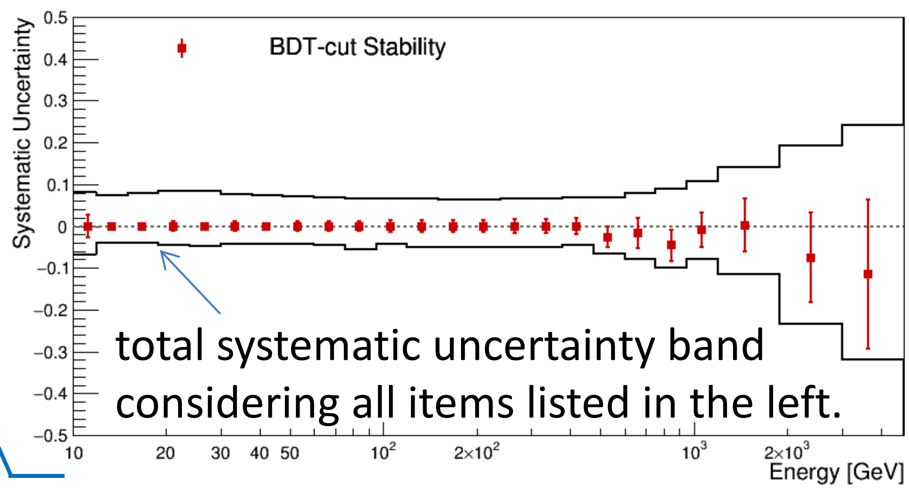
- Live time
- Radiation environment
- Long-term stability
- Quality cuts

- 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

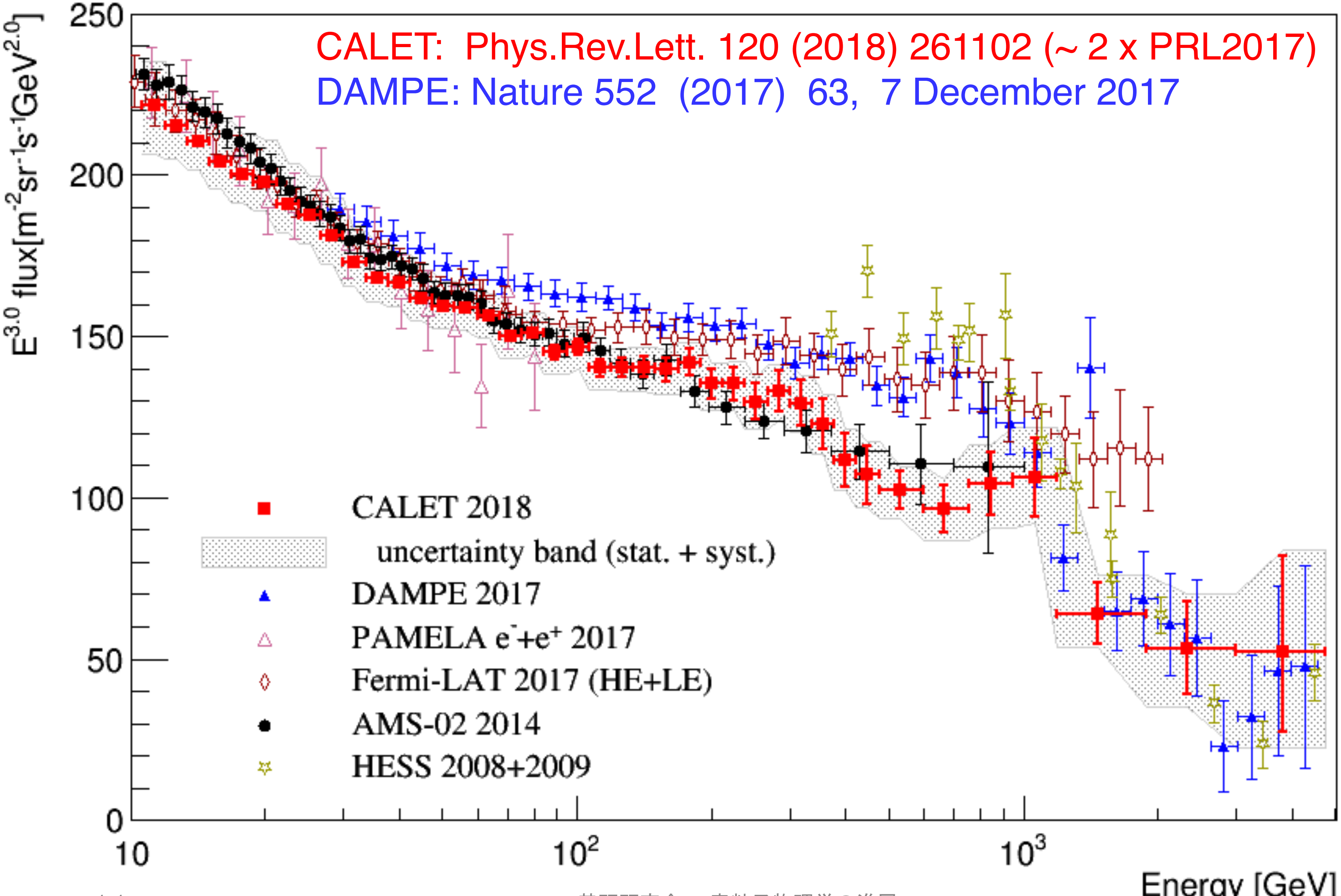



Energy Dependence of BDT stability



# Extended Measurement by CALET

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



# Extended Measurement by CALET

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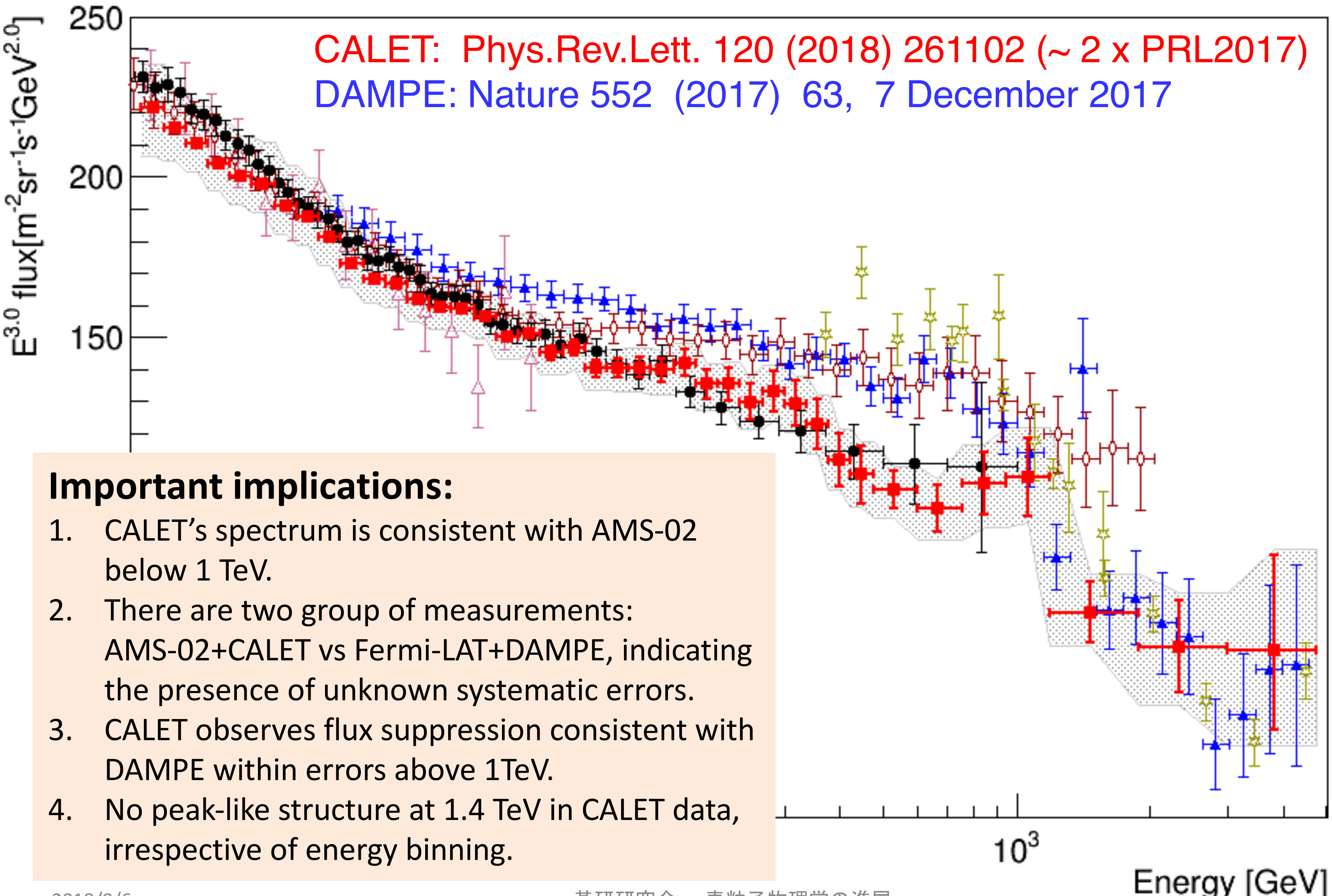
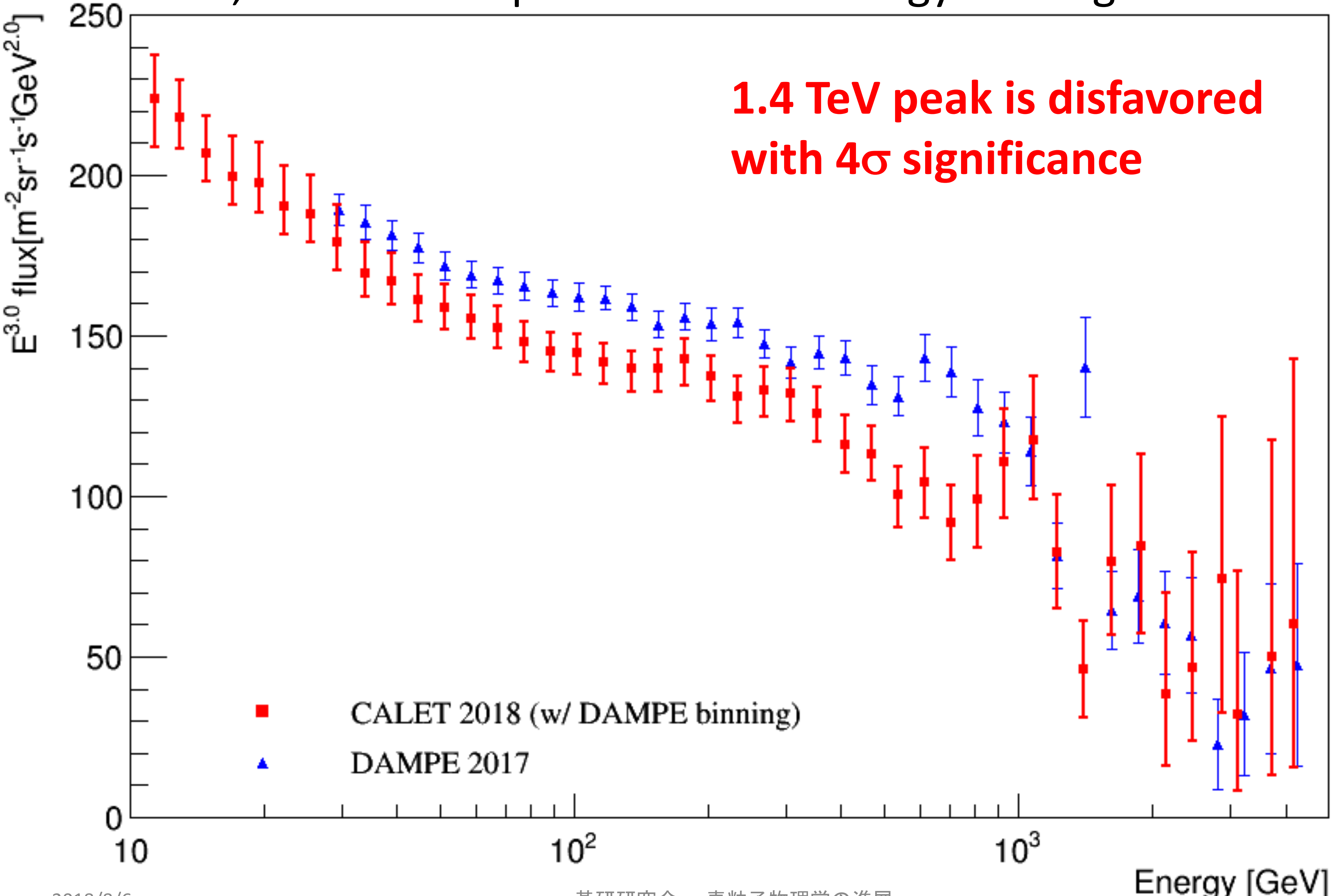



**Important implications:**

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.

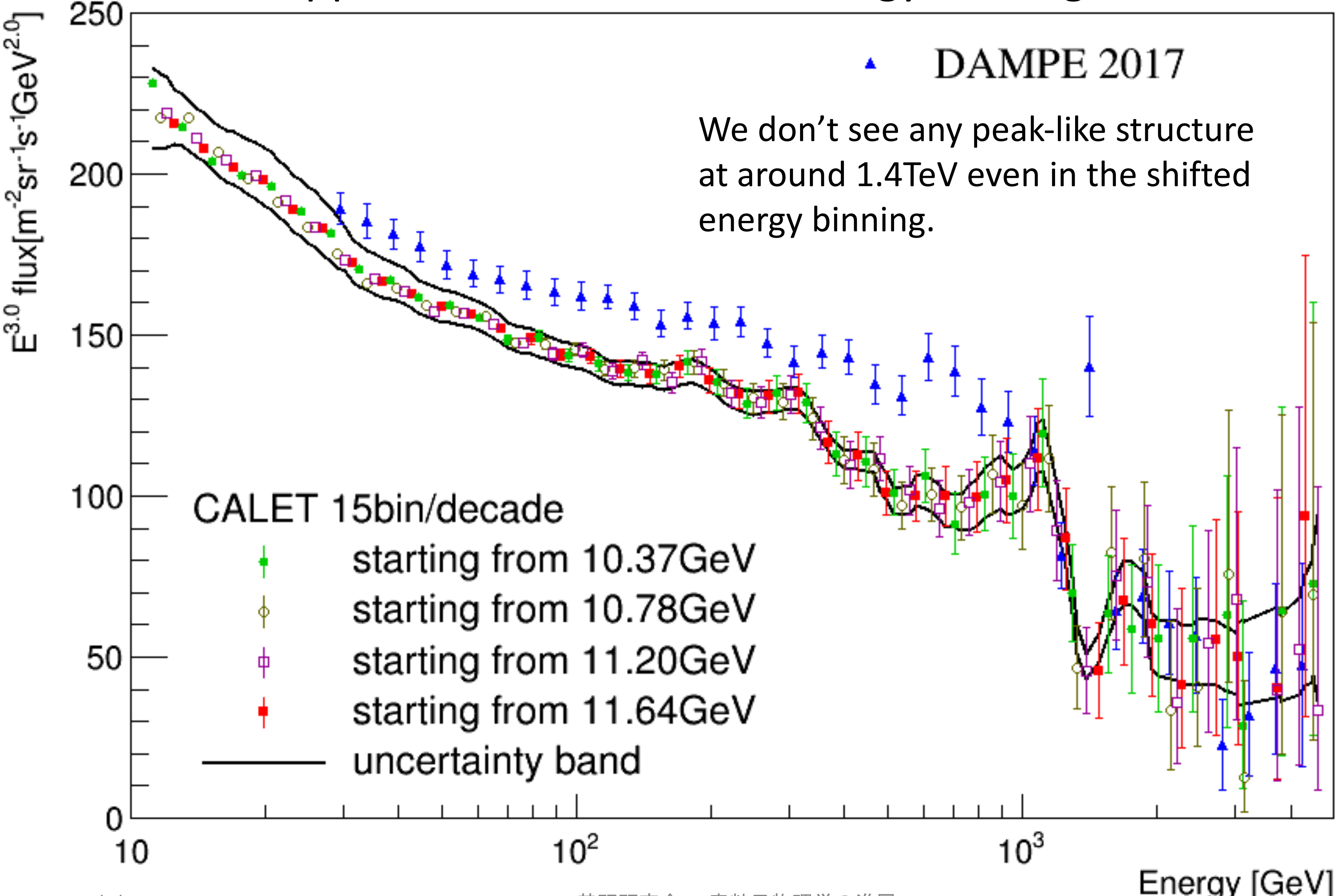
# Comparison with DAMPE's result

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



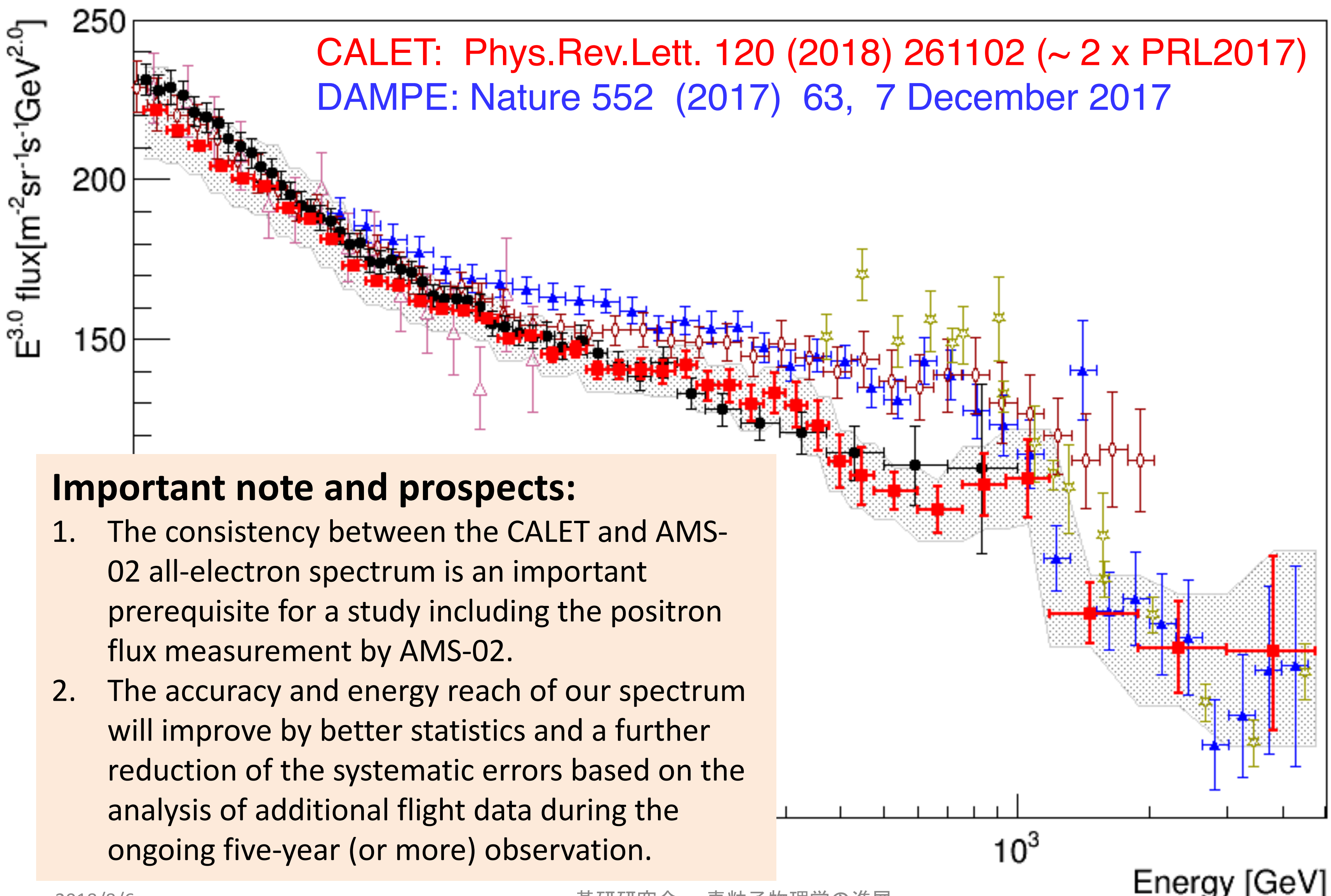
# Comparison with DAMPE's result

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:**

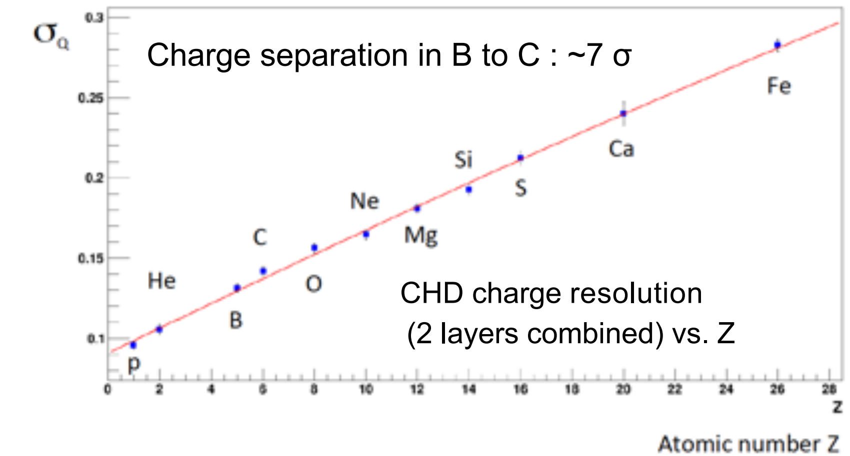
1. The consistency between the CALET and AMS-02 all-electron spectrum is an important prerequisite for a study including the positron flux measurement by AMS-02.
2. The accuracy and energy reach of our spectrum will improve by better statistics and a further reduction of the systematic errors based on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

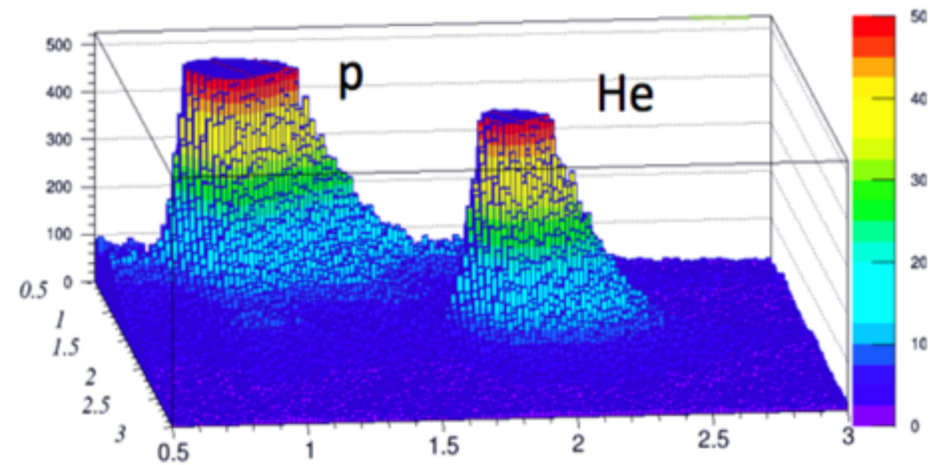
# Hadrons & Gamma-Rays

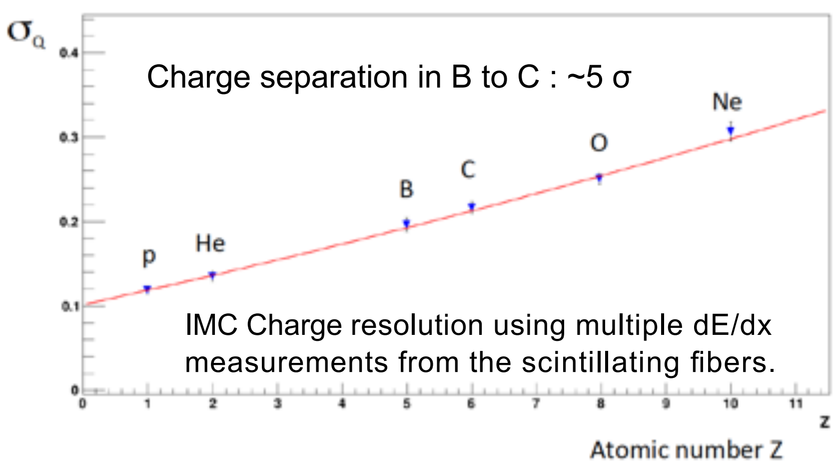
To be published in ApJS

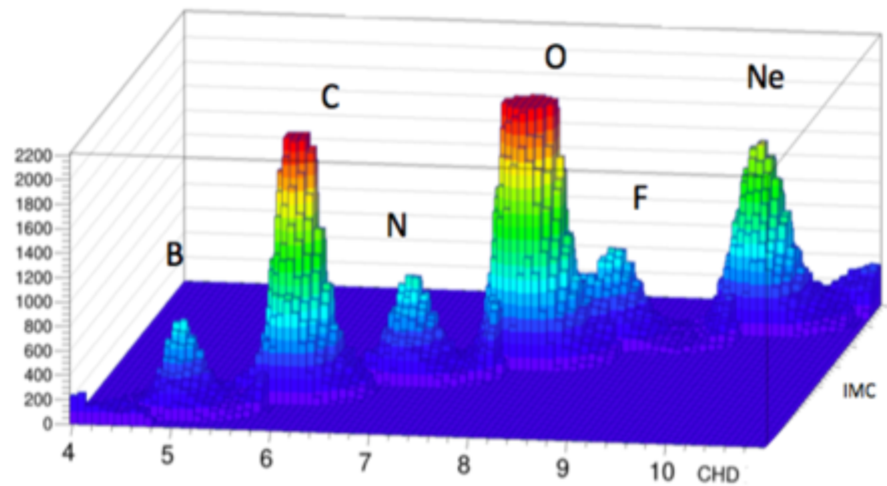
# Charge Identification of Nuclei with CHD and IMC

Single element selection for p, He and light nuclei is achieved by CHD+IMC charge analysis




*) Plots are truncated to clearly present the separation.

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

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

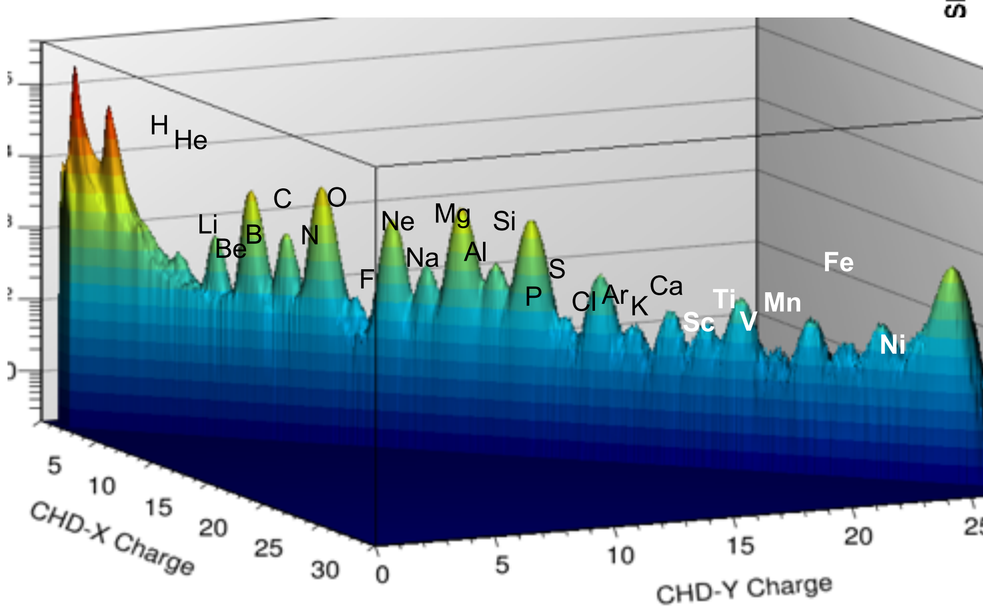
# Preliminary Flux of Primary Components

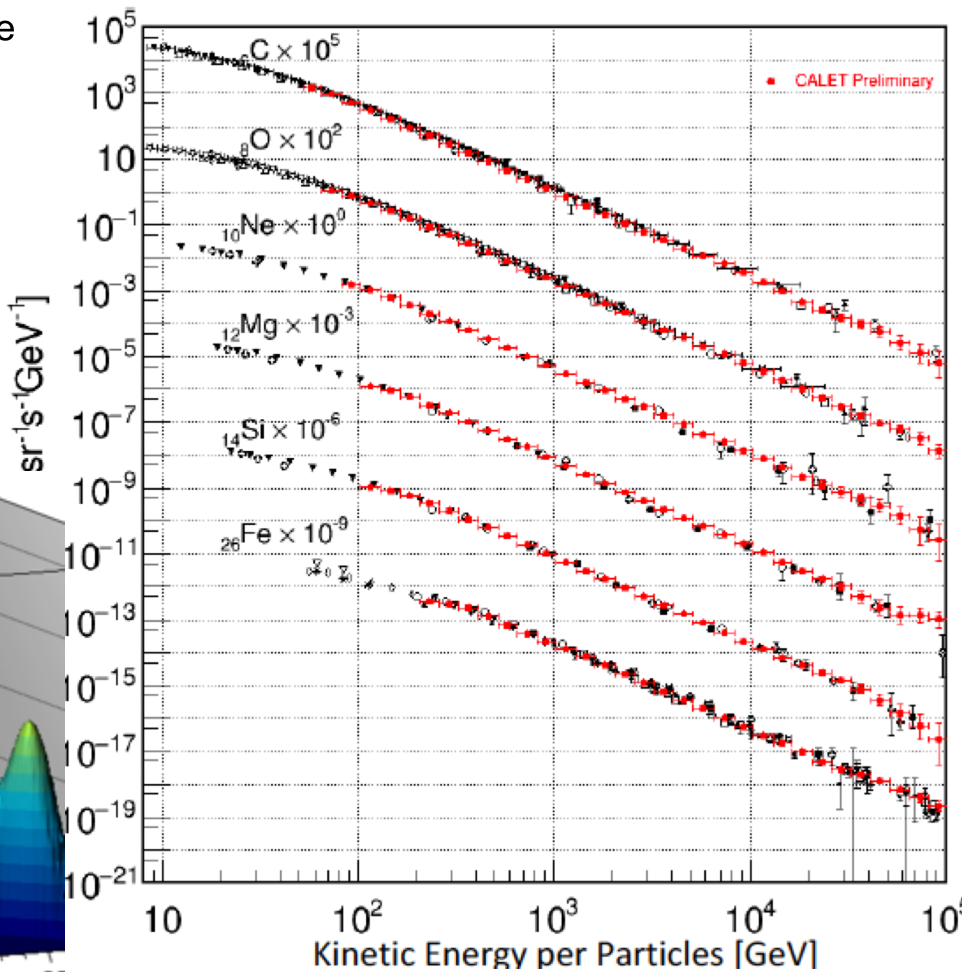
Flux measurement:

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

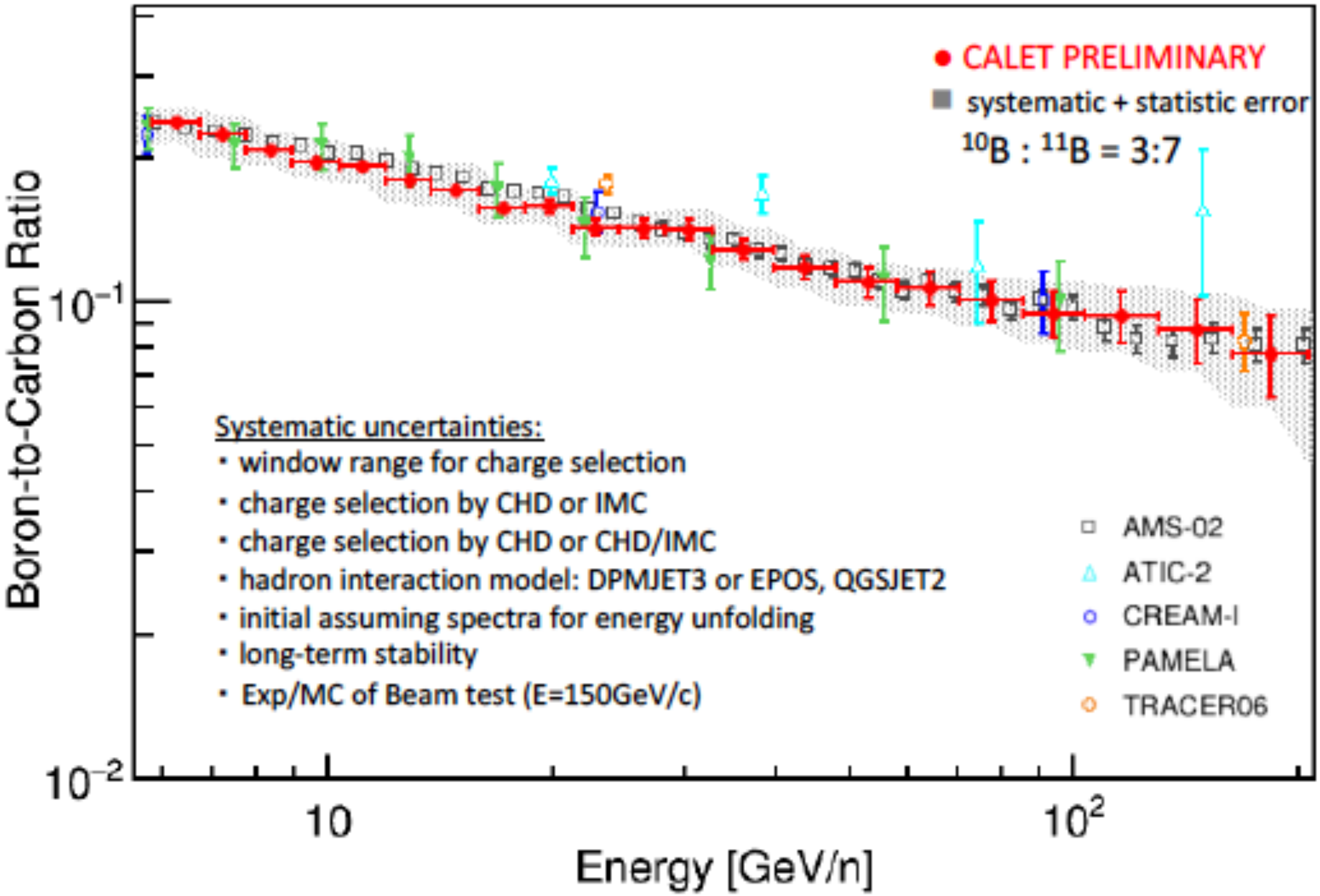
N(*E*): Events in unfolded energy bin
*SΩ* : Geometrical acceptance
*T* : Live time
ε(*E*) : Efficiency
*ΔE* : Energy bin width

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



# Preliminary Boron-to-Carbon Flux Ration



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

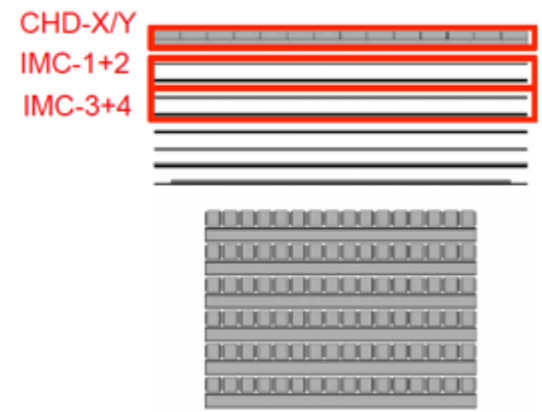
- CALET measures the relative abundances of ultra heavy nuclei through ${}_{40}Zr$
- Trigger for ultra heavy nuclei:

- signals of only CHD, IMC1+2 and IMC3+4 are required

➡ an expanded geometrical acceptance (4000 $cm^2$sr)

- Energy threshold depends on the geomagnetic cutoff rigidity

Onboard trigger for UH events

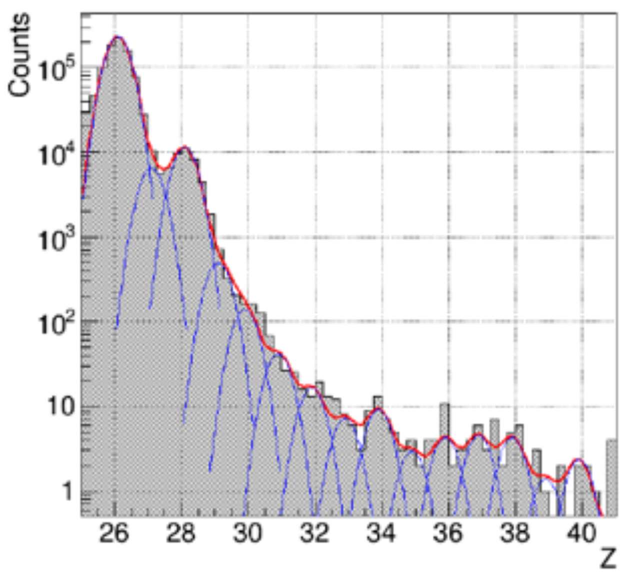



<u>Data analysis</u>

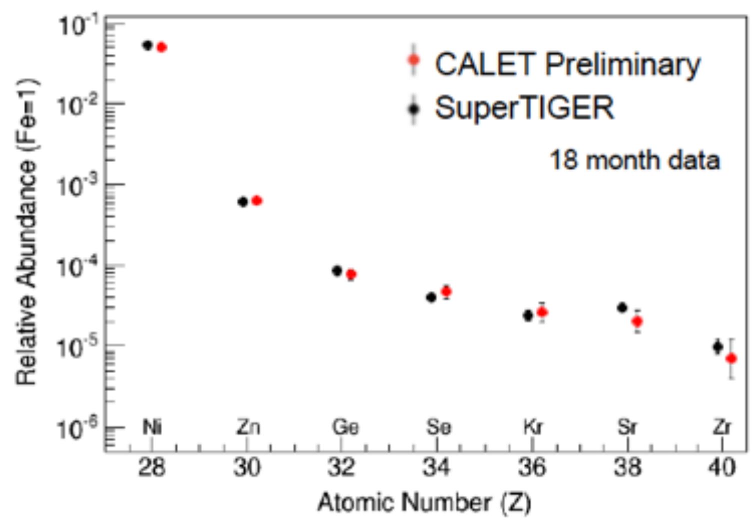
☐ Event Selection: Vertical cutoff rigidity > 4GV & Zenith Angle < 60 degrees

☐ Contamination from neighboring charge are determined by multiple-Gaussian function

Charge distribution




Relative abundance (Fe=1)



# CALET γ–ray Sky (>1GeV)

Instrument characterized using EPICS simulations

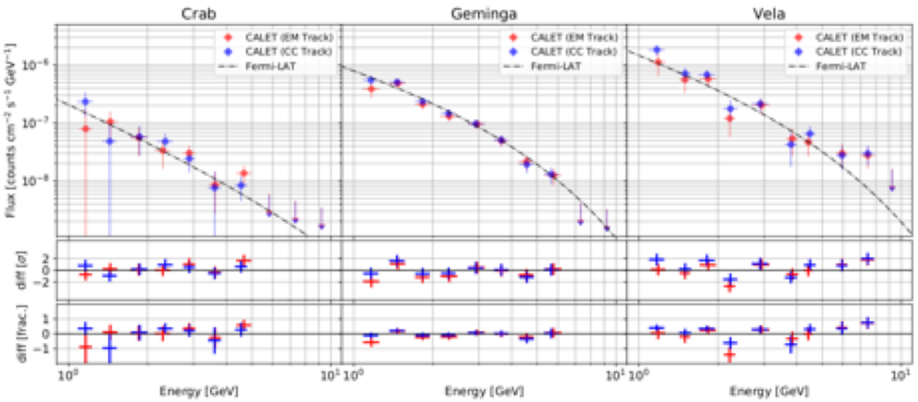
- Effective area ~400 cm² above 2 GeV
- Angular resolution < 2° above 1 GeV (< 0.2° above 10 GeV)
- Energy resolution ~12% at 1 GeV (~5% at 10 GeV)

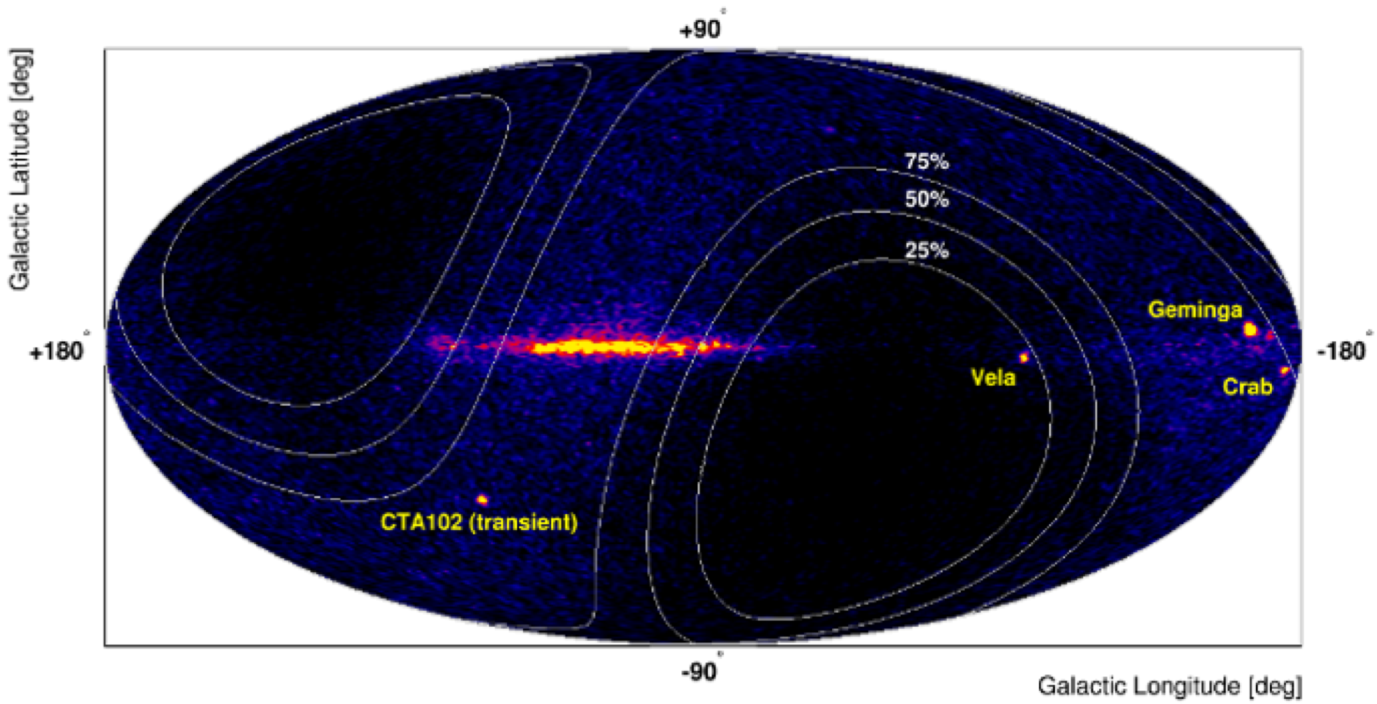
Simulated IRFs consistent with 2 years of flight data

Consistency in signal-dominated regions with Fermi-LAT

Residual background in low-signal regions

Flux validation with bright sources



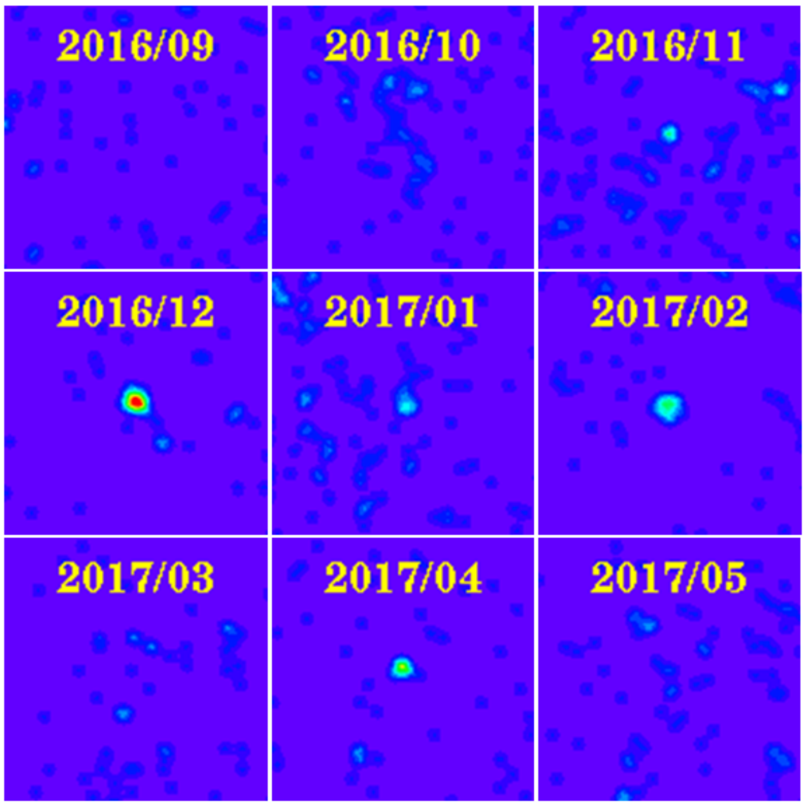




Geminga:432
Vela:138
Crab:150
All: 45740
(As of 180131)

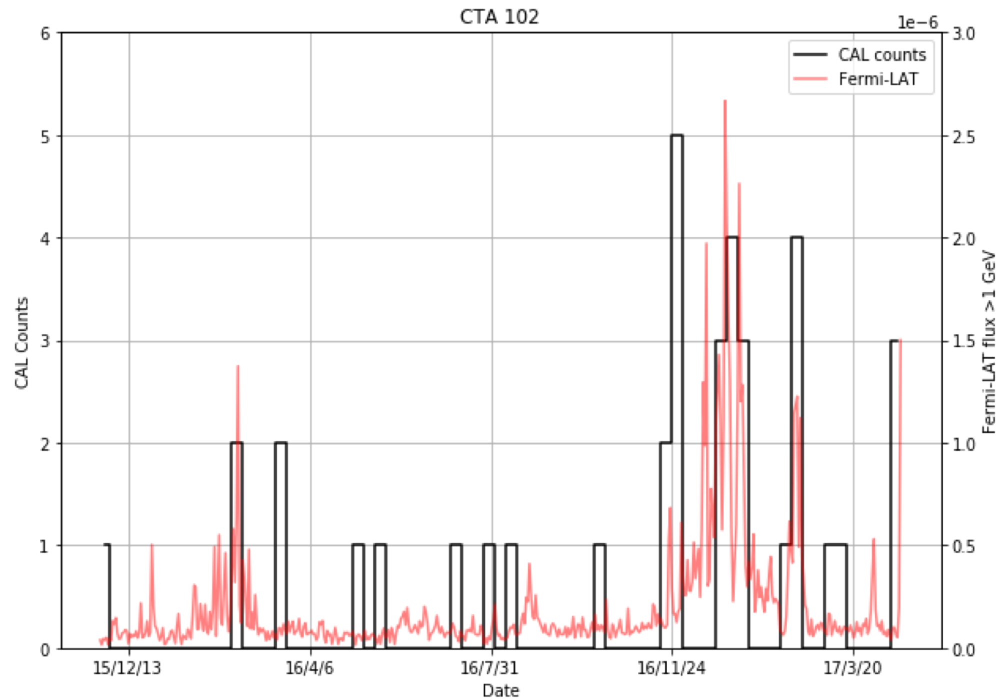
# Strong GeV Gamma-ray Activity from Quasar CTA 102

Reported to ATEL by AGILE, Fermi, DAMPE in GeV

**⇒ Also detected by CALET**




CALET observations of CTA 102 in the months 2015/10 through 2017/04.




Comparing this to the Fermi-LAT flux above 1 GeV for the same time period, it is clear that the enhancements are correlated with flares that are also reported by the Fermi-LAT collaboration

# Galactic Latitude Projection

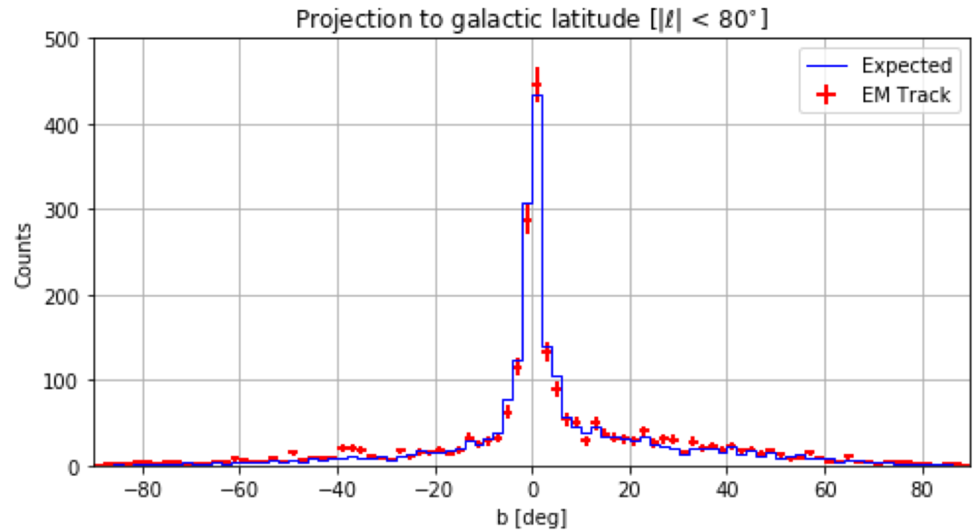
Data :

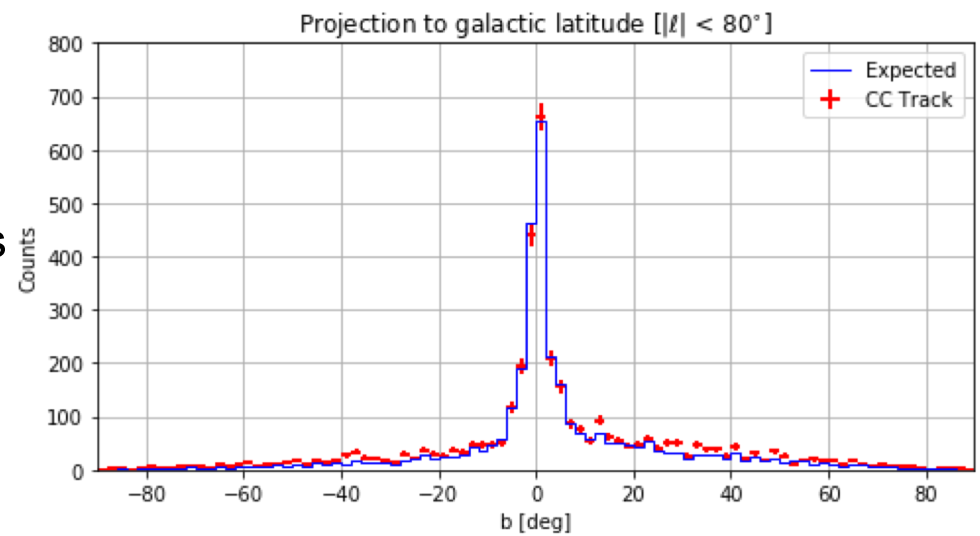
- First two years of LE-γ run data (2015/11 – 2017/10)
- Reduced threshold of ~1 GeV
- Active at low geomagnetic latitudes

Data Analysis :

- Region: galactic latitude |l| < 80°
- Project events onto galactic latitude

- EM Track:  consistent
- CC Track:  excess at higher latitudes
  - Charged particles
  - Unaccounted-for ISS structure
  - Point sources



# GW Events & GRB

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

# Electromagnetic Emission from Gravitational Wave Events ?

| Yes | No? |
|---|---|
| • NS-NS binary mergers<br>• NS-BH binary mergers?<br><br>(e.g. Phinney 2009, Rosswog 2016, Fernández&Metzger 2016) | • BH-BH binary mergers<br><br>(e.g. De Mink&King 2017) |

GW170817 (~$1.5M_\odot$+~$1.3M_\odot$)
+ EM emission + GRB 170817A

GW150914 ($36M_\odot+29M_\odot$)
GW151226 ($14M_\odot+7.5M_\odot$)
GW170104 ($31M_\odot+19M_\odot$)
GW170608 ($12M_\odot+7M_\odot$)
GW170814 ($31M_\odot+25M_\odot$)

CALET

Wide field-of-view monitors are necessary to detect prompt EM emission

CALET/CAL is watching for ~1/6 of the whole sky!

2

# CALET Upper Limits on X-ray and Gamma-ray Counterpart 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 ×$10^{49}$ erg $s^{-1}$ which is significantly lower than typical short GRBs.

CGBM light curve at the moment of the GW151226 event

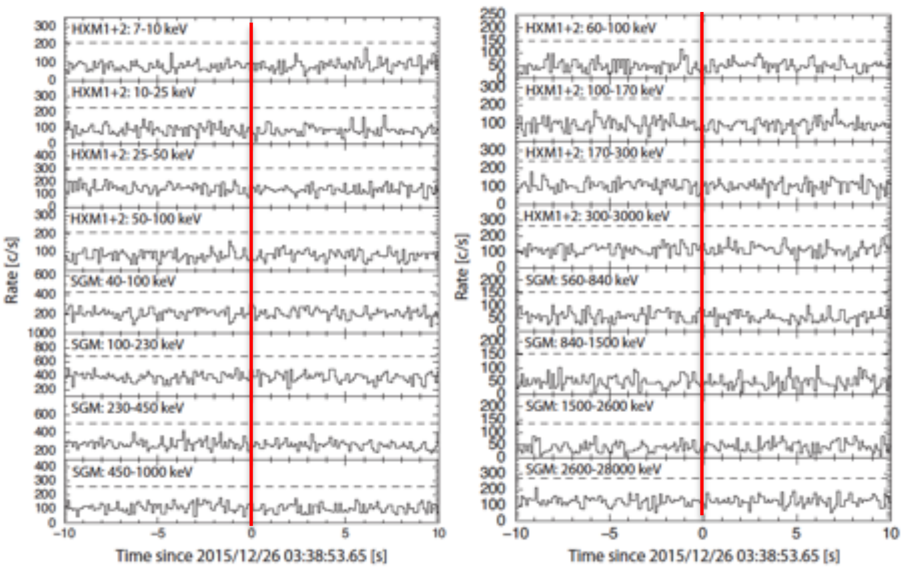



**Figure 1.** The CGBM light curves in 0.125 s time resolution for the high-gain data (left) and the low-gain data (right). The time is offset from the LIGO trigger time of GW 151226. The dashed-lines correspond to the 5 σ level from the mean count rate using the data of ±10 s.

Upper limit for gamma-ray burst monitors and Calorimeter

HXM: 7-500 keV

SGM: 50-1000 keV

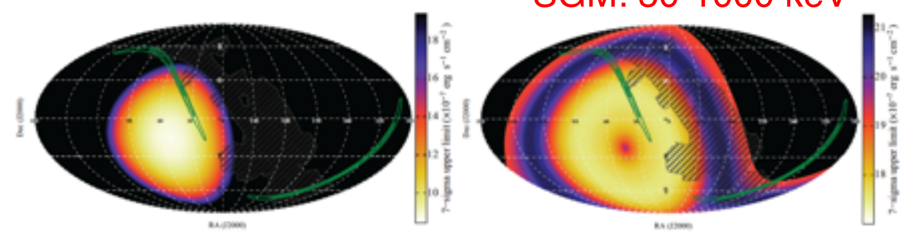


**Figure 2.** The sky maps of the 7 σ upper limit for HXM (left) and SGM (right). The assumed spectrum for estimating the upper limit is a typical BATSE S-GRBs (see text for details). The energy bands are 7-500 keV for HXM and 50-1000 keV for SGM. The GW 151226 probability map is shown in green contours.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

Calorimeter: 1-100 GeV

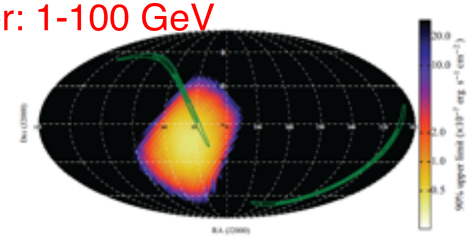
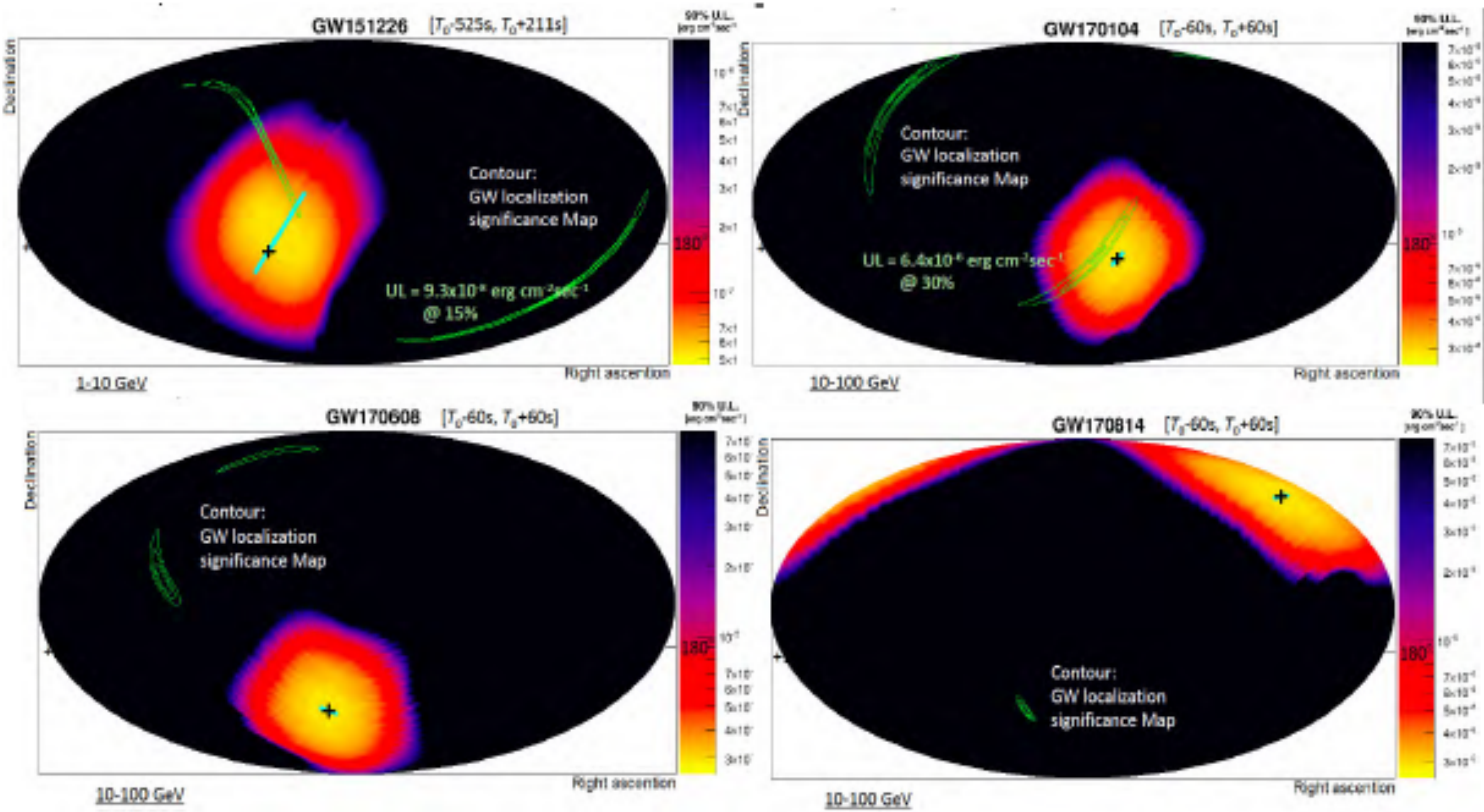


**Figure 3.** The sky map of the 90% upper limit for CAL in the 1-100 GeV band. A power-law model with a photon index of −2 is used to calculate the upper limit. The GW 151226 probability map is shown in green contours.

# 90 % CL Upper Limits for GW Counterpart Search

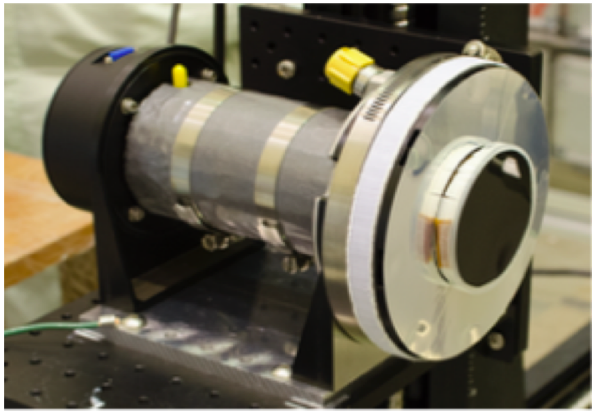
No event survived. Backgrounds are negligible. [M.Mori, E1.17-0022-18]

- For GW151226 CALET-CAL observation constrains 15% of LIGO localization map by 90% upper limit flux of 9.3x10-8erg cm-2sec-1(1-10GeV)
- For GW170104, GW170608, GW170814 no constrain on any portion of LIGO probability

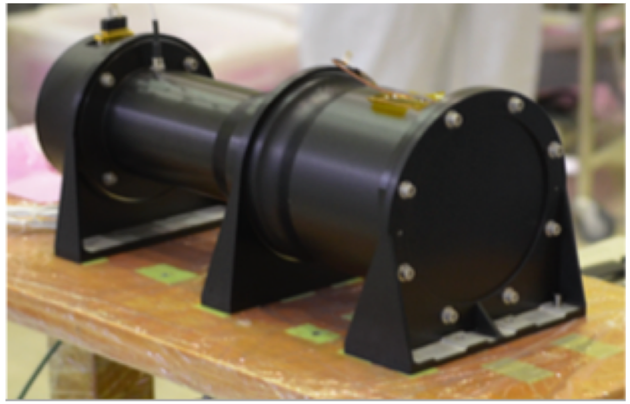


# CALET Gamma-ray Burst Monitor (CGBM)

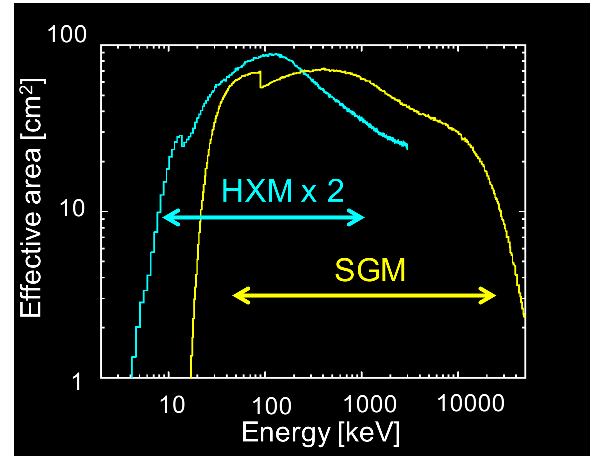
**Hard X-ray Monitor (HXM)**



**Soft Gamma-ray Monitor (SGM)**



**Energy range covered by CGBM**




**Characteristics of HXM & SGM**

*) $LaBr_3(Ce)$ used for the first time in GRB observations

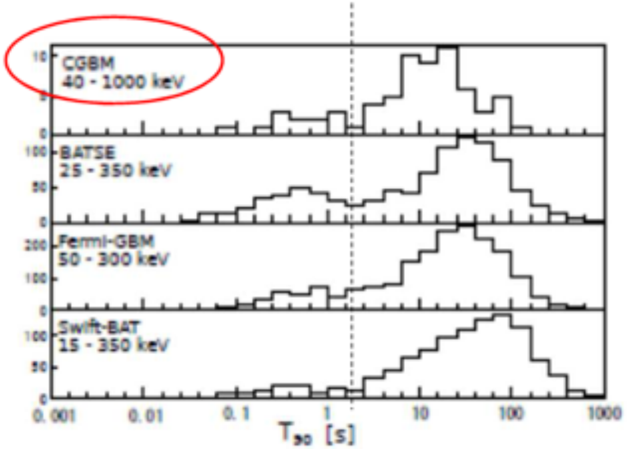
| | HXM (x2) | SGM |
|---|---|---|
| Detector (Crystal) | $LaBr_3(Ce)$* | BGO |
| Number of detector | 2 | 1 |
| Diameter [mm] | 61 | 102 |
| Thickness [mm] | 12.7 | 76 |
| Energy range [keV] | 7-1000 | 100-20000 |
| Energy resolution@662 keV | ~3% | ~15% |
| Field of view | ~3 sr | ~2π sr |

**On-board CGBM trigger response:**

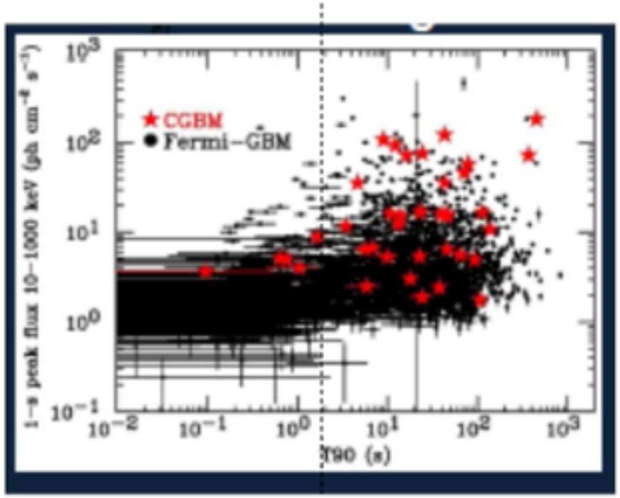
- Store the CGB event data
- Make lower the energy threshold of Calorimeter to 1 GeV
- Capture two optical images by ASC

# GRB Observations

- Observed **~35 confirmed GRB's/yr** (since Oct. 2015), issued GCN circulars with light curves.
  - Observation efficiency ~58% because of HV-off periods.
- Mostly long GRB's (~20% are short GRB's).




- Given the relatively small effective area, CGBM can observe bright GRB's.
  - **Sensitivity:** ~$10^{-8}$ erg cm$^{-2}$ s$^{-1}$ (1 keV - 1 MeV) for 50 s long bursts.




- **4 GRB's simultaneously observed by nearby experiment MAXI on ISS**, in 1 year of overlapping operation.

# Gravitational Wave Events Follow-up

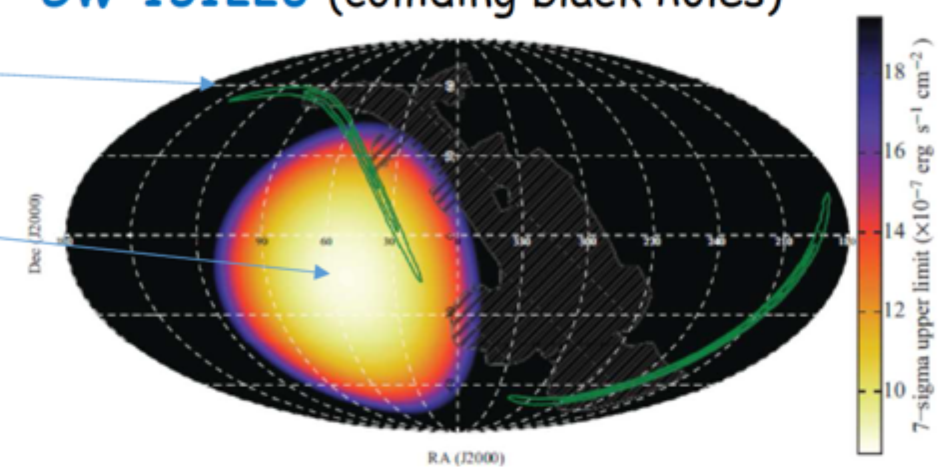
- CALET took part in the **EM follow-up of GW triggers** during LVC runs O1+O2 (4+7 months between 2015 and 2017).
  - ➢ CGBM can deliver fine-time-resolution light curves, spectral analysis possible if accurate source localization available.
- 9 (out of 14) LVC "triggers of interest" happened when CGBM active (HV on) and with probability map for GW source location overlapping significantly with CGBM field-of-view.
- In all cases, **no statistically significant background excess seen in CGBM** light curves around the GW trigger times.

**GW 151226** (colliding black holes)

probability map by LVC

- HXM 7σ upper limit on emission intensity (7 - 500 keV, typical BATSE s-GRB CPL spectrum)

  ⇒ Estimated luminosity (at 440 Mpc) is **few % of typical short GRB** (1.6 · $10^{51}$ erg/s).



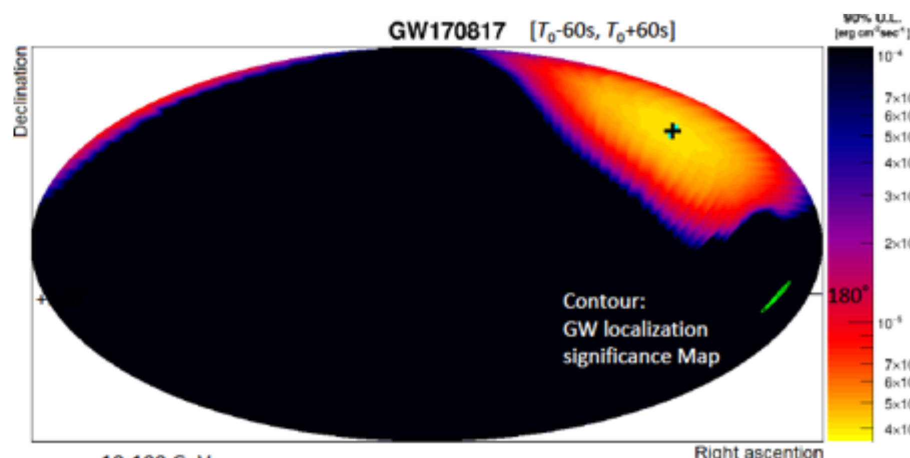
# Upper Limits on GW 170817 (GRB 170817A)

- **Multimessenger observation of binary neutron star merger**: GW 170817, GRB 170817A, optical transient SSS17a [ApJL, 848:L12, 2017].
- The source location (given from optical transient) is out of view for HXM but inside the field-of-view of SGM (though covered by ISS structure).
- **No statistically significant signal seen in SGM**, 7σ upper limit on emission intensity calculated by using Fermi/GBM best-fit parameters (cutoff power-law) and assuming no shielding by ISS structure:

  UL = $5.5 \cdot 10^{-7}$ erg $cm^{-2}$ $s^{-1}$ (10 - 1000 keV)

  - ➢ Shielding by ISS structure should be taken into account with detailed ISS modeling.
- This estimated upper limit is of the same order of the Fermi/GBM measured peak flux: $7.3 \cdot 10^{-7}$ erg $cm^{-2}$ $s^{-1}$ .

CALET-CAL Observation in 10-100GeV
90 % CL upper limit
No events survived. Backgrounds are negligible.




10-100 GeV

# 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.
- Accurate calibrations have been performed with non-interacting p & He events + linearity in the energy measurements established up to $10^6$ MIP.
- All electron spectrum has been extended in statistics and in the energy range from 11 GeV to 4.8TeV.
- Preliminary analysis of nuclei and gamma-rays have successfully been carried out and spectra are obtained in the energy range:
  - proton: 50 GeV ~ 100 TeV, helium: 10 GeV/n ~ 20 TeV/n, C-Fe: 300 GeV ~ 100 TeV.
  - B/C ratio: 20 GeV/n ~ 1 TeV/n
- Preliminary analysis of UH cosmic rays up to Z=40 was achieved.
- CALET's CGBM detected nearly 60 GRBs (~20 % short GRB among them ) per year in the energy range of 7keV-20 MeV. Follow-up observations of the GW events were carried out .
- 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.