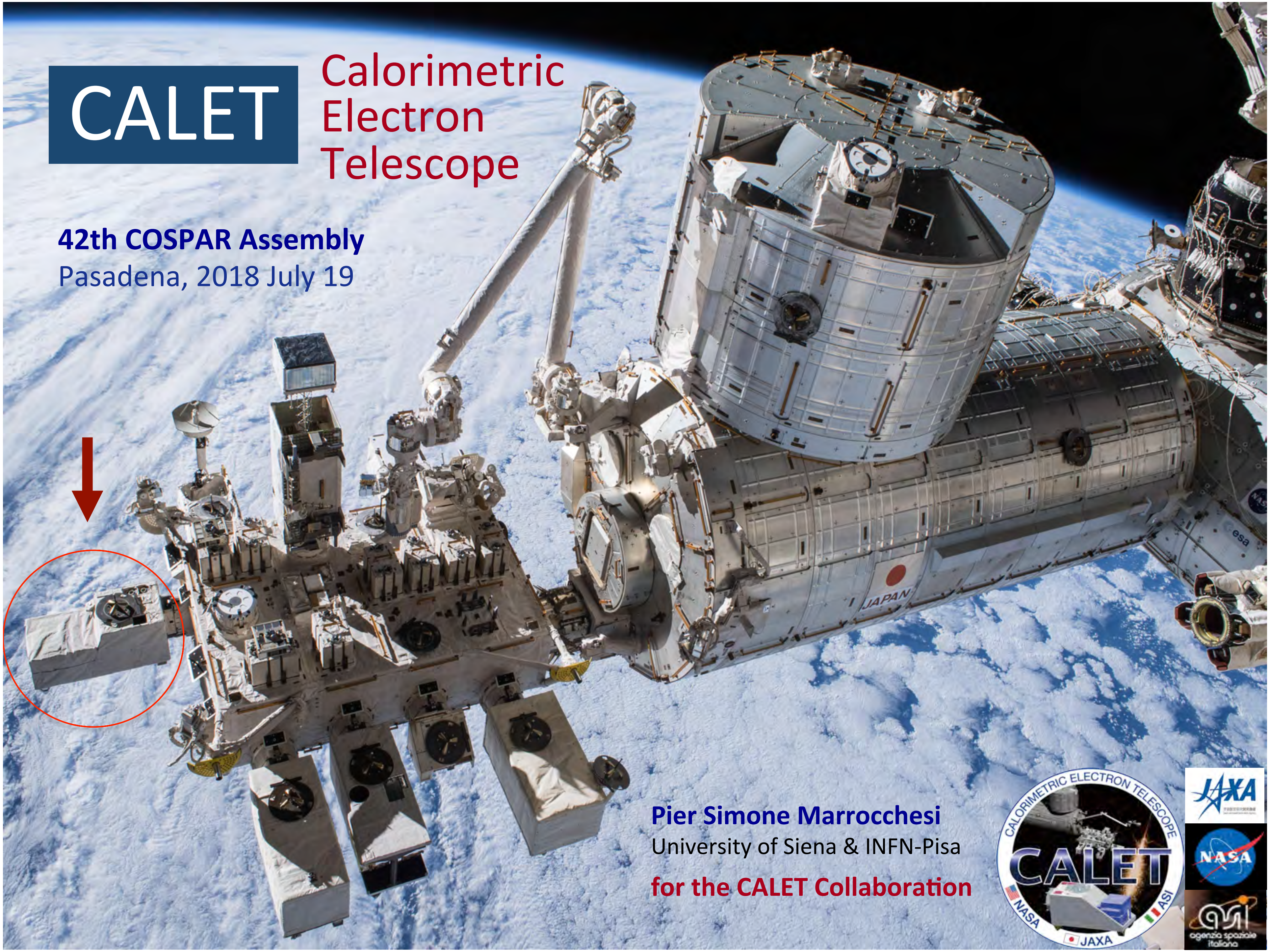
# CALET
# Calorimetric Electron Telescope

**42th COSPAR Assembly**
Pasadena, 2018 July 19



**Pier Simone Marrocchesi**
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**for the CALET Collaboration**

# CALET Collaboration Team


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19) Osaka City University, Japan
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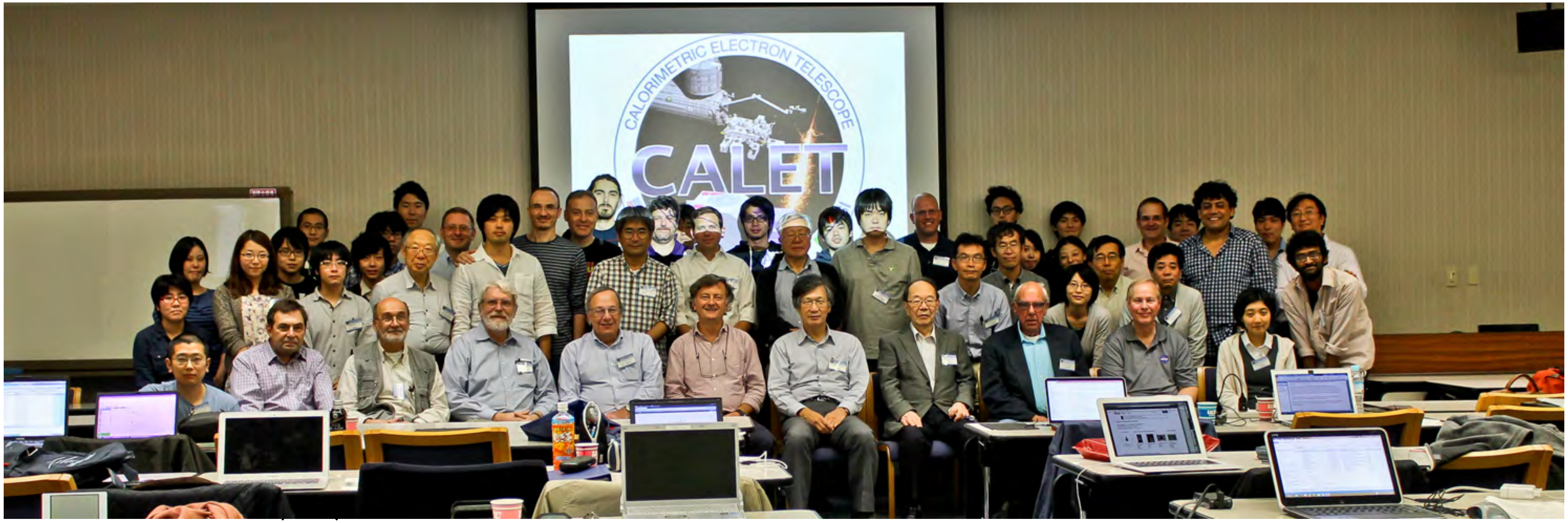
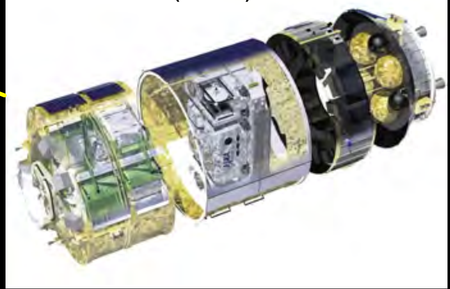
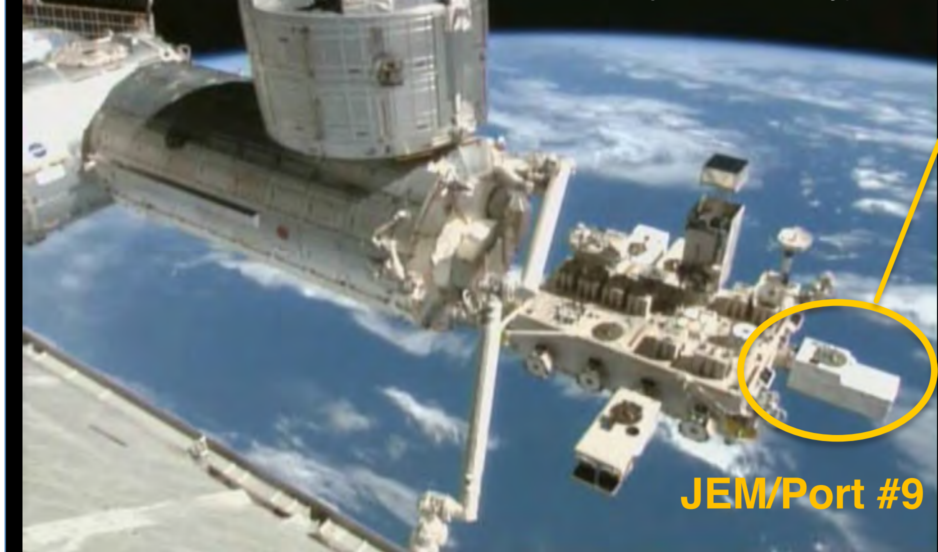


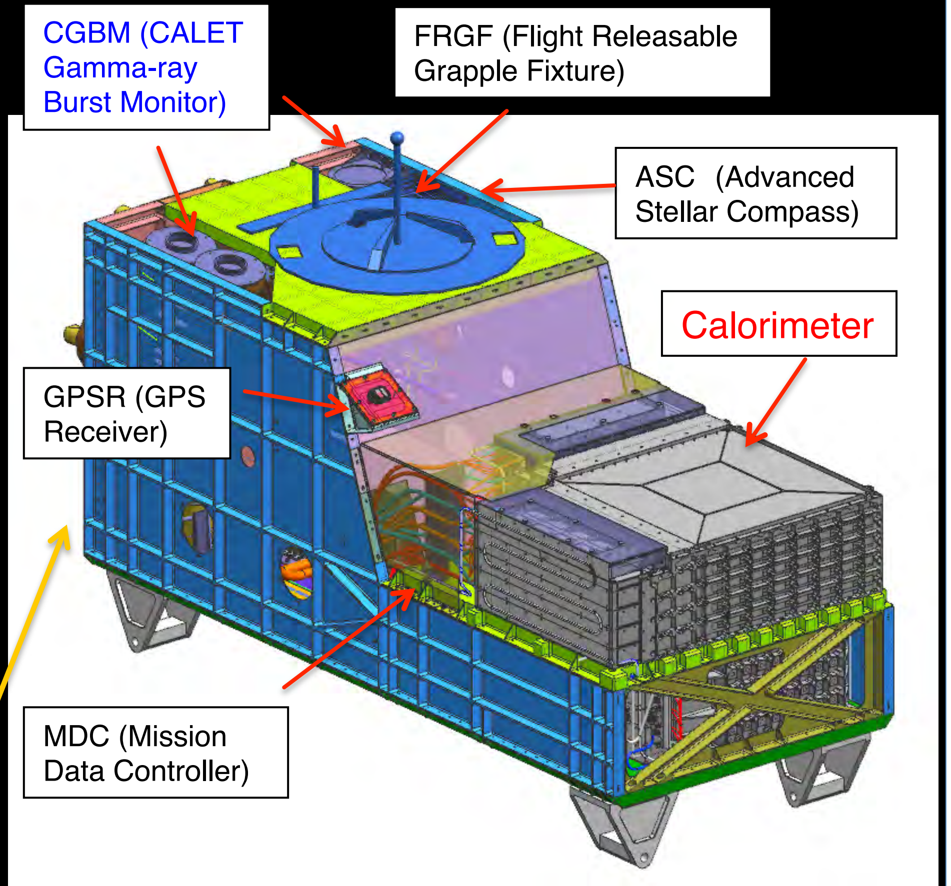
# CALET Payload




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

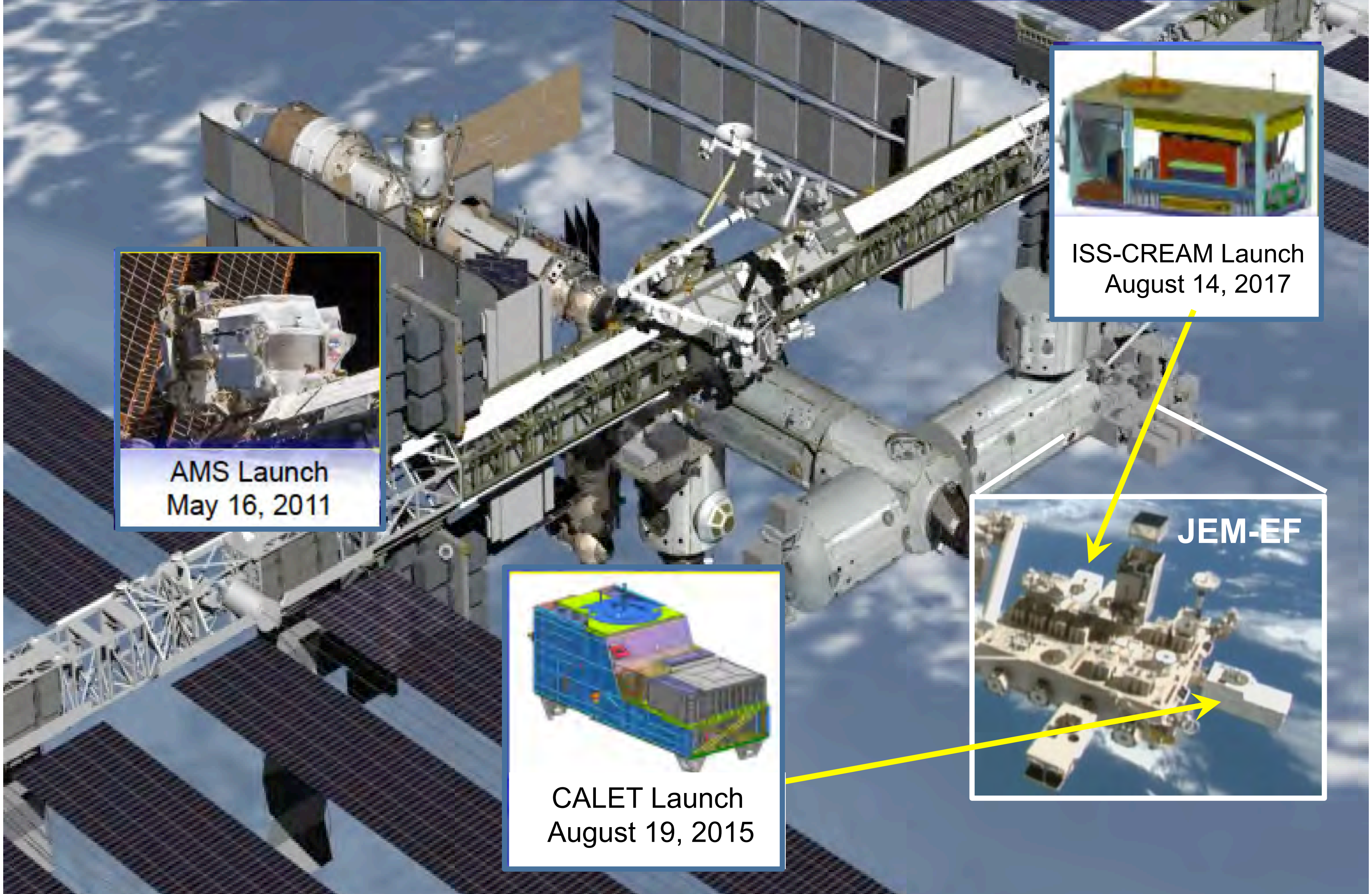
Emplaced on JEM-EF port #9 on Aug. 25th, 2015
(JEM-EF: Japanese Experiment Module-Exposed Facility)



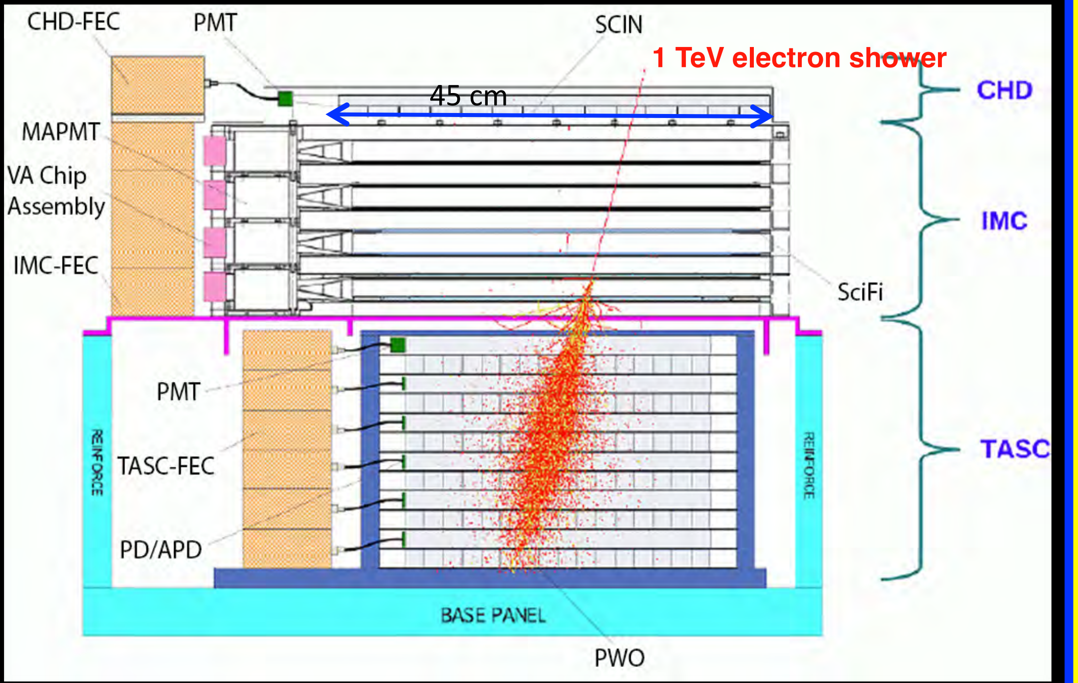

- Mass: 612.8 kg
- JEM Standard Payload Size:
  1850mm (L) × 800mm (W) × 1000mm (H)
- Power Consumption: 507 W (max)
- Telemetry:
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

# ISS: a Cosmic Ray Observatory in Low Earth Orbit



# CALET instrument in a nutshell

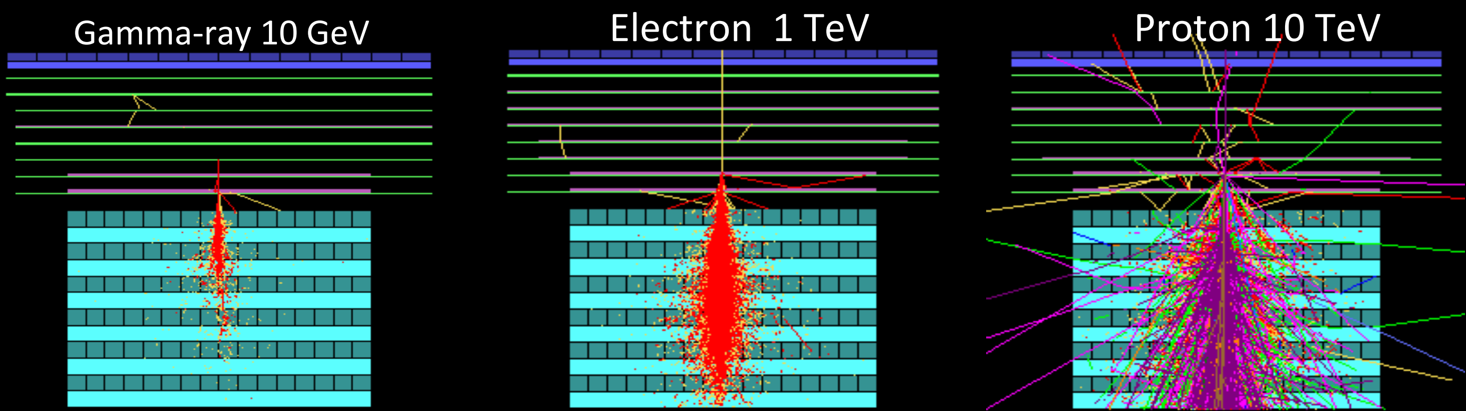
Field of view: ~ 45 degrees (from the zenith)   Geometrical Factor: ~ 1,040 $cm^2sr$ (for electrons)



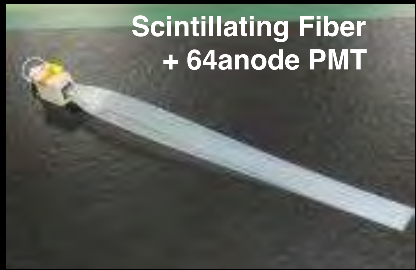

**CALET: a unique set of key instruments**

- **CHD**: a dedicated charge detector + multiple dE/dx sampling in the IMC allow to **identify individual nuclear species** (Δz~0.15-0.3 e).
- **IMC**: a high granularity (1mm) imaging pre-shower calorimeter accurately identifies **the arrival direction** of incident particles ( ~0.1°) and the **starting point** of electro-magnetic showers.
- **TASC**: a thick (~**30** $X_0$), fully active calorimeter allows to extend electron measurements into the TeV energy region with ~2% **energy resolution**.
- Combined, they **separate electrons** from the abundant protons (rejection > $10^5$).

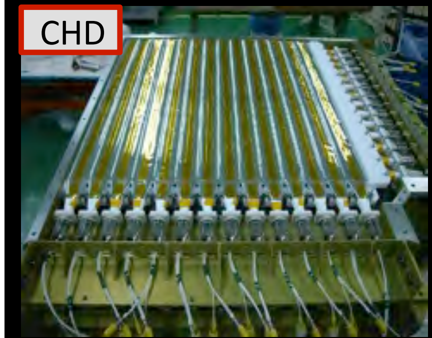
Simulated Shower Profile



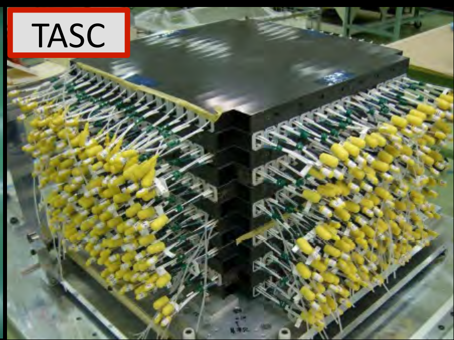
# CALET Instrument overview

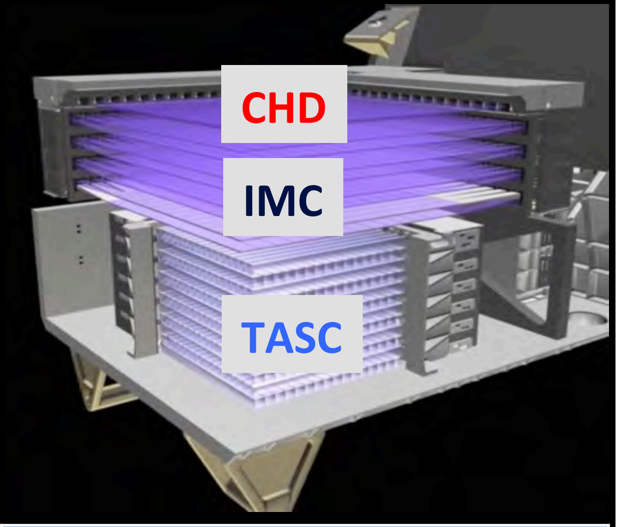








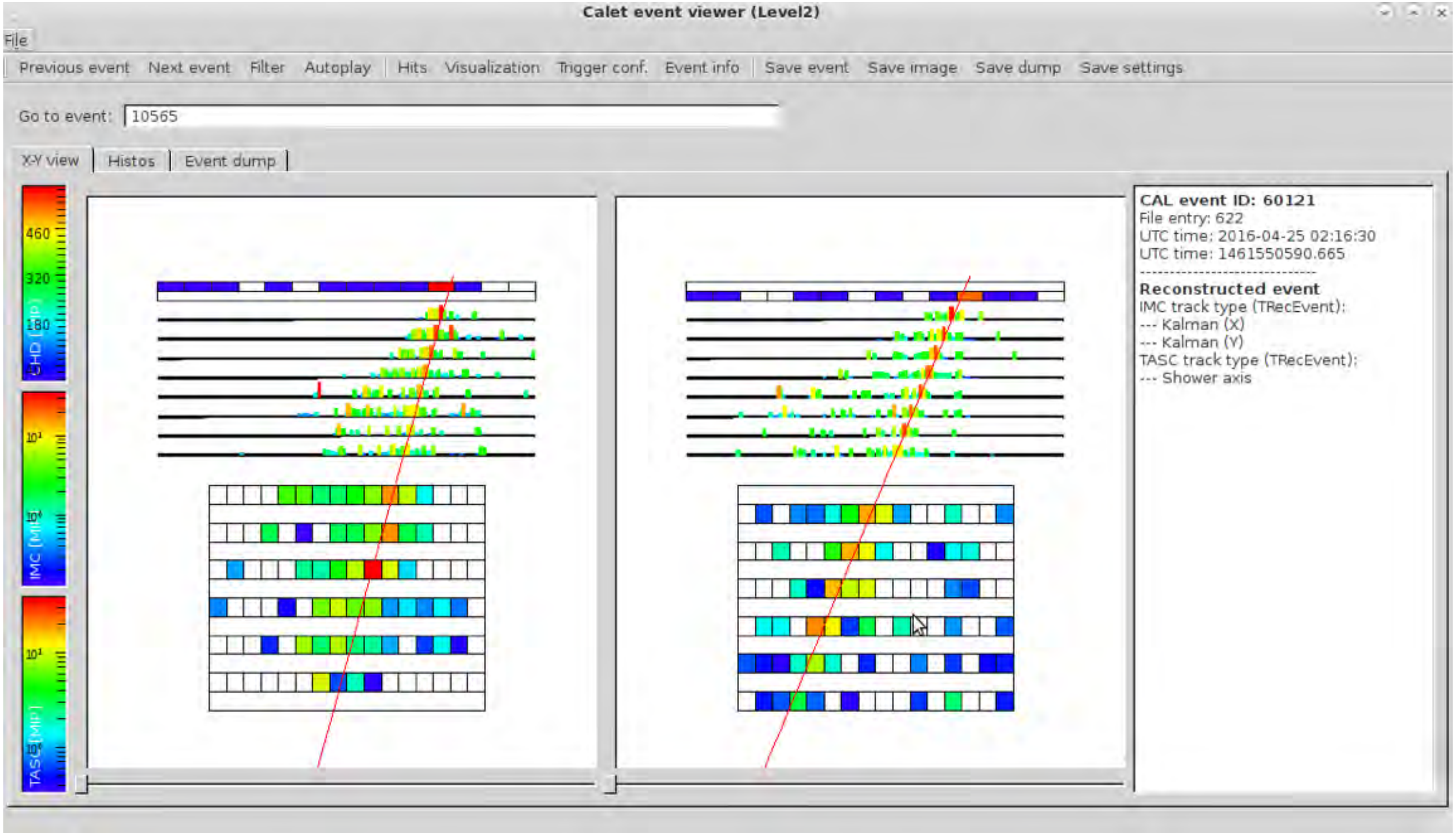

CALORIMETER




| | 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 Scintillators**: 28 paddles<br>14 paddles x 2 layers (X,Y)<br>Paddle Size: 32 x 10 x 450 mm$^3$ | **Scintillating Fibers**: 448 x 16 layers (X,Y)<br>7 W layers (3$X_0$): 0.2$X_0$ x 5 + 1$X_0$ x2<br>Scifi size: 1 x 1 x 448 mm$^3$ | **PWO logs**: 16 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 **tracking** takes advantage of the IMAGING capabilities of IMC thanks to its granularity of 1 mm with Sci-fibers **readout individually**.

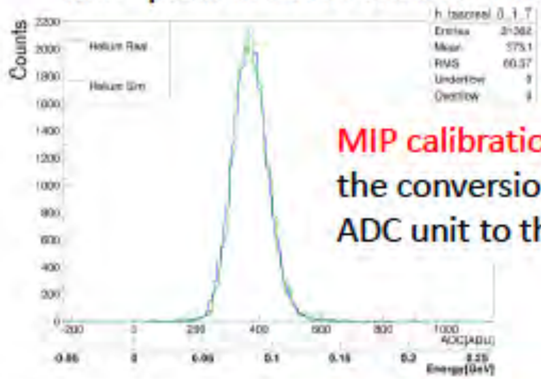
Example: A **multi-prong event** due to an interaction of the primary particle in the CHD is very well imaged by the IMC.



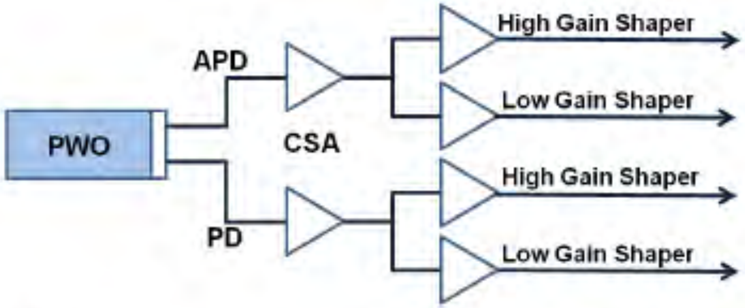
# TASC Energy Measurement: wide Dynamical Range 1-$10^6$ MIPs



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




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

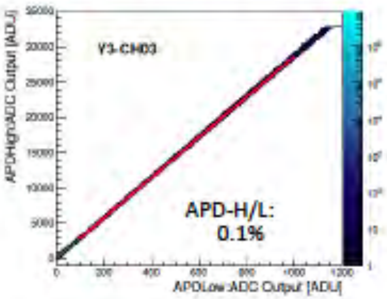


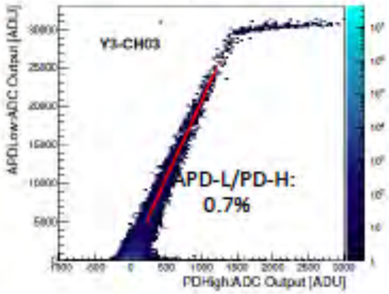

The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to $10^6$ MIPs.

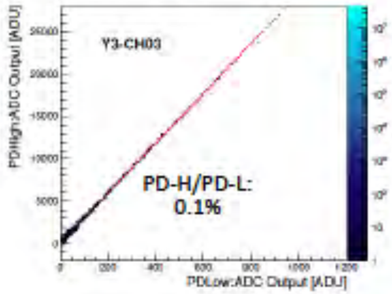
| APD-H | APD-L | PD-H | PD-L |
|---|---|---|---|
| 1.4% | 1.5% | 2.5% | 2.2% |

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

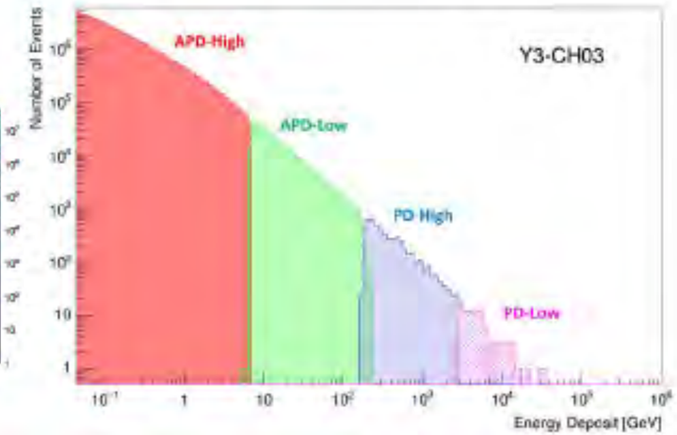
| APD-H APD-L | APD-L PD-H | PD-H PD-L |
|---|---|---|
| 0.1% | 0.7% | 0.1% |



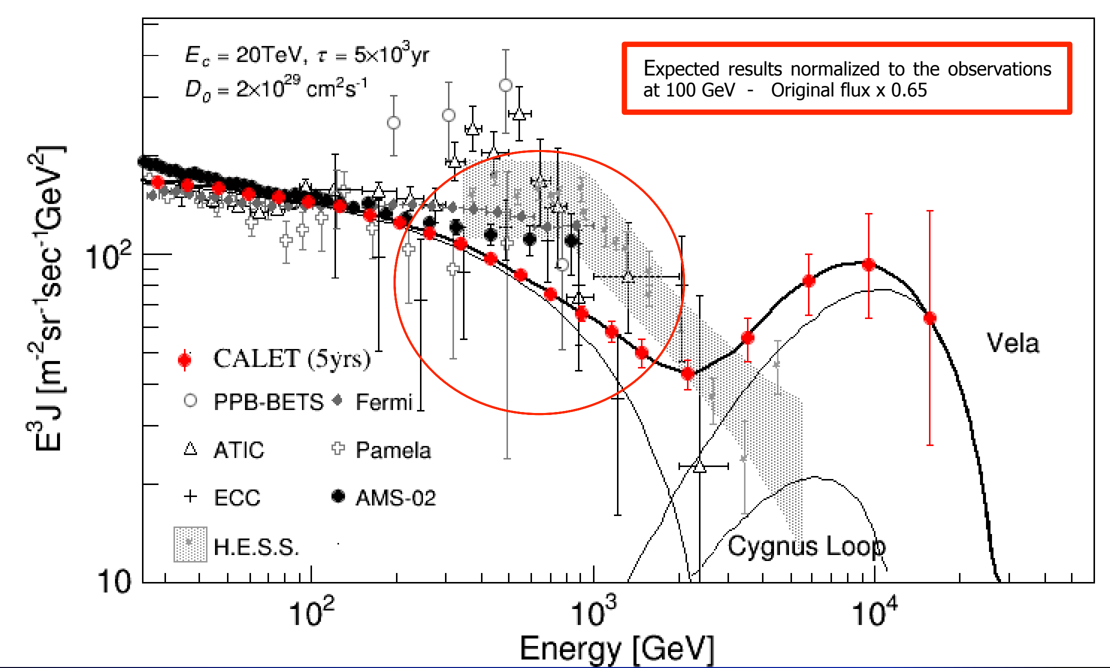



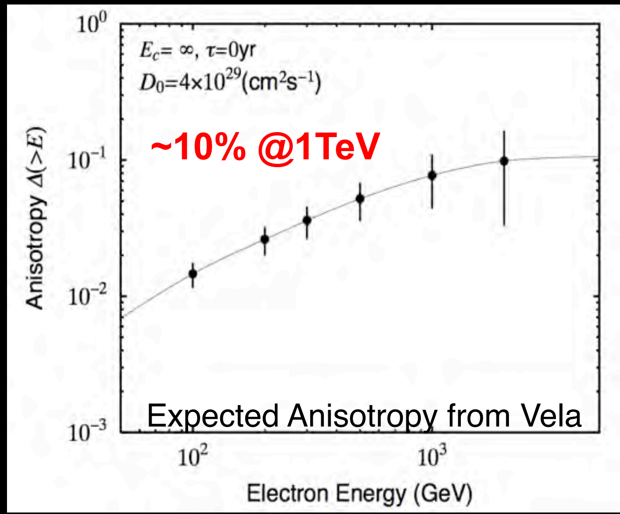




Example of energy distribution in one PWO log



# CALET Main Target: Identification of Electron Sources




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

## CALET: Cosmic-Ray Nuclei Spectra in the Multi-TeV region

- Proton spectrum to ≈ 900 TeV
- He spectrum to ≈ 400 TeV/n
- Spectra of C,O,Ne,Mg,Si to ≈ 20 TeV/n
- B/C ratio to ≈ 4 - 6 TeV/n
- Fe spectrum to ≈ 10 TeV/n

CALET energy reach (5 years)

# Main Scientific Objectives

| 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 |

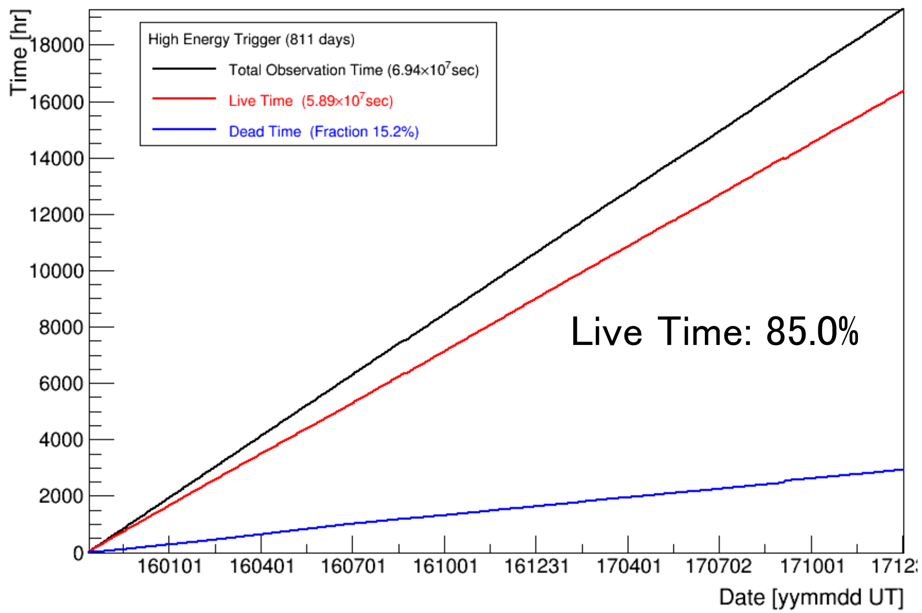
- Electron observation in 1 GeV - 20 TeV is achieved with high energy resolution due to design optimization for electron detection Search for Dark Matter and Nearby Sources
- Observation of cosmic-ray nuclei will be performed in energy region from 10 GeV to 1 PeV Unravelling the CR acceleration and propagation mechanism(s)
- Detection of transient phenomena in space by stable observations Gamma-ray bursts, Solar flares, e.m. counterpart from GW sources, ...

# Observations with High Energy Trigger (>10GeV)

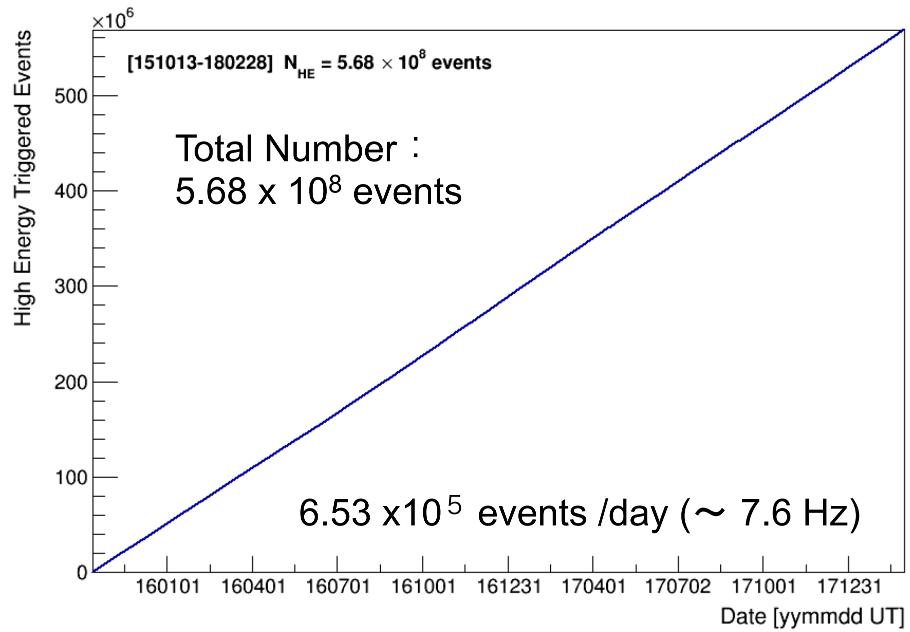
870 days : Oct.13, 2015 – Dec.31, 2017

- The exposure, SΩT, has reached to ~76.0 $m^2$ sr day for electron observations by continuous and stable operations.
- Total number of triggered events is ~ 570 million with a live time fraction of 85.0 %.

Accumulated observation time (live, dead)

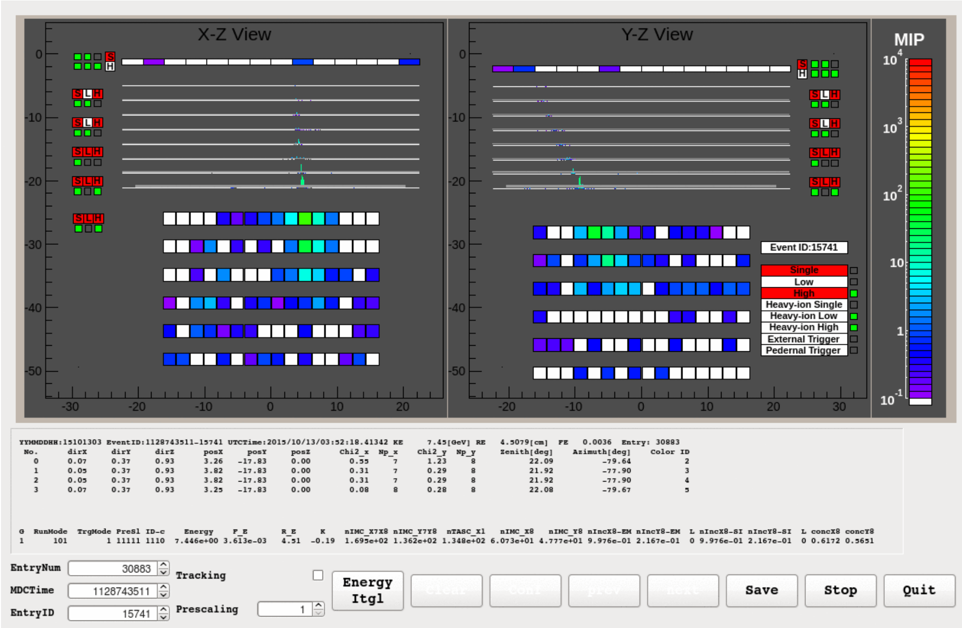



Accumulated triggered event number

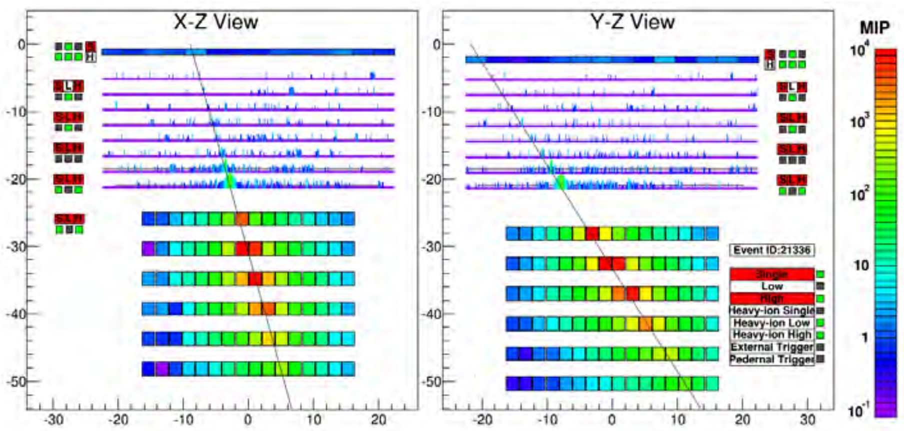


# Examples of Observed Events

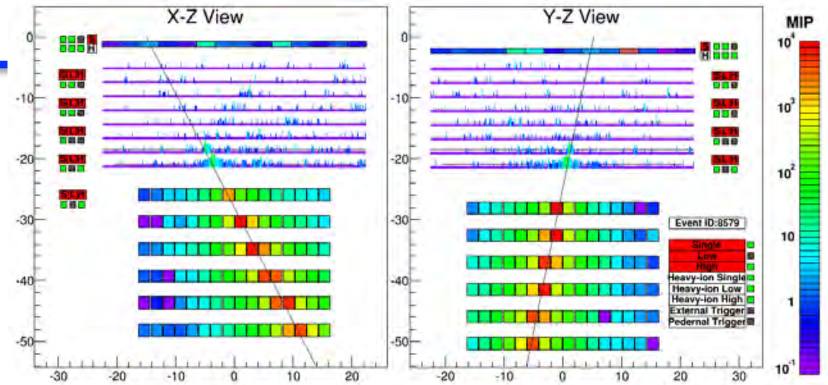
## Event Display: Electron Candidate (>100 GeV)



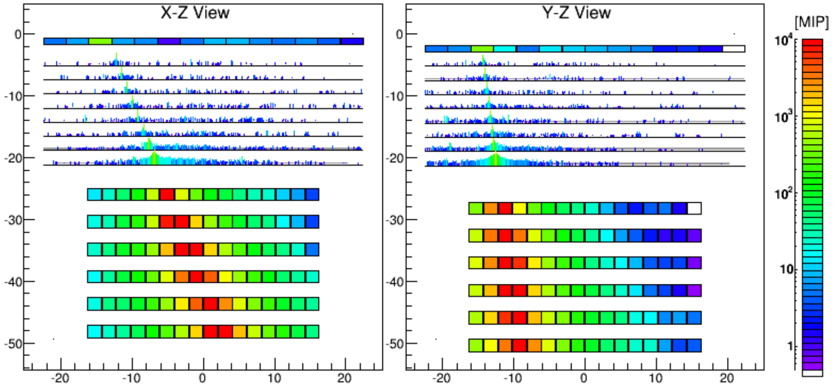

## Electron, E=3.05 TeV



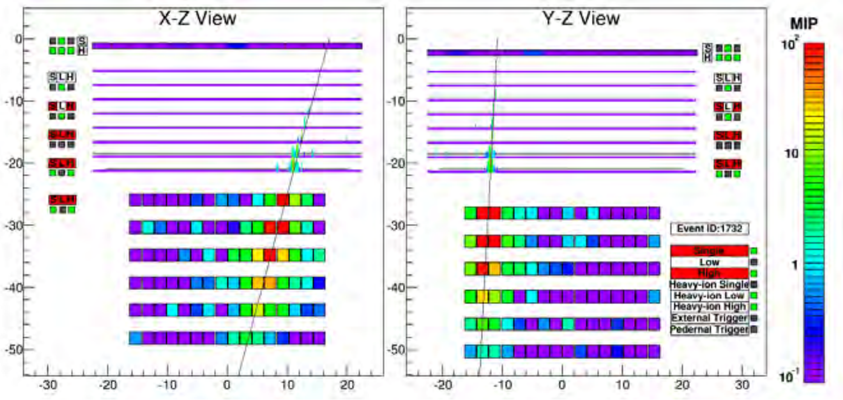

## Proton, ΔE=2.89 TeV



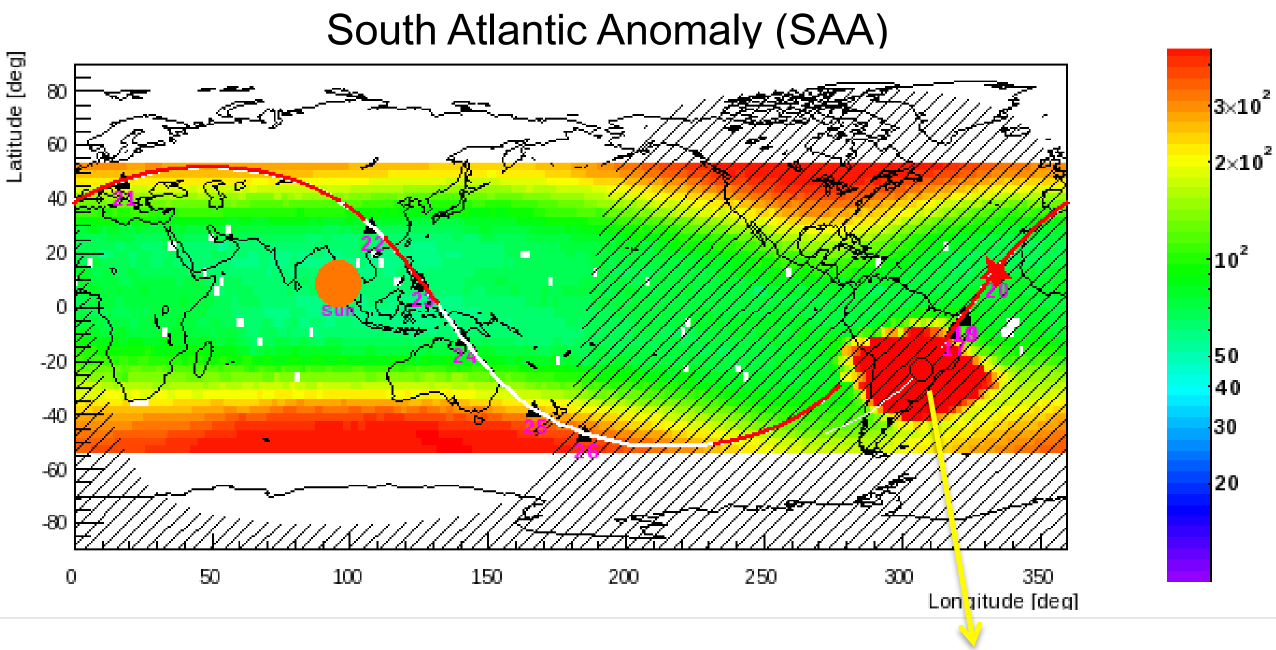

## Fe, ΔE=9.3 TeV




## Gamma-ray, E=44.3 GeV



# ISS Radiation Environment

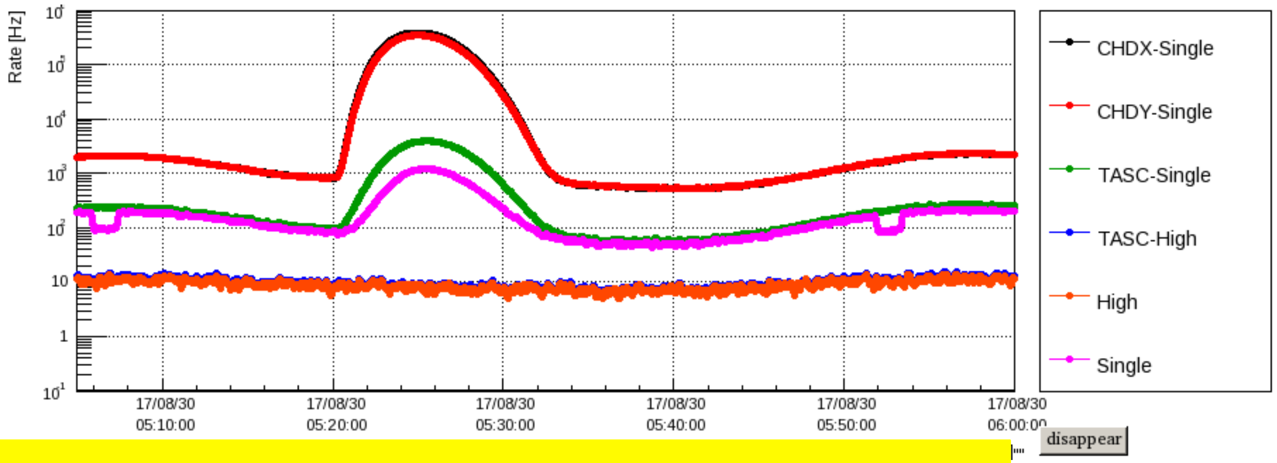



<u>ISS orbit</u>
<u>@ 2017/08/29 5:25UT</u>
ISS ran through SAA.

CHD count rate jumped up to ~$3\times10^5$ Hz from $10^3$ Hz, but the HE trigger rate remained stable.

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

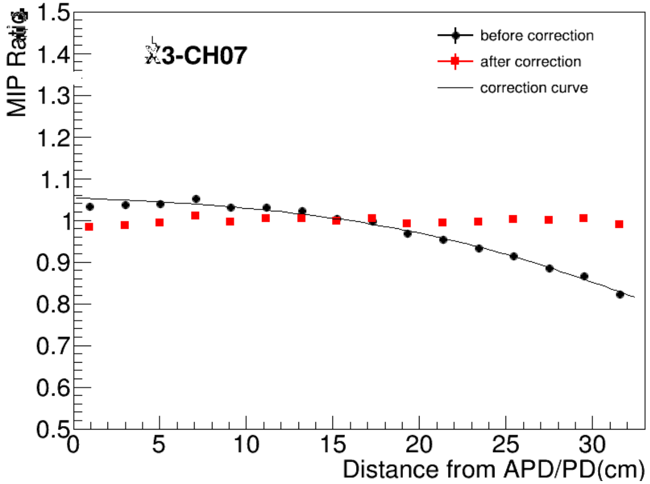
HE trigger was not affected by SAA thanks to high energy threshold (>10 GeV). (Energies of the trapped particles are too low to make a trigger for the observations.)



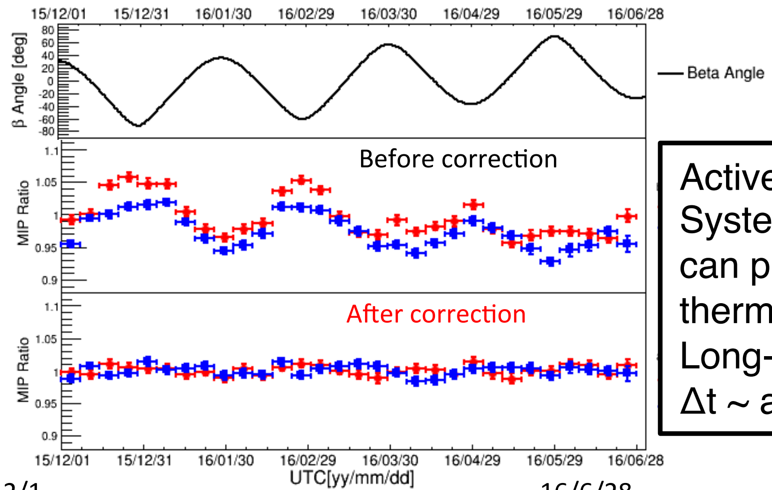

**⇒ Observation is continuously carried out even at SAA!**

# Position and Temperature Calibration, and Long-term Stability

Example of position dependence correction




Examples of temperature change correction

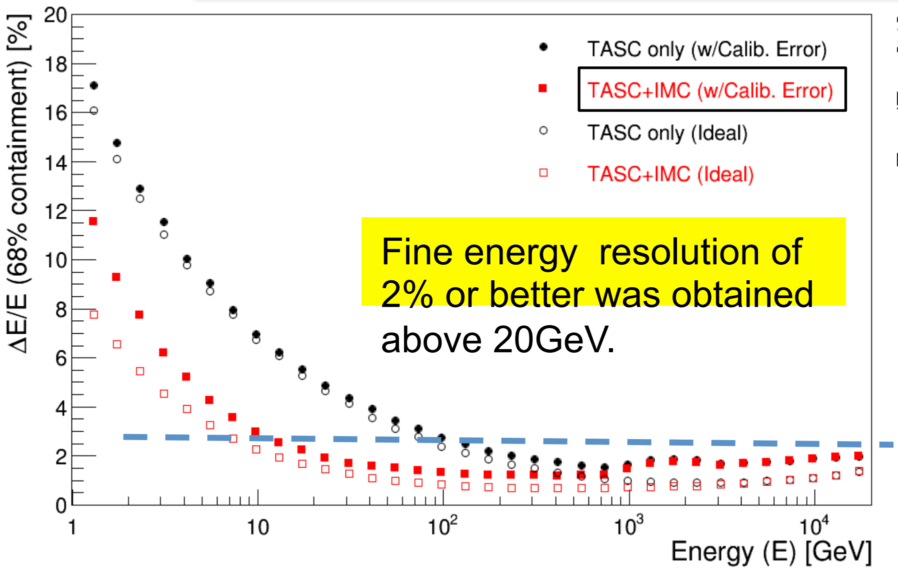


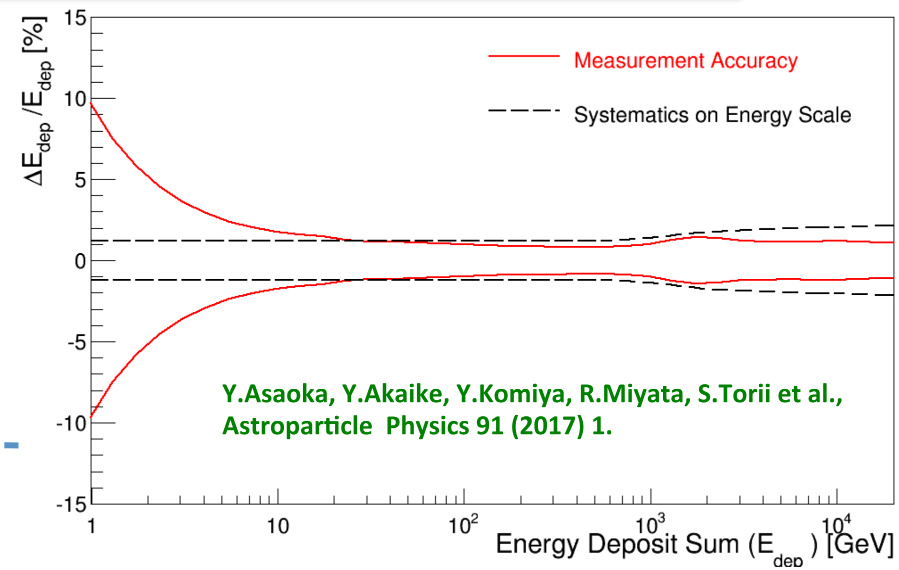

15/12/1 16/6/28

TASC

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

# Energy Resolution for Electrons by On-orbit Calibration



# Electron / Proton Separation

[Y.Asaoka, E1.5-0023-18]

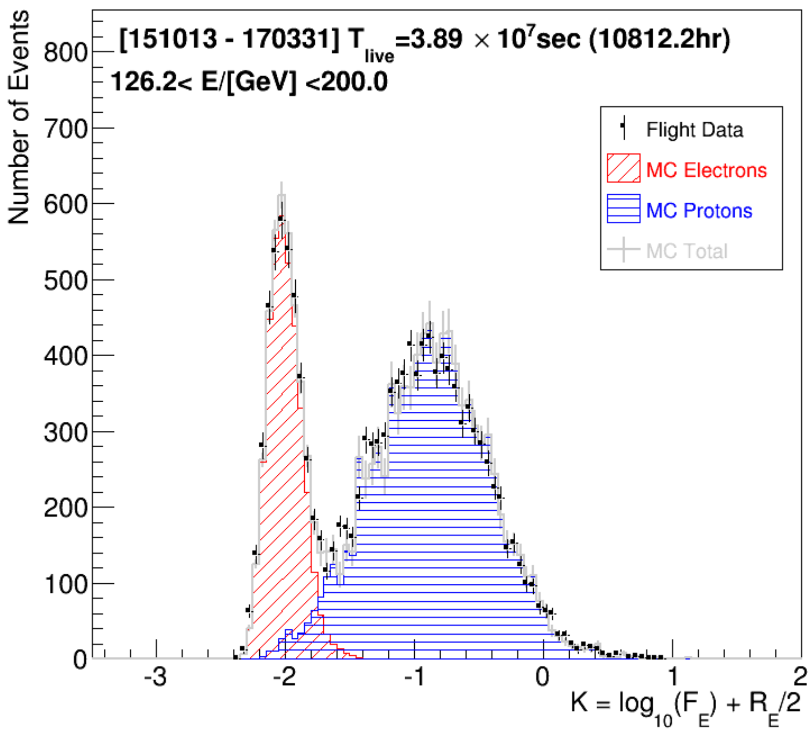
## Simple Two Parameter Cut

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

$R_E$: Lateral spread of energy deposit in TASC-X1

Cut Parameter K is defined as follows:

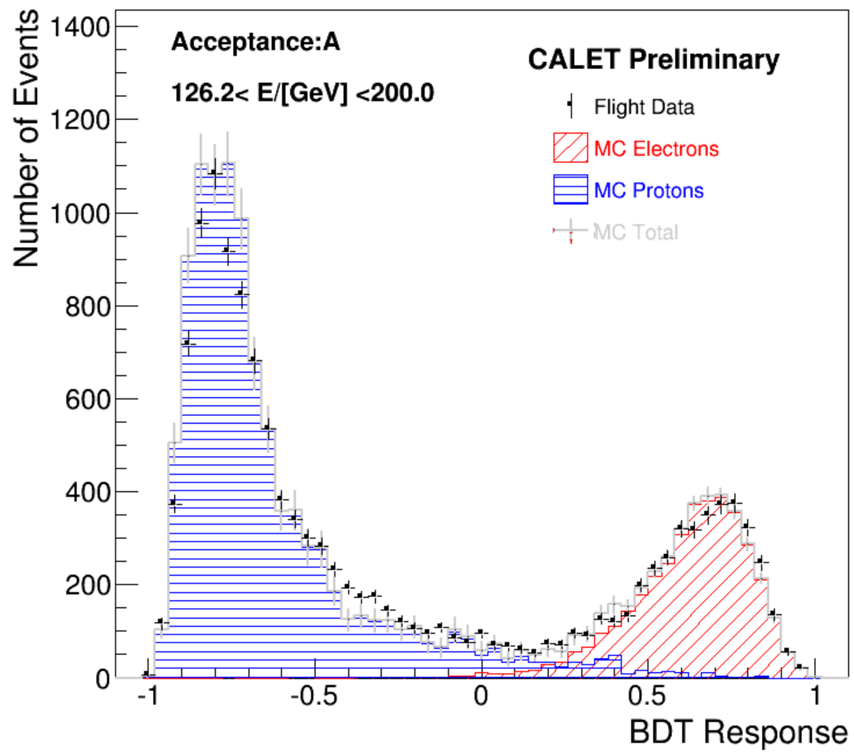
$K = \log_{10}(F_E) + 0.5\ R_E$ (/cm)




## Boosted Decision Trees (BDT)

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

BDT Response using 9 parameters



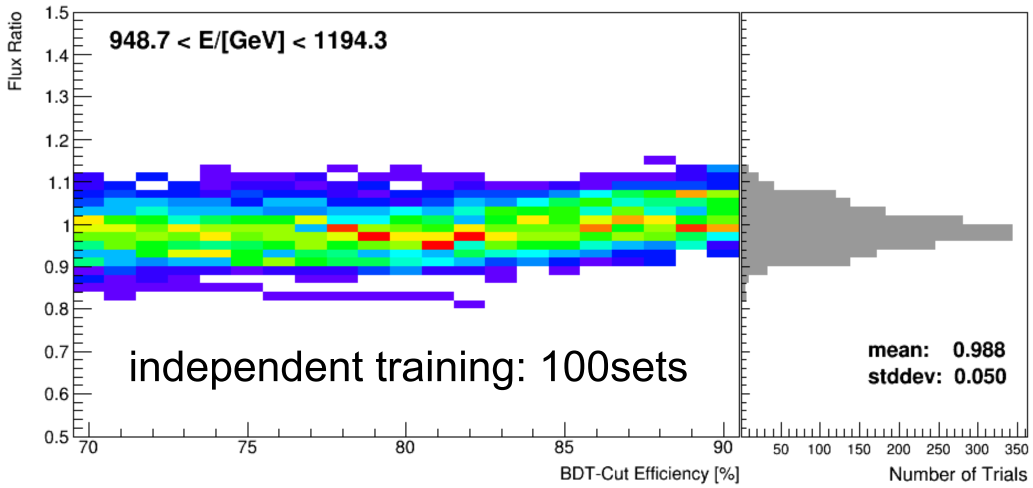
# Systematic Uncertainties in Derivation of Energy Spectrum

[Y.Asaoka, E1.5-0023-18]

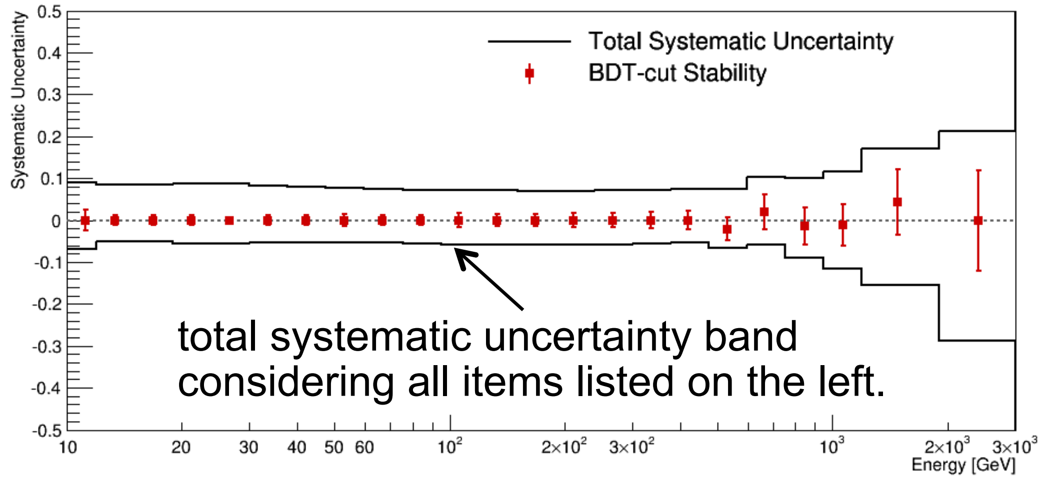
Stability of resultant flux are intensively studied in the large parameter space (i.e., viable choices to derive spectrum)

- Normalization:
  - Live time
  - Radiation environment
  - Long-term stability
  - Quality cuts
- Energy dependent:
  - Tracking
  - charge ID
  - electron ID (K-Cut vs BDT)
  - BDT stability (vs efficiency & training)
  - MC model (EPICS vs Geant4)

Systematic uncertainty in electron selection by BDT



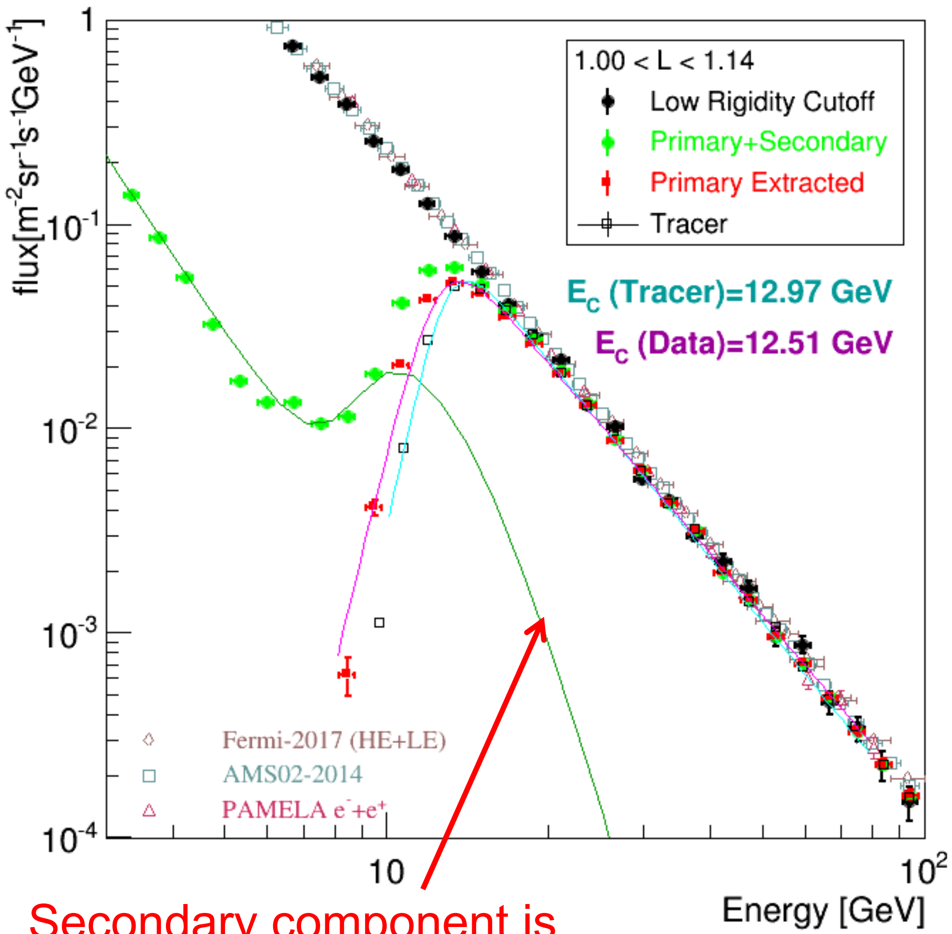

Total systematic uncertainty vs Energy




N.B. Energy scale uncertainty is not included in this analysis.

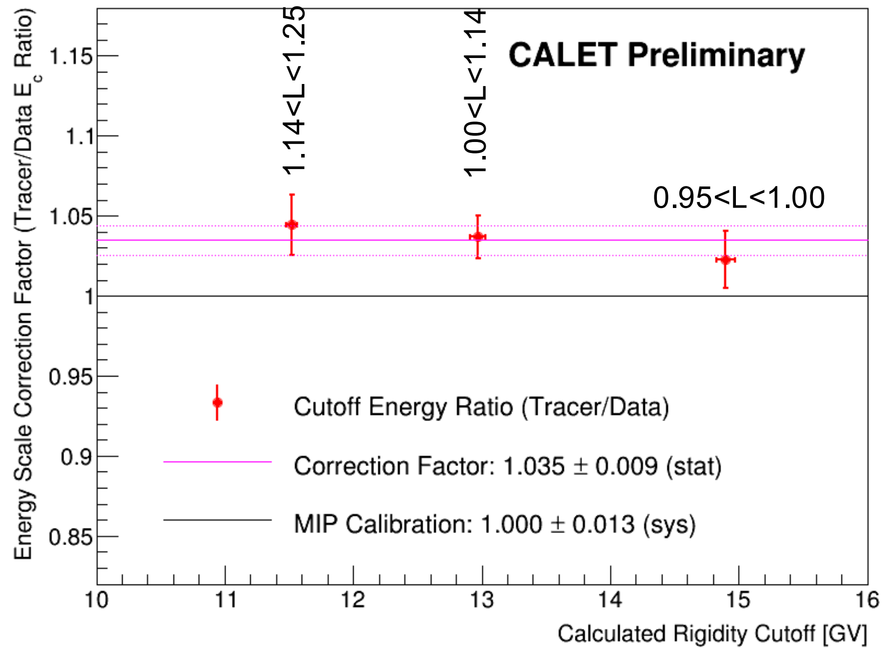
# Cutoff Rigidity Measurements and Comparison with Calculation

**BEFORE CORRECTION**




Secondary component is estimated using azimuthal distributions

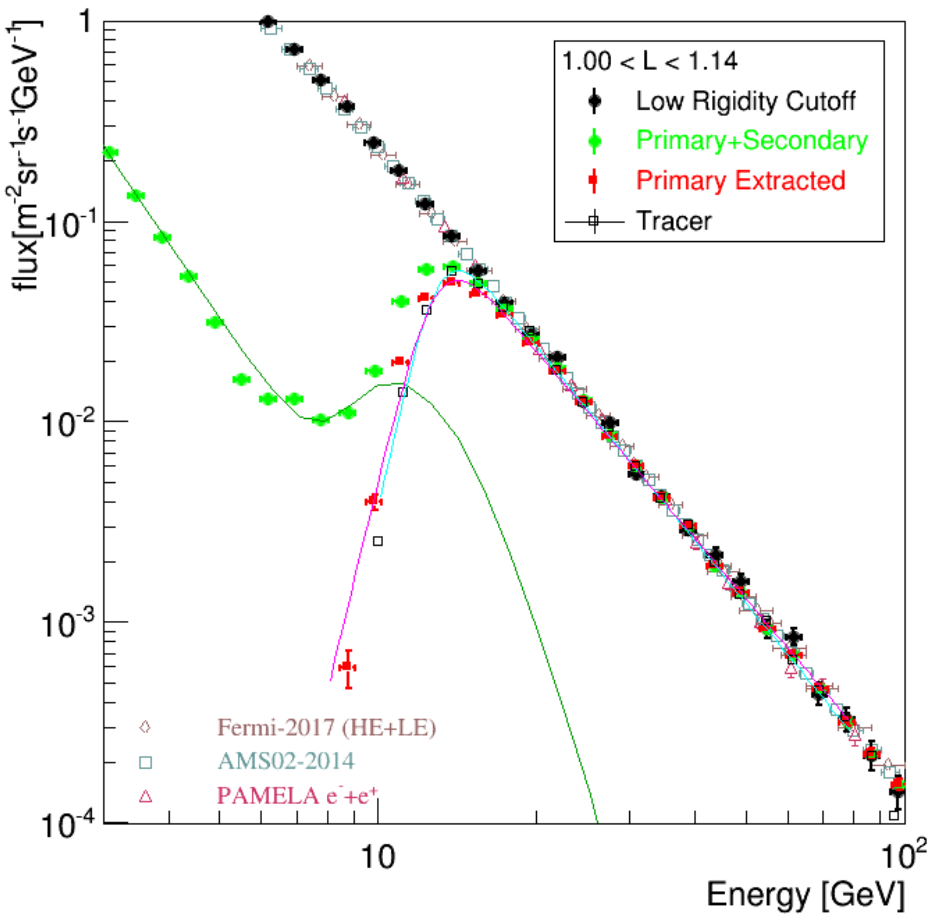
- Performed in three different cutoff rigidity regions.
- Correction factor was found to be **1.035** compared to MIP calibration.



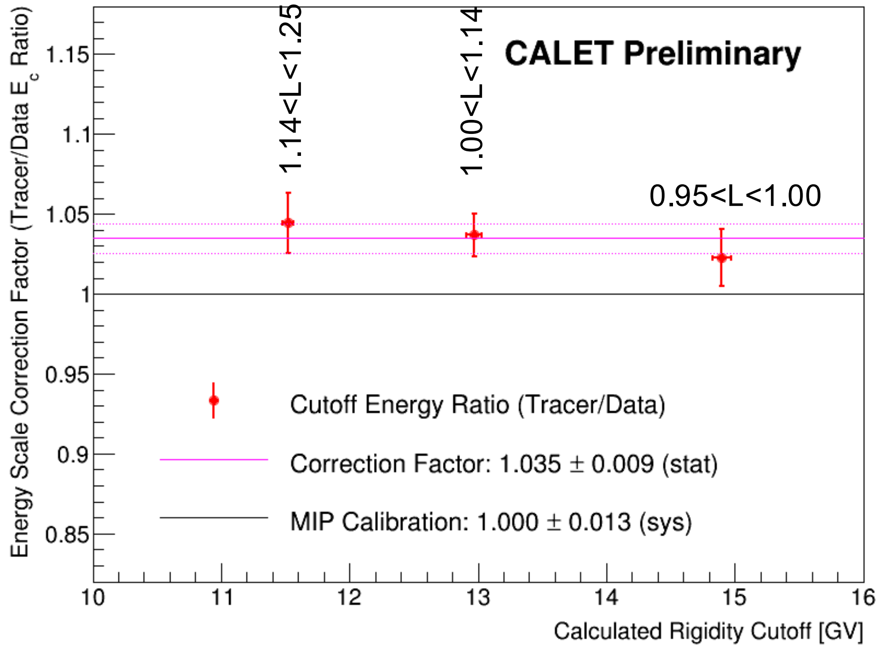

[Y.Asaoka, E1.5-0023-18] [S.Miyake, E1.5-0027-18]

# Cutoff Rigidity Measurements and Comparison with Calculation

**AFTER CORRECTION**




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

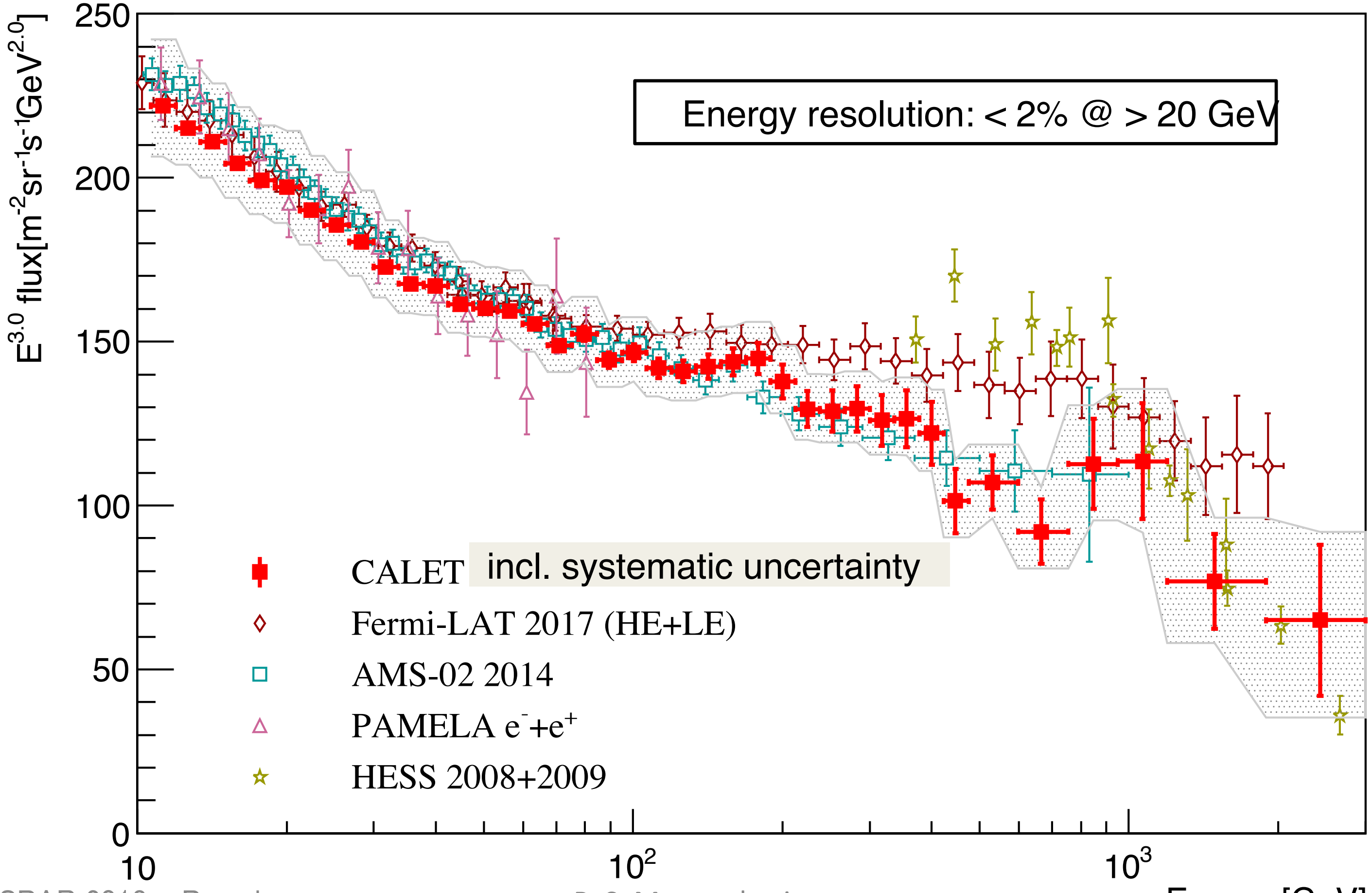



Since universal energy-scale calibration between different instruments is very important, we adopt the energy scale determined by rigidity cutoff to derive our spectrum.

# Inclusive ($e^+ + e^-$) Electron Energy Spectrum [10 GeV, ~3TeV]

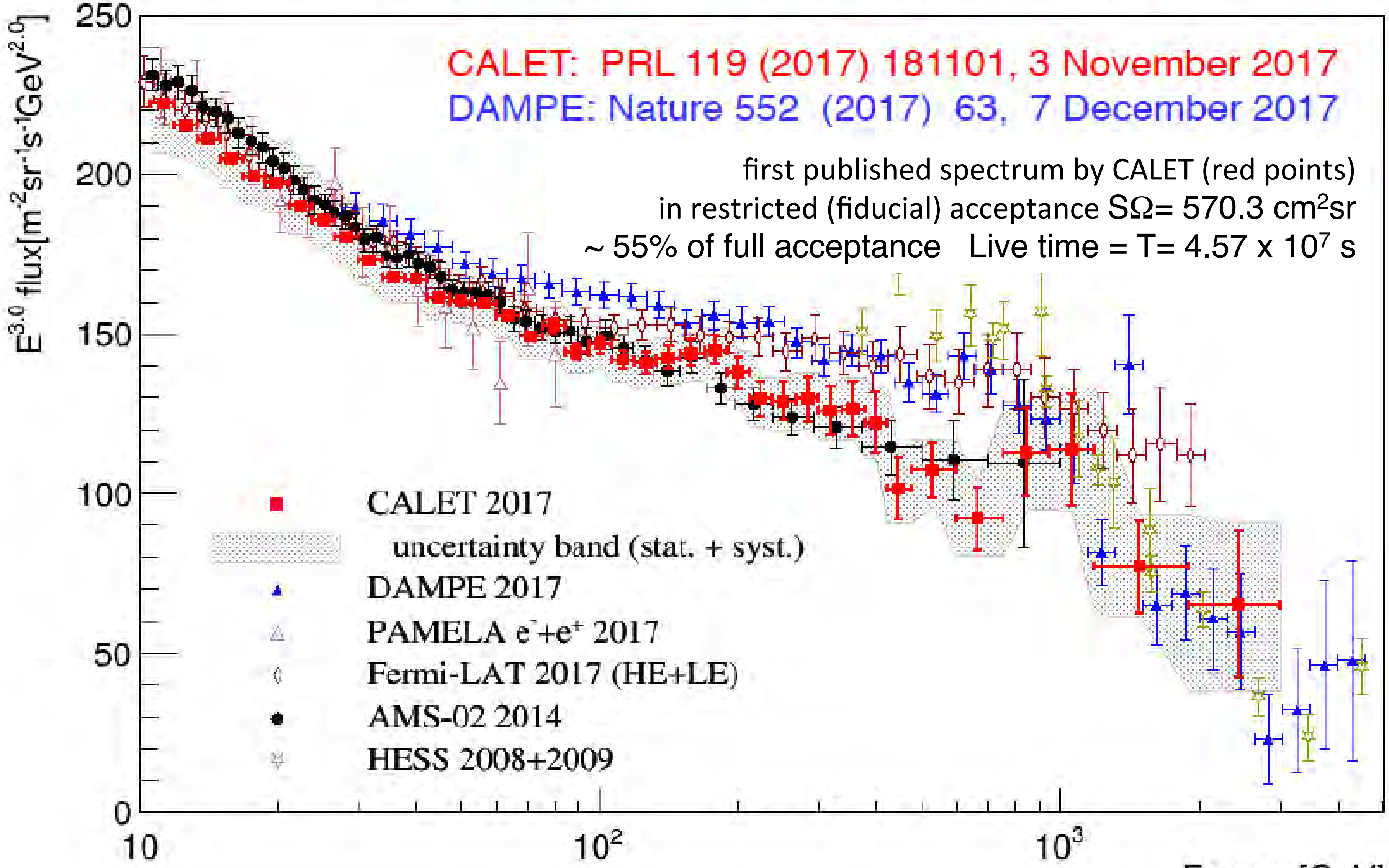
- Geometry Condition: $S\Omega$= 570.3 cm$^2$sr (Fully Contained: 55% for all acceptance)
- Live Time: 2015/10/13—2017/06/30 （x 0.85) => T= 4.57 x $10^7$ sec
- Exposure: $S\Omega T$ = 2.64 x $10^6$ m$^2$ sr sec **(less than 20% of full analysis for 5 years)**

Physical Review Letters 119 (2017) 181101, 3 November 2017



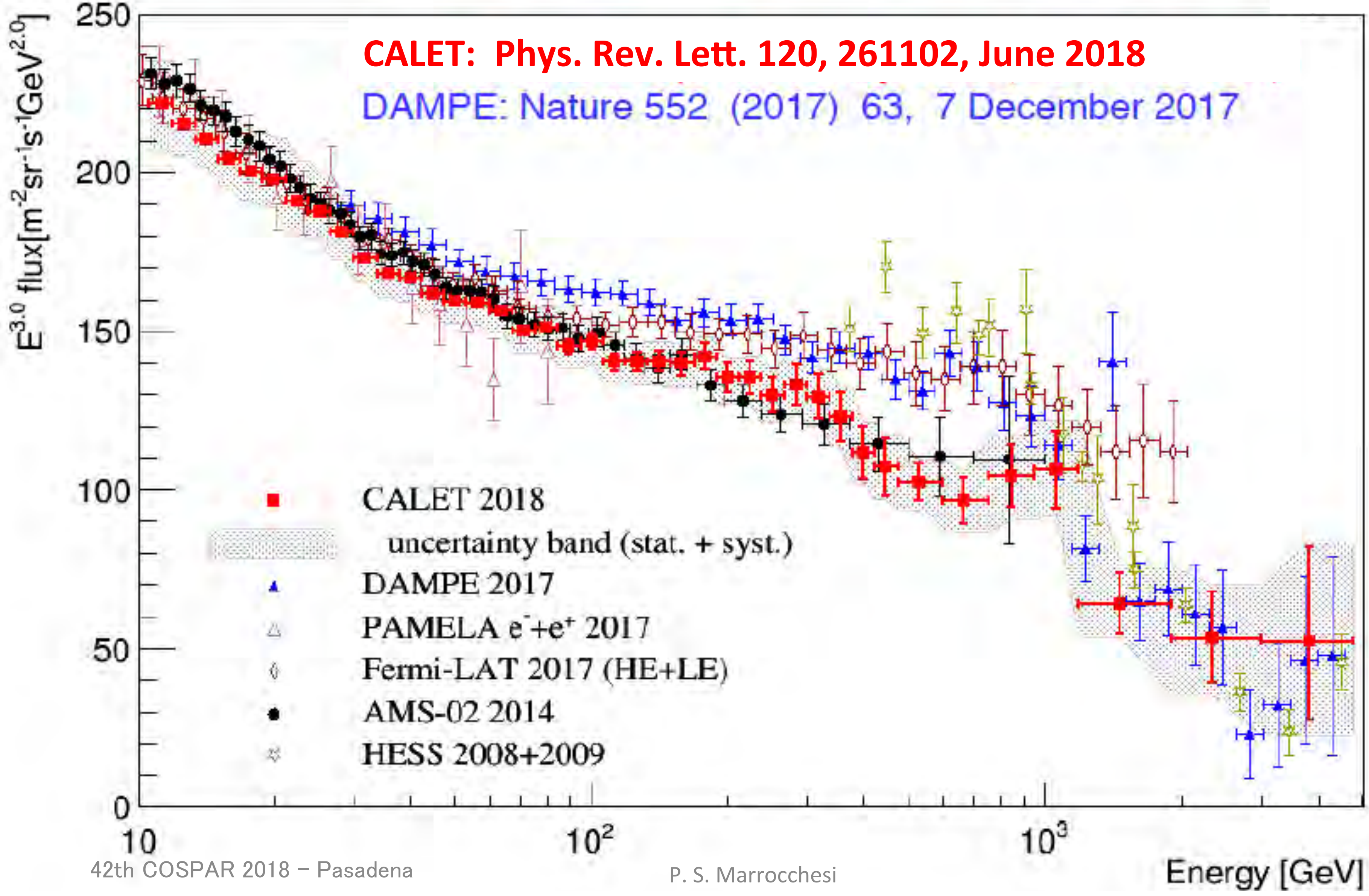
# Measurements of the electron spectrum

Comparison of CALET with DAMPE and other experiments in space



# Extended Measurement by CALET

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

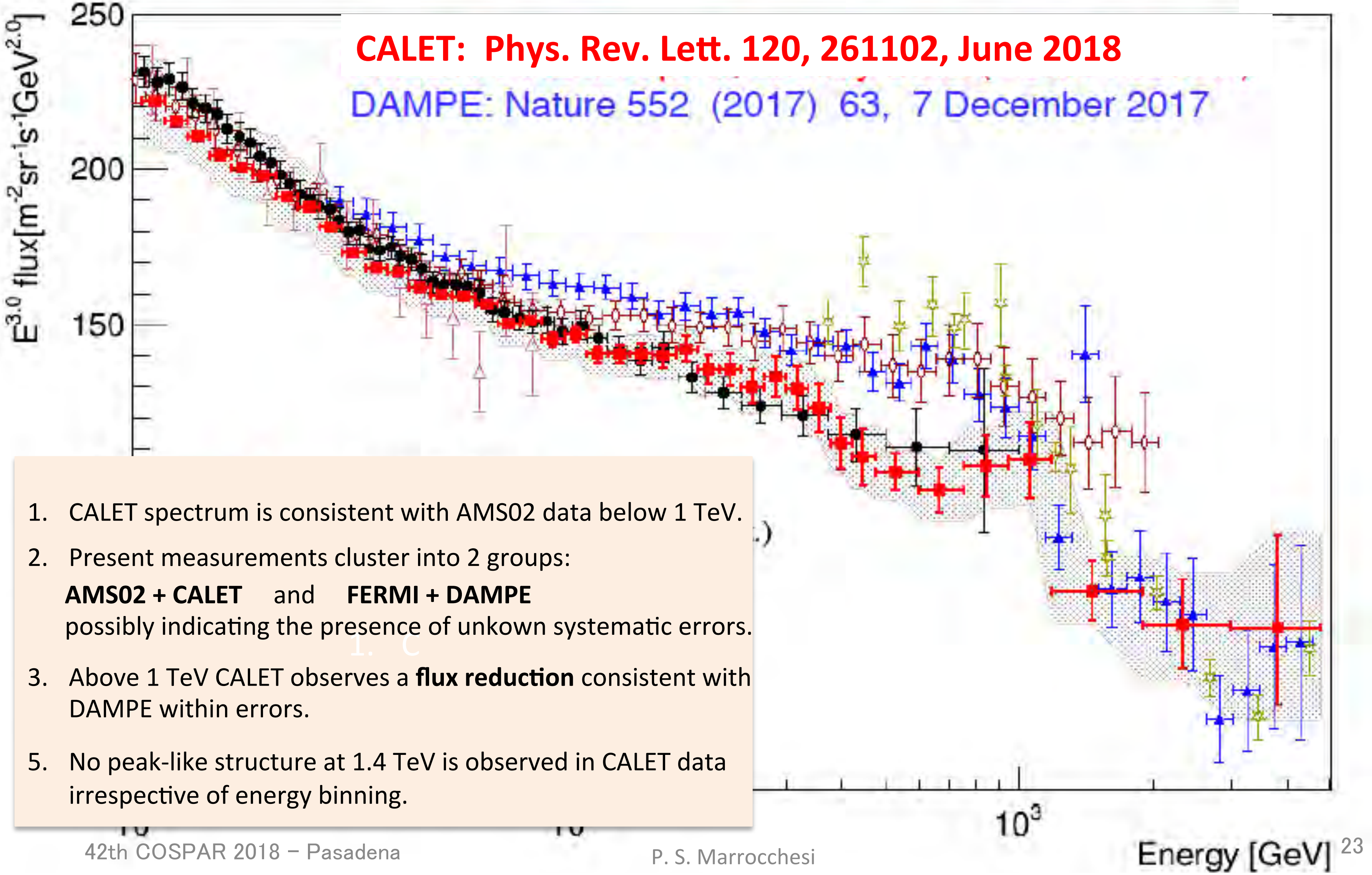


# Extended Measurement by CALET

Approximately doubled statistics above 500GeV by using full acceptance of CALET **[11 GeV, 4.8 TeV]**

**CALET: Phys. Rev. Lett. 120, 261102, June 2018**

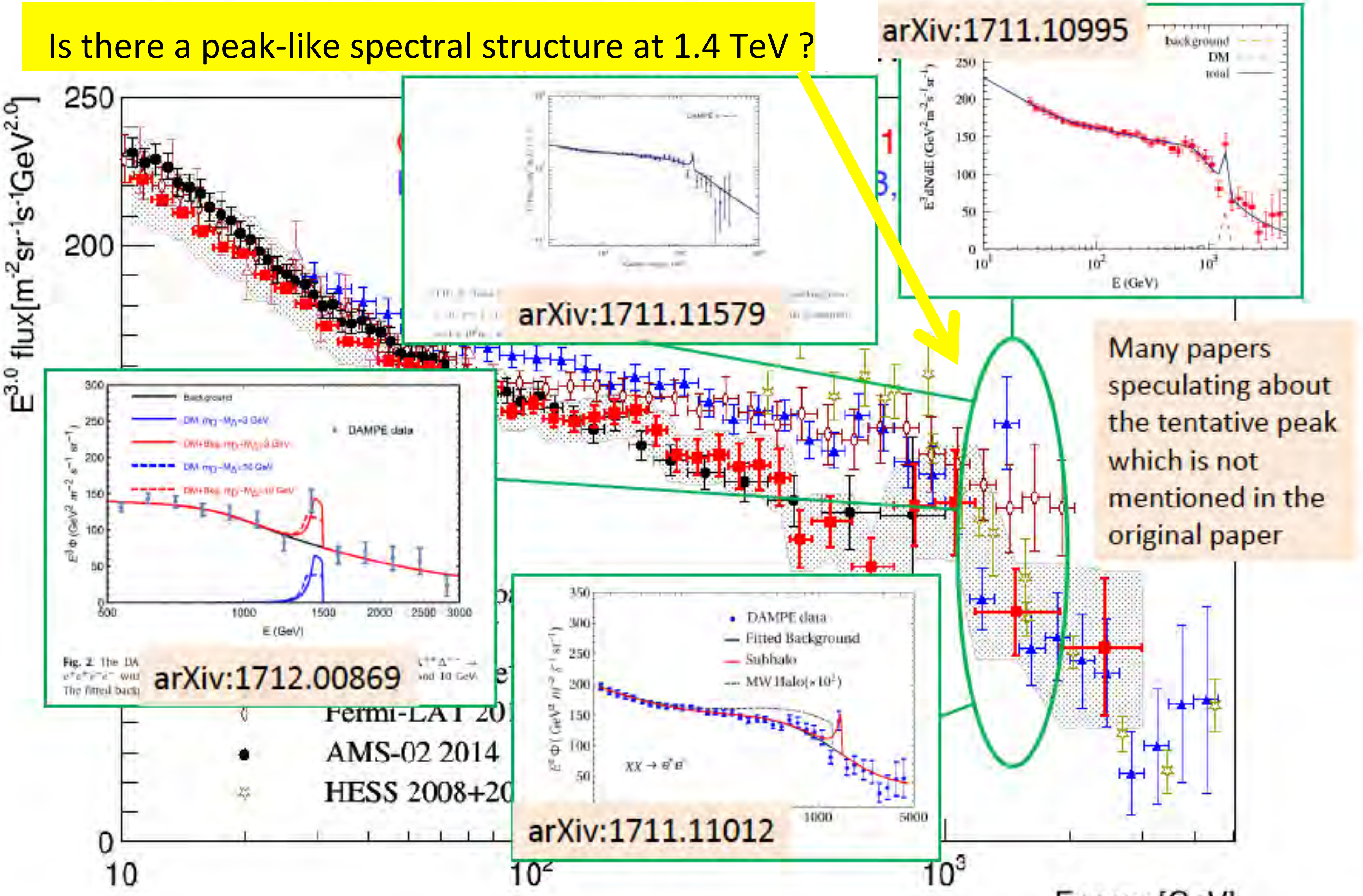
DAMPE: Nature 552 (2017) 63, 7 December 2017




1. CALET spectrum is consistent with AMS02 data below 1 TeV.
2. Present measurements cluster into 2 groups:
   **AMS02 + CALET** and **FERMI + DAMPE**
   possibly indicating the presence of unkown systematic errors.
3. Above 1 TeV CALET observes a **flux reduction** consistent with DAMPE within errors.
5. No peak-like structure at 1.4 TeV is observed in CALET data irrespective of energy binning.

# Comparison of CALET and DAMPE

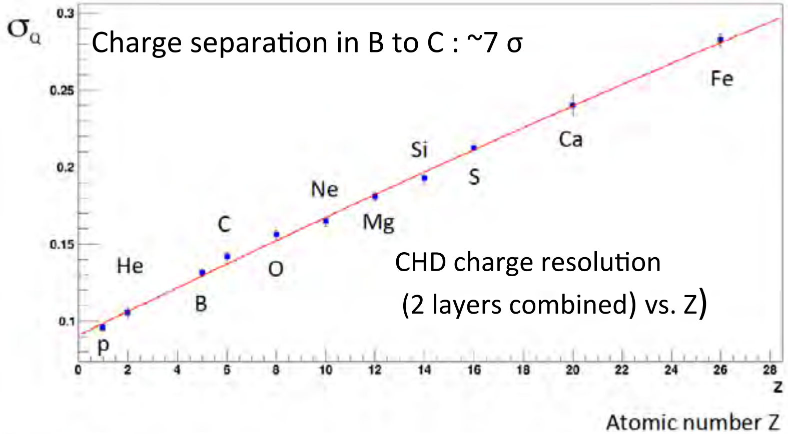
Is there a peak-like spectral structure at 1.4 TeV ?

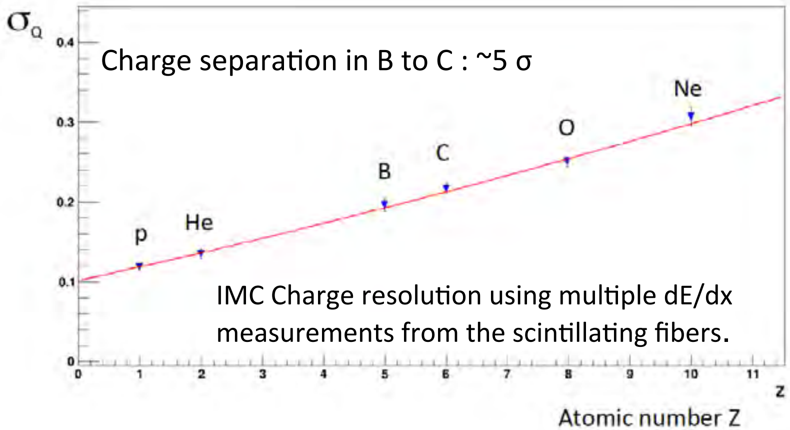



Many papers speculating about the tentative peak which is not mentioned in the original paper

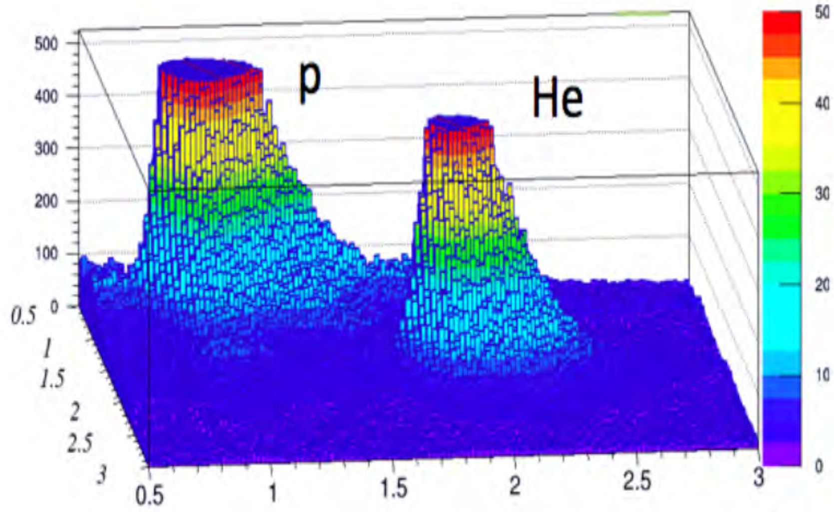
# Charge Identification of Nuclei with CHD and IMC

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

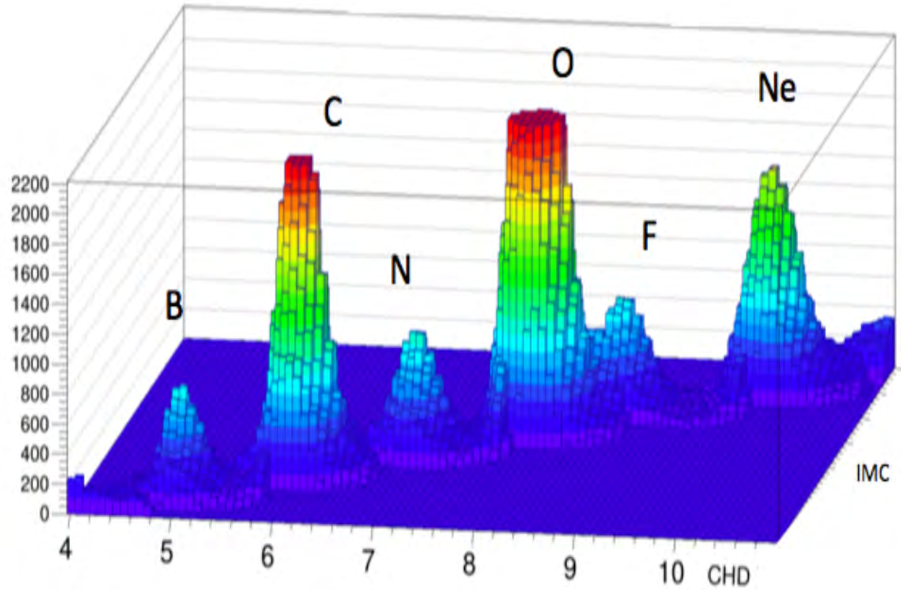



Non-linear response to $Z^2$ is corrected both in CHD and IMC using a halo model.




*) Plots are truncated to better show the elemental separation.



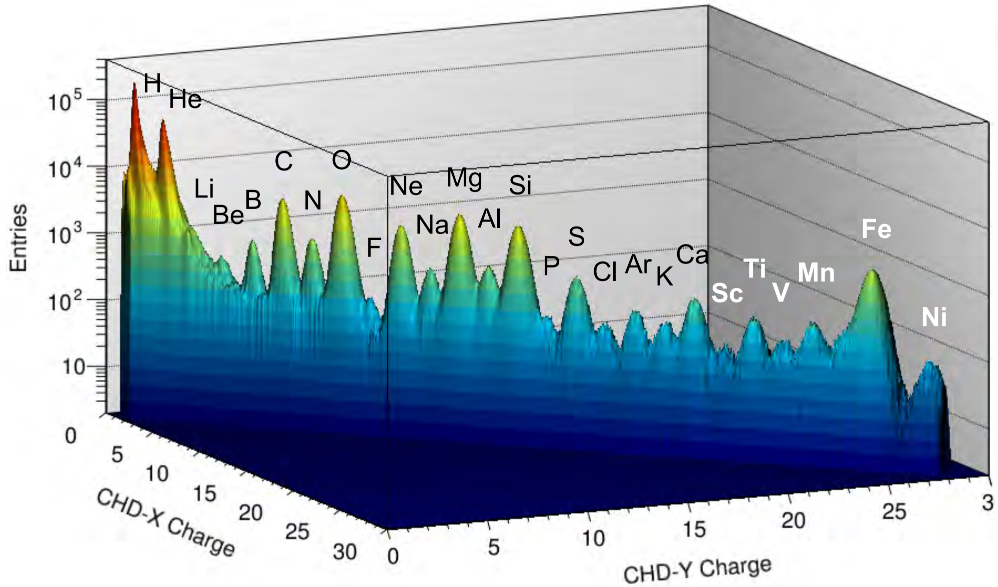
# Preliminary Flux of Primary Components

Flux measurement:

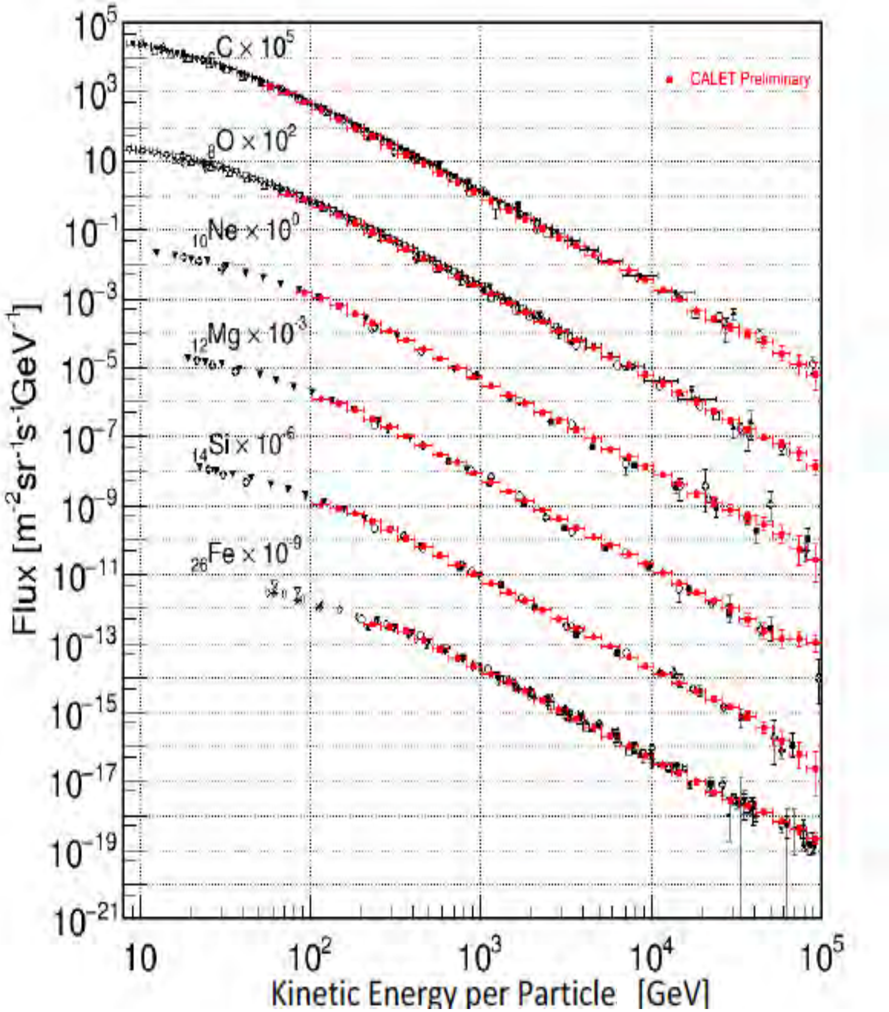
$$\Phi(E) = \frac{N(E)}{S\Omega\varepsilon(E)T\Delta E}$$

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

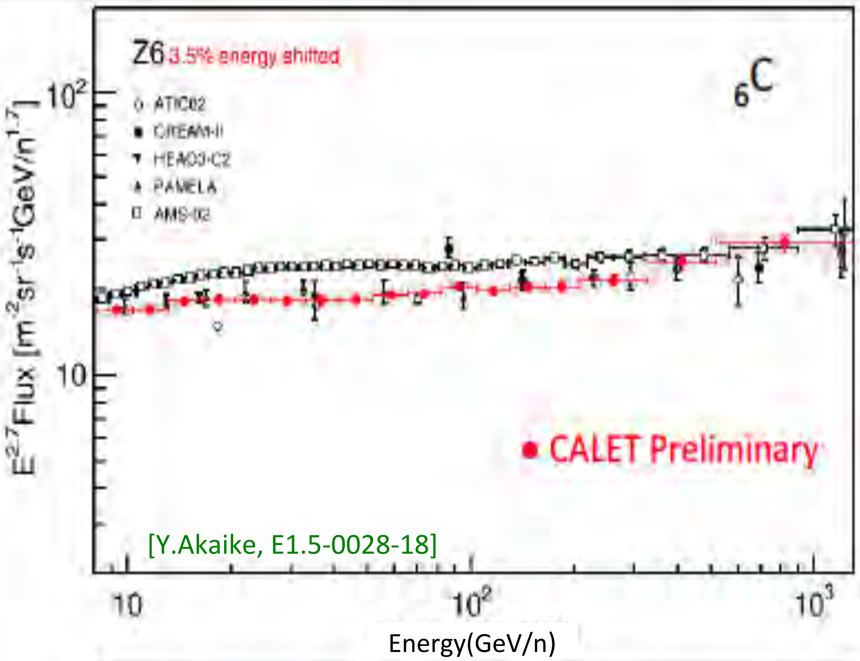


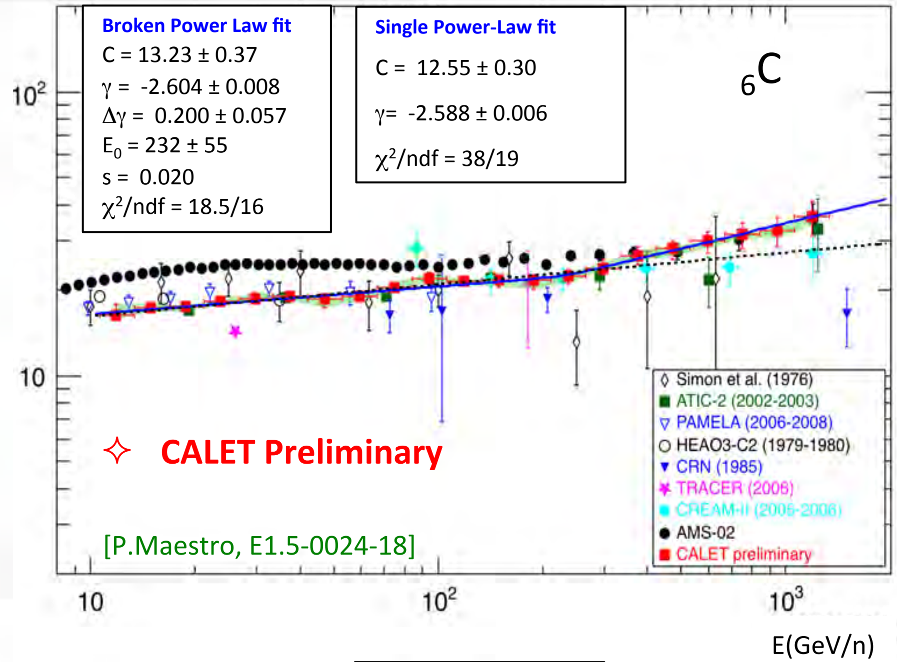

[Y.Akaike, E1.5-0028-18]

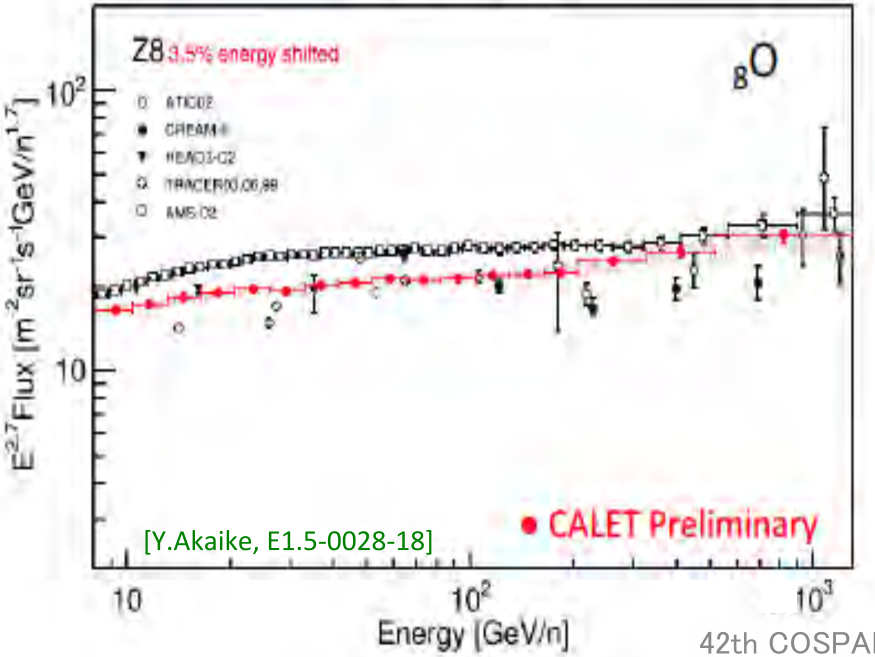


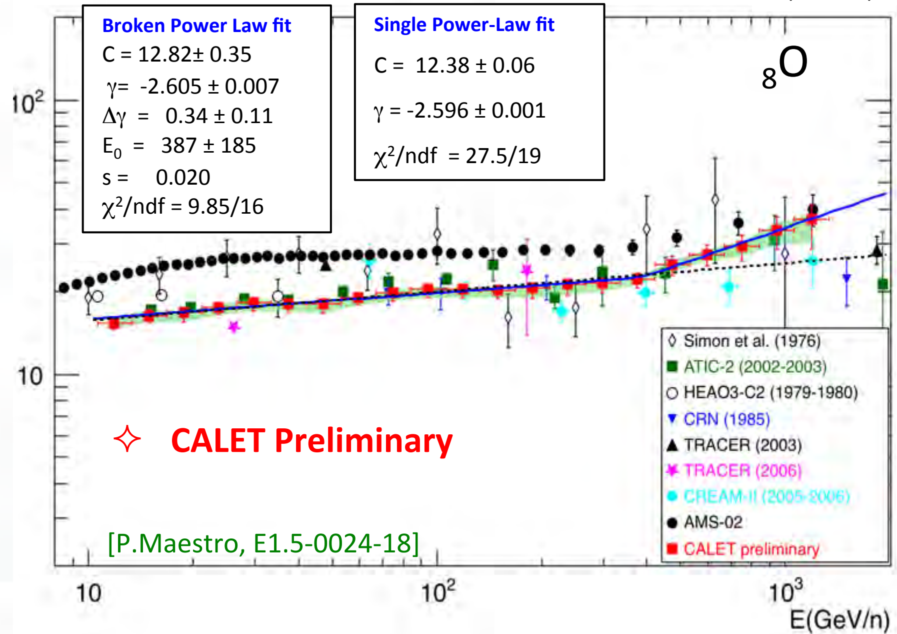
# Preliminary Energy spectra of Carbon and Oxygen

(2 independent CALET analyses)



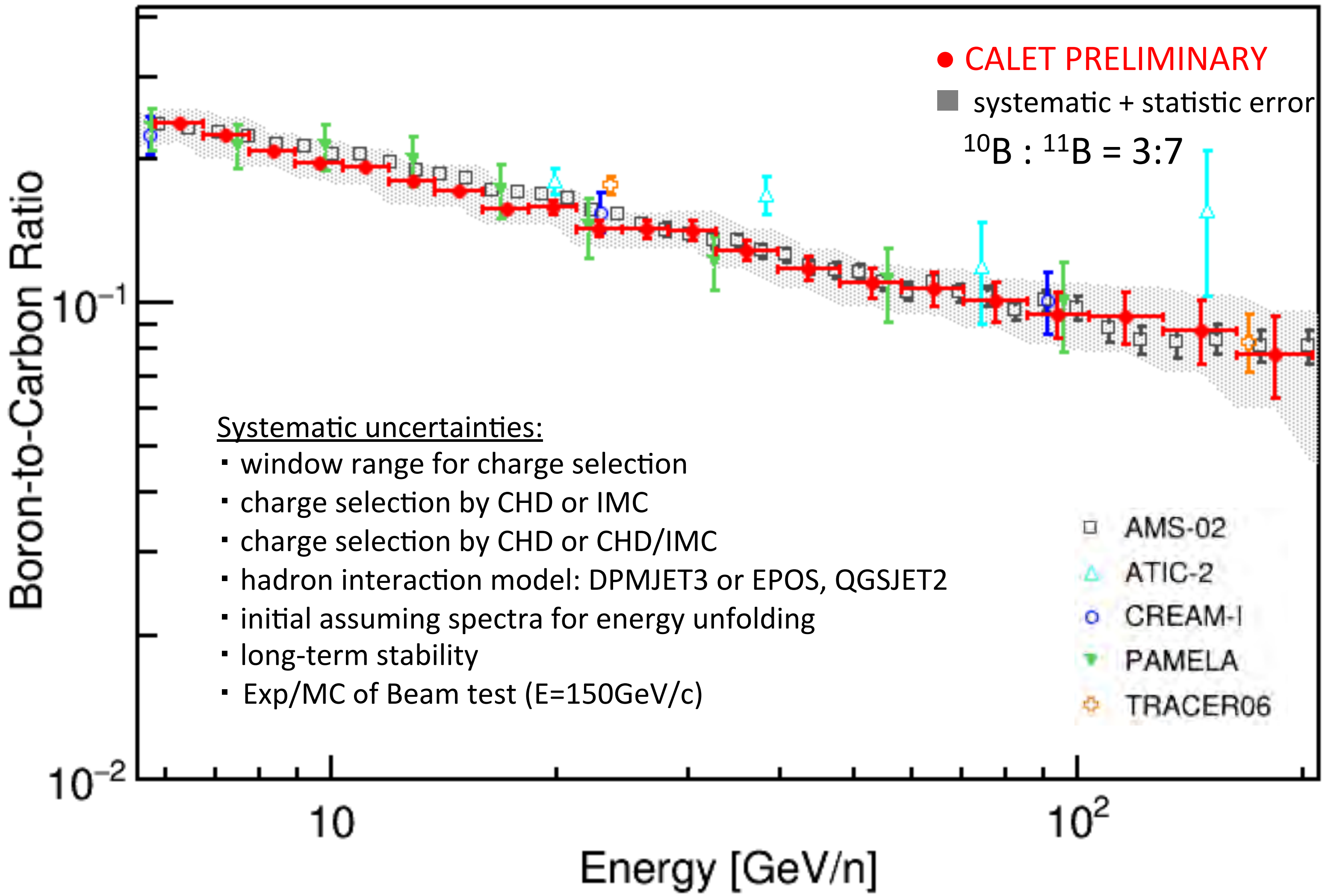



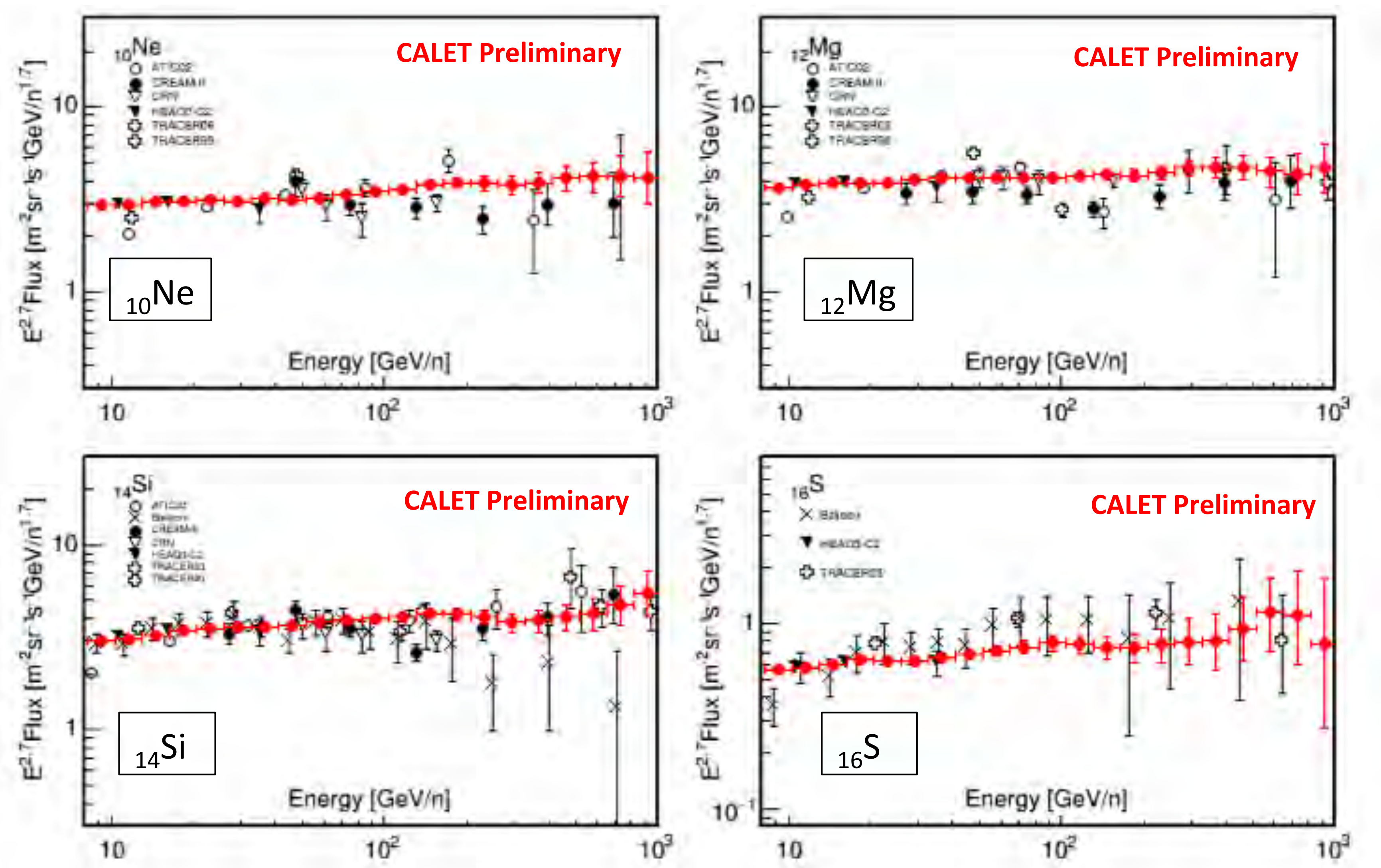
# Preliminary Boron-to-Carbon Flux Ratio

[Y.Akaike, E1.5-0028-18]



# Preliminary Spectra of Nuclei with **Even** Atomic Number  (Z = 10 ÷16)

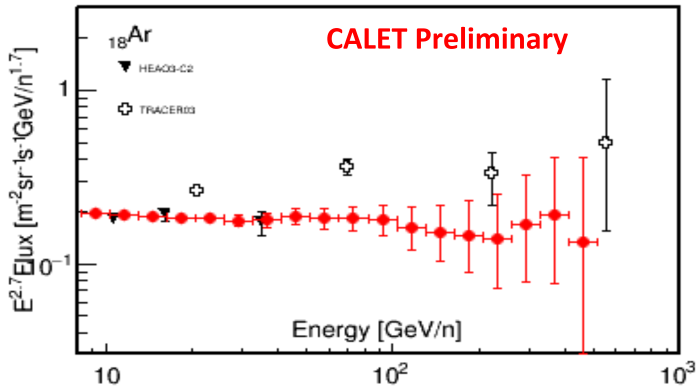
[Y.Akaike, E1.5-0028-18]



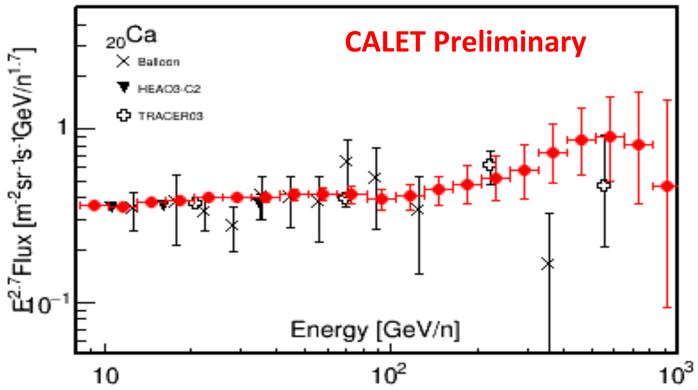
# Preliminary Spectra of Nuclei with **Even** Atomic Number (Z = 18 ÷28)

[Y.Akaike, E1.5-0028-18]

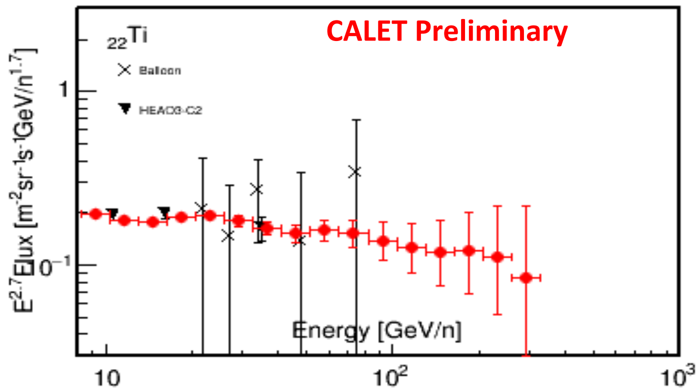
$_{18}Ar$



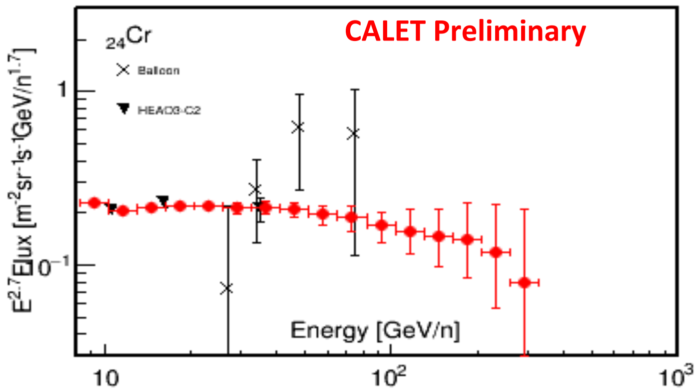

$_{20}Ca$



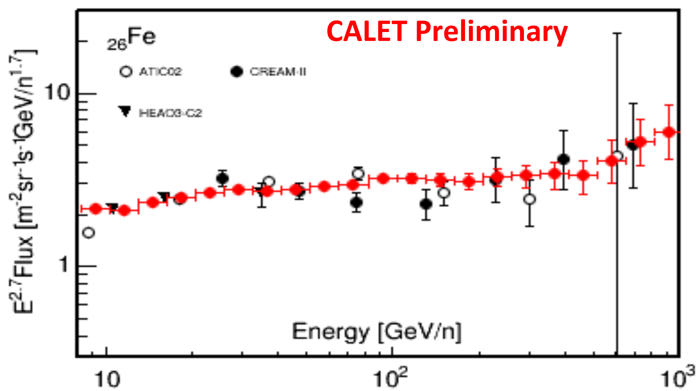

$_{22}Ti$



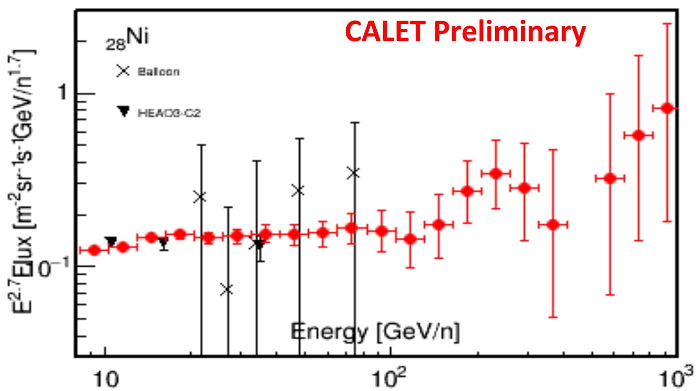

$_{24}Cr$




$_{26}Fe$




$_{28}Ni$



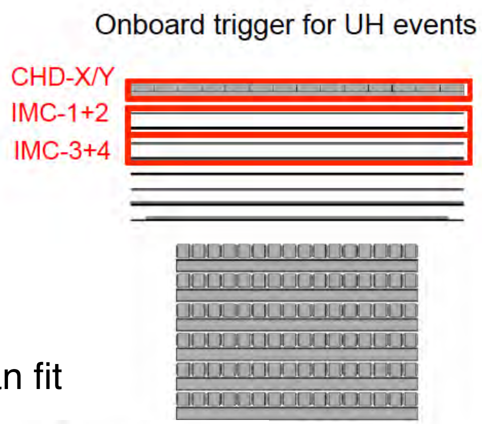
# Preliminary Ultra Heavy Nuclei Measurements for $26 < Z \leq 40$

[B.Rauch, E1.5-0029-18]

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

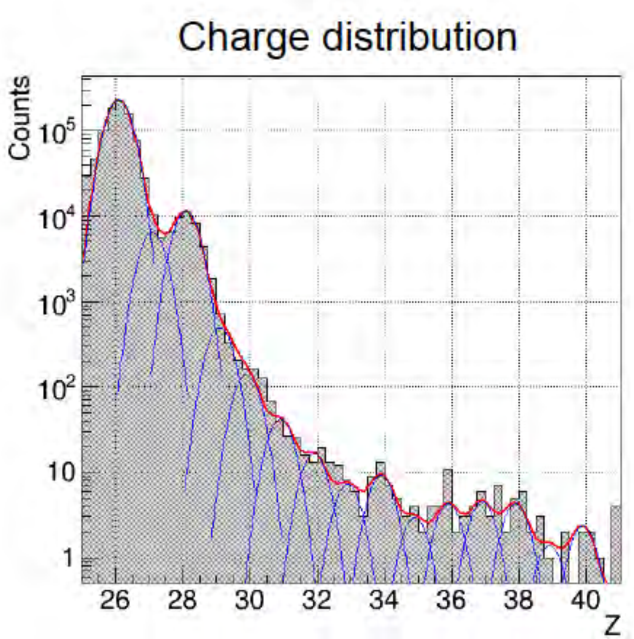
CALET has a special UH CR trigger utilizing the CHD and the top 4 layers of the IMC that:

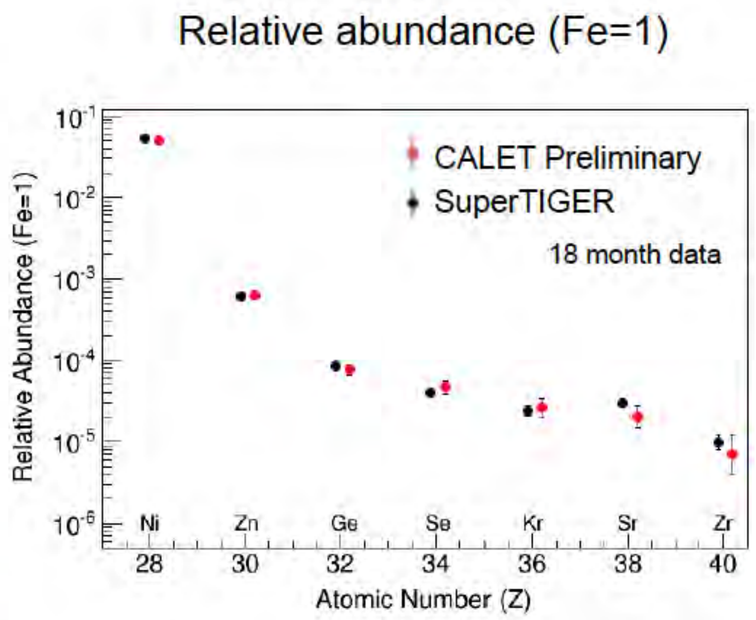
- has an expanded geometry factor of ~4000 $cm^2sr$
- has a very high duty cycle due to low event rate




Data analysis

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



# CALET γ–ray Sky (>1GeV)

Instrument characterized using EPICS simulations

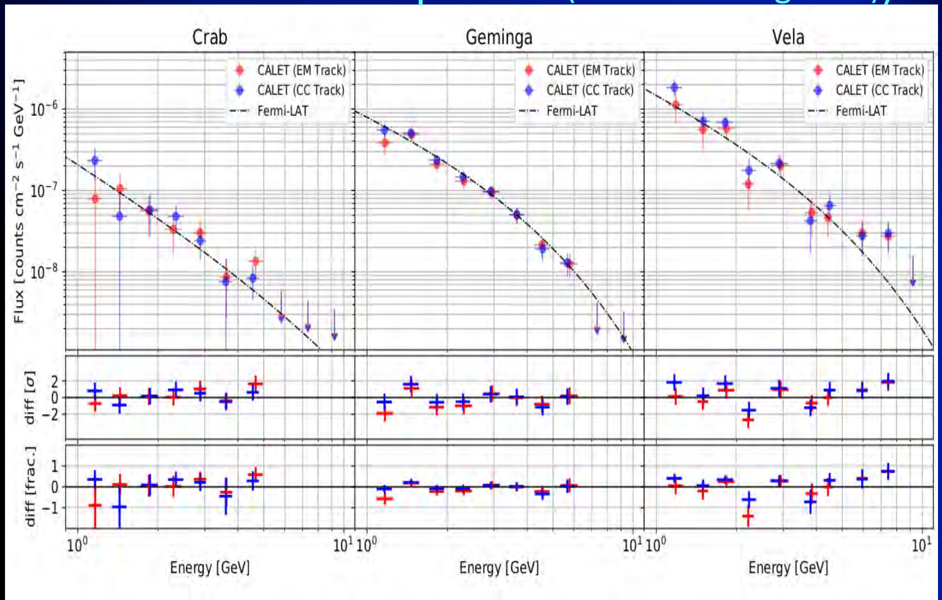
- Effective area ~400 cm$^2$ above 2 GeV
- Angular resolution < 2° above 1 GeV (< 0.2° above 10 GeV)
- Energy resolution ~12% at 1 GeV (~5% at 10 GeV)

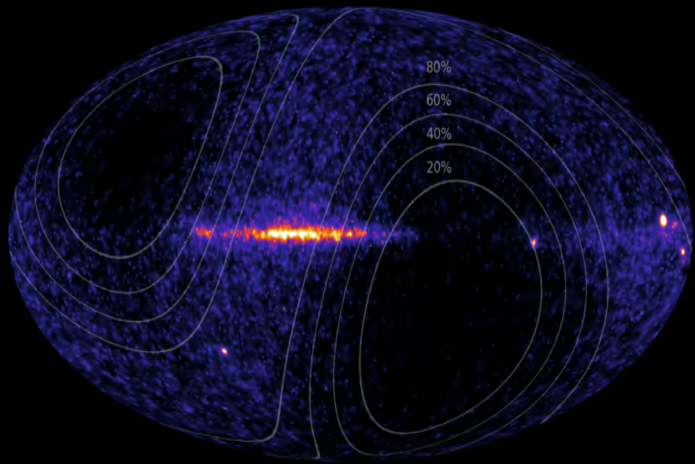
Simulated IRFs consistent with 2 years of flight data

Consistency in signal-dominated regions with Fermi-LAT

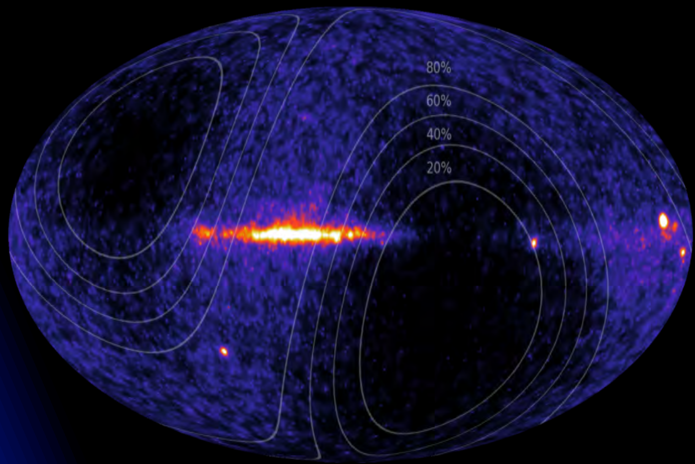
Residual background in low-signal regions

Flux validation with pulsars (under investigation))



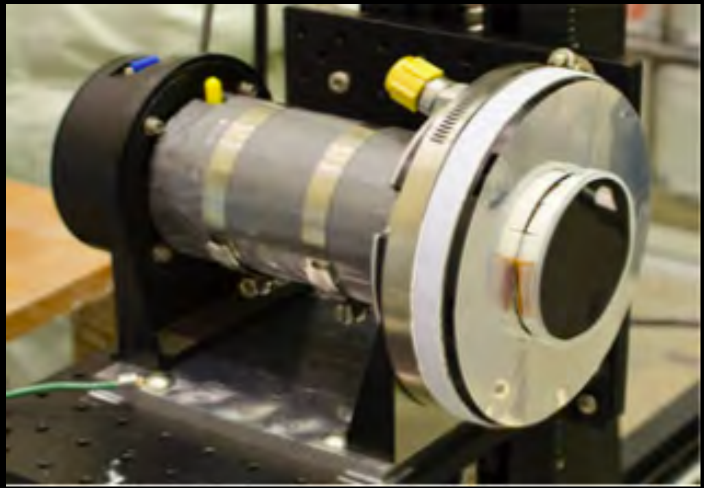

[N.Cannady, E1.17-0009-18]




See also: **E1.17-0022-18** (Mori & Asaoka)

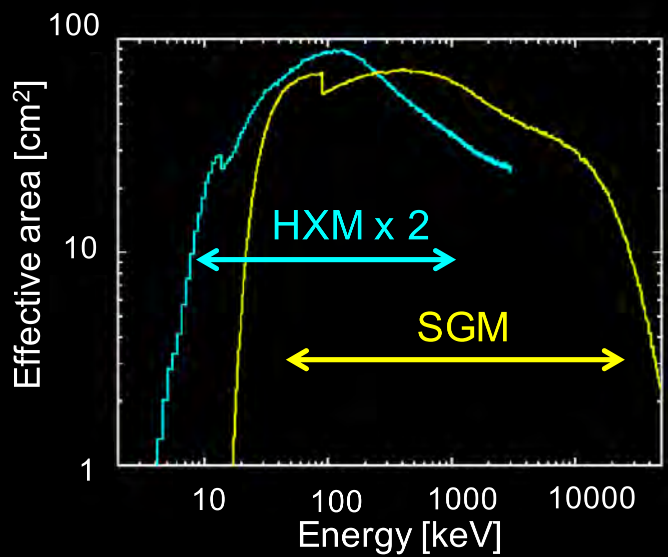
# CALET Gamma-ray Burst Monitor (CGBM

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



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

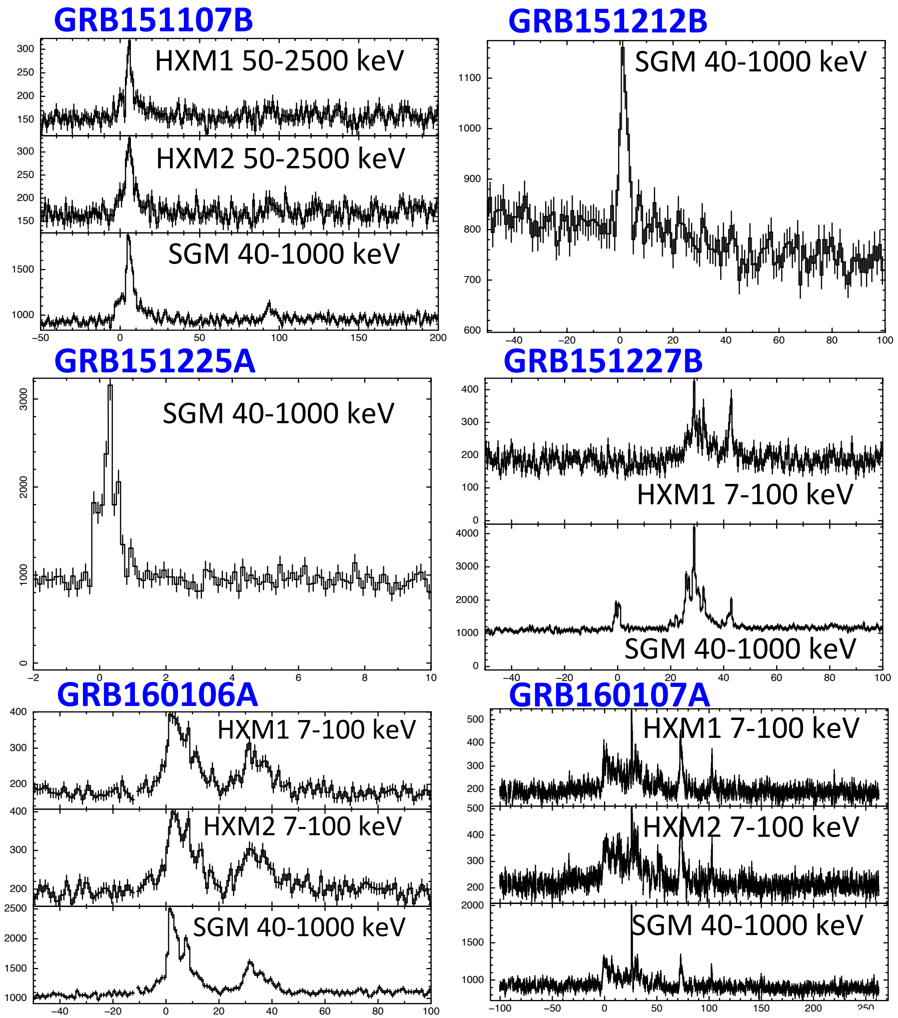
| | HXM (x2) | SGM |
|---|---|---|
| Detector (Crystal) | $LaBr_3(Ce)$ | BGO |
| Number of detector | 2 | 1 |
| Diameter [mm] | 61 | 102 |
| Thickness [mm] | 12.7 | 76 |
| Energy range [keV] | 7-1000 | 100-20000 |
| Energy resolution@662 keV | ~3% | ~15% |
| Field of view | ~3 sr | ~$2\pi$ sr |



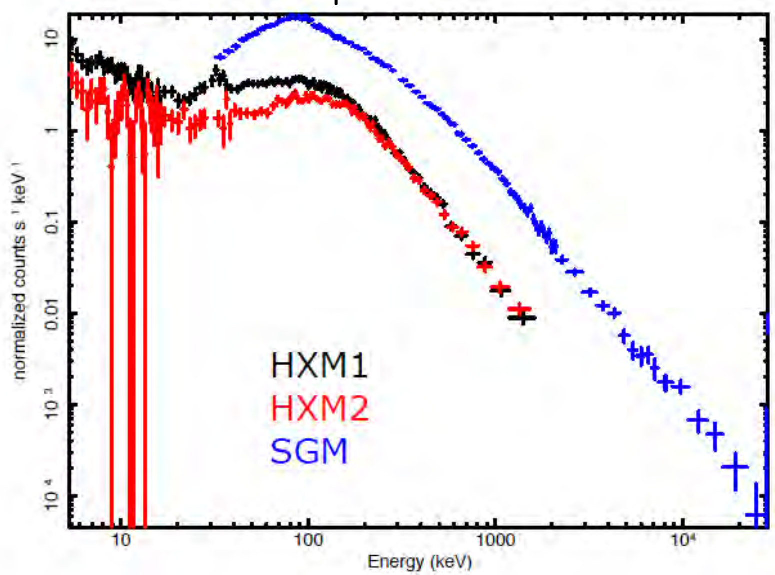
# Examples of CGBM light curves

- ✧ As of Sept 2017, 74 GRBs confirmed by other missions
- ✧ 63 Long (85%), 11 Short (15%) - Average rate ~ 37 GRBs/year

[S.Ricciarini, E1.17-00xx-18]



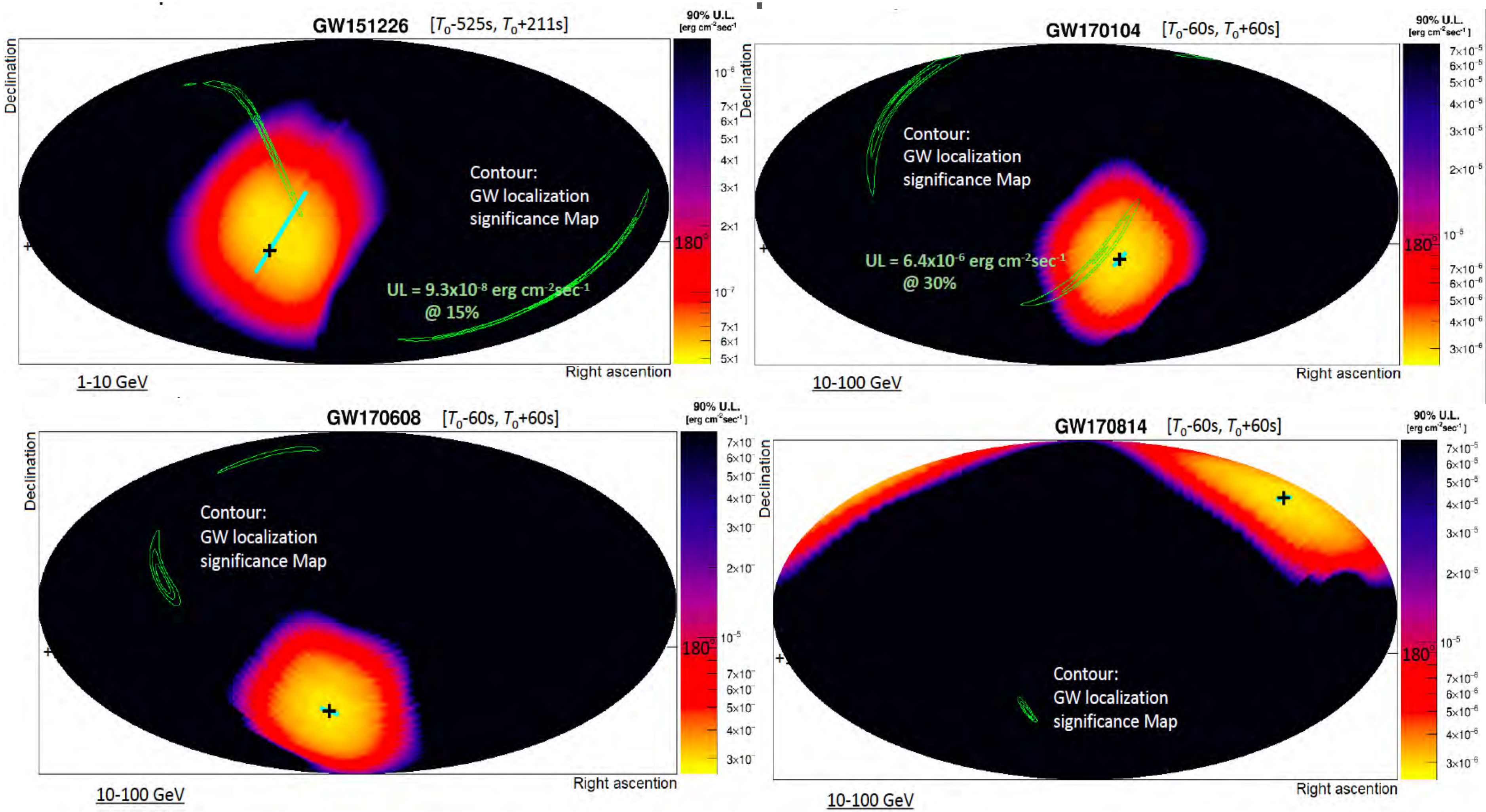

Raw count spectra of GRB 160625B



# 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



# Summary and Future Prospects

- CALET was successfully launched on Aug. 19th, 2015. The observation campaign started on Oct. 13th, 2015. Excellent performance and remarkable stability of the instrument.
- As of Feb. 28, 2018, total observation time is 870 days with live time fraction to total time close to 85 %. Nearly 570 million events 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.
- Preliminary analysis of nuclei, electrons (+ positrons) and gamma-rays have successfully been carried out and spectra obtained in the energy range:
  - proton: 50 GeV~100 TeV, helium: 10 GeV-20 TeV/n, C-Fe: 300 GeV~100 TeV,
  - B/C ratio: 20 GeV/n-1TeV/n, All electrons: 10 GeV~4.5 TeV.
- Preliminary analysis of UH cosmic rays up to Z=40.
- CALET's CGBM detected 74 GRBs in the energy range 7 keV-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.