CALET

Calorimetric Electron Telescope on the International Space Station

JPS Autumn Meeting 2018

60 years of Physical Review Letters

Shinshu Univ. 2018 Sep. 15

Shoji Torii

Waseda University

for the CALET Collaboration

CALET Collaboration Team

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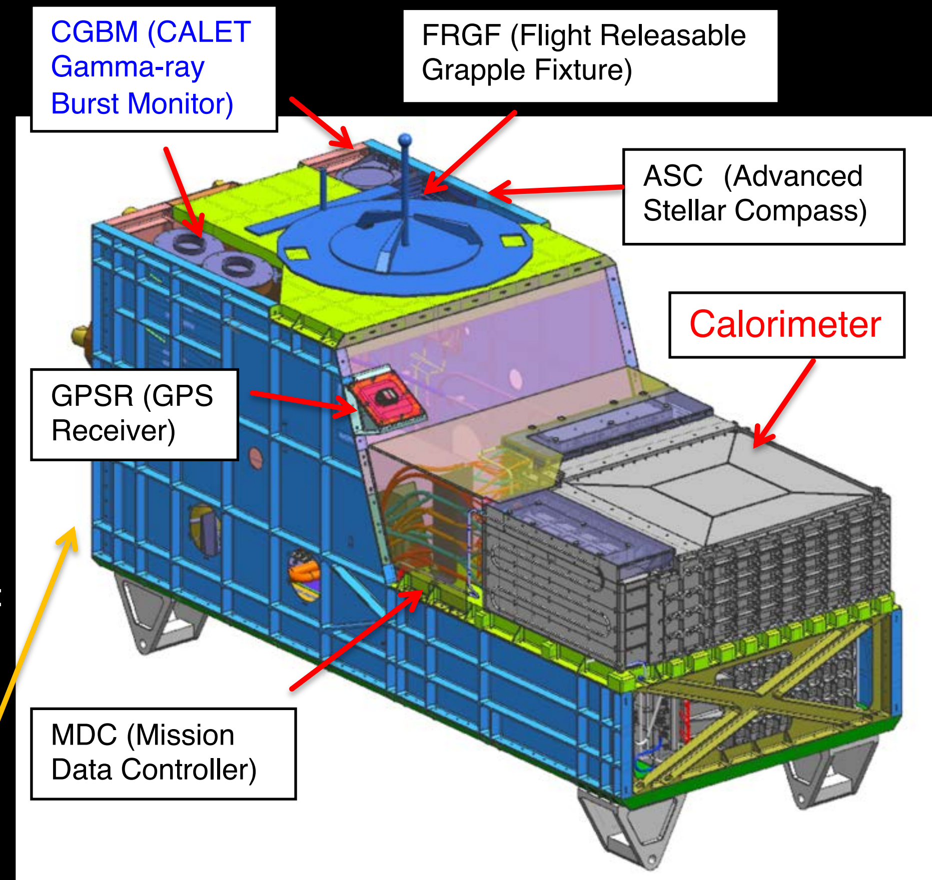
CALET Payload

Kounotori (HTV) 5

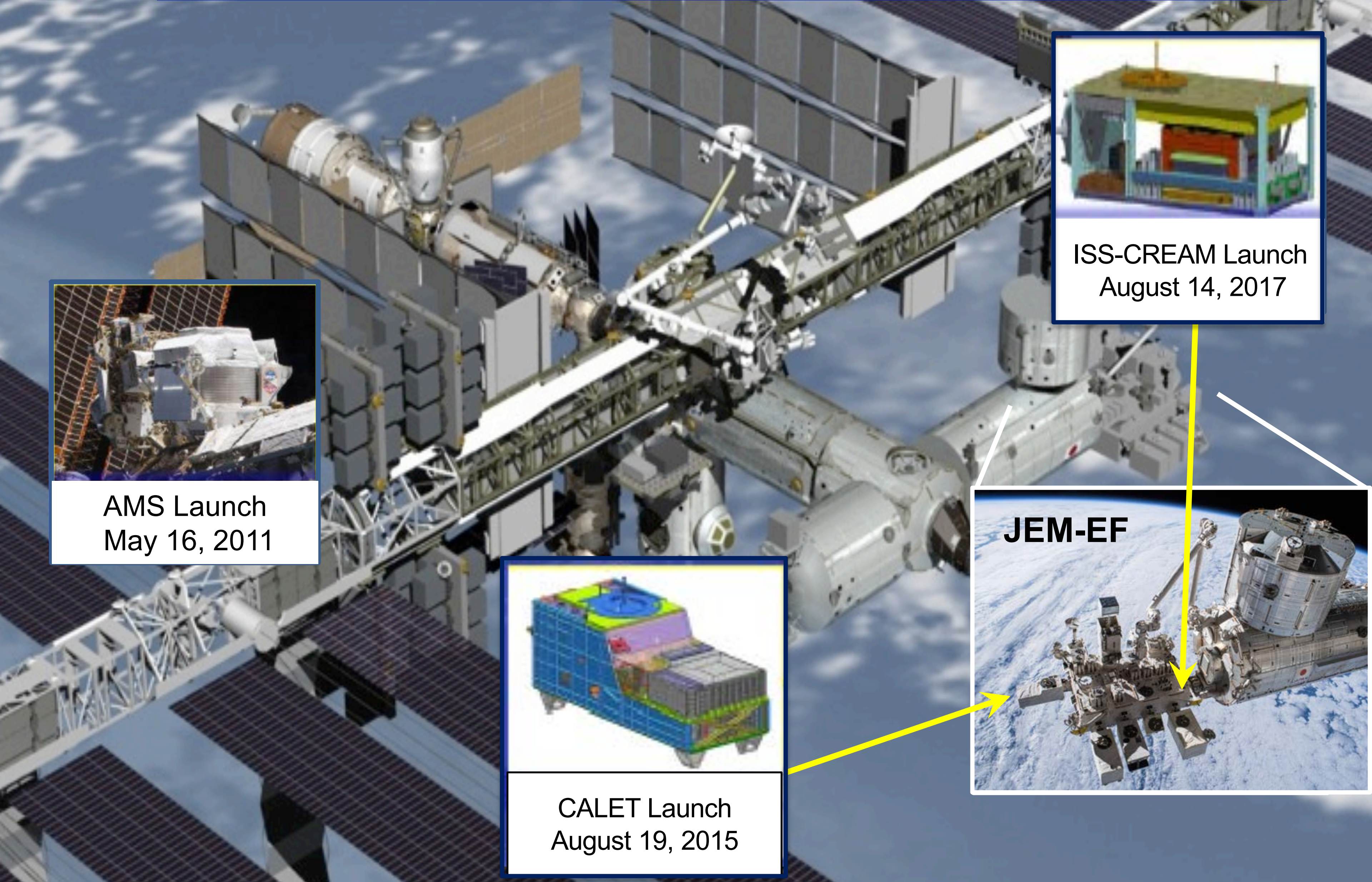
Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

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**

ISS: a Cosmic Ray Observatory in Low Earth Orbit



ISS: a Cosmic Ray Observatory in Low Earth Orbit

AMS Launch
May 16, 2011

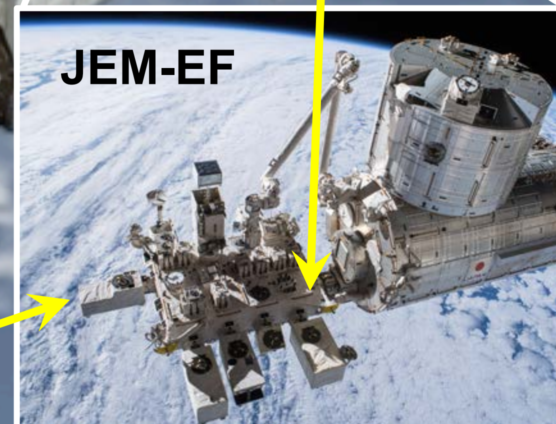
Magnet Spectrometer
- Various PID
- Anti-particles
- E ≤ TeV

Calorimeter
- Carbon target
- Hadrons
- Including TeV region

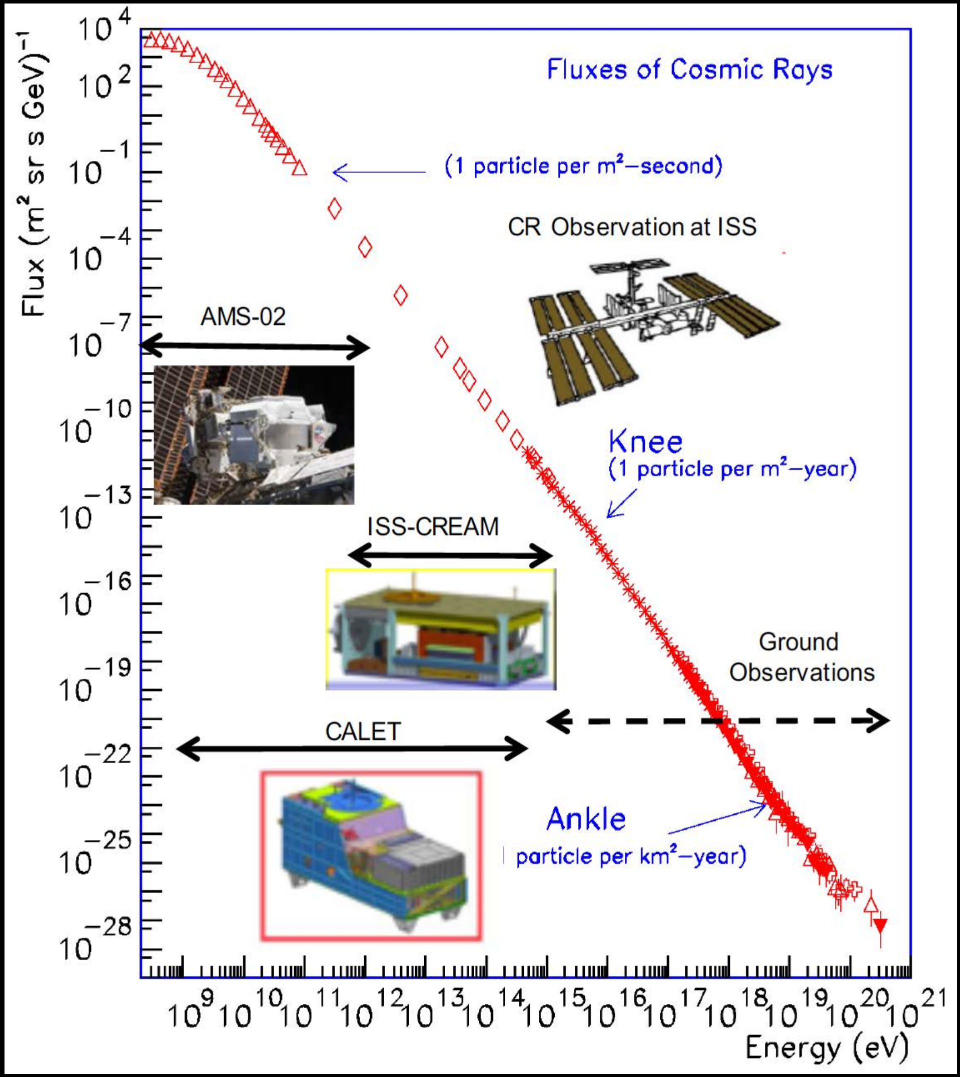
ISS-CREAM Launch
August 14, 2017

Calorimeter
- Fully active
- Electrons
- Including TeV region

CALET Launch
August 19, 2015



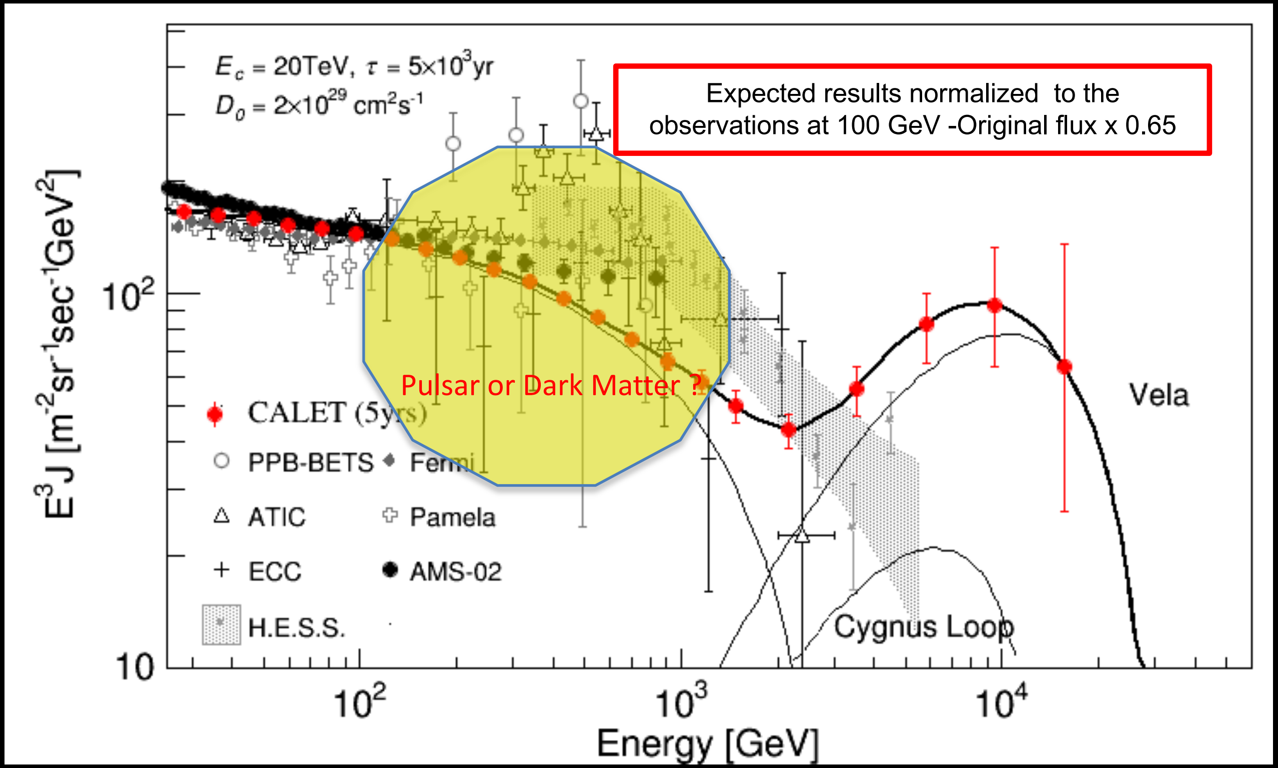
Cosmic Ray Observations at the ISS and CALET

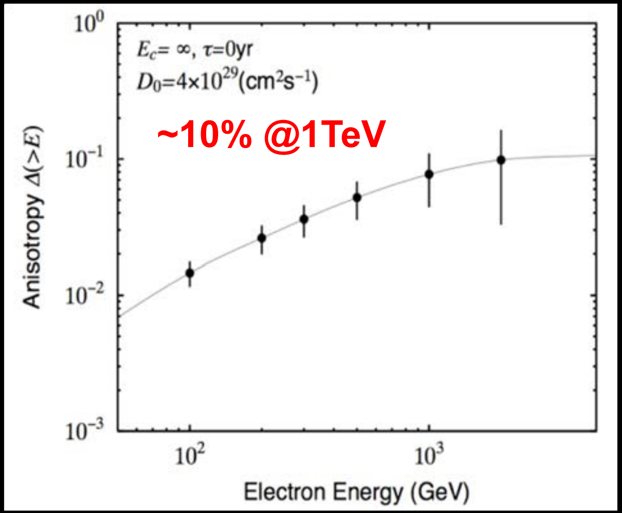


Overview of CALET Observations

- 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 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

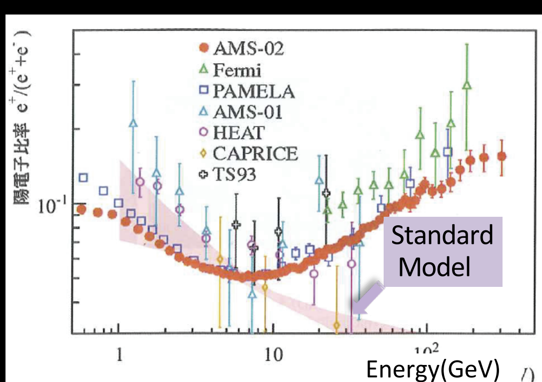
CALET energy reach (5 years)

Scientific Targets

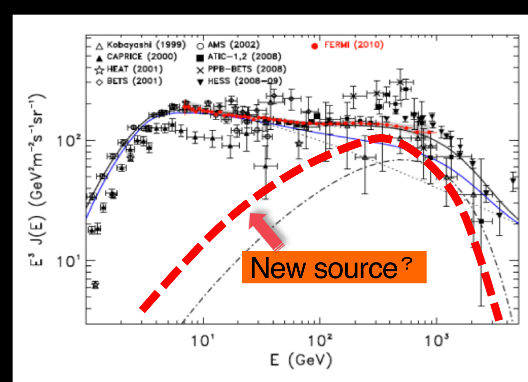
Scientific Objectives	Observation Targets	Energy Range
CR Origin and Acceleration	Electron spectrum p--Fe individual spectra Ultra Heavy Ions (26<Z≤40) Gamma-rays (Diffuse + Point sources)	1GeV - 20 TeV 10 GeV - 1000 TeV > 600 MeV/n 1 GeV - 1 TeV
Galactic CR Propagation	B/C and sub-Fe/Fe ratios	Up to 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

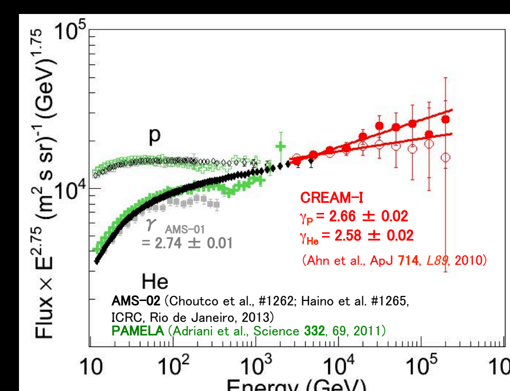
Increase of positron/electron ratio



Excess of electron+positron flux



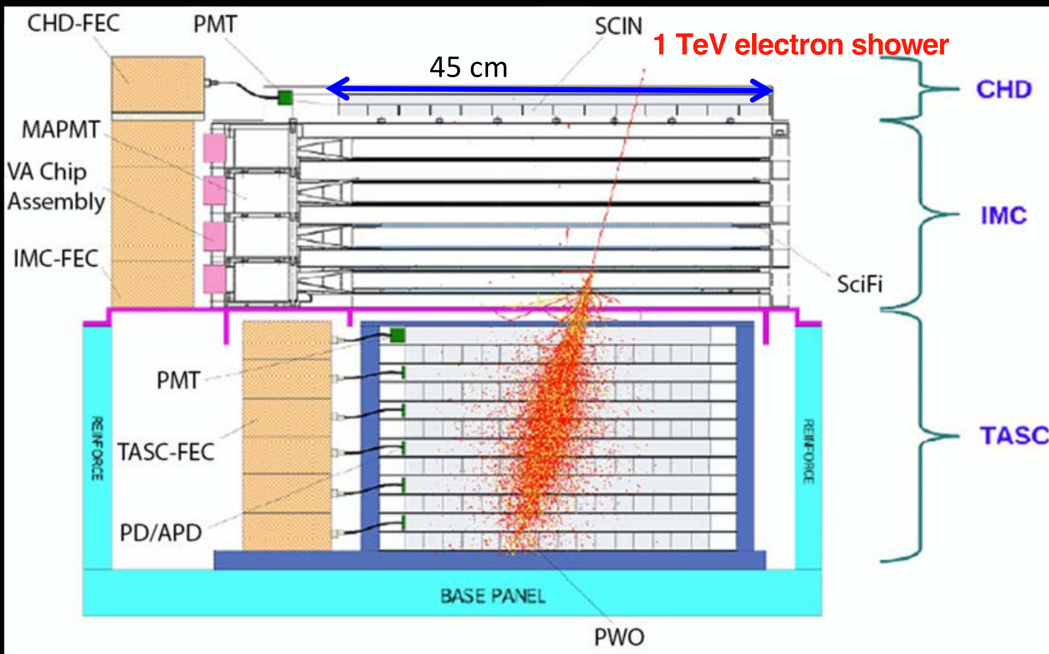
Hardening of p, He spectra



New source of electrons and positrons at 100 GeV region ?

CALET Instrument Performance

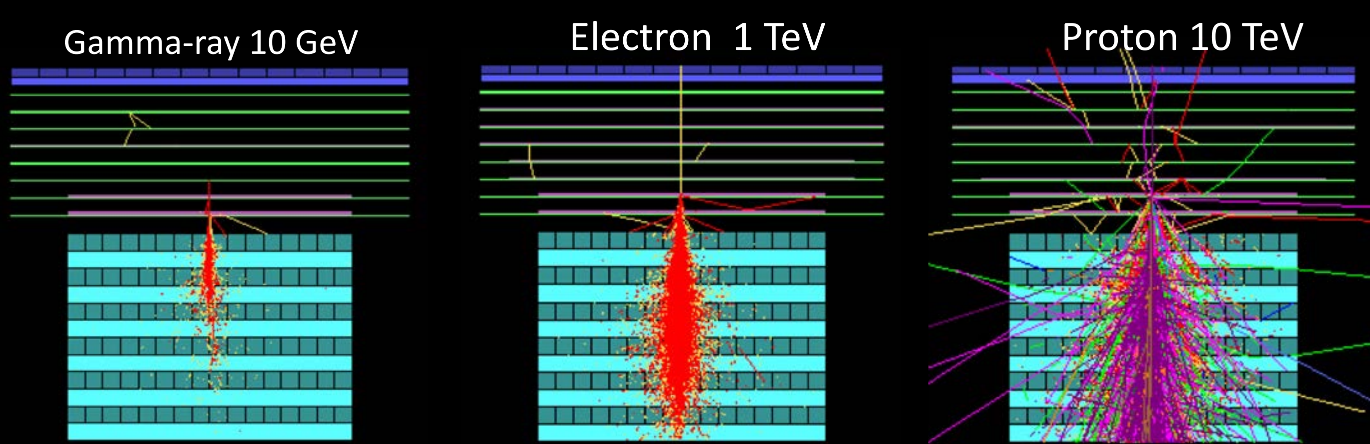
Field of view: ~ 45 degrees (from the zenith) Geometrical Factor: ~ 1,040 cm^{2}sr (for electrons)



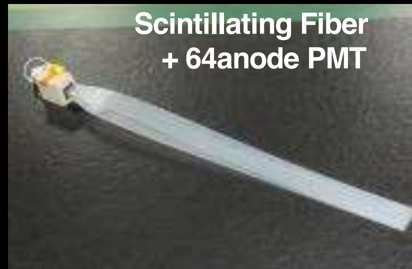
CALET: a unique set of key instruments

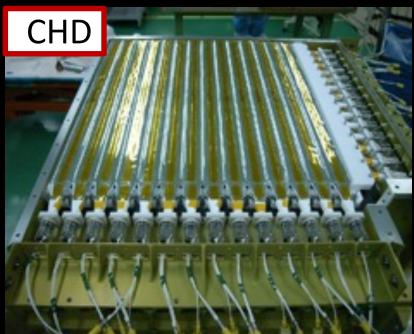
- **CHD: a dedicated charge detector + multiple dE/dx sampling in the IMC allow to identify individual nuclear species (Δz~0.15-0.3 e).**
- **IMC: a high granularity (1mm) imaging pre-shower calorimeter accurately identifies the arrival direction of incident particles (~0.1°) and the starting point of 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).**

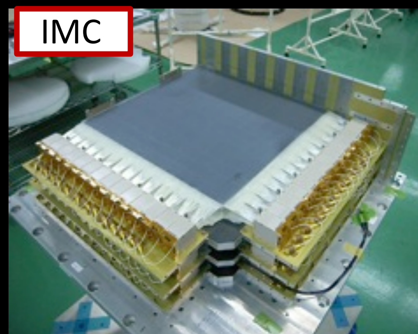
Simulated Shower Profile



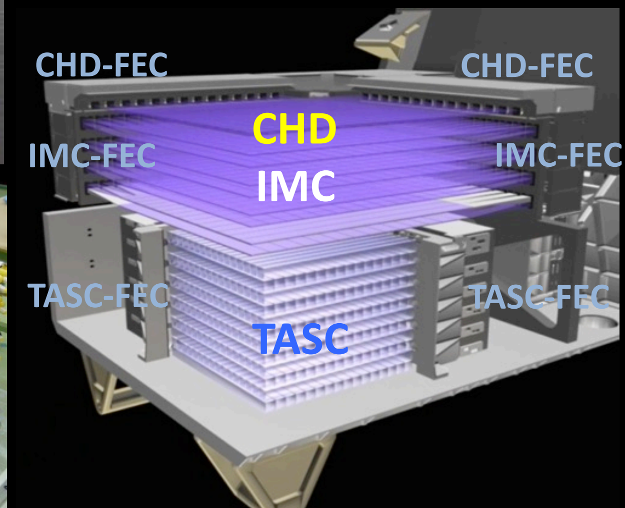
CALET Instrument Overview







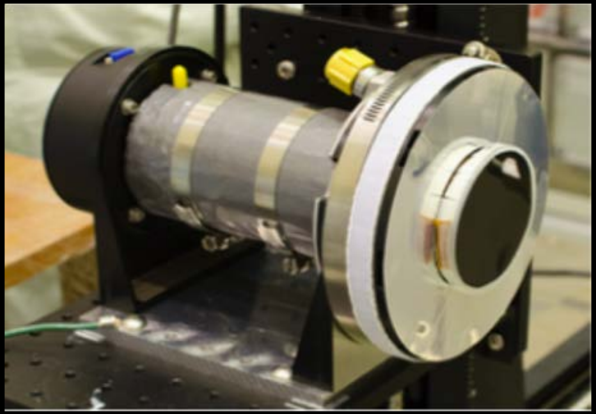
CALORIMETER



	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 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**

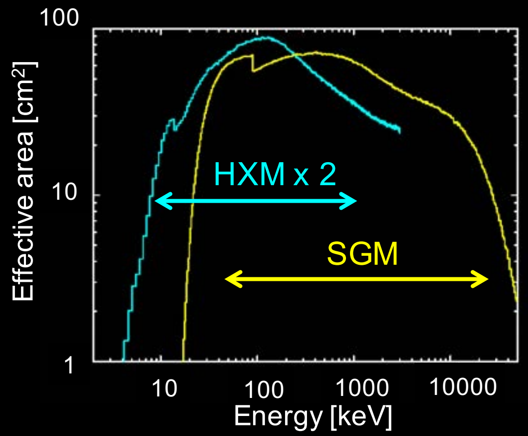
CALET Gamma-ray Burst Monitor (CGBM)

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

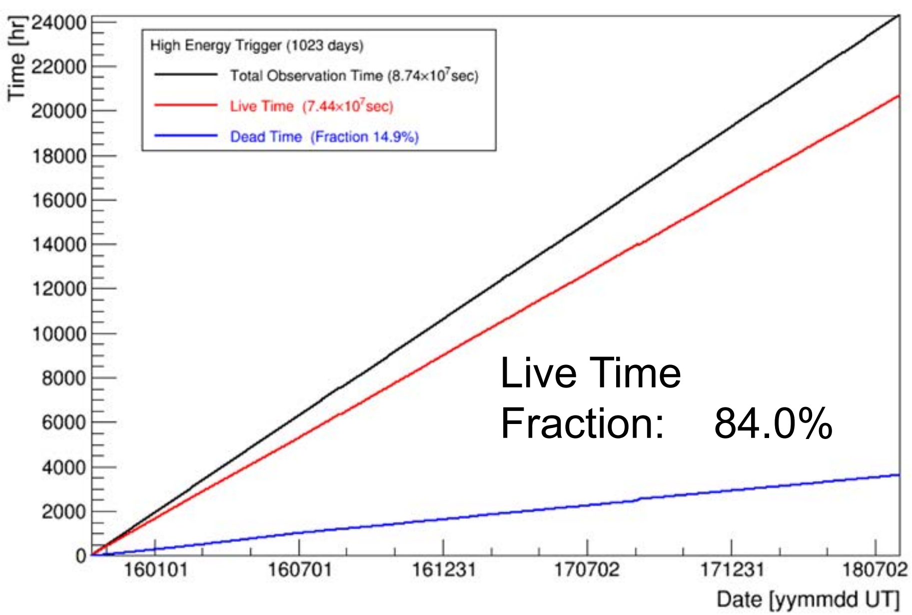
Observation with High Energy Trigger (>10GeV)

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

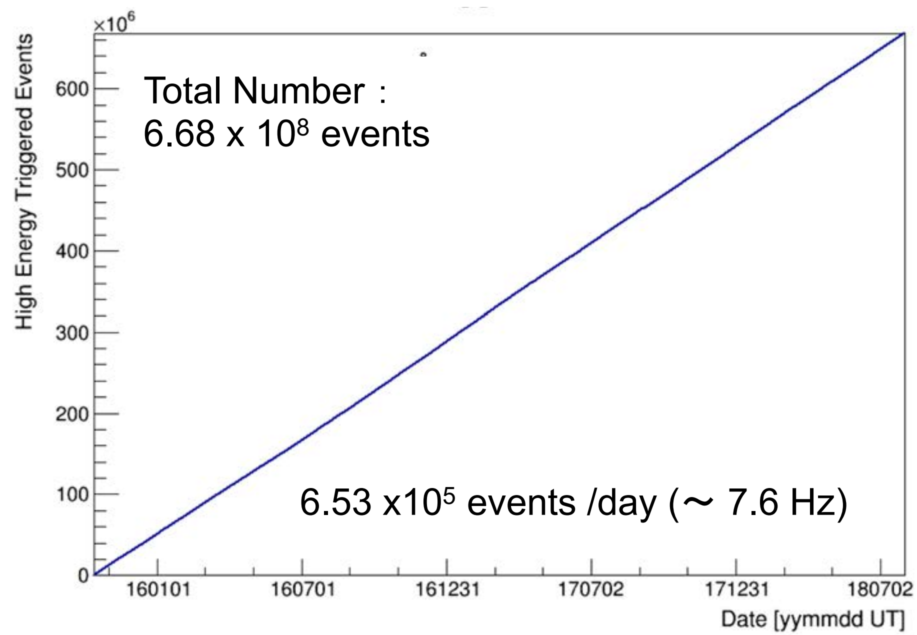
Observation by High Energy Trigger for 1032 days : Oct.13, 2015 – July 31, 2018

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

Accumulated observation time (live, dead)

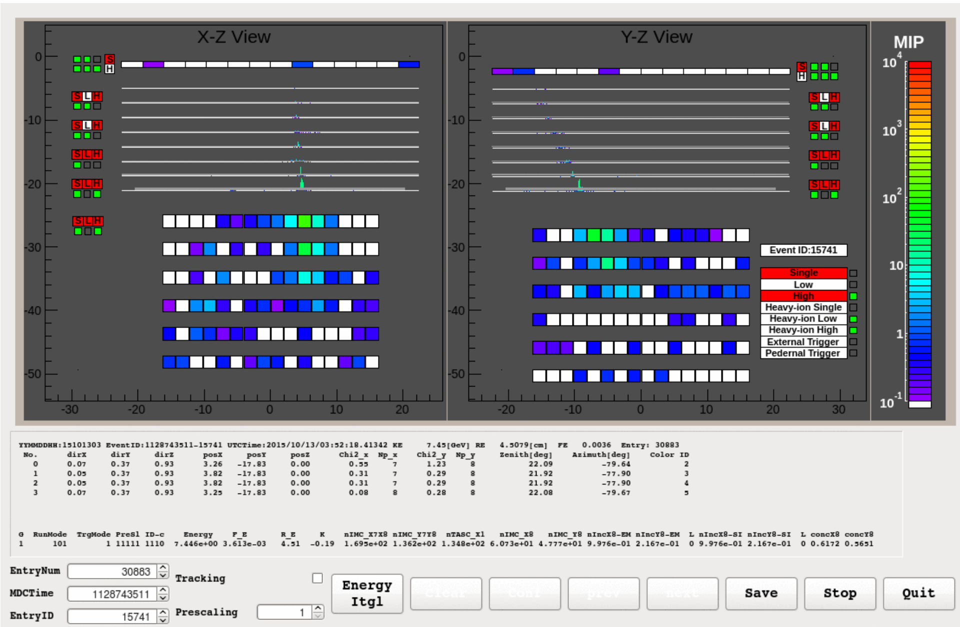


Accumulated triggered event number

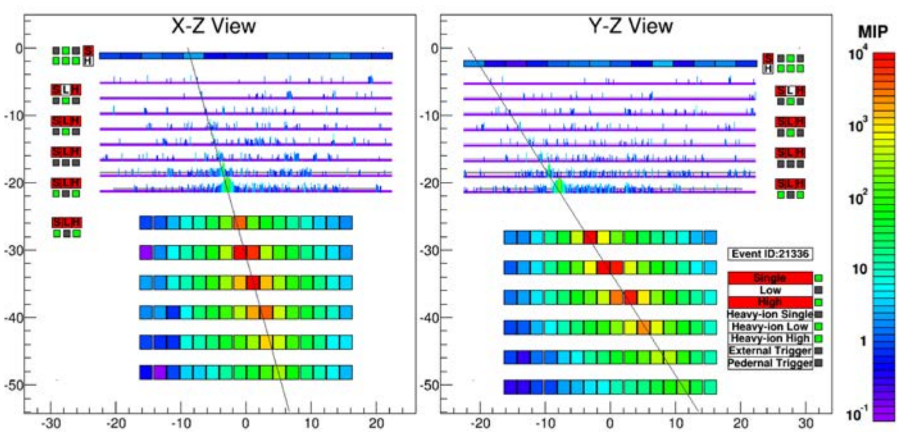


Examples of Observed Events

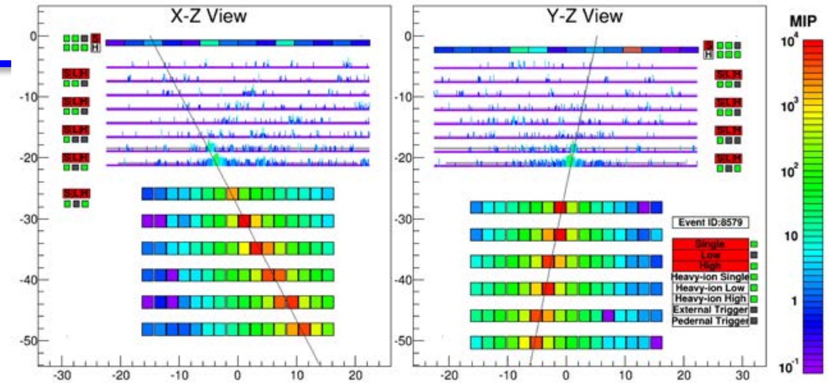
Event Display: Electron Candidate (>100 GeV)



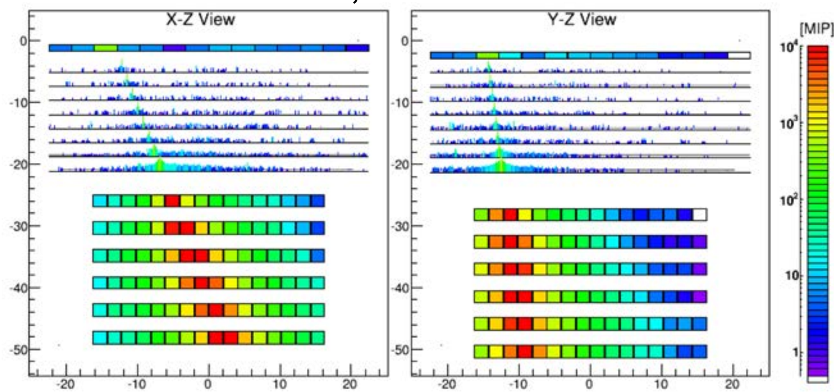
Electron, E=3.05 TeV



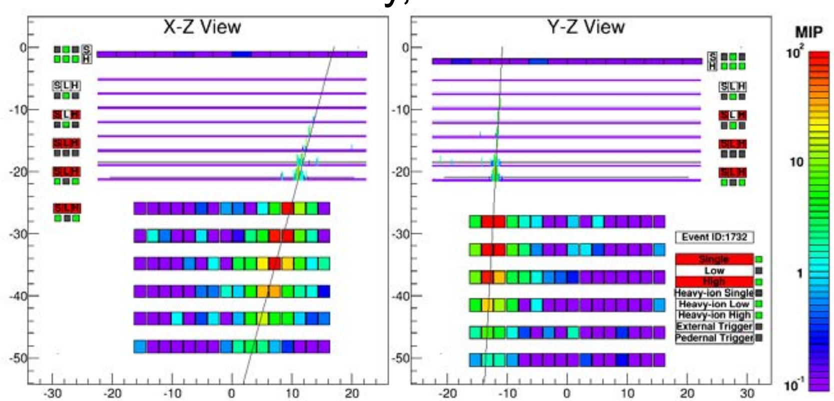
Proton, ΔE=2.89 TeV



Fe, ΔE=9.3 TeV



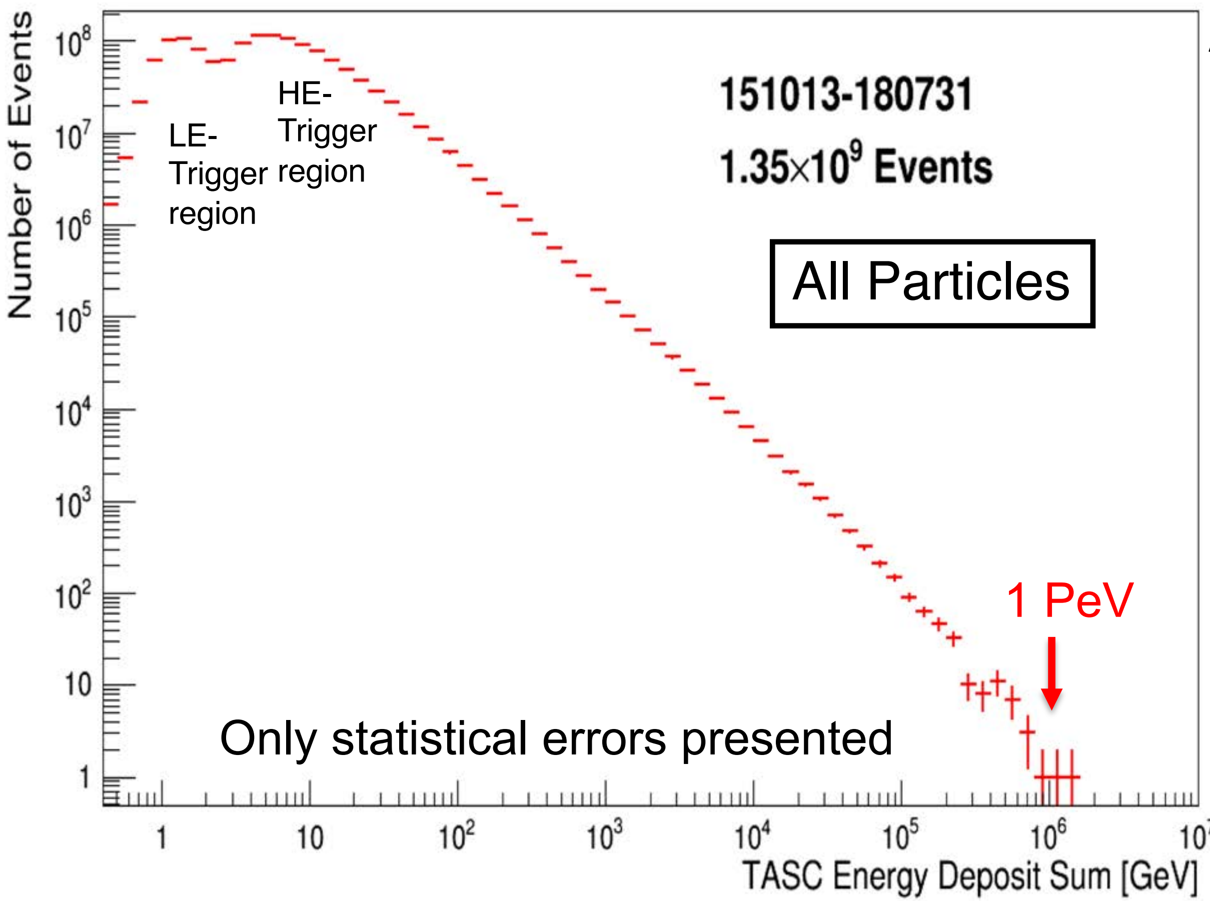
Gamma-ray, E=44.3 GeV



Unit in MIP

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

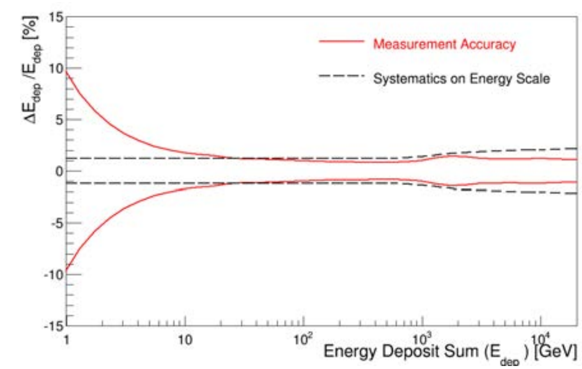
Distribution of deposit energies (ΔE) in TASC



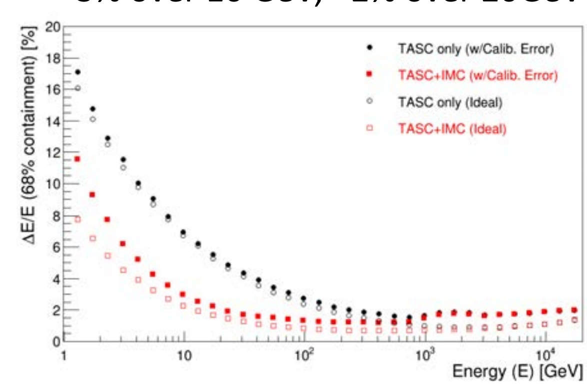
The TASC energy measurements have successfully been carried out in the dynamic range of 1 GeV – 1 PeV.

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



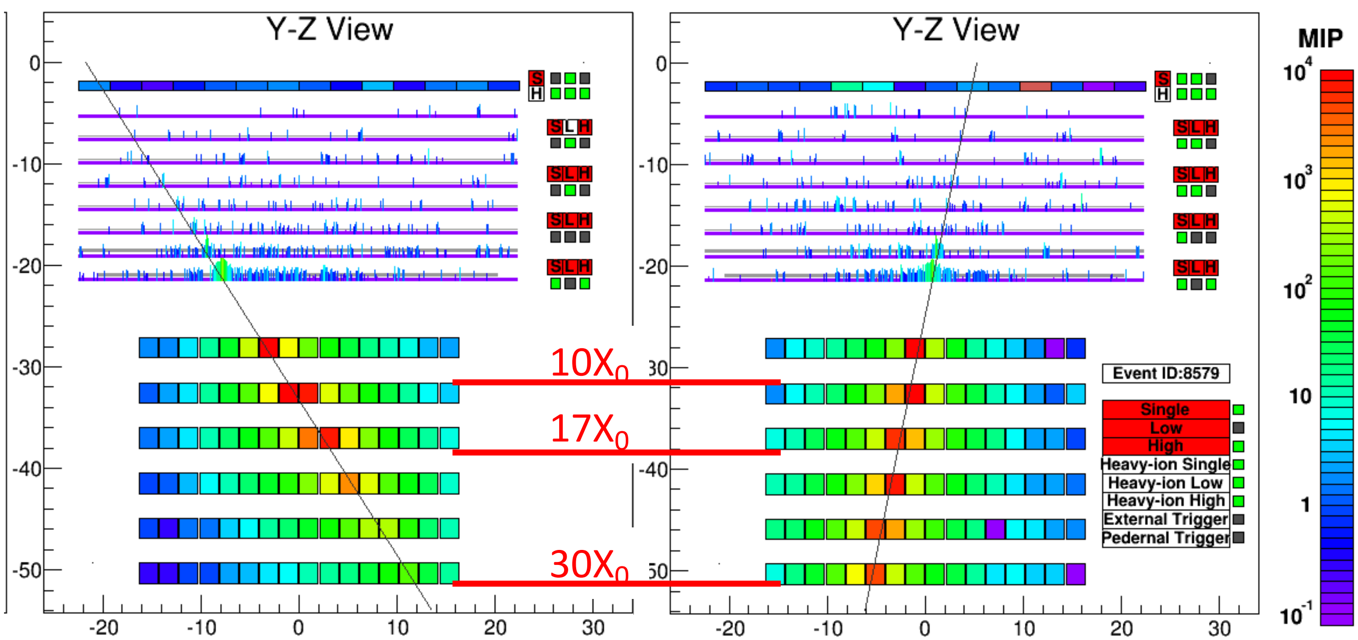
All-Electron (electron + positron) Analysis

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



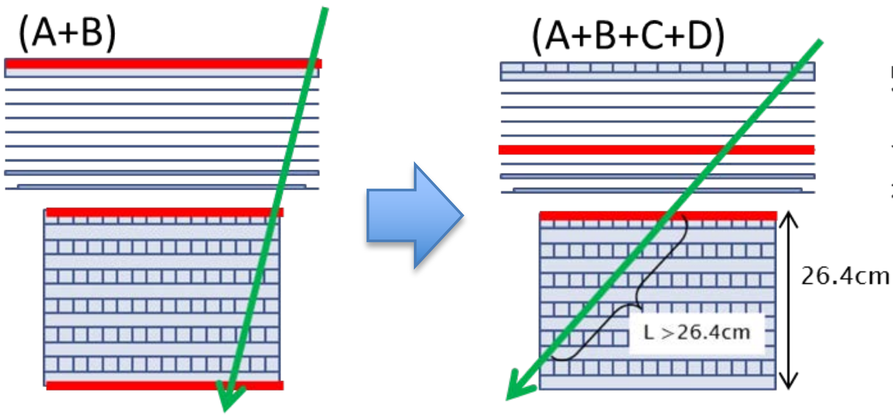
(Flight data; detector size in cm)

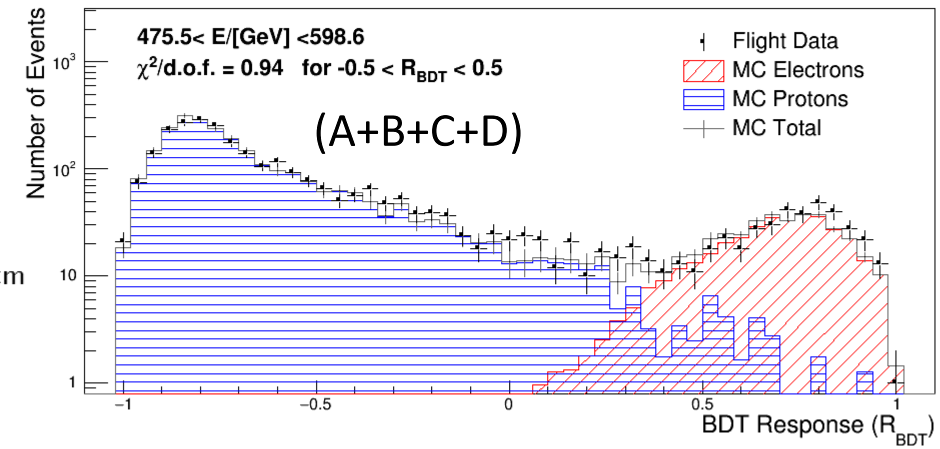
1. **Reliable tracking**
   well-developed shower core
2. **Fine energy resolution**
   full containment of TeV showers
3. **High-efficiency electron ID**
   $30X_0$ thickness, closely packed logs

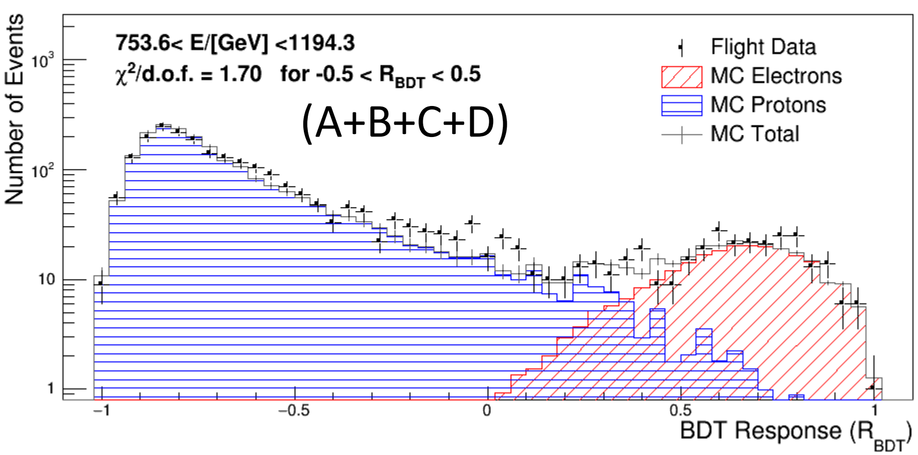
Extended Analysis of e/p Separation to Full Acceptance

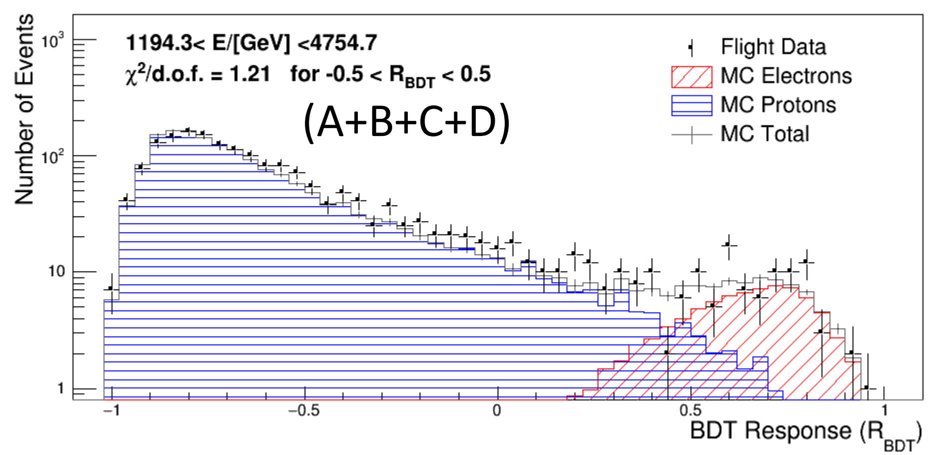
Analyzed Flight Data:

- 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)

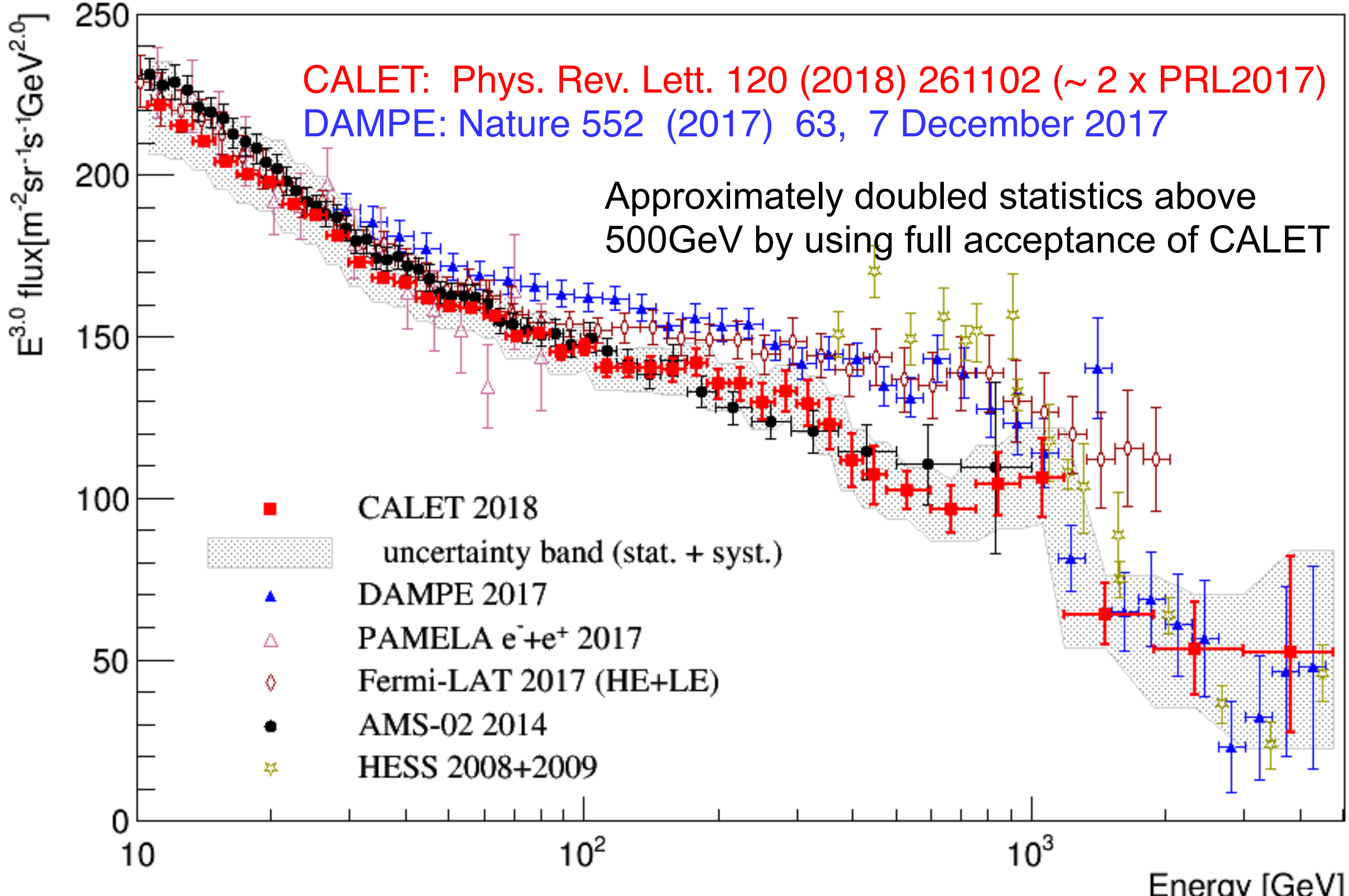




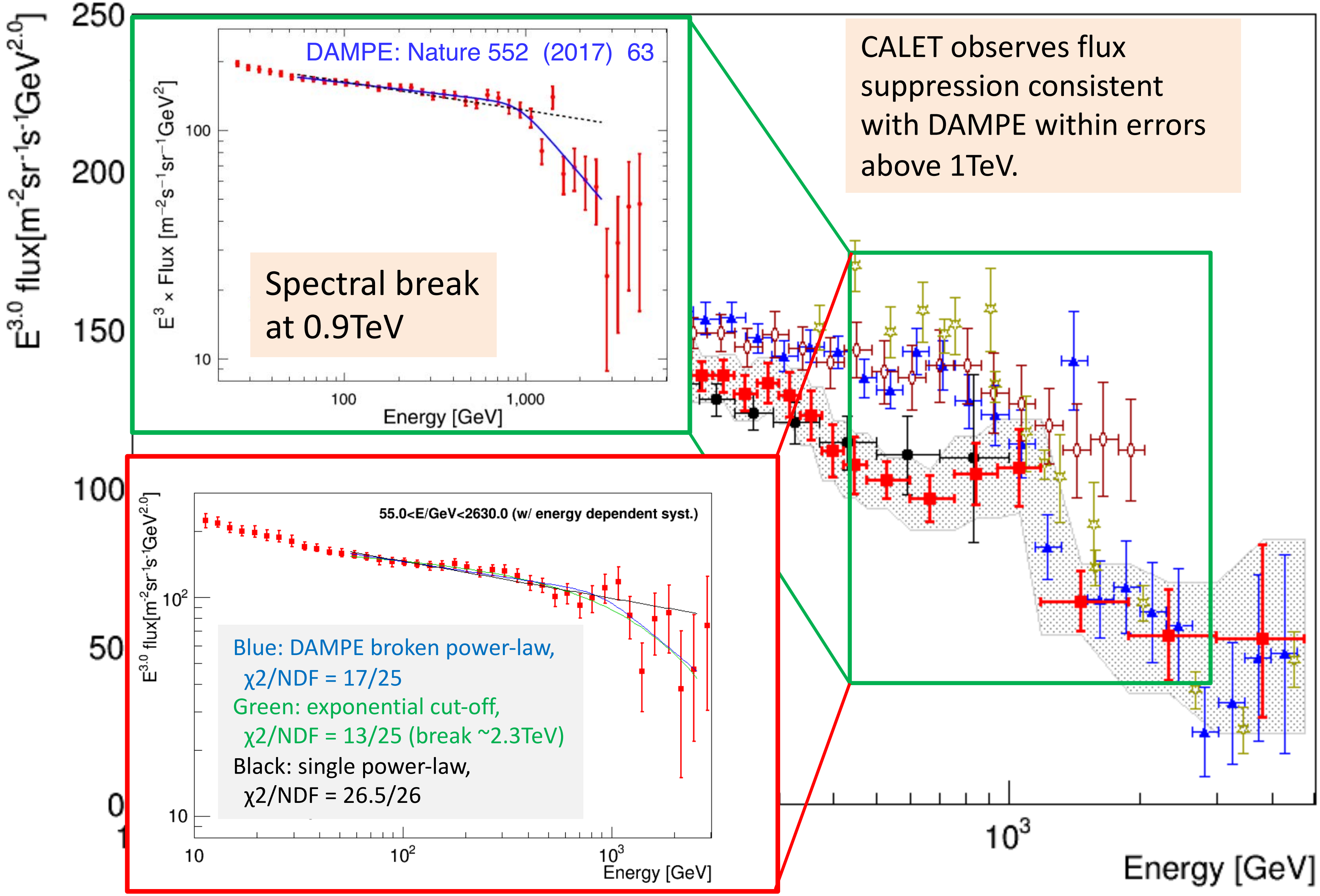




All-Electron Spectrum Measured with CALET from 11 GeV to 4.8TeV

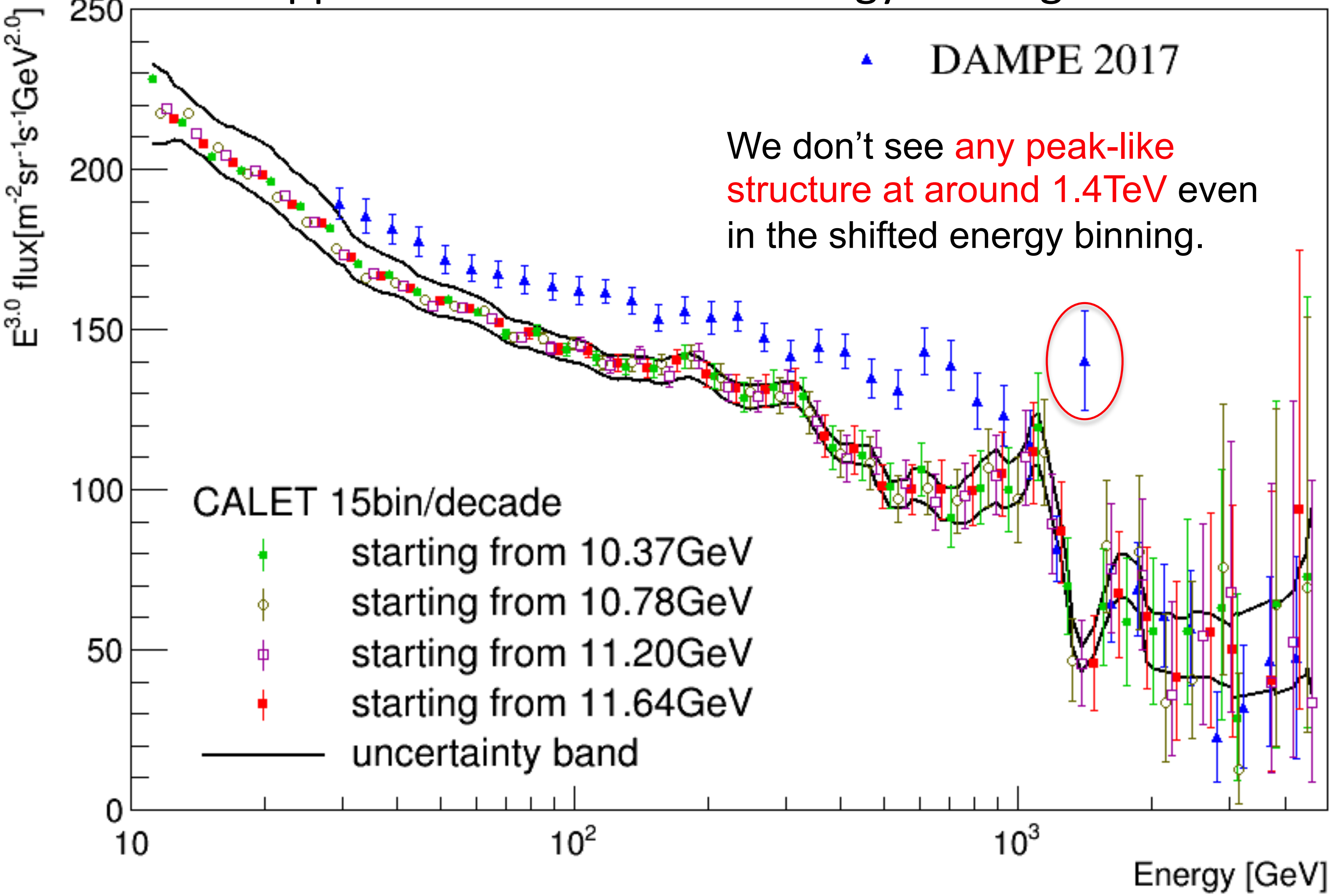


CALET All-Electron Spectrum in sub-TeV to TeV region



Comparison with DAMPE's result

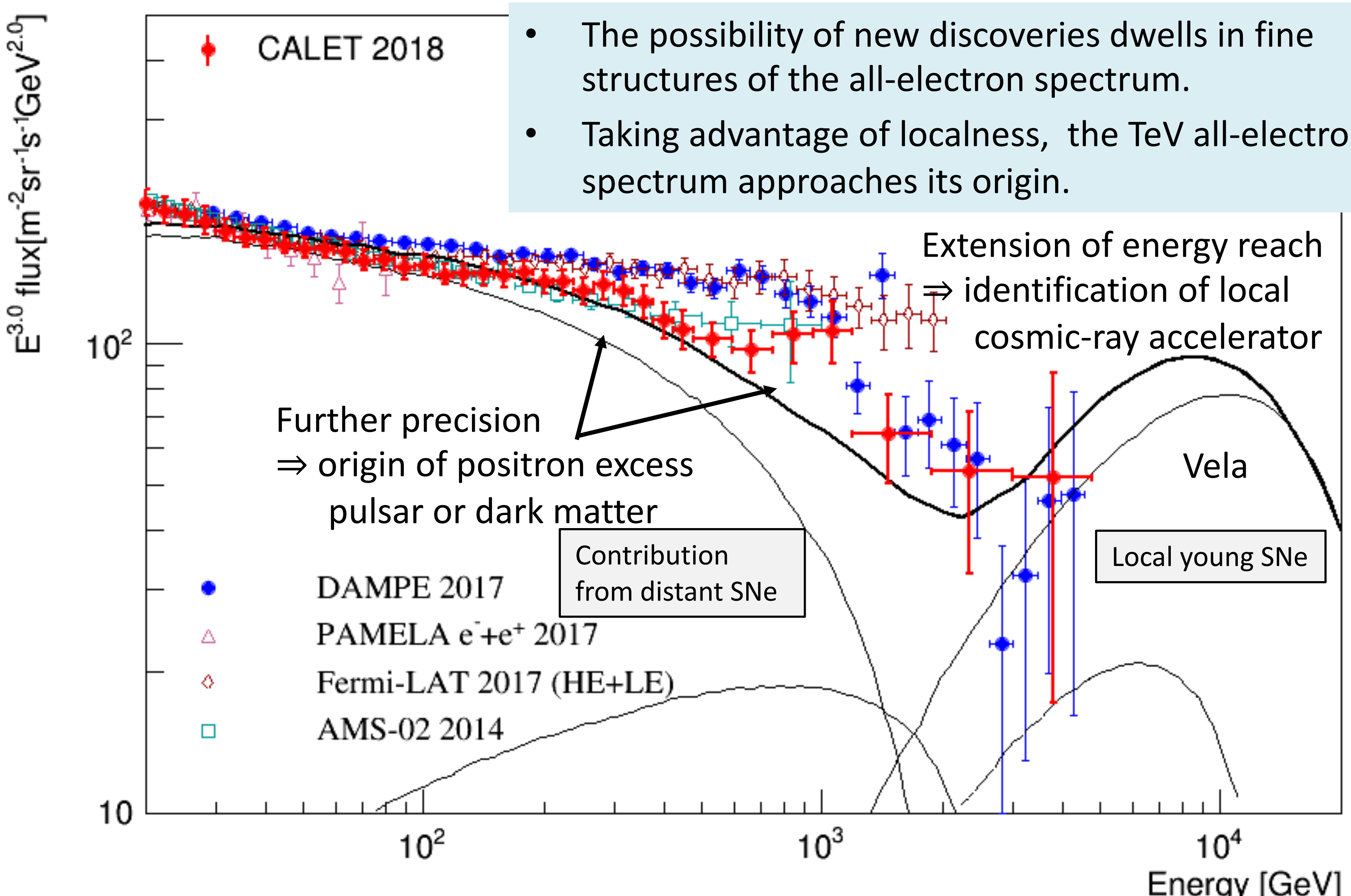
What happens if we shifted our energy binning…



Prospects for CALET All-Electron Spectrum

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

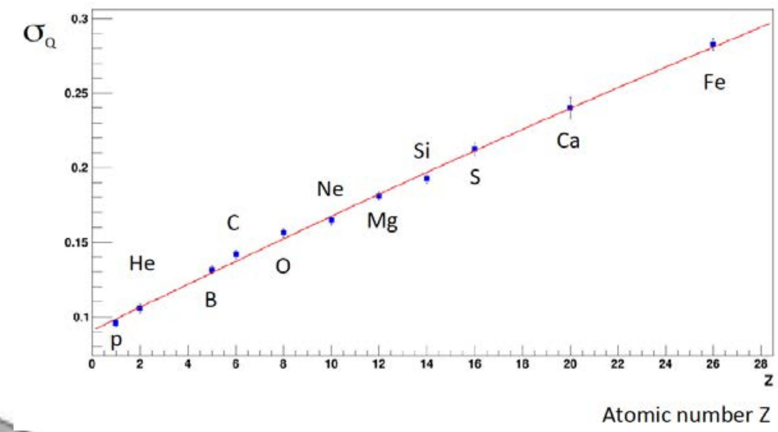
- The possibility of new discoveries dwells in fine structures of the all-electron spectrum.
- Taking advantage of localness, the TeV all-electron spectrum approaches its origin.

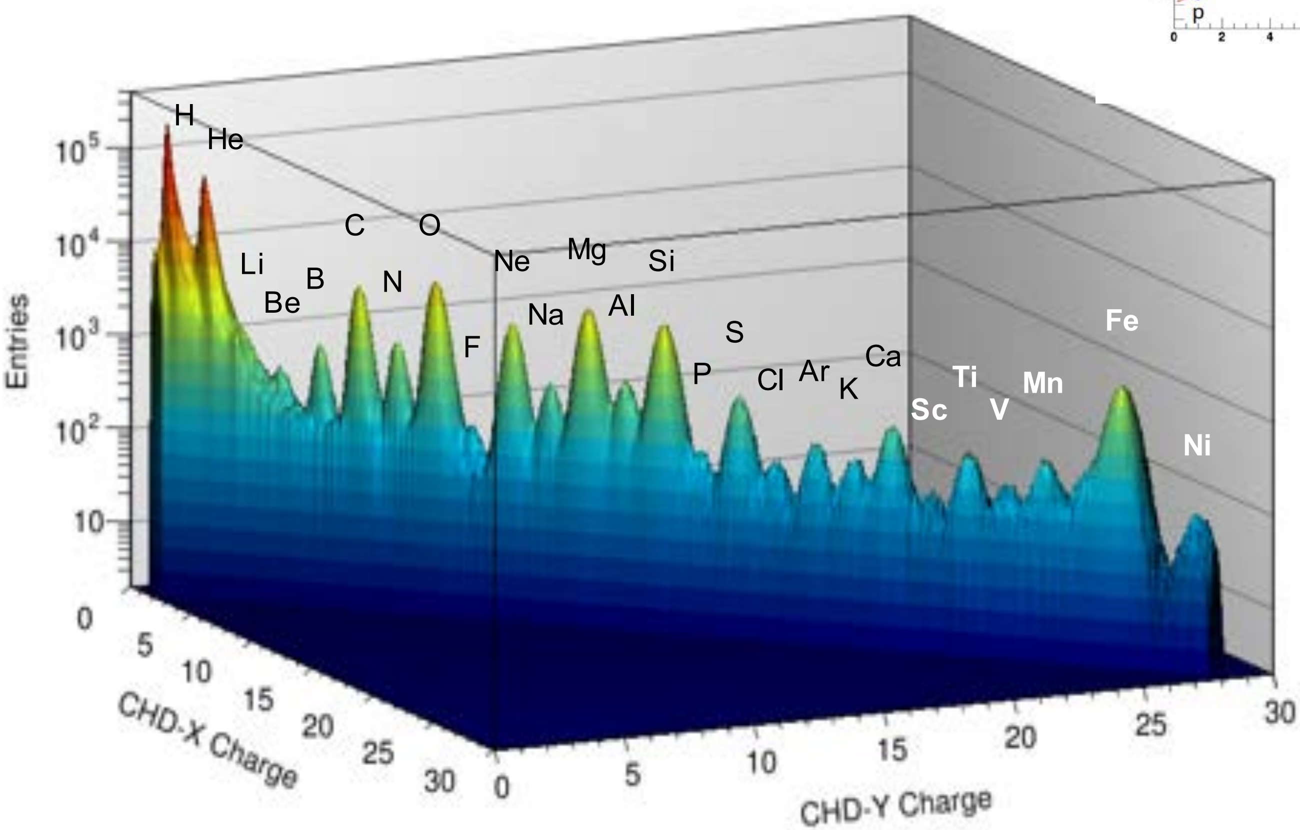


Charge Identification of Nuclei with CHD

CHD charge resolution(2 layers combined) vs. Z

- ΔZ= 0.1e (p)~ 0.28e (Fe)
- Charge separation in B to C : ~7 σ





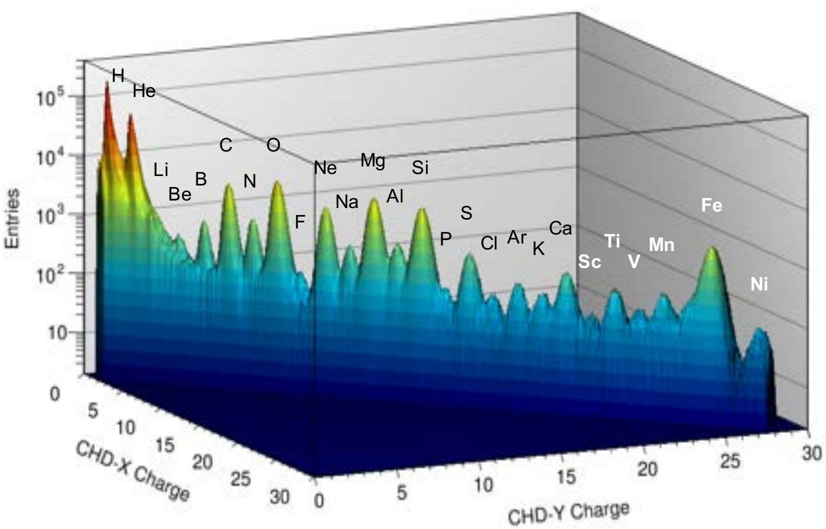
Non-linear response to Z^2 is corrected in CHD using a model.

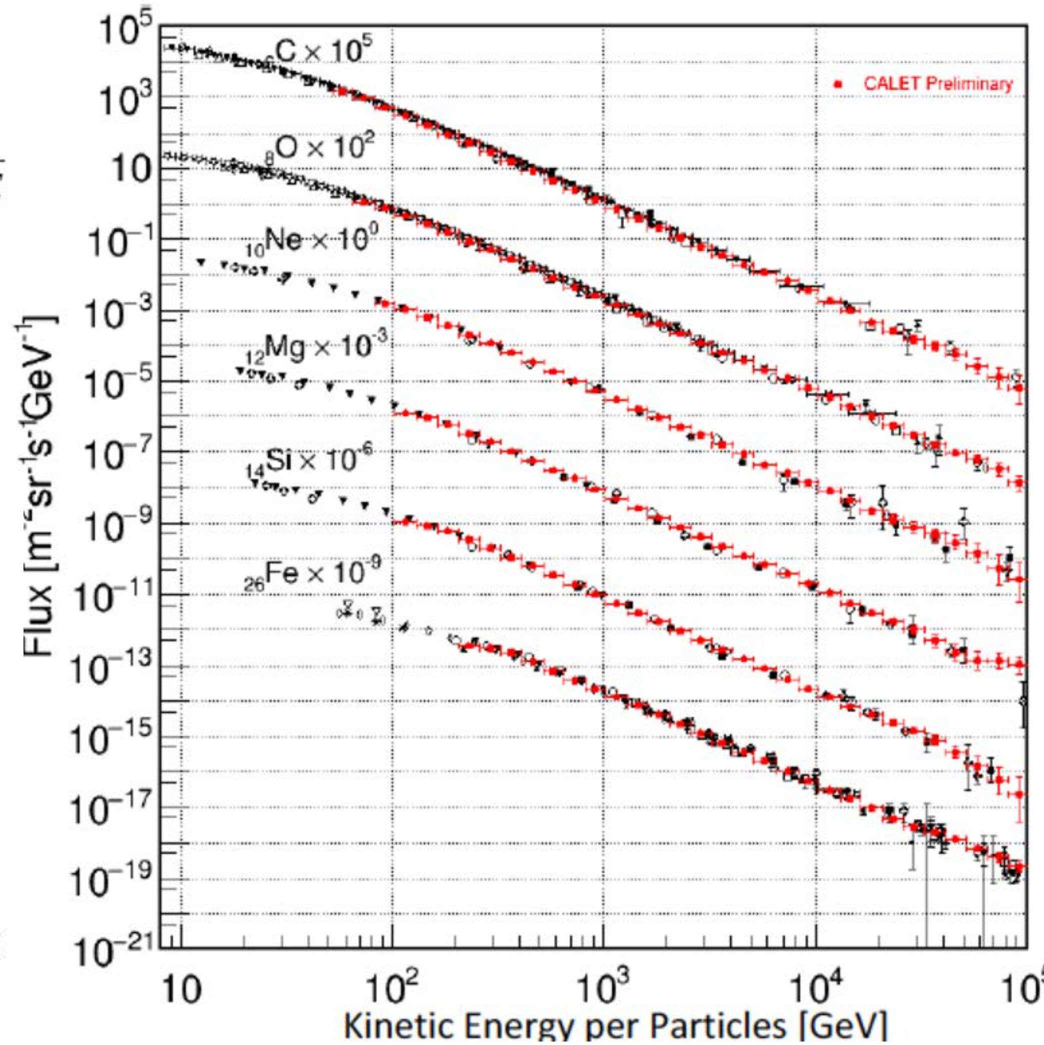
Preliminary Flux of Primary Nuclei Components

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

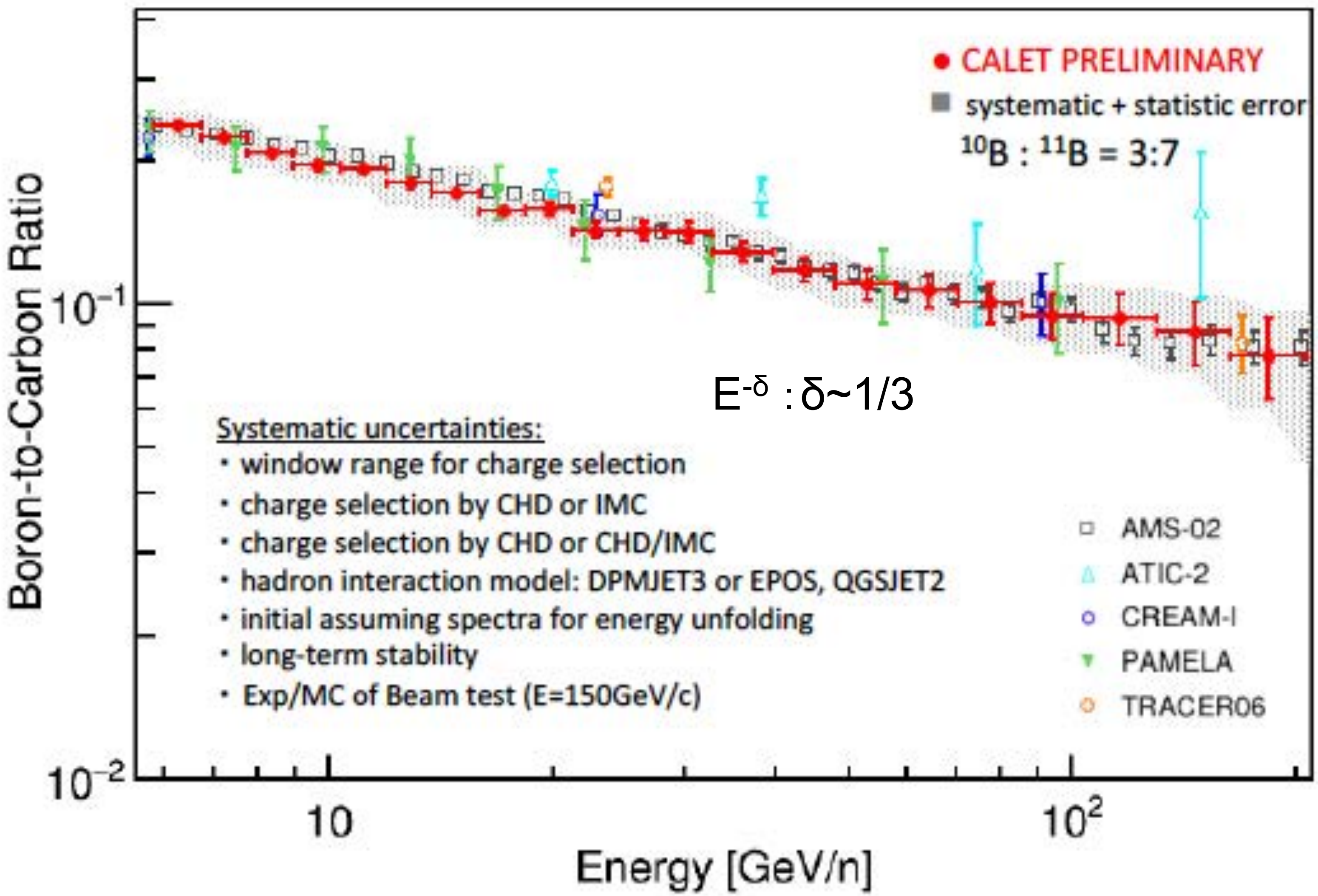
Flux measurement: $\Phi(E) = \dfrac{N(E)}{S\Omega\varepsilon(E)T\Delta E}$

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





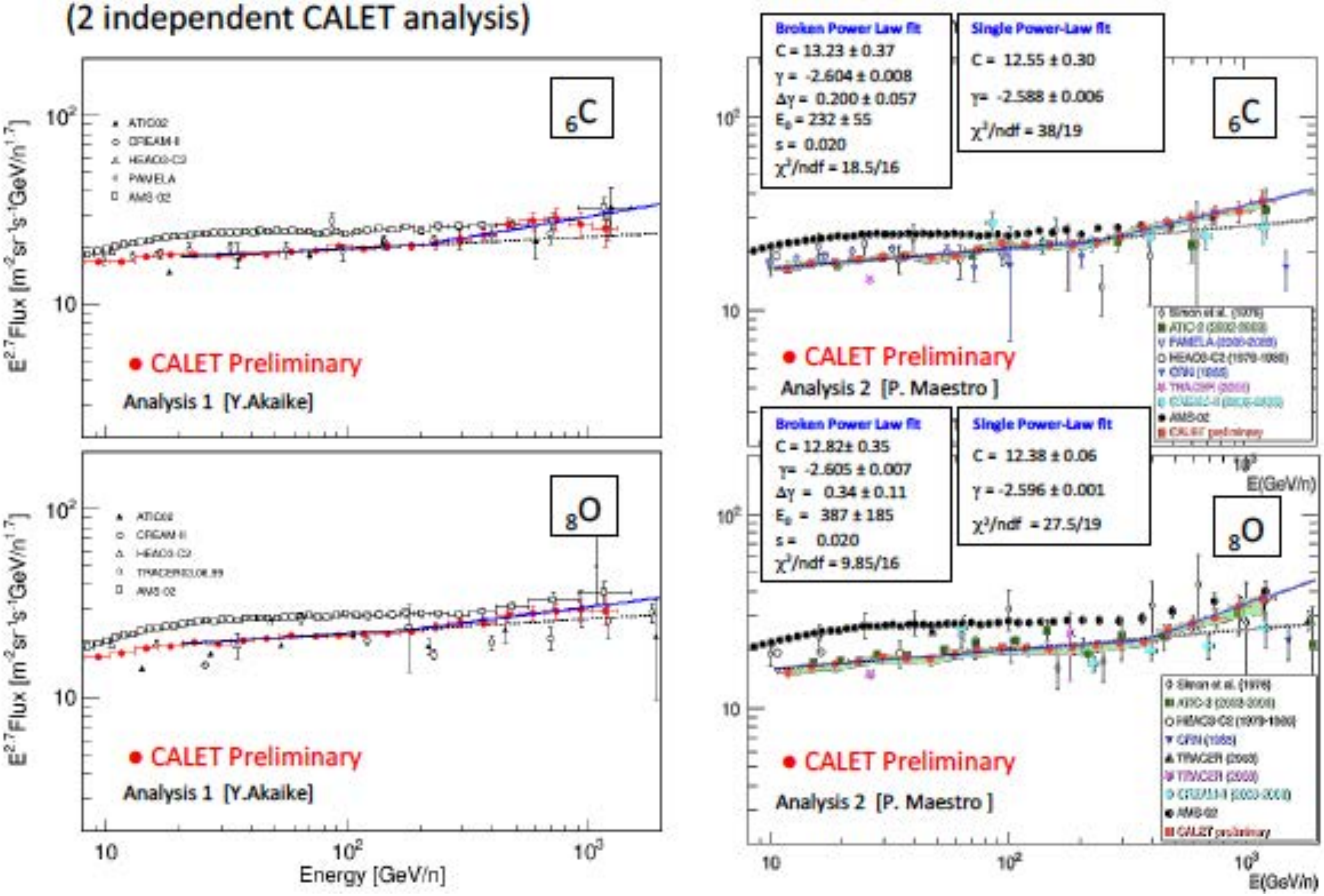
Preliminary Boron-to-Carbon Flux Ration



Two Independent Analysis of Carbon and Oxygen

Hardening of the energy spectrum is preferable for both of C and O.

(2 independent CALET analysis)



CALET Gamma-ray Sky (>1GeV)

Flux validation with bright sources

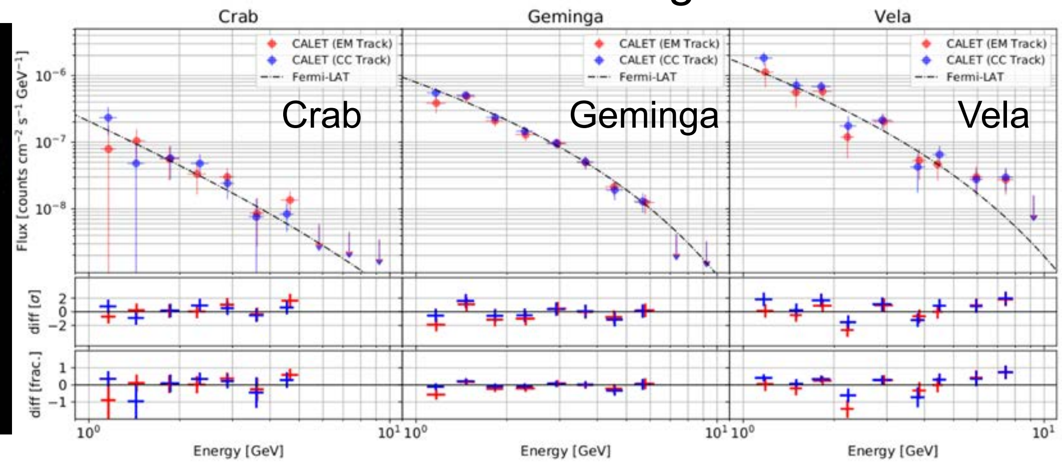
Instrument characterized using EPICS simulations

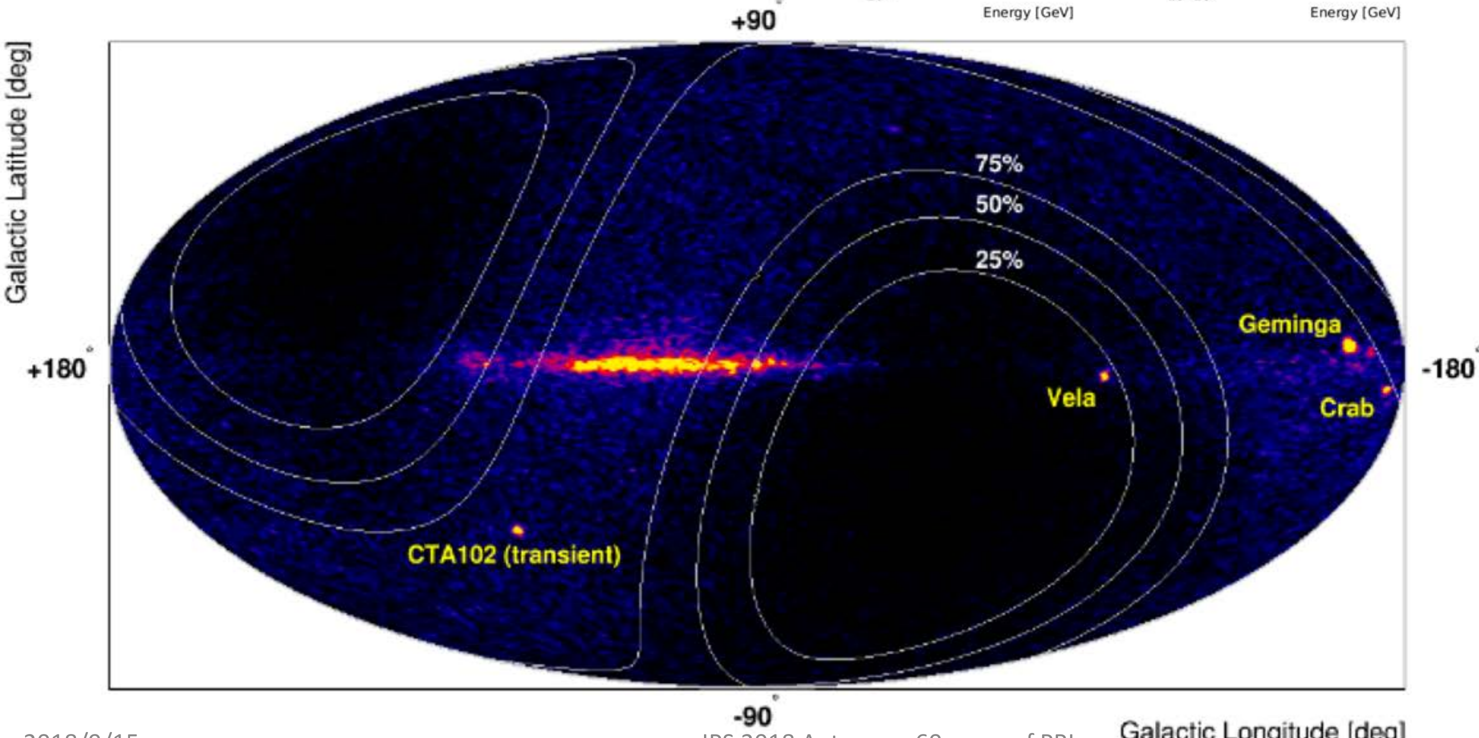
- Effective area ~400 cm² above 2 GeV
- Angular resolution < 2° above 1 GeV (< 0.2° above 10 GeV)
- Energy resolution ~12% at 1 GeV (~5% at 10 GeV)

Simulated IRFs consistent with 2 years of flight data

Consistency in signal-dominated regions with Fermi-LAT

Residual background in low-signal regions





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

Galactic Latitude Projection

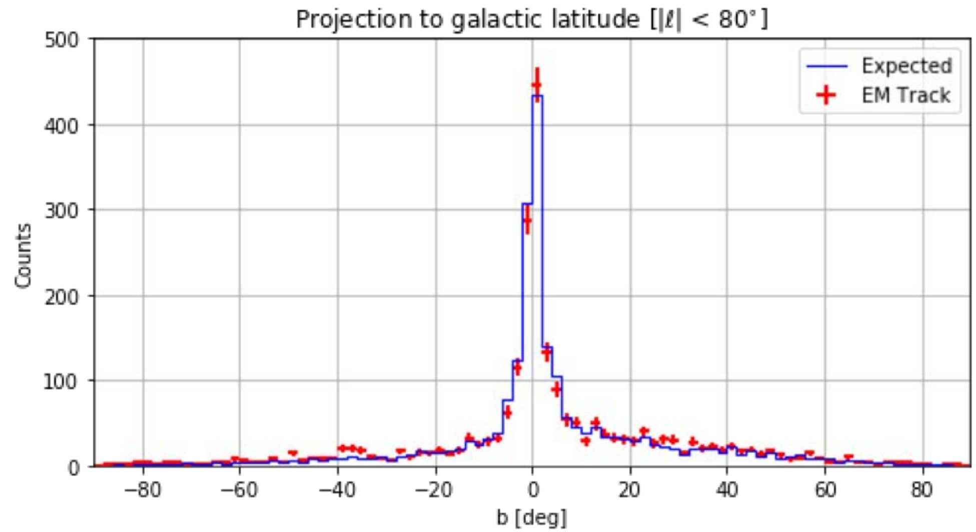
Data :

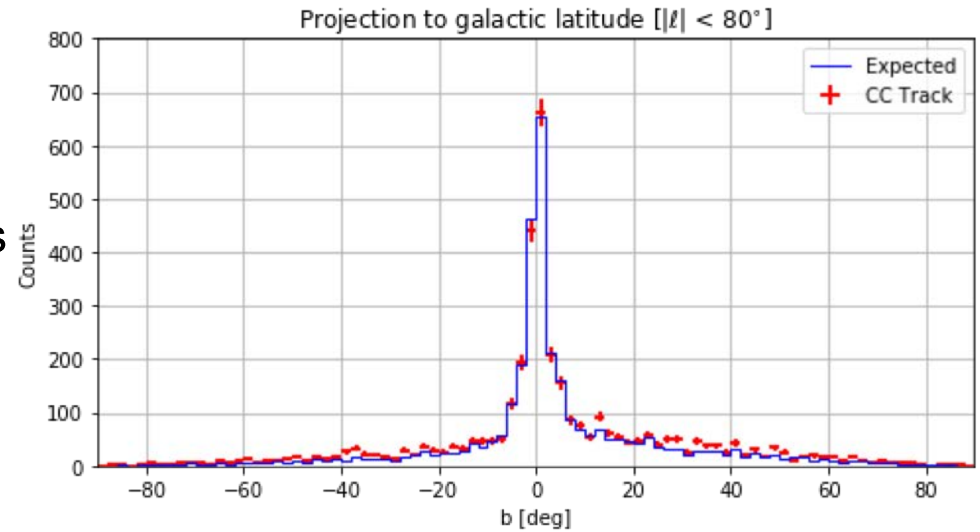
- First two years of LE-γ run data (2015/11 – 2017/10)
- Reduced threshold of ~1 GeV
- Active at low geomagnetic latitudes

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





Electromagnetic Emission from Gravitational Wave Events ?

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

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

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

CALET

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

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

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 $\times 10^{49}$ erg s^{-1} which is significantly lower than typical short GRBs.

CGBM light curve at the moment of the GW151226 event

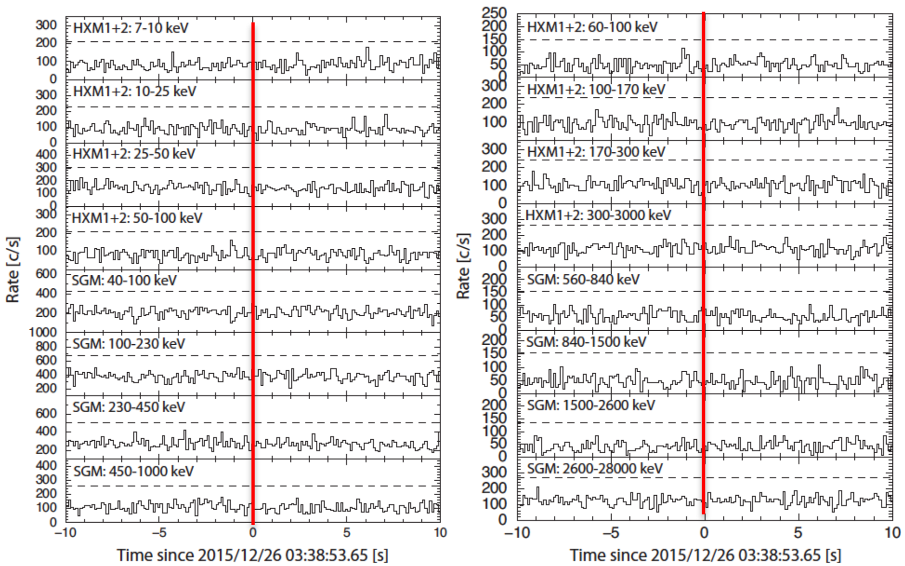


Figure 1. The CGBM light curves in 0.125 s time resolution for the high-gain data (left) and the low-gain data (right). The time is offset from the LIGO trigger time of GW 151226. The dashed-lines correspond to the 5 σ level from the mean count rate using the data of ±10 s.

Upper limit for gamma-ray burst monitors and Calorimeter

HXM: 7-500 keV

SGM: 50-1000 keV

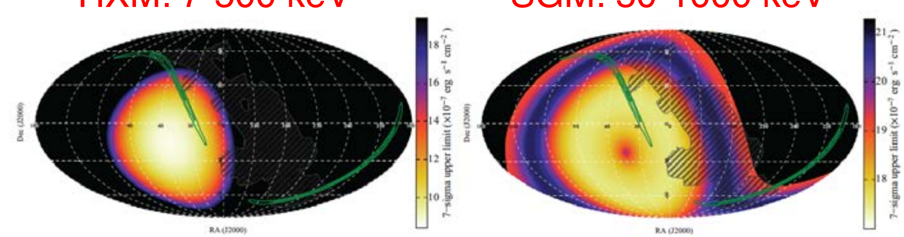


Figure 2. The sky maps of the 7 σ upper limit for HXM (left) and SGM (right). The assumed spectrum for estimating the upper limit is a typical BATSE S-GRBs (see text for details). The energy bands are 7-500 keV for HXM and 50-1000 keV for SGM. The GW 151226 probability map is shown in green contours.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

Calorimeter: 1-100 GeV

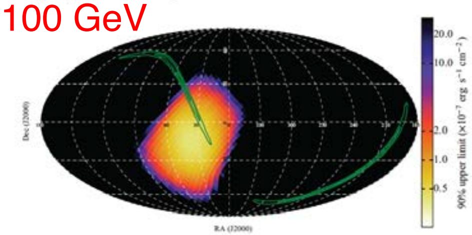
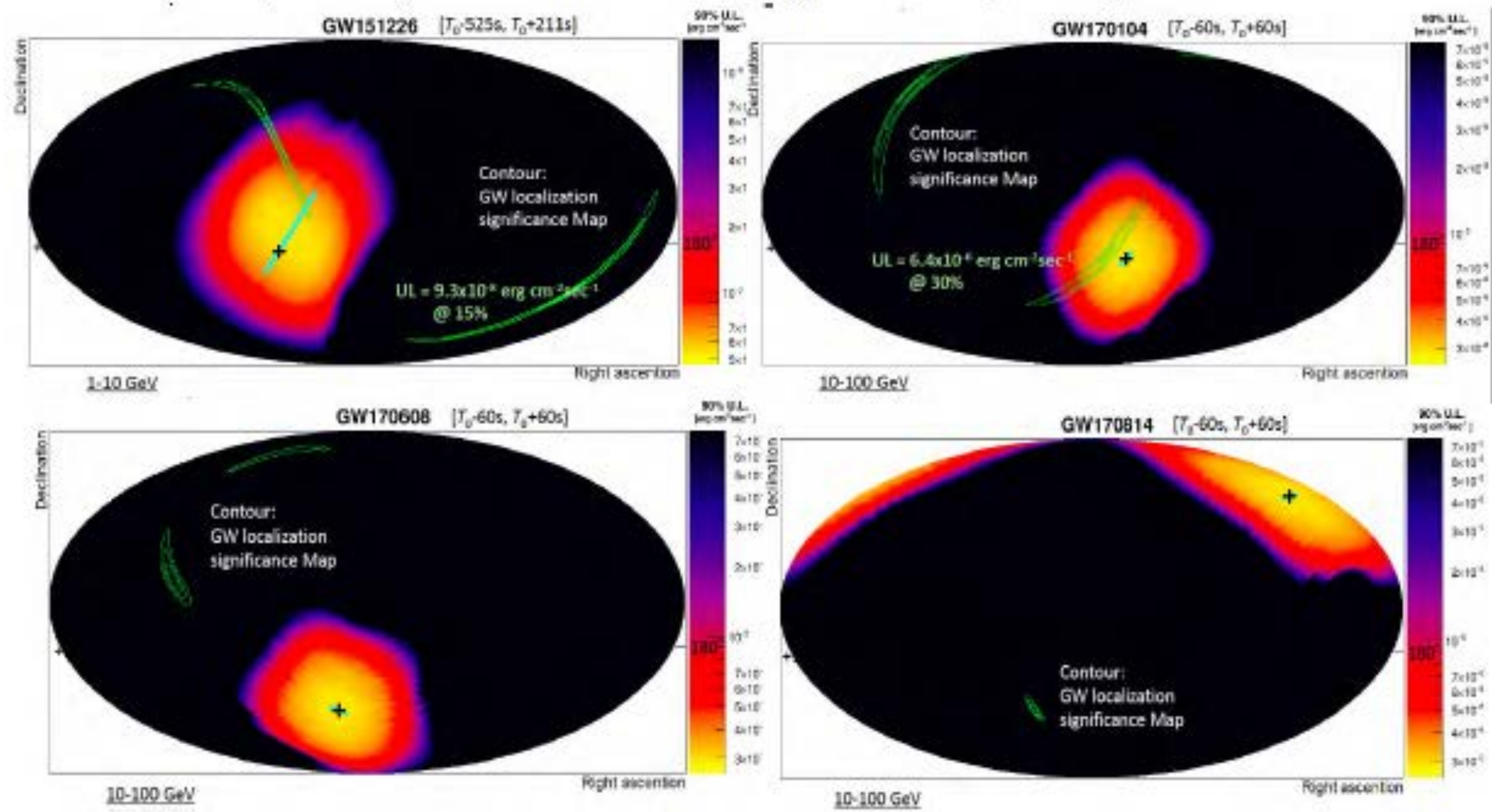


Figure 3. The sky map of the 90% upper limit for CAL in the 1-100 GeV band. A power-law model with a photon index of −2 s used to calculate the upper limit. The GW 151226 probability map is shown in green contours.

90 % CL Upper Limits for GW Counterpart Search

No event survived. Backgrounds are negligible.

- 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



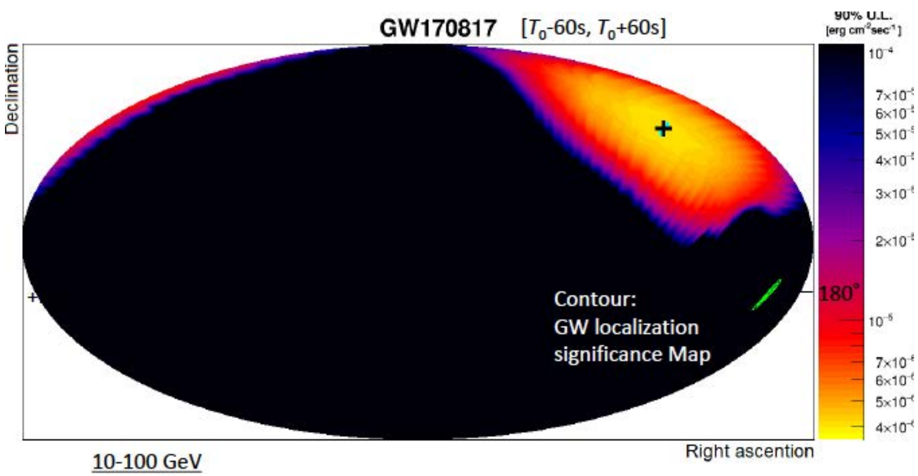
Upper Limits on GW 170817 (GRB 170817A)

- **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.



Summary and Future Prospects

- CALET was successfully launched on Aug. 19, 2015, and the detector is being very stable for observation since Oct. 13, 2015.
- As of July 31, 2018, total observation time is 1023 days with live time fraction to total time close to 84%. Nearly 670 million events are collected with high energy (>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: 50 (200) 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.