Calorimetry for the High Energy Frontier
CHEF2019
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CALET Calorimetric Electron Telescope on the International Space Station

Shoji Torii
Waseda University
for the CALET Collaboration

JAXA NASA agenzia spaziale italiana

CALET Collaboration Team

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

1) Aoyama Gakuin University, Japan
2) CRESST/NASA/GSFC and Universities Space Research Association, USA
3) CRESST/NASA/GSFC and University of Maryland, USA
4) Hirosaki University, Japan
5) Ibaraki National College of Technology, Japan
6) Ibaraki University, Japan
7) ICRR, University of Tokyo, Japan
8) ISAS/JAXA Japan
9) JAXA, Japan
10) Kanagawa University, Japan
11) Kavli IPMU, University of Tokyo, Japan
12) KEK, Japan
13) Louisiana State University, USA
14) Nagoya University, Japan
15) NASA/GSFC, USA
16) National Inst. of Radiological Sciences, Japan
17) National Institute of Polar Research, Japan
18) Nihon University, Japan
19) Osaka City University, Japan
20) Ritsumeikan University, Japan
21) Saitama University, Japan
22) Shibaura Institute of Technology, Japan
23) Shinshu University, Japan
24) University of Denver, USA
25) University of Florence, IFAC (CNR) and INFN, Italy
26) University of Padova and INFN, Italy
27) University of Pisa and INFN, Italy
28) University of Rome Tor Vergata and INFN, Italy
29) University of Siena and INFN, Italy
30) University of Tokyo, Japan
31) Waseda University, Japan
32) Washington University-St. Louis, USA
33) Yokohama National University, Japan
34) Yukawa Institute for Theoretical Physics, Kyoto University, Japan

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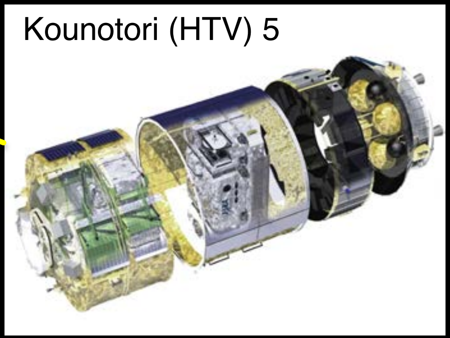
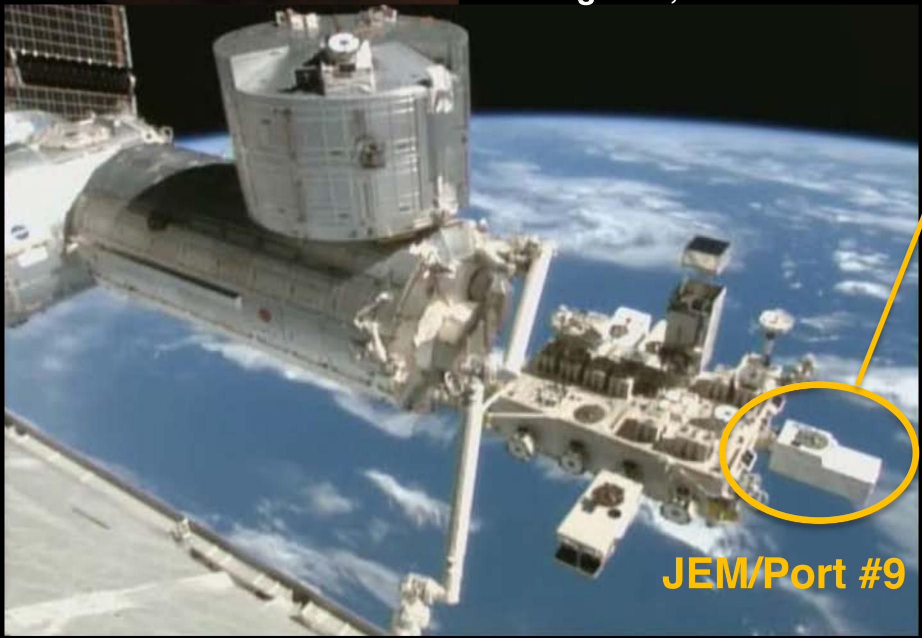
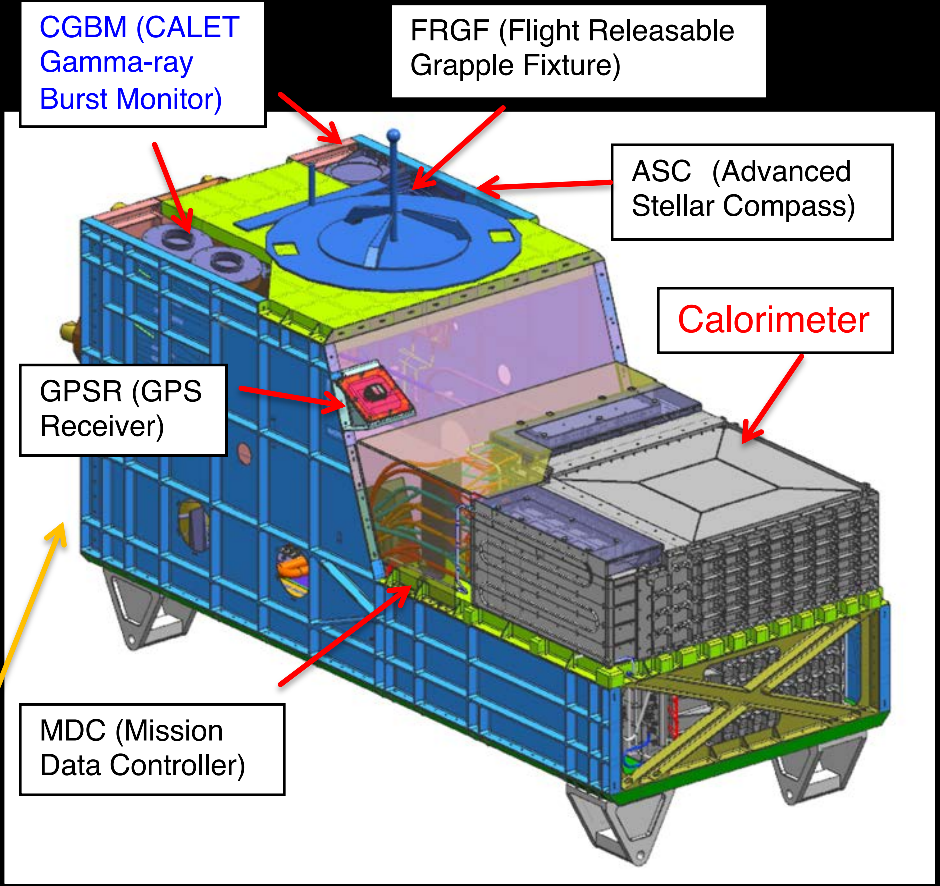
CALET Payload



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

Emplaced on JEM-EF port #9 on Aug. 25th, 2015





- **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**

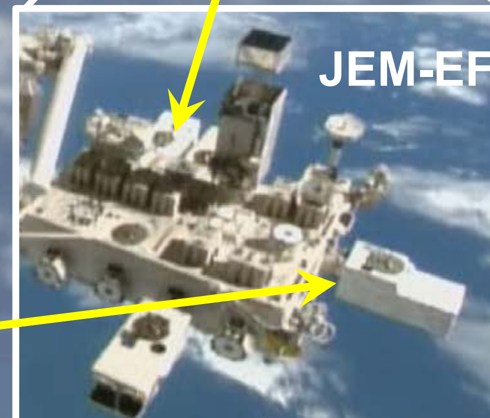
ISS as Cosmic Ray Observatory

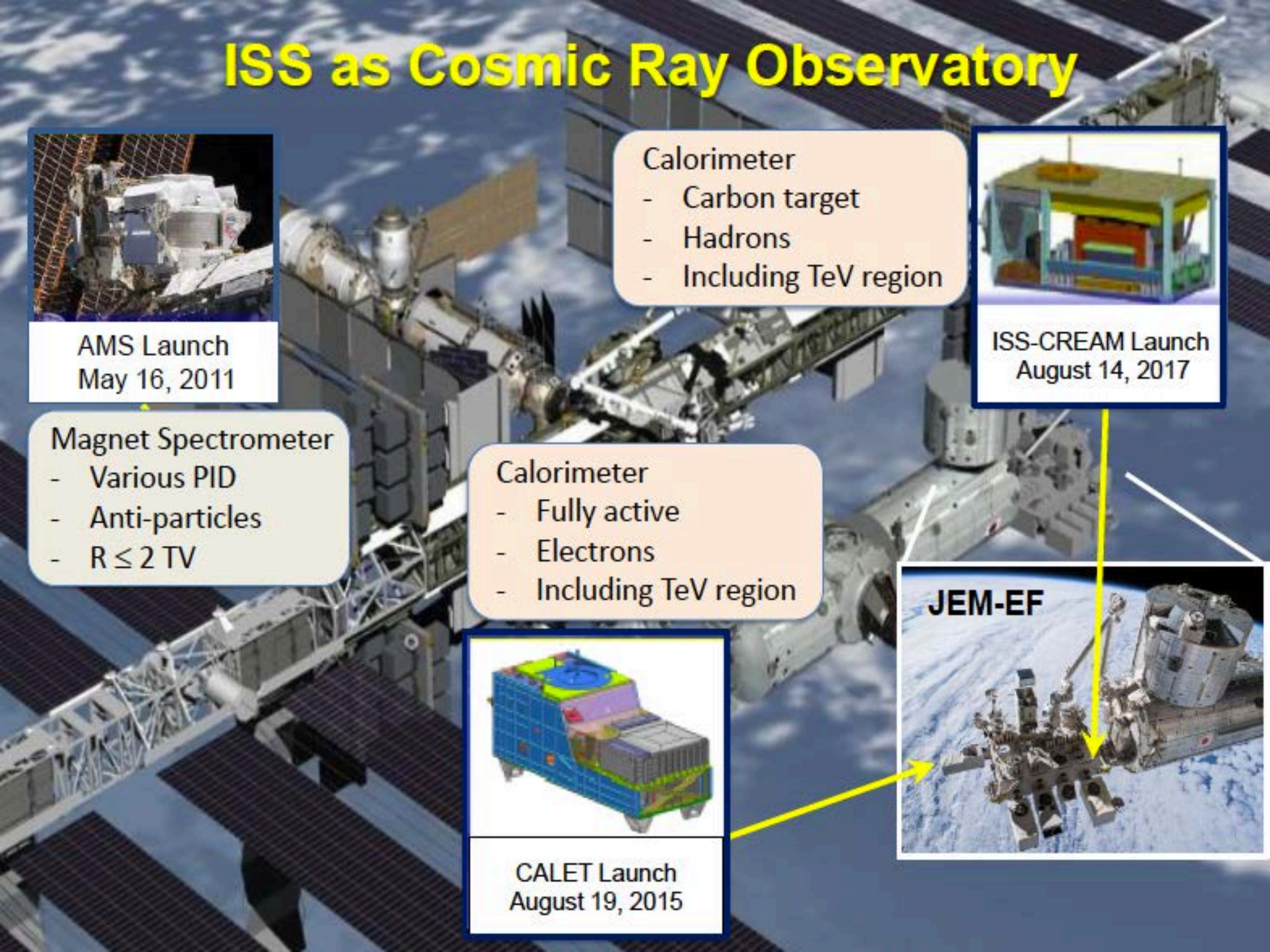
AMS Launch
May 16, 2011

- ISS can supply essential infrastructure for cosmic-ray detectors: Electric power, Thermal control system, Telemetry etc.
- Therefore, the detector scale and weight are considerably reduced , compared to same-scale satellite experiments.
- ISS is very unique platform offering an excellent opportunity of cosmic ray observations.
- AMS-02, CALET, ISS-CREAM are carrying out complementary cosmic ray observations.

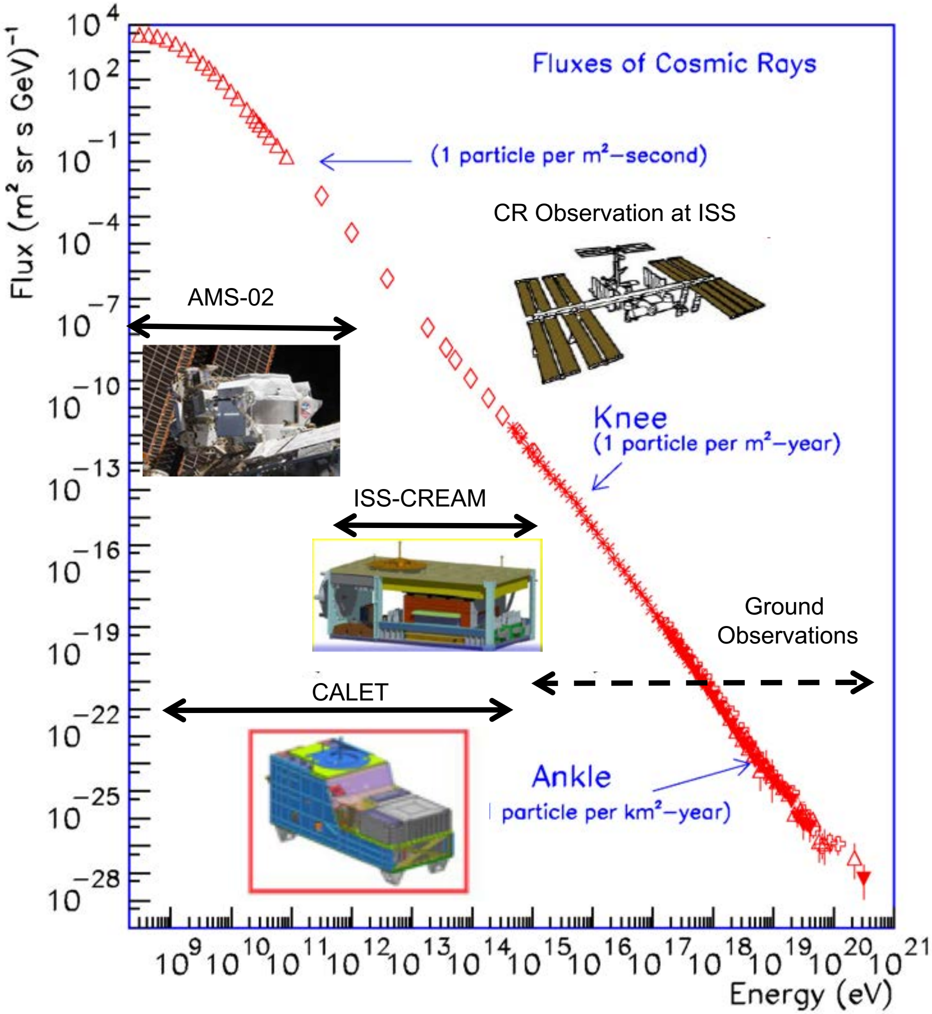
ISS-CREAM Launch
August 14, 2017

CALET Launch
August 19, 2015




ISS as Cosmic Ray Observatory
AMS Launch
May 16, 2011
Magnet Spectrometer
- Various PID
- Anti-particles
- R ≤ 2 TV
Calorimeter
- Carbon target
- Hadrons
- Including TeV region
ISS-CREAM Launch
August 14, 2017
Calorimeter
- Fully active
- Electrons
- Including TeV region
JEM-EF
CALET Launch
August 19, 2015

Cosmic Ray Observations at the ISS and CALET



Overview of CALET Observations

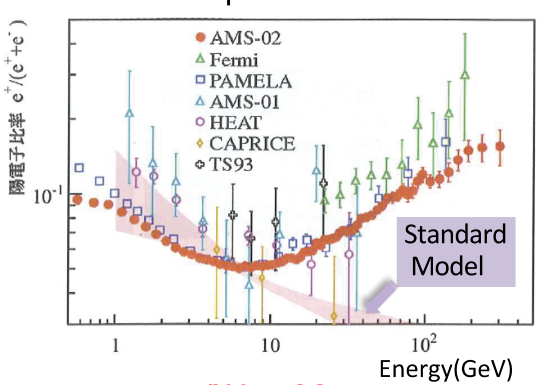
- Direct cosmic ray observations in space at highest energy region
- Cosmic ray observation at world-record level using a large-scale detector at ISS for a long-term (5 years expected)
- Electron observation in 1 GeV - 20 TeV is achieved with high energy resolution due to optimization for electron detection
  ⇨ Search for Dark Matter and Nearby Sources
- Observation of cosmic-ray nuclei will be performed in energy region from 10 GeV to 1 PeV
  ⇨ Unravelling the CR acceleration and propagation mechanism
- Detection of transient phenomena in space by stable observations
  ⇨ Gamma-ray burst, Solar flare, Radiation from GW source etc.

Scientific Targets

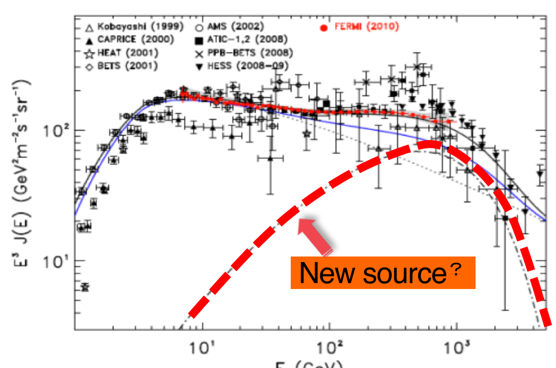
Scientific Objectives	Observation Targets	Energy Range
CR Origin and Acceleration	Electron spectrum p--Fe individual spectra Ultra Heavy Ions (26<Z≤40) Gamma-rays (Diffuse + Point sources)	1GeV - 20 TeV 10 GeV - 1000 TeV > 600 MeV/n 1 GeV - 1 TeV
Galactic CR Propagation	B/C and sub-Fe/Fe ratios	Up to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

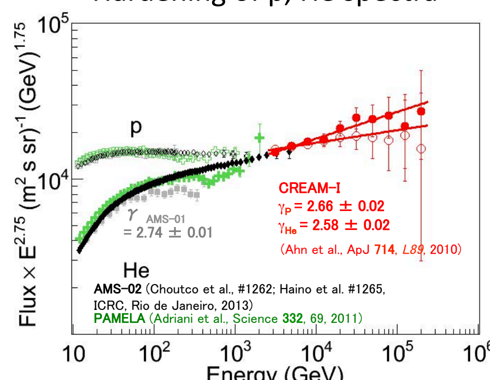
Increase of positron/electron ratio



Excess of electron+positron flux



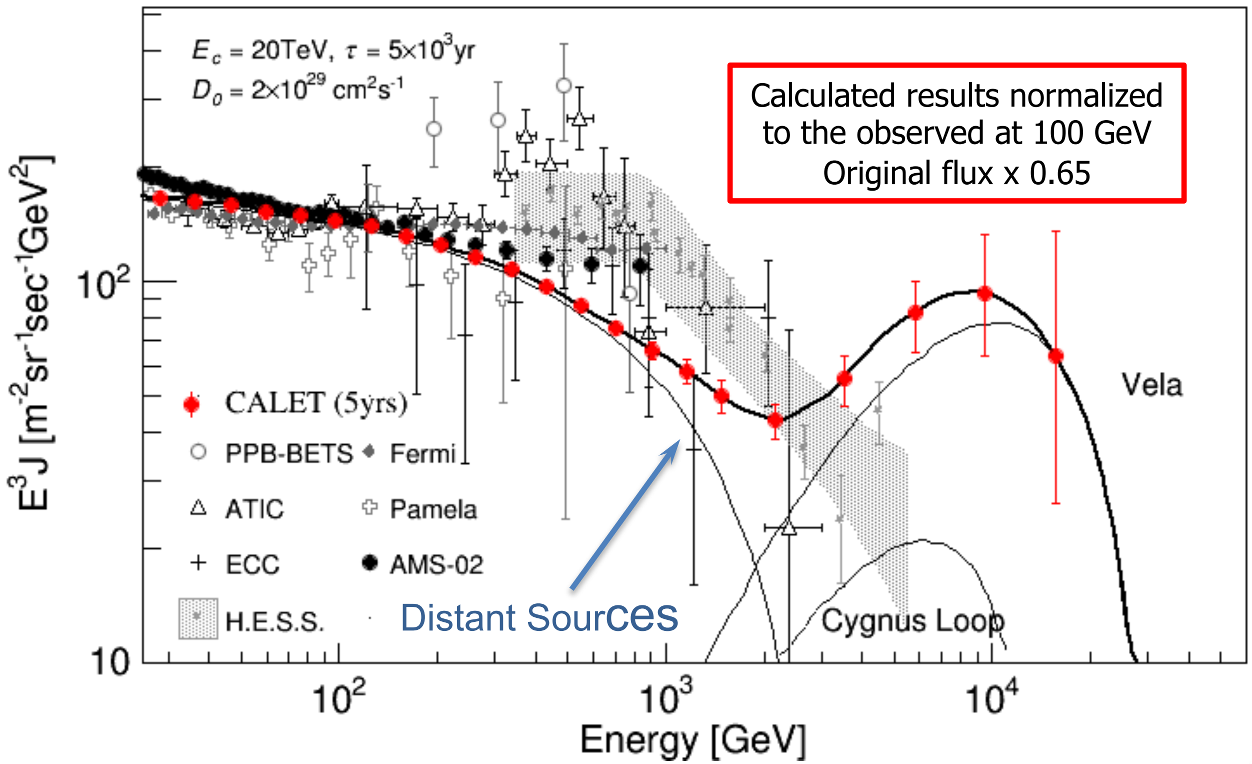
Hardening of p, He spectra



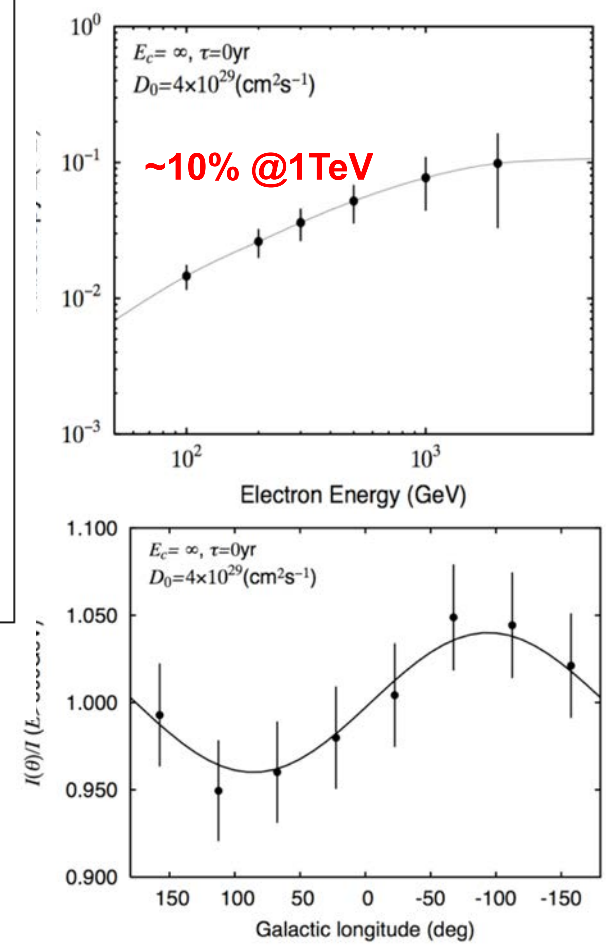
New source of electrons and positrons at 100 GeV region ?

CALET Main Target: Identification of Electron Sources

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



Expected Anisotropy from Vela



Identification of the unique signature from nearby SRNs, such as Vela, in the electron spectrum by CALET in the TeV region

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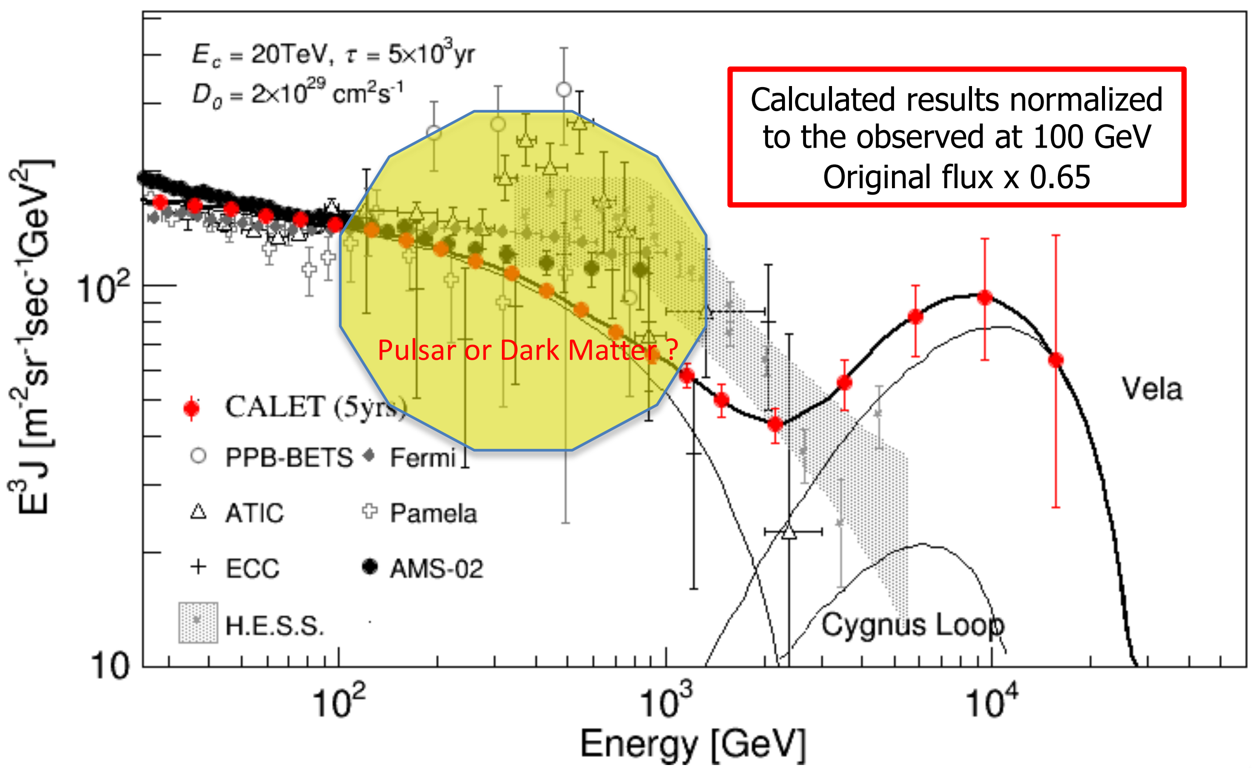
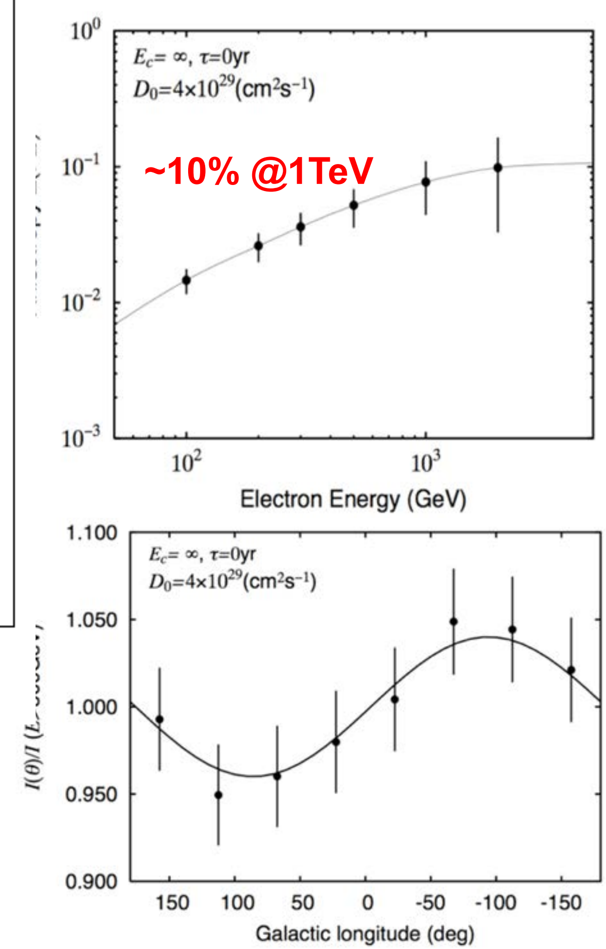


Expected Anisotropy from Vela

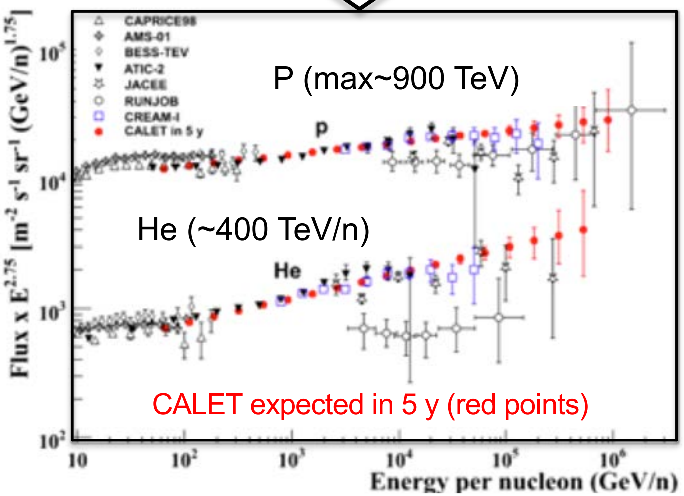


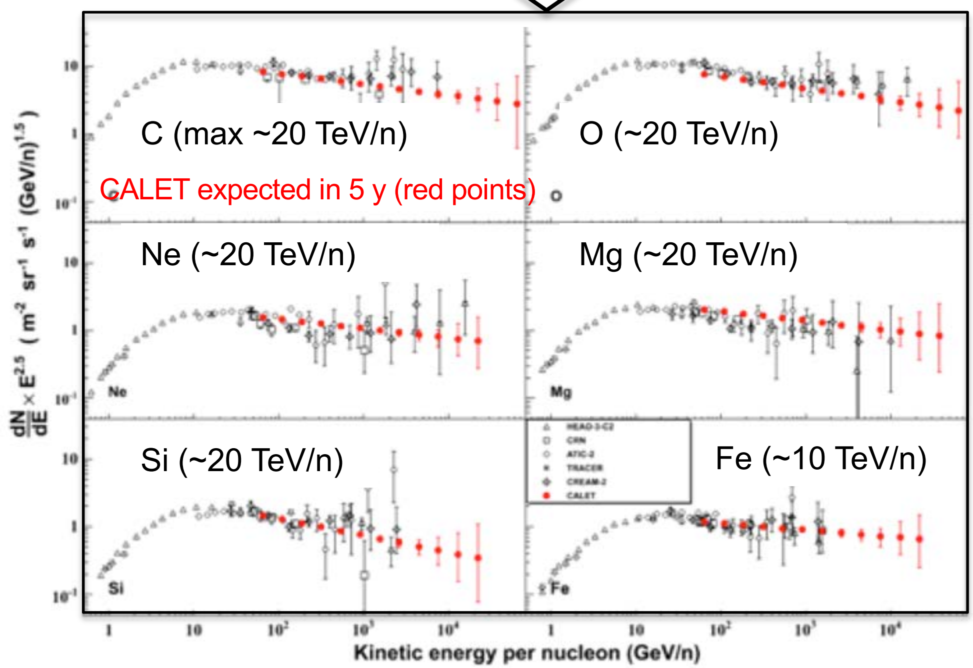
- Identification of the unique signature from nearby SRNs, such as Vela, in the electron spectrum by CALET in the TeV region

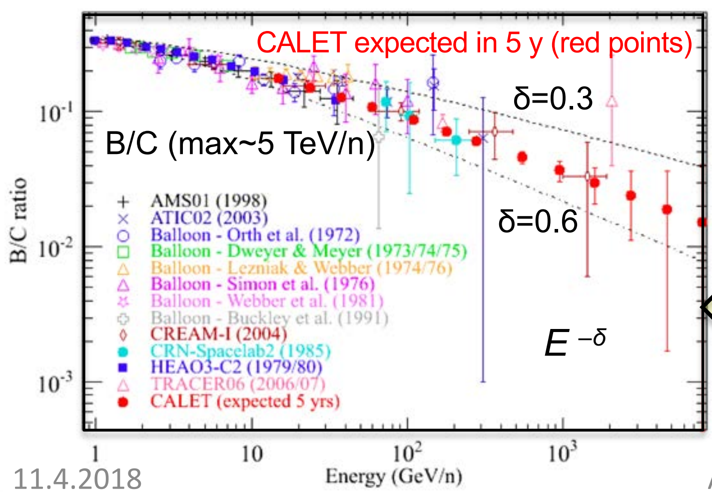
Measurements of Cosmic-Ray Nuclei Spectra with CALET

- 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 TeVxZ ?

- 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)



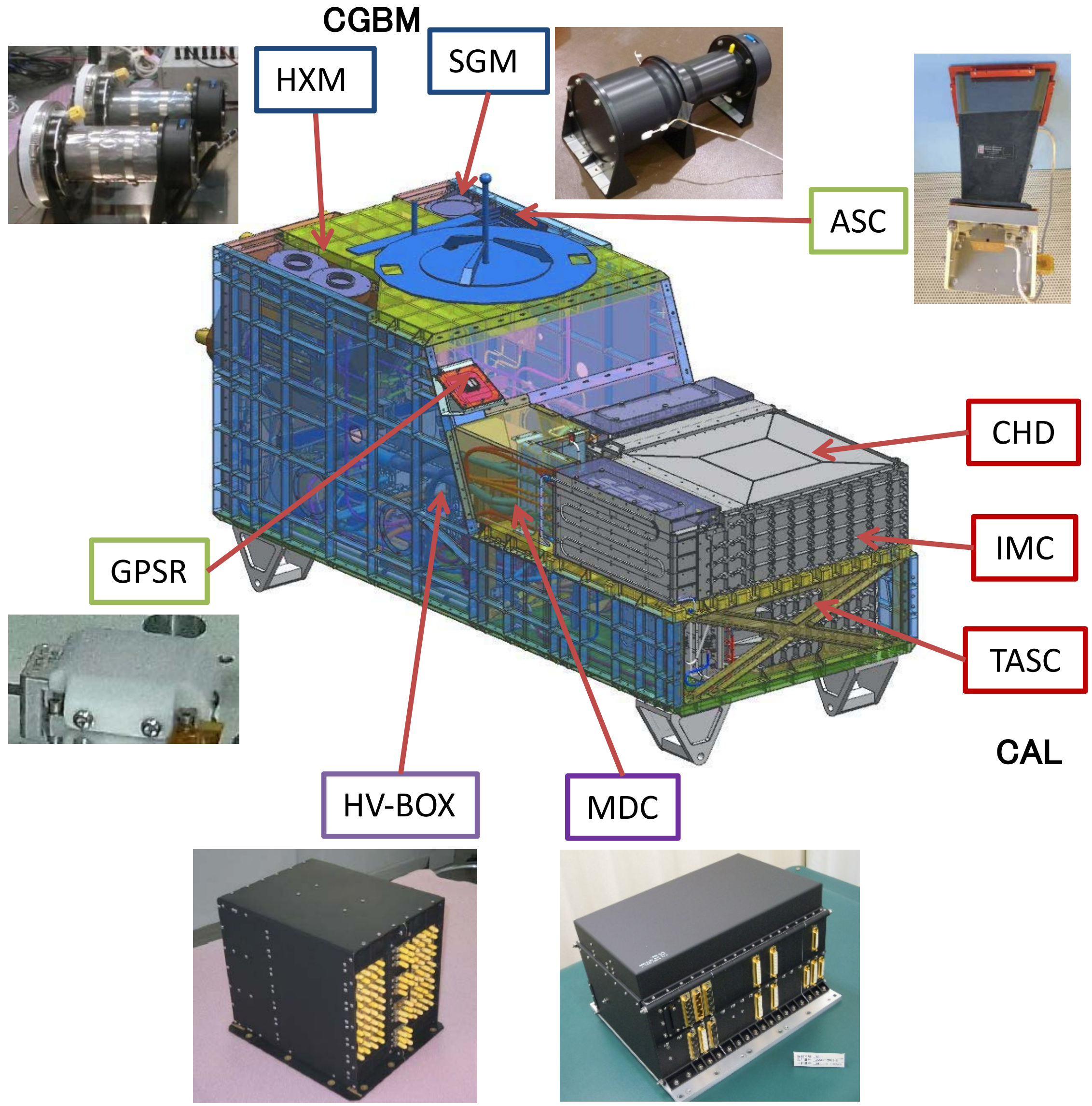




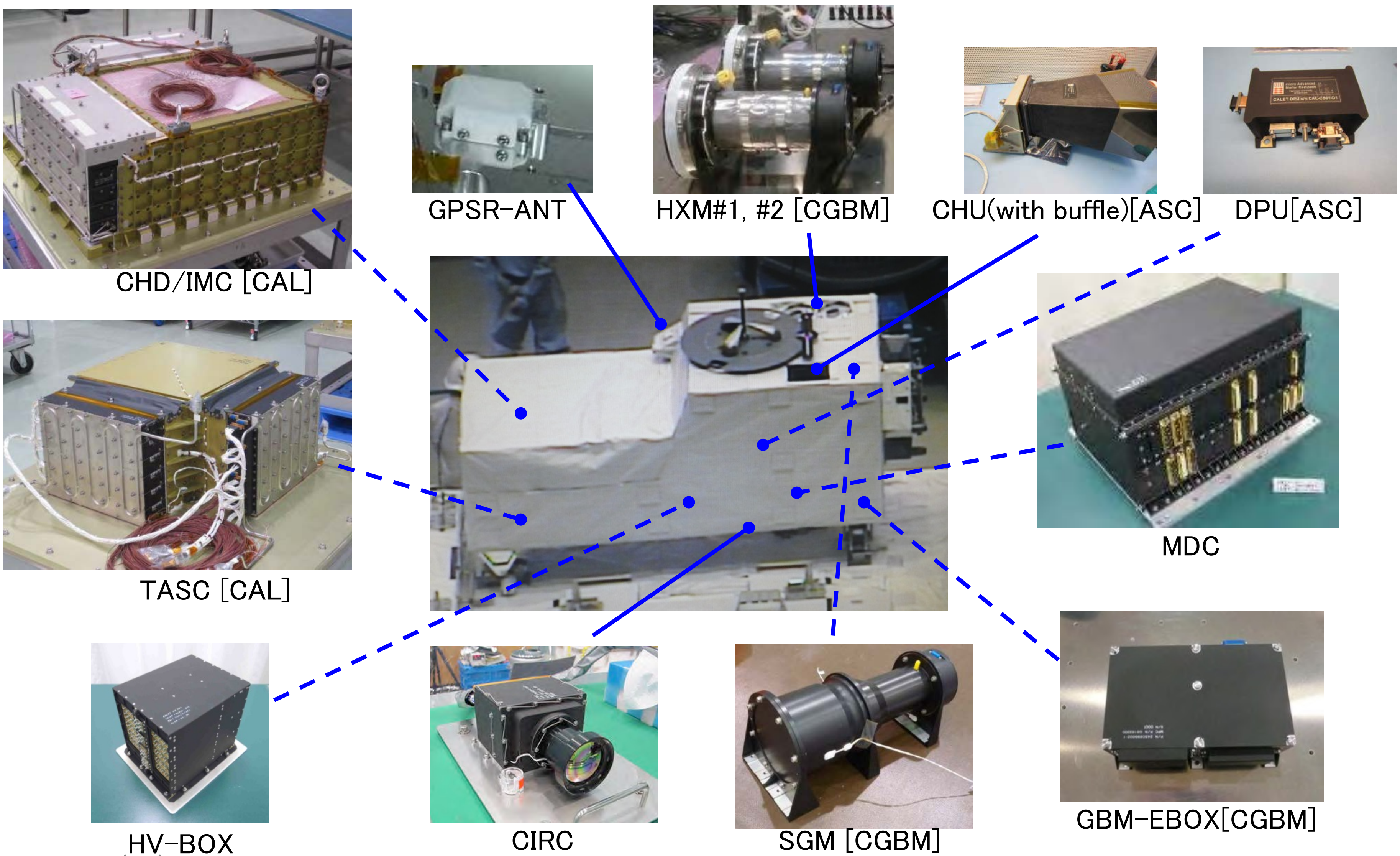
- At high energy (> 10 GeV/n) the B/C ratio measures the energy dependence of the escape path-length, $\sim E^{-\delta}$, of CRs from the Galaxy
- Data around 100 GeV/n indicate δ~1/3. At highest energy the ratio is expected to flatten out.

Overview of CALET Payload

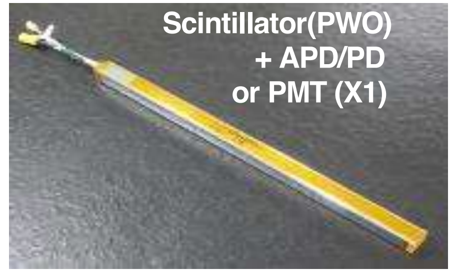
CAL
・Charge Detector (CHD) ・Imaging Calorimeter (IMC) ・Total Absorption Calorimeter (TASC)
CGBM
・Hard X−ray Monitor (HXM) $LaBr_3$: 7keV〜1MeV ・Soft γ−ray Monitor (SGM) BGO : 100keV〜20MeV
Data Processing & Power Supply
・Mission Data Controller (MDC) CPU, telemetry, power, trigger etc. ・HV−BOX (Italian contribution) HV supply (PMT:68ch, APD:22ch)
Support Sensors
・Advanced Stellar Compass (ASC) Directional measurement ・GPS Receiver (GPSR) Time stamp of triggered event (<1ms)



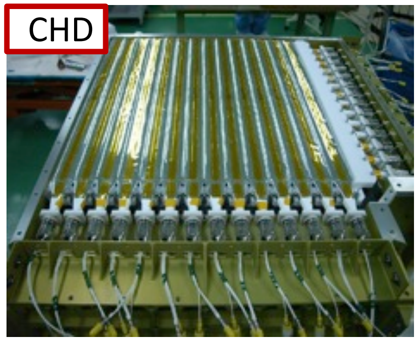
CALET Payload & the Components

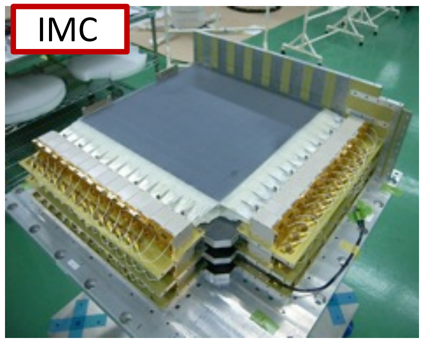


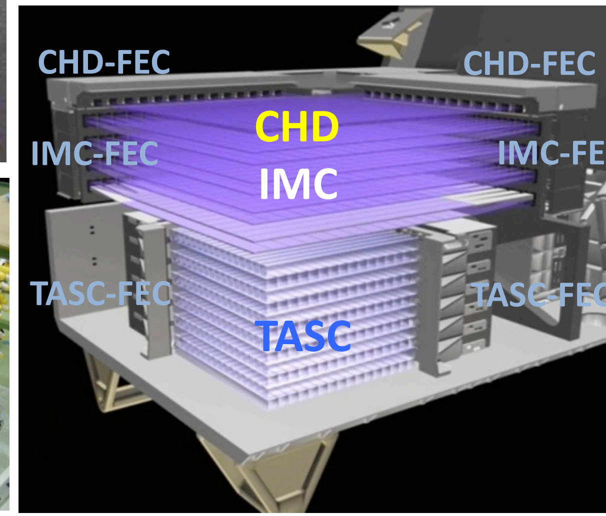
CALET Detectors



CALORIMETER



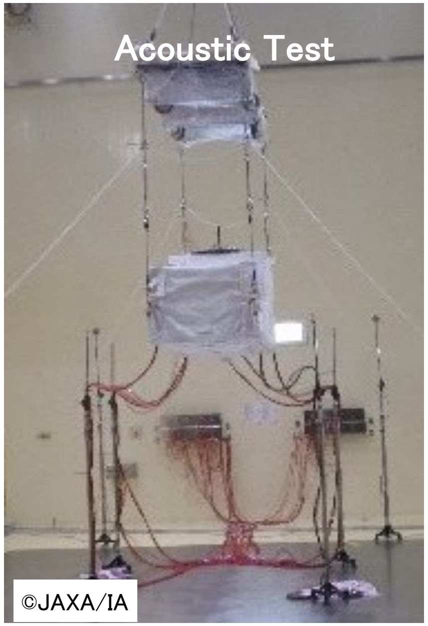


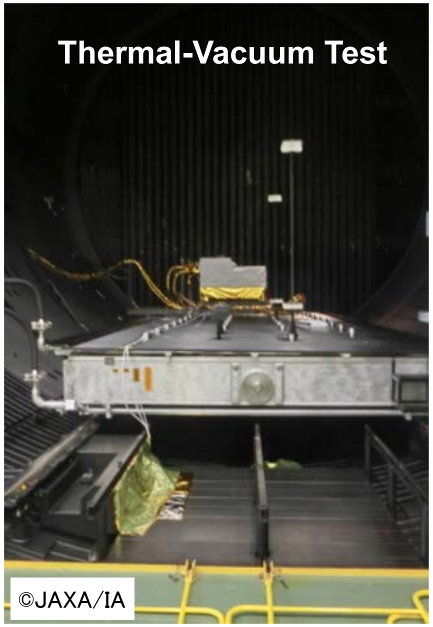


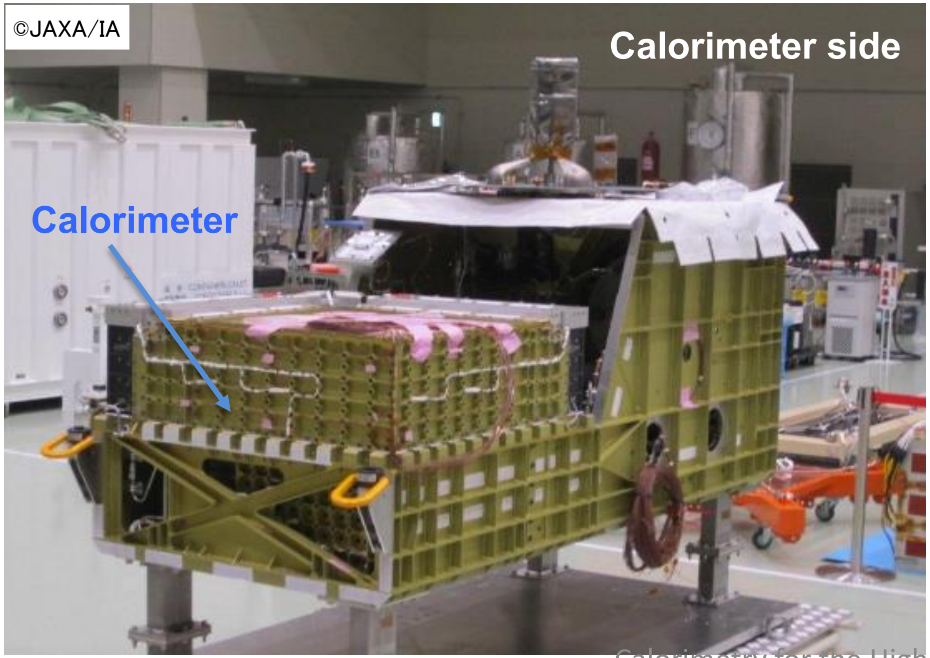
	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers (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 (VA32—HDR)**	**APD/PD+CSA PMT+CSA (for Trigger)@top layer**

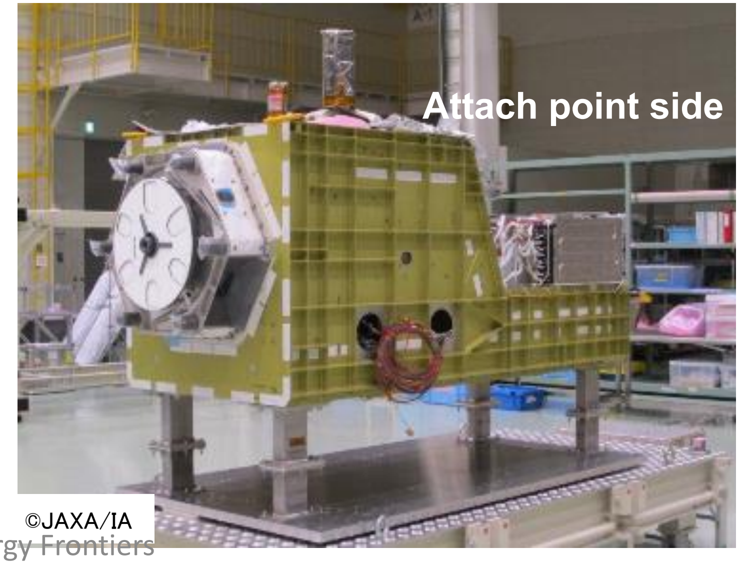
System Test of Proto Flight Model

- Acoustic test, Thermal–Vacuum test and EMC test were successfully carried out at Tsukuba Space Center (JAXA)
- After final system function test, the payload will be transferred to launching site (Tanaegashima Space Center) , and was launched with HTV–5 in 2015.





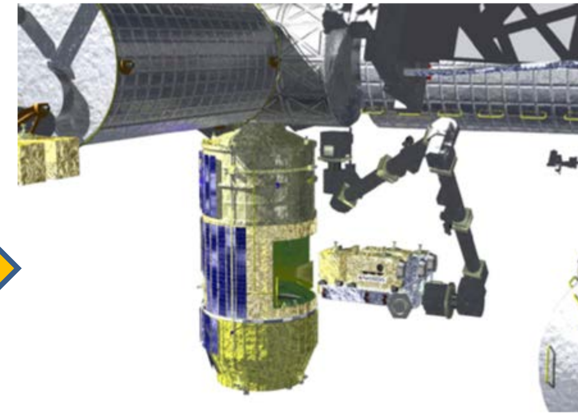




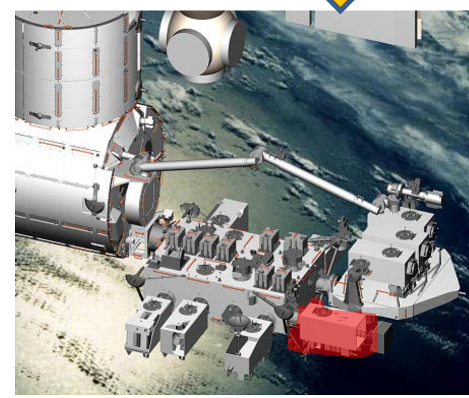
Launching Procedure of CALET

Separation from H2B

Approach to
ISS

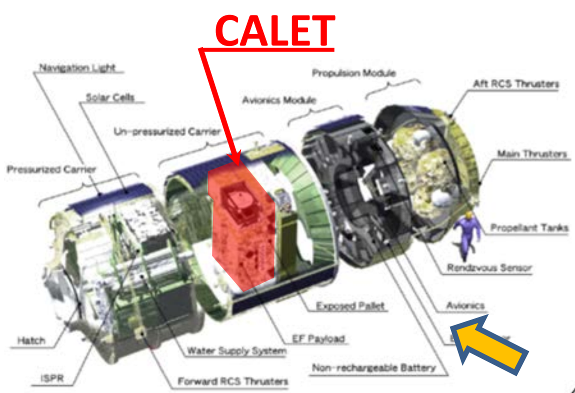


Pickup of CALET

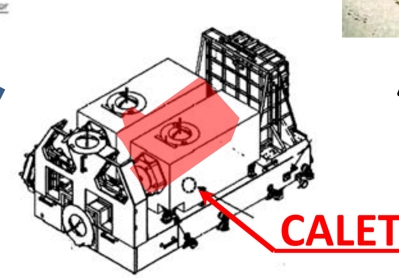


Attach to JEM-EF

Launching by
H2B Rocket



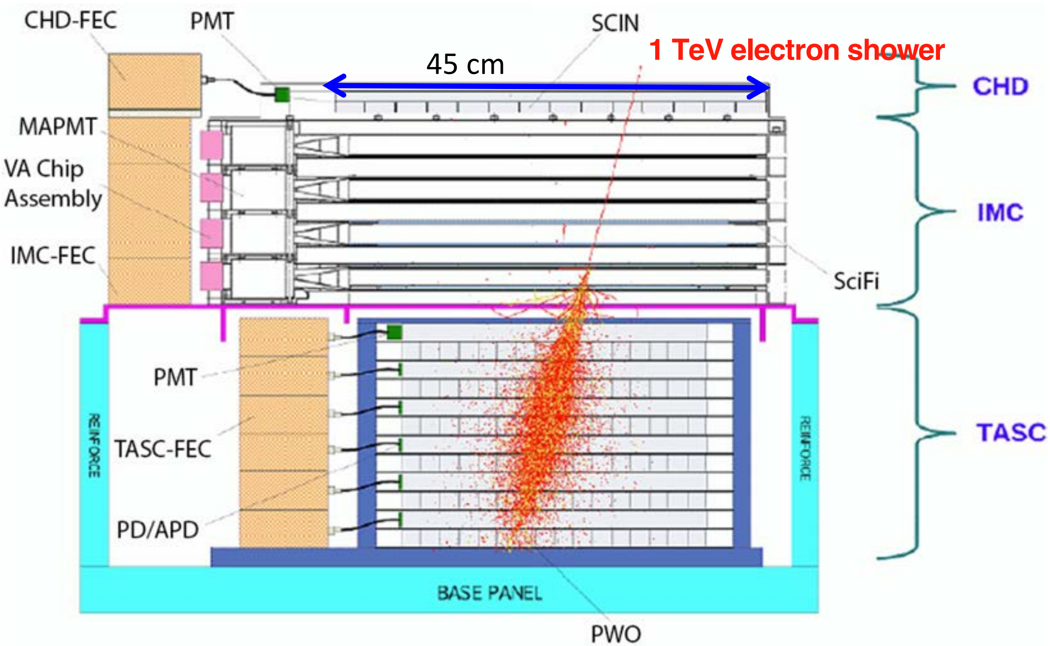
H2 Transfer Vehicle(HTV)



HTV Exposed Palette

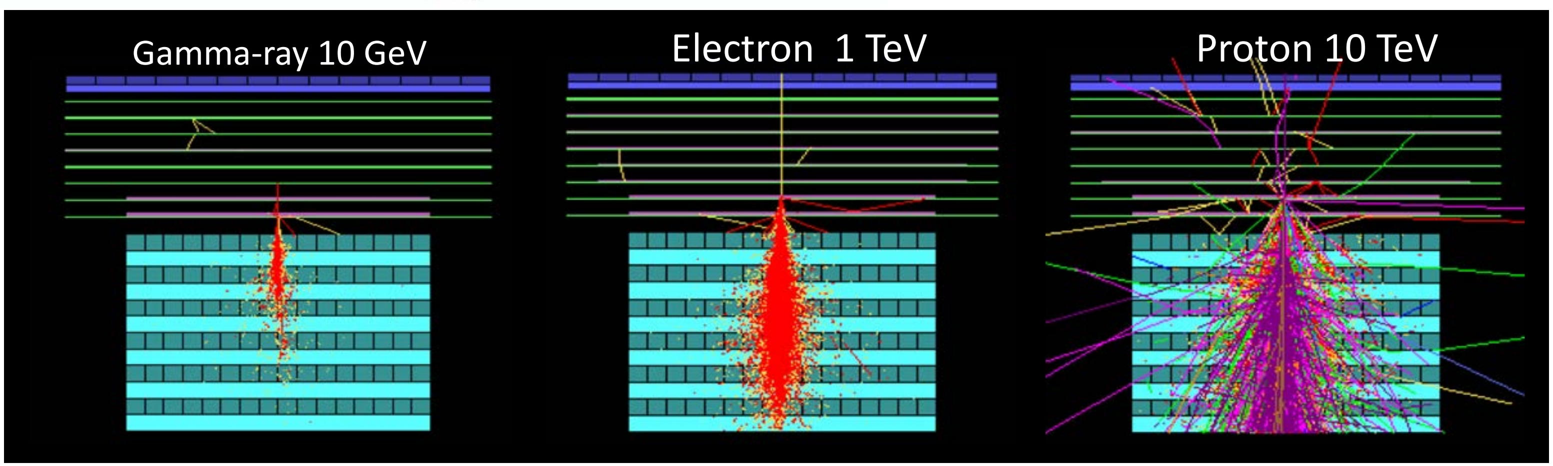
CALET Capability

Field of view: ~ 45 degrees (from the zenith)
Geometrical Factor: ~ 1,040 $cm^2 sr$ (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).**
- **Thick(~30 X_0), fully active calorimeter allows measurements well into the TeV energy region with excellent energy resolution (~2-3%)**
- **High granularity imaging pre-shower calorimeter accurately identify the arrival direction of incident particles (~0.2°) and the starting point of electro-magnetic showers.**
- ➢ **Combined, they powerfully separate electrons from the abundant protons: contamination is much less than 10 % up to the TeV region.**



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

Intrinsic Advantage of the CALET Instrument :

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

- Active and thick calorimeter absorbs most of the electromagnetic energy (~95%) up to the TeV region
  - Fine energy resolution of ~ 2 %
  - Capability of measuring shower energy from 1GeV to 1000 TeV in 6 order of magnitude !
- In principle, energy measurement with very small systematic error is possible.
- Needs to obtain the ADC unit to energy conversion factor and to calibrate the whole dynamic range channel by channel

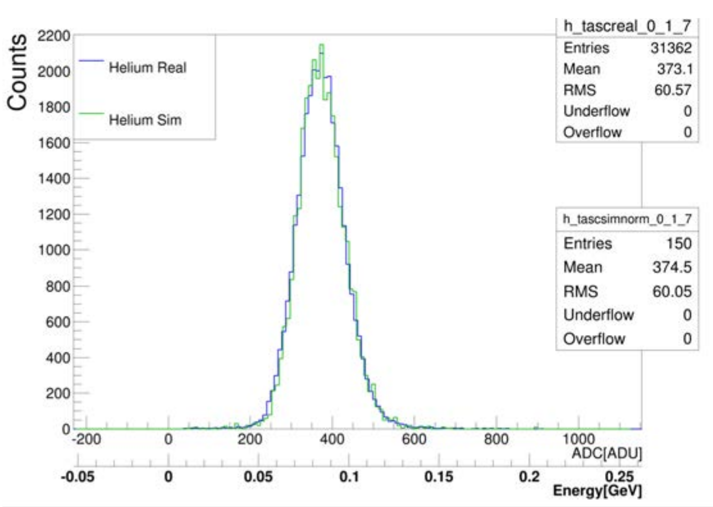
On orbit : Energy conversion factor using “MIP” of p or He

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

On ground: Linearity measurements for the whole dynamic range

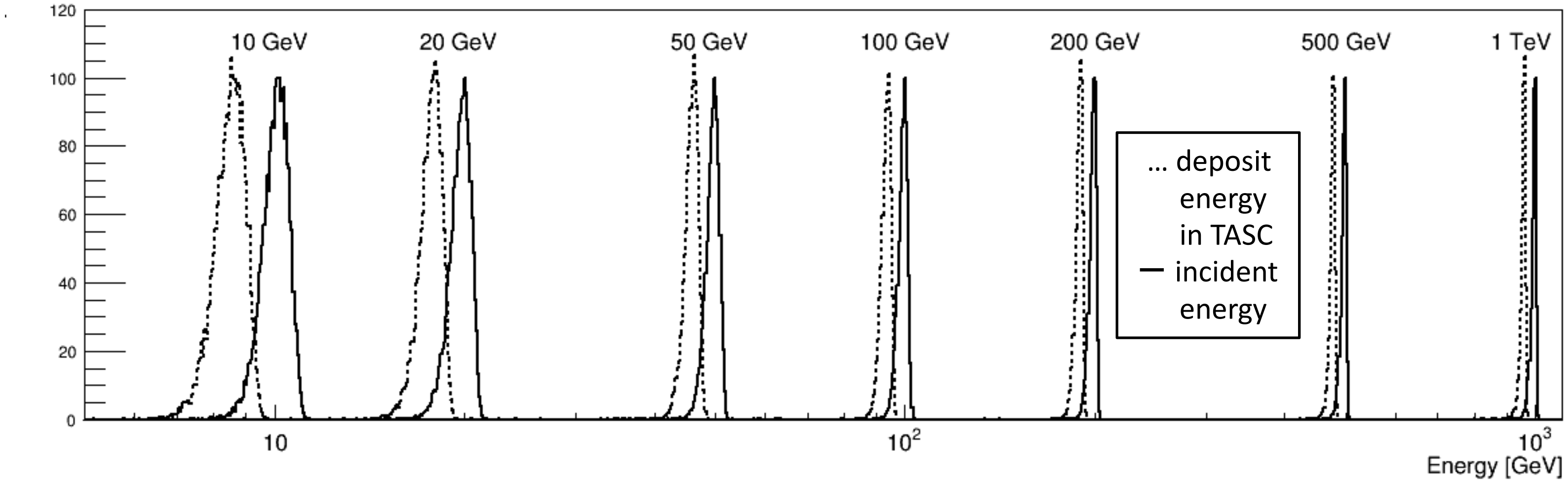
- CHD/IMC – Charge injection
- TASC – UV Laser irradiation (end-to-end)

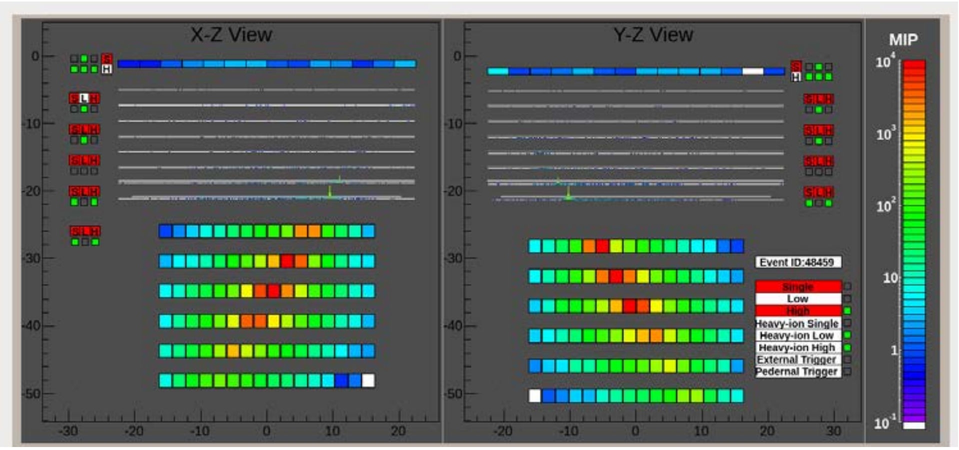
“MIP” peak in PWO: Obs. vs. MC



Energy Reconstruction for Electromagnetic Showers

Simulation: Comparison of deposit energy in TASC (ΔE) with incident energy (E_0)

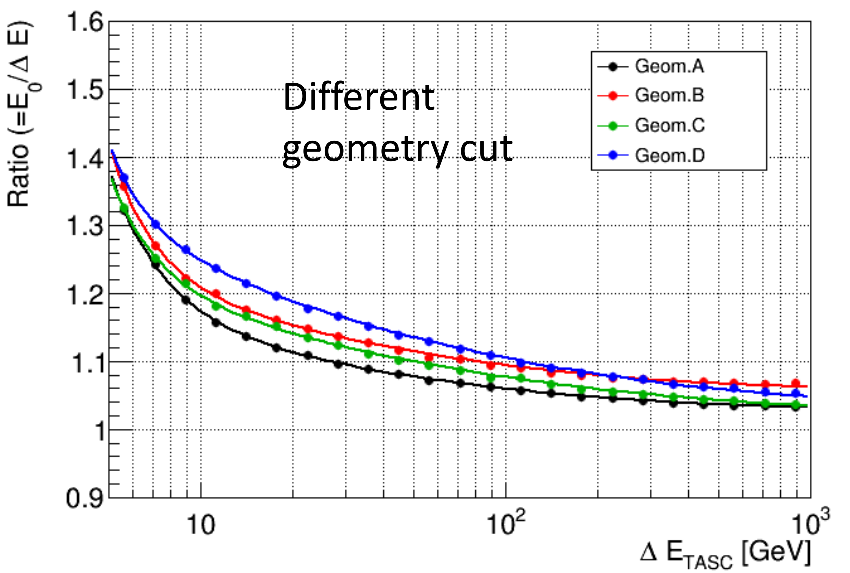




4 TeV electron candidate (well contained)

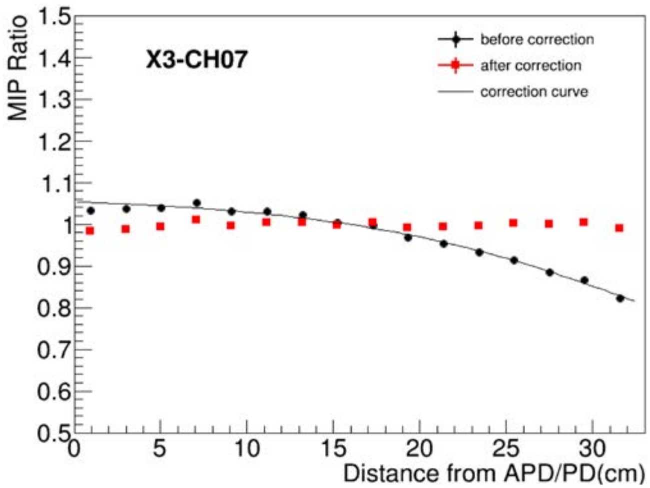
⇒ very small leakage (~ a few %)

Energy reconstruction factor vs. Energy

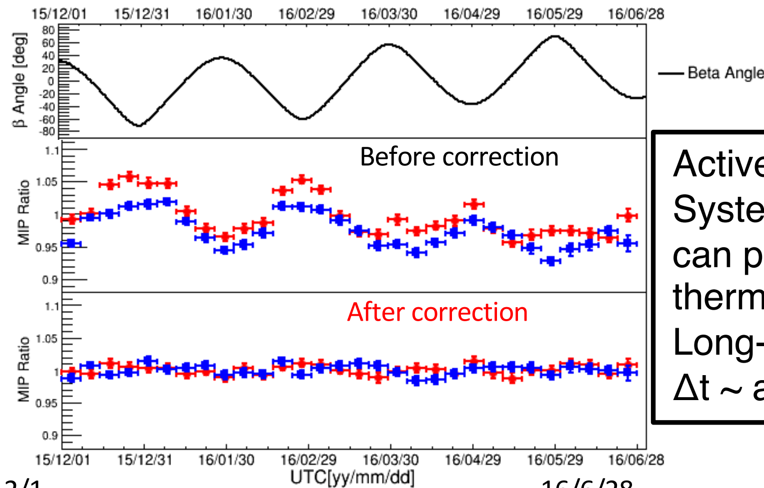


Position and Temperature Calibration, and Long-term Stability

Example of position dependence correction



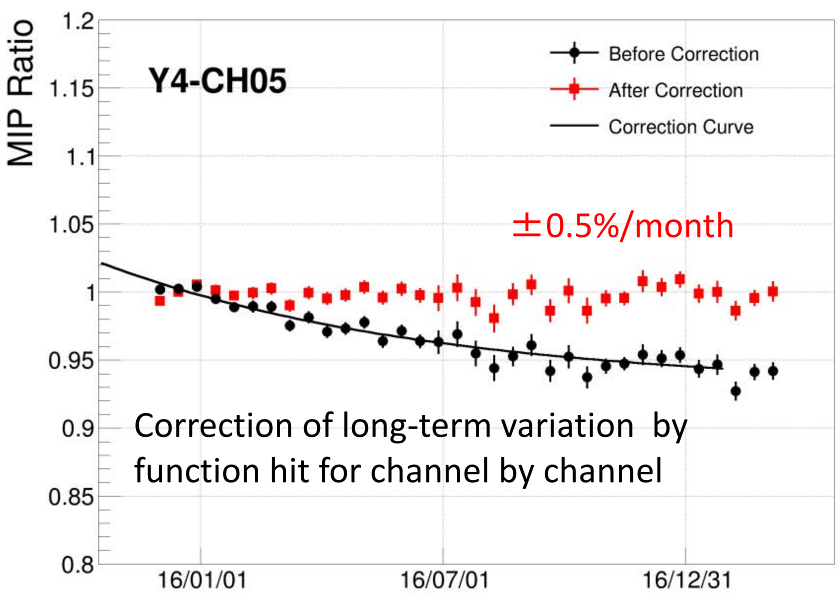
Examples of temperature change correction



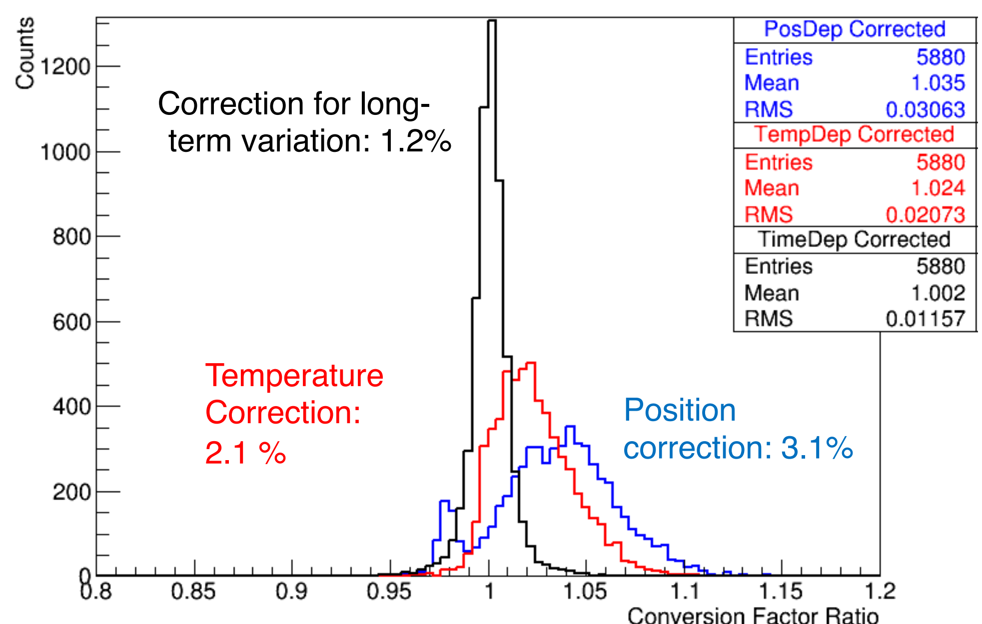
15/12/1 16/6/28

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

Example of long-tem variation correction

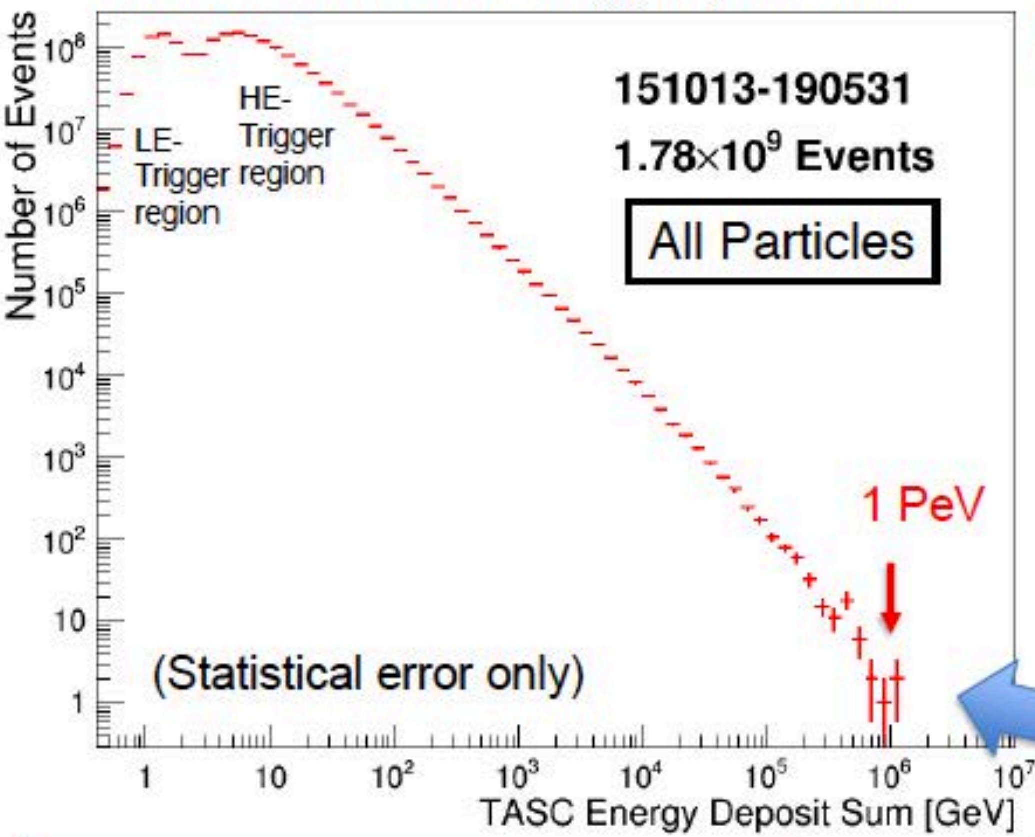


Distribution of MIPs for 192 ch x 16 segmented positions after each correction

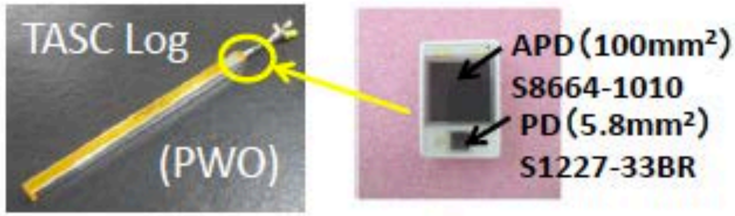


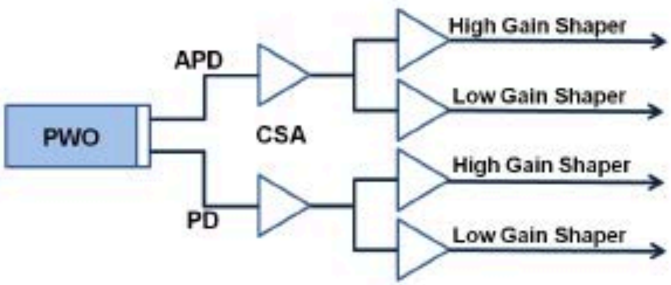
Wide Dynamic Range Energy Measurements in 1 GeV- 1 PeV

Distribution of TASC energy deposit sum



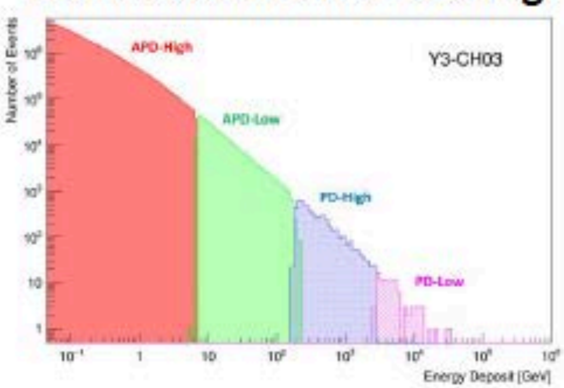
Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), Astropart. Phys. 91 (2017) 1.





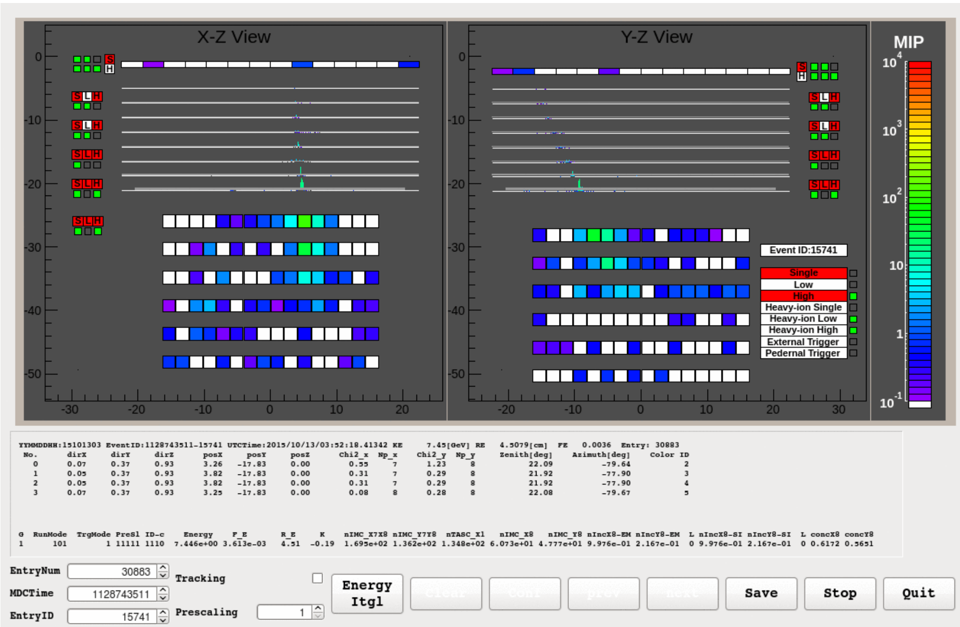
The smooth distribution clearly reflects the power-law nature of cosmic-rays, demonstrating the reliability of the energy measurement over a wide energy range.

An example of gain connection in one PWO log:

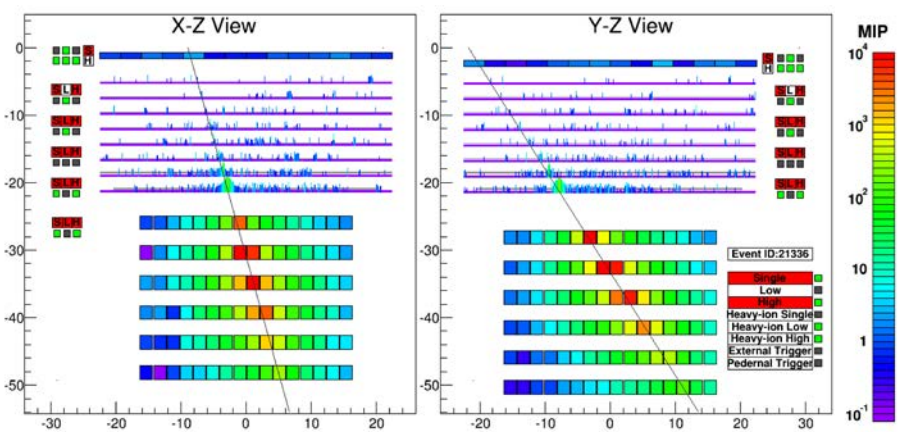


Examples of Observed Events

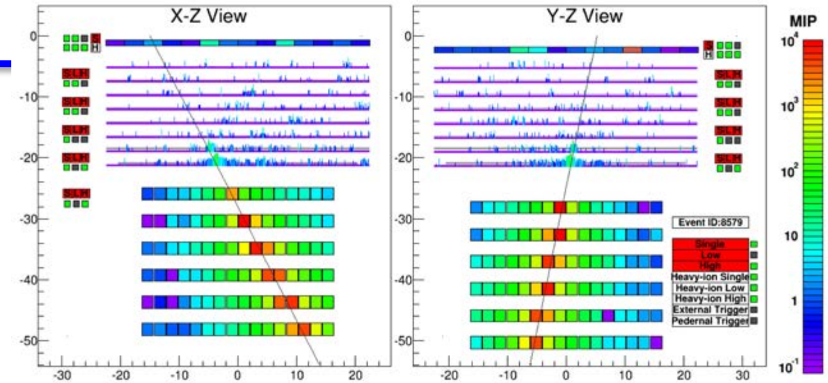
Event Display: Electron Candidate (>100 GeV)



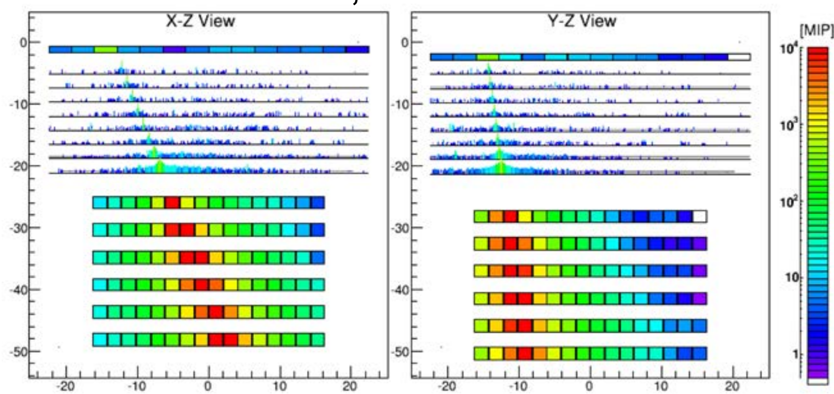
Electron, E=3.05 TeV



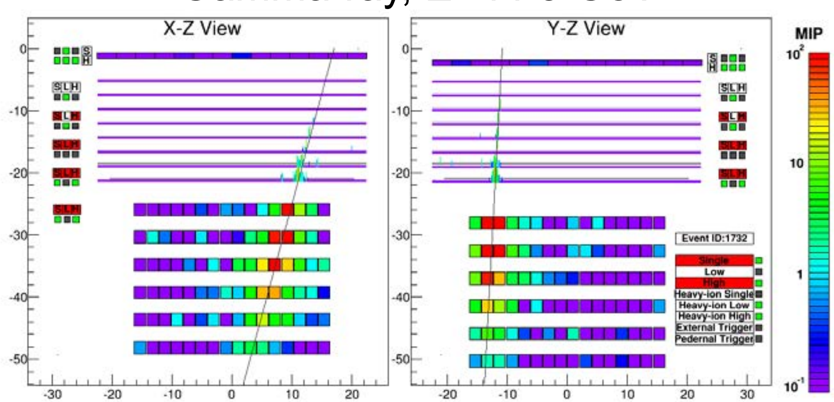
Proton, ΔE=2.89 TeV



Fe, ΔE=9.3 TeV



Gamma-ray, E=44.3 GeV

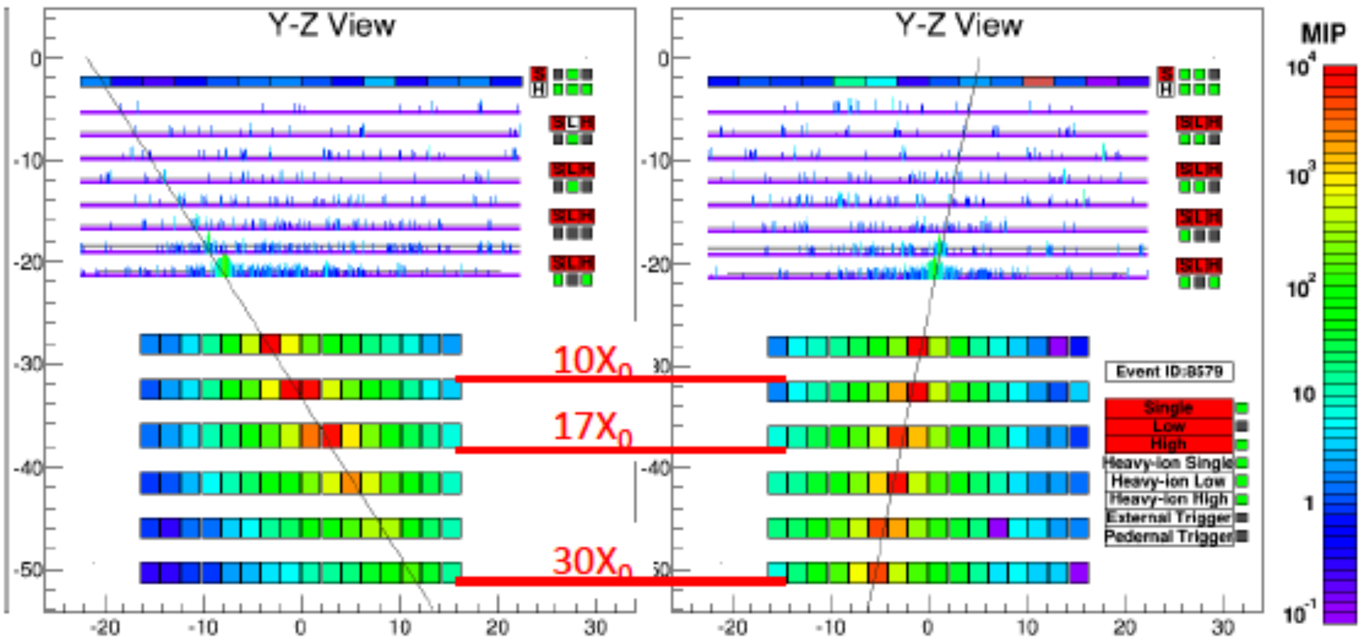


Unit in MIP

All-Electron Measurement with CALET

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

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

Electron Identification

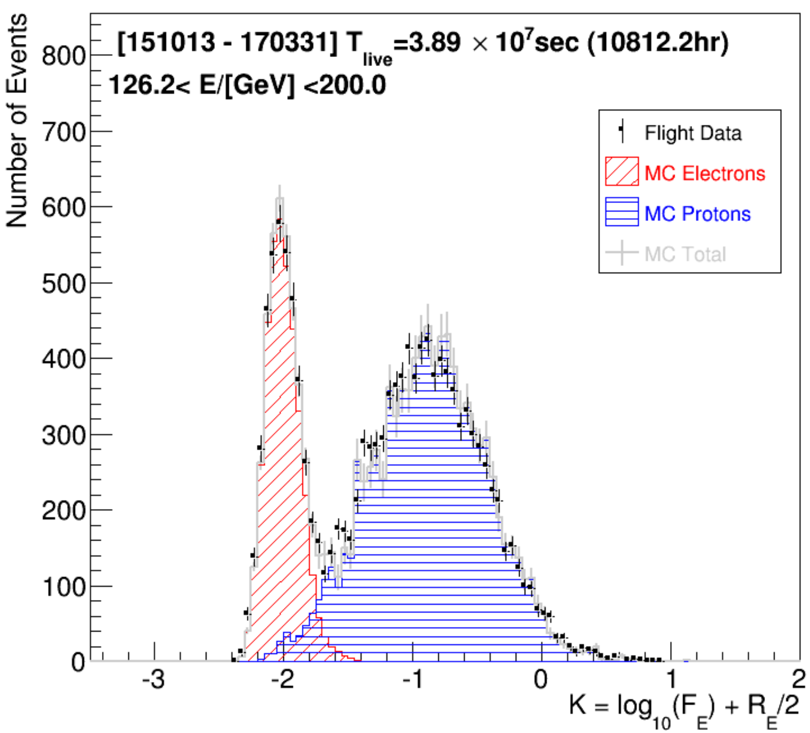
Simple Two Parameter Cut

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

Cut Parameter K is defined as follows:

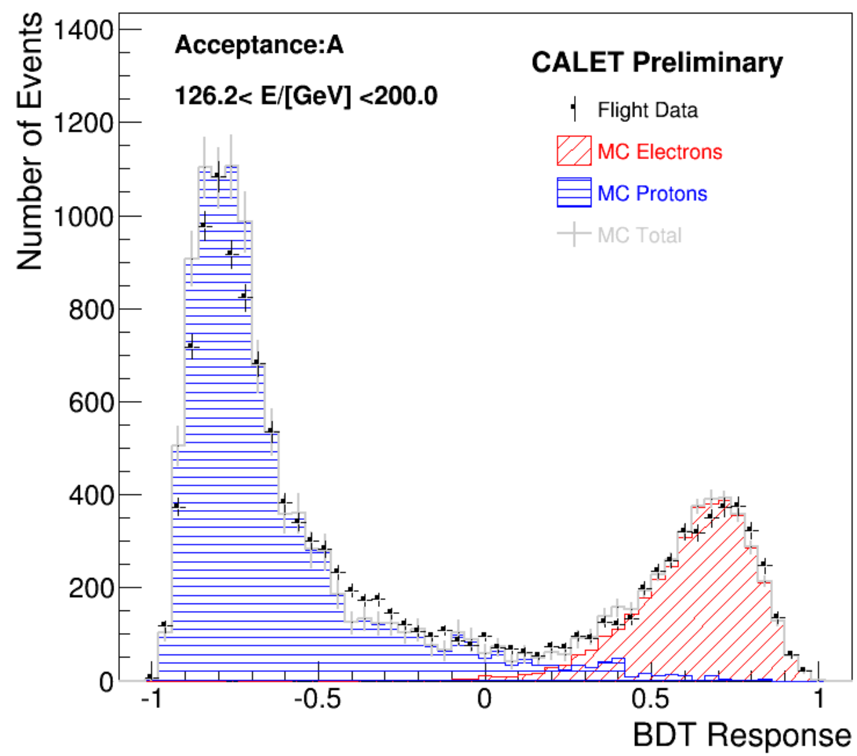
$$K = \log_{10}(F_E) + 0.5\, R_E\ (/\mathrm{cm})$$



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



All-Electron Measurement with CALET: room for "unknown" systematics

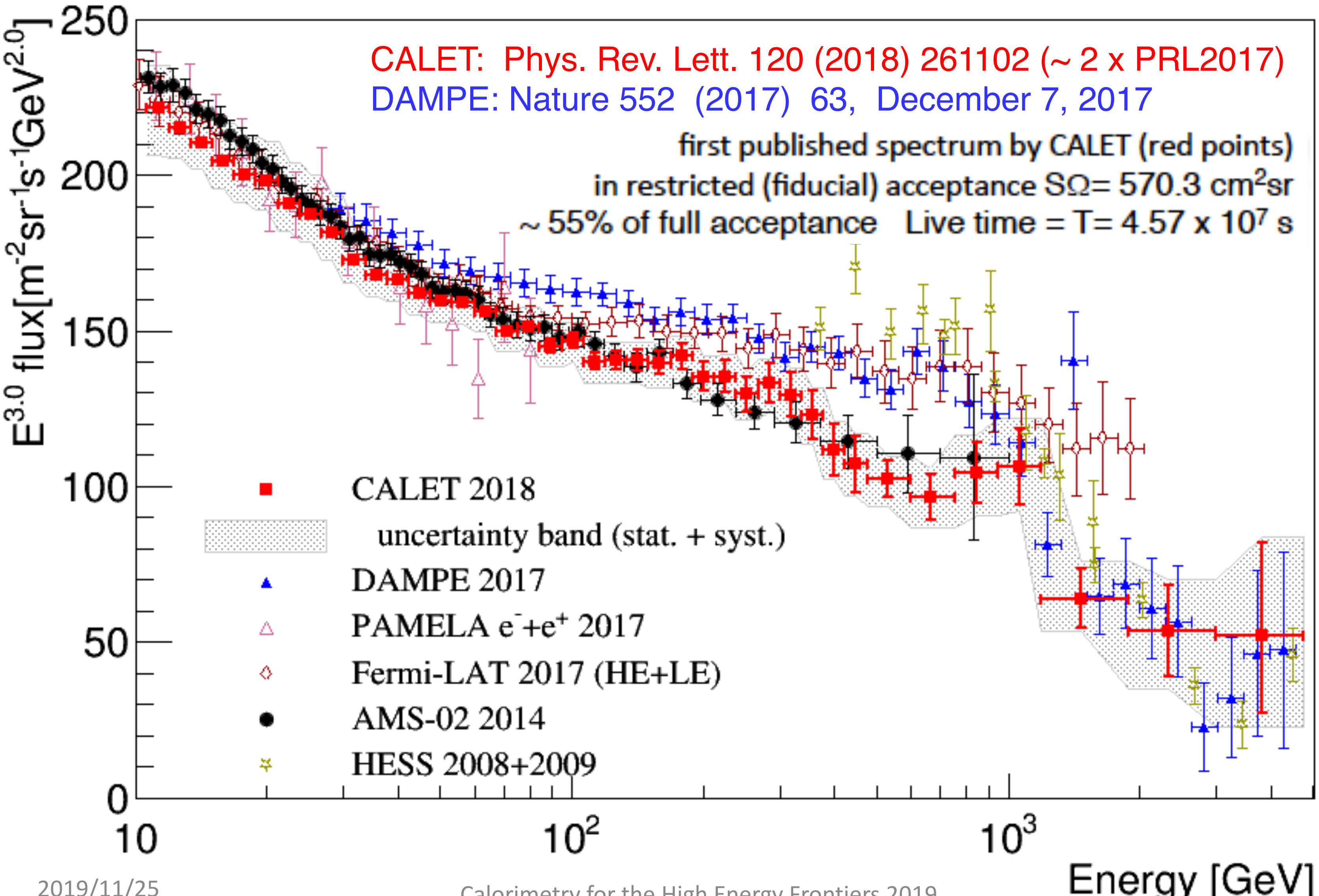
1. Acceptance ⇒ **well defined SΩ because of reliable tracking**
   - Geometrical factor
2. Energy determination ⇒ **ΔE/E ~ 2% (E>20GeV) absolute energy scale calibrated by geomagnetic rigidity cutoff**
   - Magnet Spectrometer
   - Calorimeter
3. Particle identification ⇒ **r_{BG} < 5% (E<1TeV)**
   r_{BG} ~ 10—20% (1<E<5TeV)
   - Contamination
4. Detection efficiency ⇒ **ε > 70% (E>30GeV) keeps constant value**
   - Losses in the detector

⇒ **Leaves little room for "unknown" systematics**

combined with detailed systematic studies (see PRLs + SM)

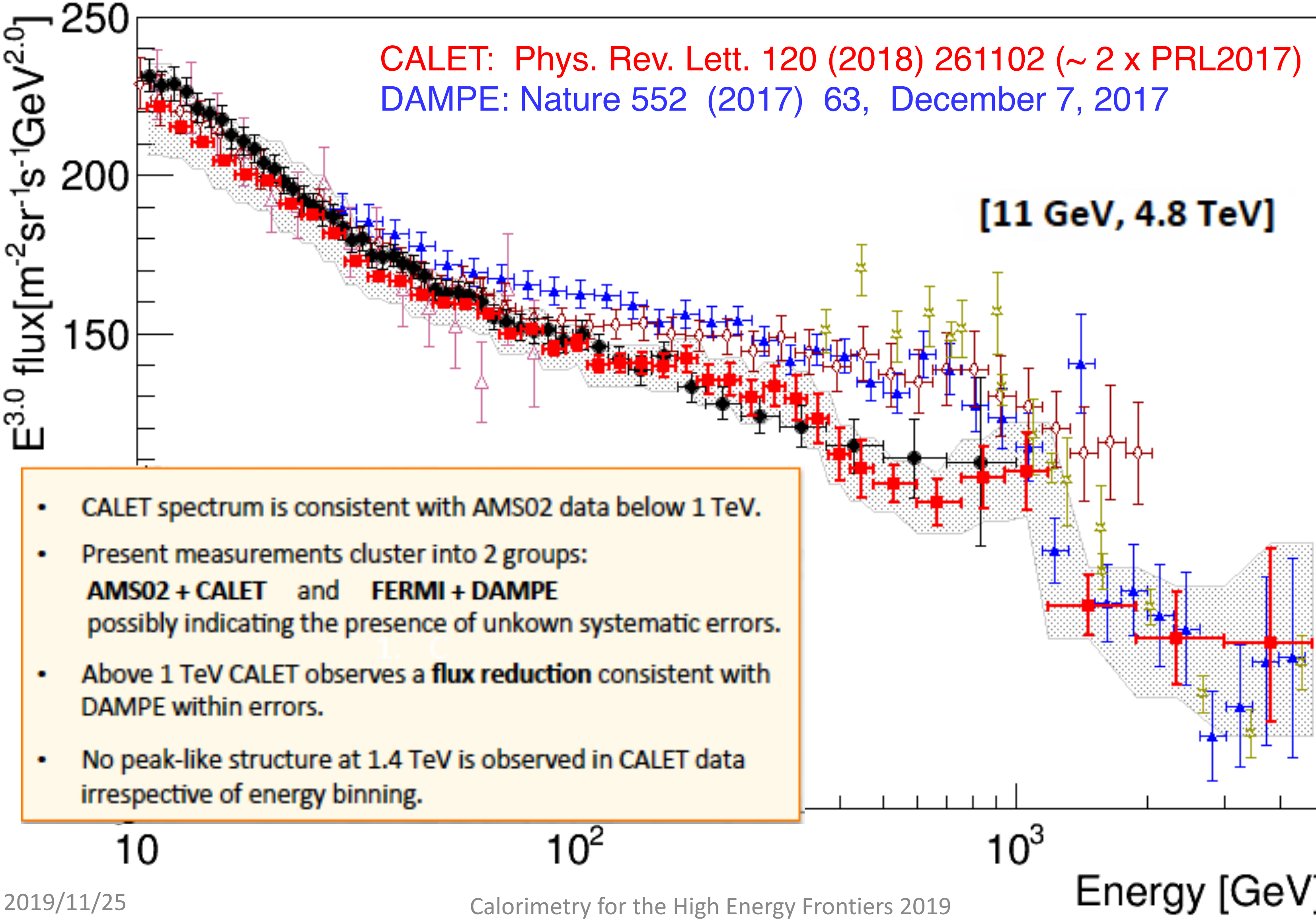
Direct Measurements of All Electron Spectrum

Comparison of CALET with DAMPE and other experiments in space



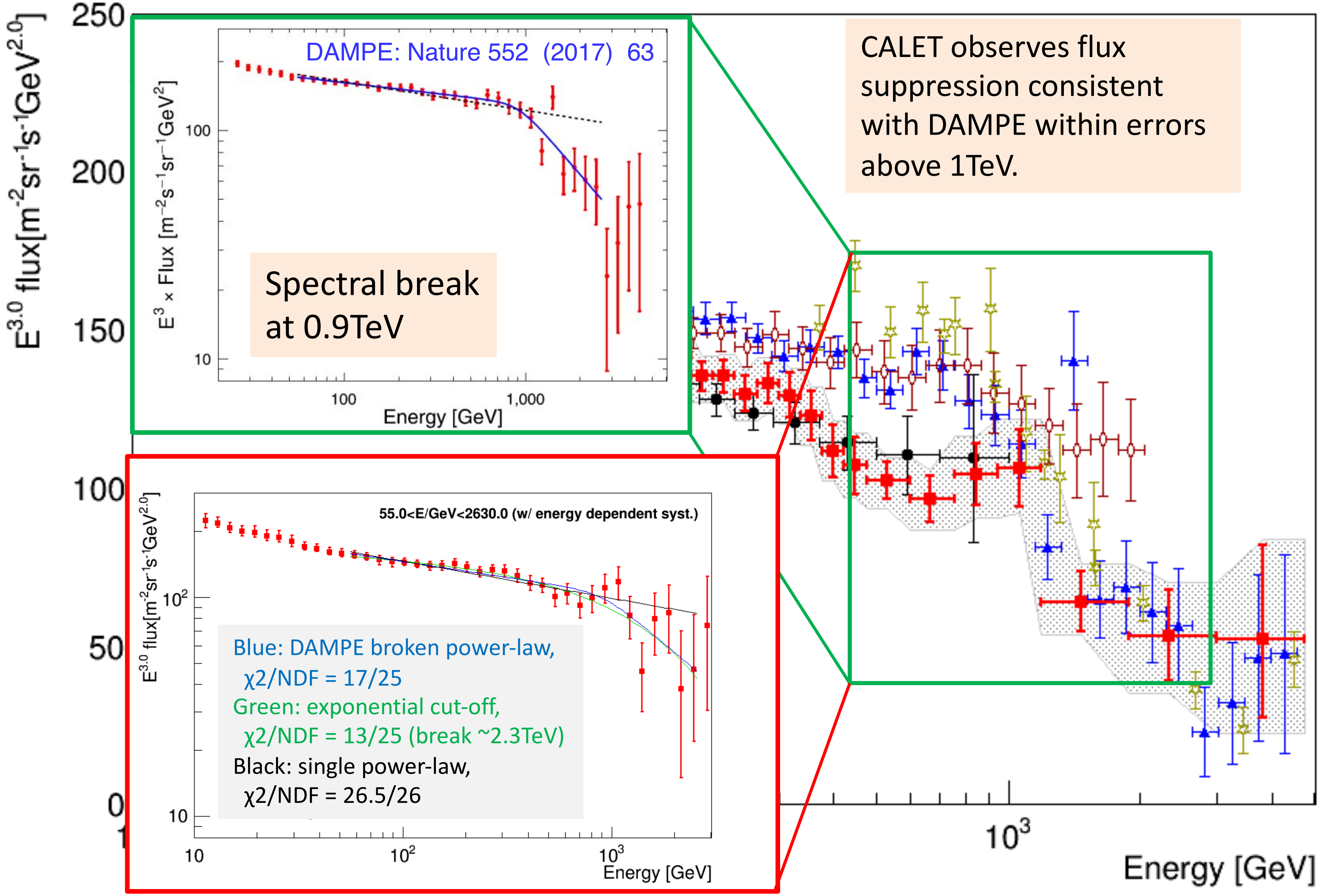
Extended CALET Measurement of Electron Spectrum

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



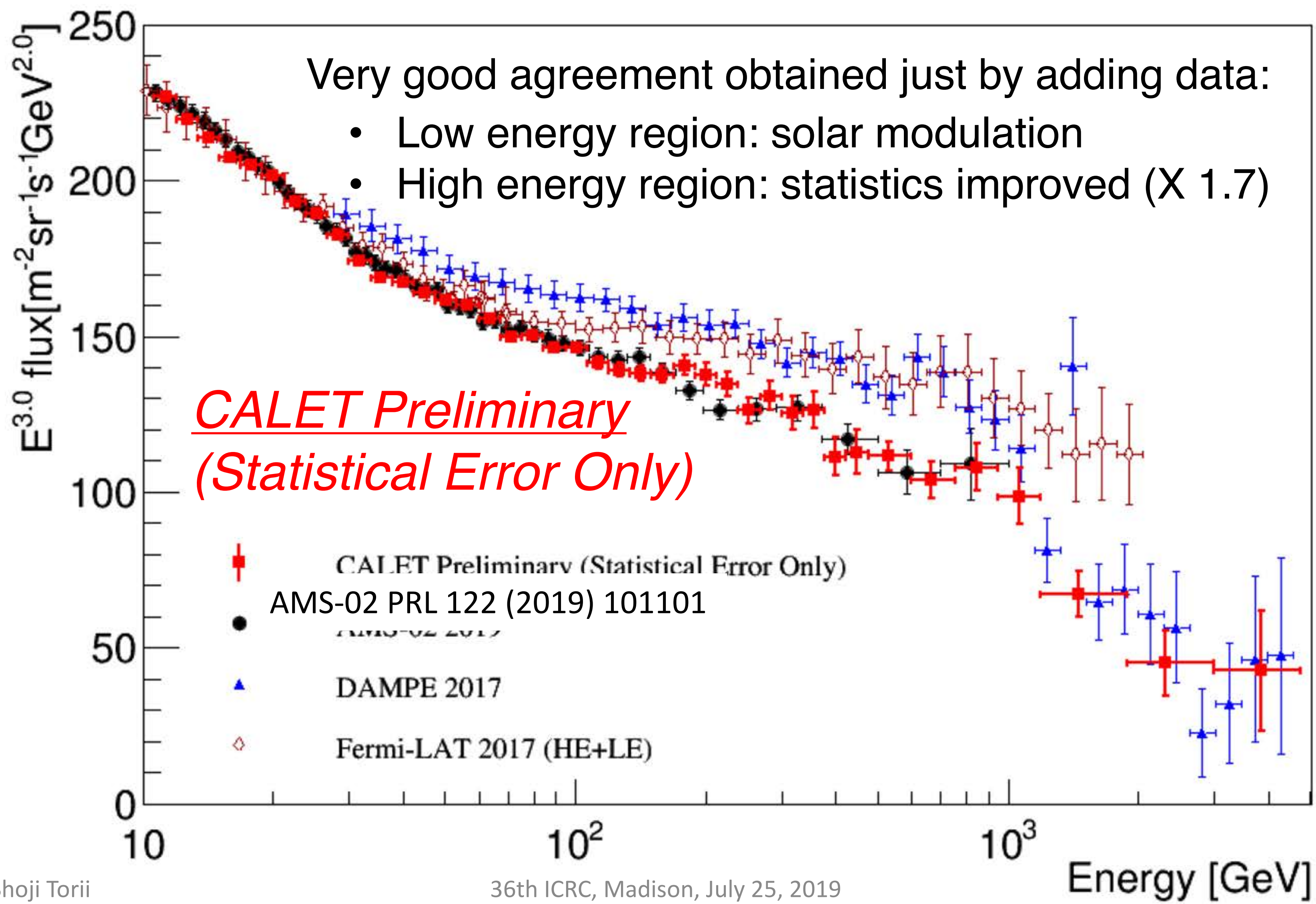
- CALET spectrum is consistent with AMS02 data below 1 TeV.
- Present measurements cluster into 2 groups:
  AMS02 + CALET and **FERMI + DAMPE**
  possibly indicating the presence of unkown systematic errors.
- Above 1 TeV CALET observes a **flux reduction** consistent with DAMPE within errors.
- No peak-like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

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



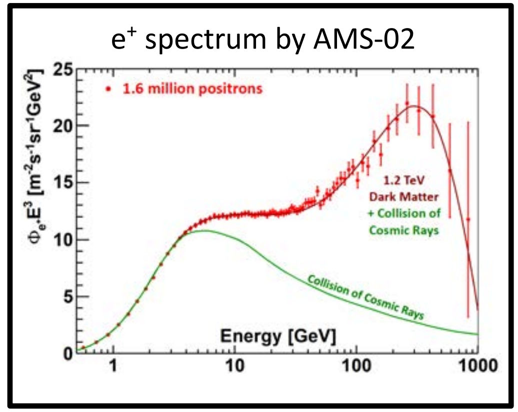
All-Electron Spectrum: Comparison between updated AMS-02 & CALET

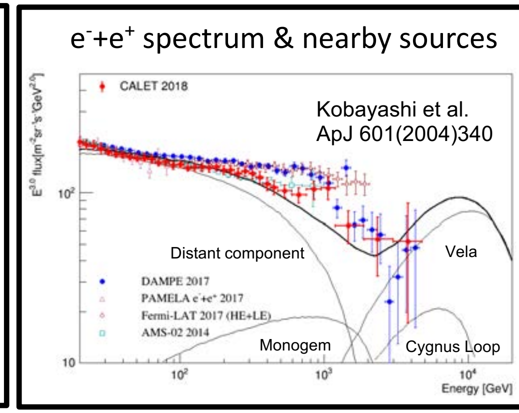
Exactly the same analysis applied, data up to the end of May 2019 are used.



Future prospects: Search for new sources

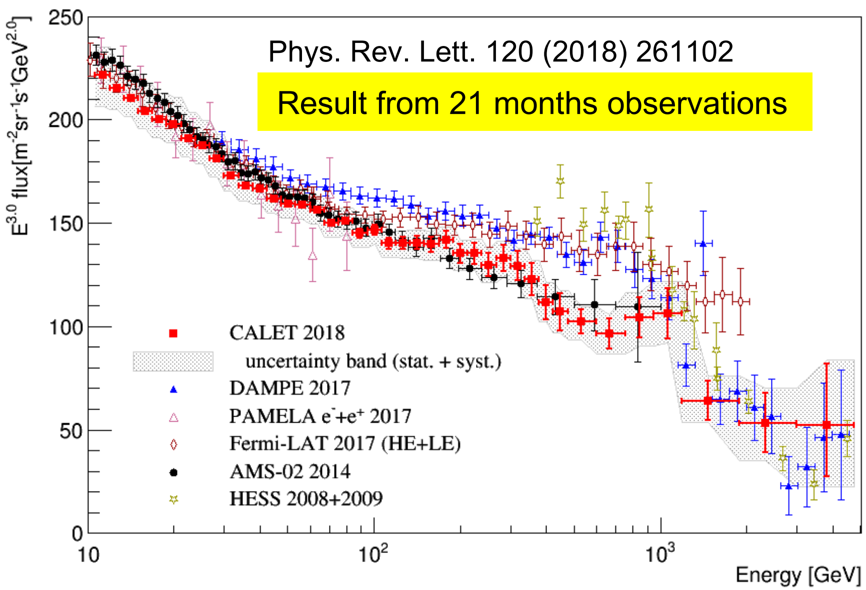
- Investigation of CR nearby sources by electron observations at the TeV region
  - Direct detection of nearby sources
  - Acceleration limit and escape process from SNR
- Search for Dark Matter signature in the electron spectrum structure
  - Detection of unknown primary source of electron and positron: Pulsar(s) or Dark Matter ?



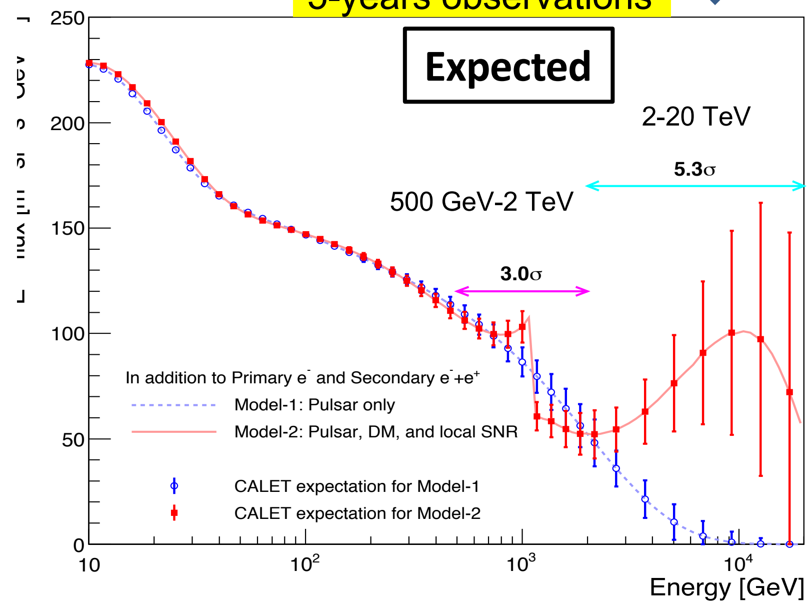


Detection of primary source of e+ & e-

Search for nearby source(s)



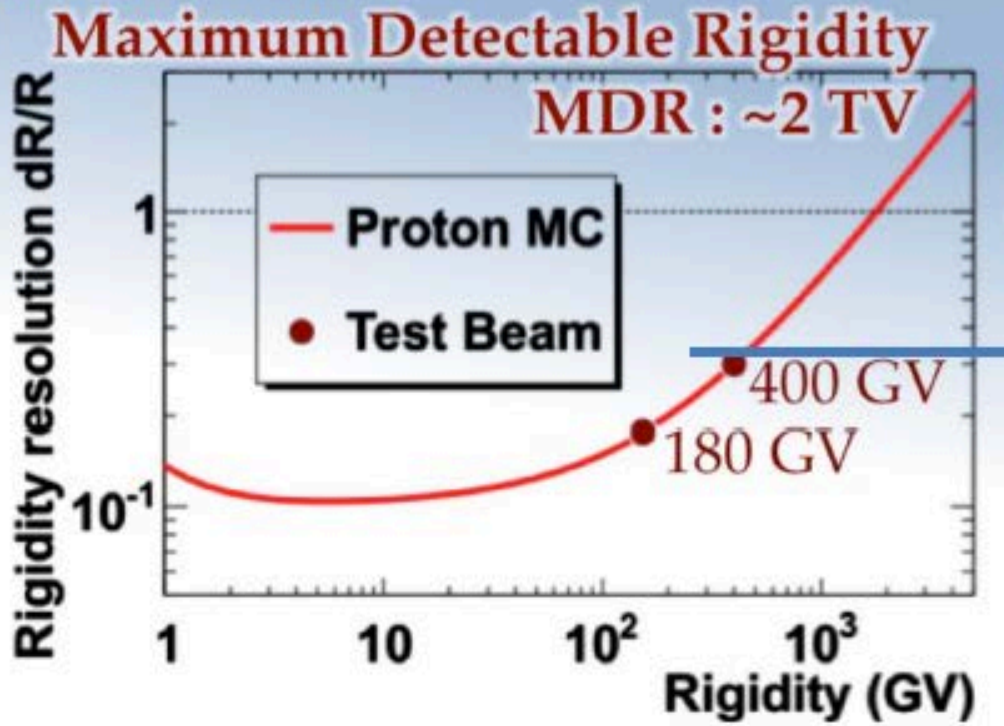
5-years observations



Energy Measurement of Protons: Magnetic Spectrometer vs Calorimeter

AMS-02: bending in magnetic field

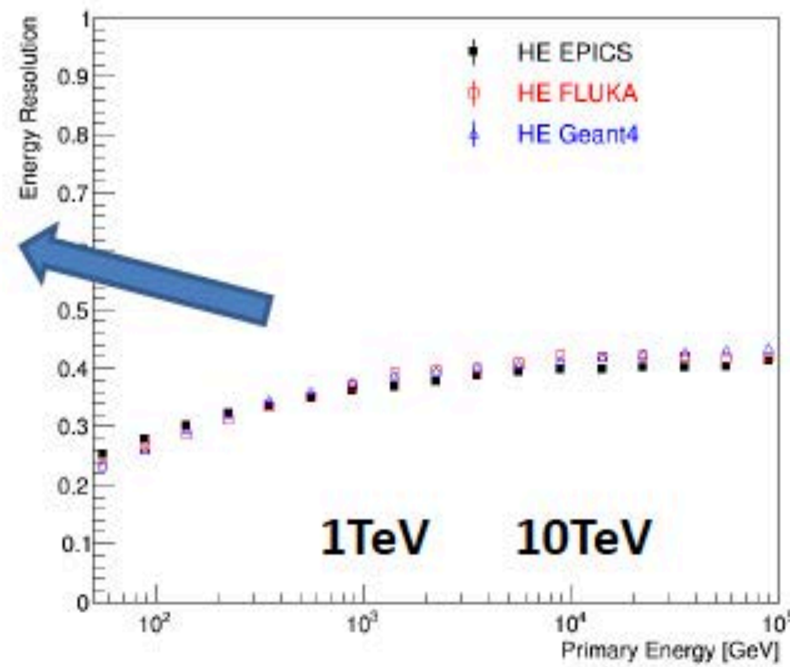
$$\Delta(1/R) = \frac{\Delta R}{R^2} \approx \frac{8\Delta s}{0.3BL^2}$$



Ref: Haino 2014

CALET: shower energy

Better resolution at E>500 GeV. Very stable above E>1TeV. Small dependence on MC models.



Proton Measurement with CALET: room for “unknown” systematics

1. Acceptance ⇒ **well defined SΩ**
   – Geometrical factor **because of KF tracking and event selection**

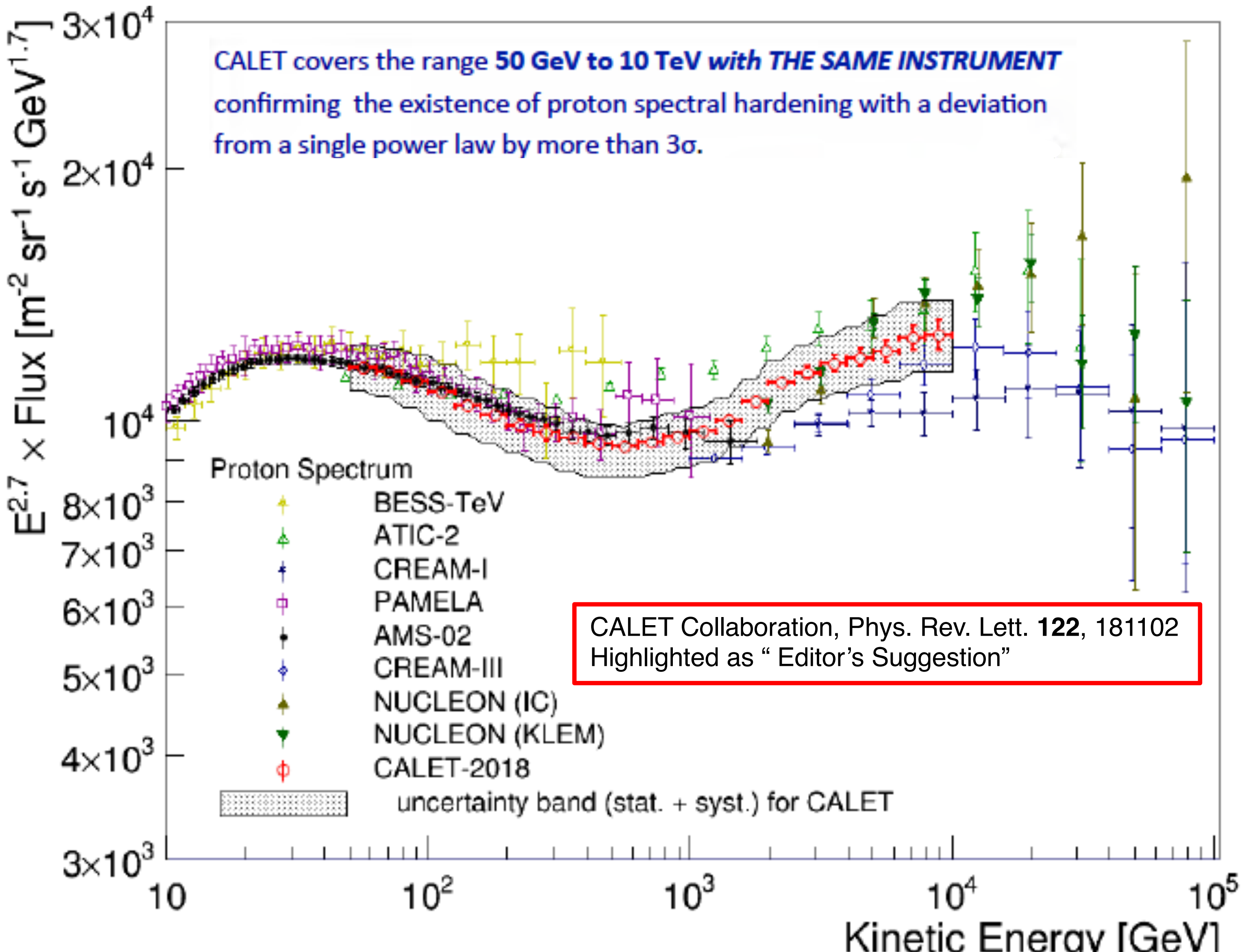
2. Energy determination ⇒ **limited energy resolution but constant response, and confirmed by test beam**
   – Magnet Spectrometer
   – Calorimeter

3. Particle identification ⇒ **excellent charge separation capability**
   – Contamination

4. Detection efficiency ⇒ **low efficiency, but confirmed by test beam**
   – Losses in the detector

⇒ **Needs special care for “unknown” systematics**
detailed systematic studies are carried out
(see the Supplement Material of PRL 122, 181102)

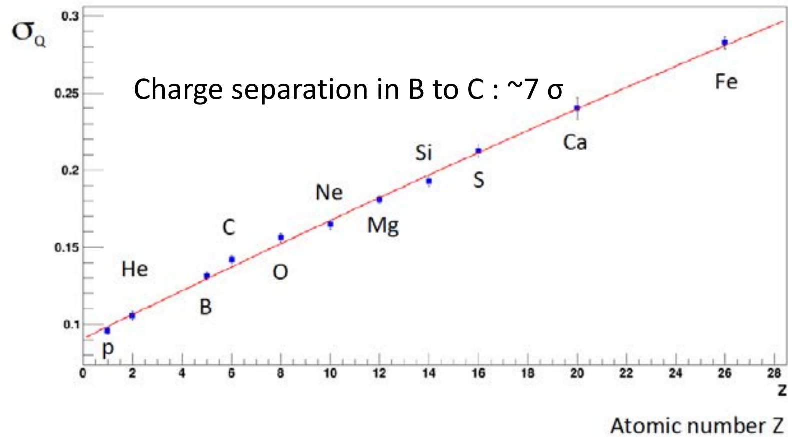
Direct Measurements of Proton Spectrum by CALET



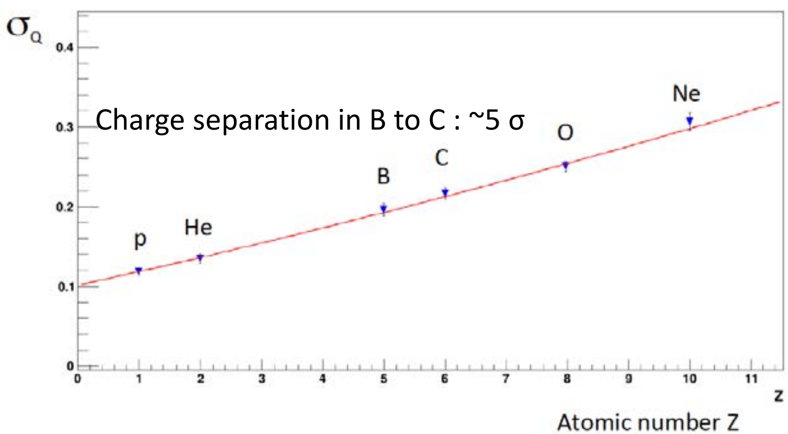
CALET Collaboration, Phys. Rev. Lett. **122**, 181102
Highlighted as " Editor's Suggestion"

Charge Identification with CHD and IMC

CHD charge resolution (2 layers combined) vs. Z

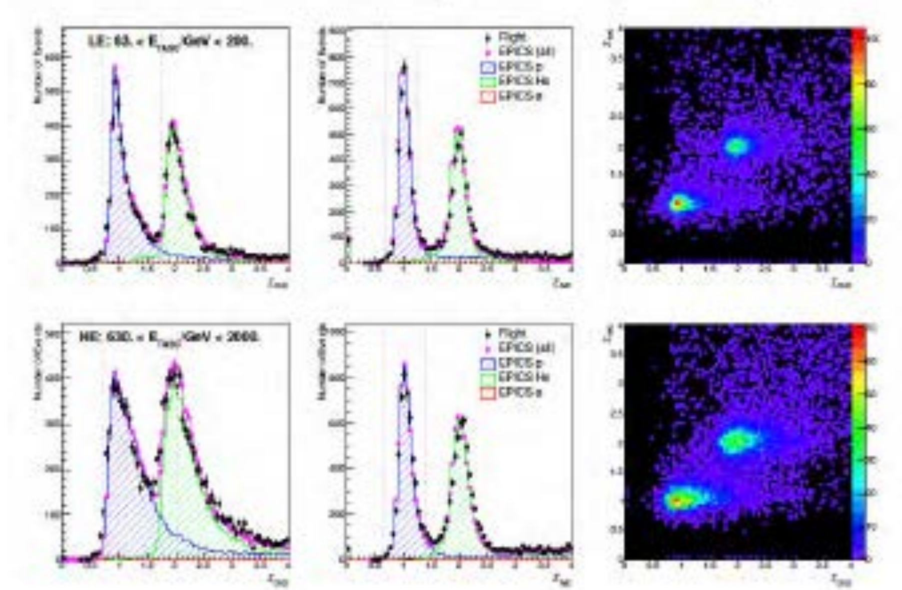


Charge resolution using multiple dE/dx measurements from the IMC scintillating fibers.

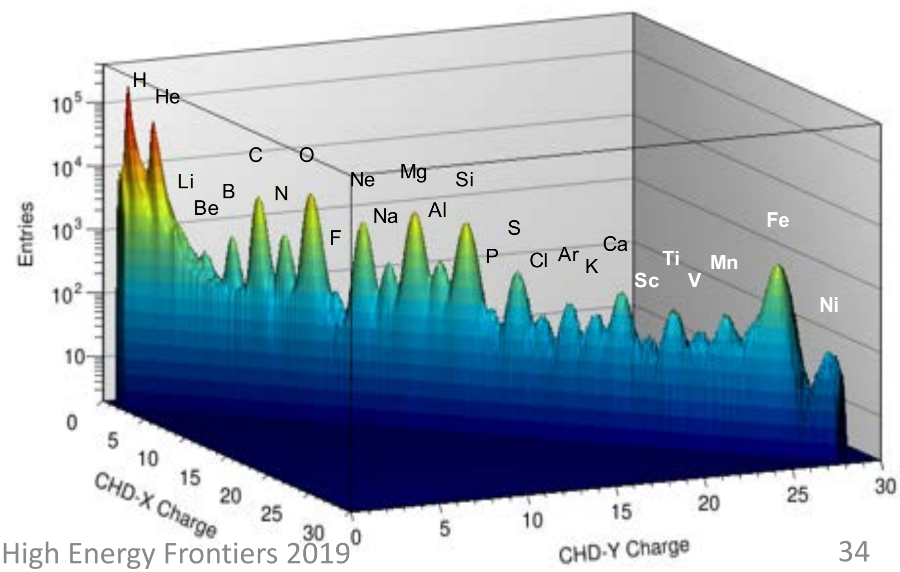


Non-linear response to Z^2 is corrected both in CHD and IMC using a core + halo ionization model (Volz).

Combined CHD-IMC proton-Helium charge-ID



CHDx-y charge-ID up to Z=28



Preliminary Flux of Primary Components

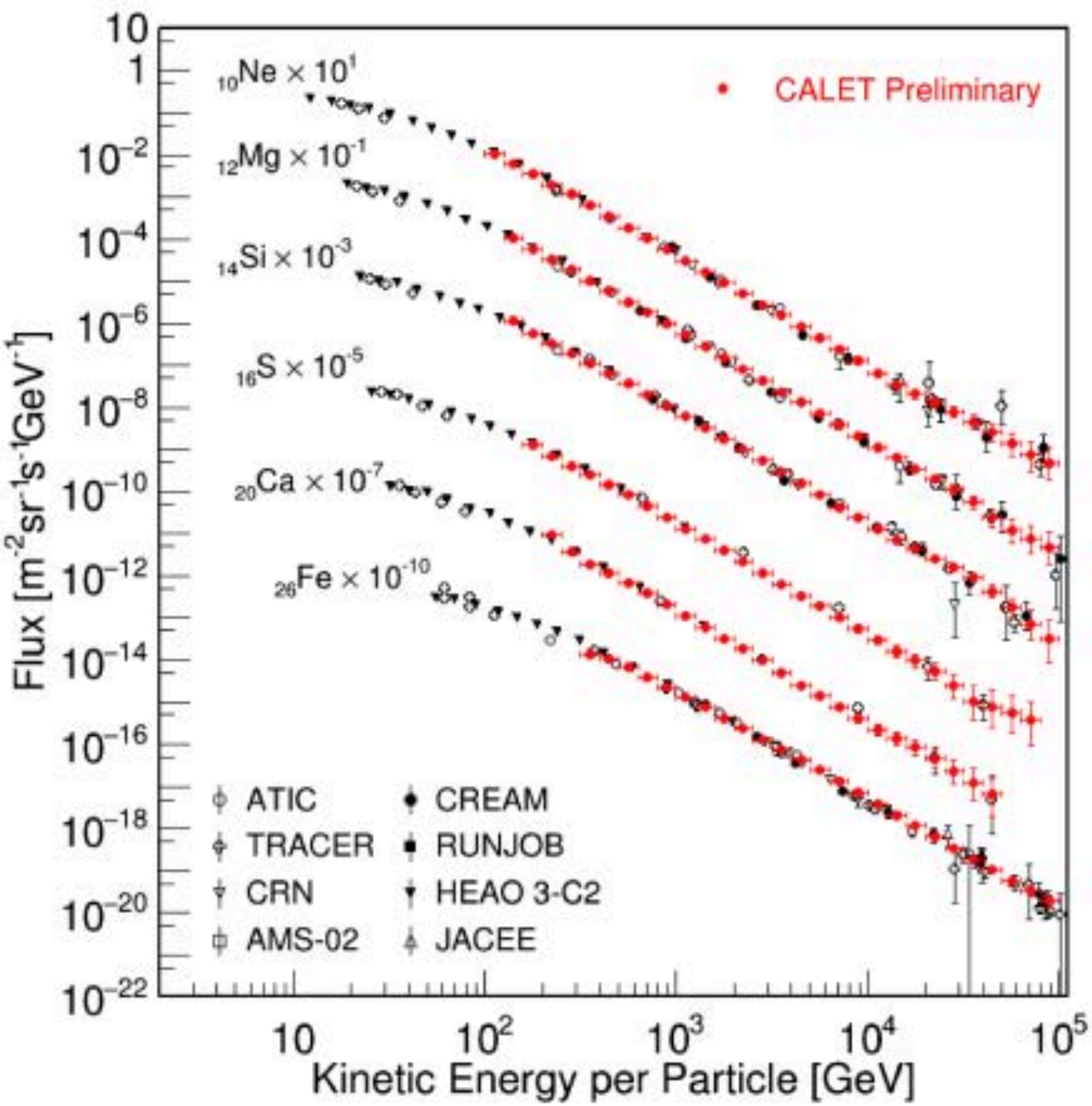
Flux measurements:

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

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

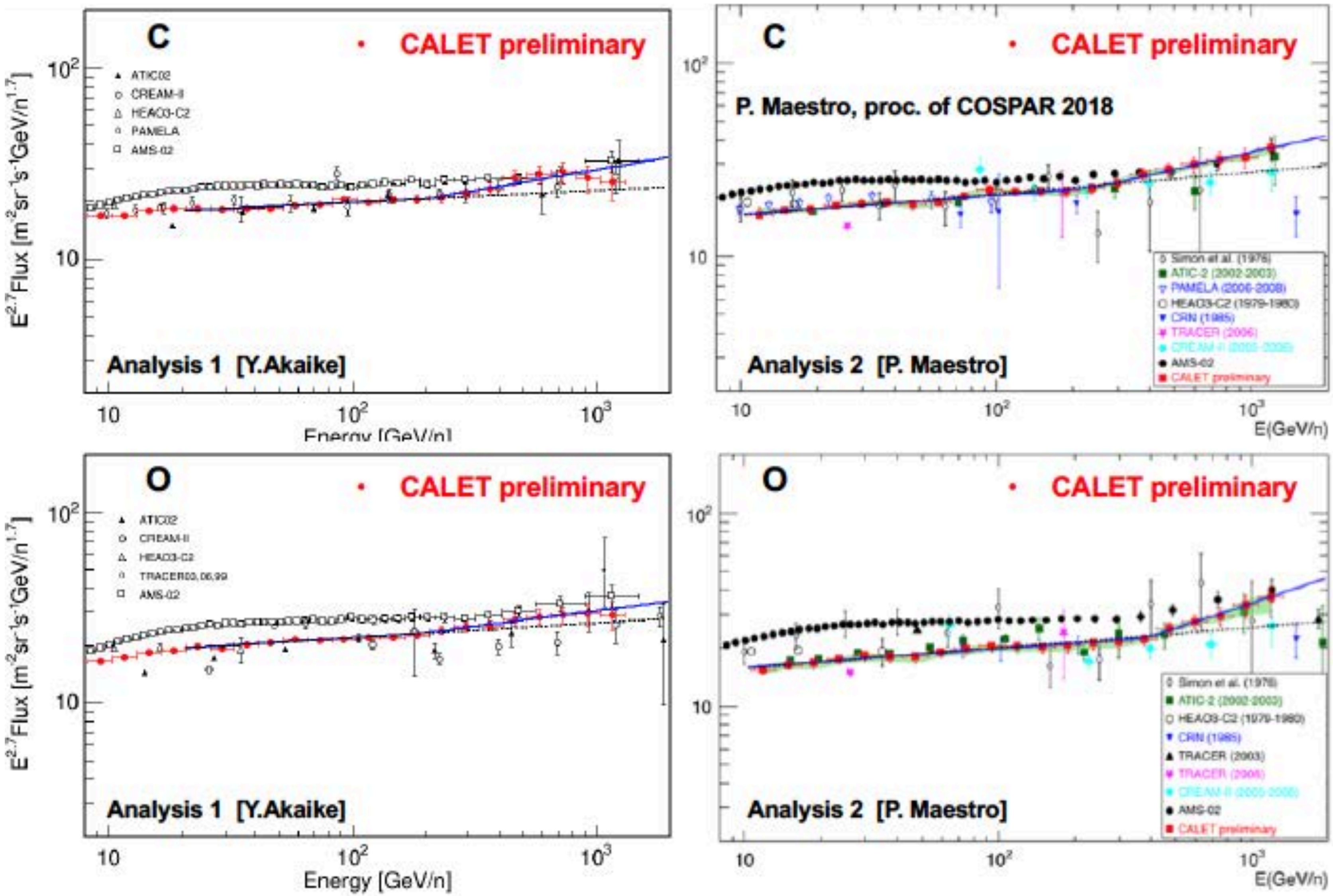
Observation period:
Oct.13 2015 – Dec.31 2018
(1,176 days)

6.8 x 10 ^{6} events (C-Fe ΔE>10 GeV)
[Y. Akaike et al., ICRC2019]



Preliminary Energy Spectra of Carbon and Oxygen

2 independent CALET analyses



Gamma-Ray Observation

Instrument characterized using EPICS simulations

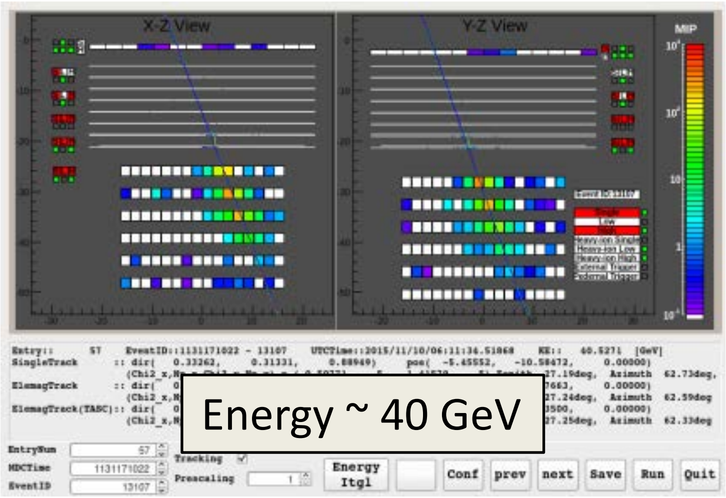
- Effective area ~400 cm^2 above 2 GeV
- Angular resolution < 2° above 1 GeV (< 0.2° above 10 GeV)
- Energy resolution ~12% at 1 GeV (~5% at 10 GeV)

Simulated IRFs consistent with 2 years of flight data

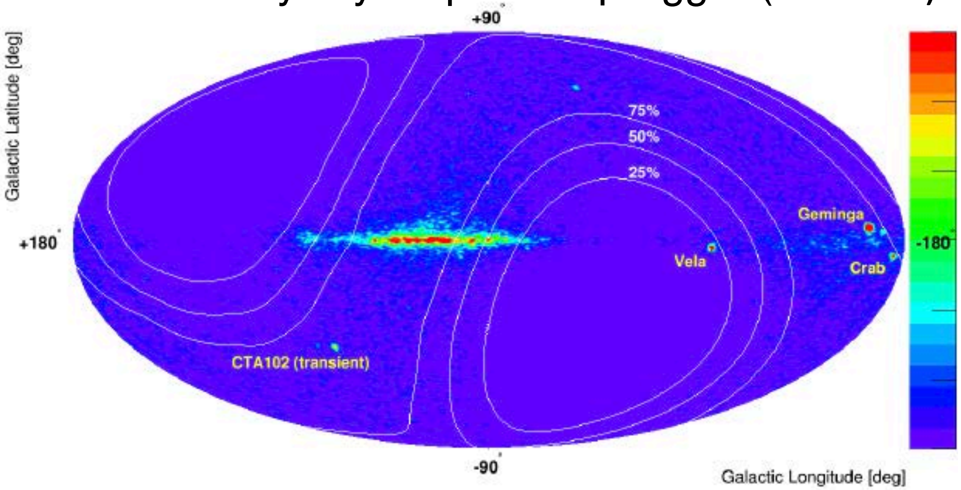
Consistency in signal-dominated regions with Fermi-LAT

Residual background in low-signal regions

Example of γ-ray event

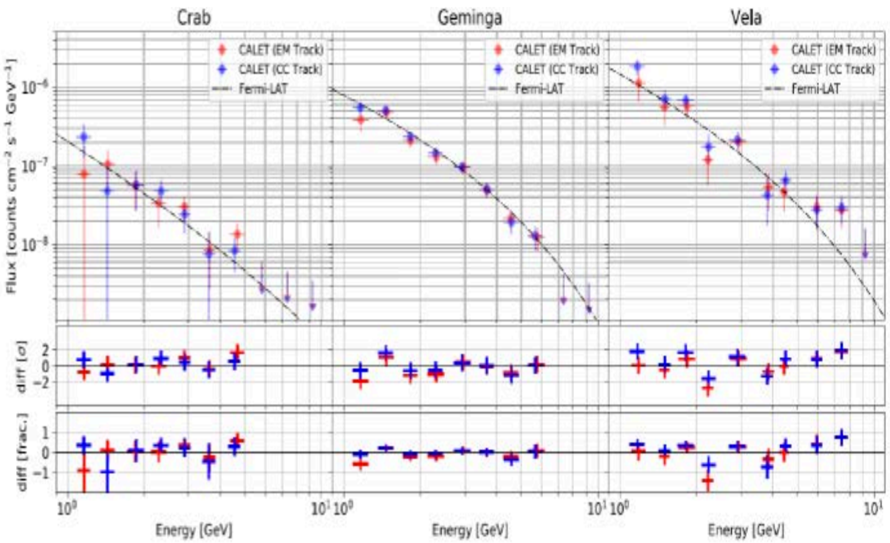


Gamma-ray sky map w/LE-γ trigger (E>!GeV)

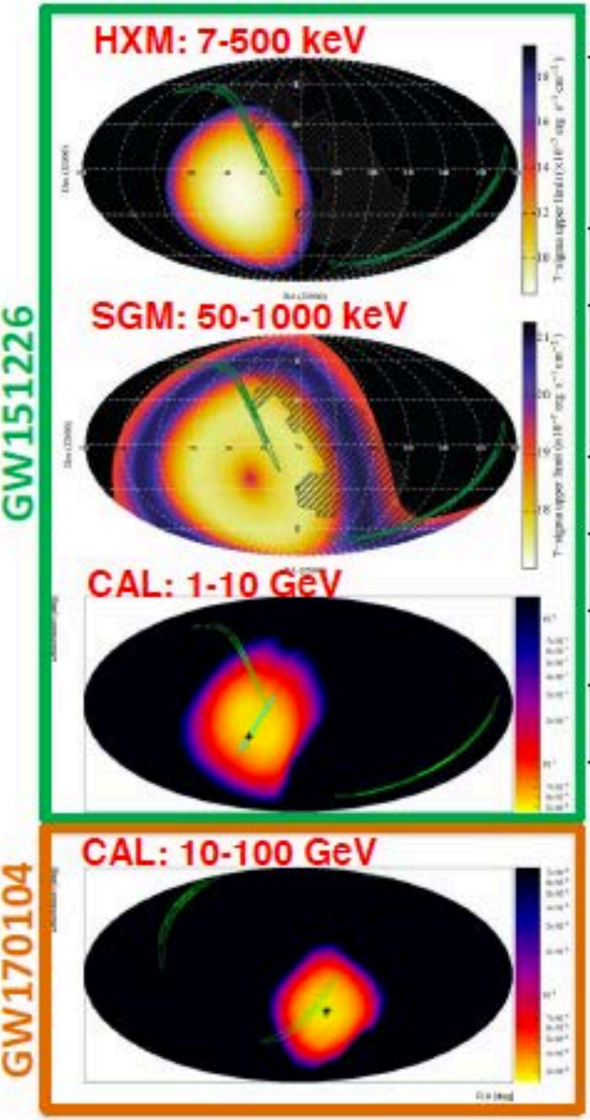


LE-γ mode, from 2015 November to 2018 May
(Contours show relative exposures)

Bright point-source spectra



Complete Search Results for GW Events during O1&O2



GW151226: O. Adriani et al. (CALET Collaboration), ApJL 829:L20 (2016).
All O1 & O2: O. Adriani et al. (CALET Collaboration), ApJ 863 (2018) 160.

Event	Type	Mode	Sum. LIGO prob.	Obs. time	Upper limits	
					Ene. Flux erg cm^{-2} s^{-1}	Lum. erg s^{-1}
GW150914	BH-BH	Before operation				
GW151226	BH-BH	LE HXM SGM	15%	T_0-525 – T_0+211	9.3×10^{-8} 1.0×10^{-6} 1.8×10^{-6}	2.3×10^{48} $3\text{-}5 \times 10^{49}$
GW170104	BH-BH	HE	30%	T_0-60 – T_0+60	6.4×10^{-6}	6.2×10^{50}
GW170608	BH-BH	HE	0%	T_0-60 – T_0+60	Out of FOV	
GW170814	BH-BH	HE	0%	T_0-60 – T_0+60	Out of FOV	
GW170817	NS-NS	HE	0%	T_0-60 – T_0+60	Out of FOV	

- CALET can search for EM counterparts to LIGO/Virgo triggers
- All O1 and O2 triggers checked – no signal in CGBM or CAL
- Upper limits set for GW151226 for CGBM+CAL in 2016 paper
- Upper limits for the CAL set using refined LE selection for triggers to-date in the 2018 paper

CALET: Summary and Future Prospects

- CALET was successfully launched on Aug. 19 th, 2015. The observation campaign started on Oct. 13th, 2015. Excellent performance and remarkable stability of the instrument.
- As of Oct.30, 2019, total observation time is 1449 days with live time fraction to total time close to 84%. **Nearly 2.0 billion events collected with low (> 1 GeV) + high energy (> 10 GeV) triggers**.
- Accurate calibrations have been performed with non-interacting p & He events + linearity in the energy measurements established up to 10^6 MIPs.

CAL

- Following results have been obtained by now.
  - Measurement of **electron + positron spectrum in 11 GeV- 4.8 TeV.**
  - Direct measurement **of proton spectrum in 50 GeV- 10 TeV energy range**, spectral hardening observed above a few hundred GeV.
  - **Preliminary analysis of primary elements up to Fe**.
  - Study of diffuse and point sources of gamma-rays. **Follow-up observations of GW events** in X-ray and gamma-ray bands.
- After an initial period of 2 years, CALET observation time has been to 5.5 years at least.

*) This work is partially supported by JSPS KAKENHI Kiban(S) Grant Number 19H05608 (2019-2024).


CALET
Thank you
for your attention !