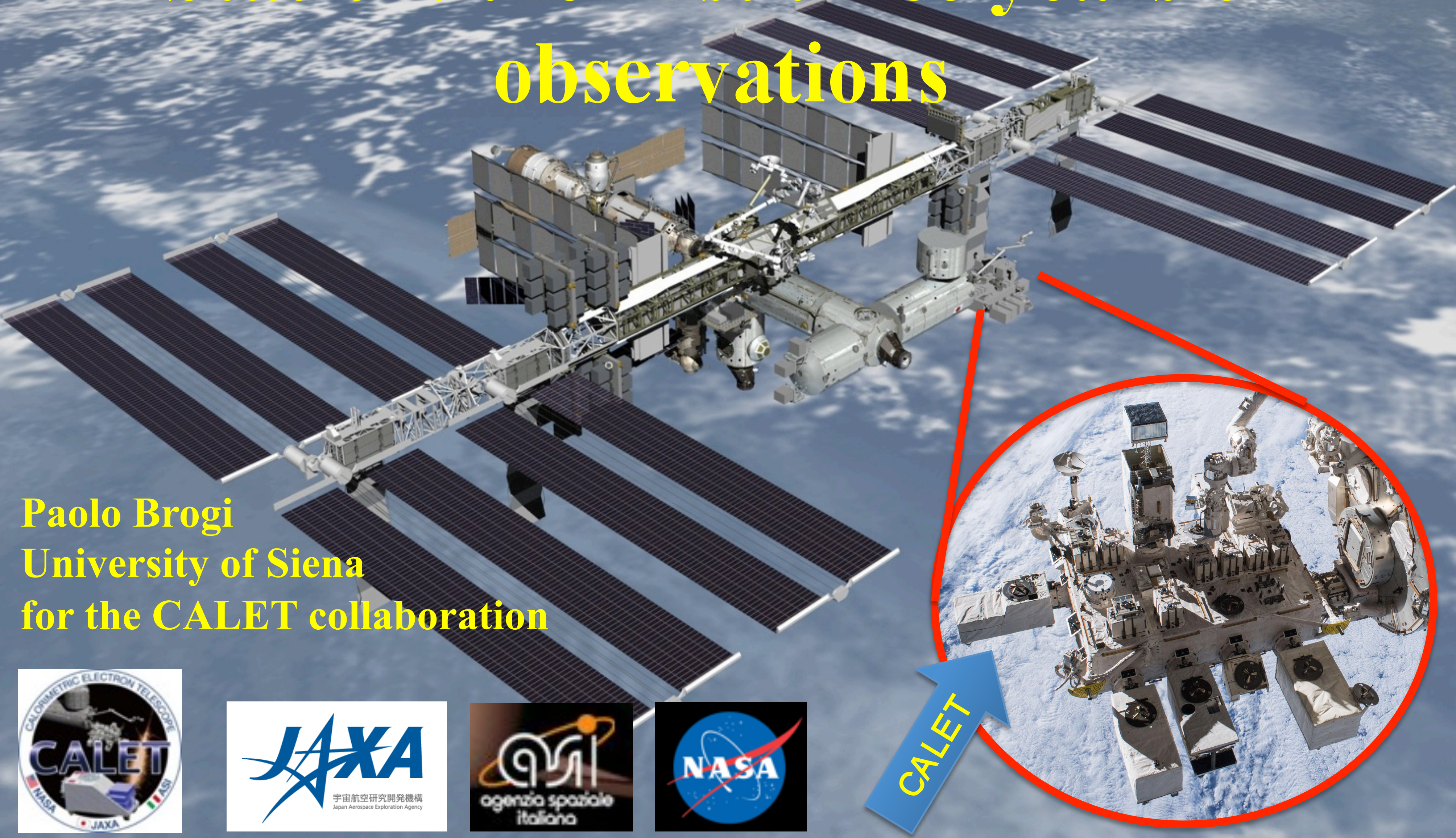
CALET on the International Space Station: the first three years of observations



Paolo Brogi
University of Siena
for the CALET collaboration

The CALET Collaboration Team

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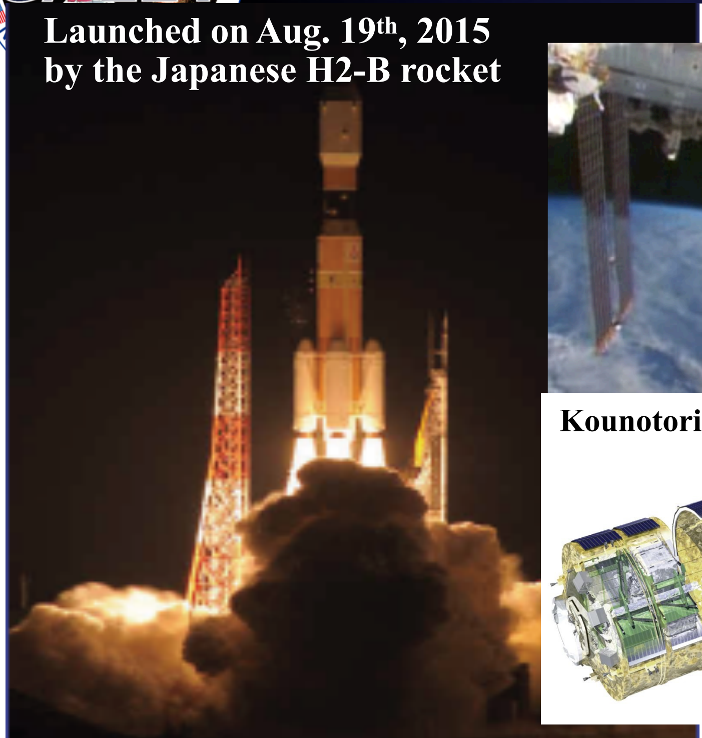
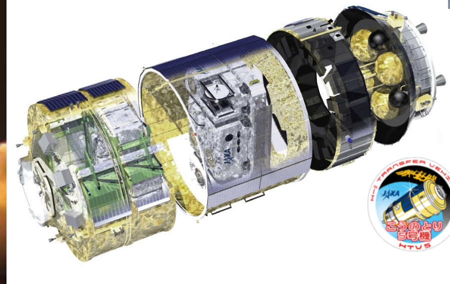
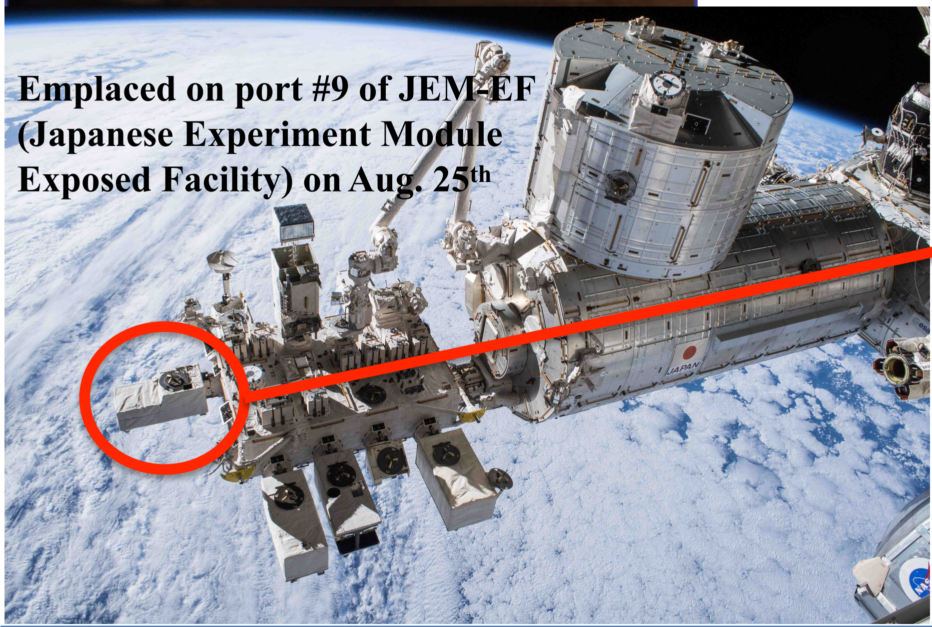
6) Ibaraki University, Japan
7) ICRR, University of Tokyo, Japan
8) ISAS/JAXA Japan
9) JAXA, Japan
10) Kanagawa University, Japan
11) Kavli IPMU, University of Tokyo, Japan
12) KEK, Japan
13) Louisiana State University, USA
14) Nagoya University, Japan
15) NASA/GSFC, USA
16) National Inst. of Radiological 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

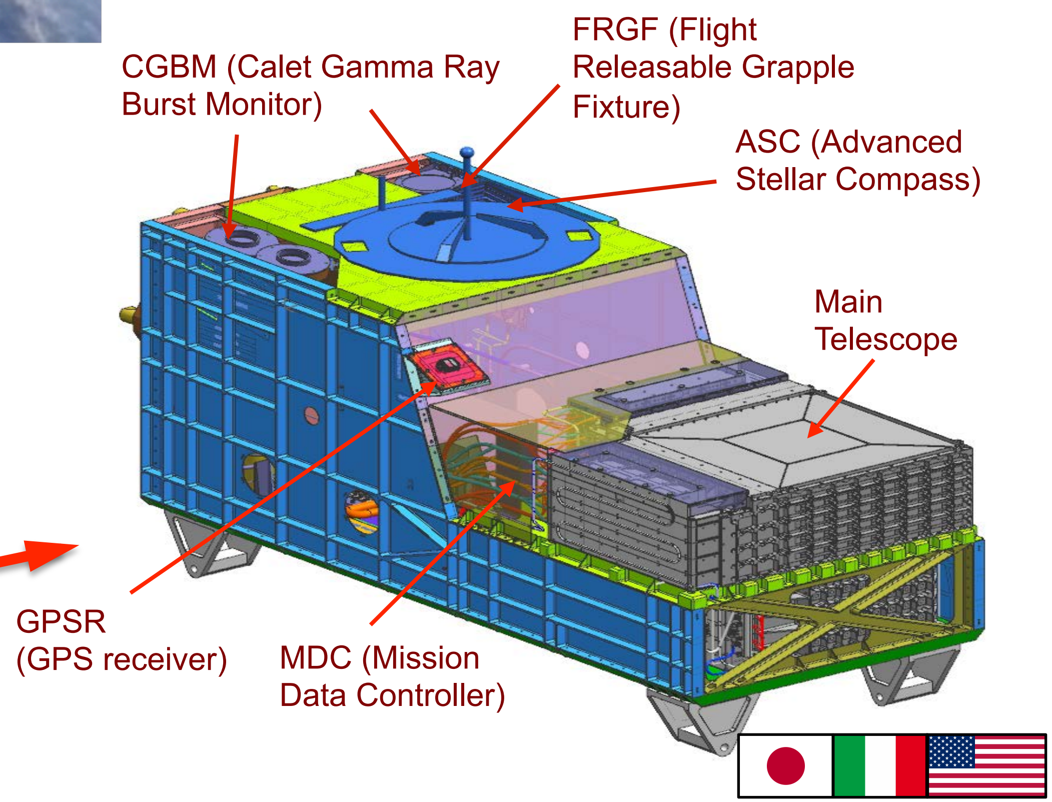
CALET payload


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


Kounotori (HTV) 5

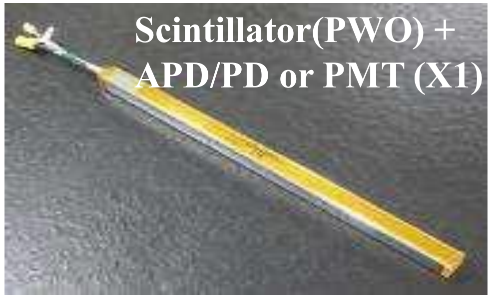
- Mass: 612.8 kg (JEM Standard Payload)
- Size: 1850mm (L) × 800mm (W) × 1000mm (H)
- Power: 507 W (max)
- Telemetry: Medium 600 kbps (6.5GB/day)


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

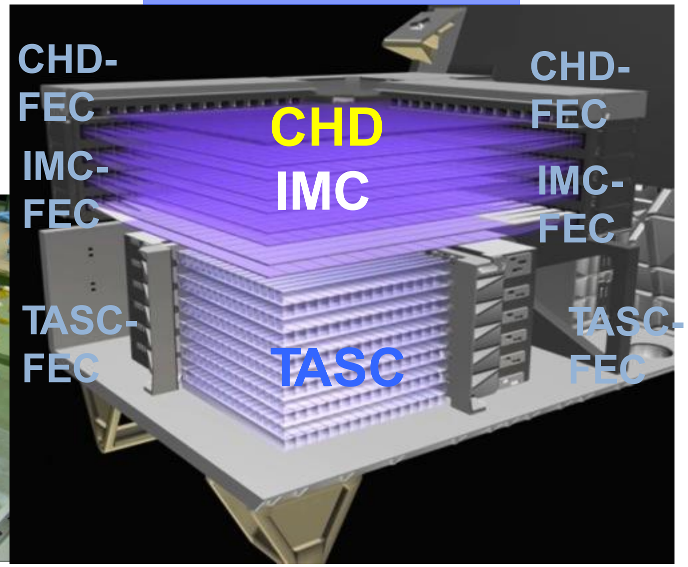


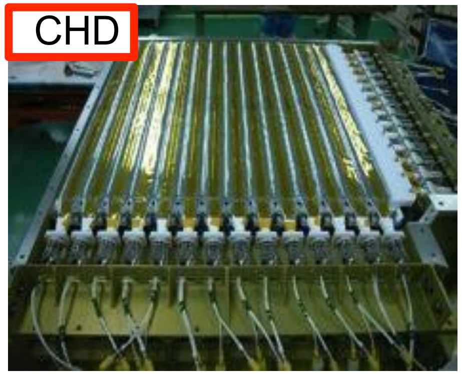
Continues stable observation since Oct. 13, 2015 and collected ~1.8 billion events so far.

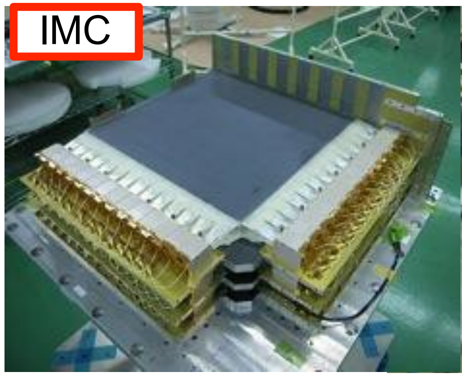
Detector overview



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 mm³**	**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 mm³**	**16 PWO logs x 12 layers (x,y): 192 logs log size: 19 x 20 x 326 mm³ 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 overview

Overview of detector performances:

Geometric Factor :
1200 cm^2sr for electrons, light nuclei
1000 cm^2sr for gamma-rays
4000 cm^2sr for ultra-heavy nuclei

- **ΔE/E** :
  ~2% (>10 GeV) for e, gamma
  ~30-35 % for protons, nuclei
- **e/p separation** : 10^{-5}
- **Charge resolution** : 0.15 - 0.3 e
- **Angular resolution** :
  0.2° for gamma-rays > ~50 GeV

Main CALET science objectives:

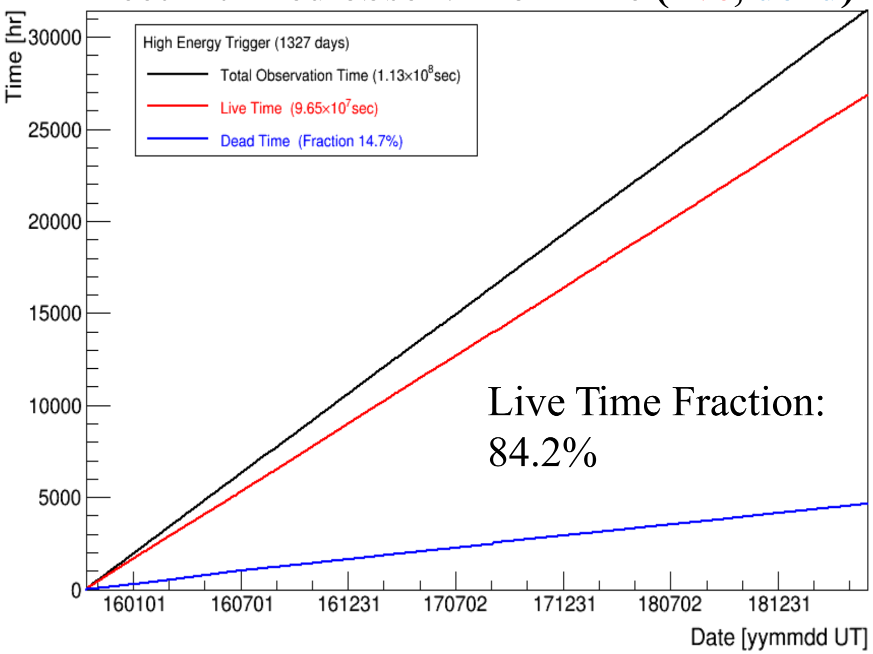
- ◆ Electron observation in the 1 GeV - 20 TeV energy range. Design optimized for electron detection: high energy resolution and large e/p separation power + e.m. shower containment.
  - Search for Dark Matter and Nearby Sources
- ◆ Observation of cosmic-ray nuclei in the 10 GeV - 1 PeV energy range.
  - Unraveling the CR acceleration and propagation mechanism(s)
- ◆ Detection of transient phenomena in space Gamma-ray bursts, e.m. GW counterparts, Solar flares, Space Weather

Scientific Objectives	Observation Targets	Energy Range
CR Origin and Acceleration	Electron spectrum Individual spectra of elements from proton to Fe 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

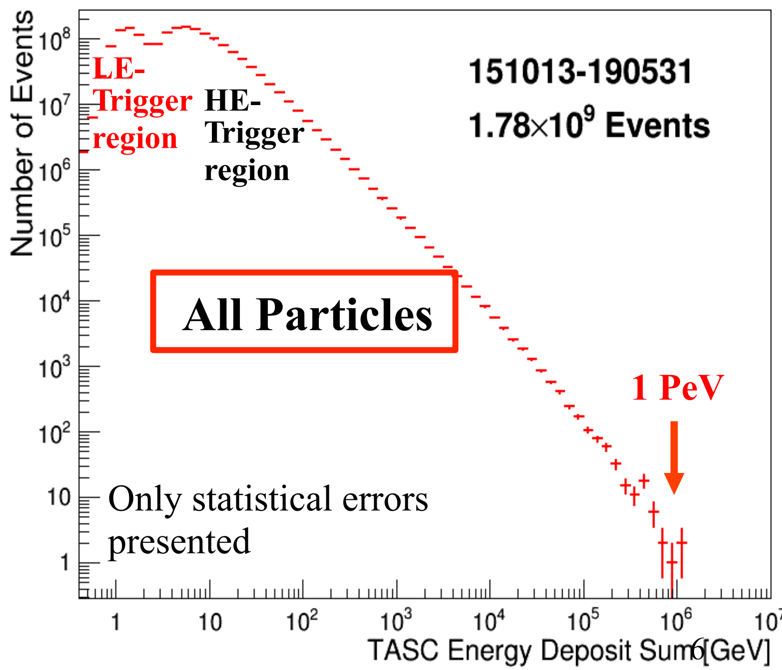
High-Energy Triggered events

- Observation with High Energy Trigger for 1327 days : Oct.13, 2015 – May 31, 2019
- The exposure, SΩT, has reached ~116 m^2 sr day for electron observations under continuous and stable operations.
- Total number of triggered events is ~1.8 billion with a live time fraction of ~84 %.

Accumulated observation time (live, dead)



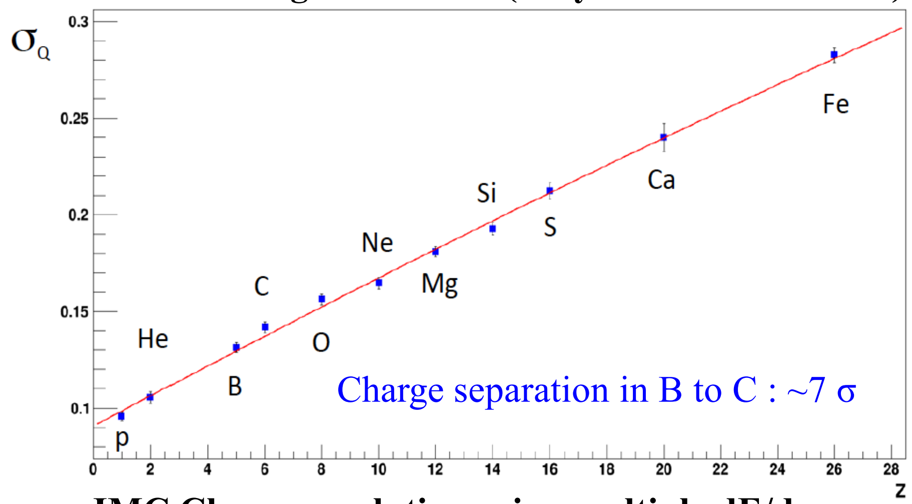
Distribution of deposit energies (ΔE) in TASC



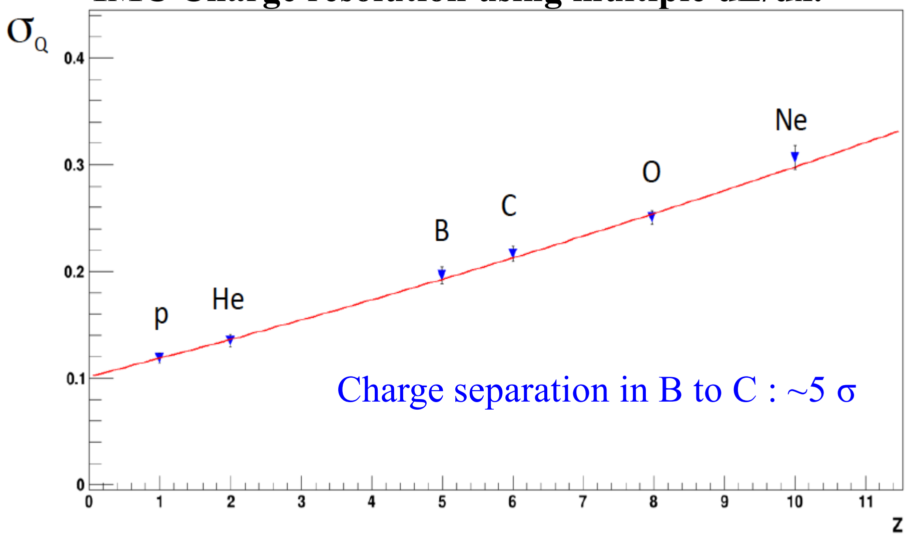
Charge identification of Nuclei

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

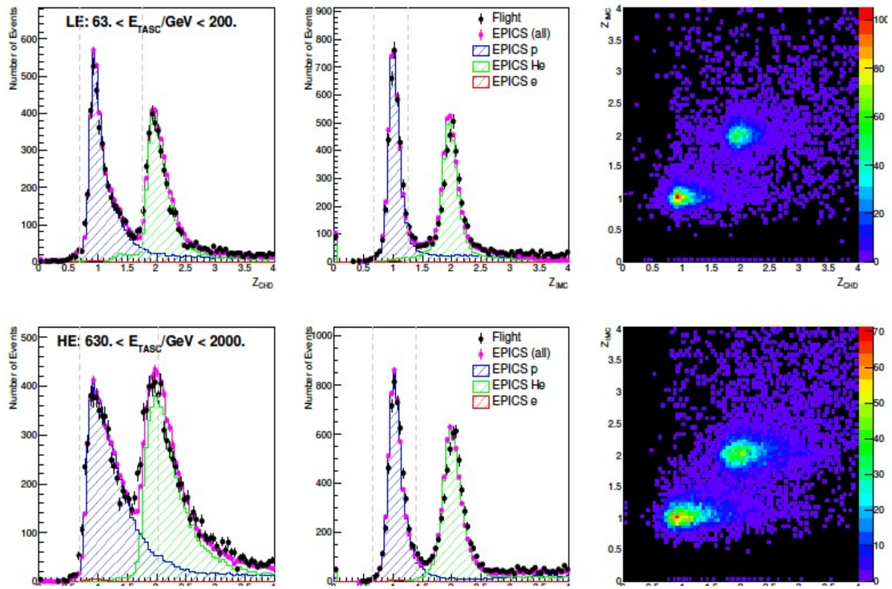
CHD charge resolution (2 layers combined vs. Z)



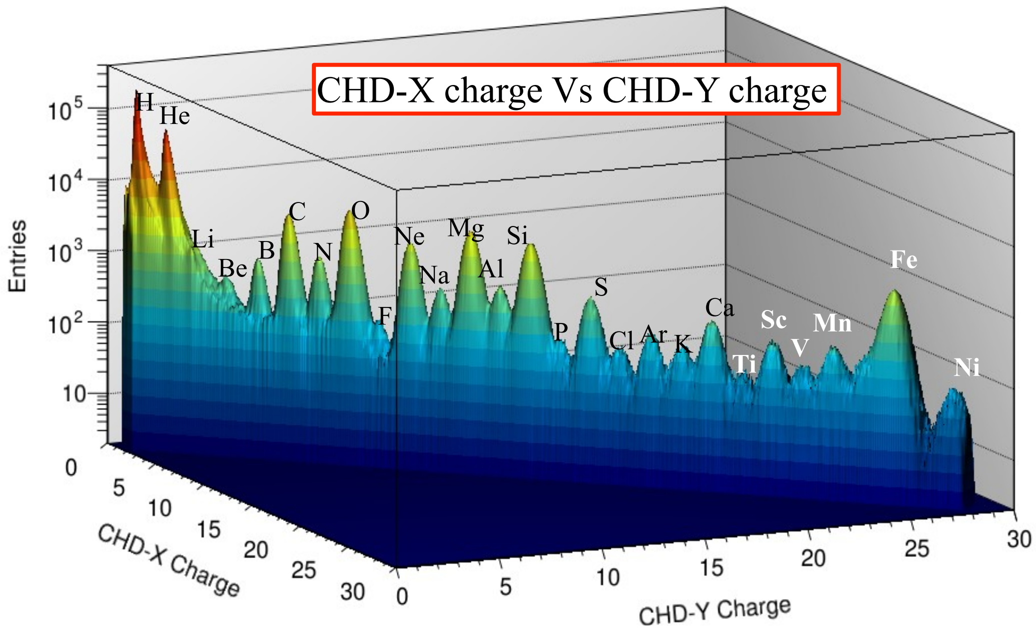
IMC Charge resolution using multiple dE/dx.



Combined CHD-IMC proton-Helium charge-ID



CHD-X charge Vs CHD-Y charge



Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

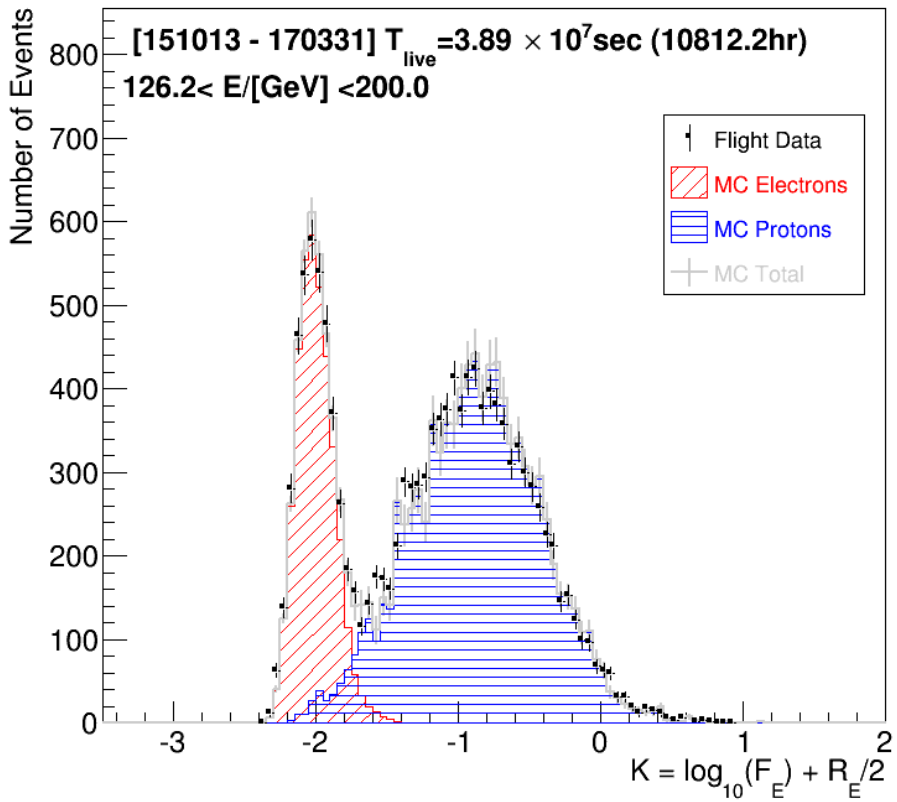
Electron Identification

Simple Two Parameter Cut

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

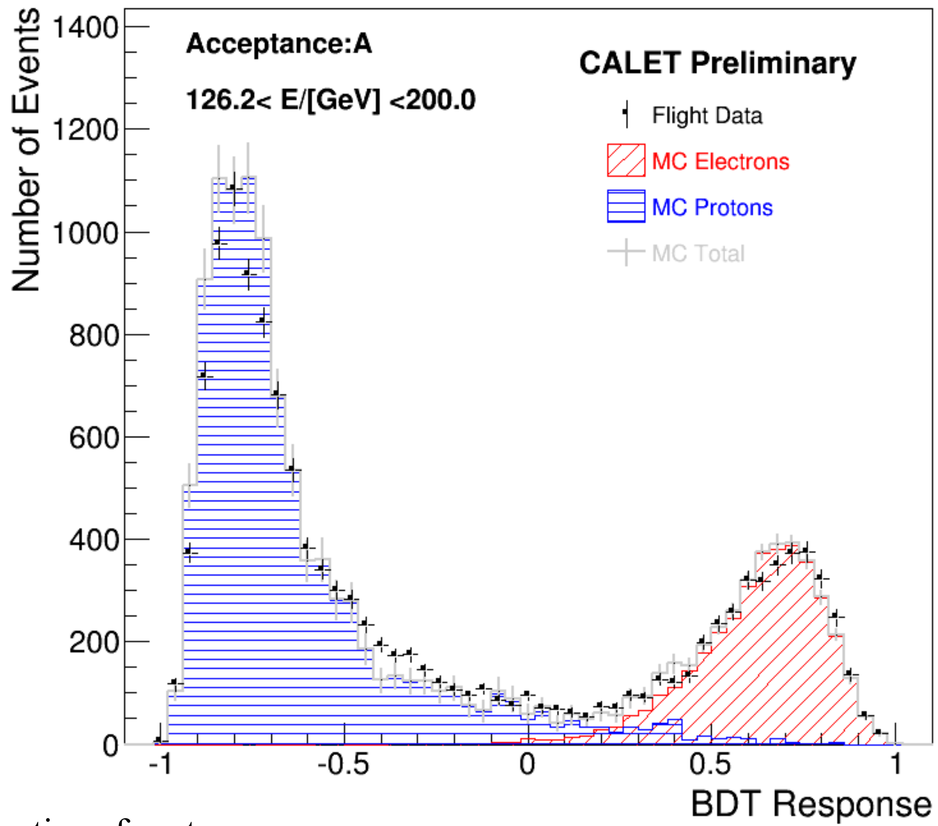
R_E: Lateral spread of energy deposit in TASC-X1

K cut parameter: $\log_{10}(F_E) + 0.5\ R_E$ (/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.

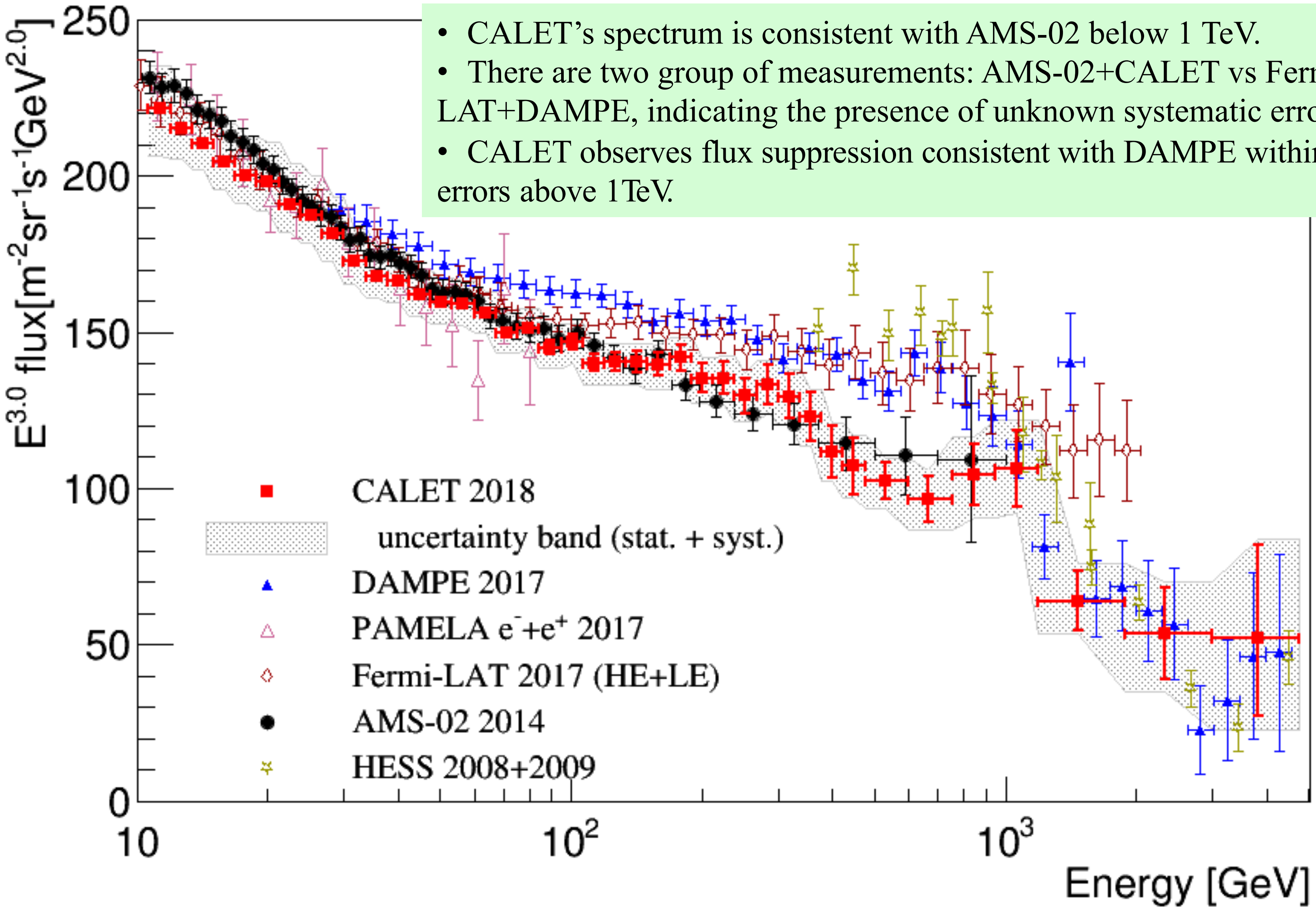


- In the final electron sample, the resultant contamination ratios of protons are: 5% up to 1 TeV; 10% - 20% in the 1 - 4.8 TeV region, keeping a constant efficiency of 80% for electrons.
- Simple **K** cut is used in the low energy region (< 500 GeV) while the difference in resultant spectrum are taken into account in the systematic uncertainty.

All Electron Spectrum by CALET

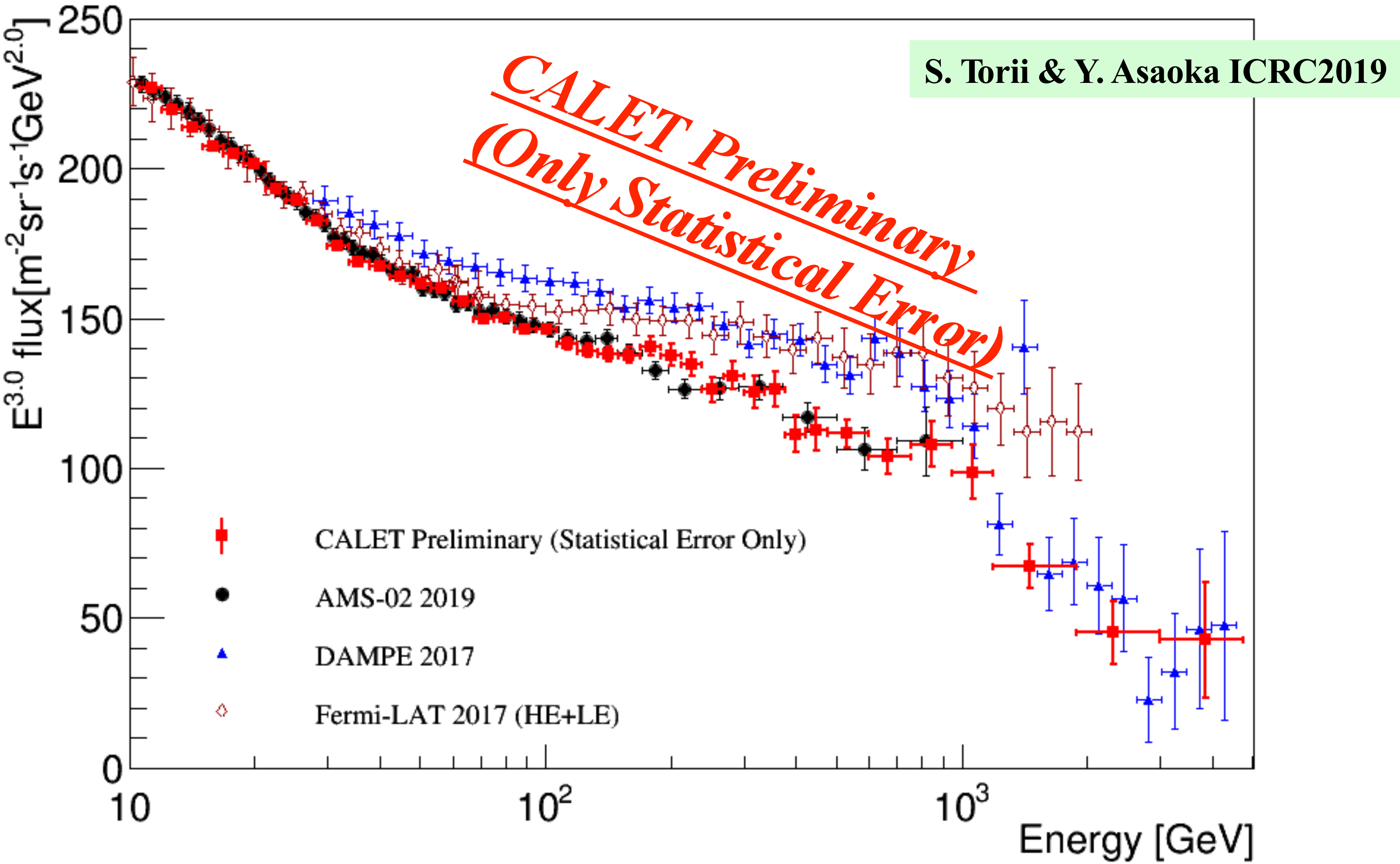
CALET: Phys.Rev.Lett. 120 (2018) 261102 (~ 2 x PRL2017)

- CALET's spectrum is consistent with AMS-02 below 1 TeV.
- There are two group of measurements: AMS-02+CALET vs Fermi-LAT+DAMPE, indicating the presence of unknown systematic errors.
- CALET observes flux suppression consistent with DAMPE within errors above 1TeV.



All Electron Spectrum: Extended Measurement

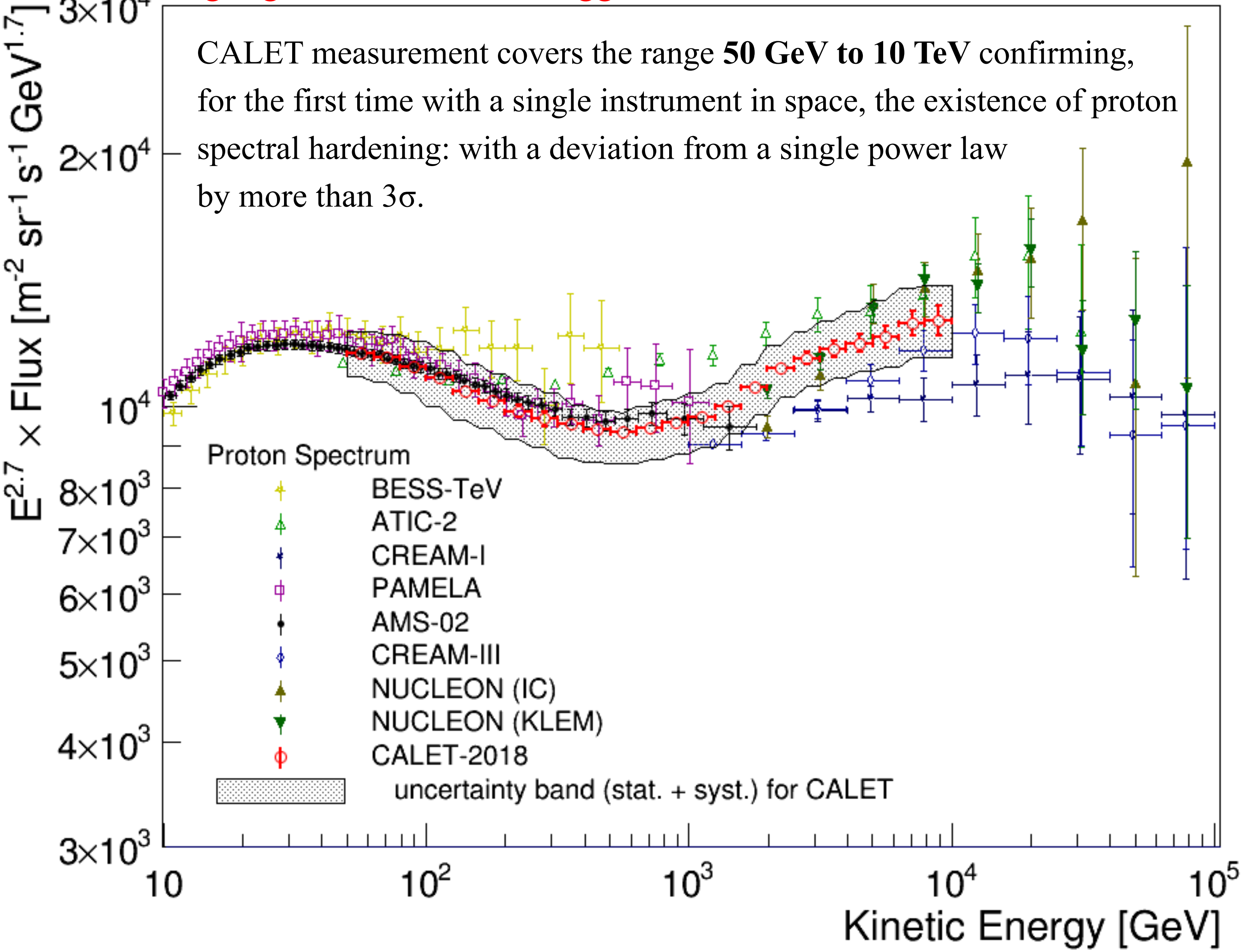
It is applied exactly the same analysis shown in the previous slide, but data up to the end of May 2019 are used:



Cosmic-Ray Proton Spectrum

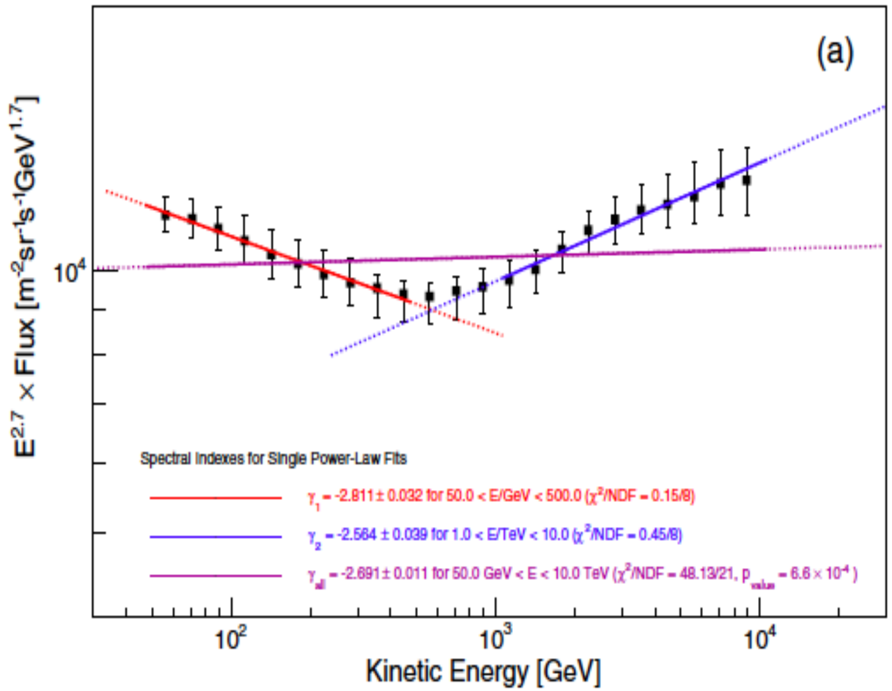
The CALET Collaboration, Phys. Rev. Lett. **122**, 181102
Highlighted as "Editor's Suggestion"

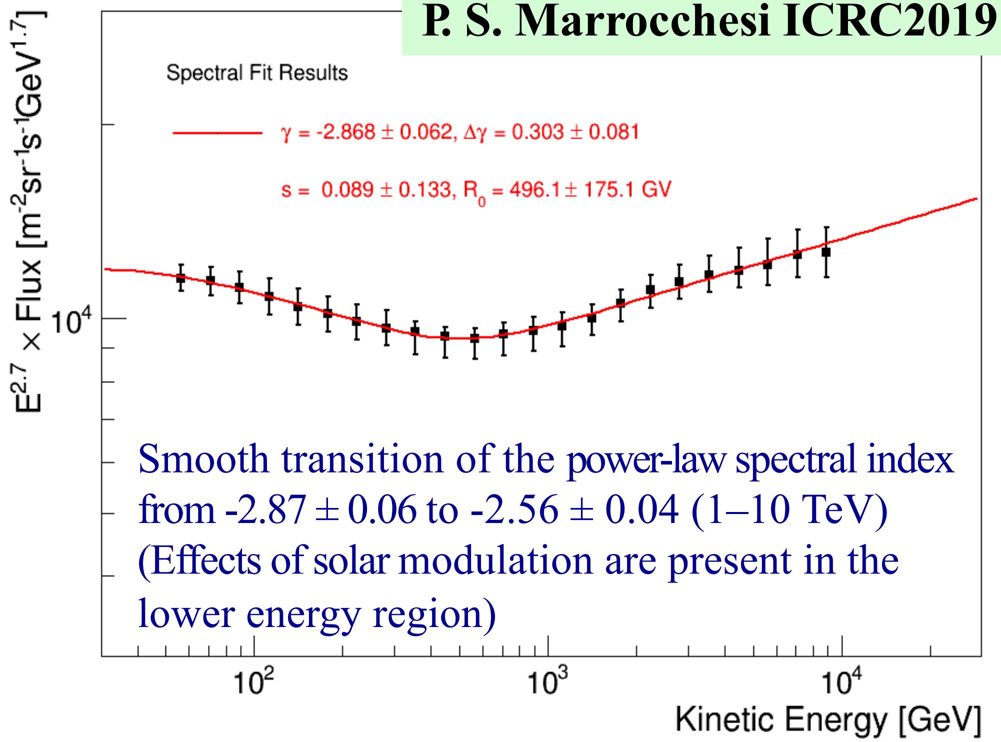
CALET measurement covers the range **50 GeV to 10 TeV** confirming, for the first time with a single instrument in space, the existence of proton spectral hardening: with a deviation from a single power law by more than 3σ.



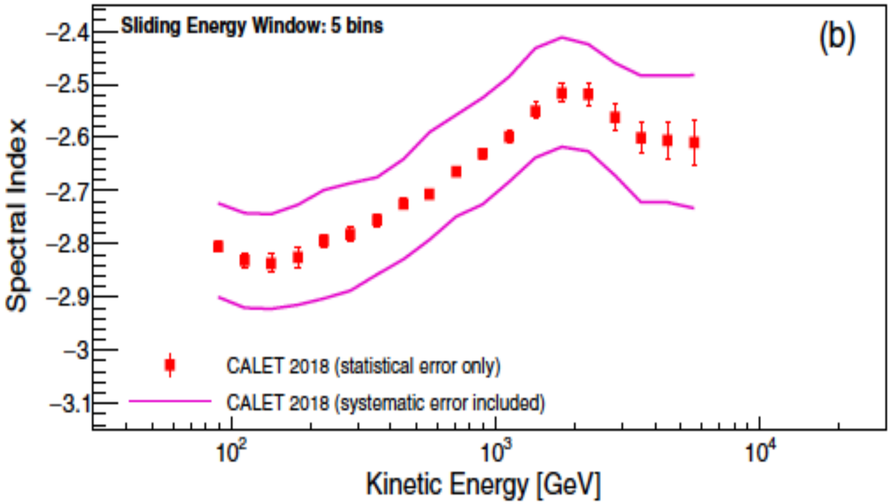
Spectral Behavior of Proton Flux

P. S. Marrocchesi ICRC2019





Smooth transition of the power-law spectral index from -2.87 ± 0.06 to -2.56 ± 0.04 (1–10 TeV) (Effects of solar modulation are present in the lower energy region)

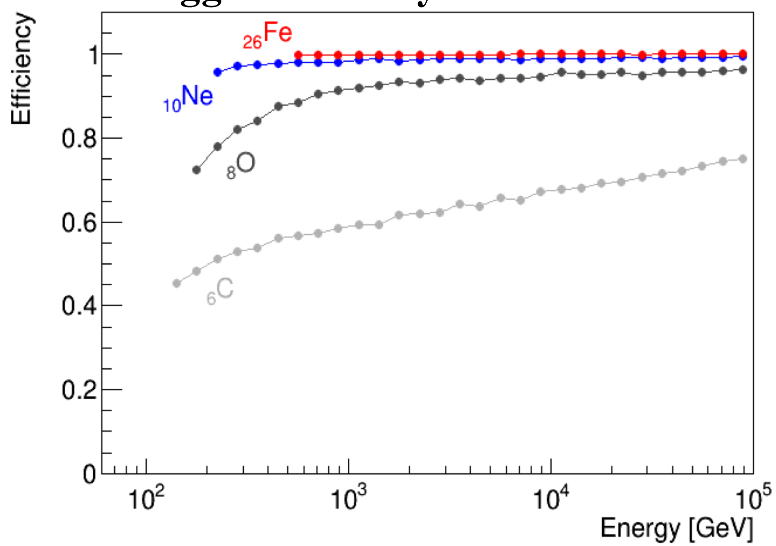


- Sub-ranges of 50-500GeV, 1-10TeV can be fitted with single power law function, but not the whole range (significance > 3σ).
- Progressive hardening up to the TeV region was observed.
- “Smoothly broken power-law fit” gives power law index consistent with AMS-02 in the low energy region, but shows larger index change and higher break energy than AMS-02.

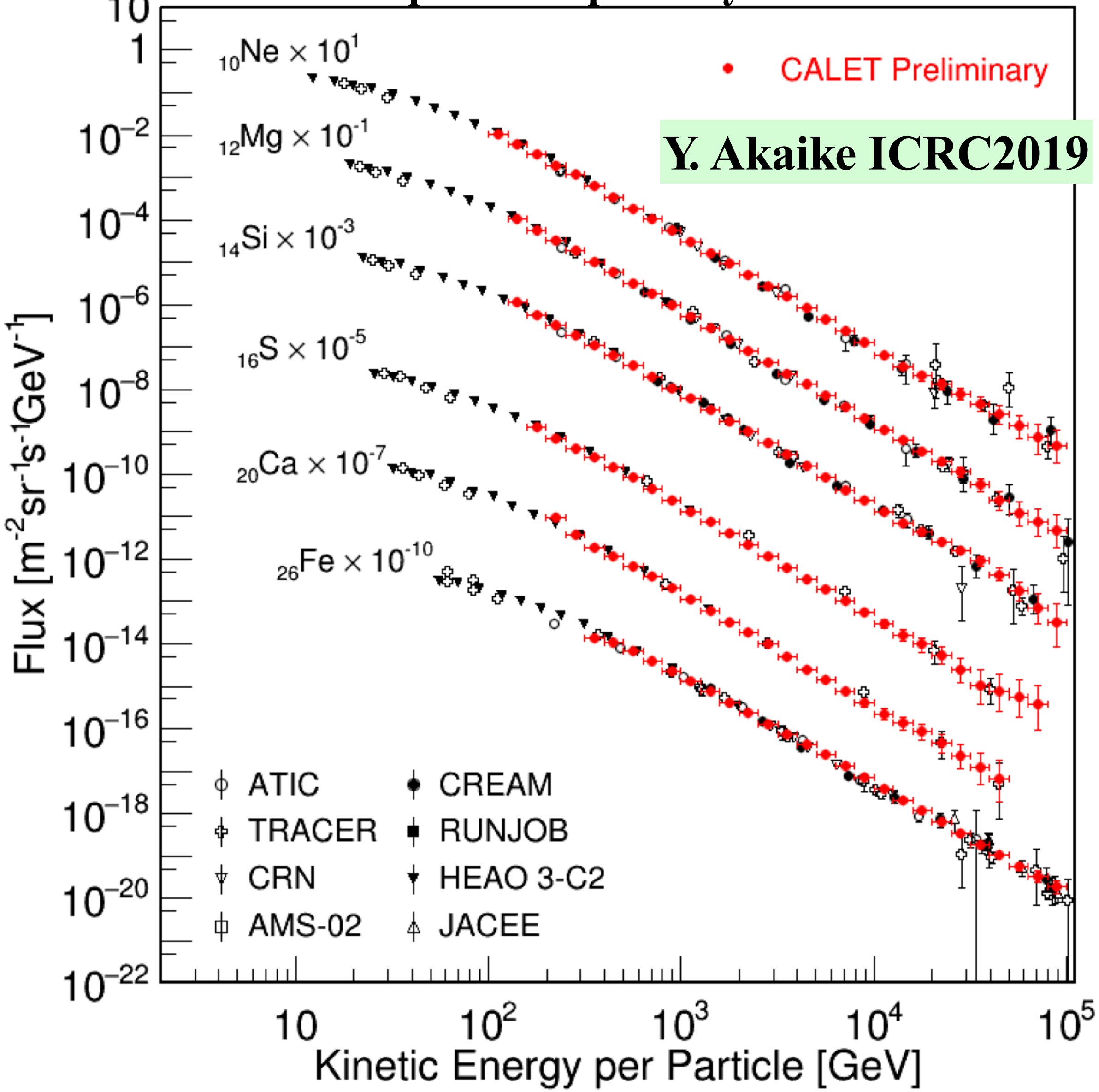
Preliminary Spectra of Primary Components

Observation period:
Oct.13 2015 – Dec.31 2018 (1176 days)

HE Trigger efficiency for several nuclei

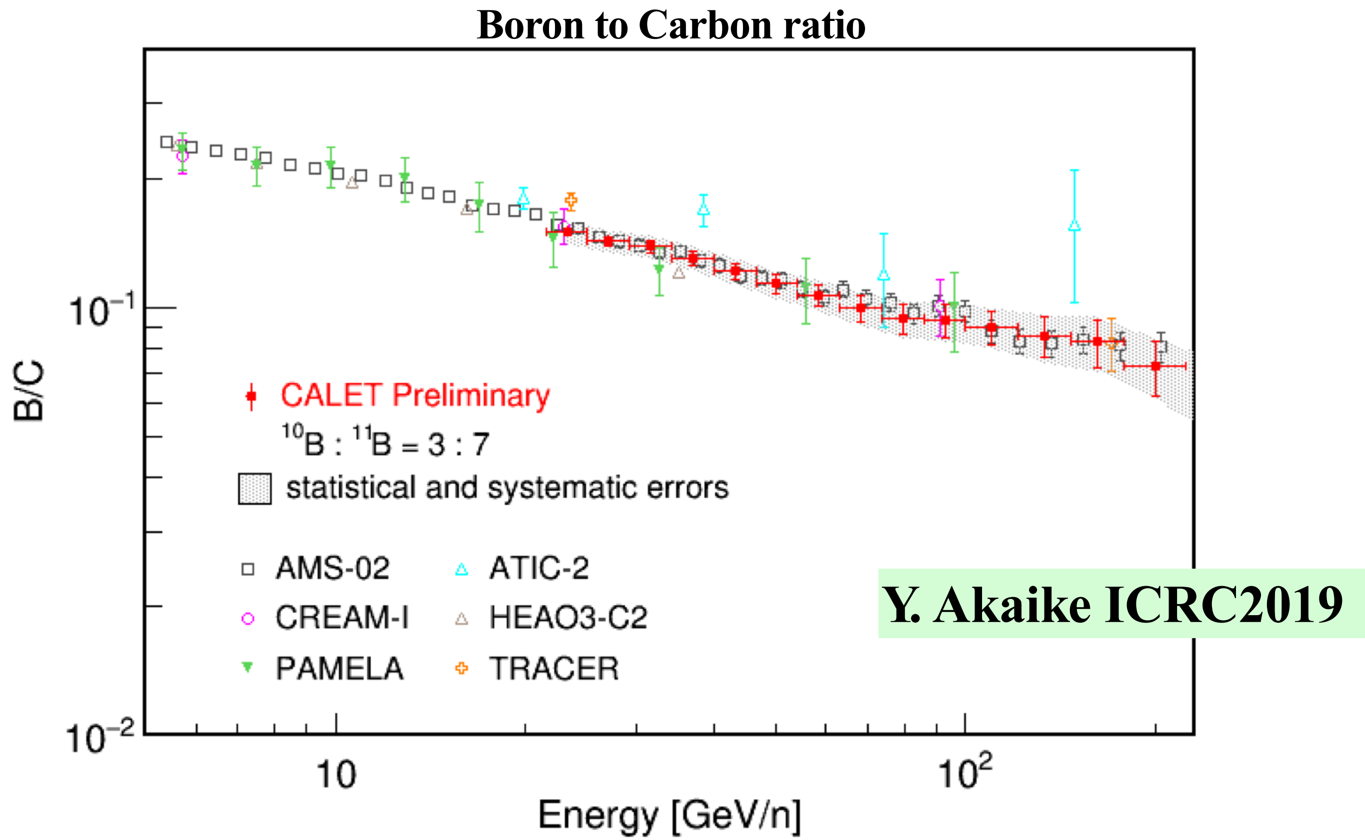


Spectra of primary CRs



Boron-to-Carbon ratio

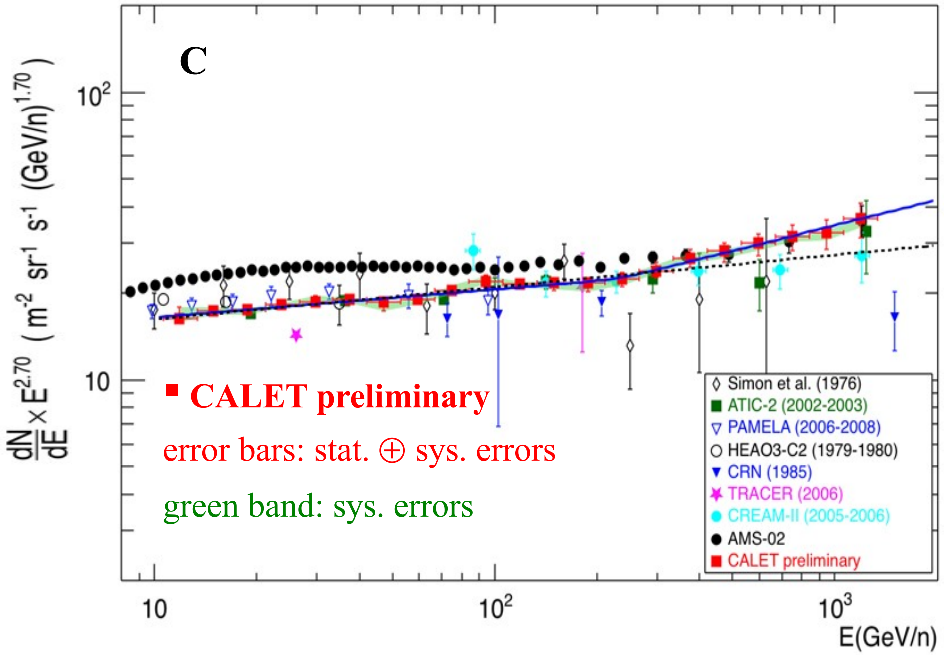
UNIVERSITÀ DI SIENA 1240

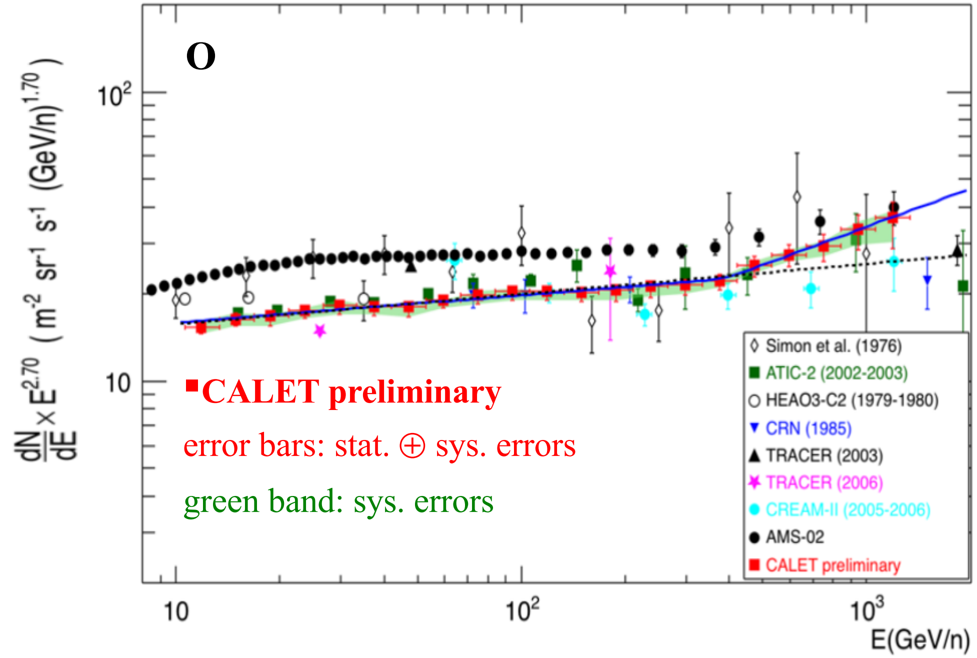


Source of systematic uncertainties:

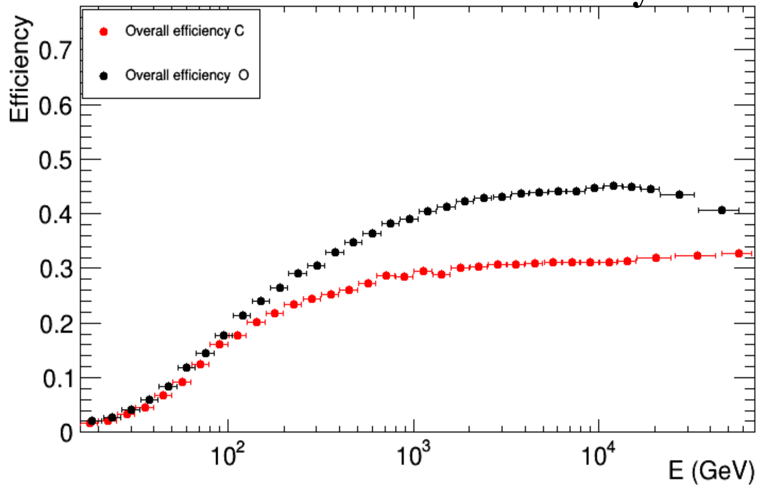
- Trigger efficiency;
- Charge consistency cuts;
- Track width selection;
- Window range for charge identification;
- Background model of p and He spectra;
- Initial prior spectra of energy unfolding;
- Energy correction with beam test results;
- Difference of beam test model and flight model;
- Long term stability;

Preliminary Flux of Carbon and Oxygen





C and O overall efficiency



P. Maestro ICRC2019

- Preliminary evaluation of systematics errors include uncertainties in trigger efficiency, acceptance, event selection efficiencies, unfolding.
- Additional sources (energy scale, hadronic interaction models) are being investigated.

Measurements of Ultra Heavy Nuclei

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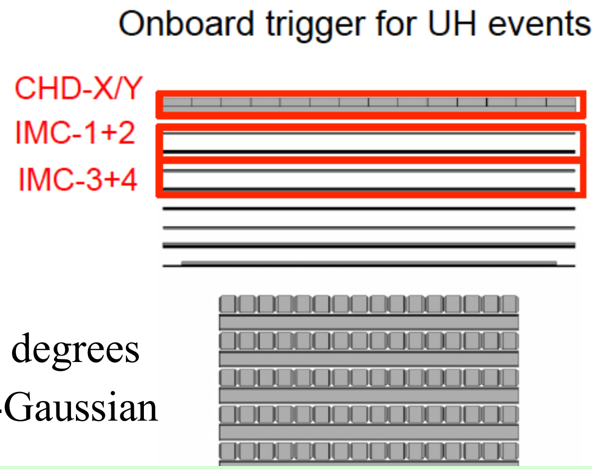
- CALET measures the relative abundances of ultra heavy nuclei (Z>26) up to Z = 40 (Zr)
- Trigger for ultra-heavy nuclei:

  CHD, IMC1+2 and IMC3+4 are required

  ⇒ an expanded geometrical acceptance (4000 $cm^2 sr$)
- Energy threshold depends on the geomagnetic cutoff rigidity

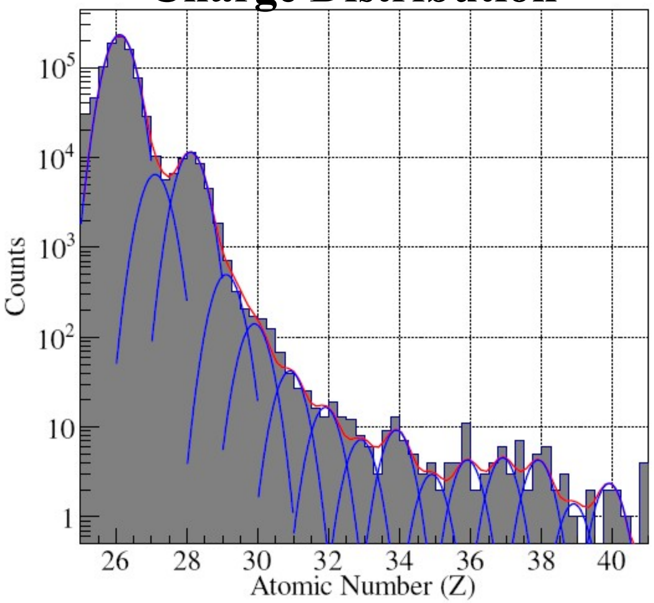


Data analysis:

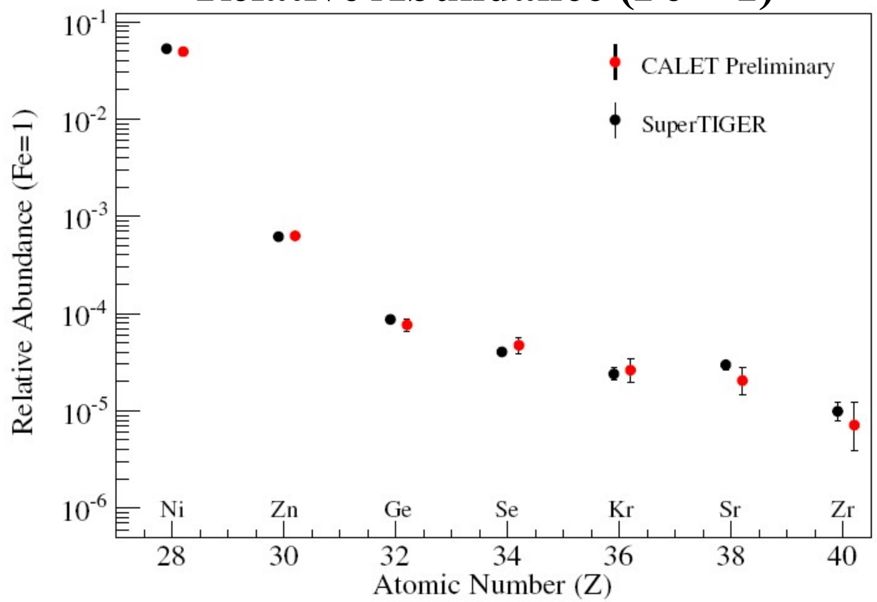
- Event Selection: Vertical cutoff rigidity > 4 GV & Zenith Angle < 60 degrees
- Contamination from neighboring charge are determined by multiple-Gaussian function

B.F. Rauch & W.R. Binns ICRC2019

Charge Distribution



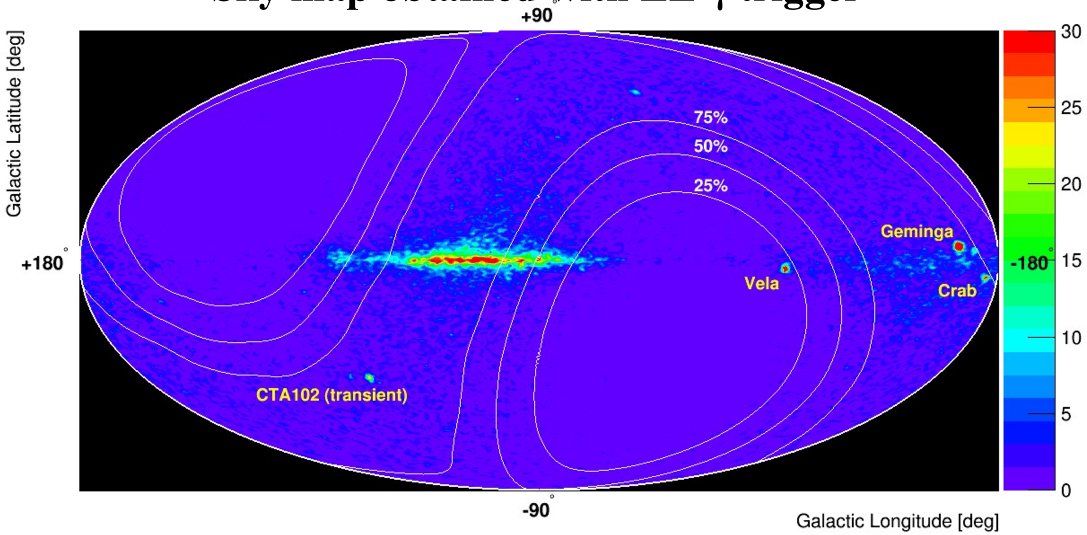
Relative Abundance (Fe = 1)



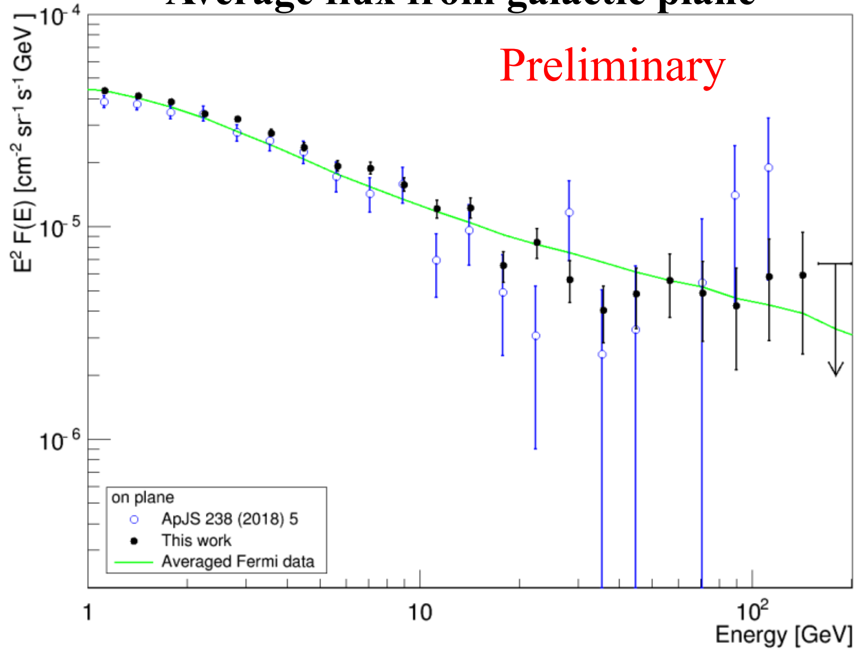
Gamma-Ray Observations

M. Mori & Y. Asaoka ICRC2019

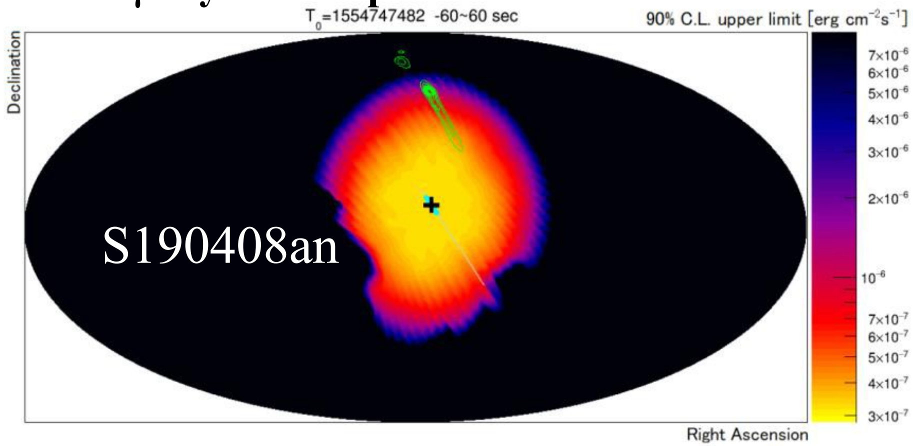
Sky map obtained with LE-γ trigger



Average flux from galactic plane



GeV γ-ray counterpart search for GW events



Upper limits (U.L.) are given in **erg*cm^{-2}s^{-1}** for the energy range 10-100 GeV except for those marked with † which are for 1-10 GeV

Summary of CALET/CAL γ-ray observations on GW candidates

GCN No.	LIGO/Virgo trigger	Trigger time T_0 (2019)	Events $T_0 \pm 60$ s	90% C.L. U.L.	Summed probability	CAL α (°)	CAL δ (°)
24088	S190408an	04-08 18:18:02.288 UTC	0	2.3×10^{-6}†	80%	352.9	8.3
24218	S190425z	04-25 08:18:05.017 UTC	0	1.0×10^{-4}	5%	131.3	-43.6
24276	S190426c	04-26 15:21:55.337 UTC	0	2.5×10^{-5}	10%	183	-50.9
24403	S190503bf	05-03 18:54:04.294 UTC	0	4.2×10^{-5}	10%	169	-45.5
24495	S190510g	05-10 02:59:39.292 UT	0	–	No	295.7	50.8
24531	S190512at	05-12 18:07:14.422 UT	0	1.9×10^{-5}	10%	214.9	37.7
24548	S190513bm	05-13 20:54:28.747 UT	0	6.0×10^{-5}†	5%	348	4.4
24593	S190517h	05-17 05:51:01.831 UT	0	–	No	126.2	-31.9
24617	S190519bj	05-19 15:35:44.398 UT	0	–	No	243.1	51.1
24648	S190521g	05-21 03:02:29.447 UT	0	6.0×10^{-6}	30%	205.7	49.2
24649	S190521r	05-21 07:43:59.463 UT	0	–	No	225.3	51.4
24735	S190602aq	06-02 17:59:27.089 UT	0	2.9×10^{-4}	5%	127.5	45.1

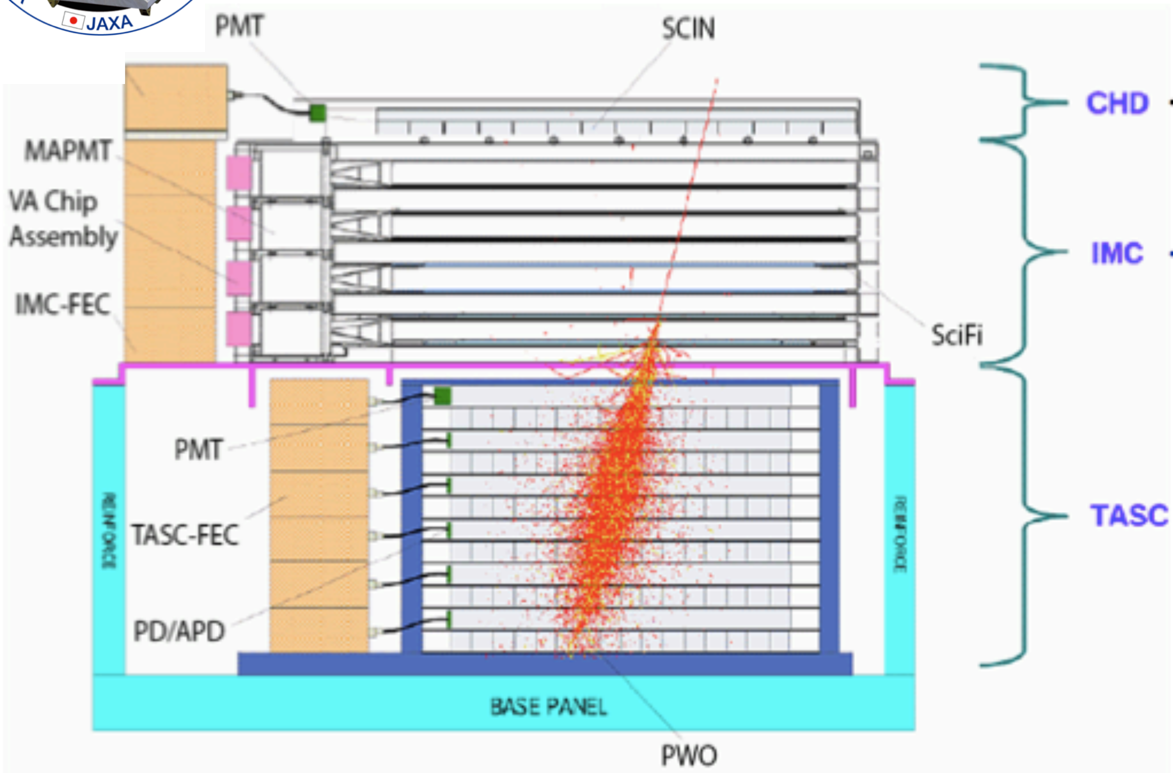
Summary and perspectives

- CALET was successfully launched on Aug. 19th, 2015, and the observation campaign started on Oct.13th, 2015.
- Excellent performances and remarkable stability of the instrument have been achieved.
- As of May 31, 2019 total observation time is 1327 days with live time close to 84% of observation time. Nearly 1.8 billion events collected with low (> 1 GeV) + high energy (>10 GeV) triggers.
- In flight calibrations with p and He events + CERN beam tests with e, p and ion fragments.
- Linearity of energy measurements established up to 10^6 MIP.
- Measurement of electron + positron spectrum in 11 GeV – 4.8 TeV energy range, using full acceptance: observation of a flux reduction above 1 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 and secondary-to-primary ratios.
- Preliminary analysis of UH cosmic rays up to Z=40.
- Study of diffuse and point sources with gamma-rays.
- Follow-up observations of GW events in X-ray and gamma-ray bands: CALET's CGBM detected 159 GRBs in the energy range 7 keV-20 MeV.
- After an initial period of 2 years CALET observation time has been extended to 5 years at least.

Thanks for your attention!

BACKUP

Instrument overview



CHD - **CHarge Detector (CHD)**
(Charge Measurement Z=1-40)

IMC - **Imaging Calorimeter (IMC)**
(Particle ID, Direction)

Total Thickness of Tungsten (W) : **3 X_0 , 0.1 λ_I**
Layer Number of Scifi Belts : 8 Layers × 2(X,Y)

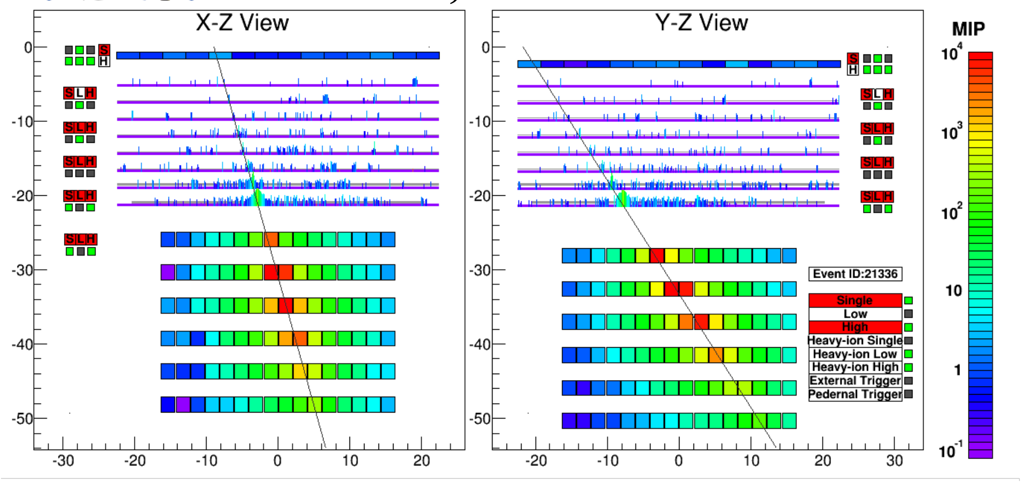
TASC - **Total Absorption Calorimeter (TASC)**
(Energy Measurement, Particle ID)

PWO 20mm x 20mm x 320mm
Total Depth of PWO : **27 X_0** (24 cm) , **1.2 λ_I**

	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Function	Charge Measurement (Z = 1 - 40)	Arrival Direction, Particle ID	Energy Measurement, Particle ID
Sensor (+ Absorber)	Plastic Scintillator : 2 layers Unit Size: 32mm x 10mm x 450mm	SciFi : 16 layers Unit size: 1mm^2 x 448 mm Total thickness of Tungsten: 3 X_0	PWO log: 12 layers Unit size: 19mm x 20mm x 326mm Total Thickness of PWO: 27 X_0
Readout	PMT+CSA	64 -anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)

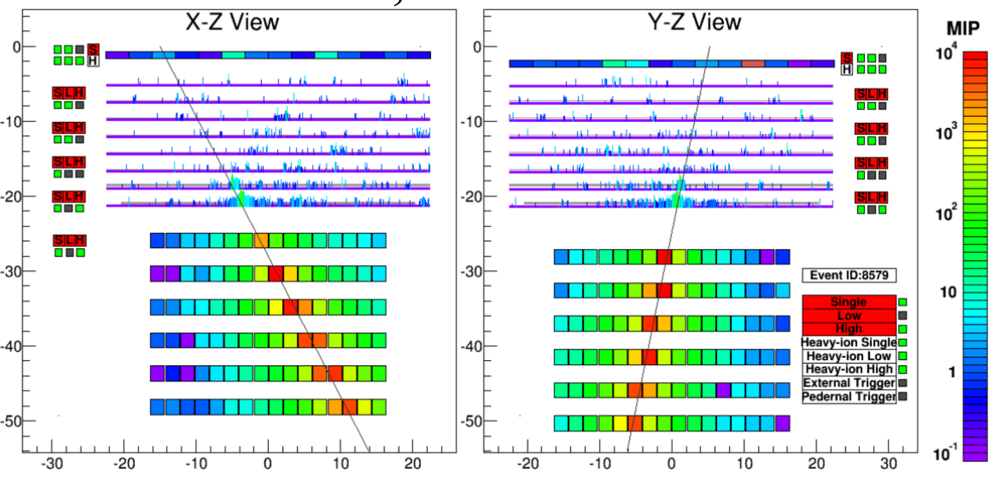
Examples of High-Energy Showers

Electron, E=3.05 TeV



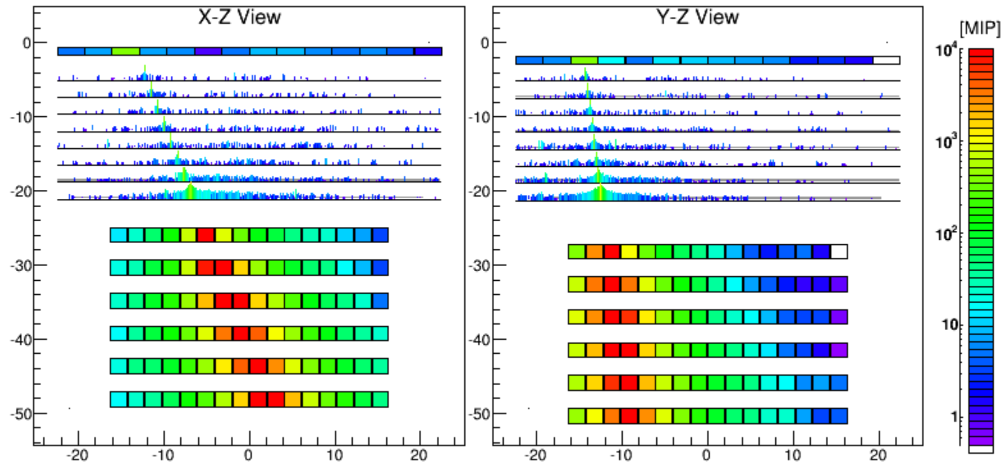
Fully contained even at 3 TeV

Proton, ΔE=2.89 TeV



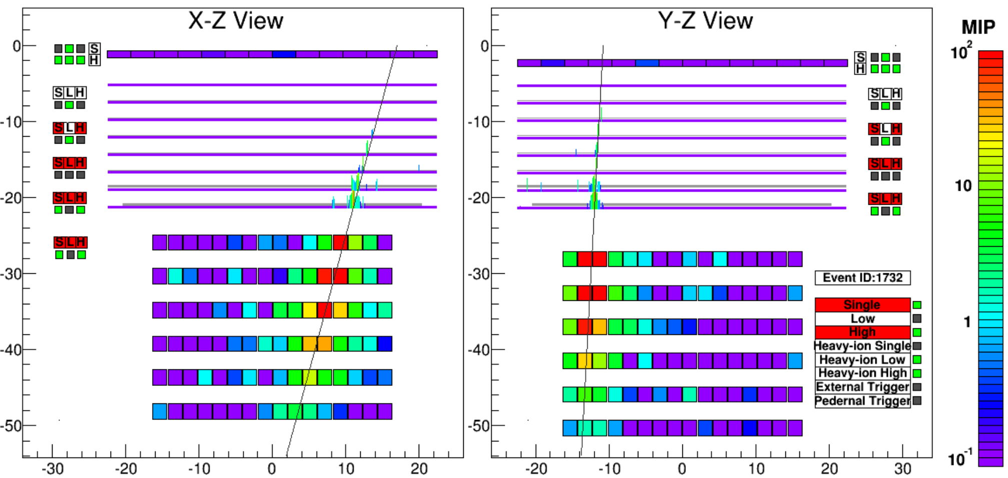
Clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



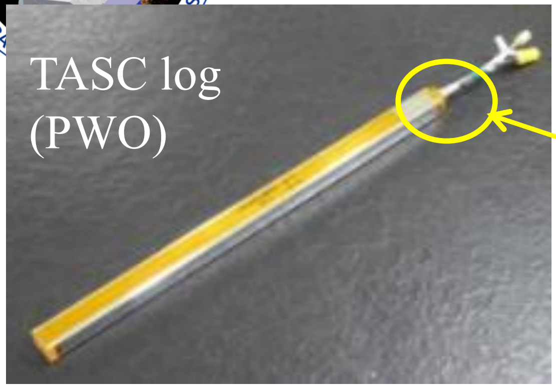
Energy deposit in CHD consistent with Fe

Gamma-ray, E=44.3 GeV

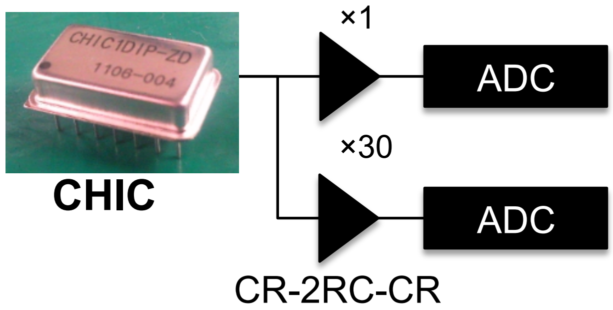


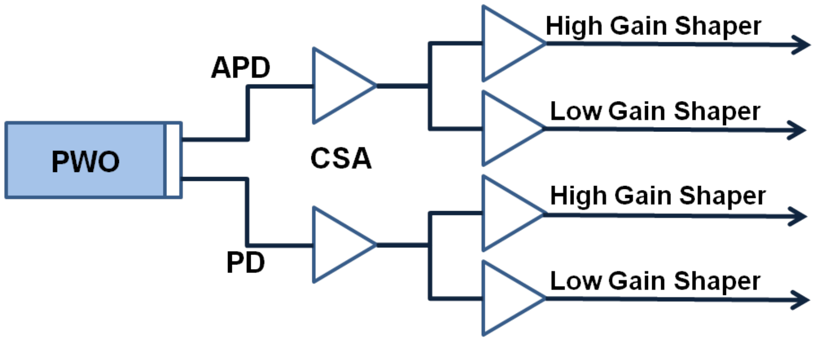
No energy deposit before pair production

Energy measurement: in a wide dynamic range of 1-10^6 MIPs



APD gain ～50





The whole dynamic range was calibrated by UV laser irradiation on ground :

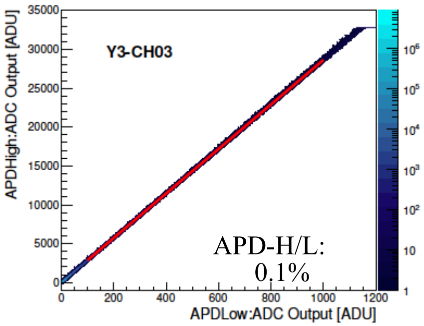
1) The linearity is confirmed in the range of 1.4-2.5 %.
2) The whole dynamic range is confirmed to cover from 1 MIP to 10^6 MIPs.

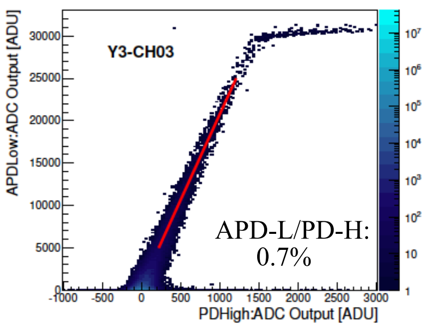
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

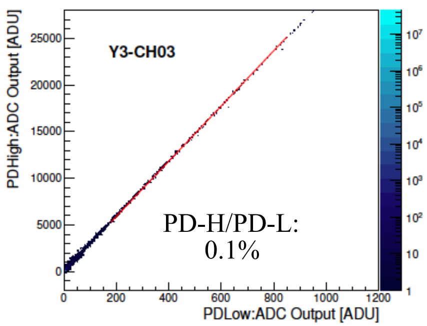
The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel.

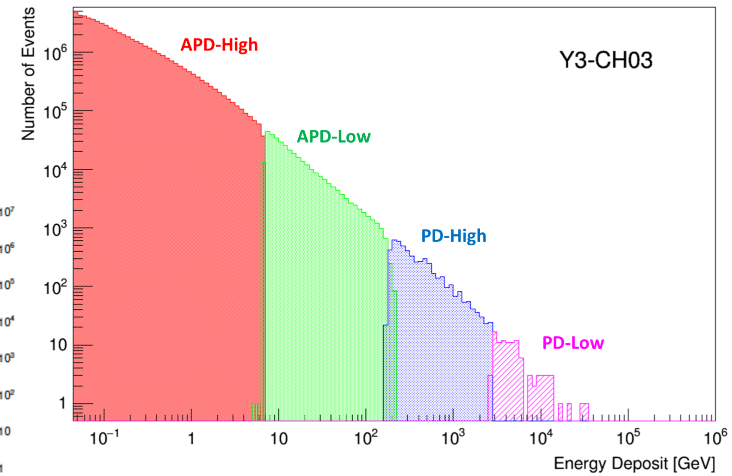
APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%

Example of energy distribution in one PWO log









Position and Temperature Calibration + Long-term Stability

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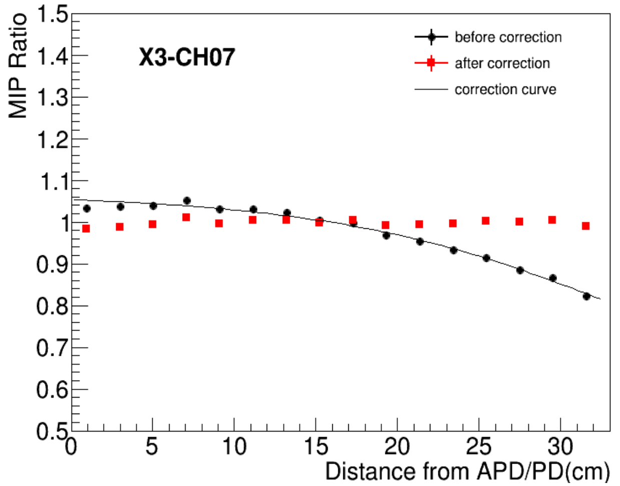
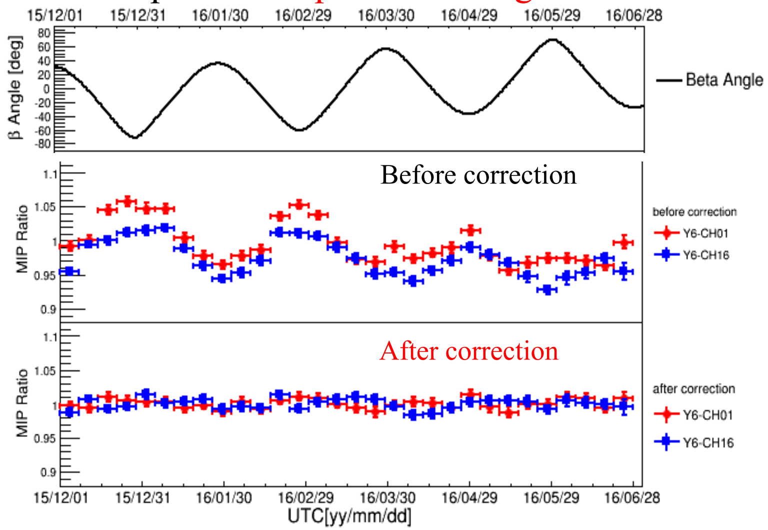
Example of position dependence correction



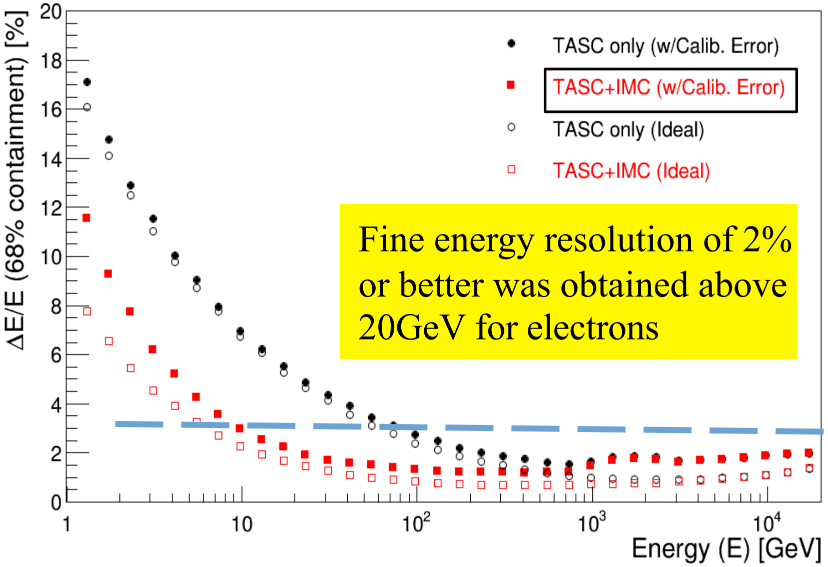
Examples of temperature change correction



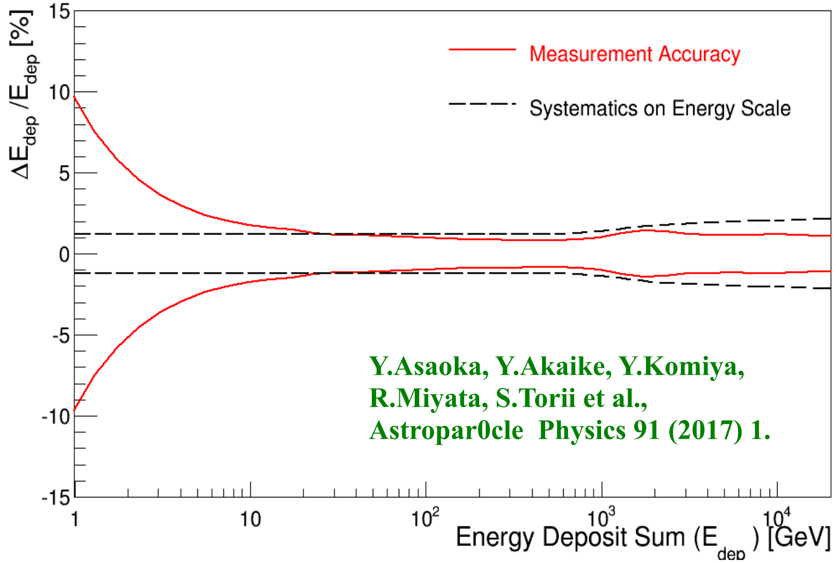
TASC

Active Thermal Control System (ATCS) on ISS provides very stable thermal conditions during long-tem observations: Δt ~ a few degrees

Energy Resolution for Electrons by On-orbit Calibration



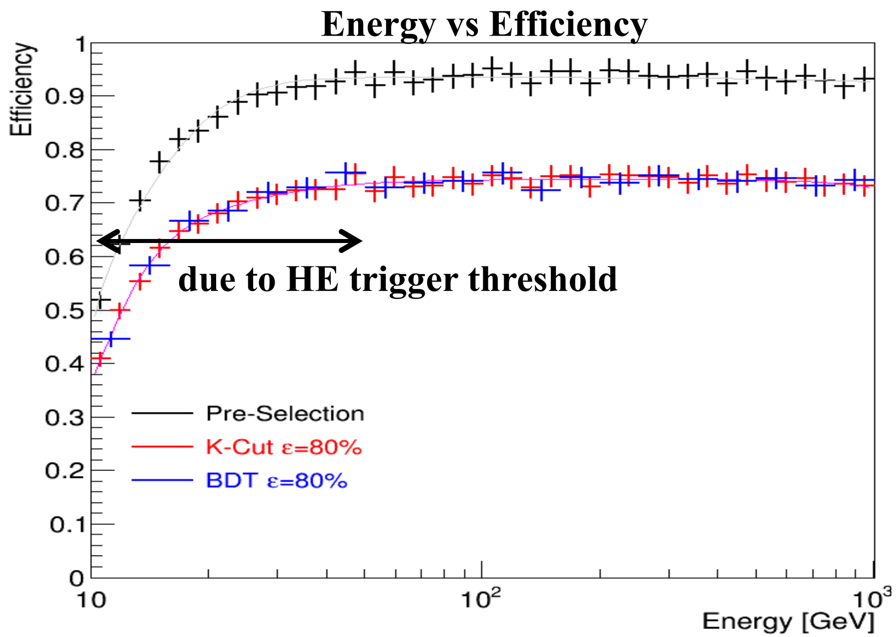
Fine energy resolution of 2% or better was obtained above 20GeV for electrons

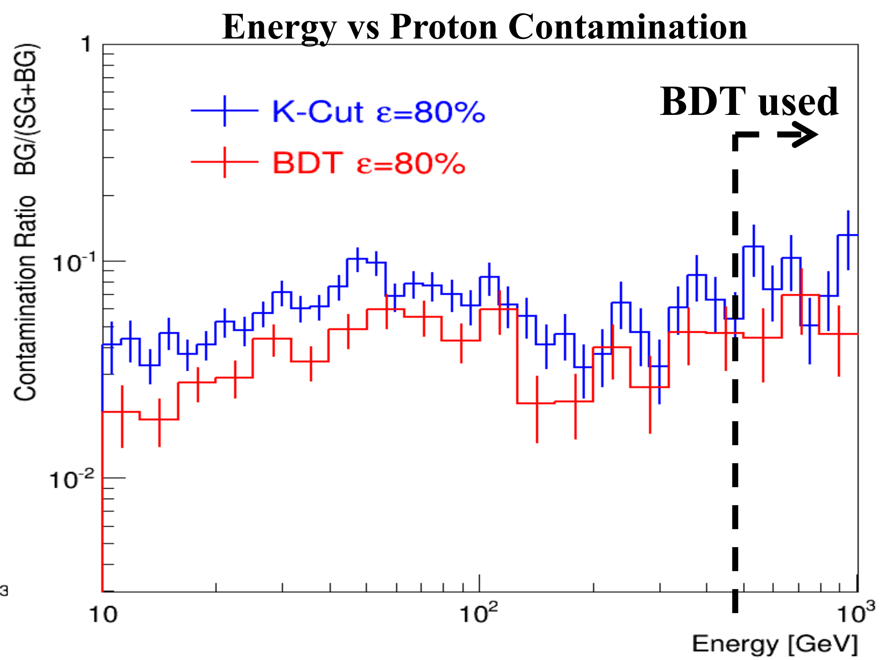


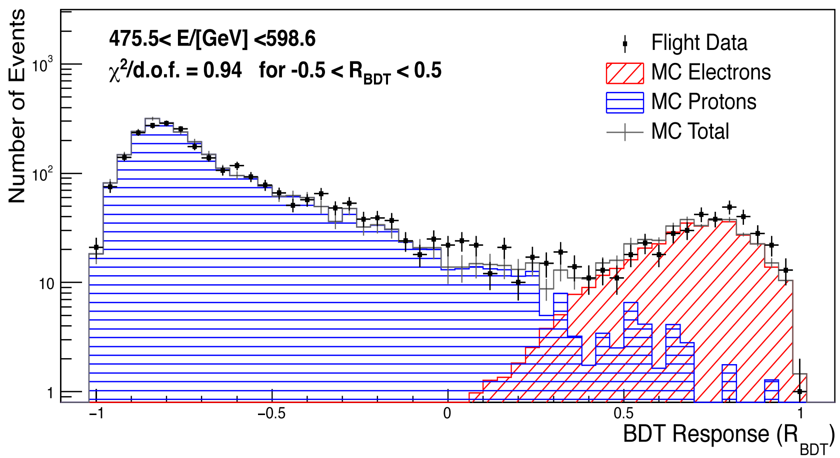
Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al., Astropar0cle Physics 91 (2017) 1.

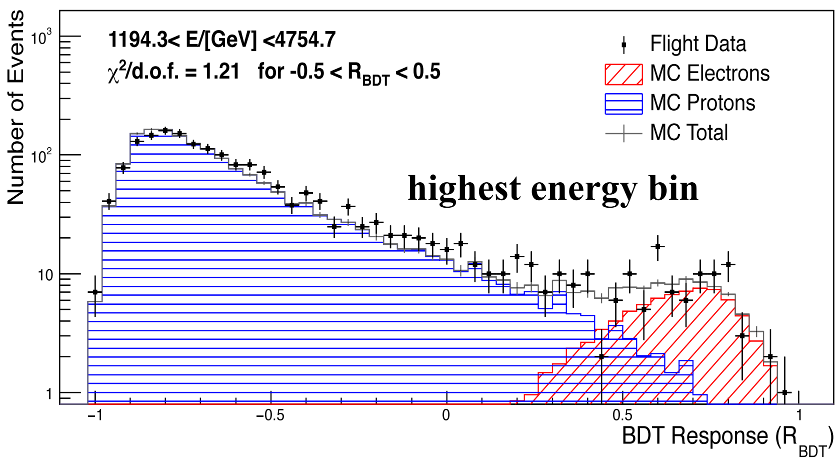
Electron identification (ii)

- In the final electron sample, the resultant contamination ratios of protons are: 5 % up to 1 TeV ; 10% - 20% in the 1 - 4.8 TeV region, keeping a constant efficiency of 80 % for electrons.
- Simple two parameter cut is used in the low energy region while the difference in resultant spectrum are taken into account in the systematic uncertainty.





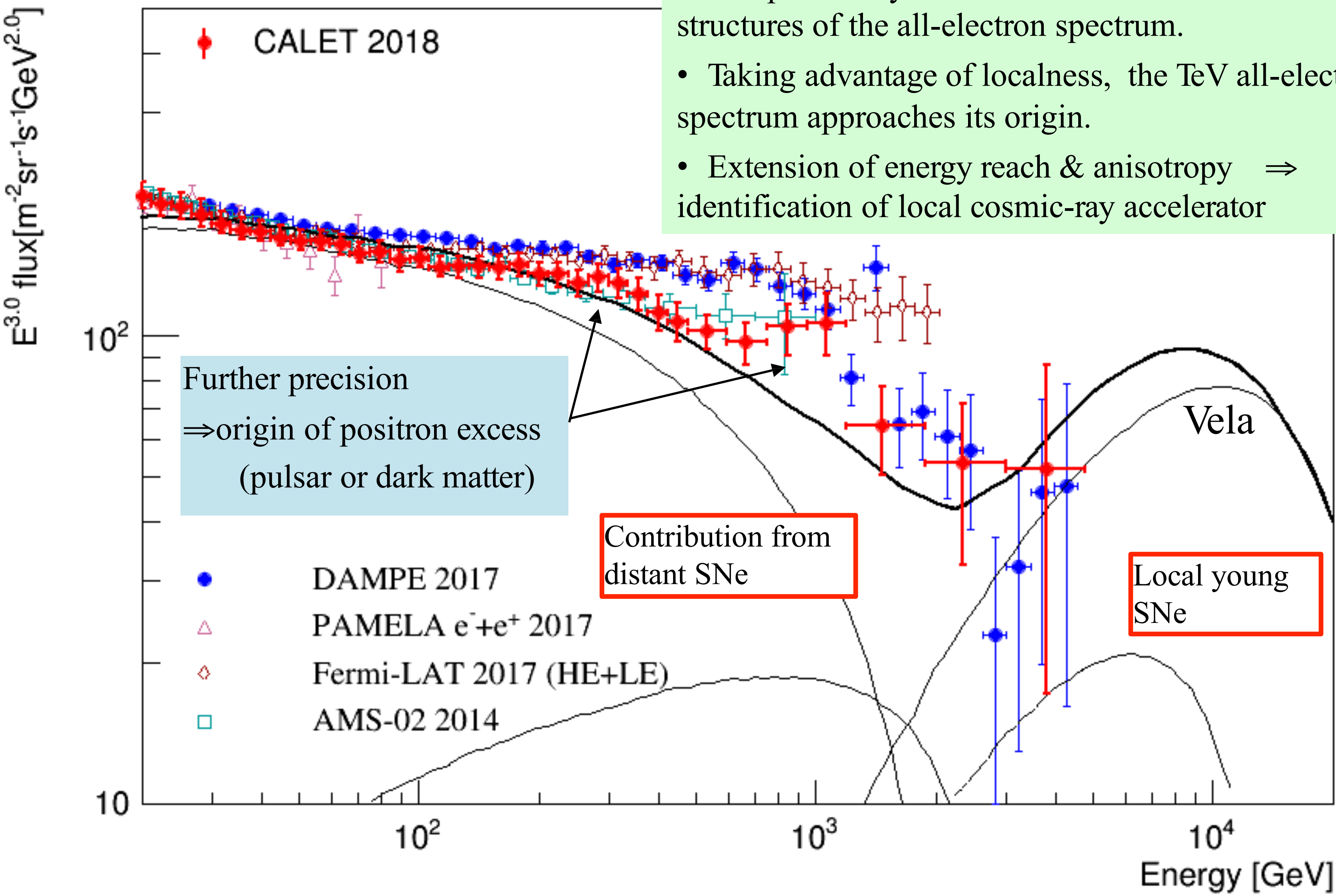




Prospects for All-Electron Spectrum by CALET

Five years or more of observations could lead to ~3 times more statistic and to a further 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.
- Extension of energy reach & anisotropy ⇒ identification of local cosmic-ray accelerator

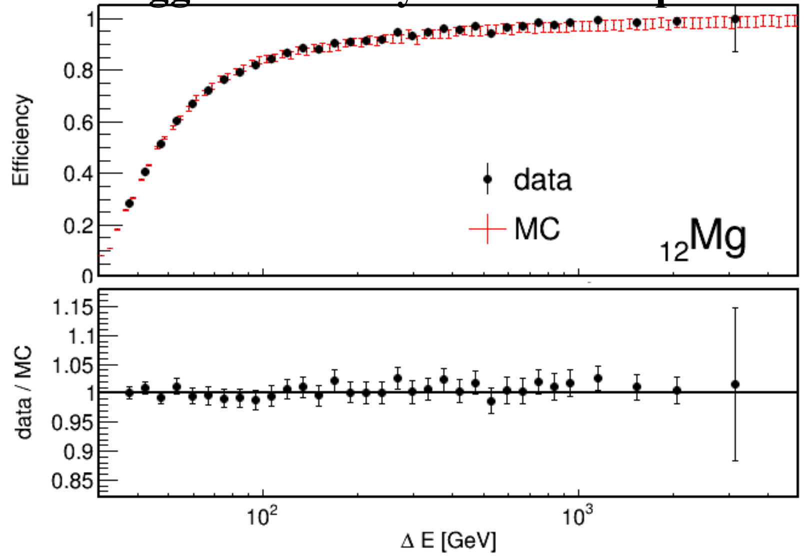


Flux measurements:

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

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

Trigger Efficiency MC/FD comparison



Selection efficiency for several nuclei