The CALorimetric Electron Telescope(CALET) : In-flight performance and preliminary results

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Japanese Experiment
Module /Exposure Facility

TeVPA2016@CERN September 12-16,2016

CALET Observations and Science Targets

Main Telescope: Calorimeter (CAL)

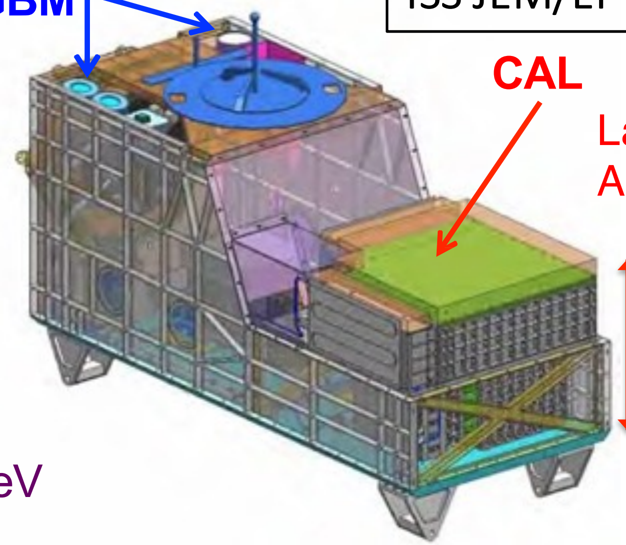
- Electrons: 1 GeV – 20 TeV
- Gamma-rays: 10 GeV – 10* TeV
  (Gamma-ray Bursts: > 1 GeV)
- Protons and Heavy Ions:
  10's of GeV – 1,000* TeV
- Ultra Heavy (Z>28) nuclei:
  E > 600 MeV/nucleon

Gamma-ray Burst Monitor (CGBM)

- X-rays/Soft Gamma-rays: 7keV – 20MeV

Talk by S.Ricciarini in Gamma-ray session on Sep.12

ISS JEM/EF Payload



Launched on Aug.19, 2015

30 X_0 : nearly atmospheric depth

Science Objectives	Observation Targets
Nearby Cosmic-ray Sources	Electron spectrum in trans-TeV region
Dark Matter Talk by H.Motz in Dark Matter session on Sep.13	Signatures in electron/gamma energy spectra in 10 GeV – 10 TeV region
Origin and Acceleration of Cosmic Rays	p-Fe over several tens of GeV, Ultra-Heavy Ions
Cosmic–ray Propagation in the Galaxy	B/C ratio up to several TeV /nucleon
Solar Physics	Electron flux below 10 GeV
Gamma-ray Transients	X-rays/Gamma-rays in 7 keV –20 MeV

CALET collaboration team

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9) JAXA, Japan
10) Kanagawa University, Japan
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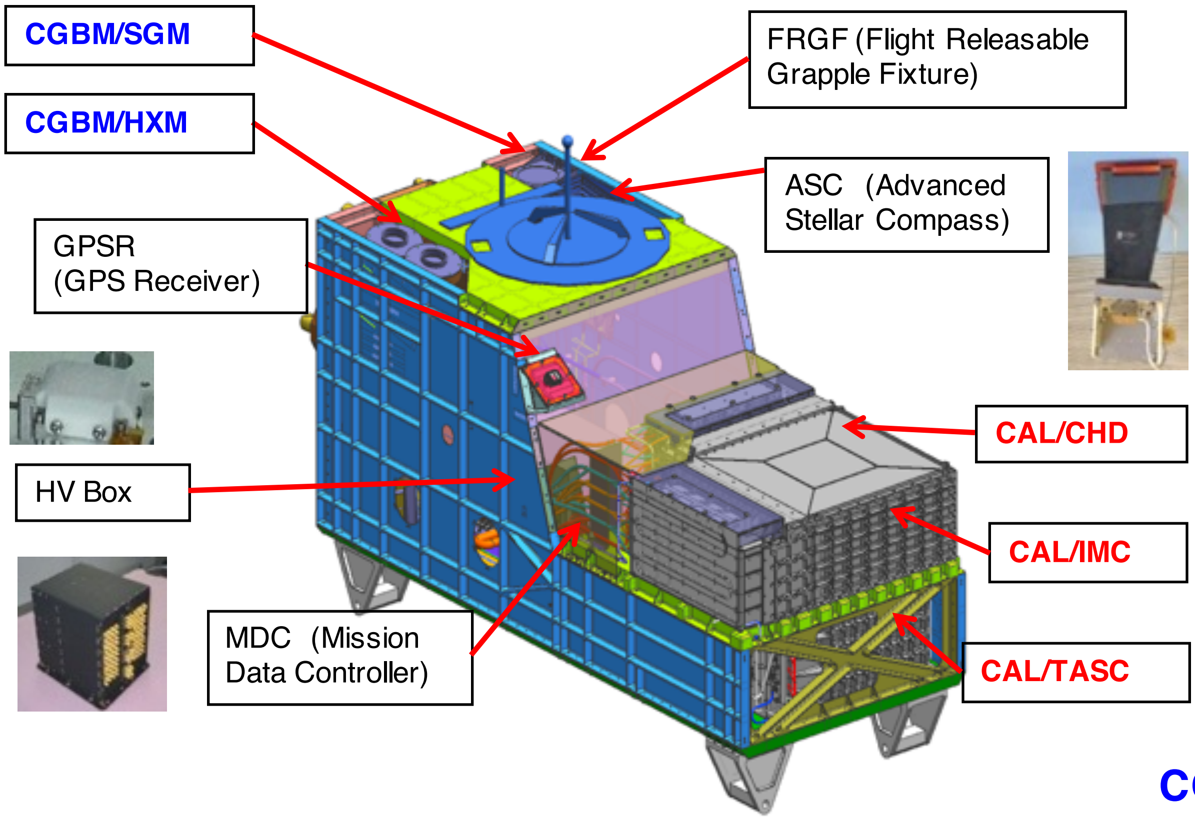
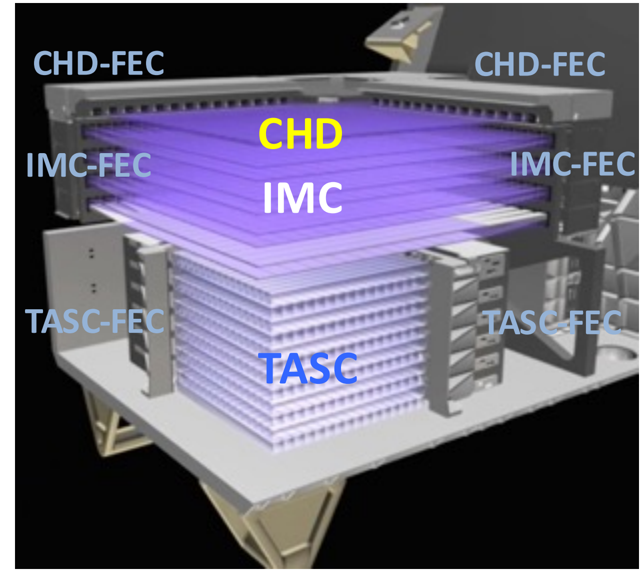
CALET System Overview



CALORIMETER (CHD/IMC/TASC)

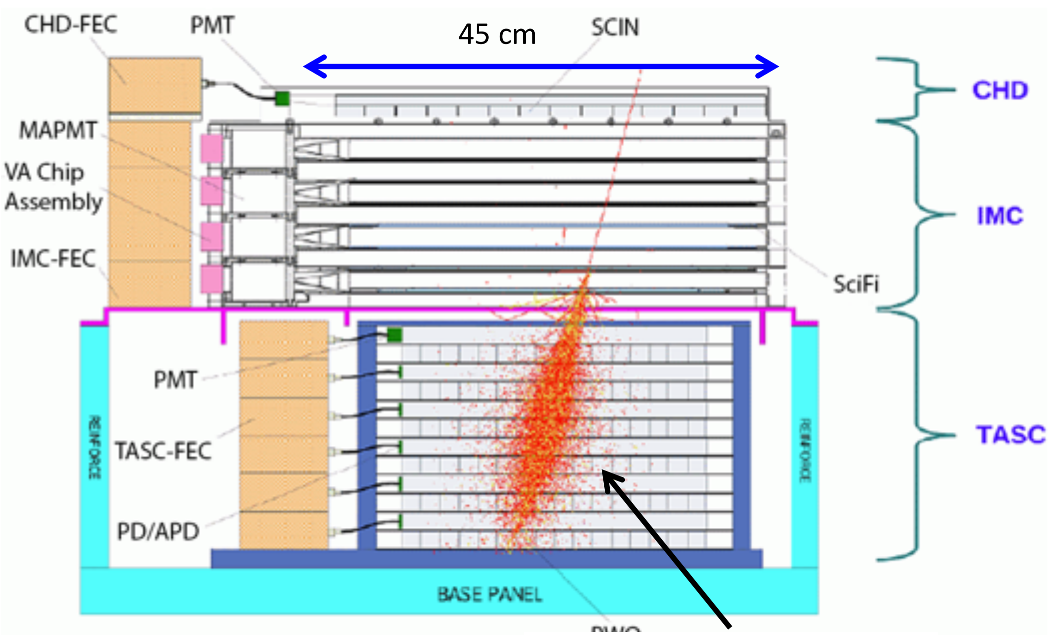


- **Mass:** 612.8 kg
- JEM Standard Payload Size
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption:** 507 W (max)
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

CGBM (CALET Gamma-ray Burst Monitor)

CALET: Instrument Overview

Field of view: ~ 45 degrees (from the zenith)
Geometrical Factor: ~ 0.12 m^2sr (for electrons)



1 TeV electron shower

Unique features of CALET

A dedicated charge detector + multiple dE/dx track sampling in the IMC allow to identify individual nuclear species (Δz~0.15-0.35e).

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: rejection power ~10^5.

	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 : 14 × 1 layer (x,y)** Unit Size: 32mm x 10mm x 450mm	**SciFi : 448 x 8 layers (x,y) = 7168** Unit size: 1mm^2 x 448 mm **Total thickness of Tungsten: 3 X_0**	**PWO log: 16 x 6 layers (x,y)= 192** Unit size: 19mm x 20mm x 326mm **Total Thickness of PWO: 27 X_0**
Readout	**PMT+CSA**	**64 -anode PMT(HPK) + ASIC**	**APD/PD+CSA** PMT+CSA (for Trigger)@top layer

Calorimeter Flight Components

CHD

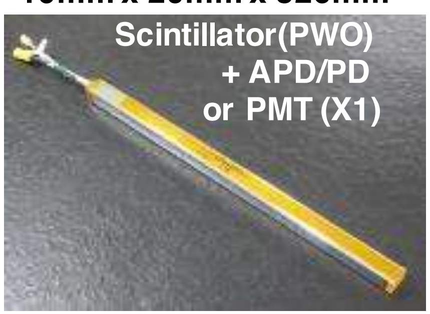
14 × 1 layer (x,y) = 28
32mm x 10mm x 450mm

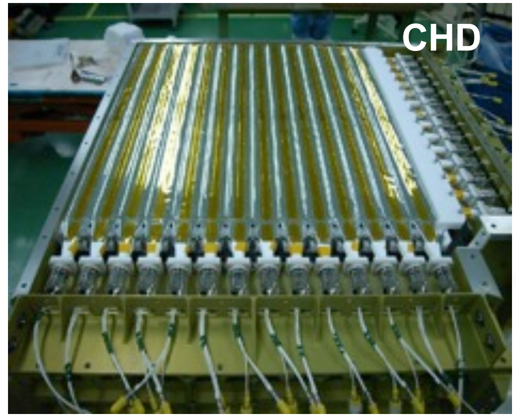
IMC

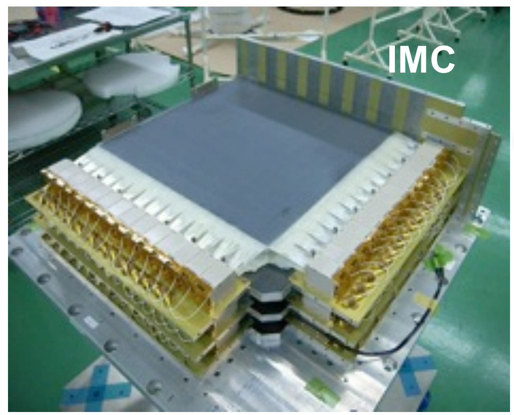
448 x 8 layers (x,y) = 7168
1mm^2 x 448 mm

TASC

16 x 6 layers (x,y)= 192
19mm x 20mm x 326mm

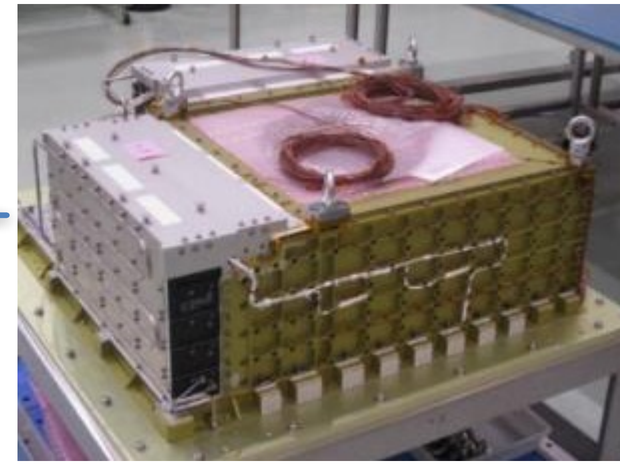






Completed Component with Front End Circuit

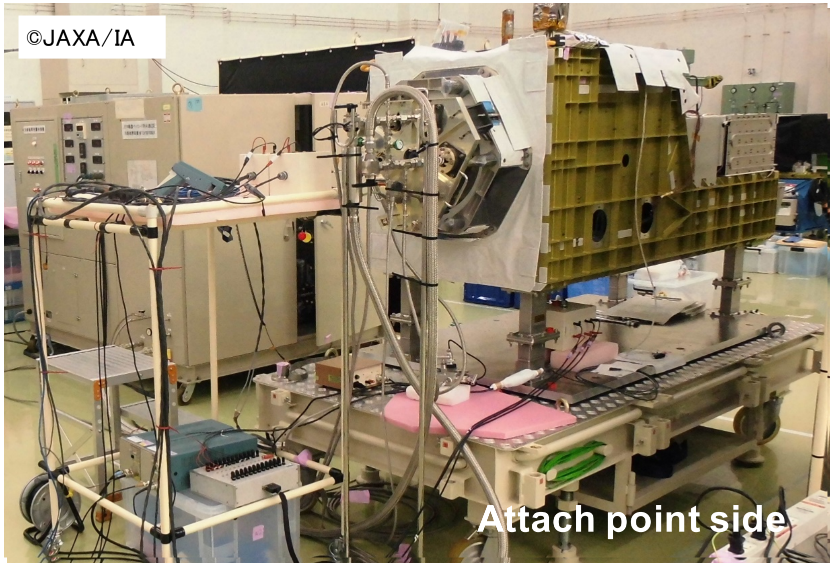
CHD/IMC

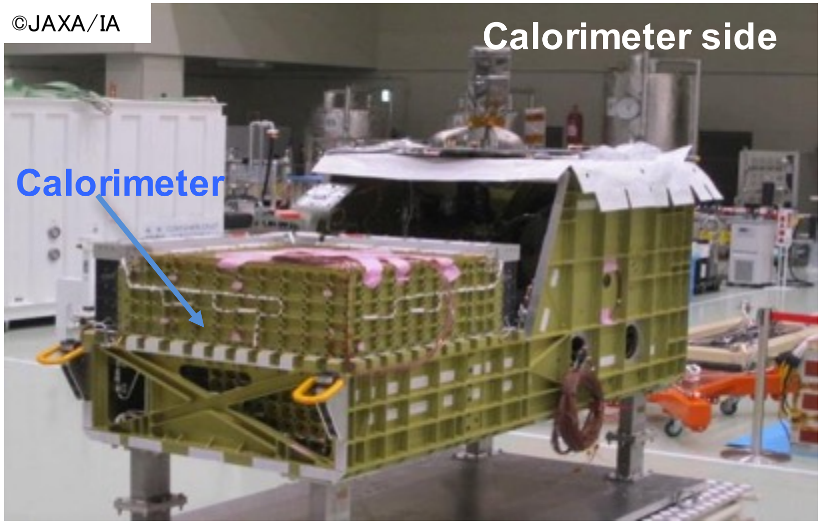


TASC

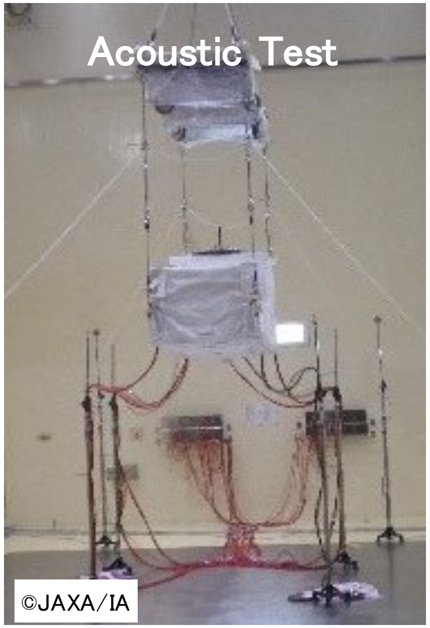
System Test of Flight Model

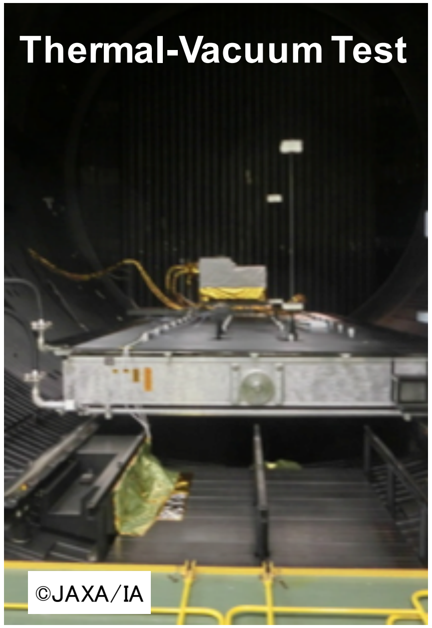
System Integration Test for Payload

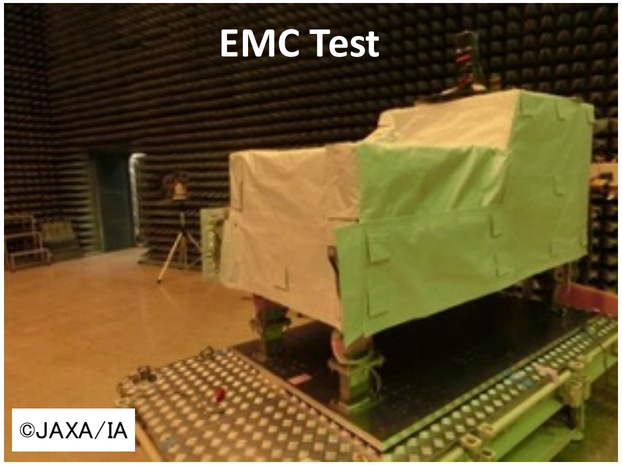




Acoustic test, Thermal–Vacuum test and EMC test at Tsukuba Space Center (JAXA)

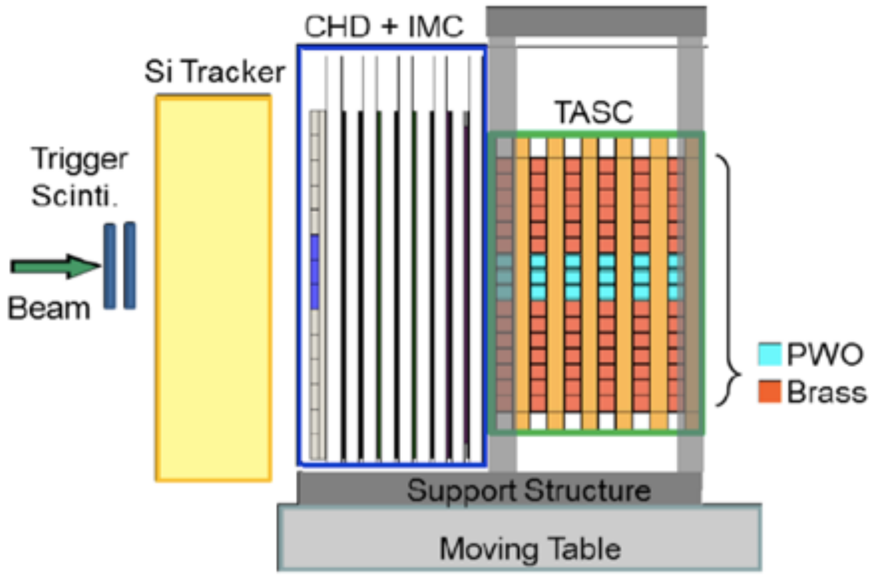




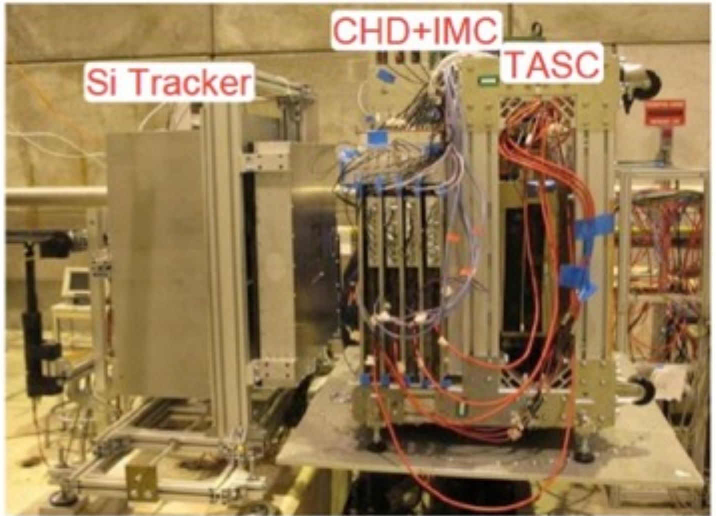


CERN Beam Test using the STM

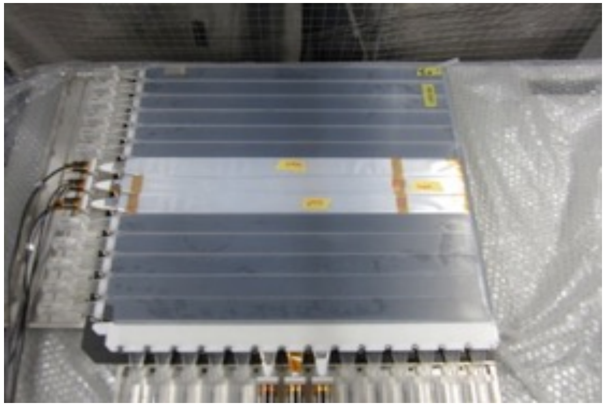
Schematic Side View of the Beam Test Model



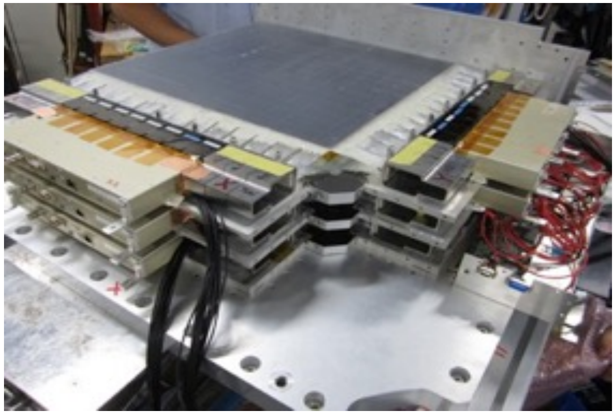
The Beam Test Model at CERN SPS H8 Beam Line



Charge Detector: CHD

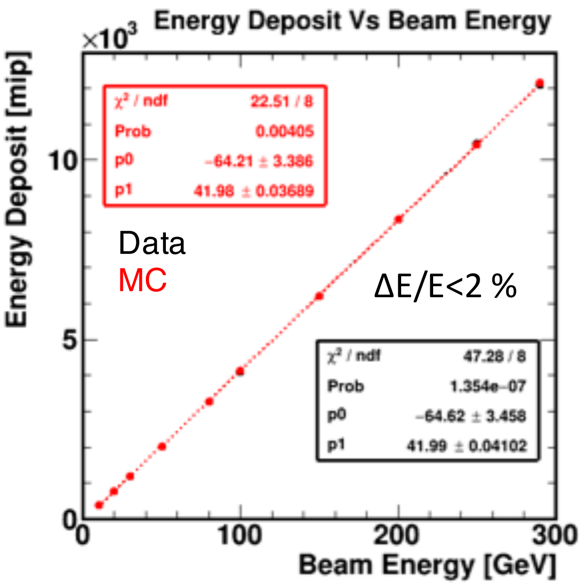


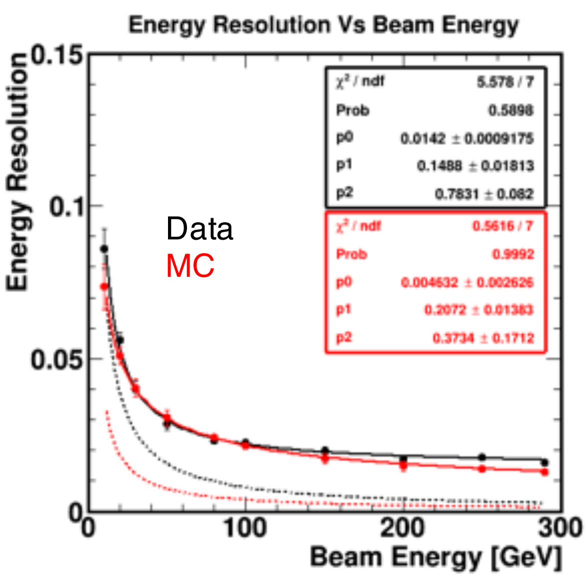
Imaging Calorimeter: IMC



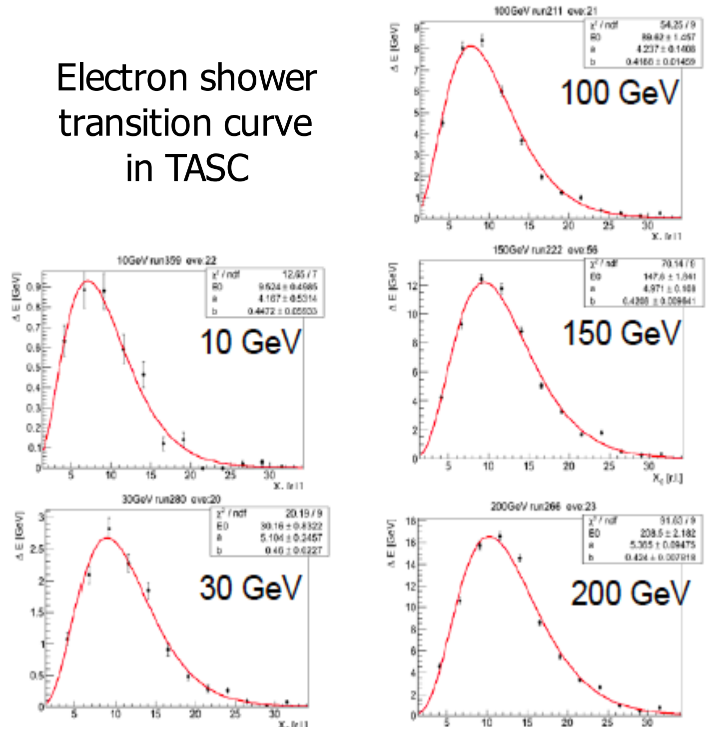
Total Absorption Calorimeter: TASC

CERN-SPS Beam Test: protons and electrons

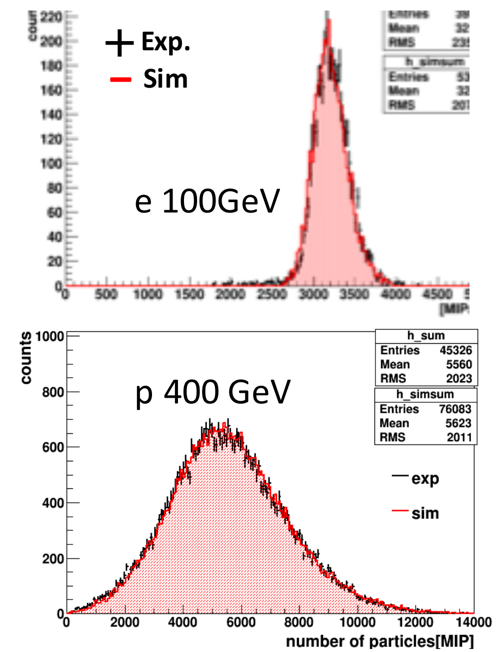


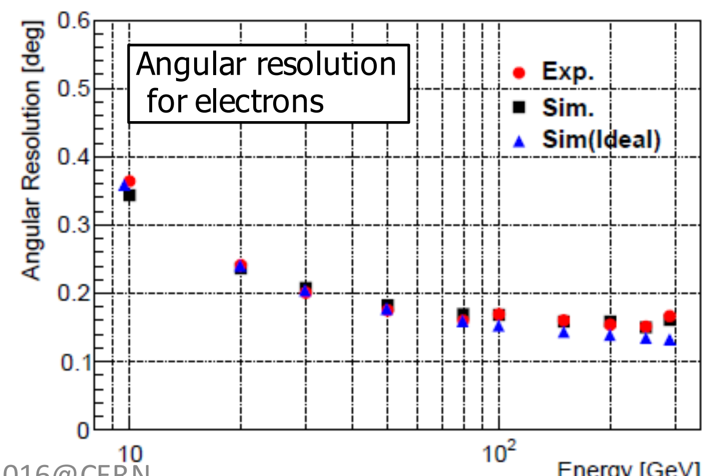


Electron shower transition curve in TASC

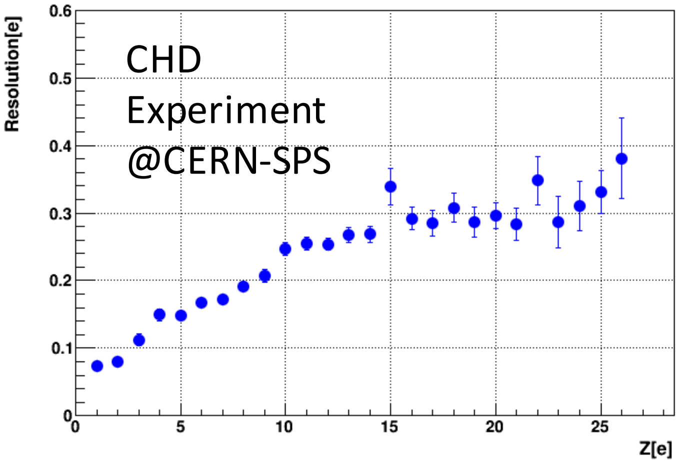


Energy distribution

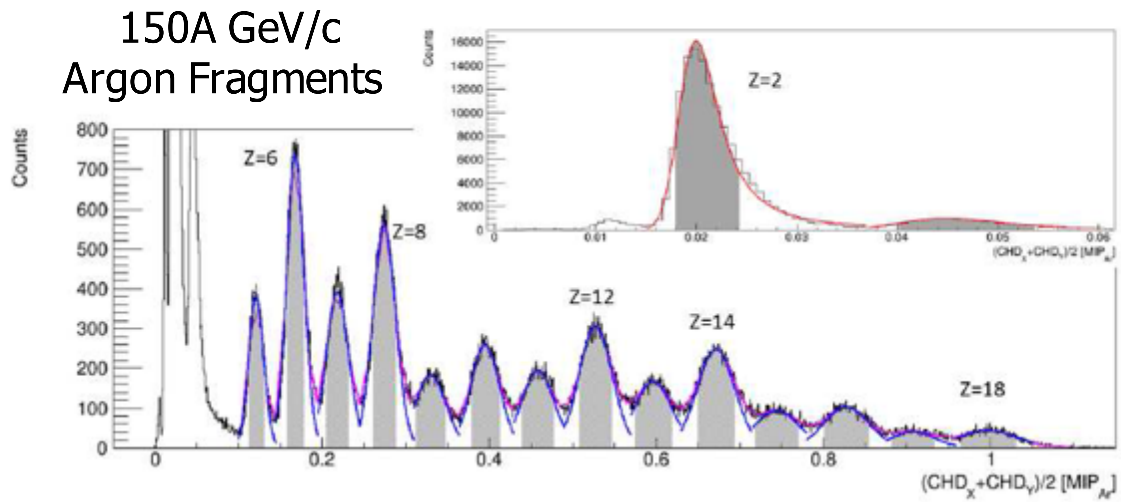


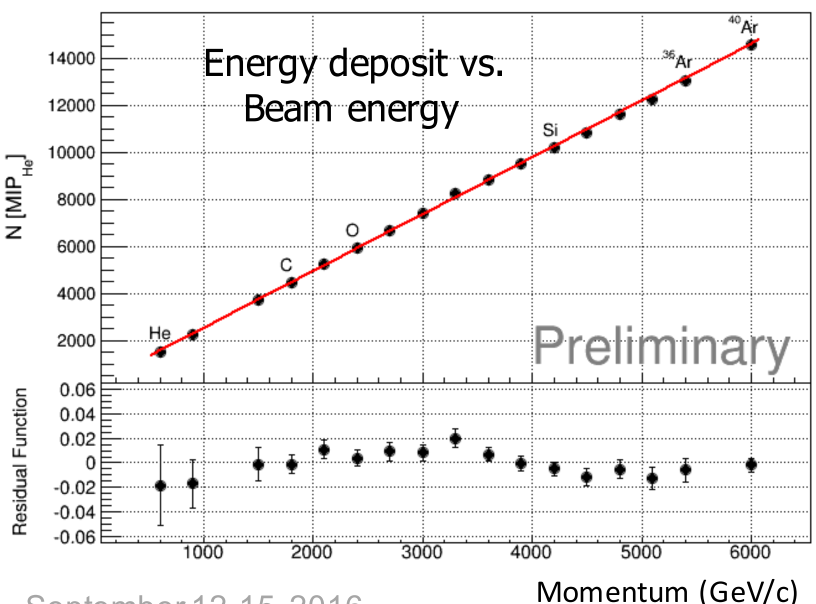


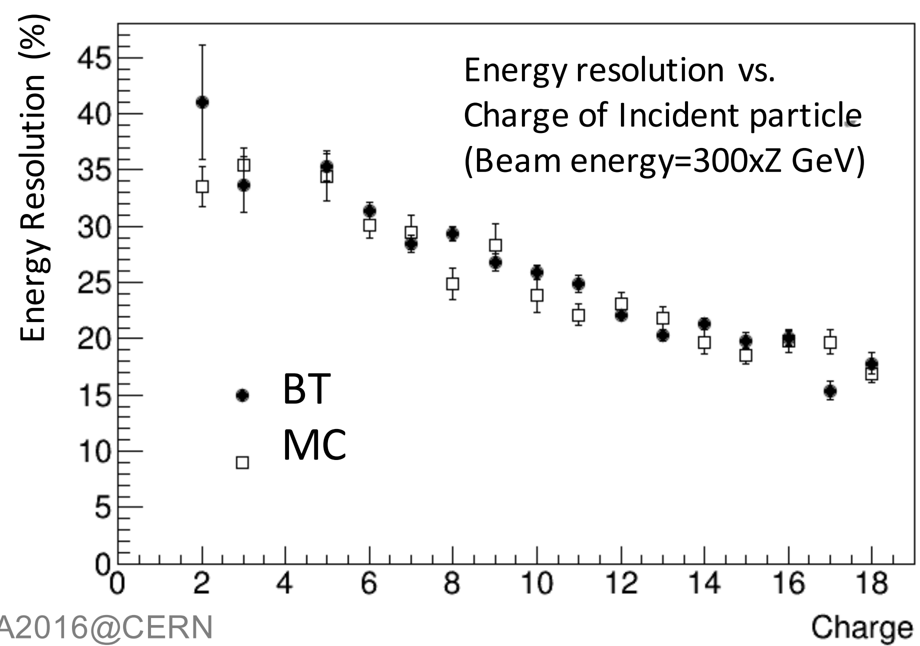
Heavy Ion Beam Test @ CERN 2014 & 2015



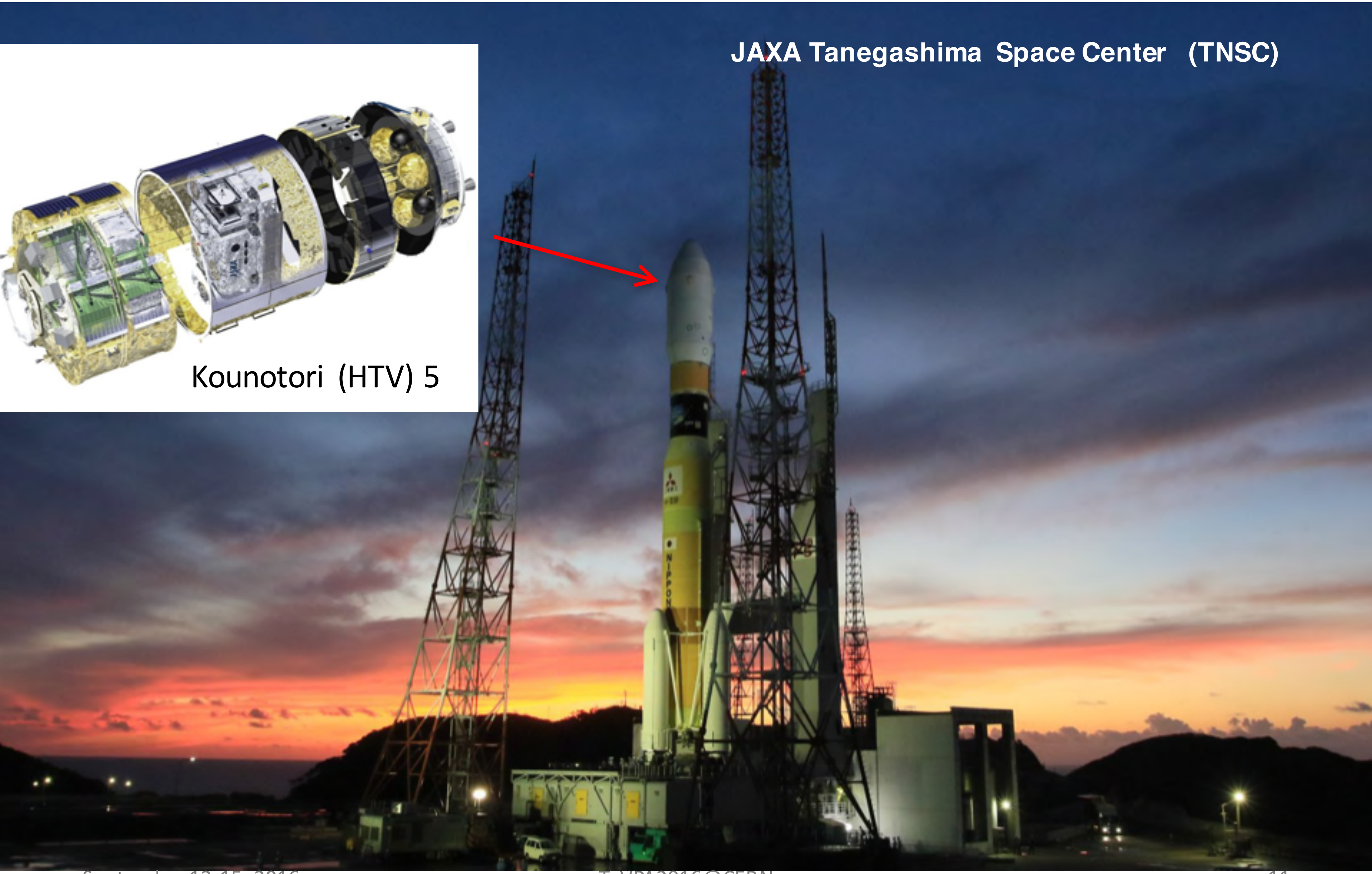
Charge resolution:
σ_Z = 0.15e(@B) – 0.35e(@Fe)







CALET Launch: August 19, 2015 at 12:50:49 (UT)

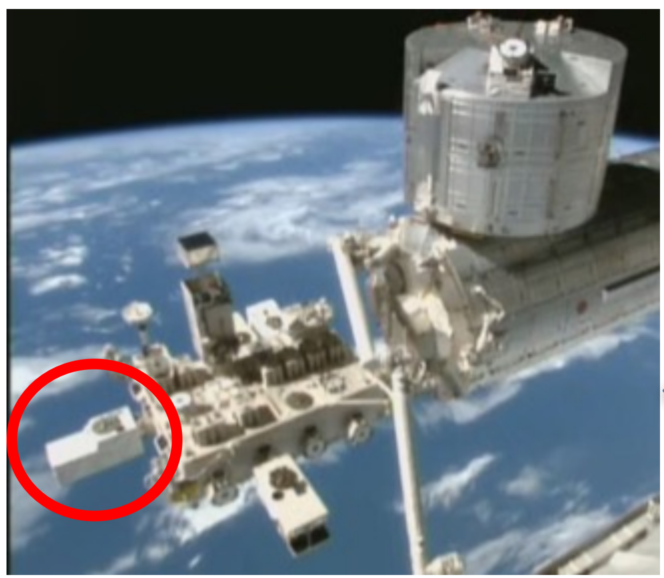


CALET is now on the ISS !

① **August 19th**: Launch of the Japanese H2-B rocket by JAXA at 20:50:49 (JST)

② **August 24th:**
The HTV-5 Transfer Vehicle (HTV-5) is grabbed by the ISS robotic arm.

③ **August 24th:**
The HTV-5 docks to the ISS at 2:28 (JST).



④ **August 25th:**
CALET is emplaced on port #9 of the JEM-EF and data communication with the payload is established.

Progress from the launch to the initial operation (1)

(1) Launch on 8/19 via H-IIB/HTV5. Dock on 8/25 to JEM port 9. No problem for their start up.

(2) Performed the function checkout during 8/25 to 10/8. Confirmed there were no problems on their functions and performances.

(3) Until 11/17, 90 days after the launch, conducted an observation to achieve the minimum mission success and obtained an appropriate amount of data. Since then, the observation has been carried out according to the steady processes.

8/19 L+0 — HTV5 launch

8/24 L+5 — HTV5 ISS arrived, moored on ISS

HTV-EP JEM-EF moored

CALET JEM-EF#9 attached

8/25 L+6 — CALET boot up

機器動作確認

MDC/GPSR/ASC checkout

IMC/CHD/TASC-FEC checkout

8/31 L+12

9/3 L+15

9/4 L+16

HV-BOX/GBM-EBOX/CIRC checkout

System(interlock function) checkout

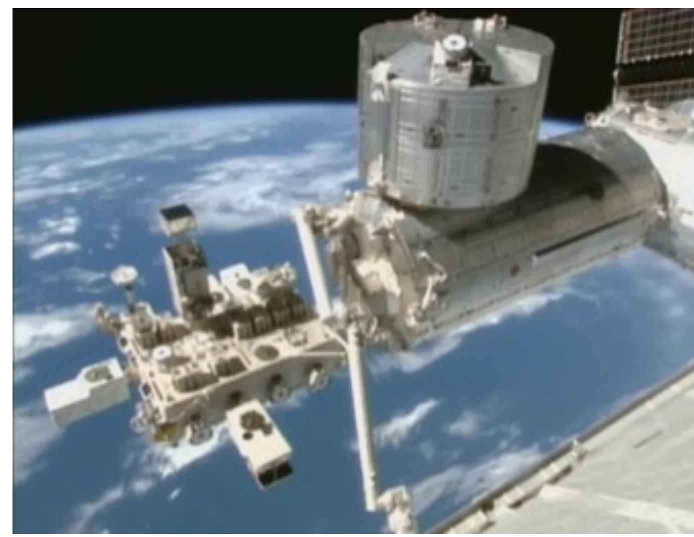
9/14 L+26

9/15 L+27 — Schedule command file loaded

9/18 L+30








Progress from the launch to the initial operation (2)

9/22 L+34 — CGBM High Voltage checkout

9/24 L+36 — Reached required vacuum for Calorimete

高電圧印加確認

- CHD checkout
- IMC checkout
- TASC checkout
- Calorimeter checkout
- CGBM detecting function checkout
- CALET overall operation checkout

10/5 L+47 — Confirmed 72 hours continuous operation

10/8 L+50 — **Calibration Run Start**

Measurement of the calorimeter Calibration data

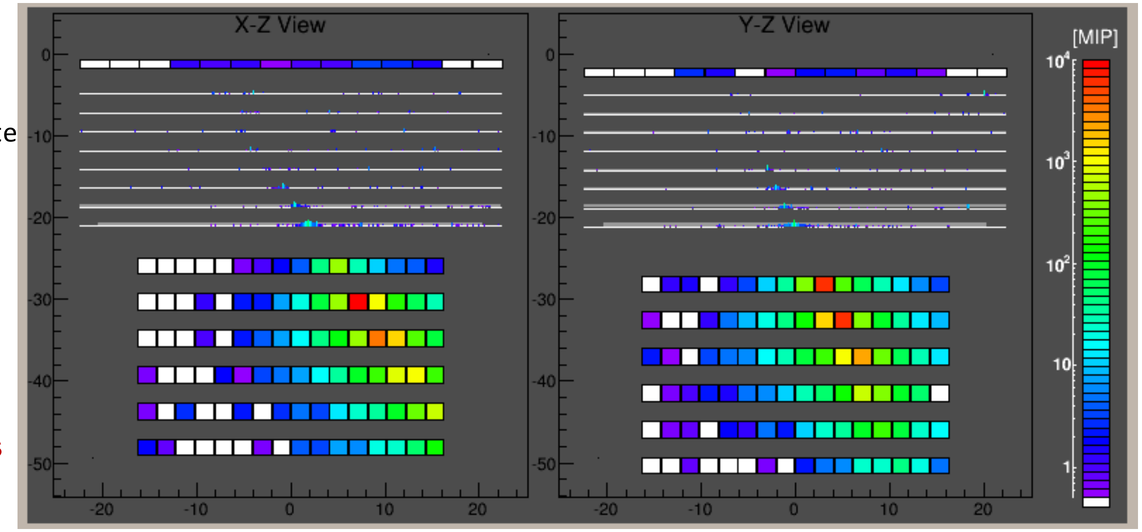
10/20 L+62 — **Initial Operation Start**

Observation for the minimum mission success

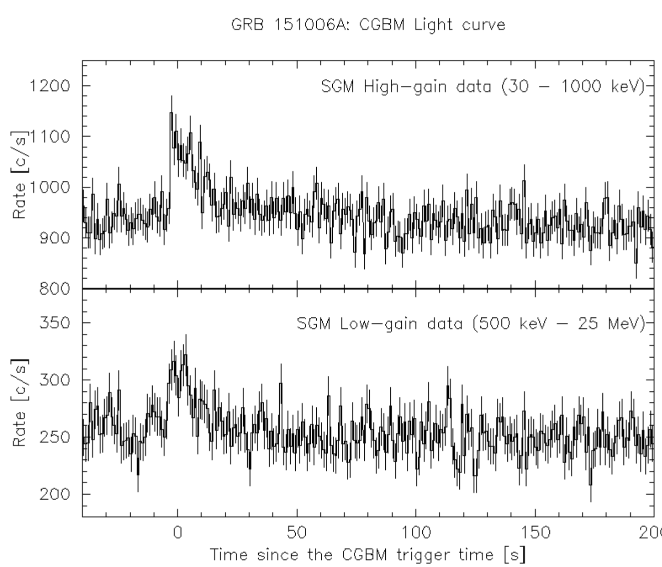
Trial for the steady observation process

11/17 L+90 — **End of the initial operation**

Start observation with the steady process

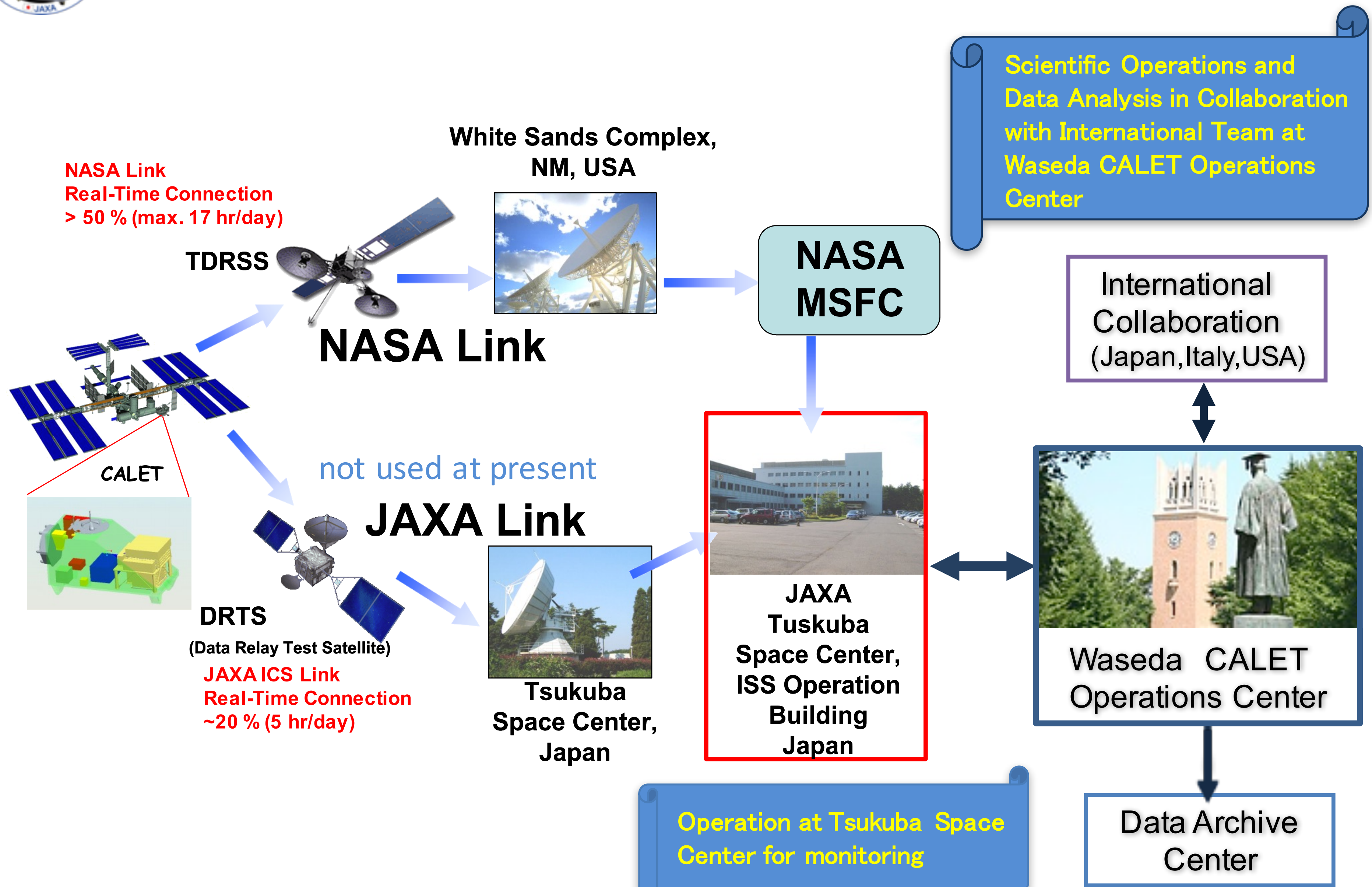


Calorimeter :
Electron event around the TeV region (candidate)



CGBM :
First observed GRB event Light Curve(GRB 151006A)

Data Downlink Using TDRSS and Operations Center



Overview of Trigger Modes for CALET

High Energy Shower Trigger (HE)	- High energy electrons (10GeV ～20TeV) - High energy gamma rays (10GeV ～10TeV) - Nuclei (a few10GeV～1000TeV)
Low Energy Shower Trigger (LE)	- Low energy electron at high latitude (1GeV ～10GeV) - GeV gamma-rays originated from GRB (1GeV ～) - Ultra heavy nuclei (combined with heavy mode)
Single Trigger (Single)	- For detector calibration : penetrating particles (mainly non-interacting protons and heliums)

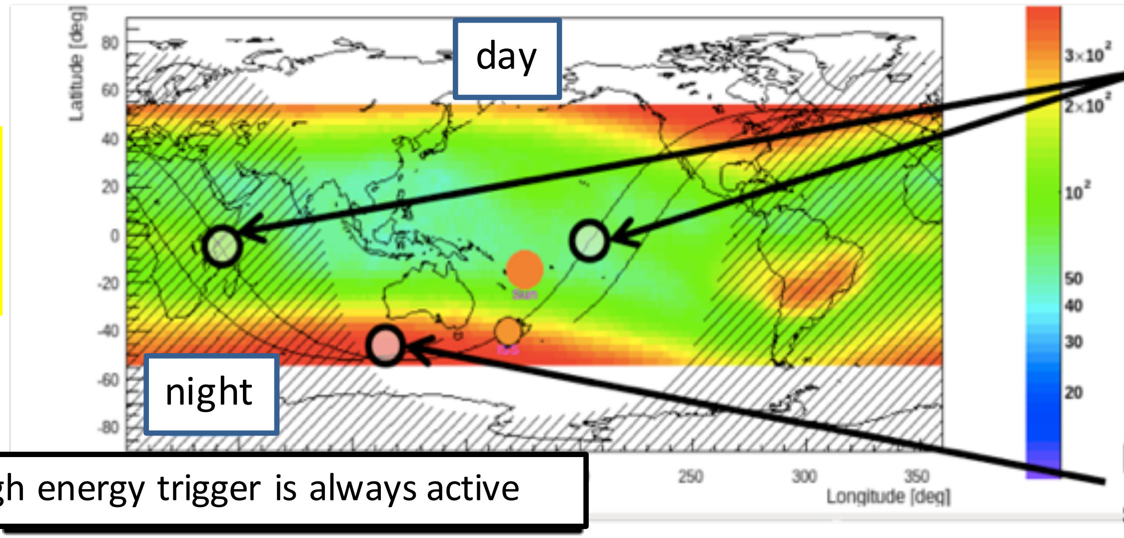
(*) In addition to above 3 trigger modes, heavy modes are defined for each of the above trigger mode. They are omitted here for simple explanation.

Auto Trigger (Pedestal/Test Pulse)	- For calibration: • ADC offset measurement (Pedestal) • FEC's response measurement (Test pulse)

ISS Orbit and CALET On-orbit Operations

ISS orbit: inclination 51.6 degree, ~400 km

Concept of on-orbit operations

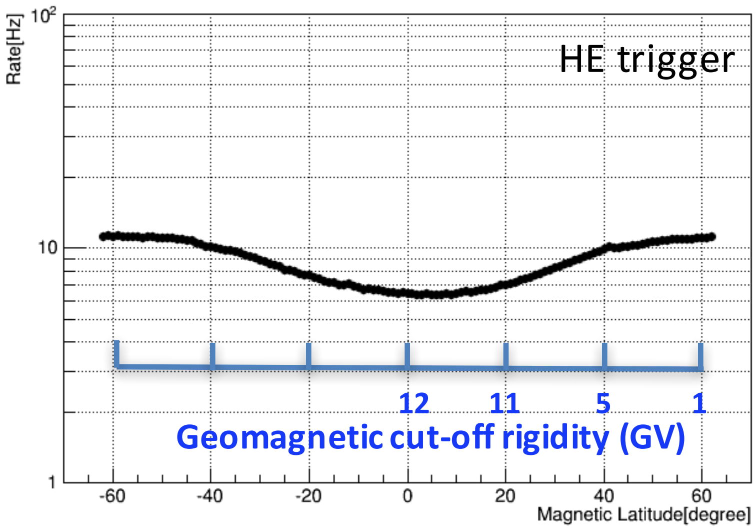


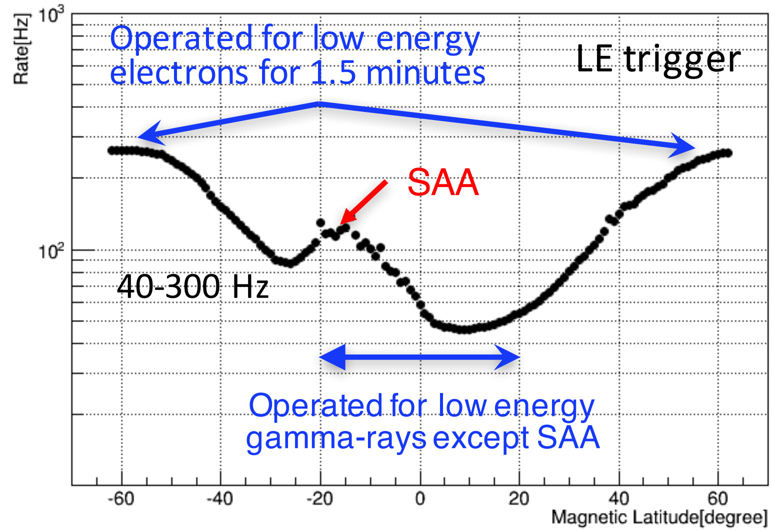
Pedestal data acquisition

Schedule file: sequence of time and command

Low energy electron shower data acquisition

Dependence of the count rate on geomagnetic latitude



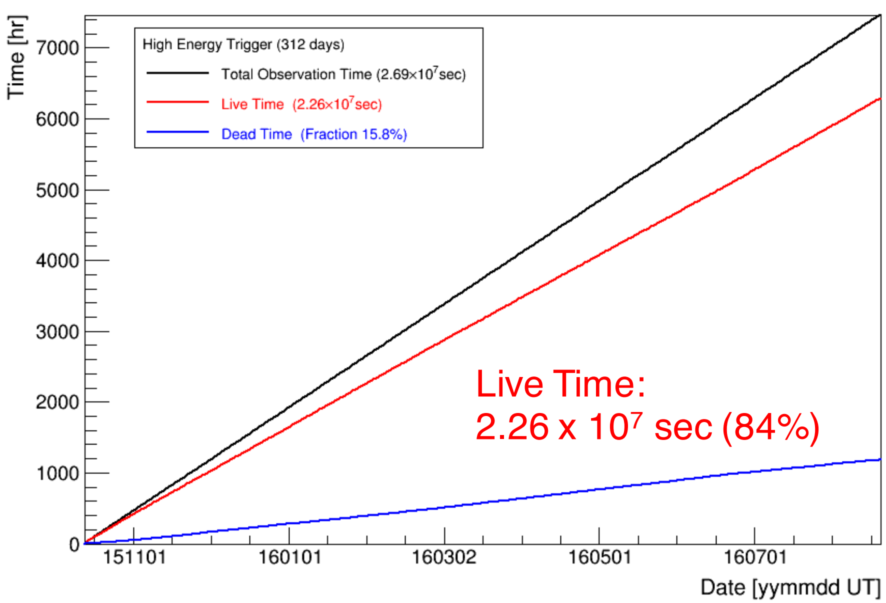


Observation by High Energy Trigger

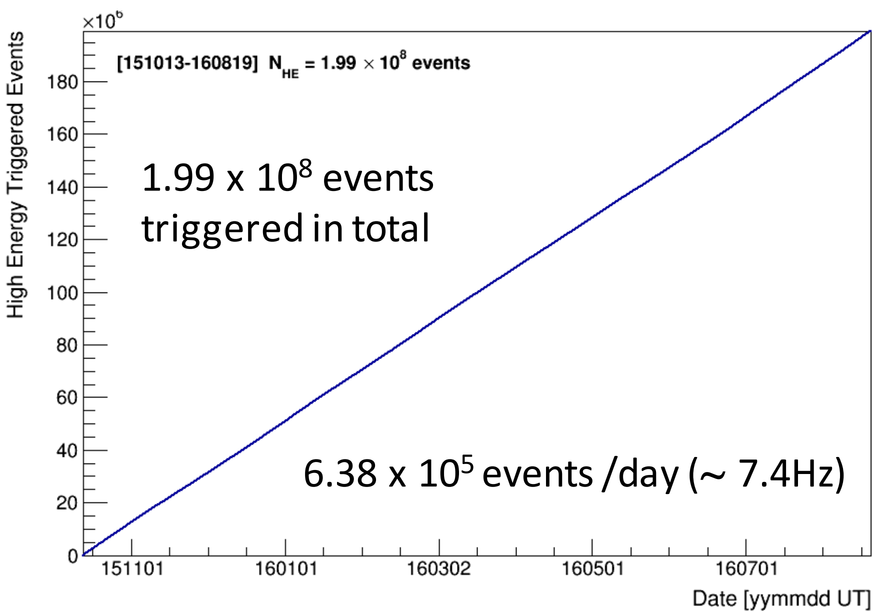
Observation by High Energy Trigger for 312 days : Oct. 13, 2015 – Aug.19, 2016

- The exposure, SΩT, has reached to ~27.1 m² sr day. by continuous observation.
- Total number of the triggered events is ~ 200 million with a live time of 84 %.

Accumulated observation time (live, dead)



Accumulated triggered event number



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

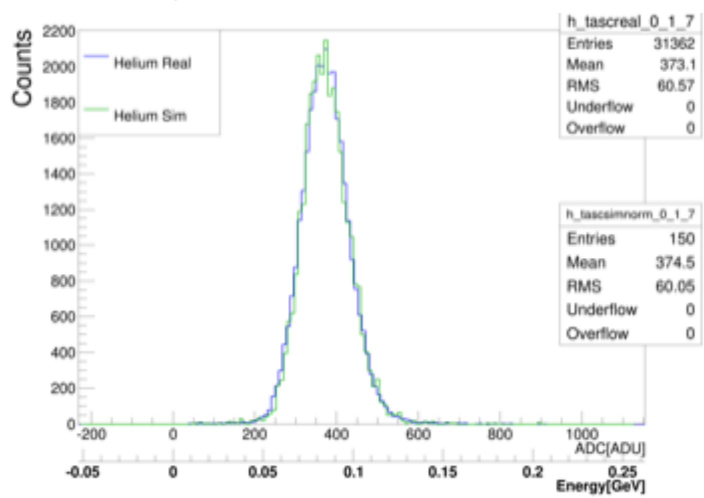
On orbit : Energy conversion factor using "MIP" of p or He

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

On ground: Linearity measurements for the whole dynamic range

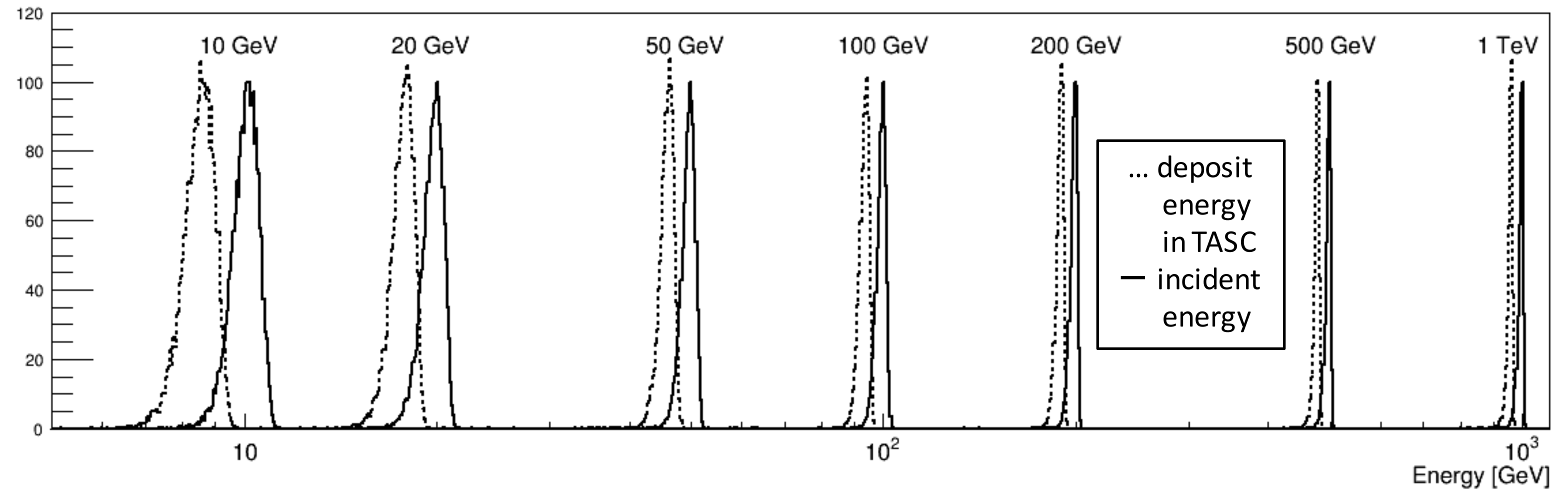
- CHD/IMC – Charge injection
- TASC – UV Laser irradiation (end-to-end)

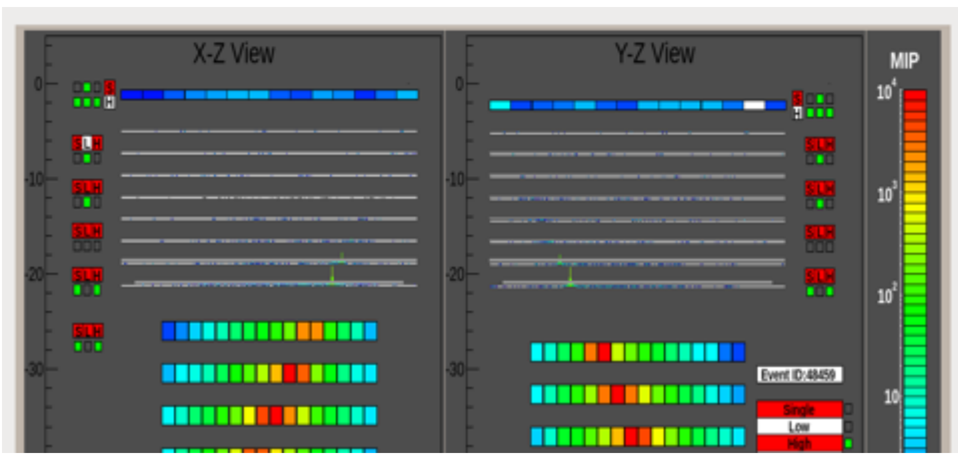
"MIP" peak in PWO: Obs. vs. MC



Energy Reconstruction for Electromagnetic Showers

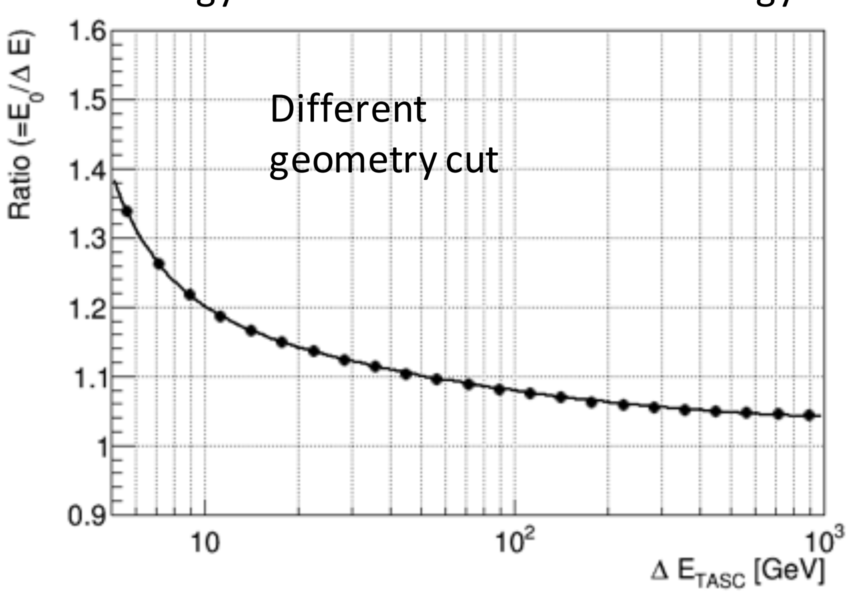
Comparison of deposit energy in TASC (ΔE) with incident energy (E_0) by simulation





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

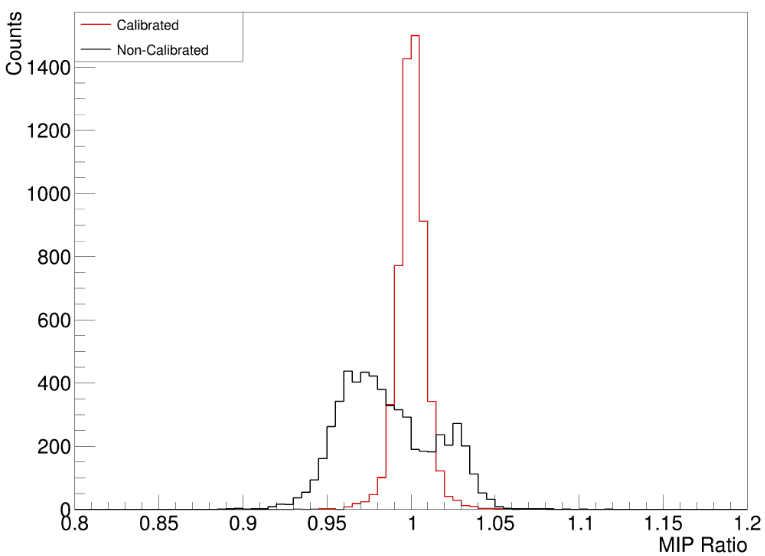
Energy reconstruction factor vs. Energy



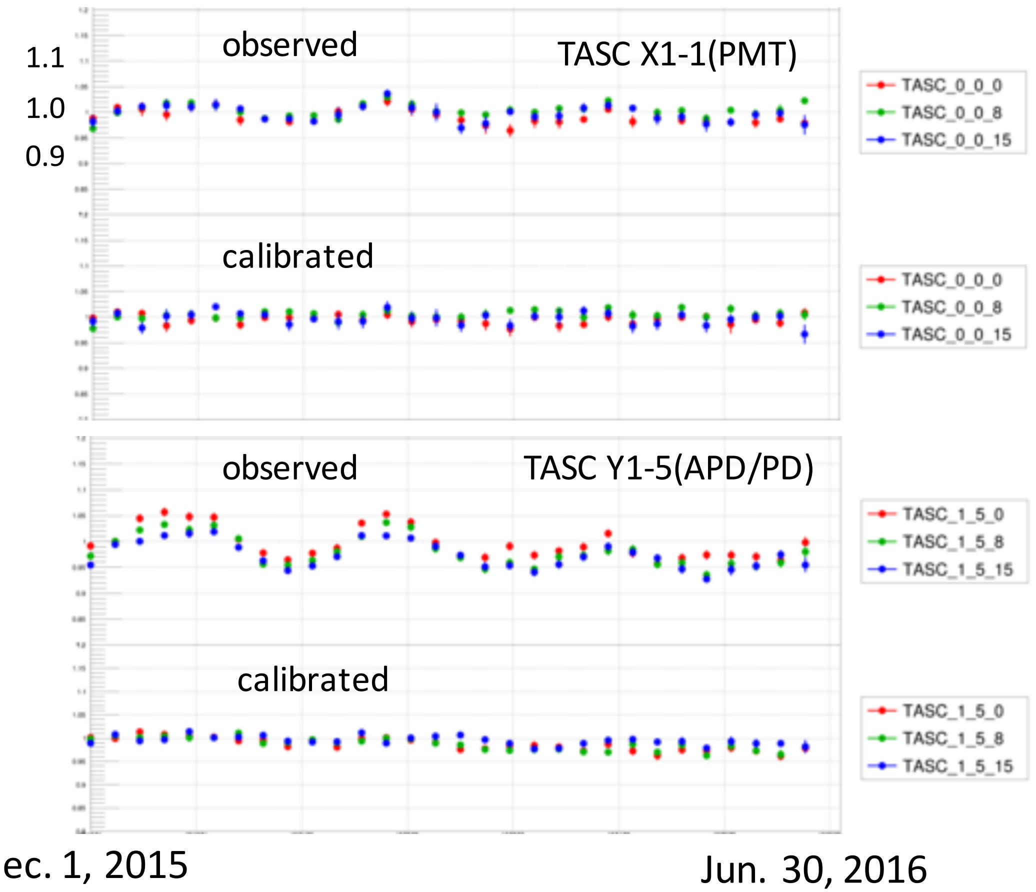
Correction of “MIP” for Temperature Variation in Time

The Active Thermal Control System (ATCS) is adopted to stabilize temperatures at around 20℃.

MIP variation in time



Variation of MIP values for 7 months by temperature difference



Correction for temperature variation in time showed by MIP ratio:
0.9 % in r.m.s after calibration
in comparison to 2.8% before .

*) Typical temperature dependence of MIP signal:
PMT -1.9%/°C, APD/PD -3.4%/°C

Position Dependence of “MIP” Signal in TASC (PWO)

Position Dependence of MIP signals of non-interacting He in PWO Log:

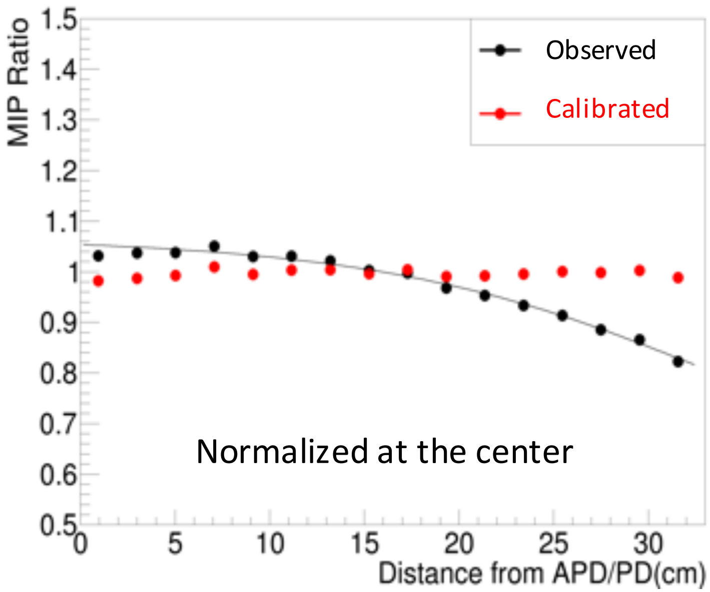
Attenuation of Light Yield (1) + Temperature Distribution(2)

(1) Measured by Flight data using non-interacting p or He

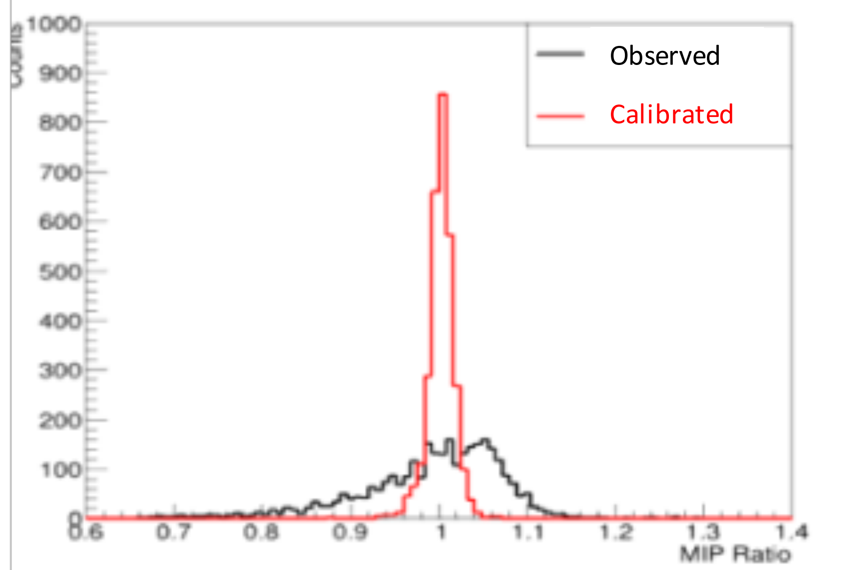
(2) Analyzed by measured temperatures using thermal-vacuum test results on ground

Observed signal are affected by attenuation in length and light yield depending on temperature gradient (Δt～2°C）. These effects tend to compensate with each other.

An example of the position dependence and the calibration.

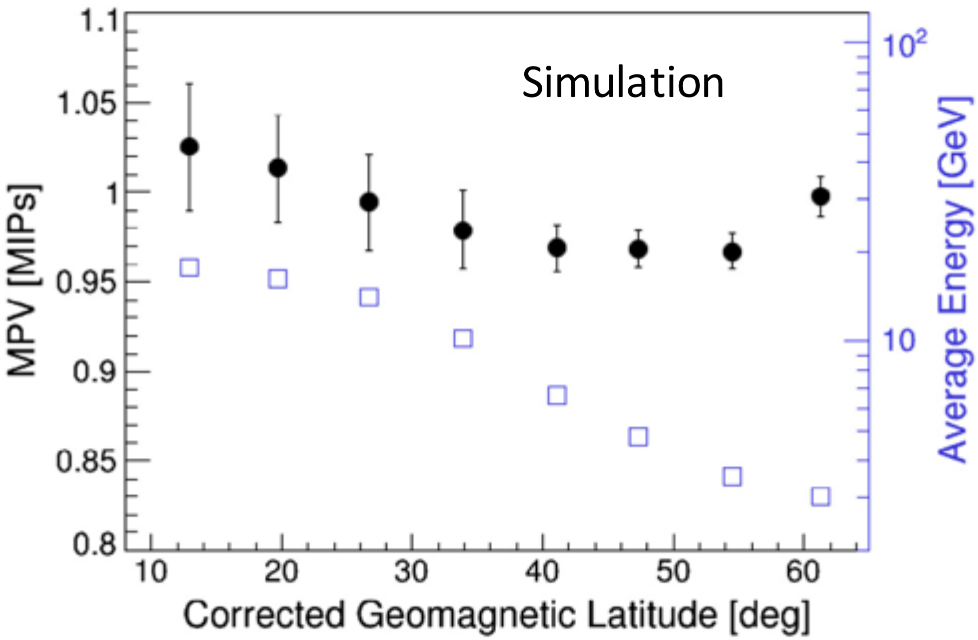


The dependence is reduced to 1.57 % (r.m.s) for a whole of the PWO logs after calibrations.



Correction of “MIP” Variation for Geomagnetic Cut-off

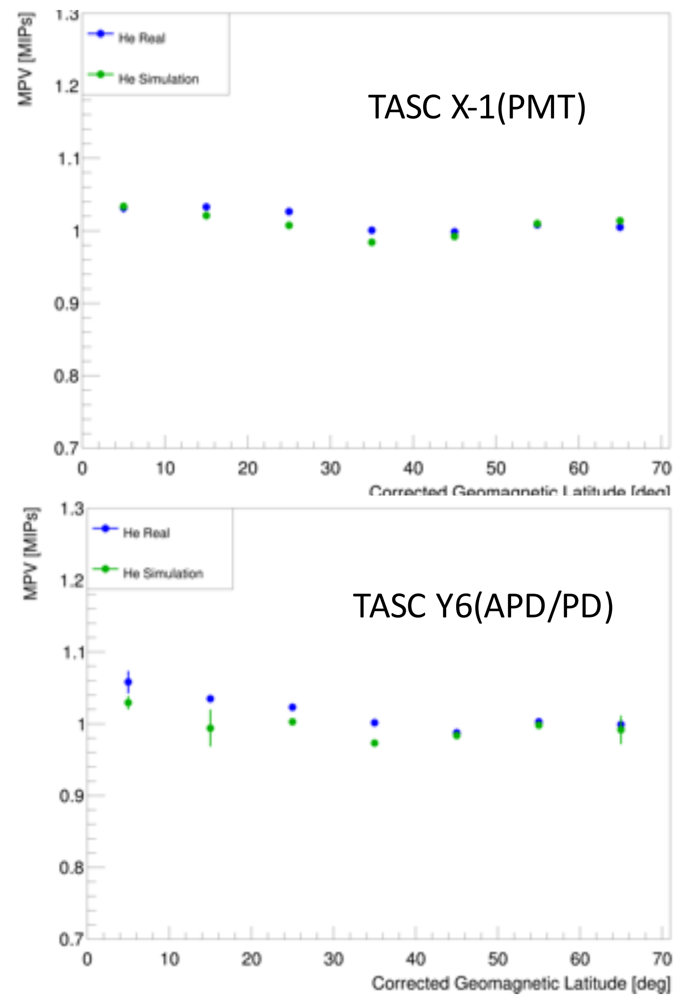
T.Niita et al. ASR 55(2015) 2500



The MIP values depends on the Geomagnetic Latitudes since the observed average energy varies with the rigidity from 3 to 15 GeV. (Since an inclination angle of the ISS orbit is 51.6 degree)

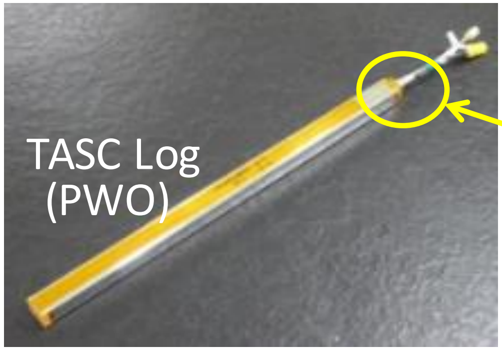
The variation of the MIP values is expected within a few %.

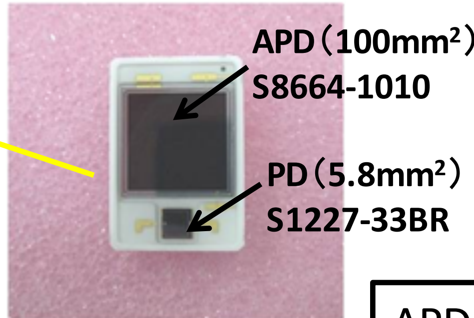
Comparison of observed MIP of non-interacting He with simulations

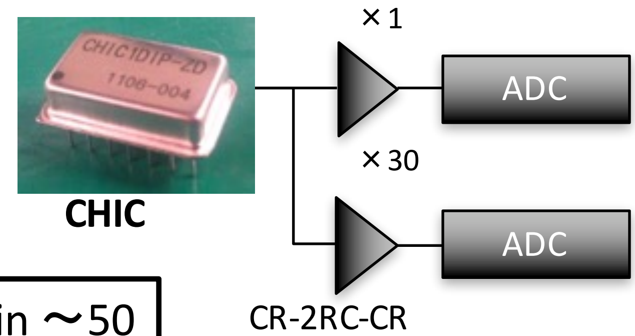


Discrepancy between observed MIP and simulated is within 3 %.

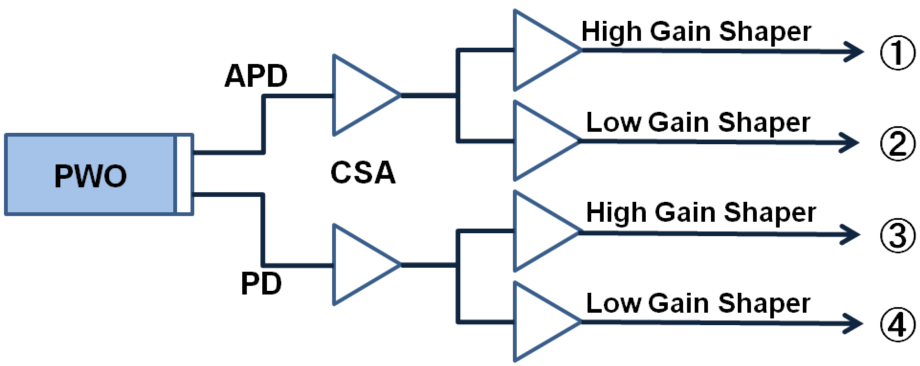
Energy Calibration in Dynamic Range of 1-10^6 MIP in TASC



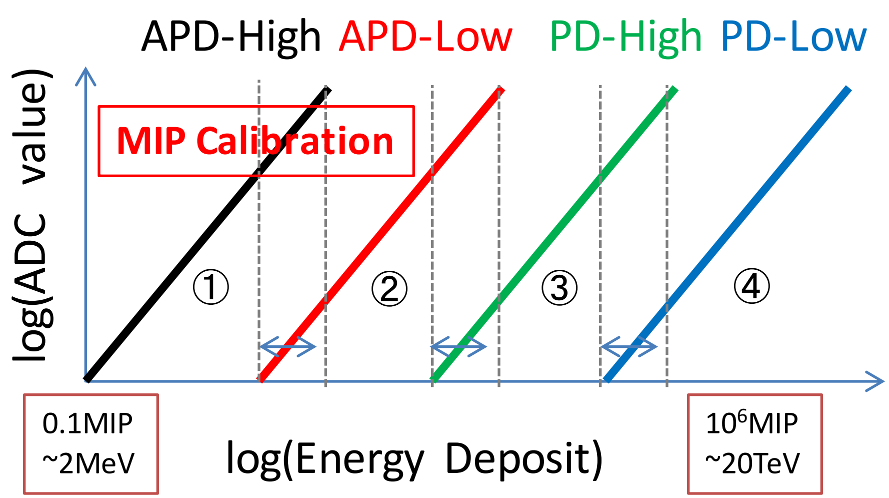




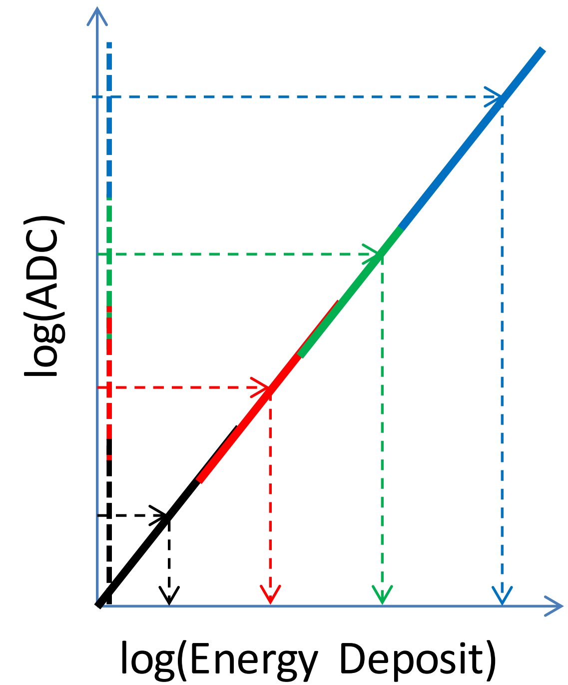
APD gain ～50



Calibrating full range (6 order of magnitude) is quite a challenge !

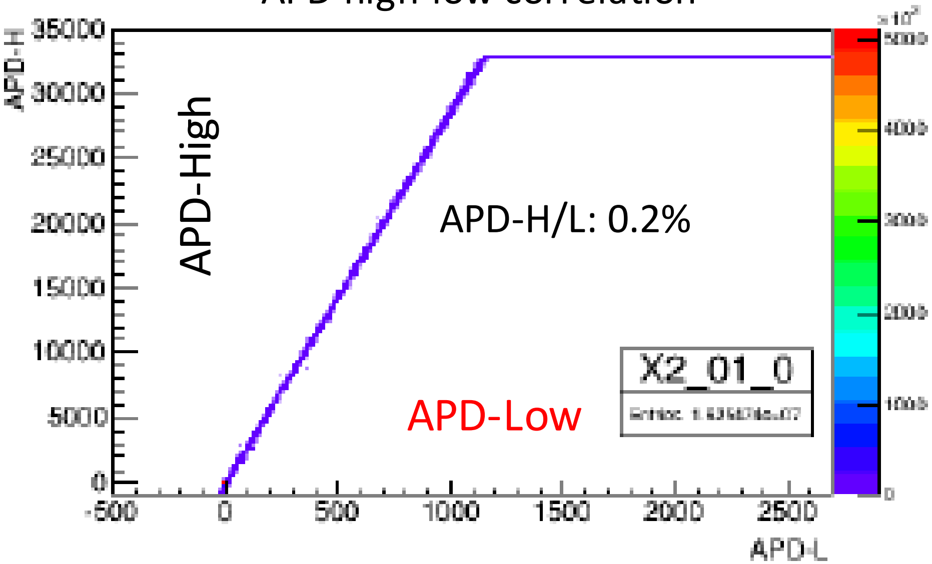


Gain Ratio Calibration Using UV Pulse Laser

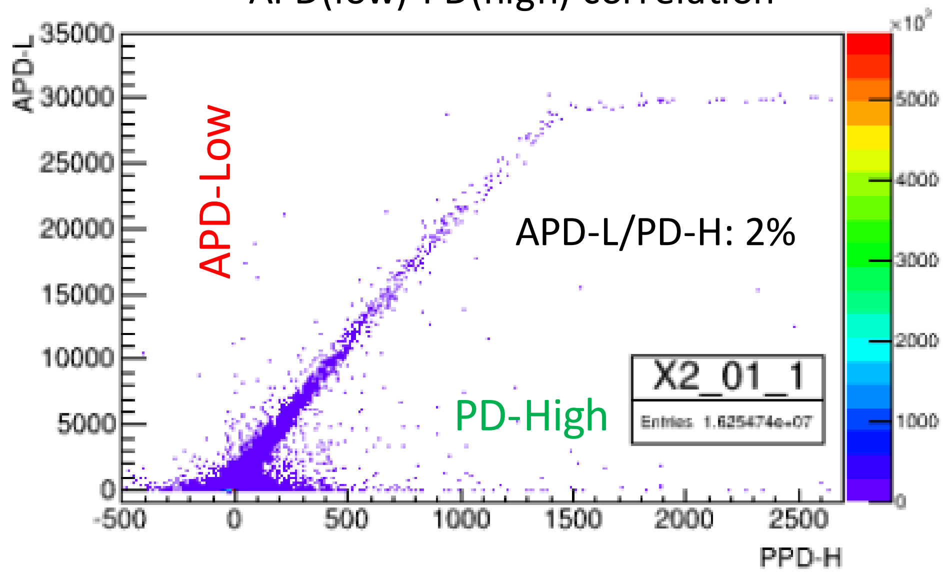


Correlation between Adjacent Gain Range for In-flight Data

APD high-low correlation



APD(low)-PD(high) correlation

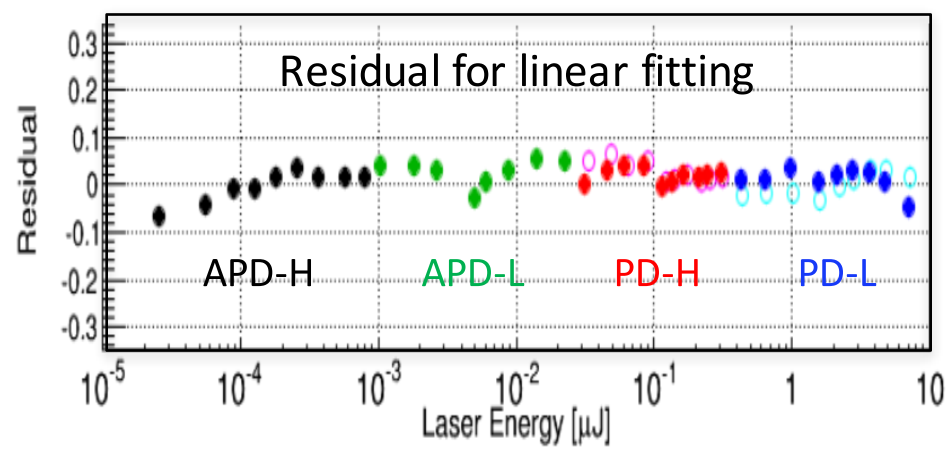


The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel . The linearity has been calibrated by using UV laser irradiation on ground :

1) The linearity is confirmed in the range of 1.2-2.4 %.

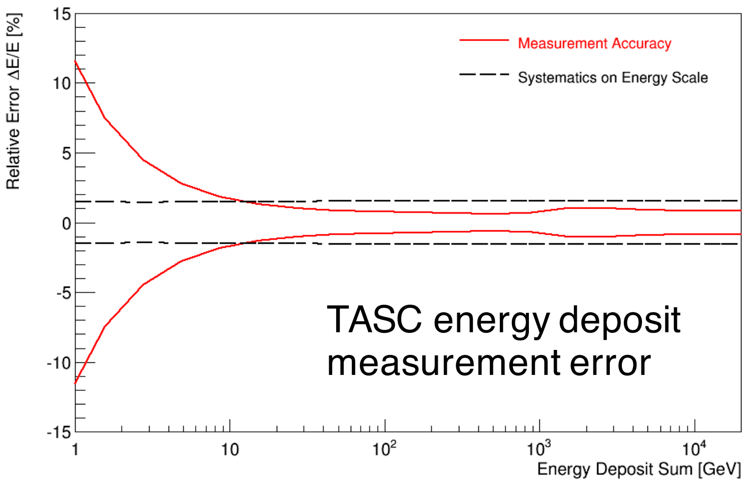
2) The whole dynamic range is confirmed to cover from 1 MIP to 10^6 MIPs.

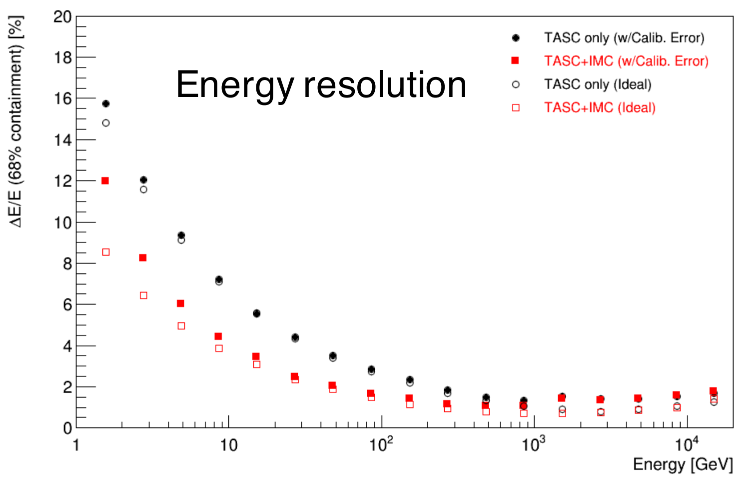
On-ground UV laser test for linearity



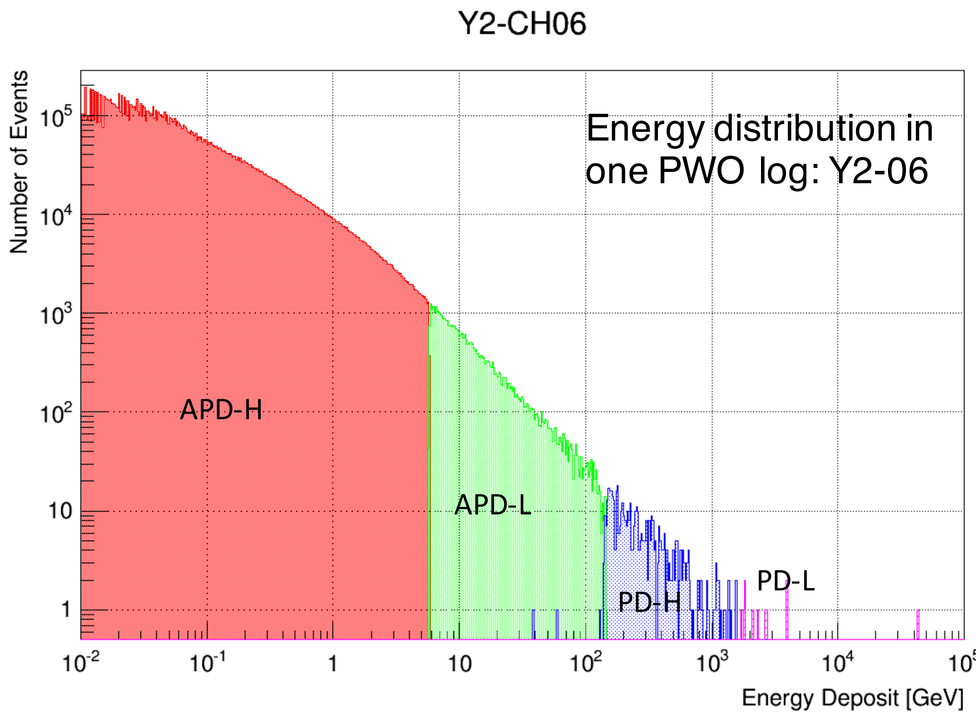
Energy Measurement by Adopting the In-flight Calibrations

Expected performance of energy measurement using TASC by simulations in which the in-flight calibration errors are included.



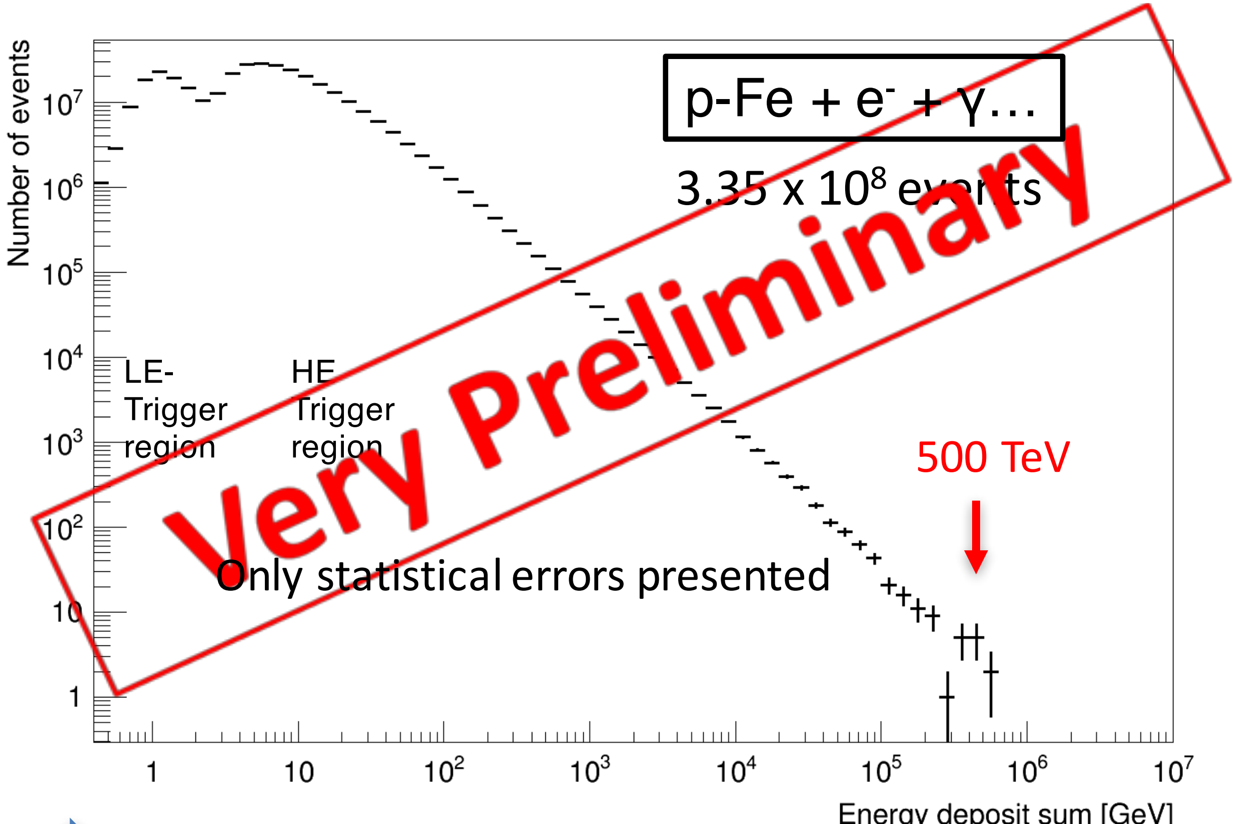


Confirmation of range connection accuracy using the observed events:
The different four ranges are smoothly connected from 1 MIP (~0.1GeV for He) to over 10^3 GeV in one PWO log.



Energy Deposit Distribution of All Triggered-Events by Observation for Nearly 10 months

Distribution of deposit energies in TASC observed in 2015.10.13—2016.08.19

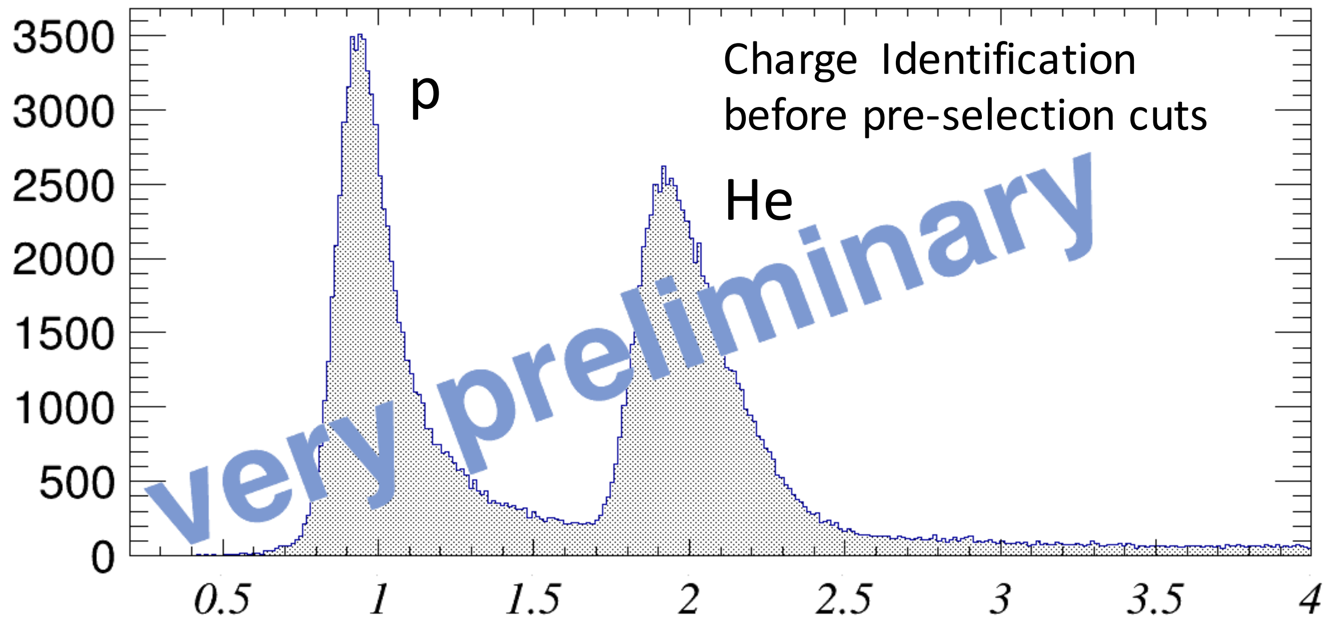


Energies are calibrated but non reconstructed

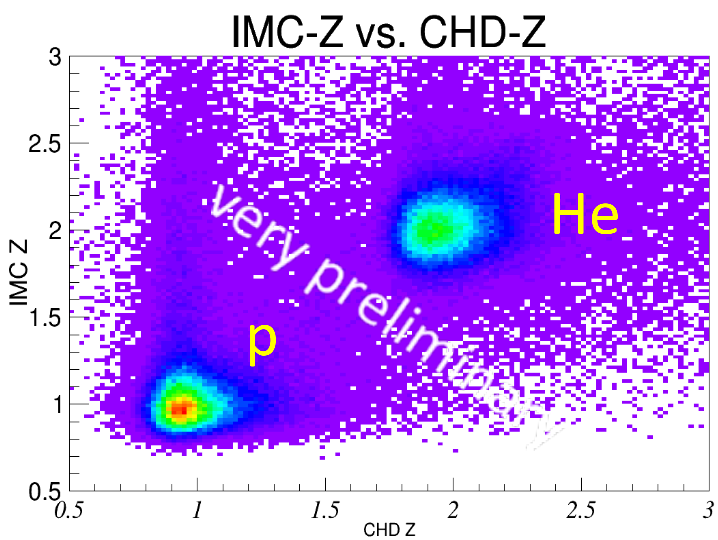
The TASC energy measurements have successfully been carried out in the dynamic range of 1 GeV – several 100 TeV.

Preliminary Nuclei Measurements – p , He –

data selection is NOT representive of elemental abundances



Atomic Number Z

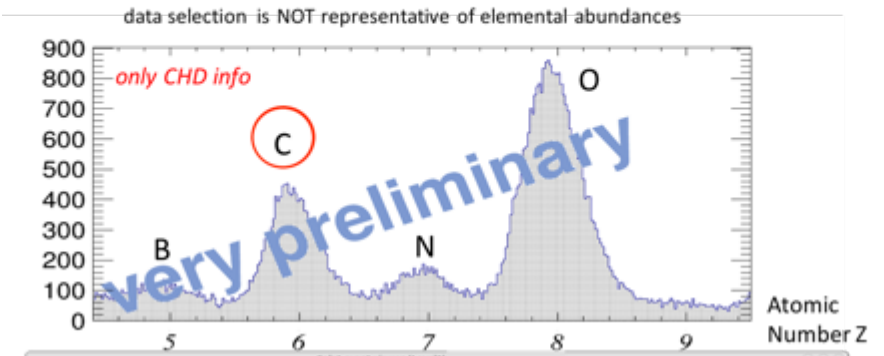


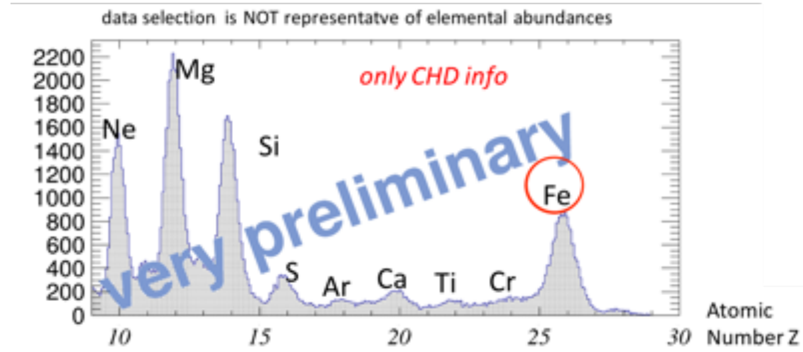
Using multiple dE/dx measurements from the IMC scin/lla/ng fibers (upstream the interaction point), a complementary charge measurement from IMC is ploted vs the CHD charge assignment (abscissa).

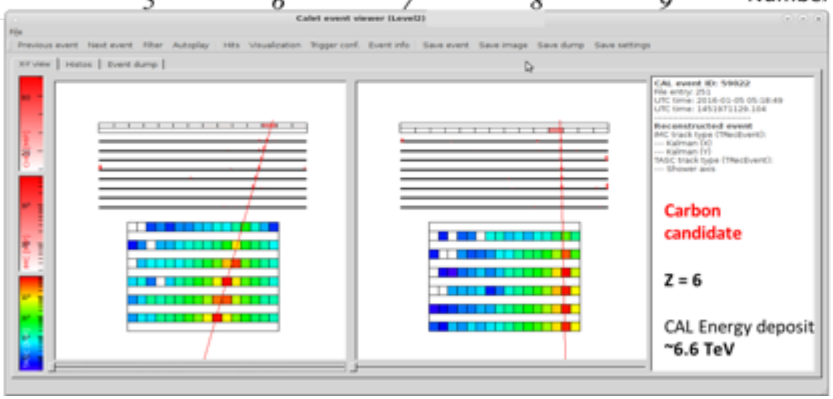
A clear separation between p and He can be seen from preliminary data analysis.

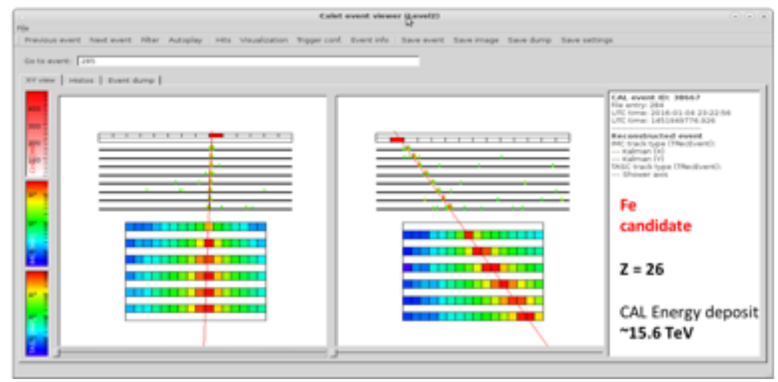
Preliminary Nuclei Measurements – Z = 3 ~ 40 –

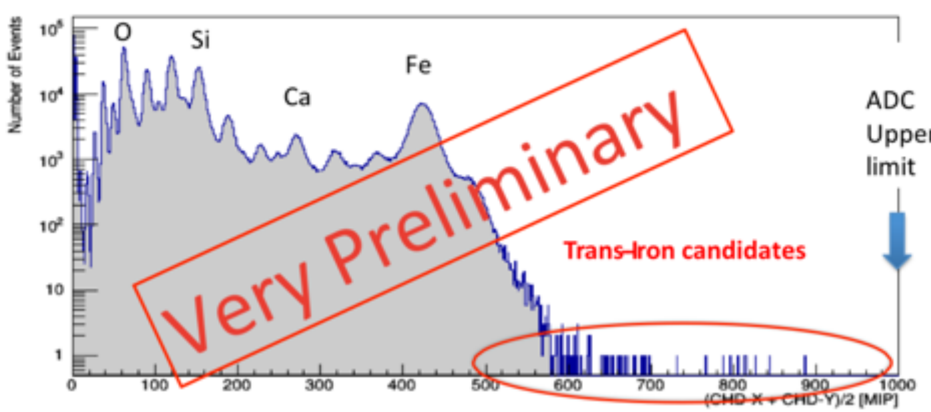
Charge Identification after pre-selection cuts

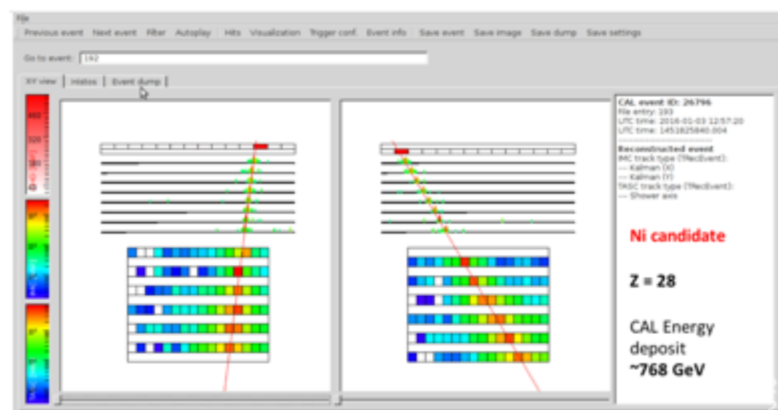








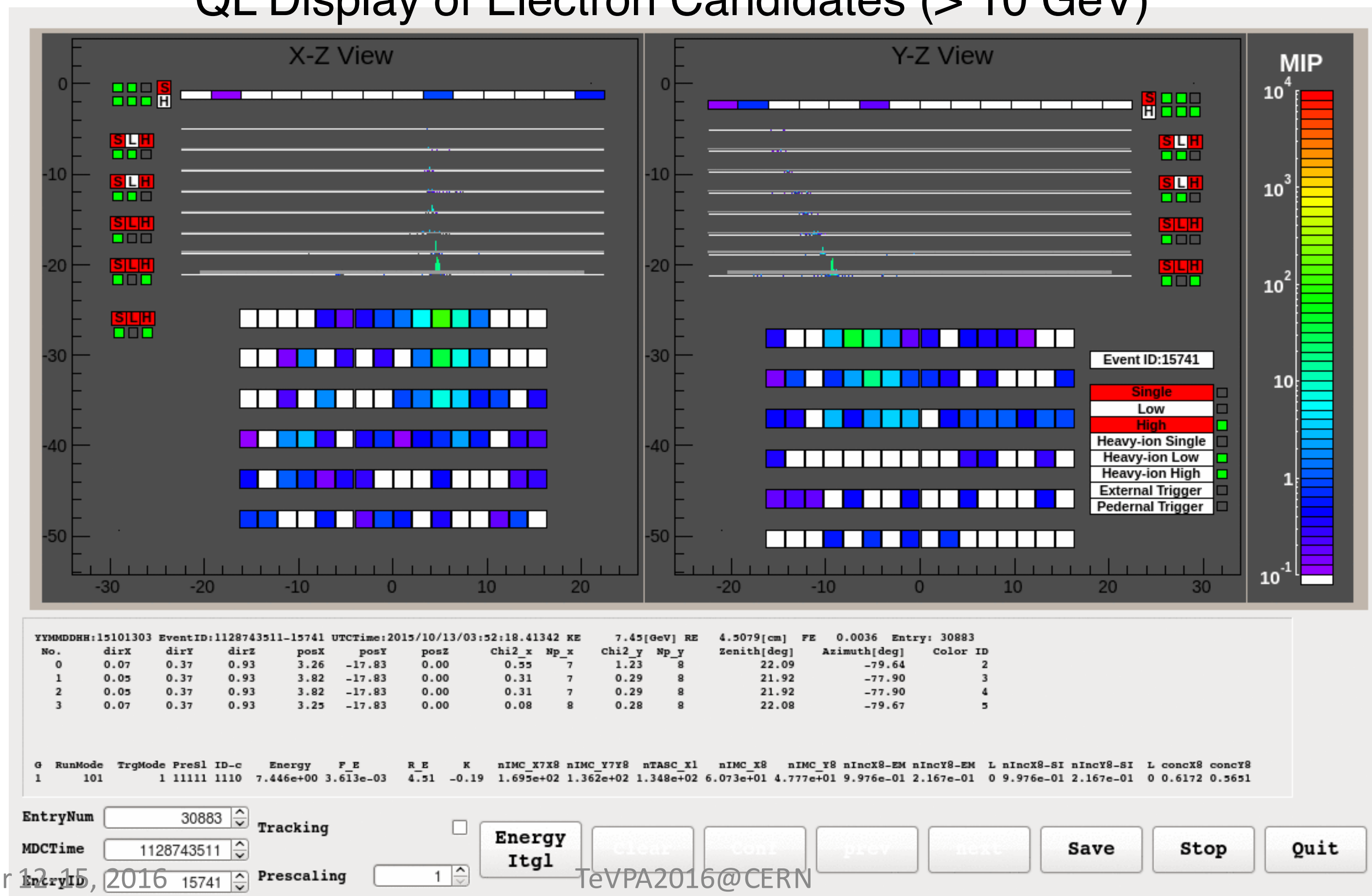




Preliminary Status of Electron Observations

For an observation for 312 days (Oct. 13, 2015 – Aug. 19, 2016), a number of the selected electron candidates is about 1.14 x 10^6 event (>10GeV) with an efficiency cut of 90 % (without correction of proton contamination: less than several %).

QL Display of Electron Candidates (> 10 GeV)



Preliminary Simple e/p Separation

Definition of parameters

$$R_E = \sqrt{\frac{\sum_i \{\sum_j \Delta E_{i,j} \times R^2{}_i\}}{\sum_i \sum_j \Delta E_{i,j}}}$$

(Lateral Spread)

$$F_E = \frac{\sum_j \Delta E_{12,j}}{\sum_i \sum_j \Delta E_{i,j}}$$

(Shower development)

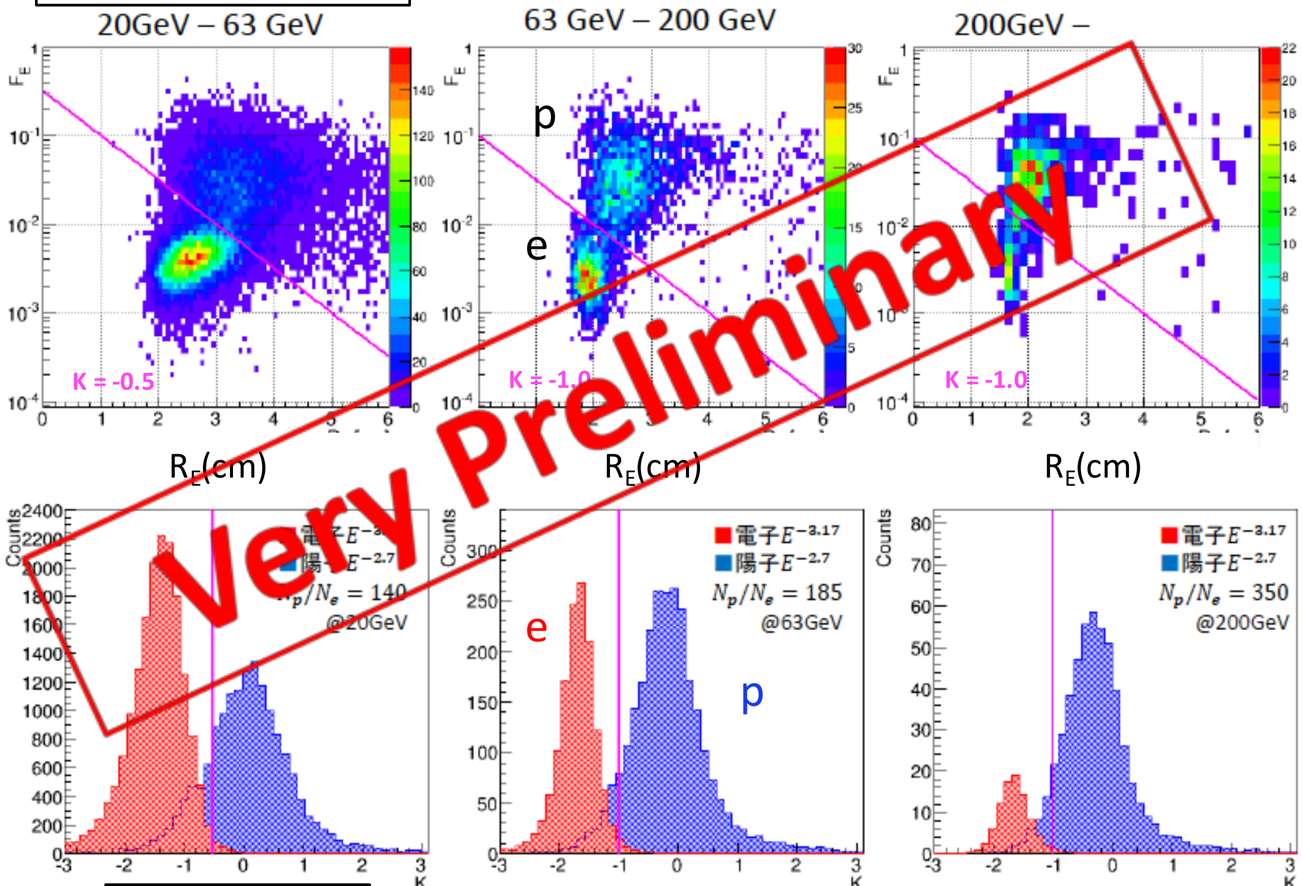
$$R_i = \sqrt{\frac{\sum_j \{\Delta E_{i,j} \times (x_j - x_c)^2\}}{\sum_j \Delta E_{i,j}}}$$

x_c : shower axis center

$\Delta E_{i,j}$: ΔE at i-th layer, j-th PWO

Observed events

(As of Nov.17, 2015 -- 90 days after launch: observation ~1 month)



Simulation

e/p separation parameter

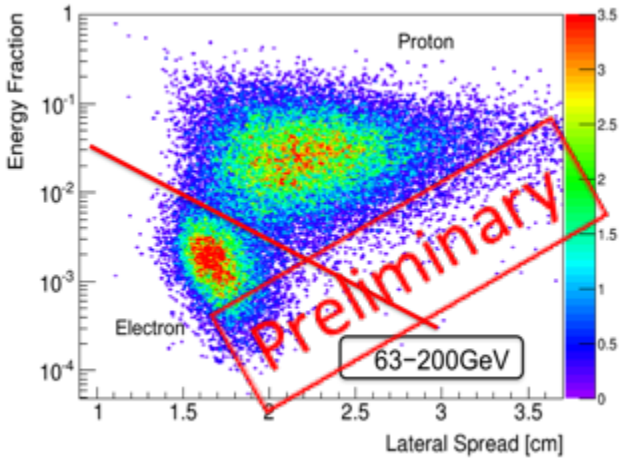
$$K = \frac{R_E}{2} + \log_{10}(F_E)$$

The K values are optimized by simulation to get a selection efficiency of 90% in each energy range.

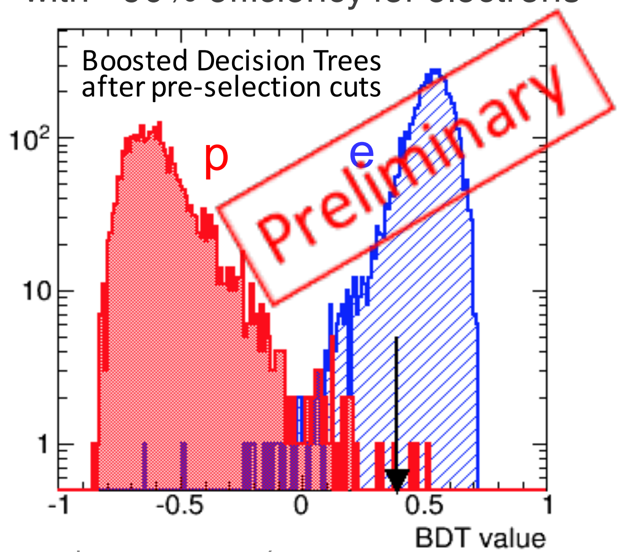
Very preliminary analysis using only two parameters. Multi parameter analysis will be applied to achieve better separation as expected from simulations.

Differential Energy Distribution of the Electron-Candidates in 10-1000 GeV by observation for nearly 10 months

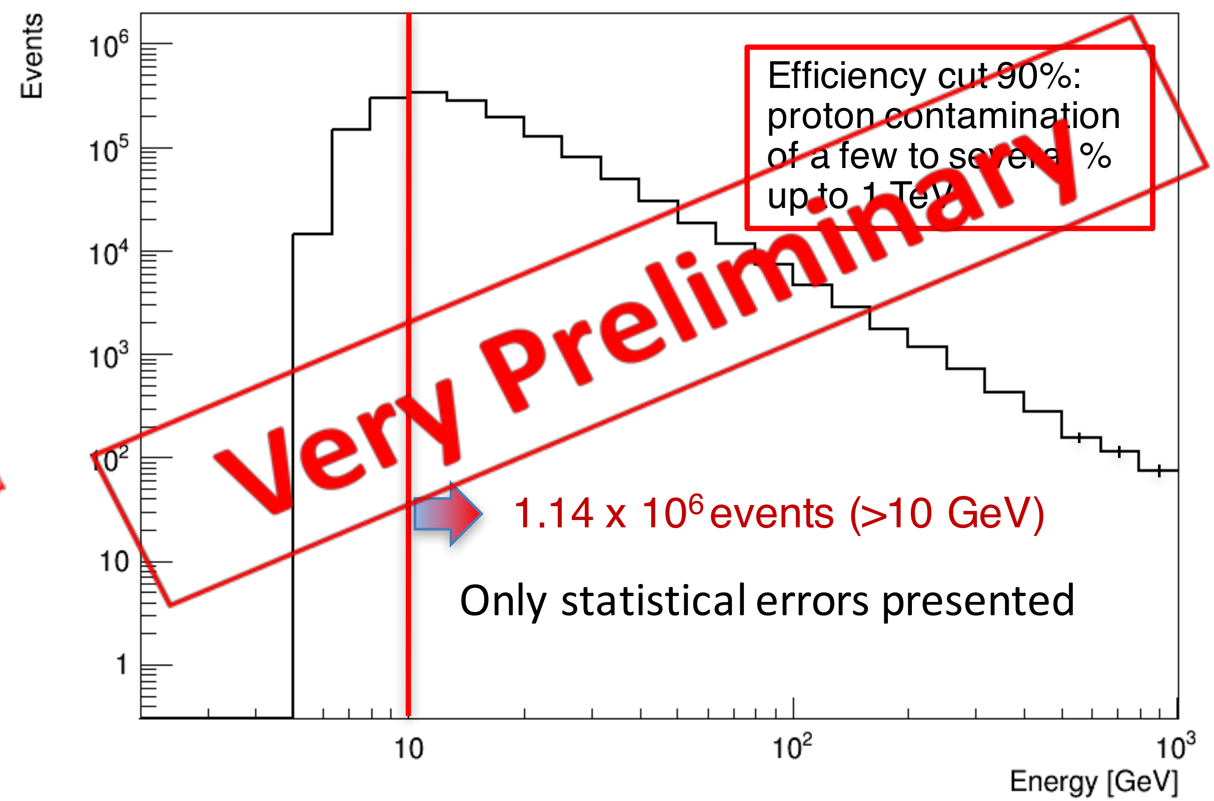
Observation: e/p separation after pre-selection cuts



Simulation : e/p at 1TeV ~1.3 x10^5 with ~90% efficiency for electrons



Differential energy distribution reconstructed by using the electron candidate events observed in 2015.10.13—2016.08.19

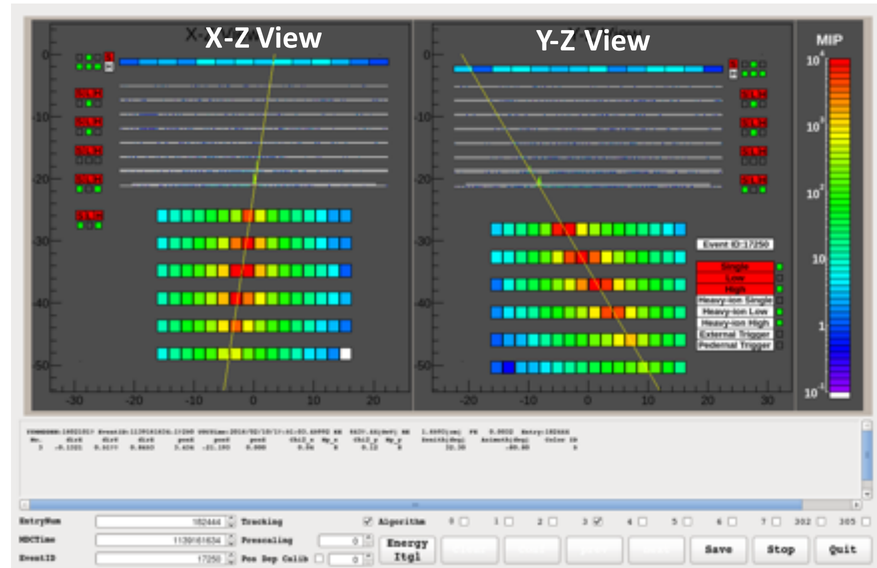


Energies are reconstructed after the calibrations.

Examples of Electron Candidates in TeV Region

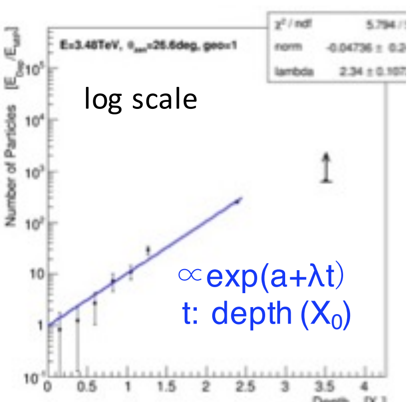
Energy: 3.62 TeV (θ=26.5°)

Energy: 6.75 TeV (θ=32.3°)

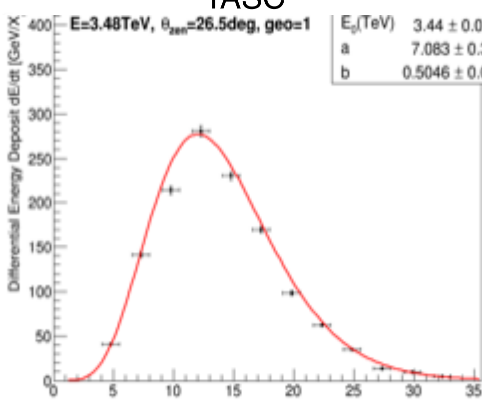


Longitudinal development of shower particles in IMC and TASC with fit of EM shower

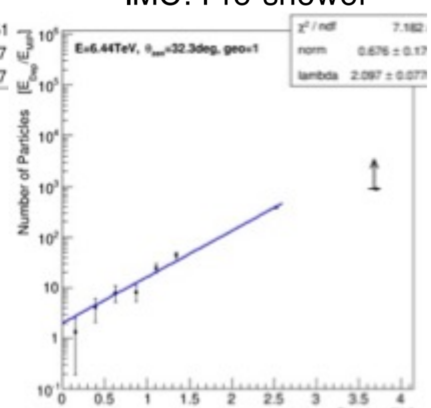
IMC: Pre-shower



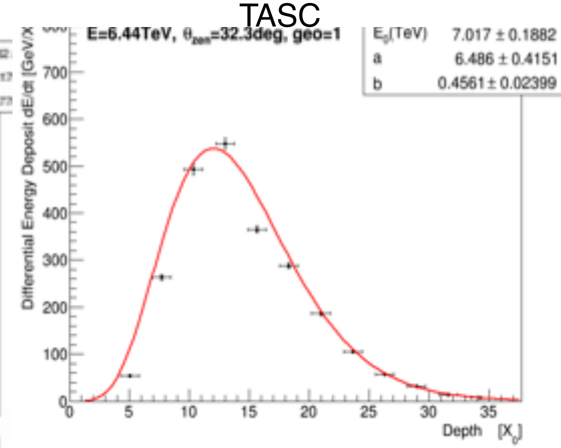
TASC



IMC: Pre-shower



TASC

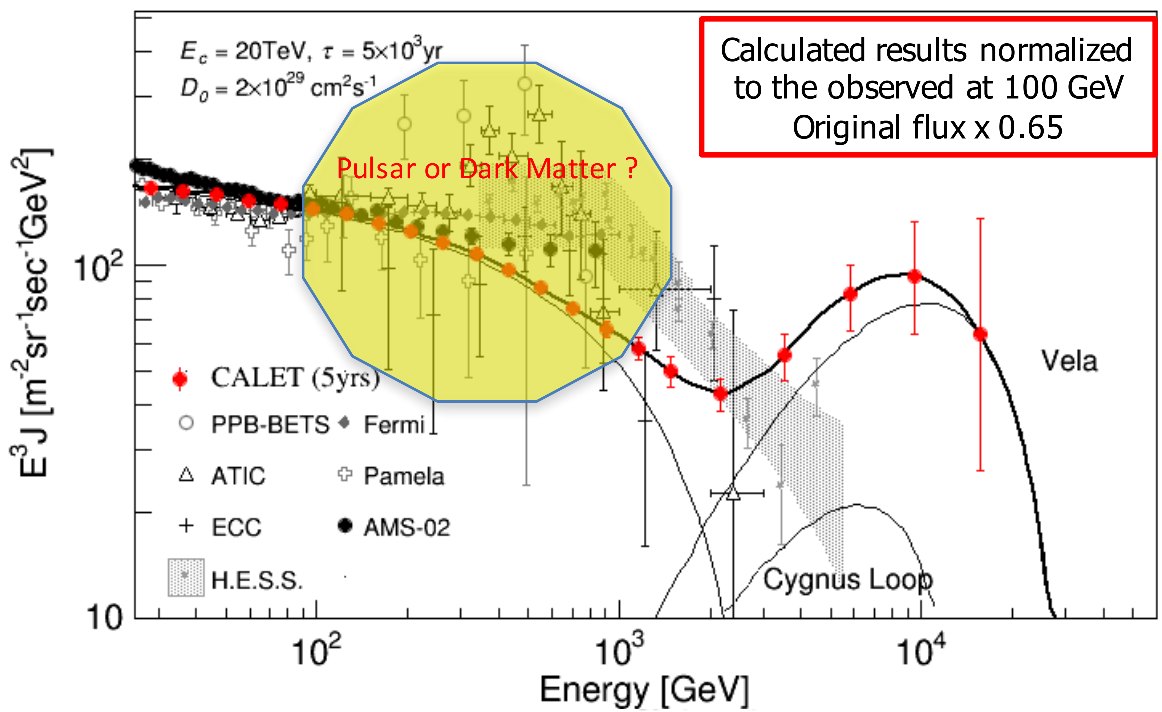


CALET Main Target: Identification of Electron Sources

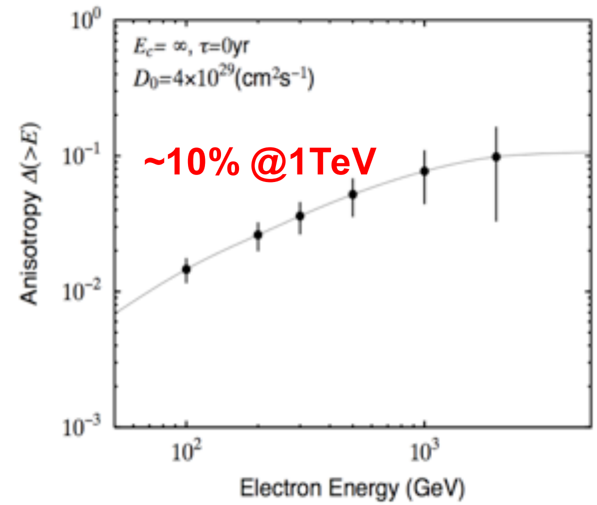
Some nearby sources, e.g. Vela SNR, might have unique signatures in the electron energy spectrum in the TeV region (Kobayashi et al. ApJ 2004)

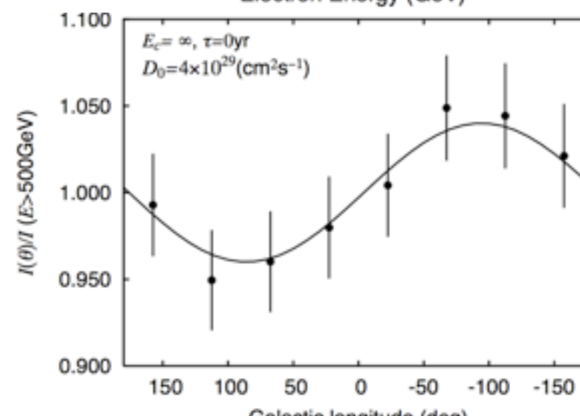
Expected flux for 5 year mission assuming E^{-3}

> 10 GeV	~ 2.7 x 10^7
>100 GeV	~ 2.0 x 10^5
>1000 GeV	~ 1.0 x 10^3



Expected Anisotropy from Vela SNR

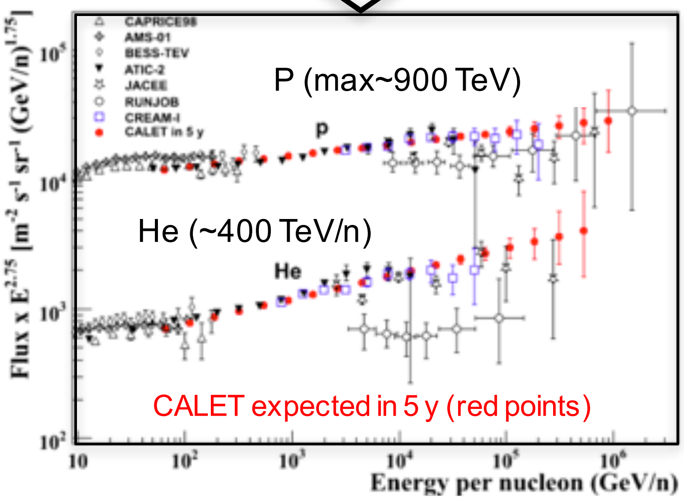




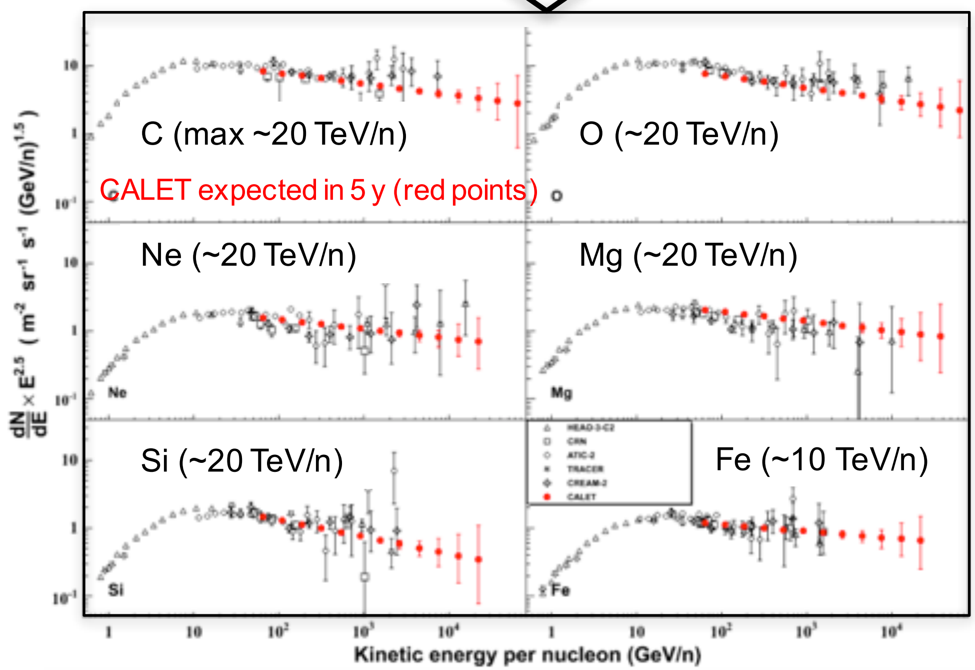
Identification of the unique signature from nearby SRNs, such as Vela, in the electron spectrum by CALET

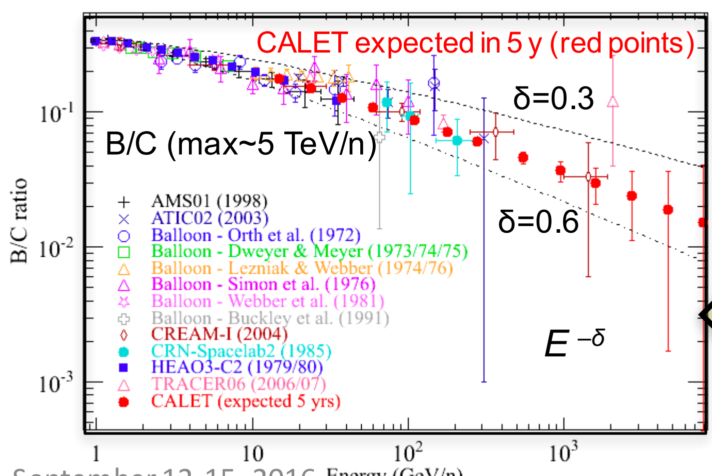
Measurements of Cosmic Nuclei Spectra with CALET

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



- All primary heavy nuclei spectra well fitted to single power-laws 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 below 100 GeV/n indicate δ~0.6. At high energy the ratio is expected to flatten out (otherwise CR anisotropy should be larger than that observed)

CALET’s first publication NOT for Cosmic Rays

Accepted article online 25 APR 2016

Geophysical Research Letters

Relativistic electron precipitation at International Space Station: Space weather monitoring by Calorimetric Electron Telescope

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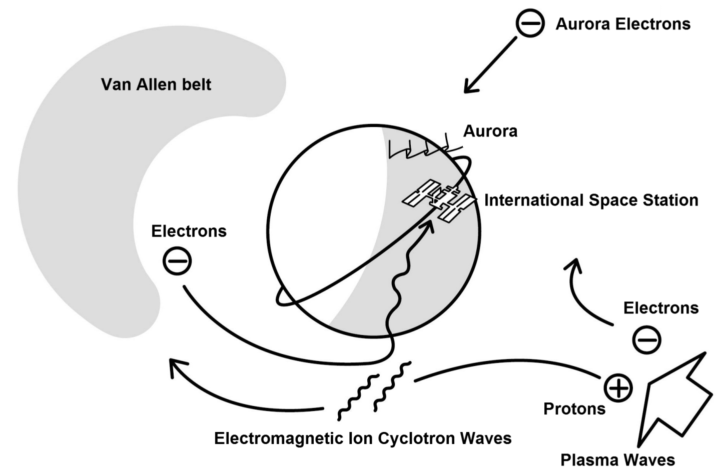
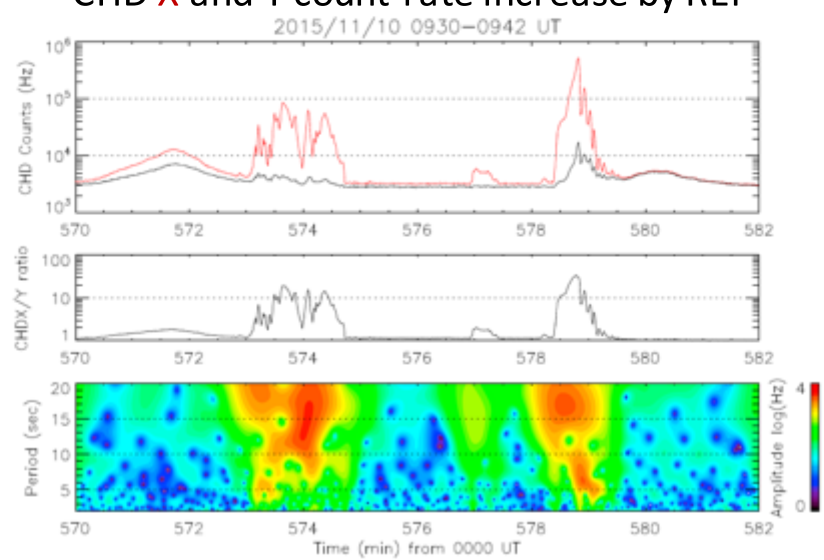
Abstract The charge detector (CHD) of the Calorimetric Electron Telescope (CALET) on board the International Space Station (ISS) has a huge geometric factor for detecting MeV electrons and is sensitive to relativistic electron precipitation (REP) events. During the first 4 months, CALET CHD observed REP events mainly at the dusk to midnight sector near the plasmapause, where the trapped radiation belt electrons can be efficiently scattered by electromagnetic ion cyclotron (EMIC) waves. Here we show that interesting 5–20 s periodicity regularly exists during the REP events at ISS, which is useful to diagnose the wave-particle interactions associated with the nonlinear wave growth of EMIC-triggered emissions.

Space Weather is now a new topic of the CALET science !!

Relativistic Electron Precipitation



CHD X and Y count rate increase by REP



CALET UPPER LIMITS ON X-RAY AND GAMMA-RAY COUNTERPARTS OF GW 151226

http://arxiv.org/abs/1607.00233v2: accepted by Astrophysical Journal Letters

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 a moment of the GW151226 event

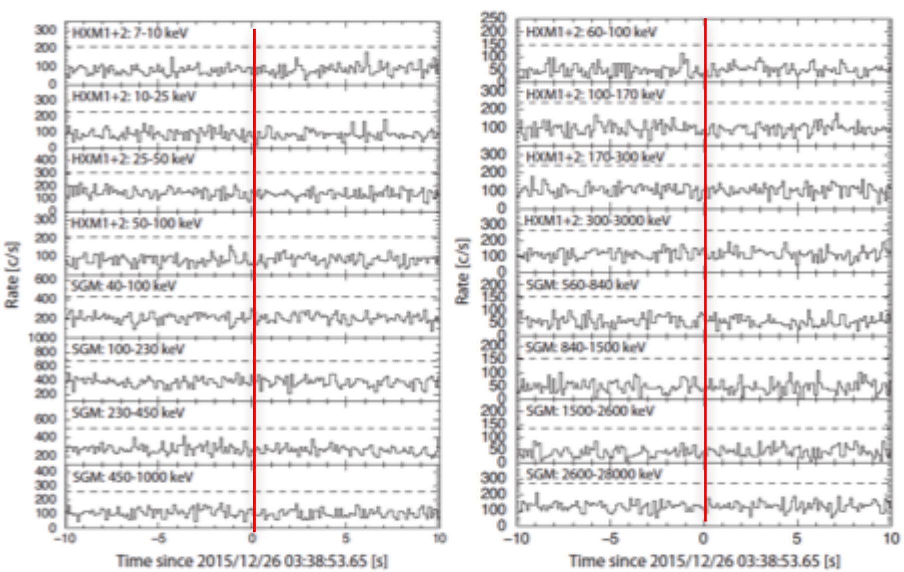


Figure 1. The CGBM light curves in 0.125 s time resolution for the high-gain data (left) and the low-gain data (right). The time is offset from the LIGO trigger time of GW 151226. The dashed-lines correspond to the 5 σ level from the mean count rate using the data of ±10 s.

Upper limit for gamma-ray burst monitors and Calorimeter

HXM: 7-500 keV

SGM: 50-1000 keV

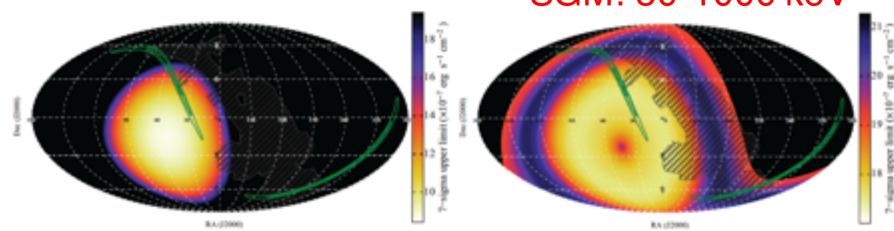


Figure 2. The sky maps of the 7 σ upper limit for HXM (left) and SGM (right). The assumed spectrum for estimating th upper limit is a typical BATSE S-GRBs (see text for details). The energy bands are 7-500 keV for HXM and 50-1000 keV fo SGM. The GW 151226 probability map is shown in green contours. The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

Calorimeter: 1-100 GeV

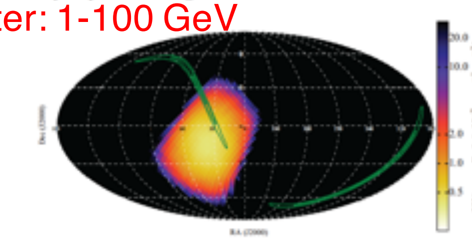


Figure 3. The sky map of the 90% upper limit for CAL in the 1-100 GeV band. A power-law model with a photon index of − is used to calculate the upper limit. The GW 151226 probability map is shown in green contours.

Summary

- CALET was successfully launched from Tanega-shima Space Center (TNSC) on Aug. 19, 2015, and the detector is being very stable for observation since Oct. 13, 2015. As of Aug.19, 2016, nearly 200 million events are collected with high energy trigger.

- Careful calibrations have been adopted by using "MIP" signals of the non-interacting p & He events, and the linearity in the energy measurements up to 10^6 MIPs is established within a few % by using observe shower events. As a result, the TASC energy measurement is confirmed to be: (1) Errors over 10 GeV are less than a few %. (2) Energy resolution is less than 2 % over 100 GeV for electromagnetic showers. (3) TASC energy deposits are successfully measured up to 500 TeV.
- Electron selection is carried out with 90% efficiency cut up to 1 TeV, and 1.14×10^6 electron candidates are selected over 10 GeV among 1.47×10^8 triggered events. Electron event candidates have been observed above 1 TeV.
- Cosmic rays from proton to Fe and Ultra Heavy ions ($26 < Z < 40$), as well as gamma-rays have been detected. Energy spectra, relative elemental abundances and secondary-to-primary ratios are being measured.
- CALET's CGBM has measured the light curves of 30 GRB's as of July, 2016.
- 5-year Observations are planned.