CALET preliminary results on the cosmic ray observations for the first two-years on the ISS

<u>Yoichi Asaoka</u>

for the CALET collaboration

WISE, Waseda University

CALET collaboration team

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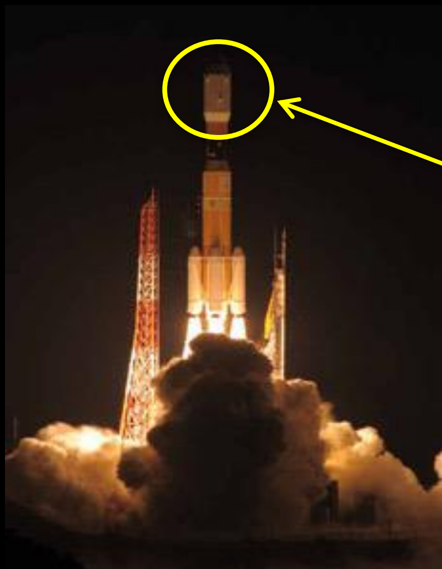
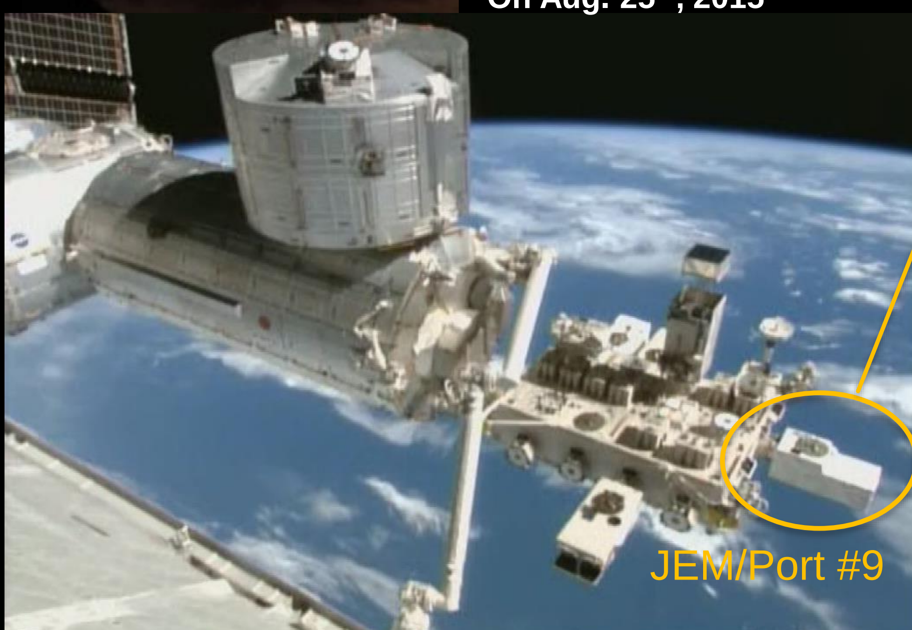
CALET Payload

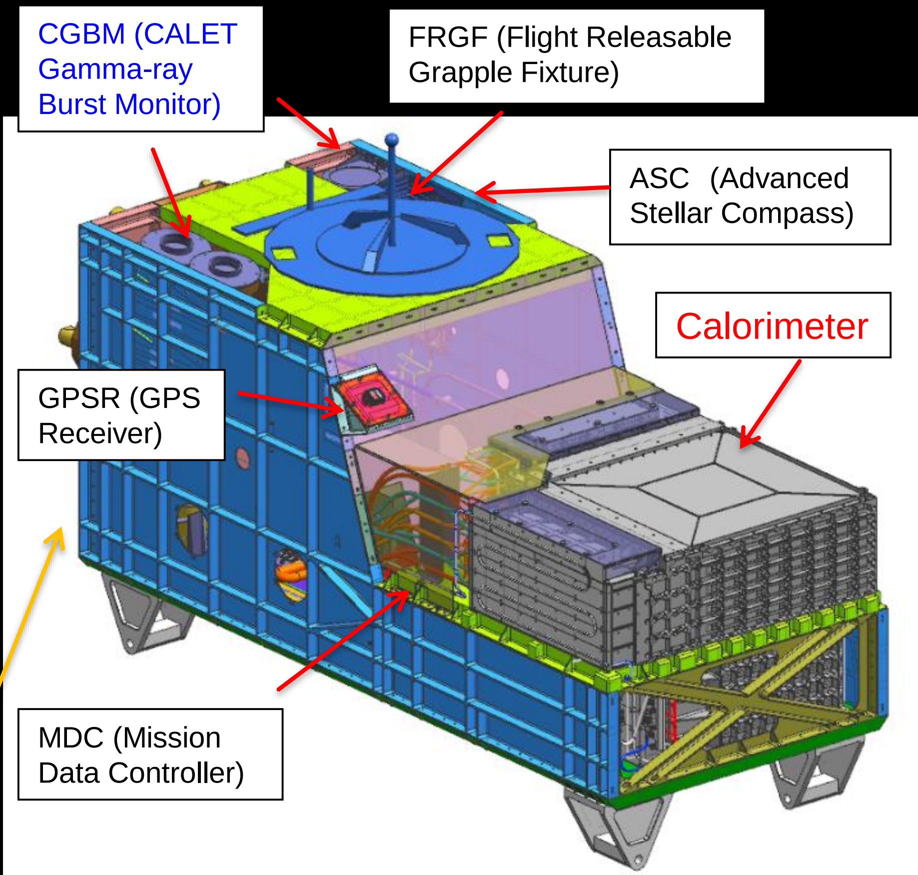


Kounotori (HTV) 5

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

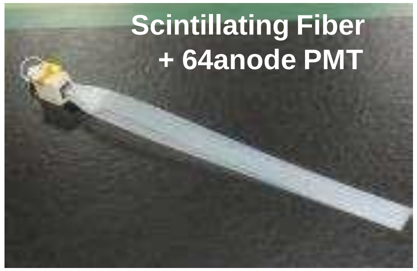
Emplaced on JEM-EF port #9
On Aug. 25th, 2015

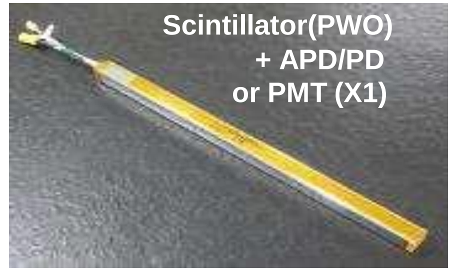




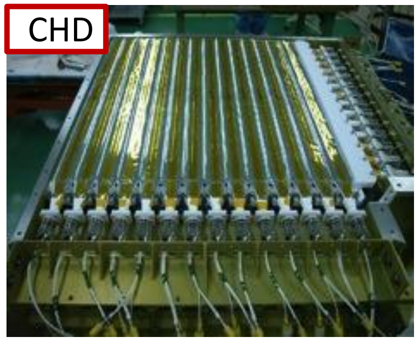
- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W（max）**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

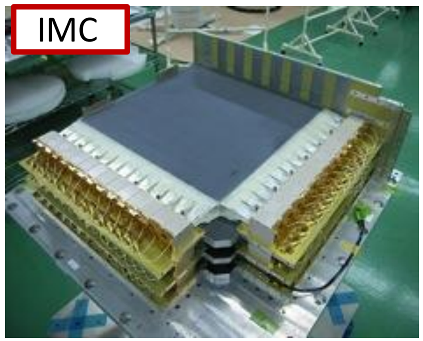
CALET Instrument

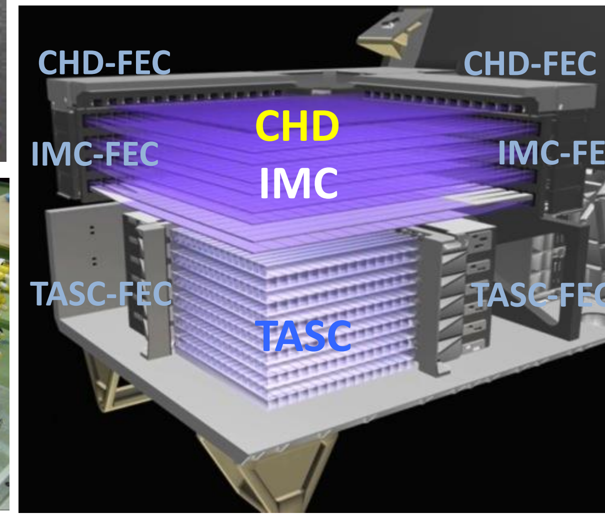




CALORIMETER







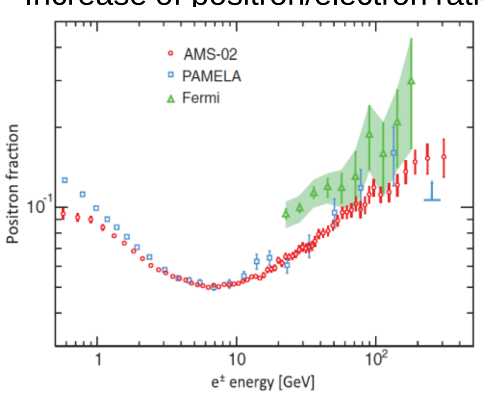
	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers (X,Y) : 7168 Scifi 7 W layers (3X_0): 0.2X_0 x 5 + 1X_0 x2 Scifi size : 1 x 1 x 448 mm^3**	**16 PWO logs x 12 layers (x,y): 192 logs log size: 19 x 20 x 326 mm^3 Total Thickness : 27 X_0 , ~1.2 λ_I**
Readout	**PMT+CSA**	**64-anode PMT+ ASIC**	**APD/PD+CSA PMT+CSA (for Trigger)@top layer**

Scientific Goals

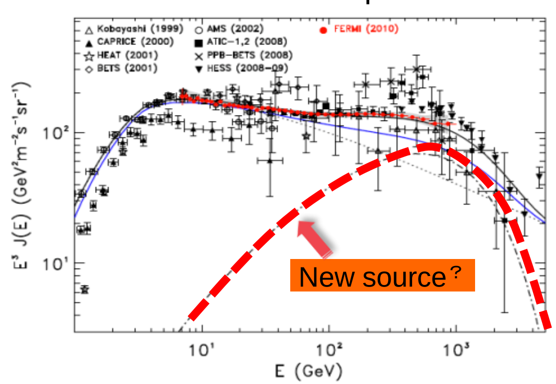
Scientific Objectives	Observation Targets	Energy Range
CR Origin and Acceleration	Electron spectrum p- - Fe individual spectra Ultra Heavy Ions (26<Z≤40) Gamma-rays (Diffuse + Point sources)	1GeV - 20 TeV 10 GeV - 1000 TeV > 600 MeV/n 1 GeV - 1 TeV
Galactic CR Propagation	B/C and sub-Fe/Fe ratios	Up 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	< 10 GeV
Gamma-ray Transients	Gamma-rays and X-rays	7keV - 20 MeV

Respond to the unresolved questions from the results found by recent observations

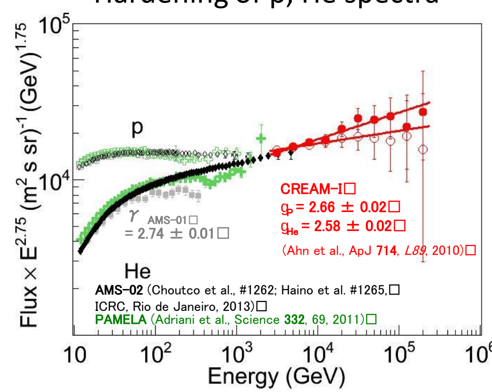
Increase of positron/electron ratio



Excess of electron+positron flux



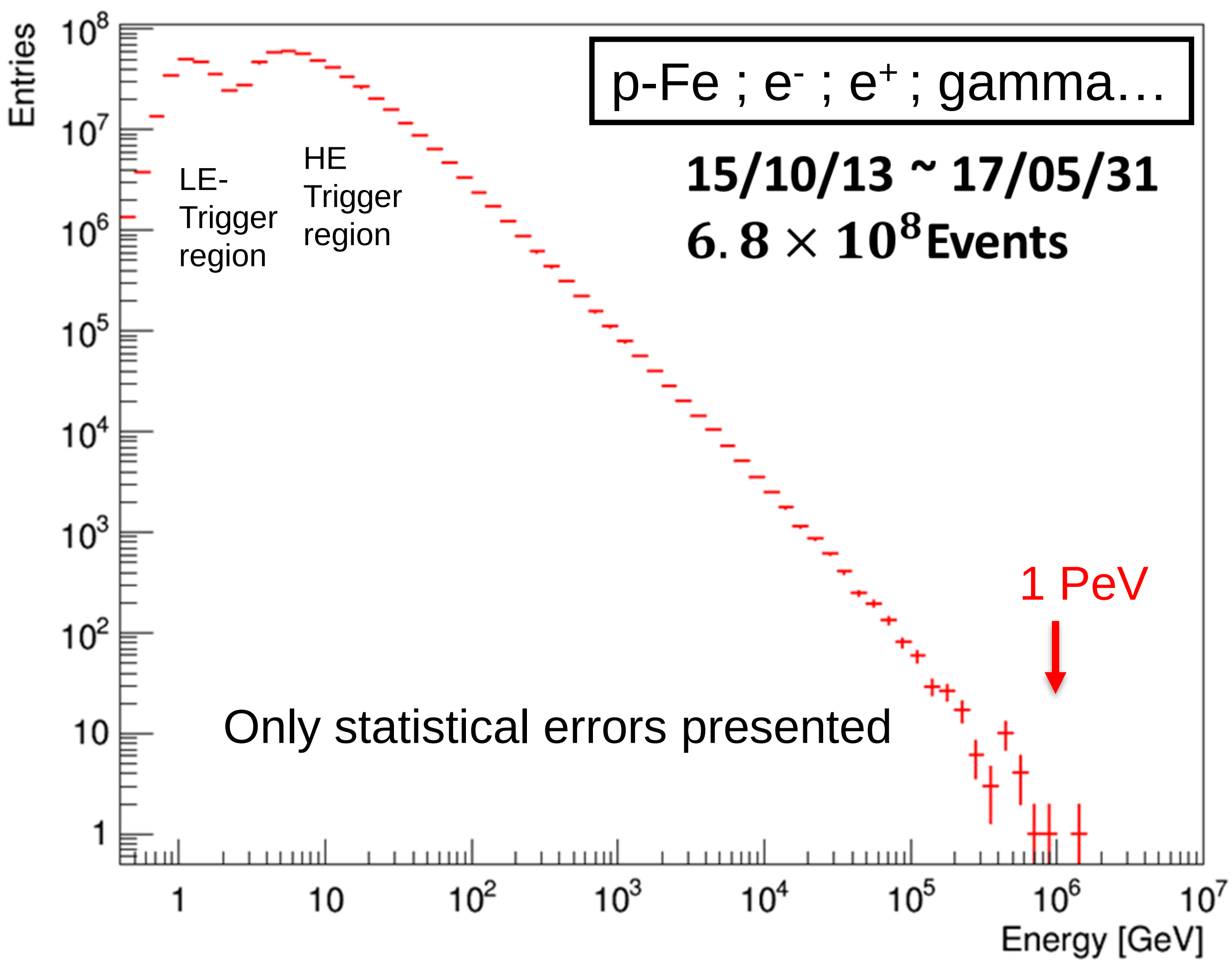
Hardening of p, He spectra



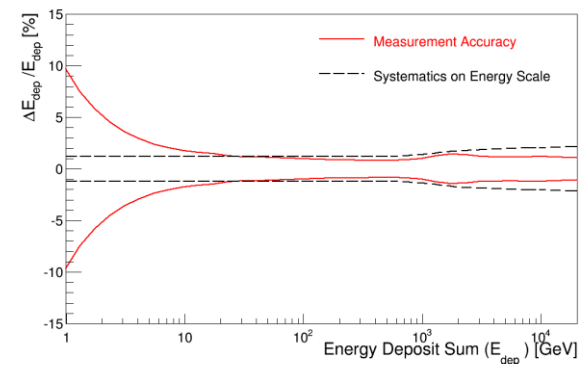
New source of electrons and positrons at 100 GeV ?

Energy Deposit Distribution of All Triggered-Events by Observation for 597 days

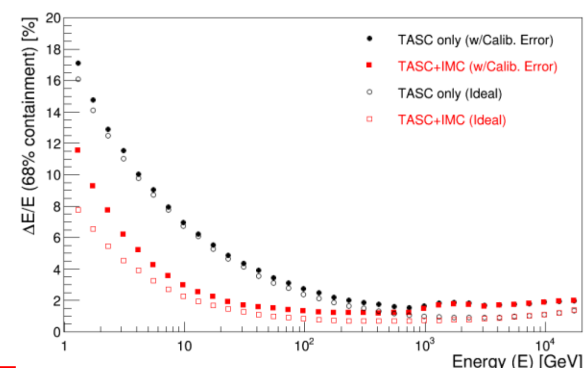
Distribution of deposit energies (ΔE) in TASC



Performance of energy measurement in 1GeV-20TeV



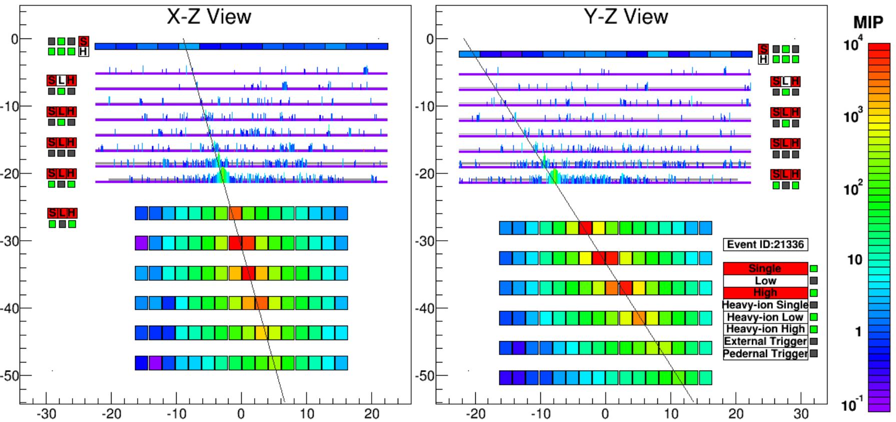
Energy resolution for electrons (TASC+IMC): < 3% over 10 GeV; <2% over 100GeV



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

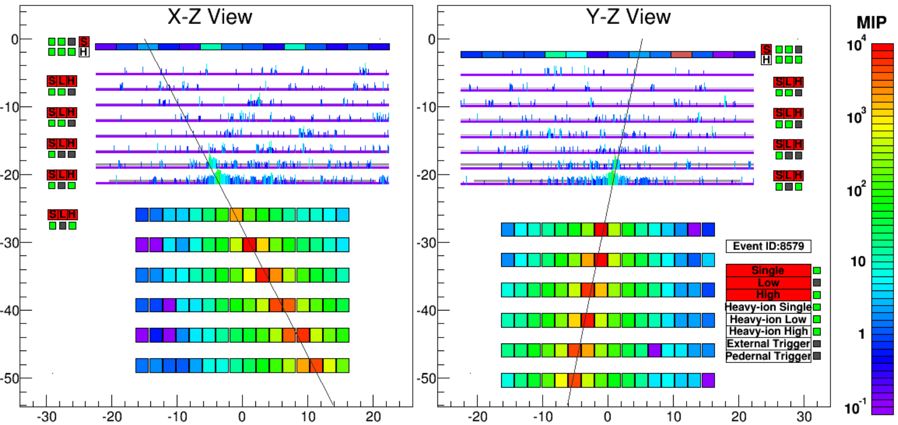
Event Examples of High-Energy Showers

Electron, E=3.05 TeV



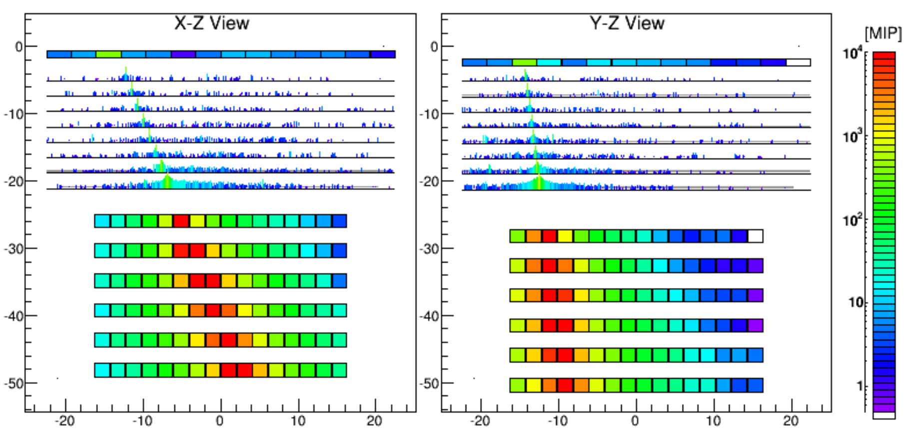
fully contained even at 3TeV

Proton, ΔE=2.89 TeV



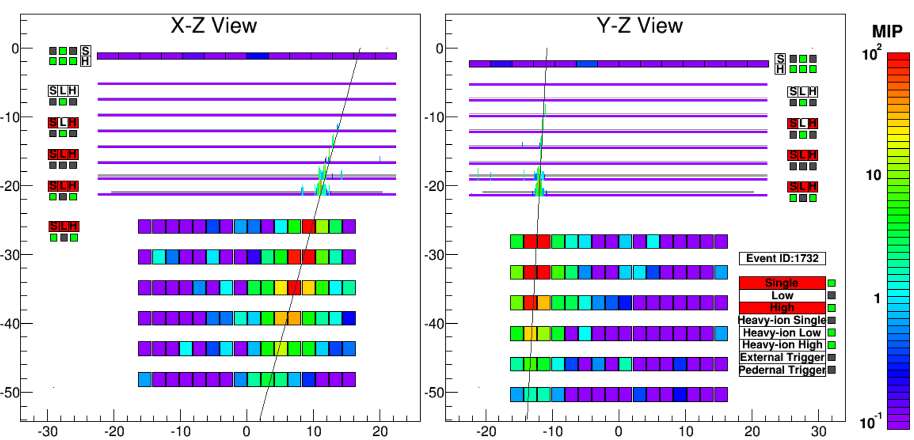
clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

Gamma-ray, E=44.3 GeV

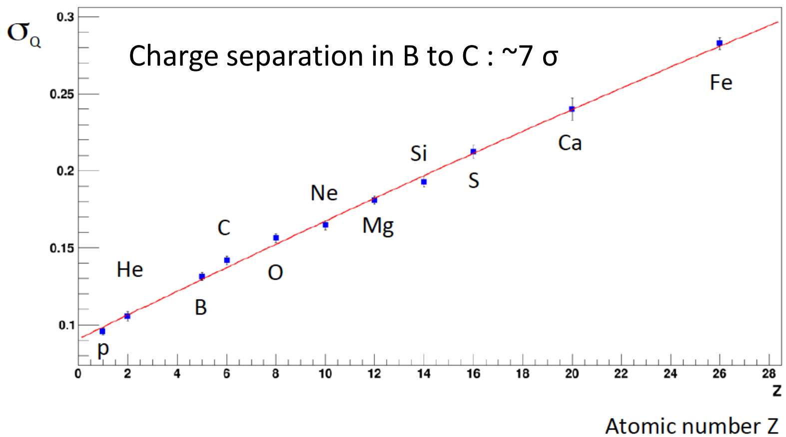


no energy deposit before pair production

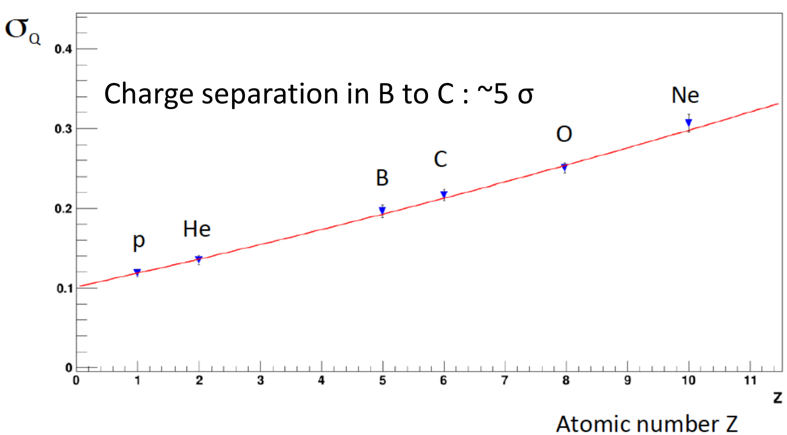
Preliminary Nuclei Measurements
(p, He, $Z \leq 8$)

P.S.Marrocchesi et al., ICRC 2017, PoS 205.

CHD charge resolution (2 layers combined) vs. Z

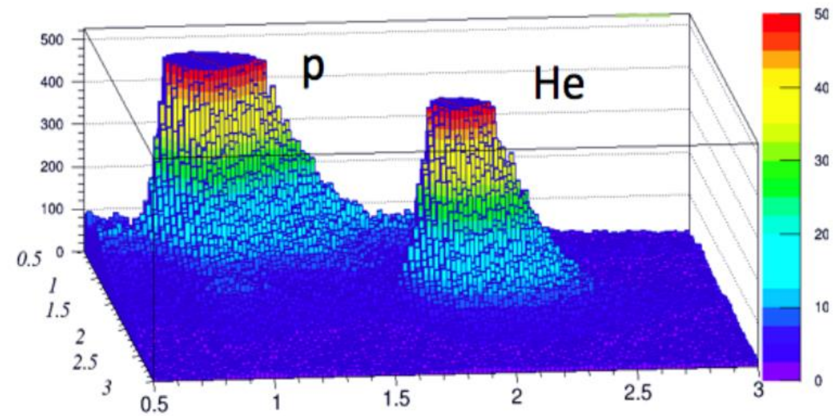


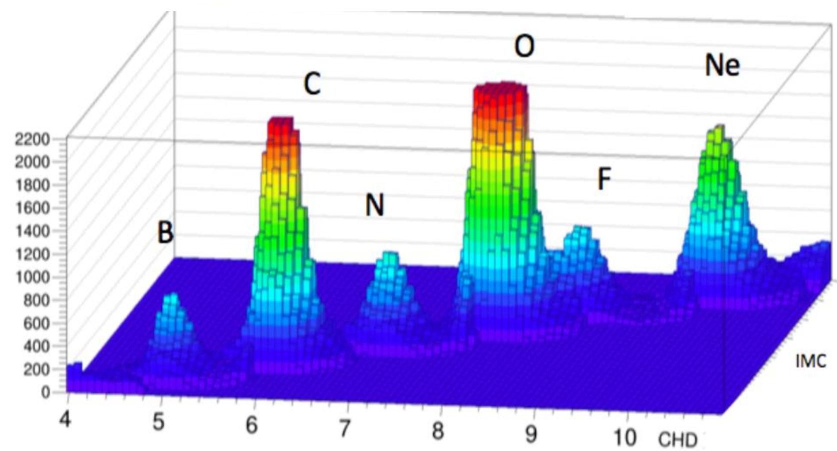
Charge resolution using multiple dE/dx measurements from the IMC scintillating fibers



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

Charge resolution combined CHD+IMC





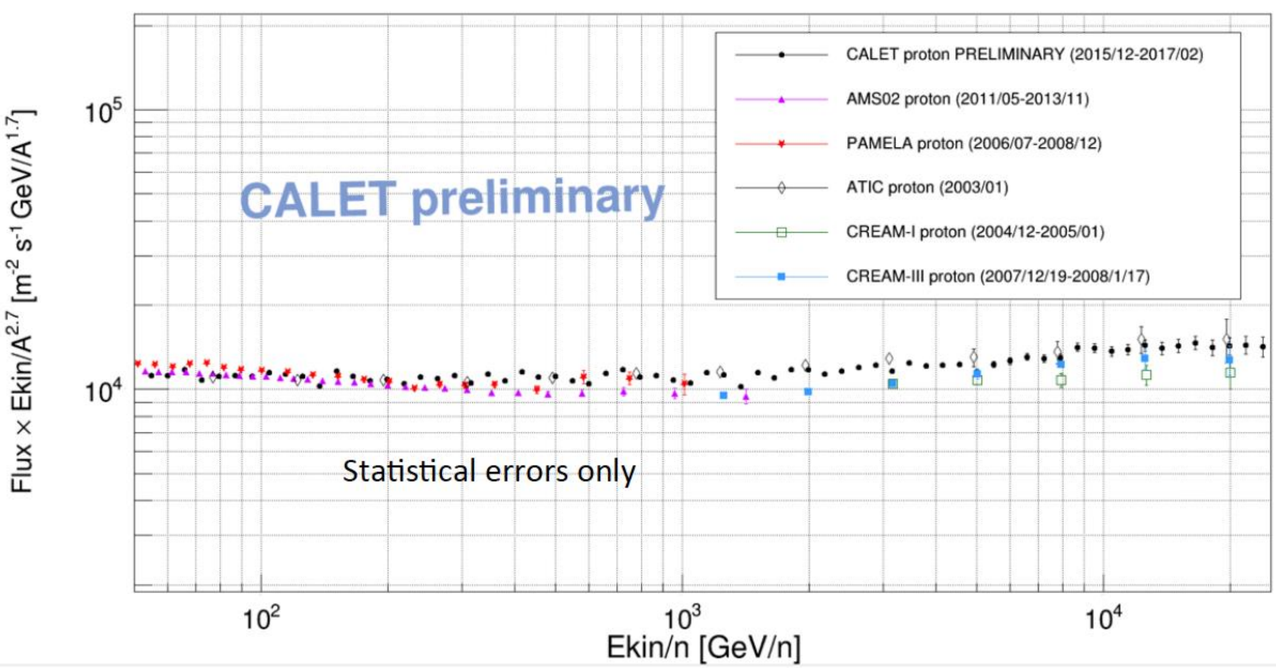
*) Plots are truncated to clearly present the separation.

A clear separation between p, He, up to Z=8, can be seen from CHD+IMC data analysis.

P.S.Marrocchesi et al., ICRC 2017, PoS 205.

Preliminary Proton Energy Spectrum

Preliminary proton flux $E^{2.7}$ from 50 GeV to 22 TeV



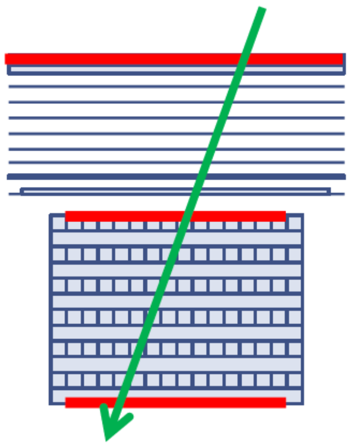
- 15 months of observation from December 1st , 2015 to February 28th, 2017
- subset of total acceptance: acceptance A (fiducial) with SΩ = 416 cm^2 sr
- Assessment of the systematic errors: IN PROGRESS

☐ Proton Event Selection

1) Fully-contained (Acceptance A) event in geometry
2) Good tracking (KF)
3) High Energy Trigger
4) Charge selection Z=1
5) Helium rejection cuts
6) Electron rejection cuts

☐ Energy Unfolding using an *energy overlap matrix* from MC data

(A) Fully-contained

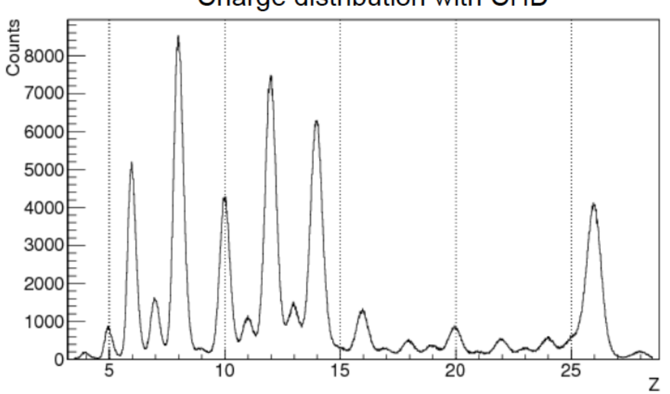


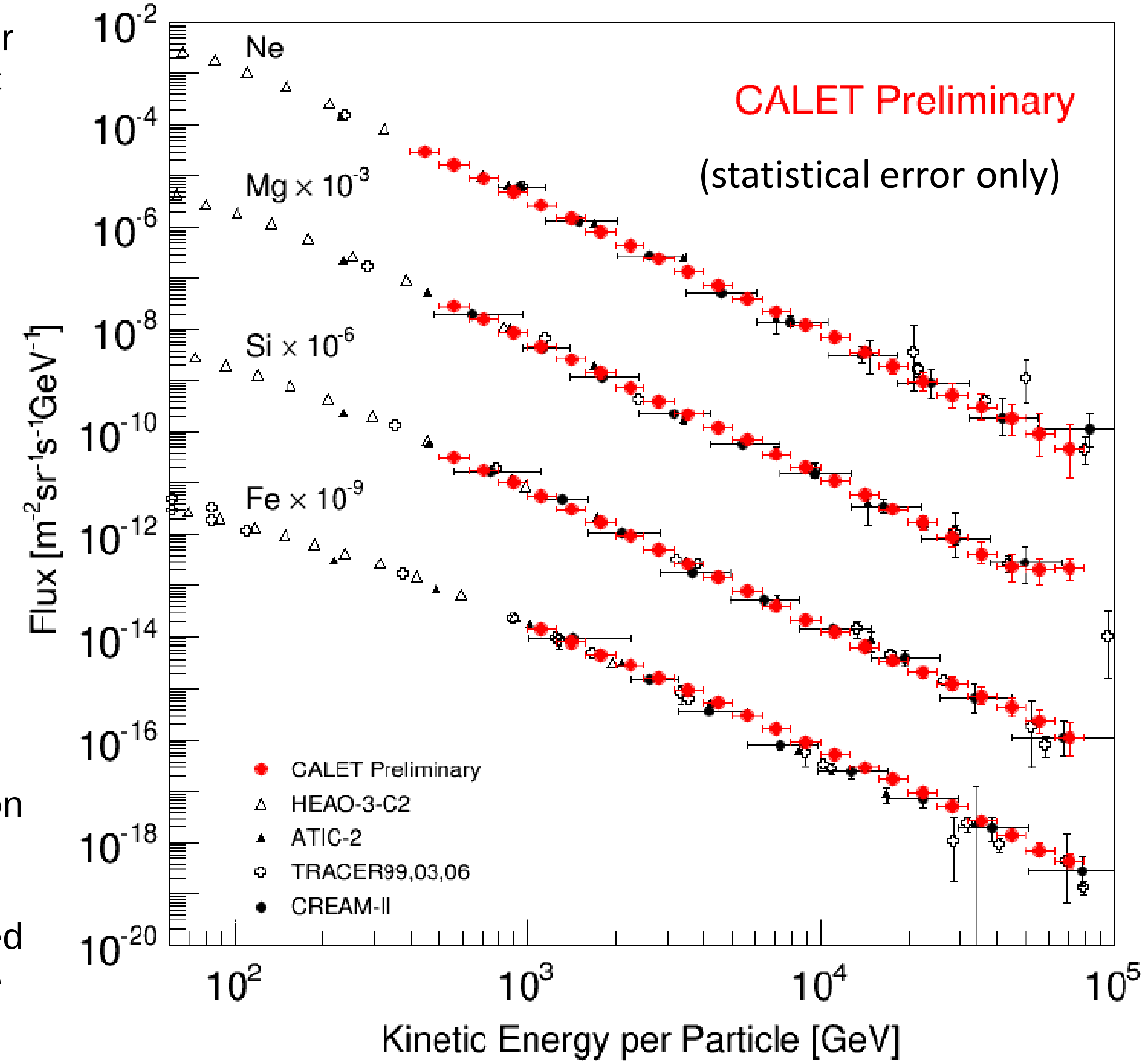
Preliminary Nuclei Measurements (Z= 8~26)

Y.Akaike et al., ICRC 2017, PoS 156.

Independent analysis is carried out for heavy nuclei in Z=8-26.

- Charge determination by CHD together with consistency requirement with IMC
- Consistent charge resolutions were obtained between the two analysis methods.





Analysis Method (in particular for heavy nuclei)

- Unfolding procedure based on *Bayes' theorem is* applied with response function from MC data.
- Charge selection efficiencies and contaminations from neighboring charged nuclei are also taken into account in the unfolding procedure.

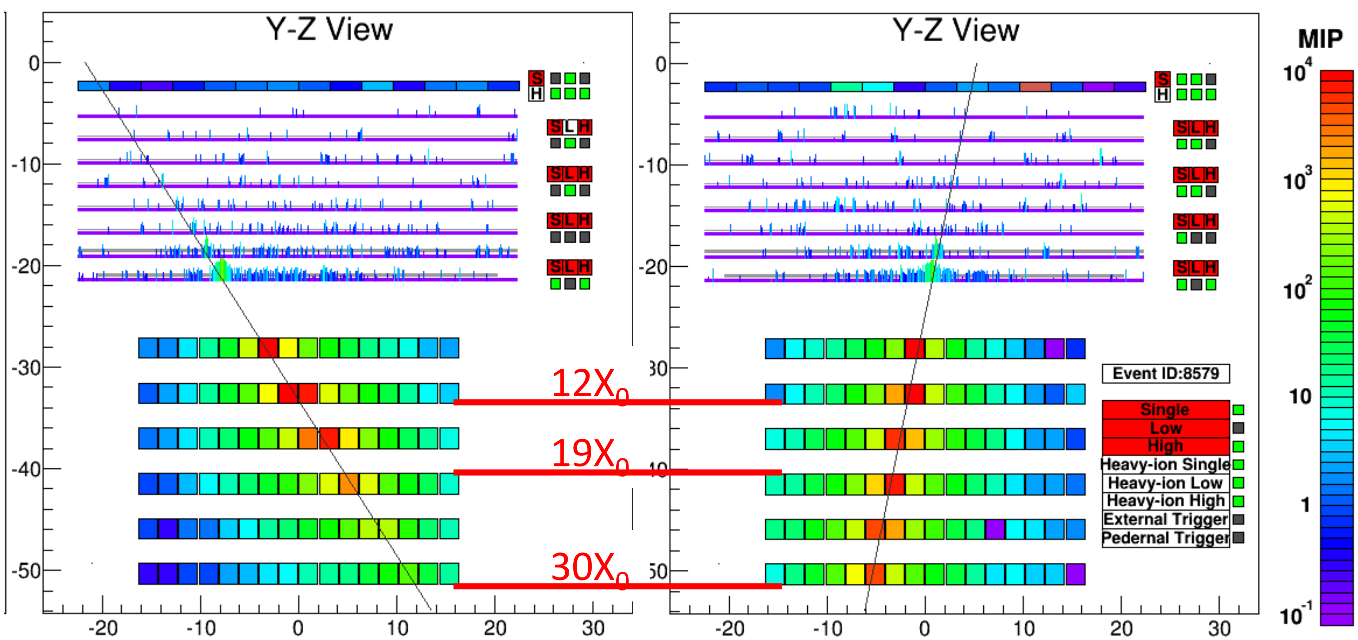
All-Electron (electron + positron) Analysis

CALET is a dedicated detector for all-electron spectrum measurements.

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

3TeV Electron Candidate

Corresponding Proton Background



(Flight data; detector size in cm)

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

Electron Identification

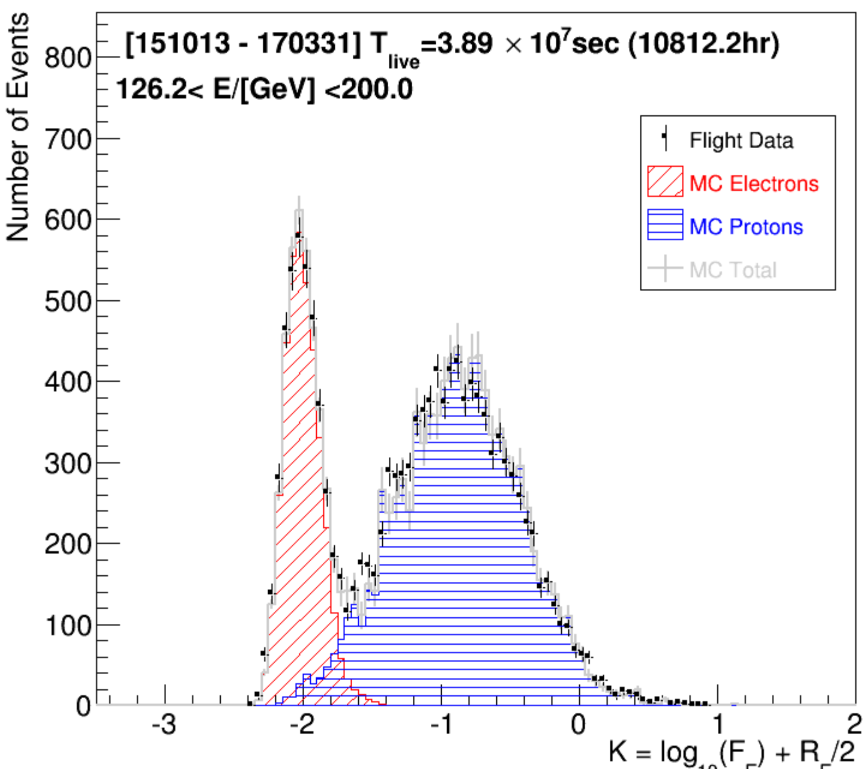
Simple Two Parameter Cut

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

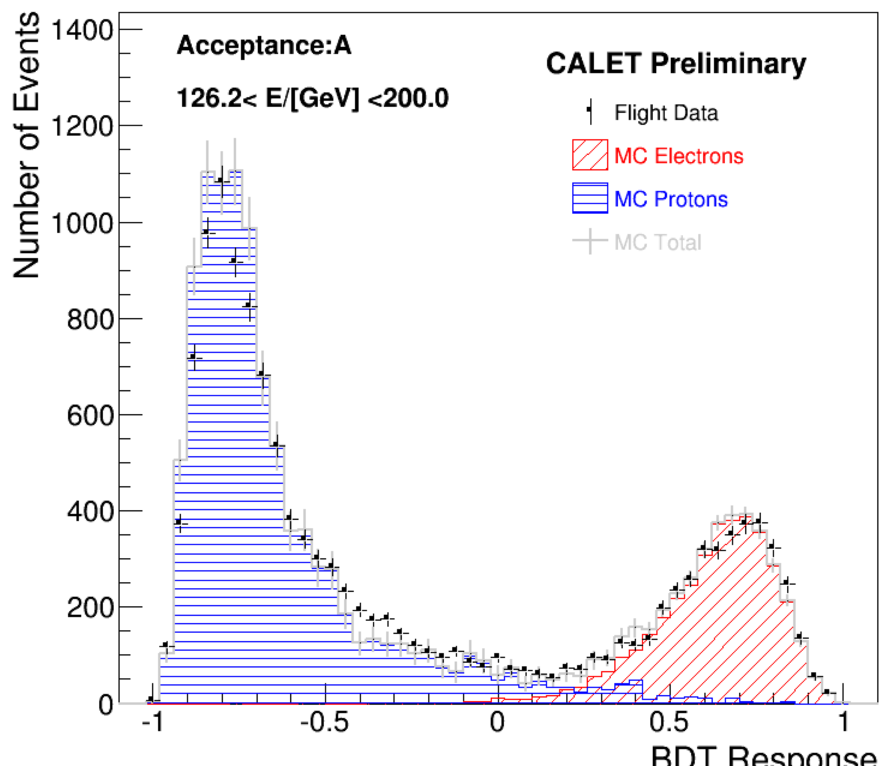
Separation Parameter K is defined as follows:

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



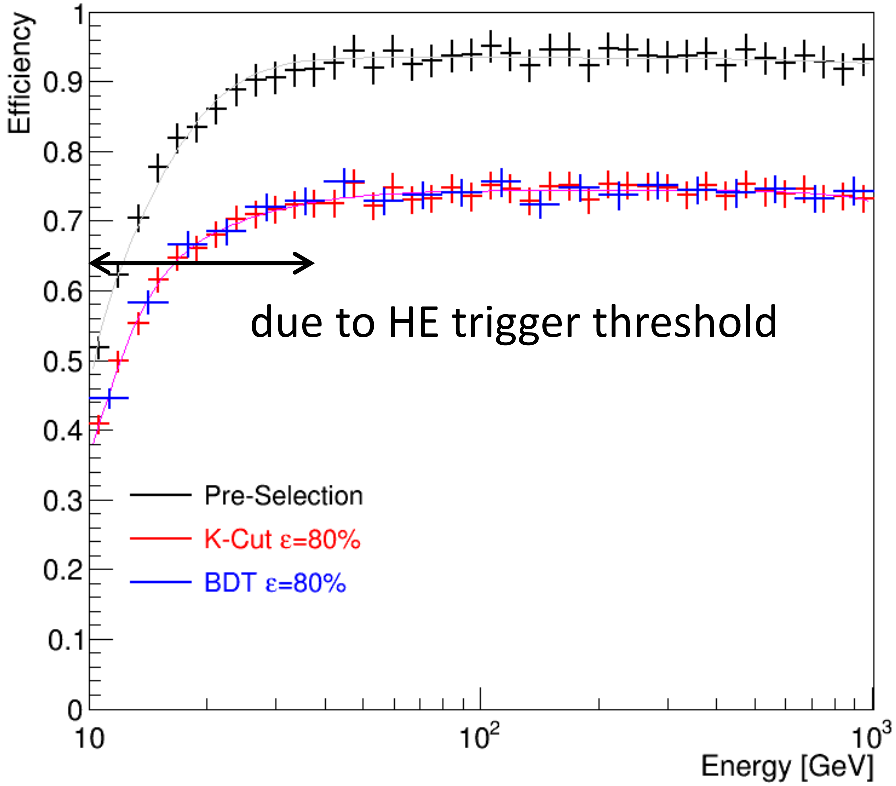
Boosted Decision Trees (BDT)

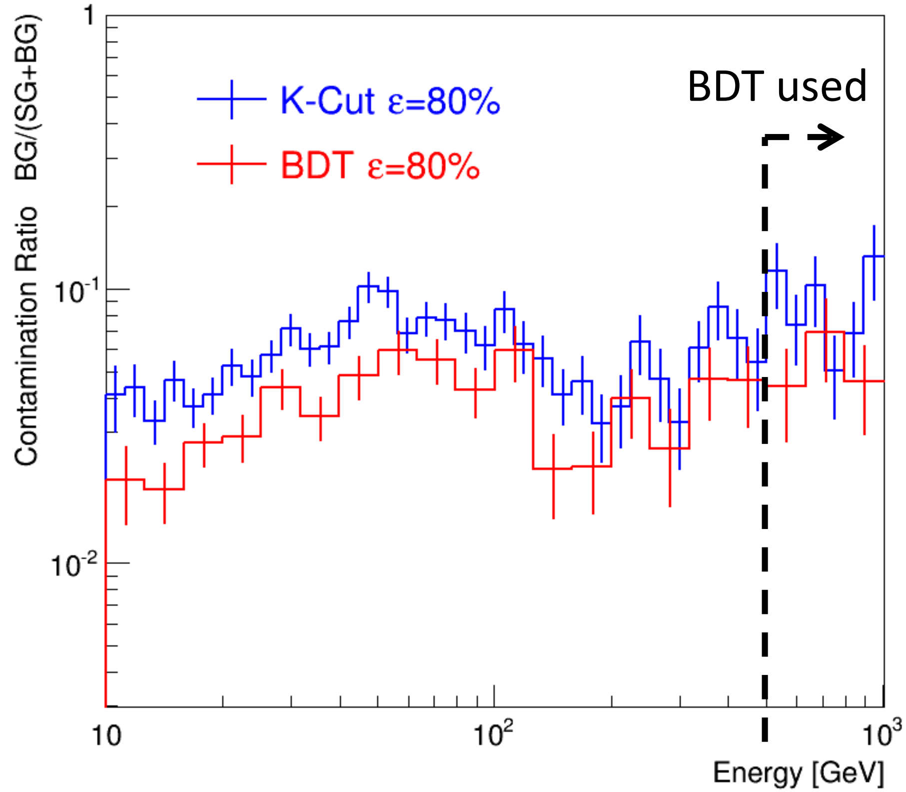
In addition to the two parameters in the left, TASC and IMC shower profile fits are used as discriminating variables.



Electron Efficiency and Subtraction of Proton Contamination

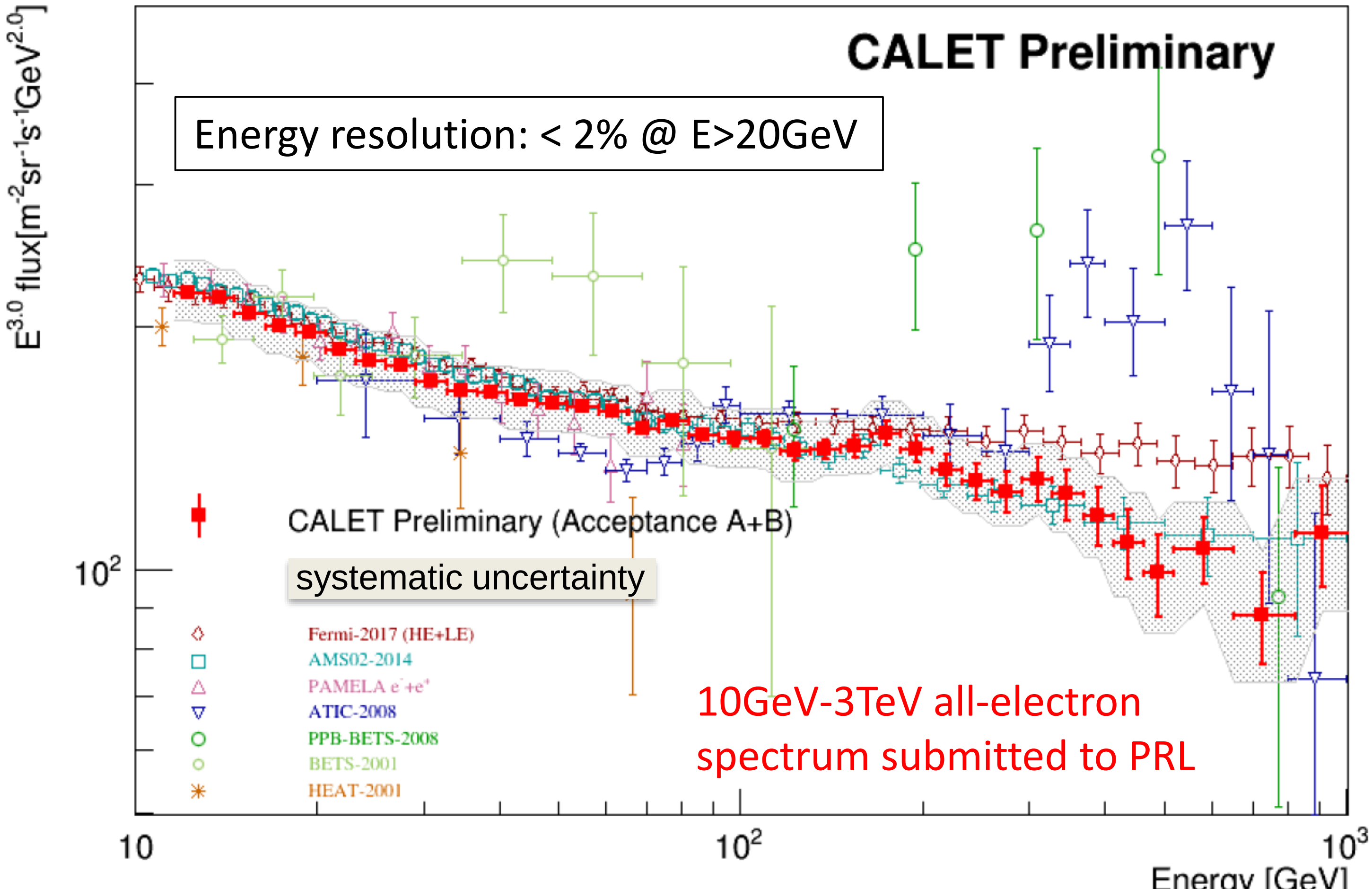
- Constant and high efficiency is the key point in our analysis.
- Simple two parameter cut is used in the low energy region while the difference in resultant spectrum are taken into account in the systematic uncertainty.





All-Electron Energy Spectrum in 10 GeV～1TeV

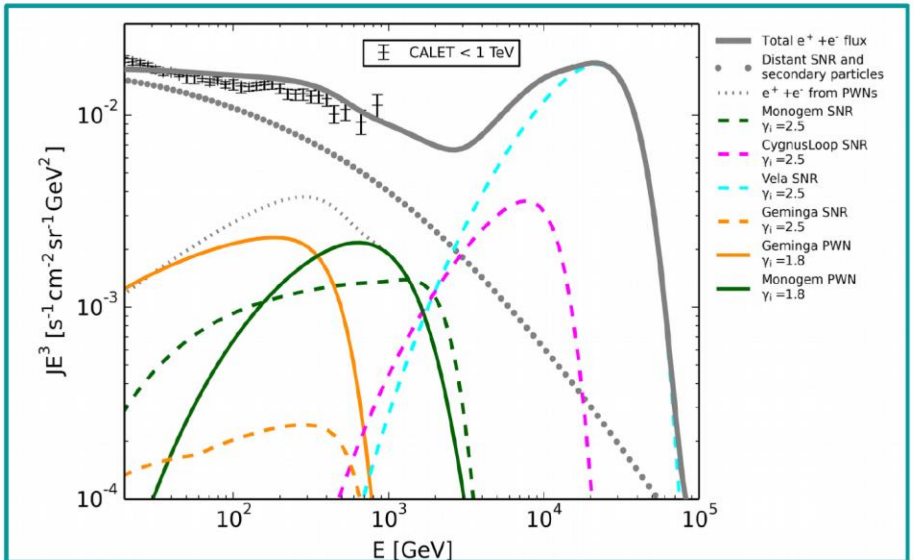
- Geometry Condition: SΩ= 570.3 cm^2sr (55% for all acceptance)
- Live Time: 2015/10/13—2017/03/31（x 0.84)=> T= 3.89 x 10^7 sec
- Exposure: SΩT = 2.24 x 10^6 m^2 sr sec **~1/7 of full analysis for 5 years**
- Absolute energy scale determined by geomagnetic cutoff energy.

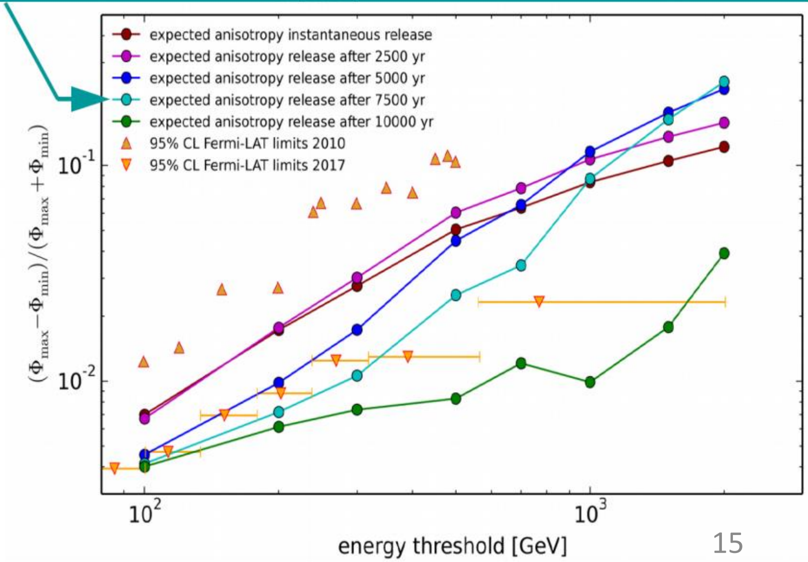


H.Motz et al., ICRC 2017, PoS 265, & JPS 2017 (13aU31-4)

Nearby SNR and Anisotropy of the All-Electron Flux

- The Vela SNR could cause significant anisotropy in the TeV-region, depending on the cosmic-ray injection and propagation conditions
- With suitable conditions it is possible that the anisotropy signal occurs **only** at high energy, not detected by current measurements (Fermi-LAT)*
- CALET can search for such signals due to good energy determination up to several TeV





* PoS ICRC 2017, 265

All-Electron Anisotropy Analysis

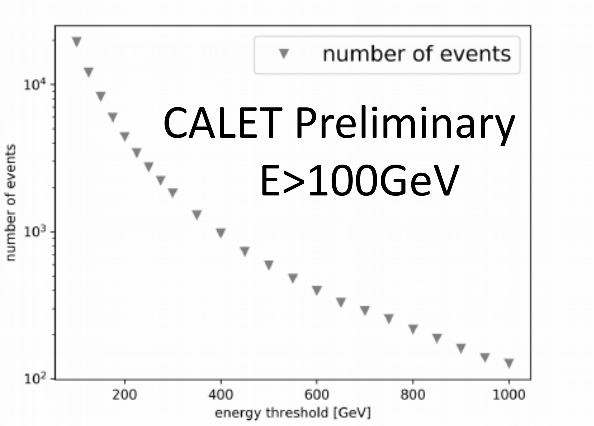
H.Motz et al., ICRC 2017, PoS 265, & JPS 2017 (13aU31-4)

Analysis Method and Electron + Positron Event Sky Map

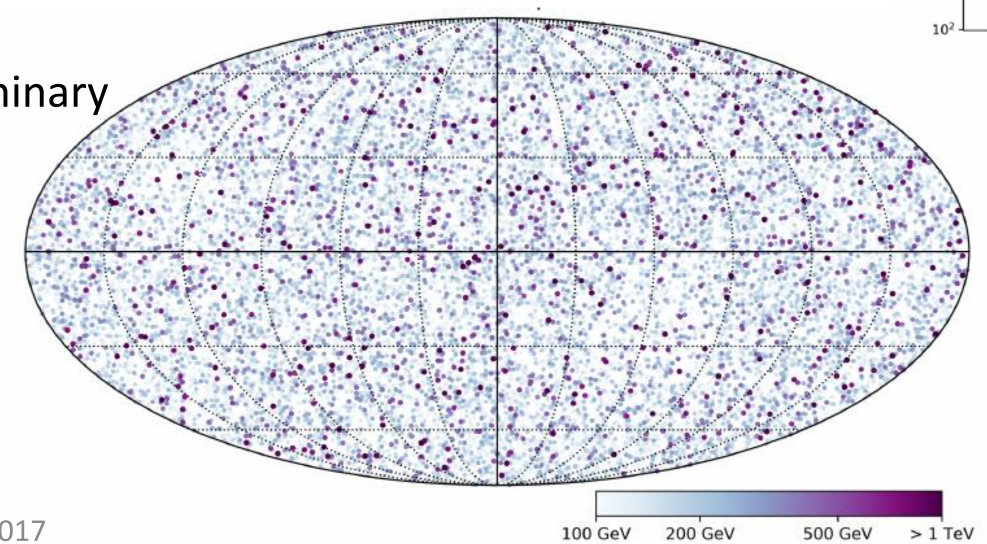
- Limits on anisotropy by finding the value of δ for which the probability of the measured and smaller anisotropy is 5% (1-CL; CL=95%).
- Analysis method is based on M. Ackermann et al., Phys. Rev. D 82, 092003 (2010).

$$\delta=\frac{\Phi_{max}-\Phi_{min}}{\Phi_{max}+\Phi_{min}} \;;\; P(\hat{\delta},\delta)=\frac{3\sqrt{6}}{\sqrt{\pi}}\frac{\hat{\delta}^2}{\delta^3}e^{\left(-\frac{3}{2}\frac{\hat{\delta}^2}{\delta^2}\right)} \;;\; \int_0^{\delta_{meas}} P(\hat{\delta},\delta)\,d\hat{\delta}=1-CL$$

- 627 days of flight data up to 170630.
- Full acceptance of $1040 cm^2 sr$ (Preliminary)
- Electron identification by using BDT.



CALET Preliminary
E>100GeV

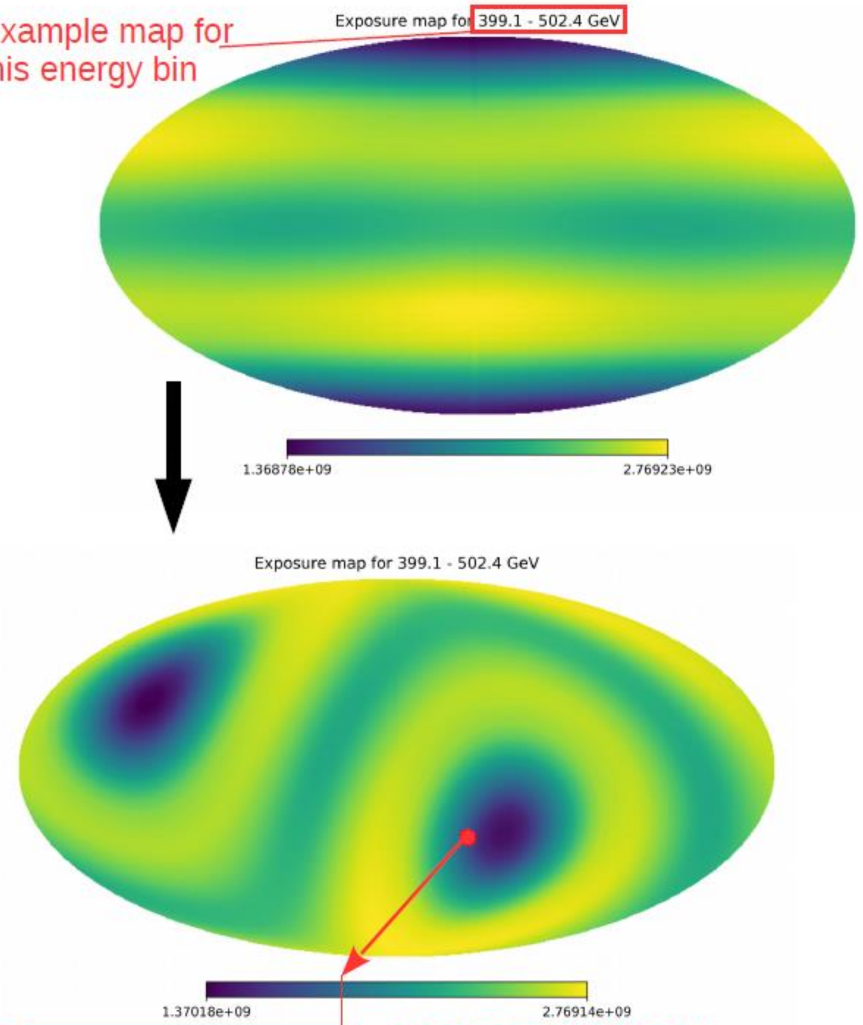


Galactic Coordinates

H.Motz et al., ICRC 2017, PoS 265, & JPS 2017 (13aU31-4)

Correction for Uneven Exposure

- ISS orbit convolved with CALET's energy and direction dependent effective area → exposure in equatorial coordinates
- Converted to galactic coordinates
- Each event receives a weight which is the inverse of this energy and direction dependent exposure, normalized to the average exposure to the sky for the measured spectrum.



w_i : weight for event i

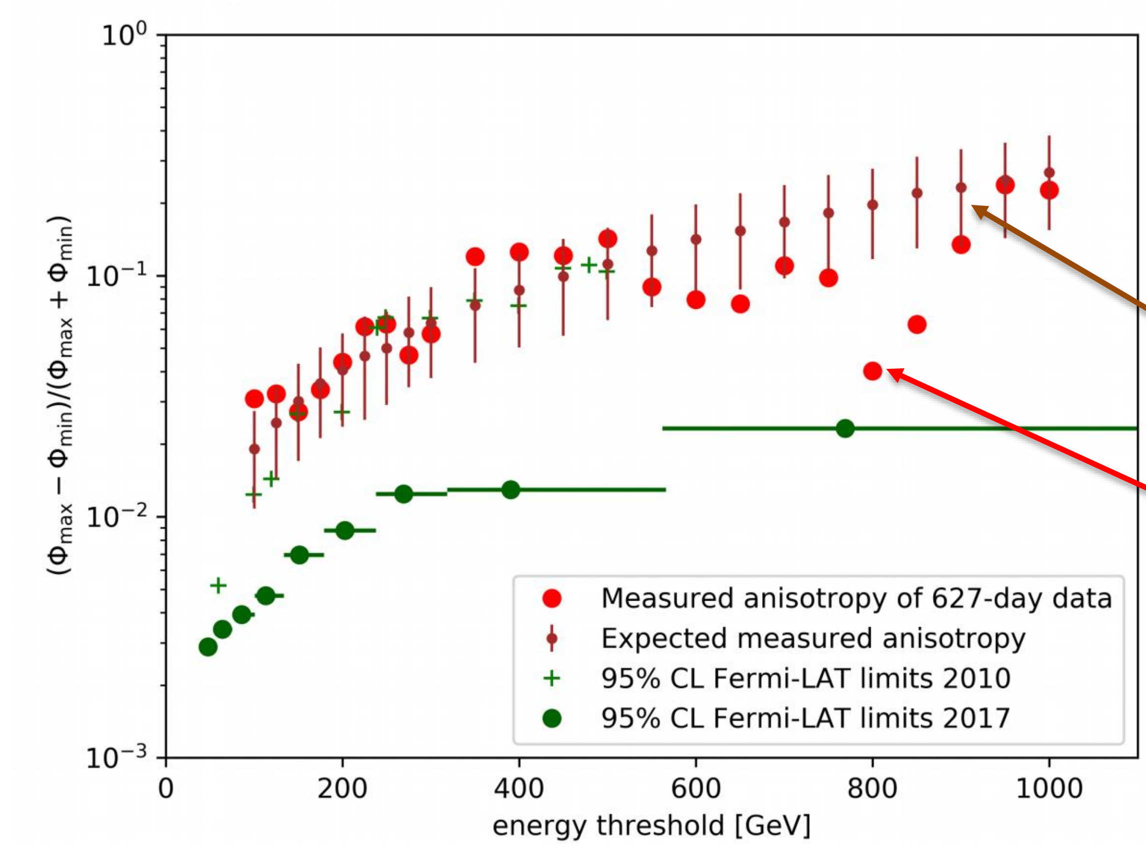
$$w_i = \frac{1}{A_i} \left(\frac{\sum_{events} \sum_{pixels} A(E, pixel)}{N_{events} N_{pixels}} \right)$$

All-Electron Anisotropy Analysis

H.Motz et al., ICRC 2017, PoS 265, & JPS 2017 (13aU31-4)

Results: Measured Anisotropy

$$\delta = \frac{\Phi_{max} - \Phi_{min}}{\Phi_{max} + \Phi_{min}}$$



Multipole expansion with *anafast* routines of *Healpix*:

$\delta = \Phi_{dipole} / \Phi_{monopole}$

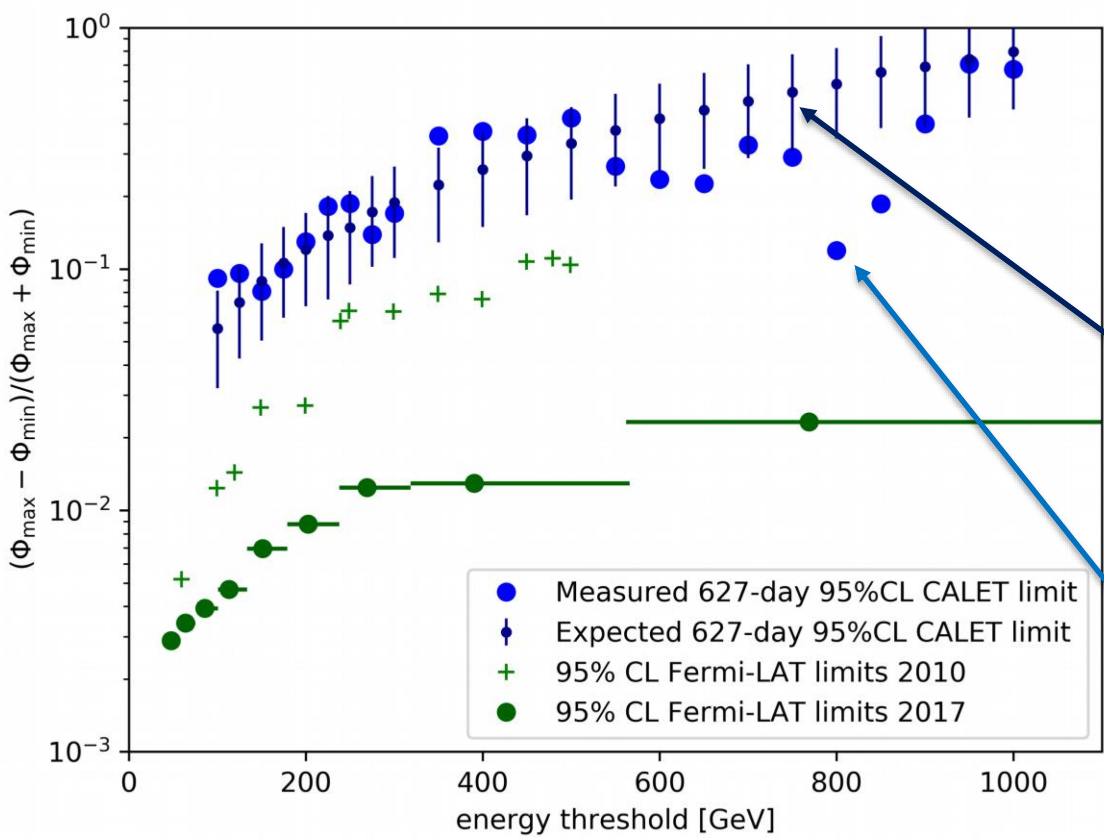
Expected anisotropy (calculated by simulated uniform sky)

Measured anisotropy is much smaller than expected for this bin (1.4% prob.)
⇔ Need to consider trial factor

All-Electron Anisotropy Analysis

H.Motz et al., ICRC 2017, PoS 265, & JPS 2017 (13aU31-4)

Results: 95% Confidence Level Limit



$$P(\hat{\delta},\delta)=\frac{3\sqrt{6}}{\sqrt{\pi}}\frac{\hat{\delta}^2}{\delta^3}e^{\left(-\frac{3}{2}\frac{\hat{\delta}^2}{\delta^2}\right)}$$

$$\int_0^{\delta_{meas}} P(\hat{\delta},\delta)\,d\hat{\delta}=1-CL$$

Upper limit

Expected limit (calculated by simulated uniform sky)

Measured limit is even more uniform than expected value (1.4% prob.)

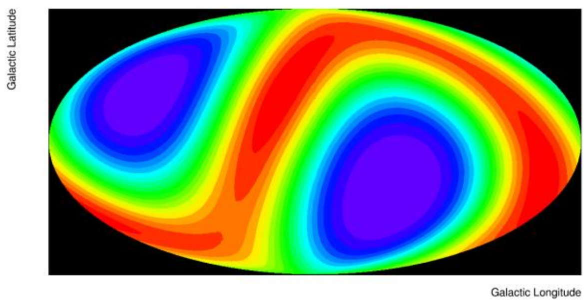
⇔ Need to consider trial factor

Prospects:

1. Proving 1TeV region where significant limit can be set with more statistics
2. A dedicated search directed at the position of Vela (PoS, ICRC2017, 265)

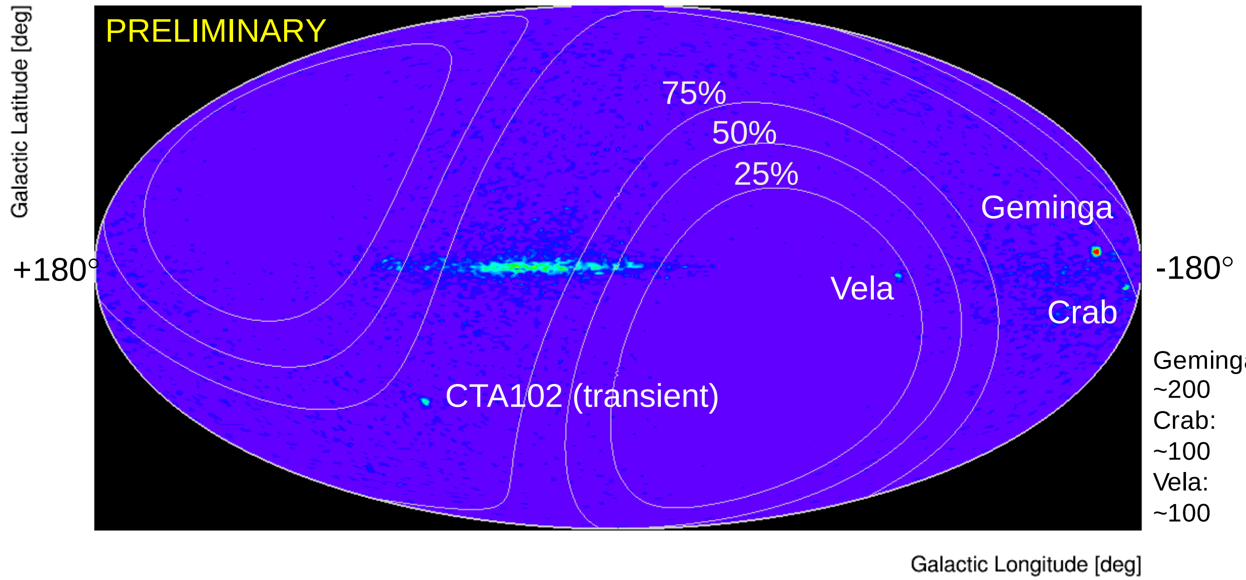
CALET γ–ray Sky in LE (>1GeV) Trigger

Exposore

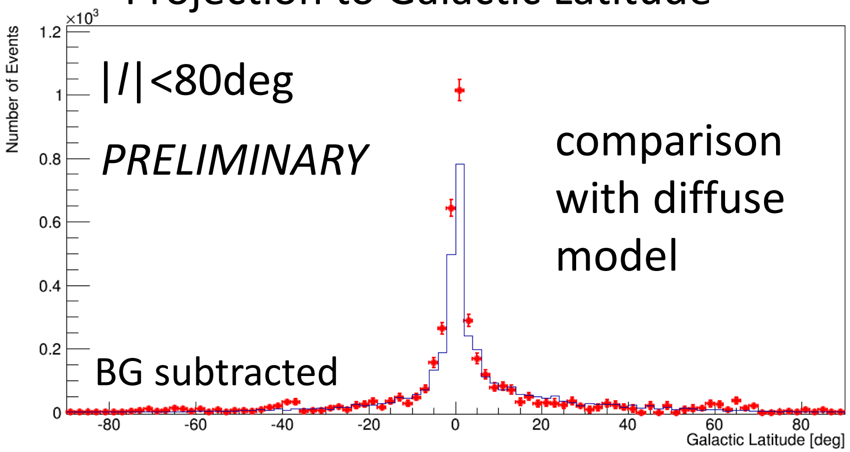


Exposure is limited to low latitude region
=> |declination| > 60 deg is hardly seen in LE gamma-ray trigger mode.

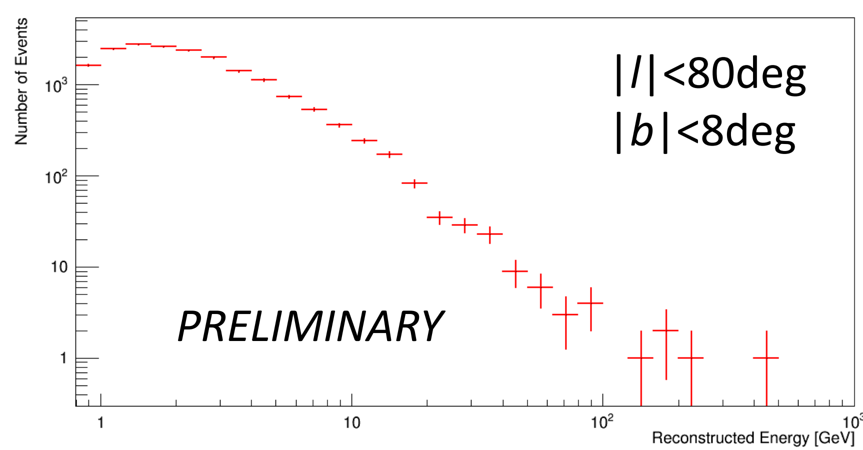
151013—170228 E>1GeV Galactic Coordinate



Projection to Galactic Latitude



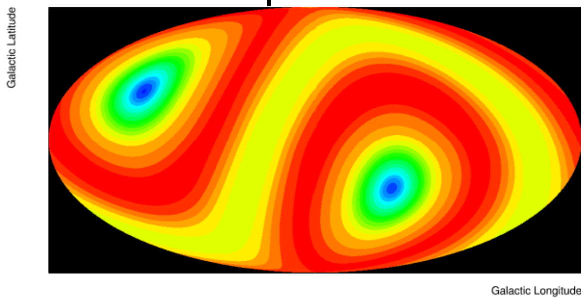
Galactic Diffuse Spectrum



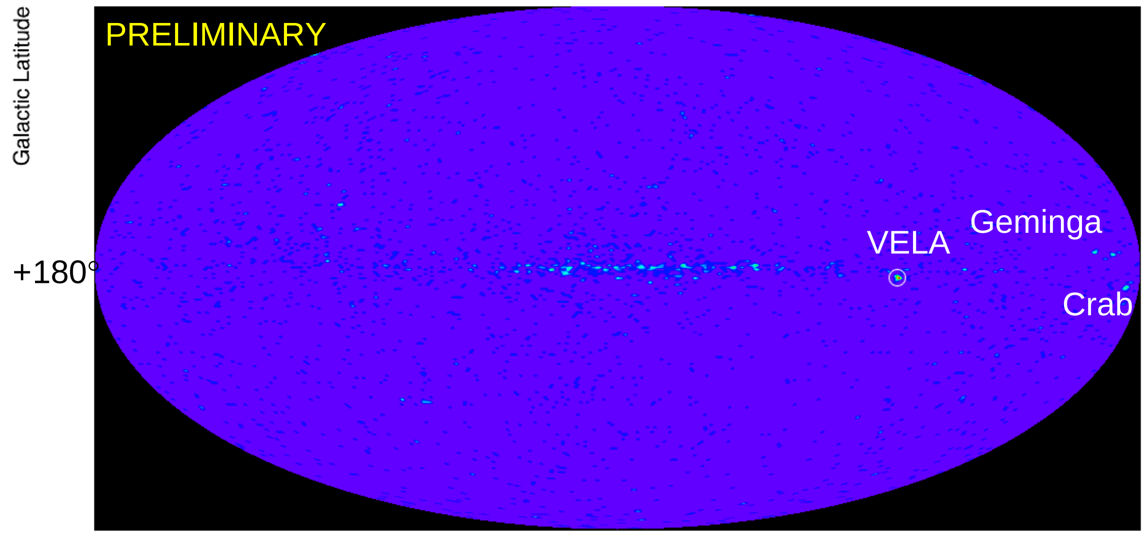
contribution from point sources is not included in the model

CALET γ–ray Sky in HE (>10GeV) Trigger

Exposure



151013—170228 E>10GeV Galactic Coordinate



-180°

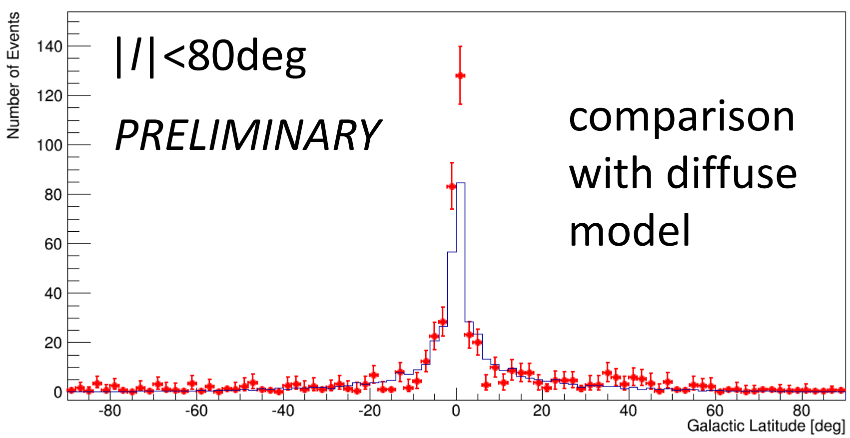
Geminga ~10
Crab: ~20
Vela: ~20

Vela, Crab and Geminga are identified.

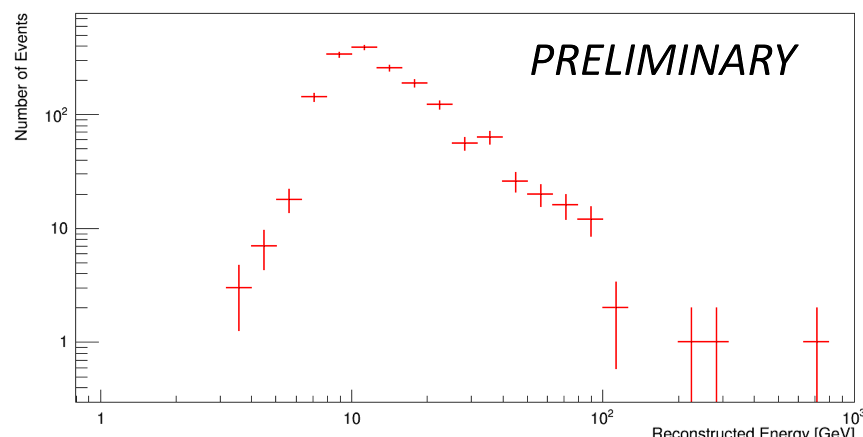
Galactic Longitude

HE trigger is always ON
=> Exposure is more uniform than LE trigger.

Projection to Galactic Latitude



Diffuse Spectrum



contribution from point sources is not included in the model

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

Astrophysical Journal Letters 829:L20(5pp), 2016 September 20

The CGBM covered 32.5% and 49.1% of the GW 151226 sky localization probability in the 7 keV - 1 MeV and 40 keV - 20 MeV bands respectively. We place a 90% upper limit of 2×10^{-7} erg cm^{-2} s^{-1} in the 1 - 100 GeV band where CAL reaches 15% of the integrated LIGO probability (~1.1 sr). The CGBM 7 σ upper limits are 1.0×10^{-6} erg cm^{-2} s^{-1} (7-500 keV) and 1.8×10^{-6} erg cm^{-2} s^{-1} (50-1000 keV) for one second exposure. Those upper limits correspond to the luminosity of 3-5 $\times 10^{49}$ erg s^{-1} which is significantly lower than typical short GRBs.

CGBM light curve at a moment of the GW151226 event

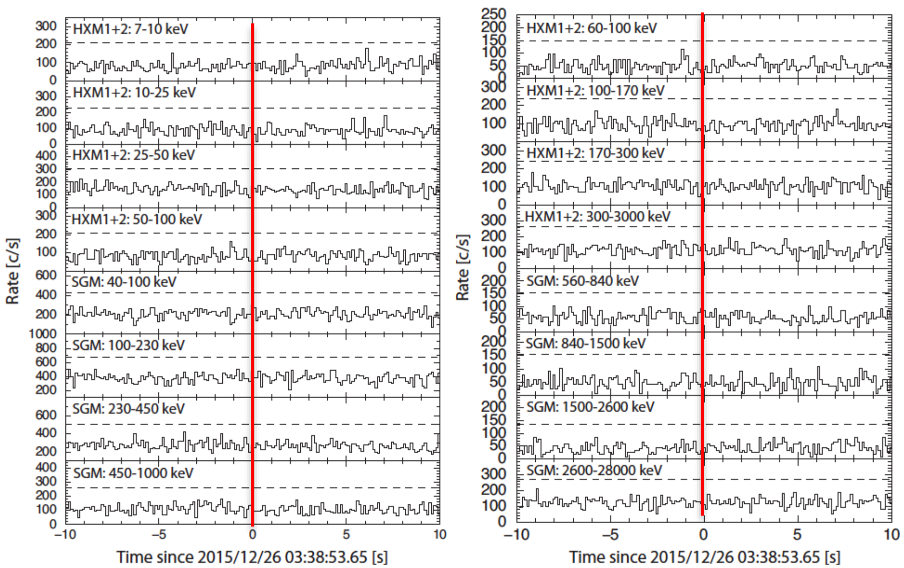


Figure 1. The CGBM light curves in 0.125 s time resolution for the high-gain data (left) and the low-gain data (right). The time is offset from the LIGO trigger time of GW 151226. The dashed-lines correspond to the 5 σ level from the mean count rate using the data of ±10 s.

Upper limit for gamma-ray burst monitors and Calorimeter

HXM: 7-500 keV

SGM: 50-1000 keV

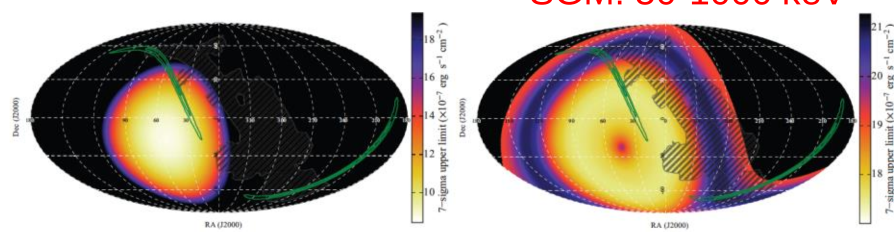


Figure 2. The sky maps of the 7 σ upper limit for HXM (left) and SGM (right). The assumed spectrum for estimating th upper limit is a typical BATSE S-GRBs (see text for details). The energy bands are 7-500 keV for HXM and 50-1000 keV fo SGM. The GW 151226 probability map is shown in green contours. The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

Calorimeter: 1-100 GeV

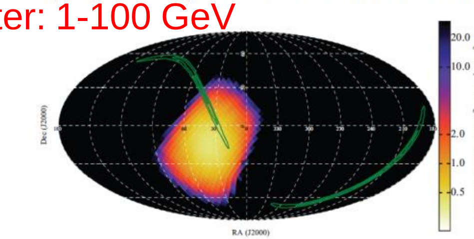


Figure 3. The sky map of the 90% upper limit for CAL in the 1-100 GeV band. A power-law model with a photon index of − is used to calculate the upper limit. The GW 151226 probability map is shown in green contours.

Summary and Future Prospects

- CALET was successfully launched on Aug. 19, 2015, and the detector is being very stable for observation since Oct. 13, 2015.
- As of Jun.30, 2017, total observation time is 627 days with live time fraction to total time to close 84%. Nearly 409 million events are collected with high energy (>10 GeV) 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 by using observed events.
- Preliminary analysis of nuclei, all elections and gamma-rays have successfully been carried out to obtain the energy spectra in the energy range;
  Protons: 55 GeV~22 TeV, Ne-Fe: 500 GeV~70 TeV, All electrons: 10 GeV~1 TeV.
- Preliminary analysis of electron anisotropy is presented.
- CALET's CGBM detected nearly 60 GRBs (~20 % short GRB among them) per year in the energy range of 7keV-20 MeV, as expected. Follow-up observation of the GW events is carried out. (Not reported in this talk)
- The so far excellent performance of CALET and the outstanding quality of the data suggest that a 5-year observation period is likely to provide a wealth of new interesting results.