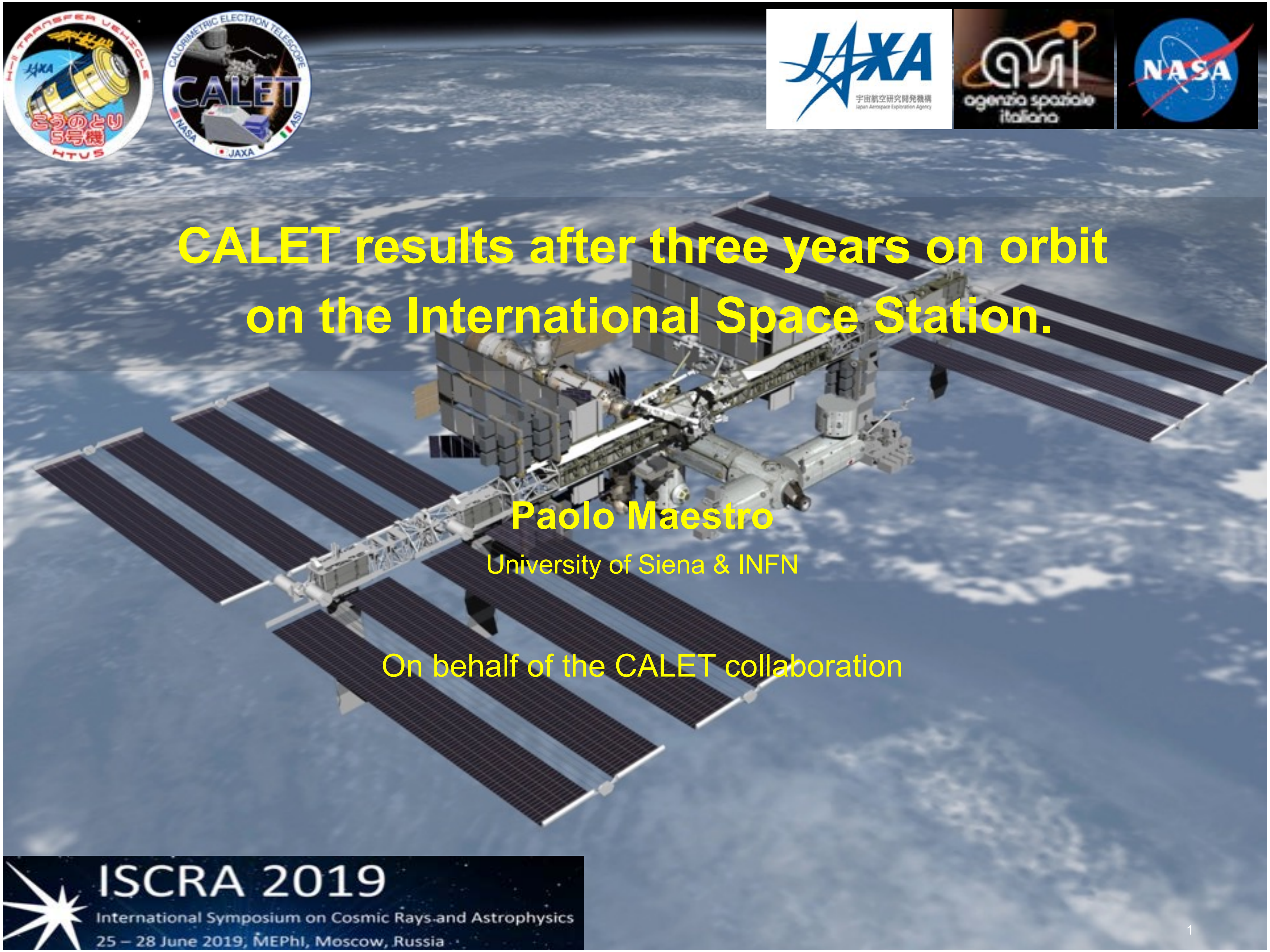

CALET results after three years on orbit on the International Space Station.

Paolo Maestro

University of Siena & INFN

On behalf of the CALET collaboration

ISCRA 2019
International Symposium on Cosmic Rays and Astrophysics
25 – 28 June 2019, MEPhI, Moscow, Russia

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[21], N. Mori[25], H.M. Motz[31], K. Munakata[23], H. Murakami[31], S. Nakahira[20], 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[9,31], 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
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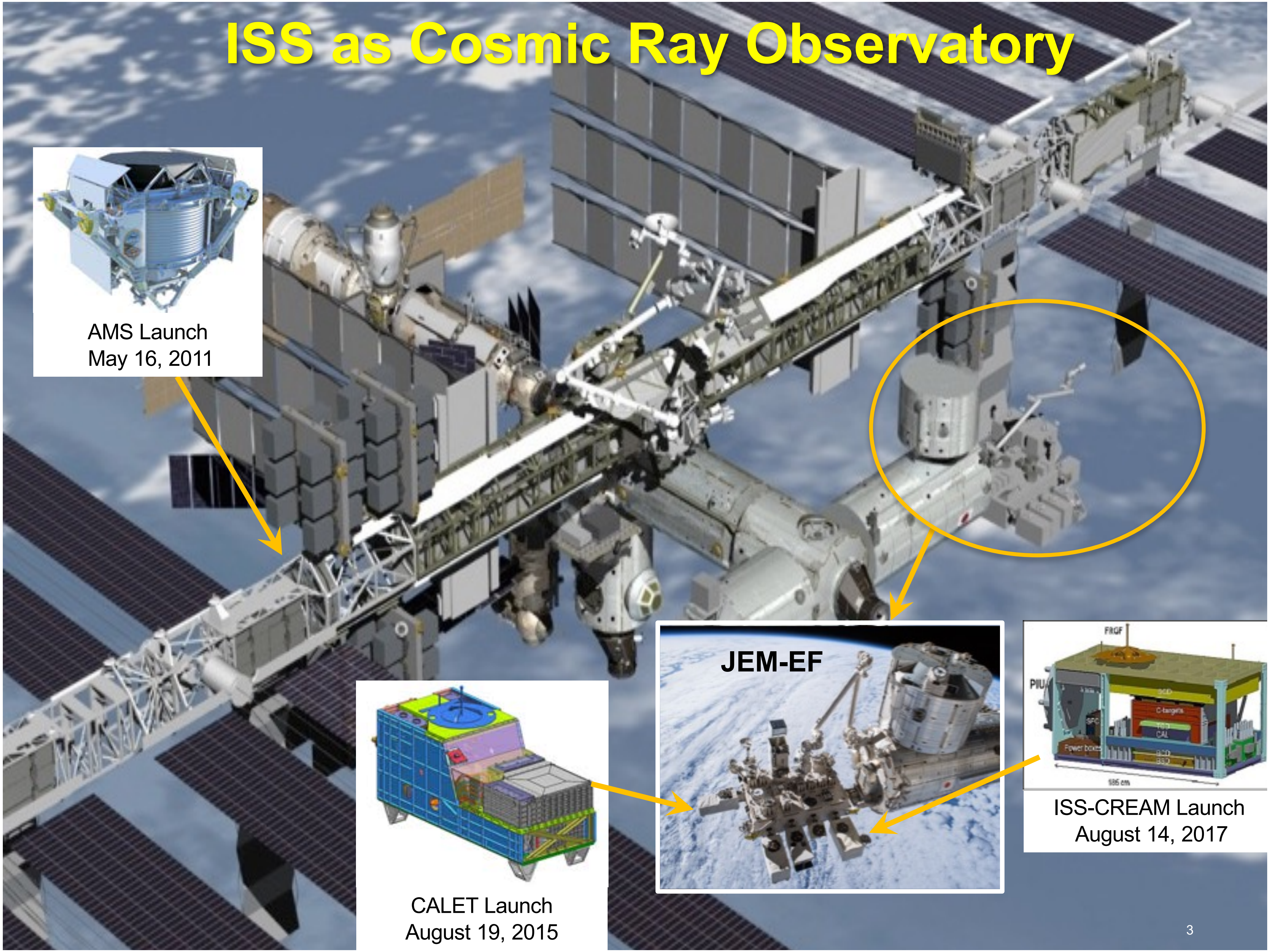
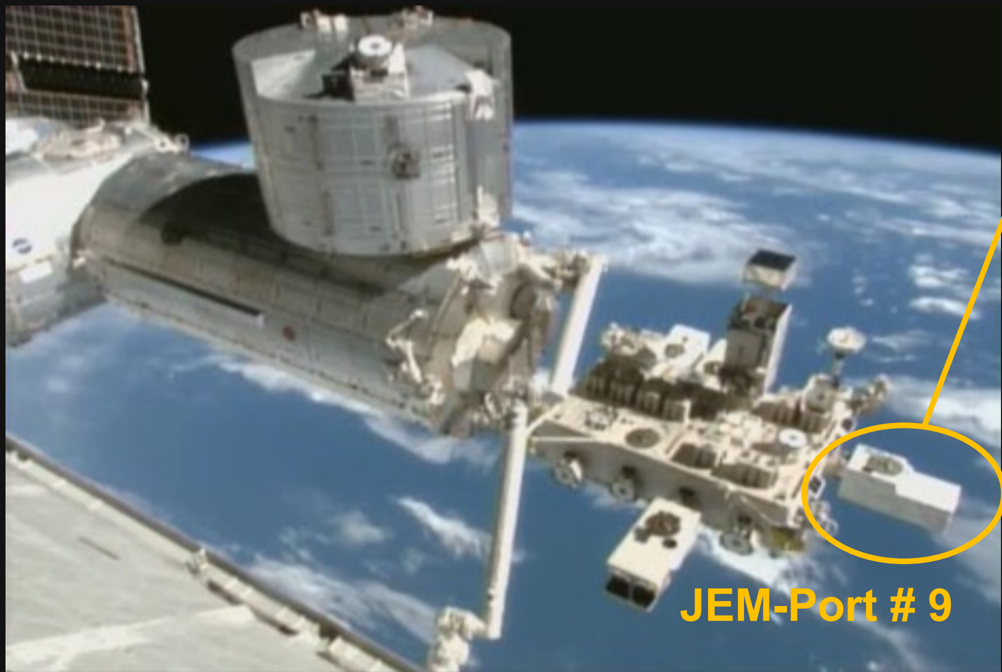
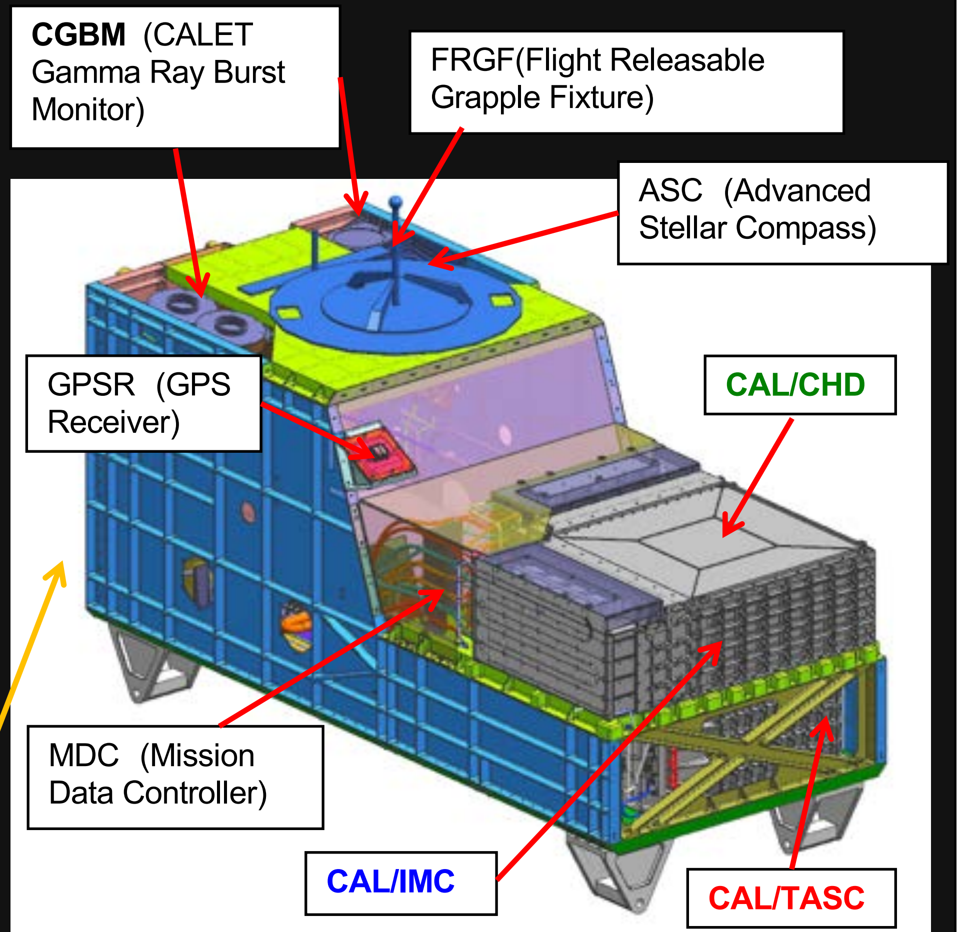
7) ICRR, University of Tokyo, Japan
8) ISAS/JAXA Japan
9) JAXA, Japan
10) Kanagawa University, Japan
11) Kavli IPMU, University of Tokyo, Japan
12) KEK, Japan
13) Louisiana State University, USA
14) Nagoya University, Japan
15) NASA/GSFC, USA
16) National Inst. of Radiological Sciences, Japan
17) National Institute of Polar Research, Japan
18) Nihon University, Japan
19) Osaka City University, Japan
20) RIKEN, Japan
21) Ritsumeikan 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


ISS as Cosmic Ray Observatory
AMS Launch
May 16, 2011
JEM-EF
FRGF
ISS-CREAM Launch
August 14, 2017
CALET Launch
August 19, 2015

CALET payload

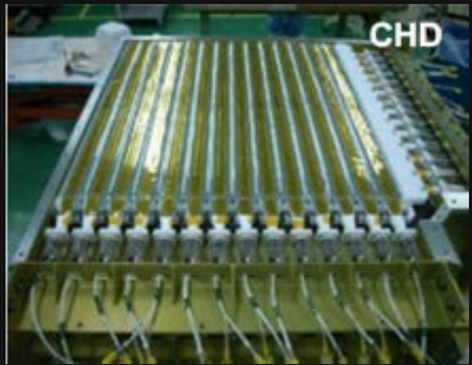
Launched on Aug. 19th 2015
on the Japanese H2-B rocket
Emplaced on JEM-EF port#9
On Aug. 25th 2015

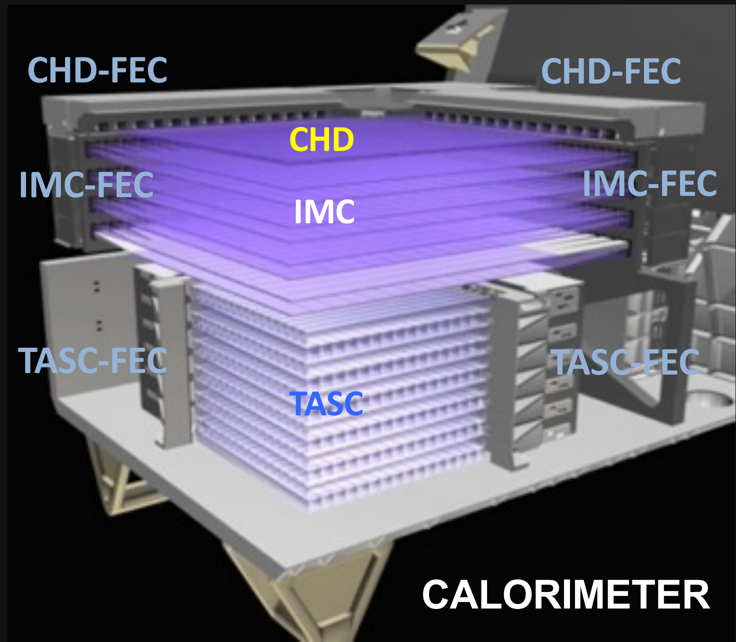




- Mass: 612.8 kg
- JEM Standard Payload Size
  1850 mm (L) × 800 mm (W) × 1000 mm (H)
- Power Consumption: 507 W (max)
- Telemetry: Medium 600 kbps (6.5GB/day) /
  Low 50 kbps

CALET instrument





CGBM

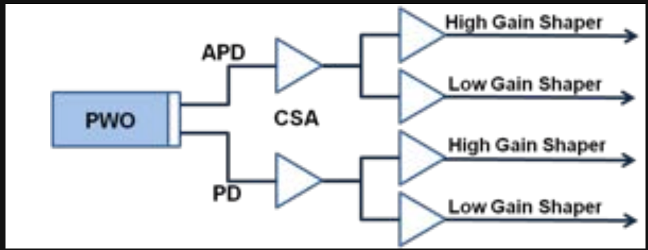
Detector	Measure	Geometry/Material	Readout
CHD (Charge Detector)	**Charge (Z=1-40)**	**Plastic Scintillator 14 paddles × 2 layers (X,Y) Paddle size: 3.2×1×45 cm^3**	**PMT+CSA**
IMC (Imaging Calorimeter)	**Tracking Particle ID**	**448 Scifi × 16 layers (X,Y) 7 W layers (3 X_0) Scifi size: 1×1×448 mm^3**	**64 MAPMT+ ASIC**
TASC (Total Absorption Calorimeter)	**Energy e/p separation**	**16 PWO logs × 12 layers (X,Y) log size: 1.9×2×32.6 cm^3 Total thickness: 27 X_0 , ~1.2 λ**	**APD/PD + CSA PMT+CSA (for Trigger)**

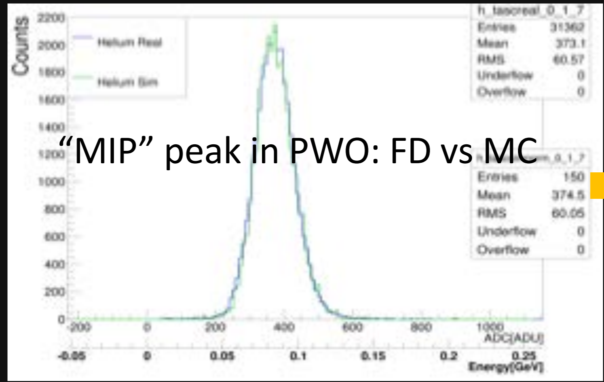
CALET main scientific objectives

Science Objectives	Observation Targets	Energy range
Nearby CR sources	Electron spectrum	100 GeV – 20 TeV
Dark Matter	Signatures in e/γ spectra	100 GeV – 20 TeV
CR Origin and Acceleration	Electron spectrum p-Fe individual spectra Ultra Heavy Ions ($26<Z\leq40$)	1 GeV – 20 TeV 10 GeV – 10^3 TeV few GeV/n
Galactic CR Propagation	B/C sub-Fe/Fe ratios	Up to some TeV/n
Solar Physics	Electron flux	< 10 GeV
Transient phenomena (GRB, e.m. counterpart of GW)	Gamma and X-rays	7 keV – 20 MeV

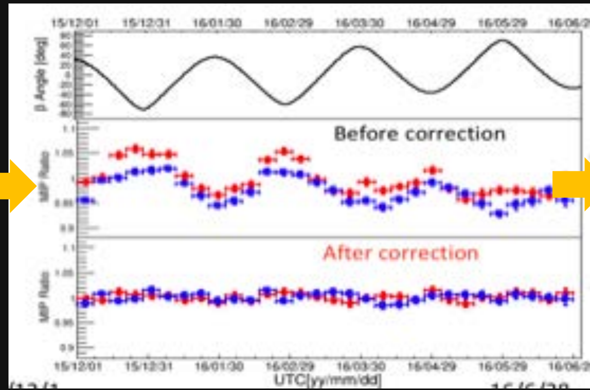
TASC calibration

Y. Asaoka et al. (CALET Collaboration)
Astropart. Phys. 91 (2017) 1



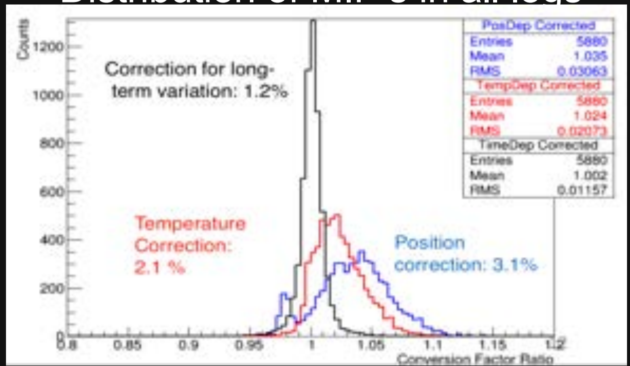


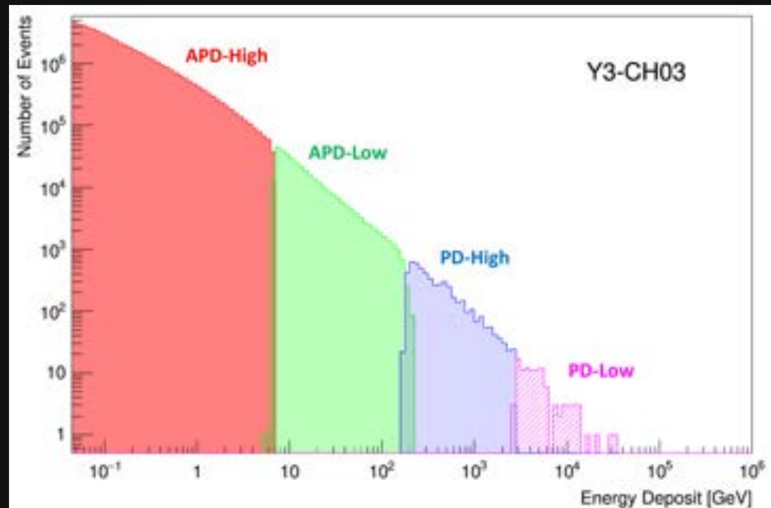
Calibration on orbit with p and He MIP's

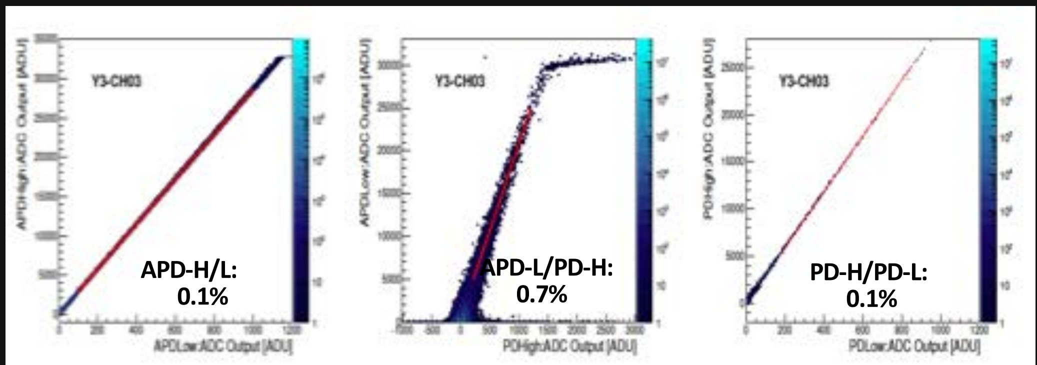


Corrections for position, temperature, and latitude (due to rigidity) dependence

Distribution of MIP's in all logs







Gain ranges calibrated by UV laser irradiation on ground
Correlation of gain ranges calibrated in-flight

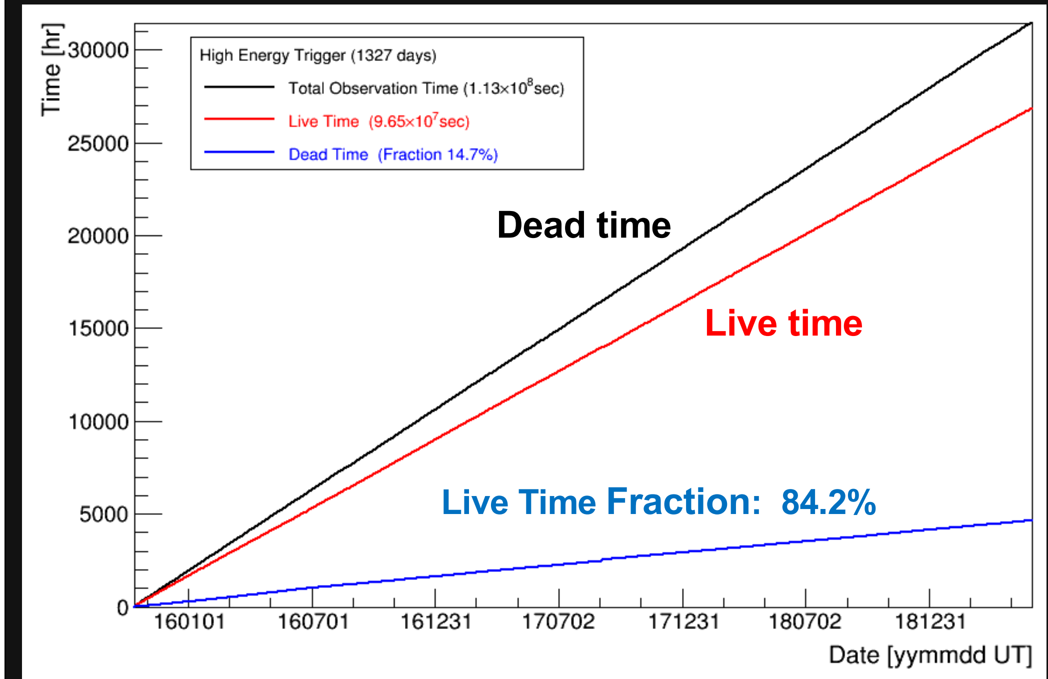
Energy distribution in one PWO log.
Dynamic range of each channel: **1 - 10^6 MIP**

Observations with High Energy Trigger (>10GeV)

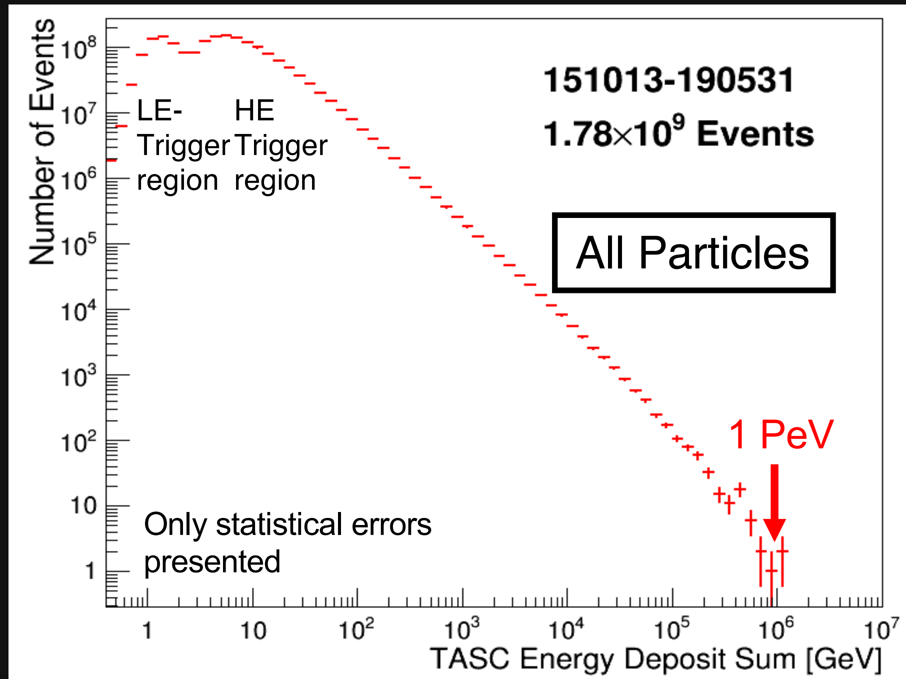
Observation by High Energy Trigger for 1327 days : Oct.13, 2015 – May 31, 2019

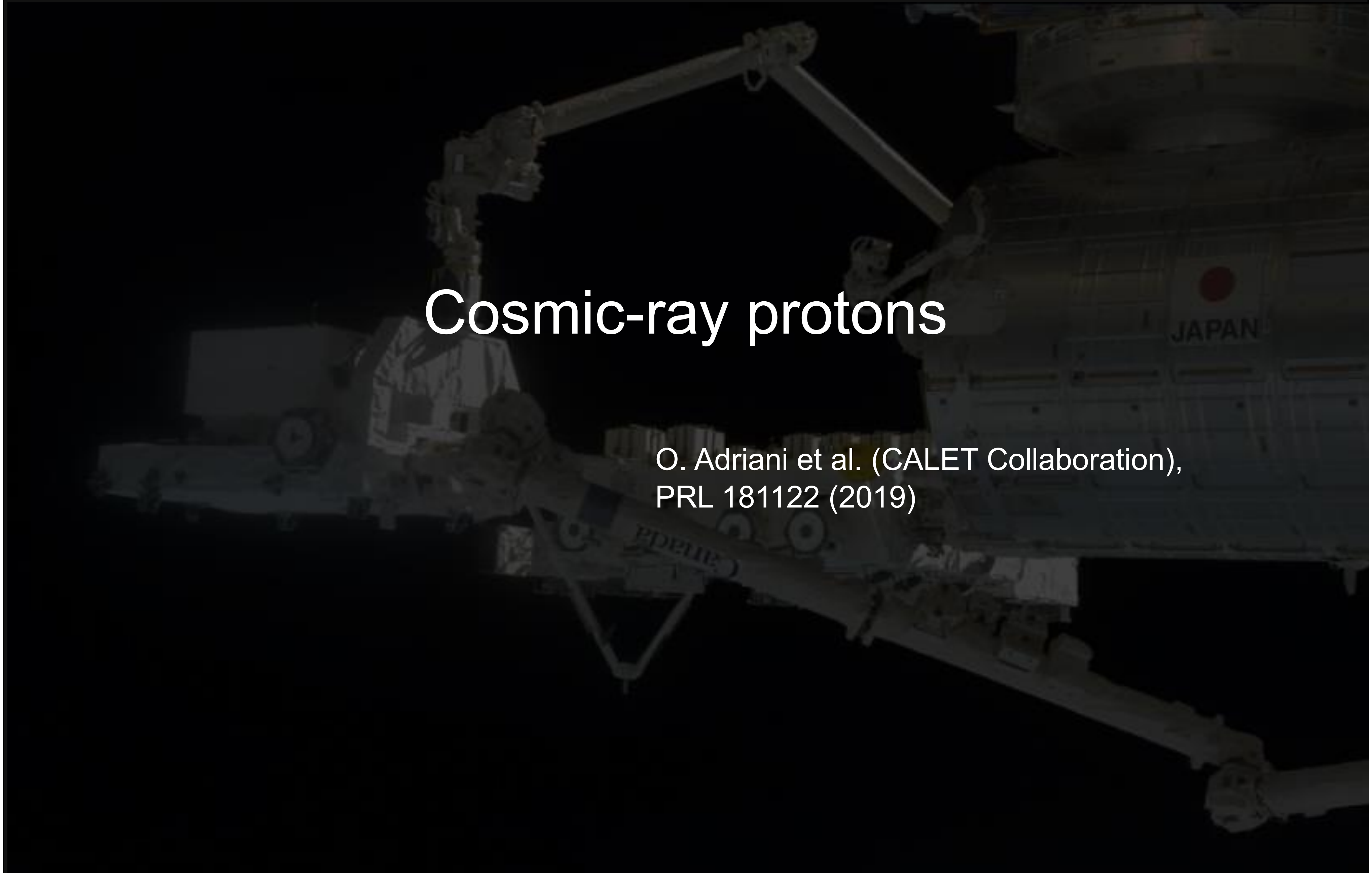
- The exposure, SΩT, has reached ~116 m^2 sr day for electron observations under continuous and stable operations.
- Total number of triggered events is ~1.8 billion with a live time fraction of 84.0 %.

Accumulated observation



Distribution of deposit energies (ΔE) in TASC





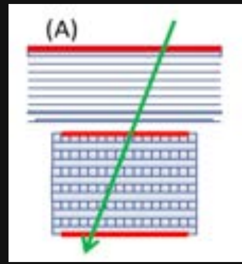
Cosmic-ray protons

O. Adriani et al. (CALET Collaboration),
PRL 181122 (2019)

Event Selection

Analyzed Flight Data:

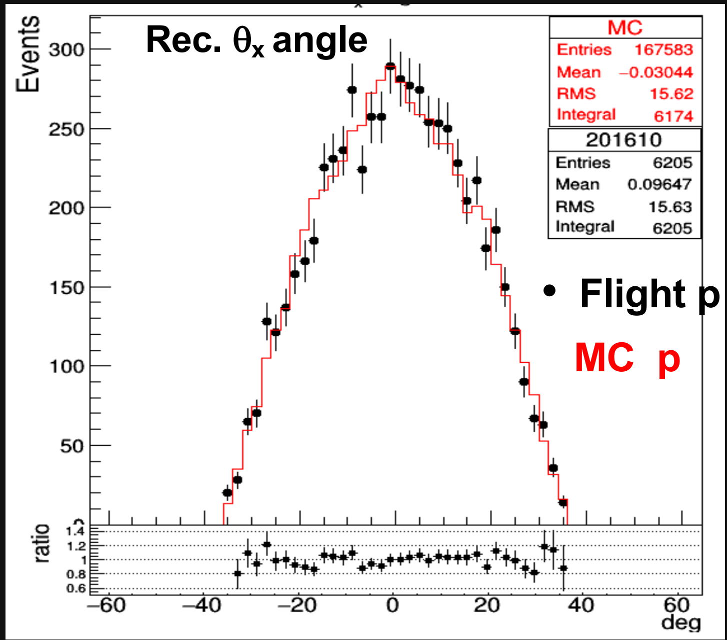
- 1054 days (Oct. 13, 2015 to Aug. 31, 2018)
- 40% of full CALET acceptance (Acceptance A; 416 cm^2 sr)

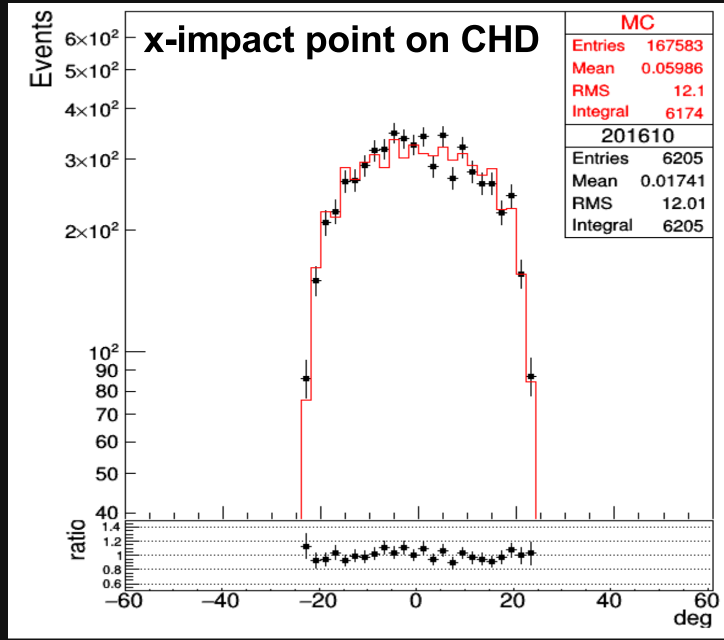


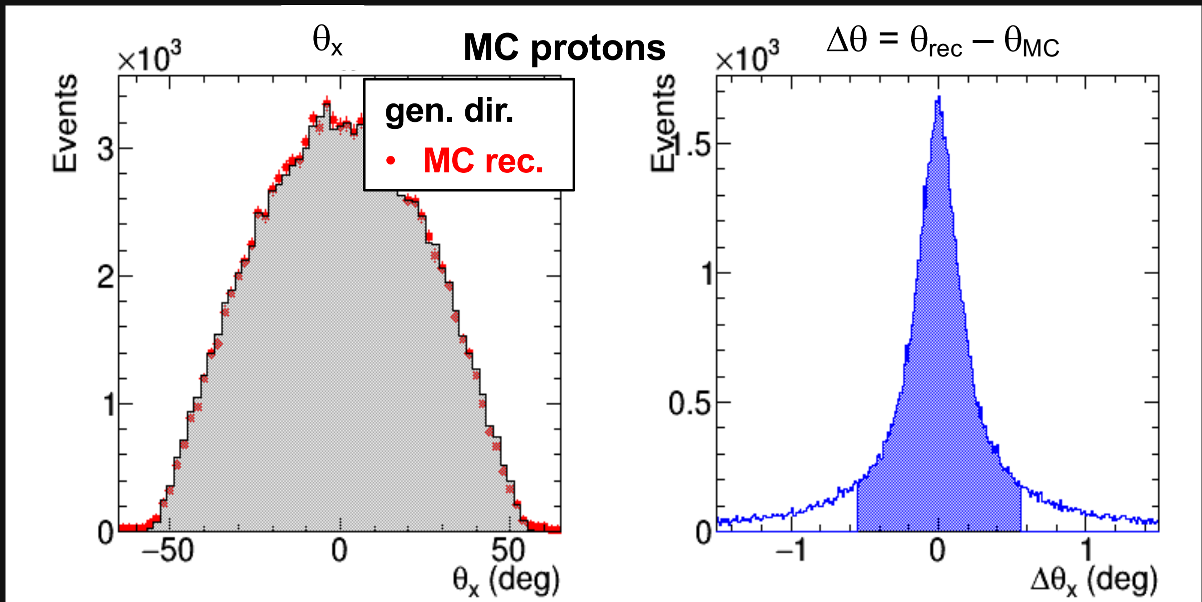
1. Offline trigger confirmation (LE/HE shower triggers: > 5 (50) MIP for IMC-X/Y78,
   > 10 (100) MIP for TASC-X1)

1. Acceptance Cut (events crossing CHD, TASC top and bottom layers within 2 cm from the edge)
2. Track quality cut
3. Electron rejection cut (based on Moliere concentration)
4. Off-acceptance events rejection (topological cuts on fraction of energy deposited in each TASC layers and in edge TASC logs)
5. Track consistency with TASC energy deposit
6. Existence of a shower core in IMC
7. Charge ID (CHD and multiple dE/dx sampling along the track in IMC)

Tracking performance







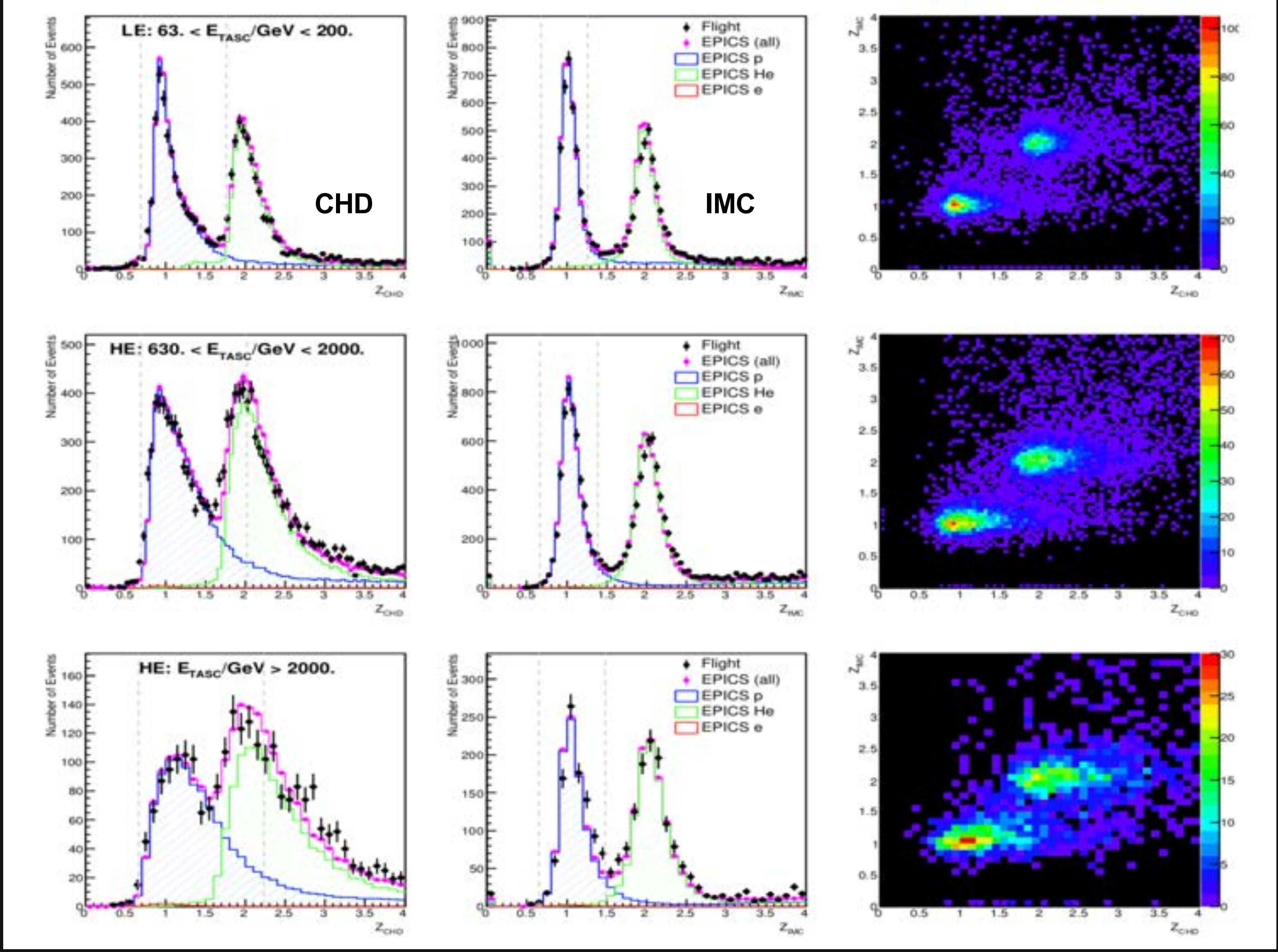
Protons

Angular resolution: 0.55°

CHD IP resolution: ~1 mm

P. Maestro, N. Mori,
PoS (ICRC2017) 208

p/He charge identification

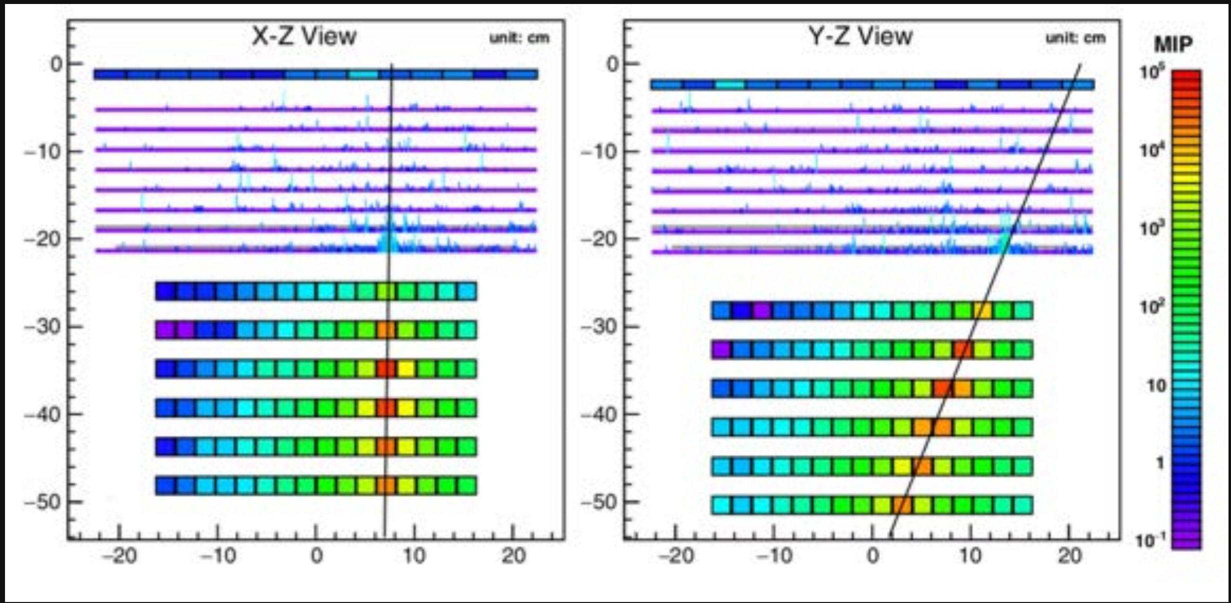


Corrections to adjust the peak positions which shift as the energy increases due to backscattering effect

TASC energy scale

- Beam test calibration at CERN-SPS with proton beams up to 400 GeV.
- Trigger efficiency and energy response derived from MC simulations were accurately tuned using the beam test results.
- Three detailed MC simulations of CALET instrument were developed based on EPICS, FLUKA (with hadronic package DPMJET-III), and GEANT4 → compare response at high energy where no beam calibration is available
- Energy fraction for protons ~35%.

  Energy resolution 30-40% → Unfolding



Example of a proton event with an energy deposit sum E_{TASC} ~10 TeV

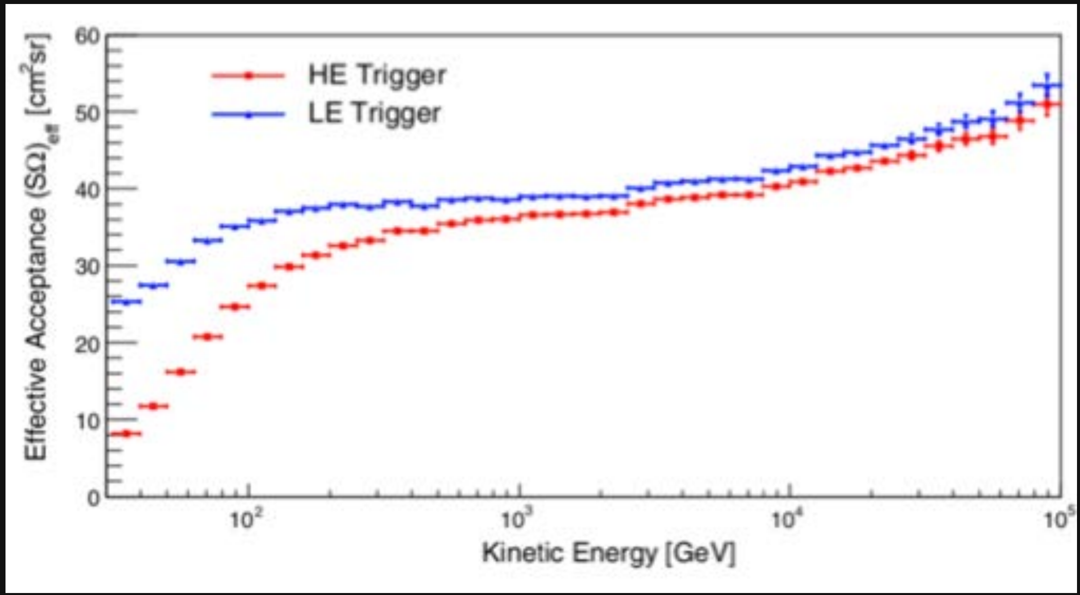
Flux measurement

$$\Phi(E) = \frac{n(E)}{S\Omega_{eff}(E)\ \Delta E\ T}$$

$$n(E) = U\left(N_{obs}(E_{TASC}) - N_{bkg}(E_{TASC})\right)$$

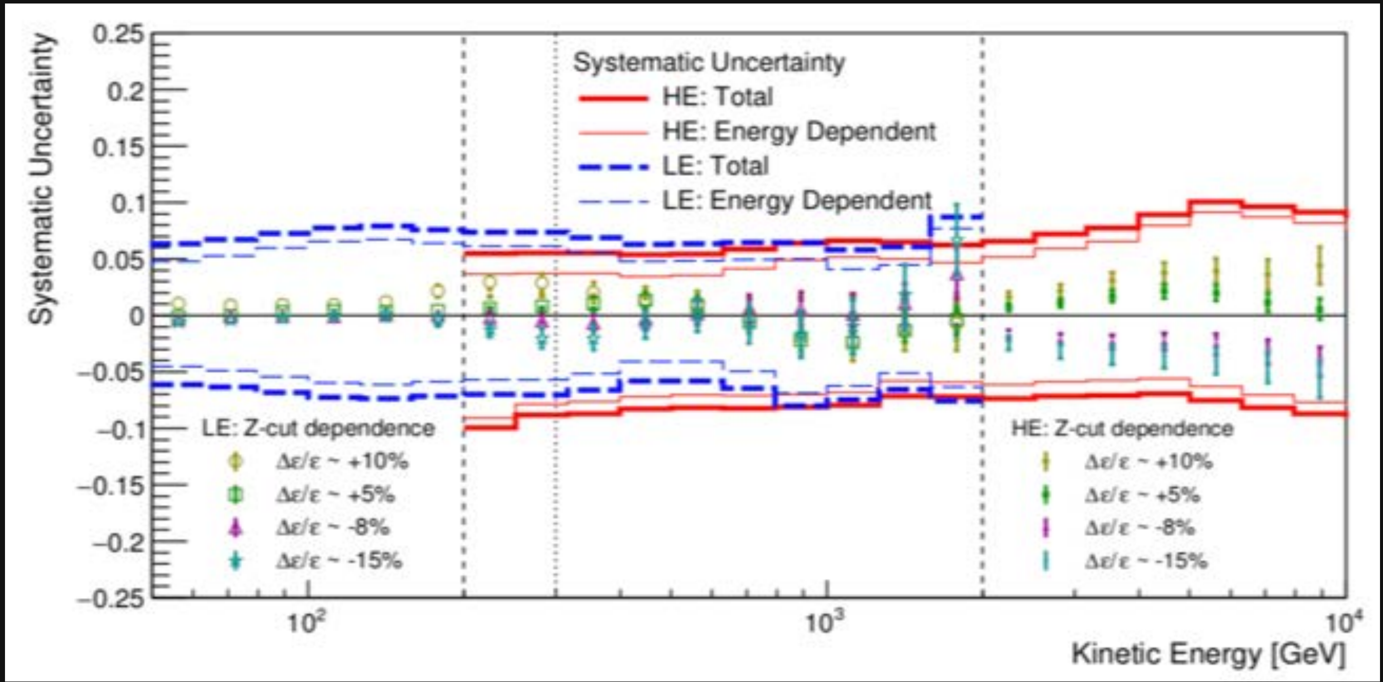
n(E): bin counts of the unfolded distribution

Background correction for He contamination and off-acceptance events (at most 5% in lowest and highest energy region, few % in intermediate region)



$S\Omega_{eff}$: effective acceptance including all selection efficiencies for HE and LE trigger analysis

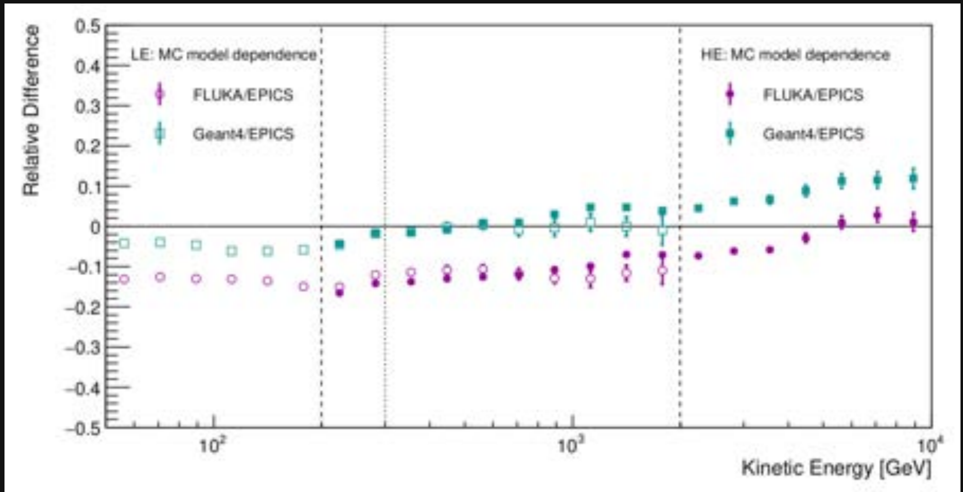
Systematic uncertainties



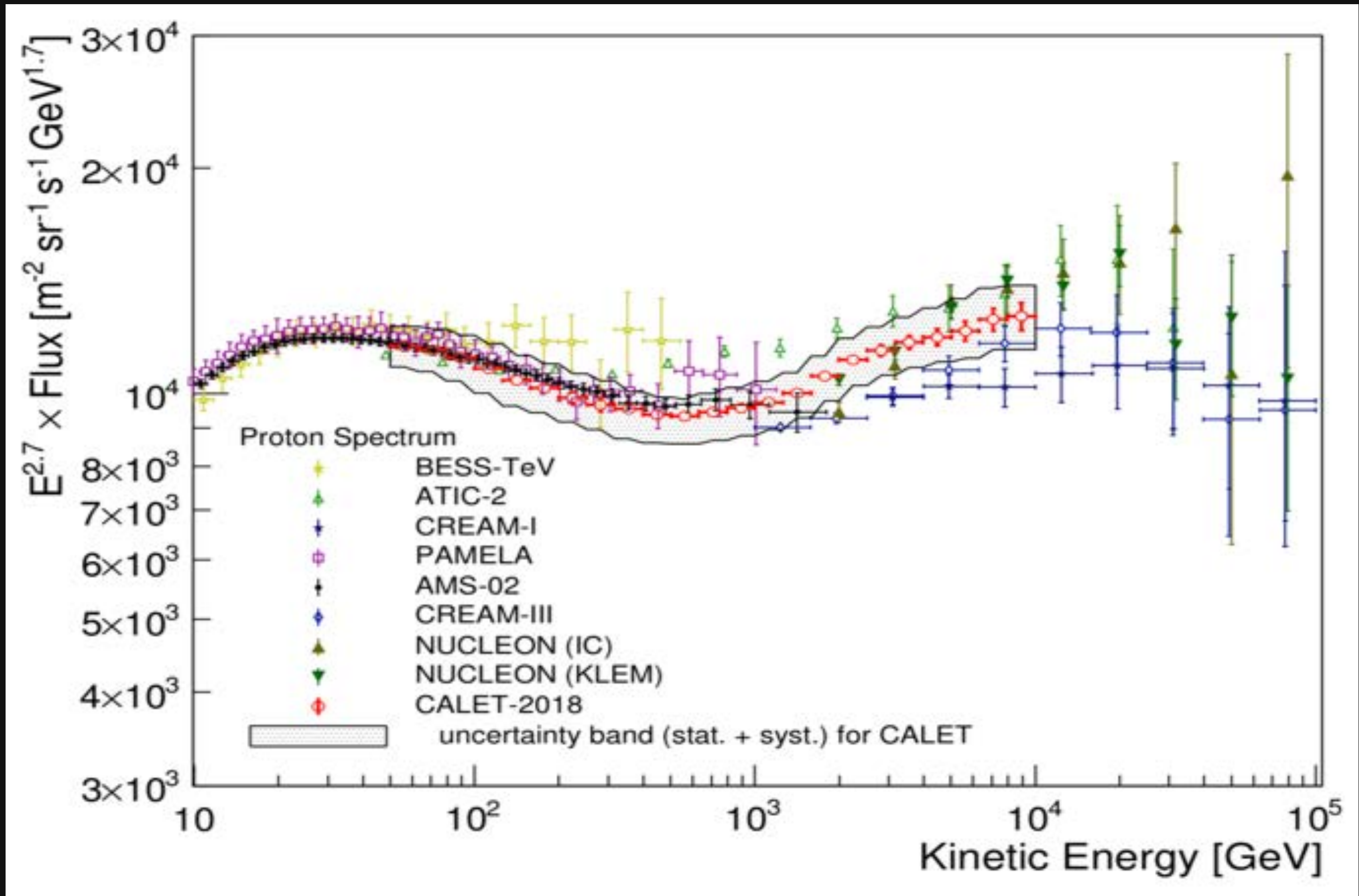
Main sources of systematics uncertainties:

- hadronic interaction modeling
- energy response
- track reconstruction
- charge identification

Stability of the measured spectrum vs. variations of analysis cuts and different MC simulations for efficiencies and unfolding.



Proton spectrum

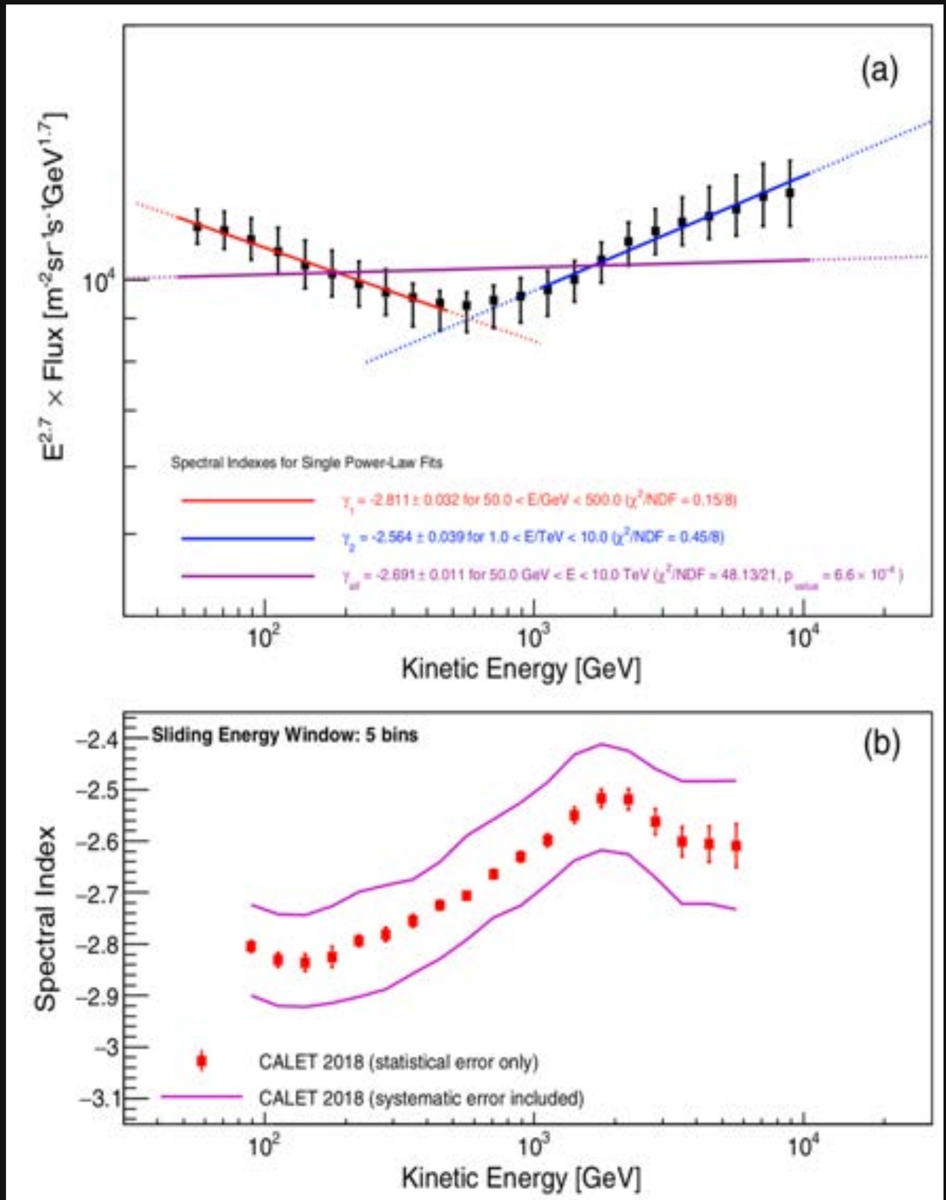


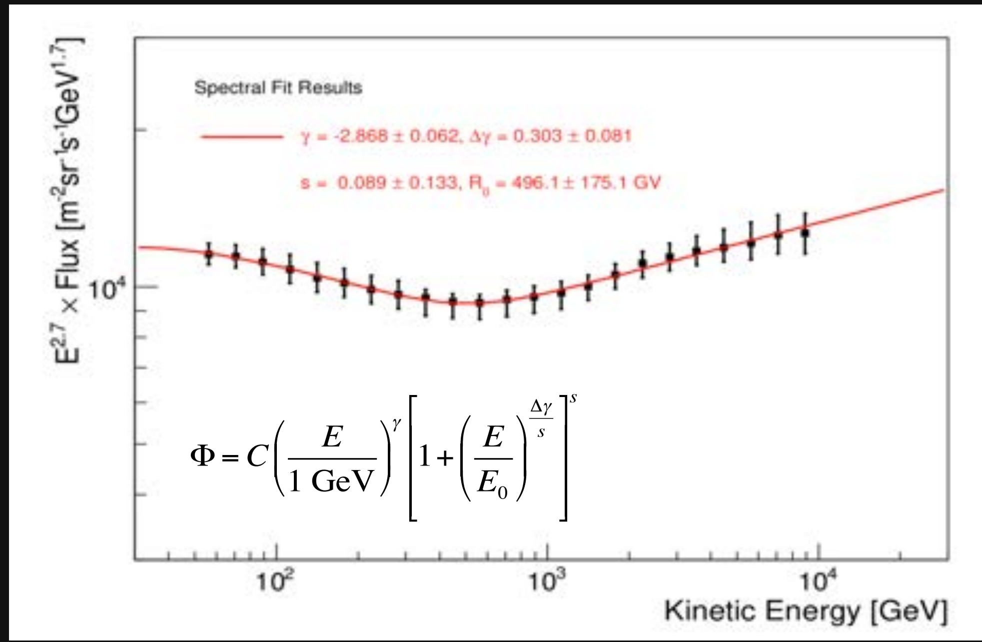
CALET proton measurement energy interval: 50 GeV - 10 TeV.

Consistent with AMS02 (CREAM-III) in low (high) energy region

First space-based instrument covering the whole energy range previously investigated in separate subranges by magnetic spectrometers and calorimeters.

Spectral analysis





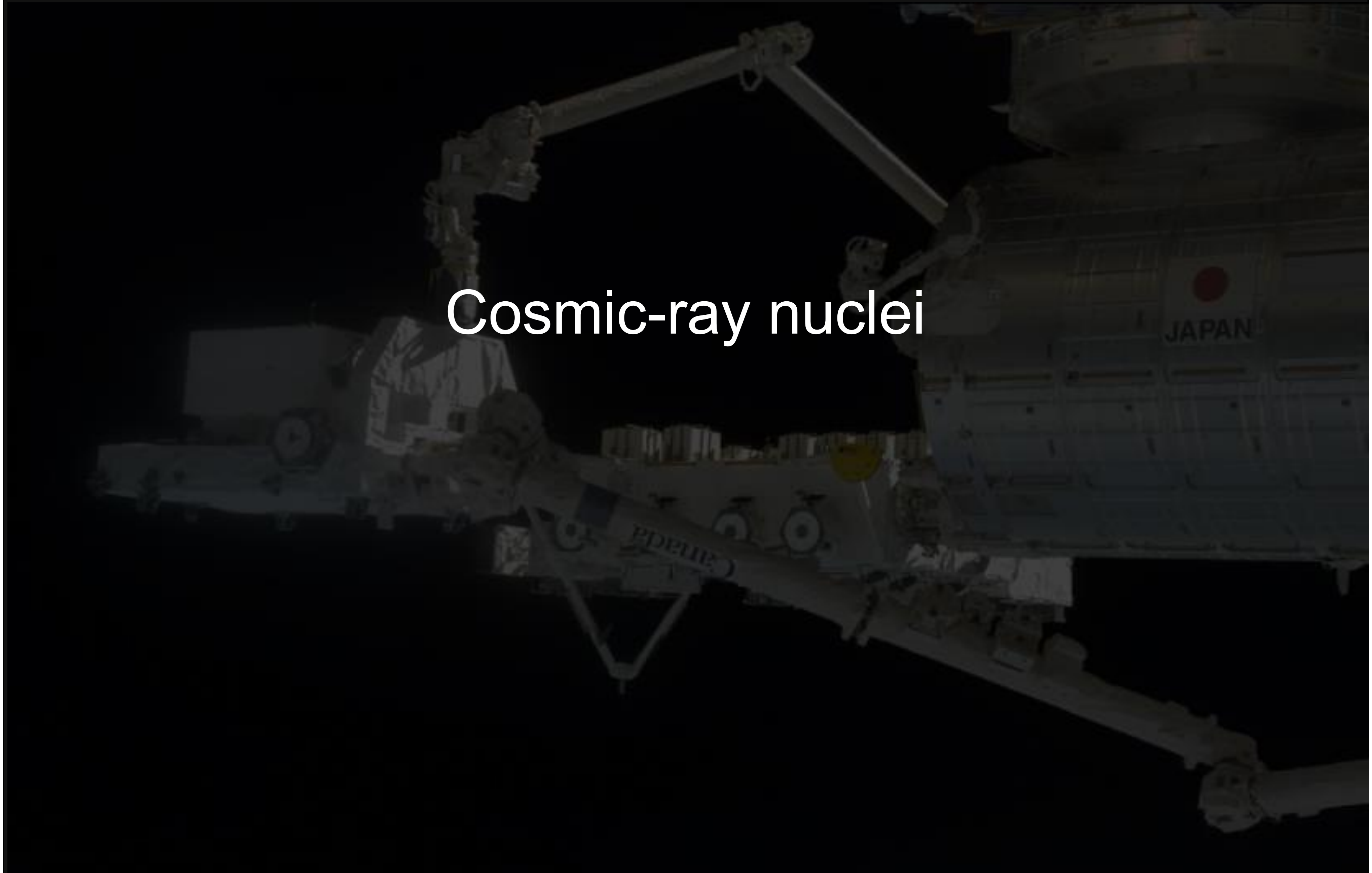
Single power-law hypothesis disfavored by >3σ

Smoothly broken power-law fit:

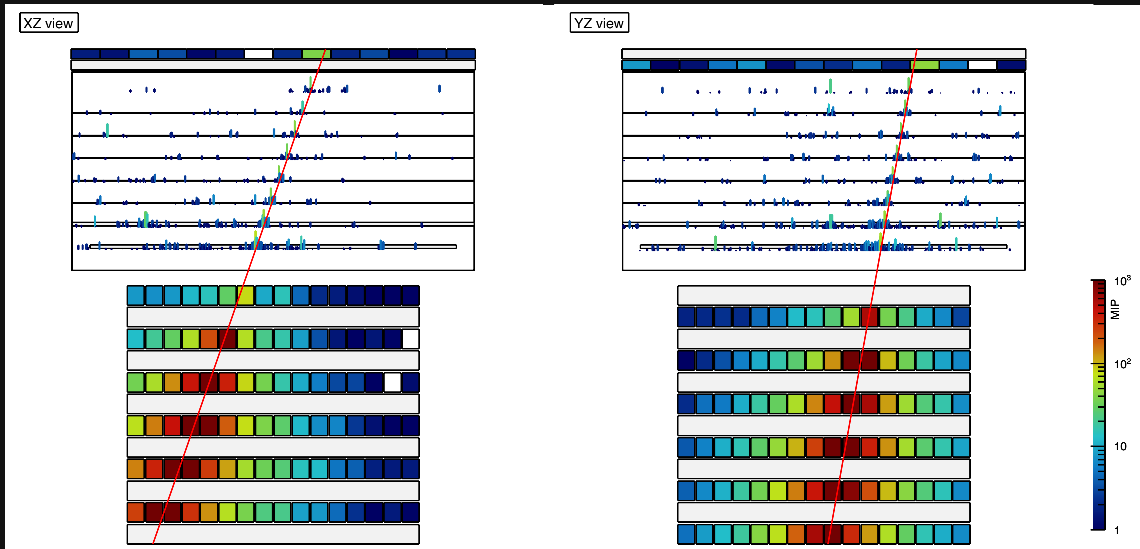
- γ = -2.87 ± 0.06 (consistent with AMS-02)
- $\Delta\gamma$ = 0.30 ± 0.08 (larger than AMS-02)
- R_0 = 496 ± 175 GV (larger than AMS-02)

→ Clear hardening above few hundreds of GeV

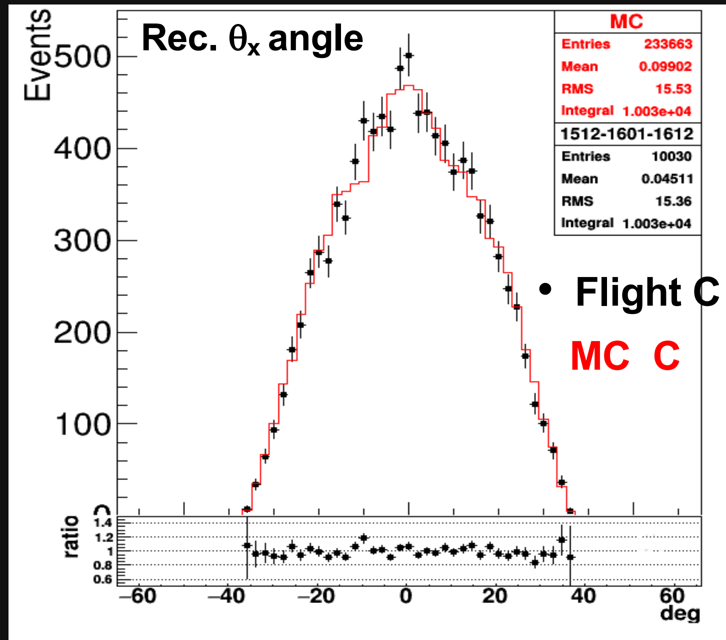
Cosmic-ray nuclei

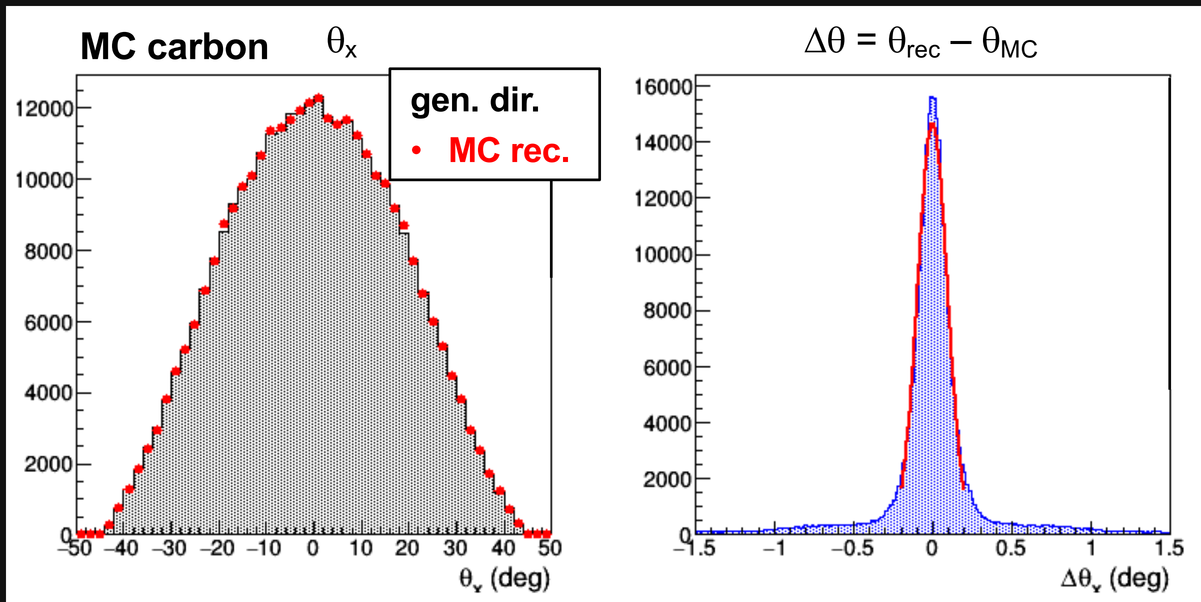


Tracking performance



A carbon event with E_{TASC} ~ 11 TeV





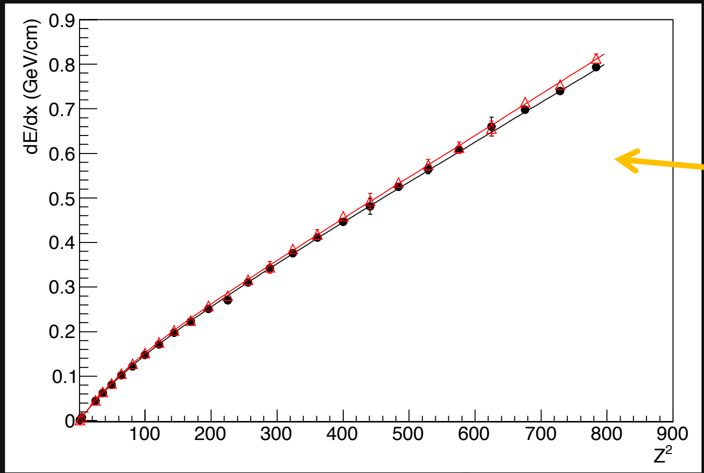
In BCNO region

Angular resolution: 0.09°

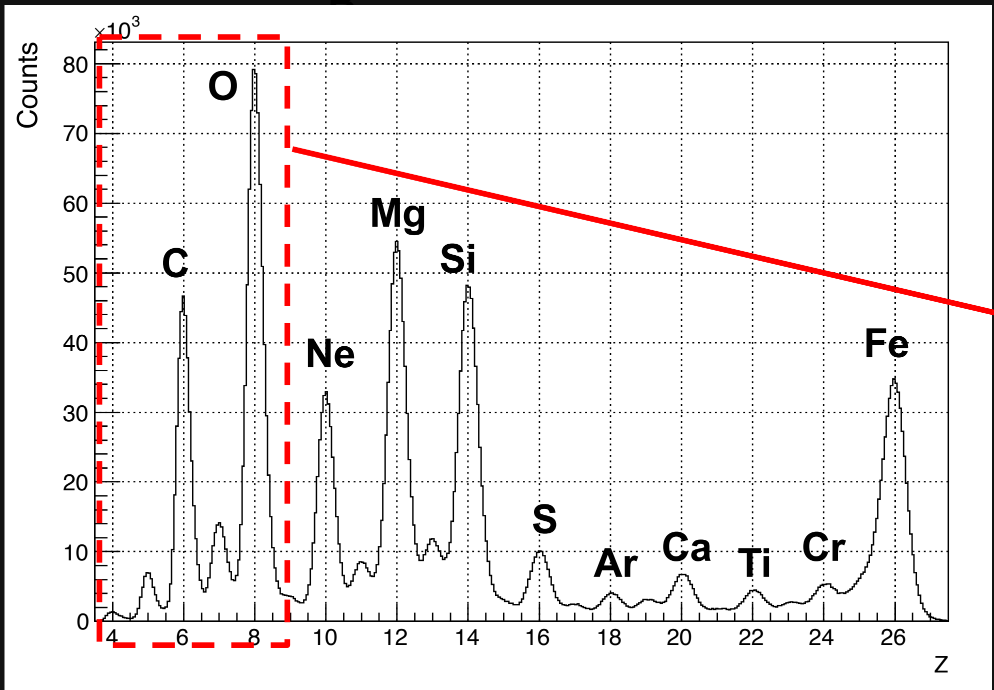
CHD IP resolution: 240 μm

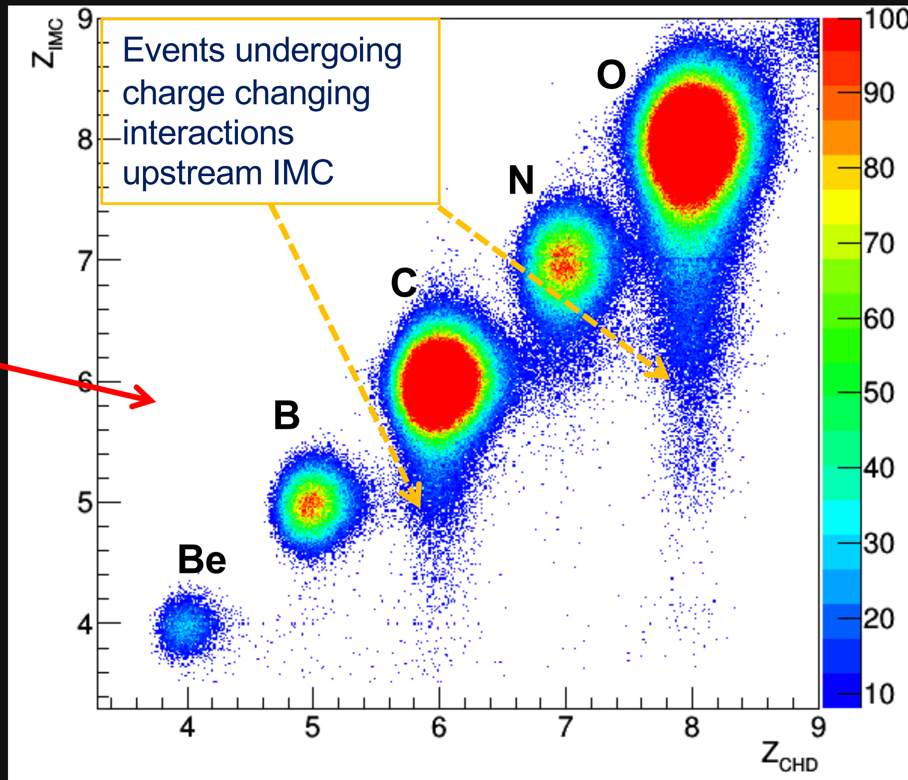
P. Maestro, N. Mori, PoS (ICRC2017) 208

Charge identification

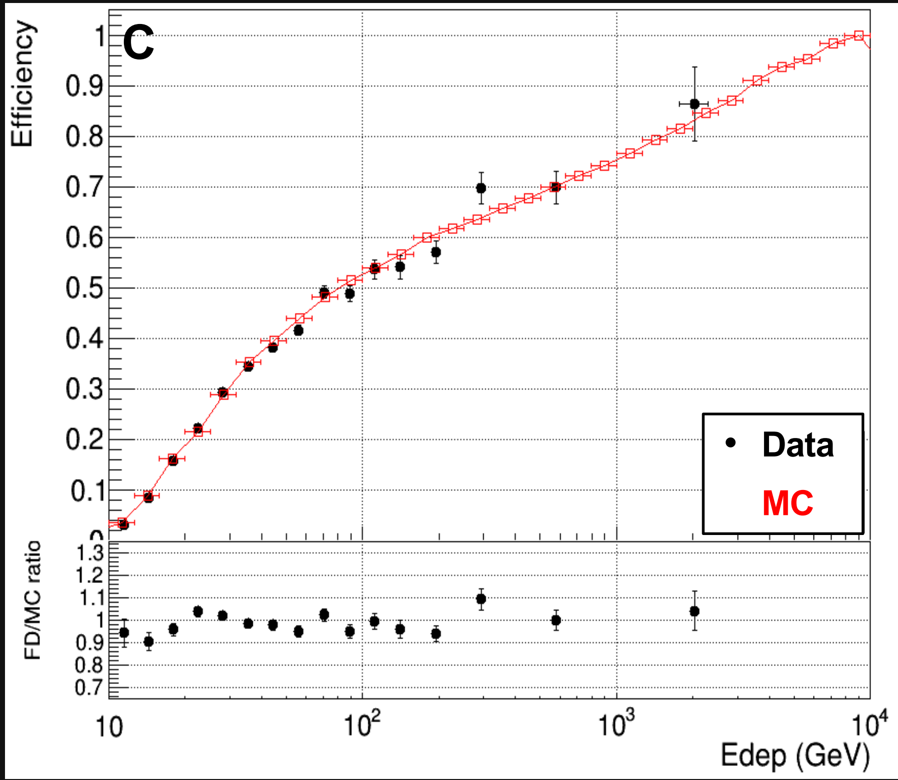


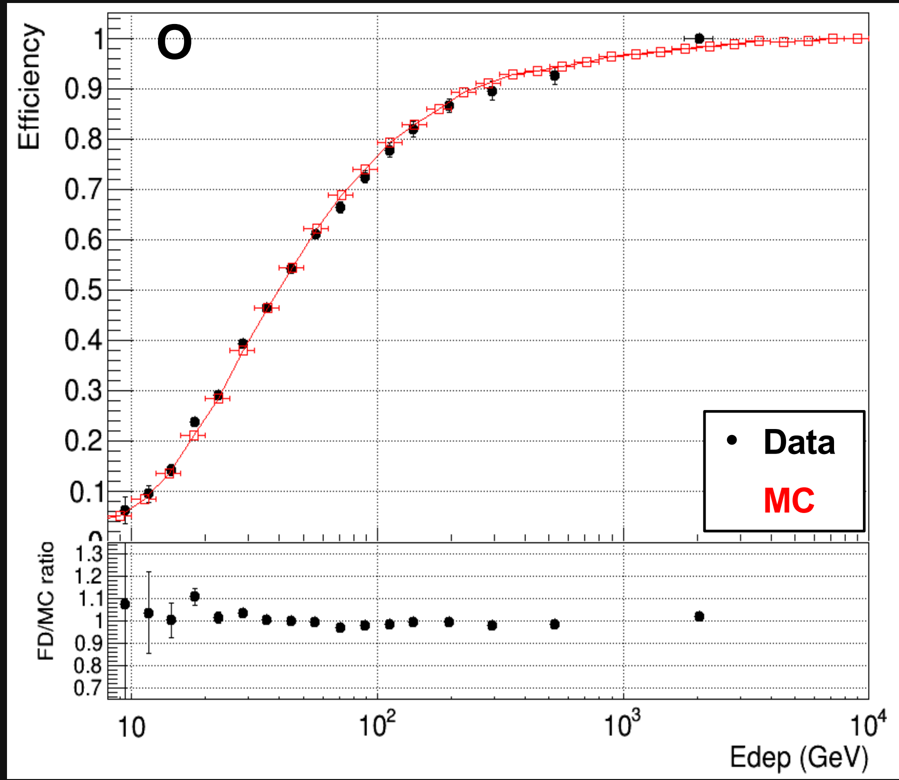
- Redundant charge measurements by combined CHD and multiple dE/dx in IMC fibers in the first 4 X/Y layers.
- Non linear response to Z^2 due to light saturation in the scintillators is corrected using a core+halo model (Voltz).
- Excellent resolution:
  - CHD σ_Z ~0.15 e (BCNO), ~0.28 e (Fe)
  - IMC σ_Z ~0.2 e in BCNO region





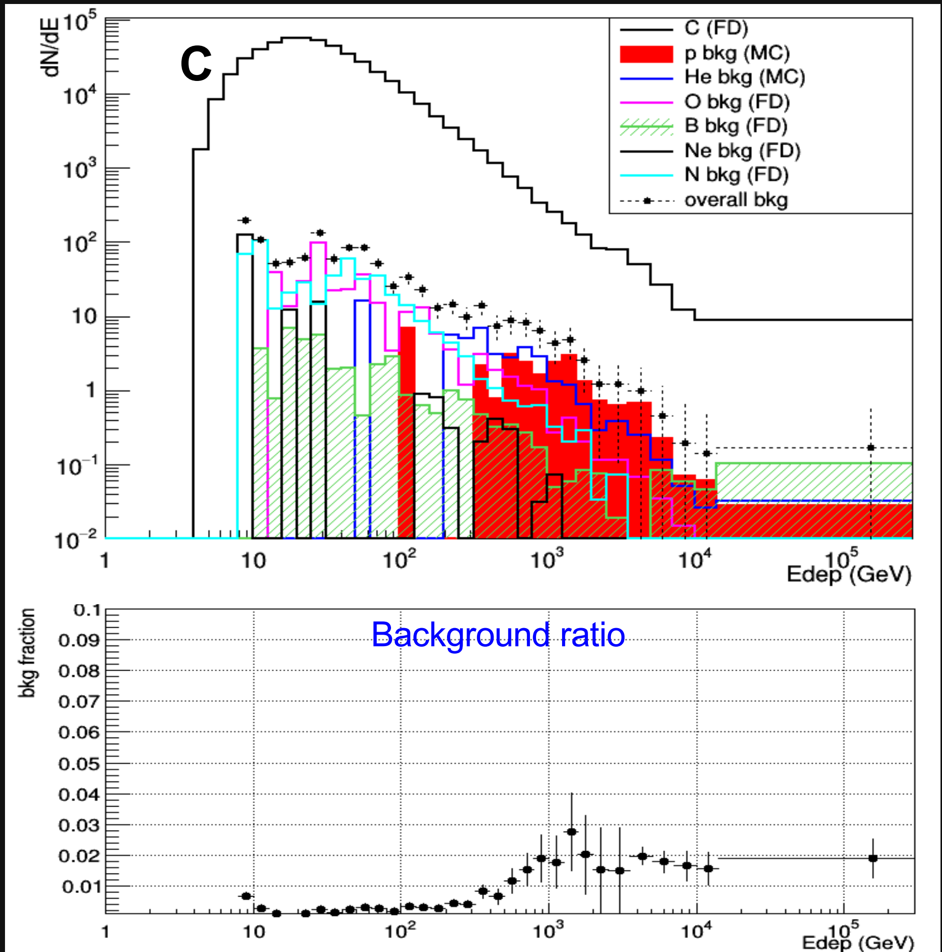
High-energy trigger efficiency

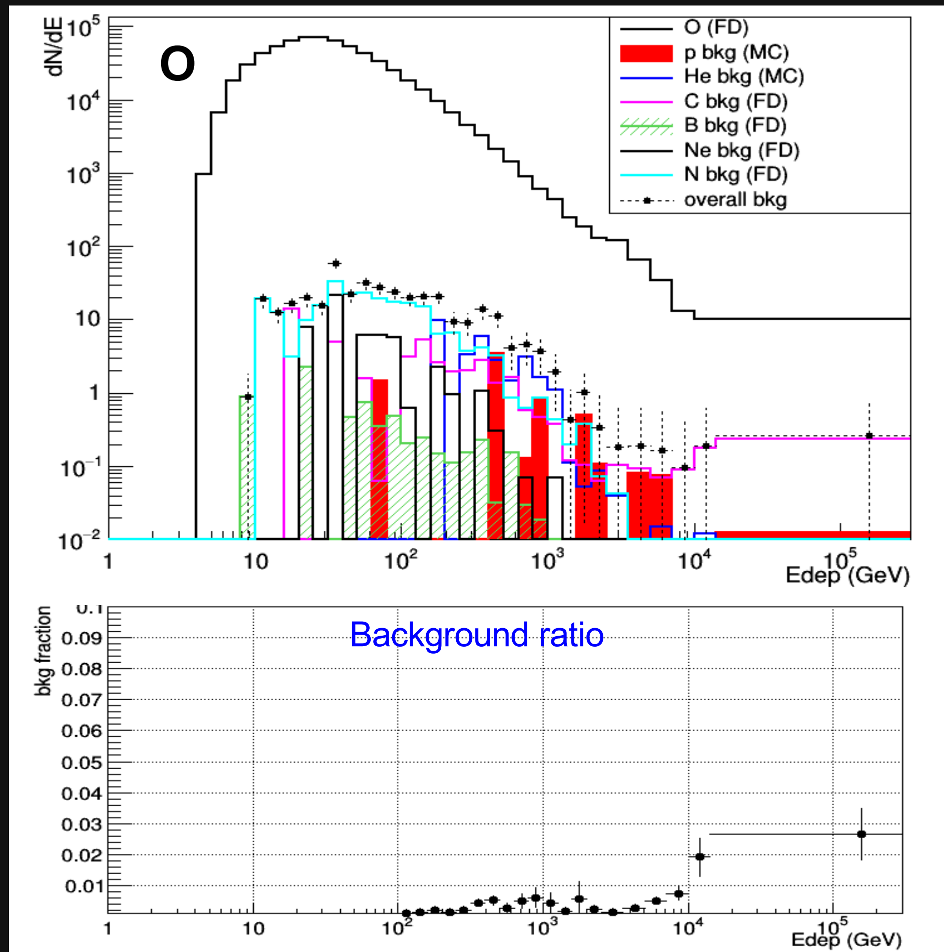




- High-Energy Trigger (HET) is the primary CALET mission trigger.
- It is based on the coincidence of signals in last four IMC layers and top TASC layer, with thresholds chosen to ensure >95% efficiency for electrons > 10 GeV
- HET efficiency for nuclei is measured using subset of data taken with same trigger logic but lower thresholds (allowing to trigger also penetrating particles).
- HET is modelled in simulation: good agreement between MC and flight data

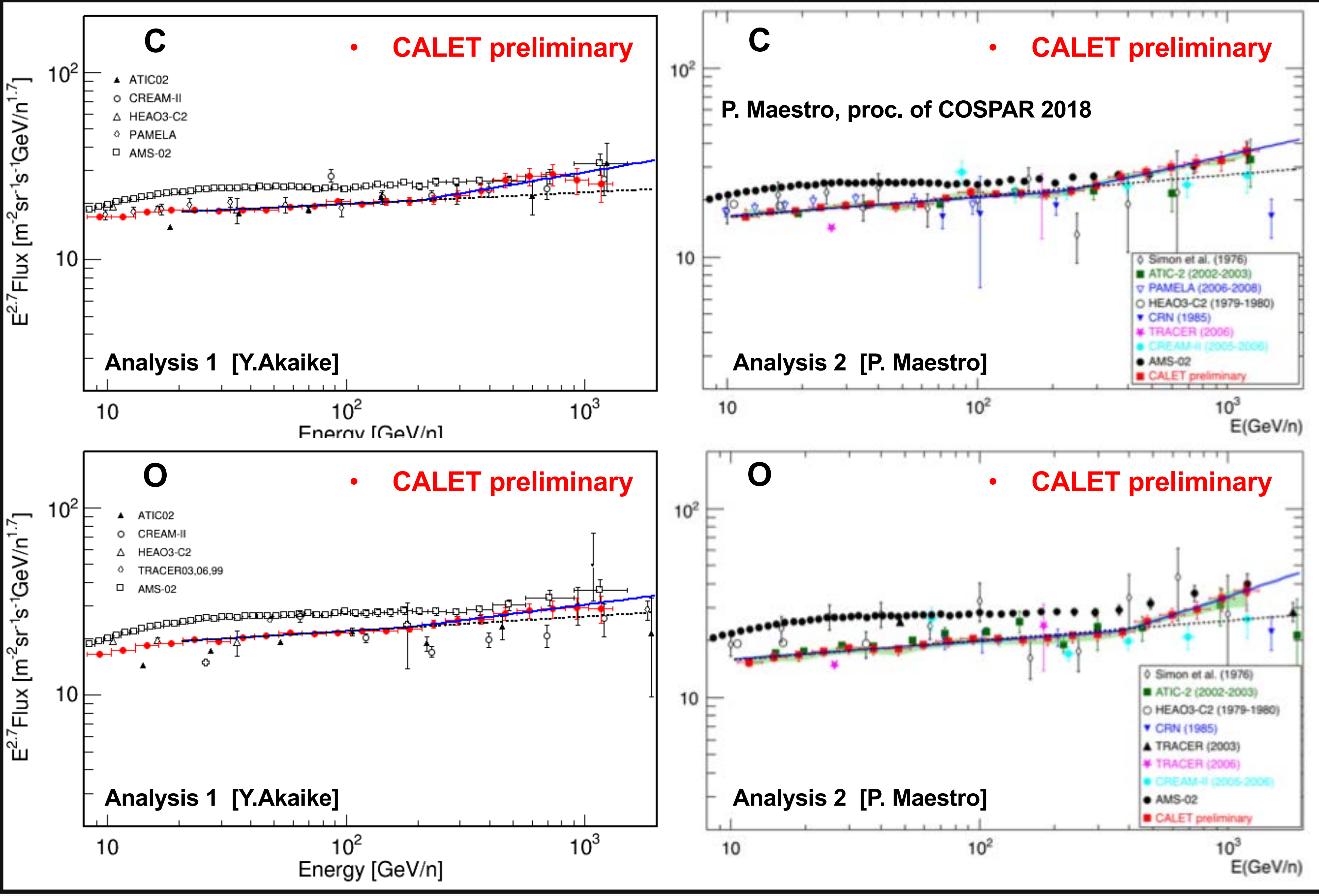
C/O dN/dE and background estimate





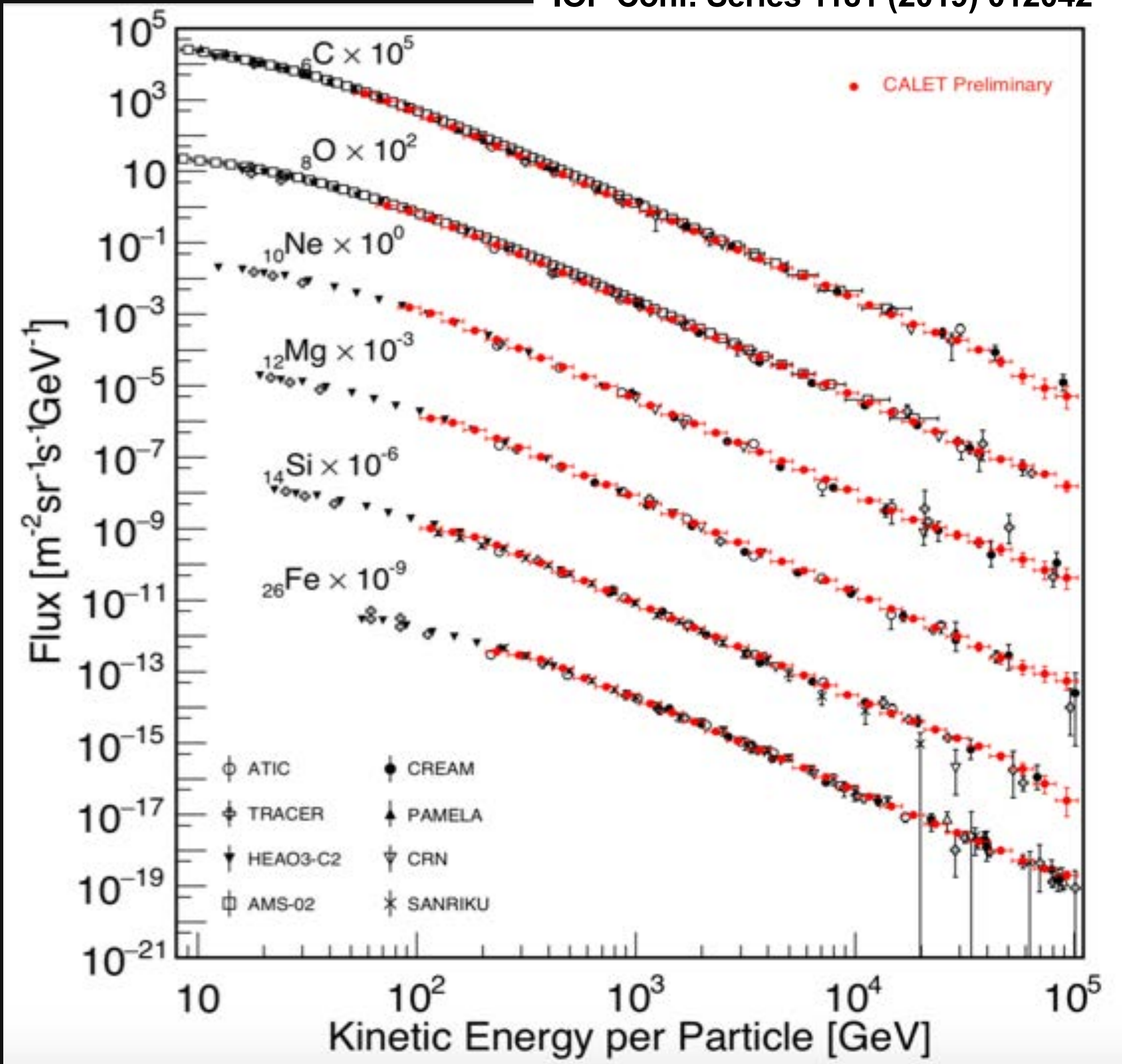
- dN/dE distributions of Z>4 nuclei mis-identified as C/O are estimated from data.
- Background due to H/He is computed by normalizing MC distributions to the real fluxes
- Total background is few % in all energy bins

Preliminary carbon and oxygen spectra



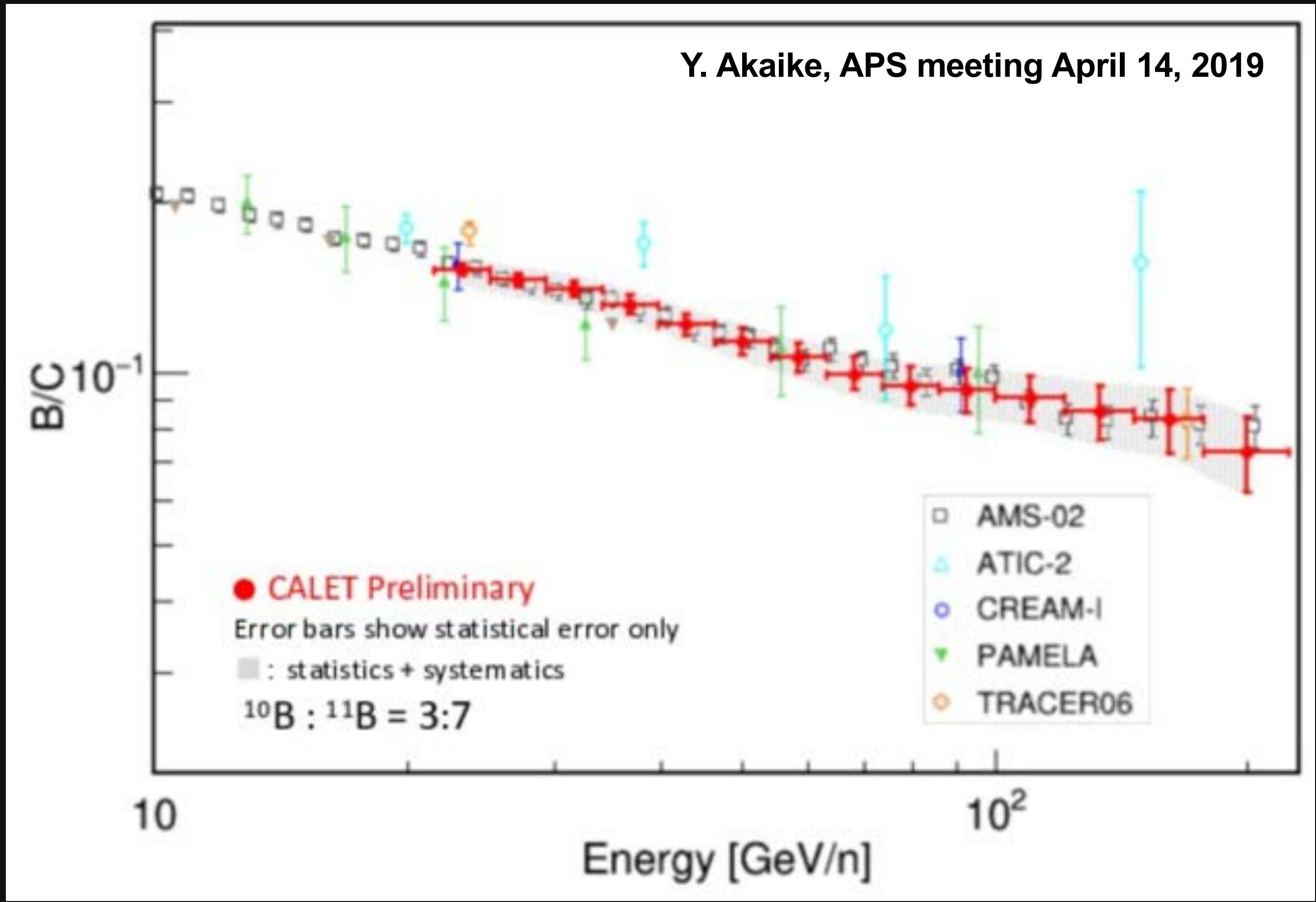
Preliminary flux of primary components

Y. Akaike, Journal of Physics:
IOP Conf. Series 1181 (2019) 012042



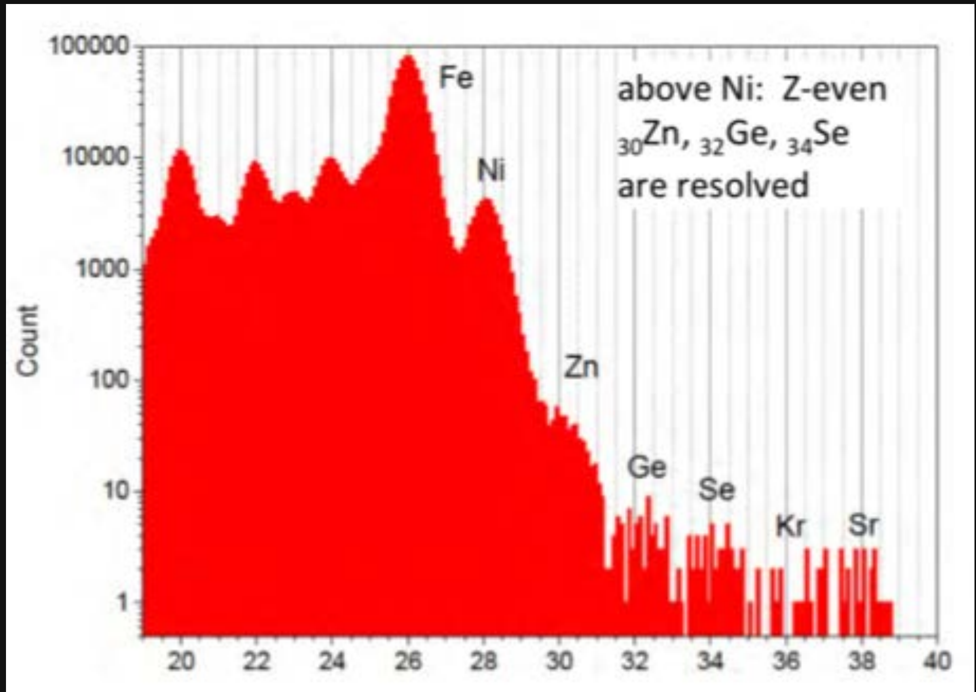
Observation period: 962 days

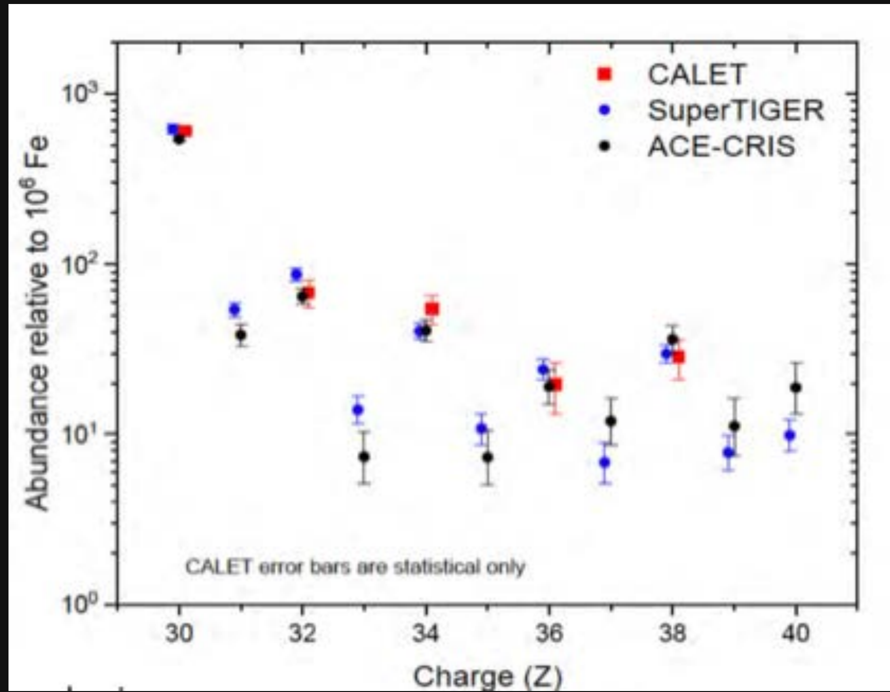
Preliminary B/C flux ratio



Preliminary abundances of ultra-heavy nuclei

B. Rauch, APS meeting April 14, 2019



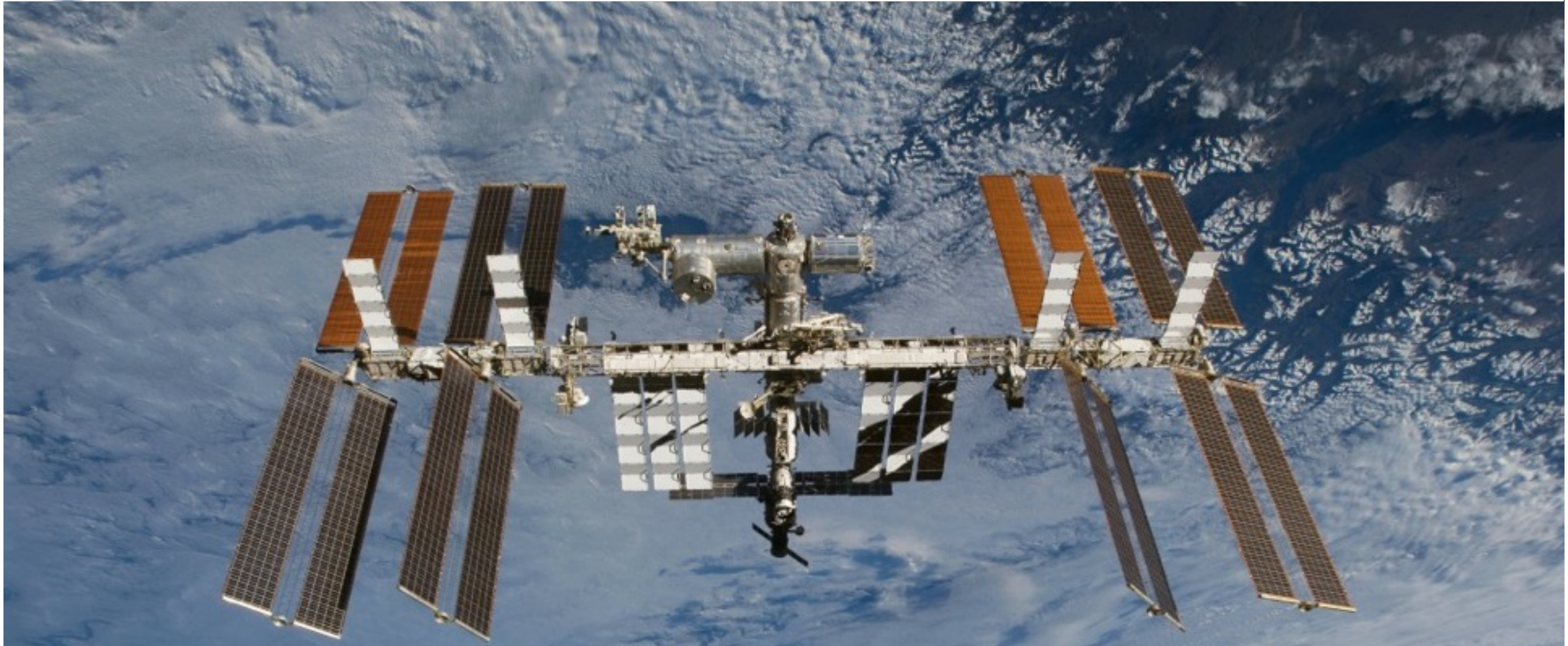


CALET measures the relative abundances of nuclei above Fe through ^{40}Zr

Event Selection: Vertical cutoff rigidity > 4 GV & Zenith Angle < 60 degrees

Contamination from neighboring charge are determined by multiple-Gaussian fit

The CALET UH element ratio relative to ^{26}Fe show good agreement with SuperTIGER and ACE abundances.

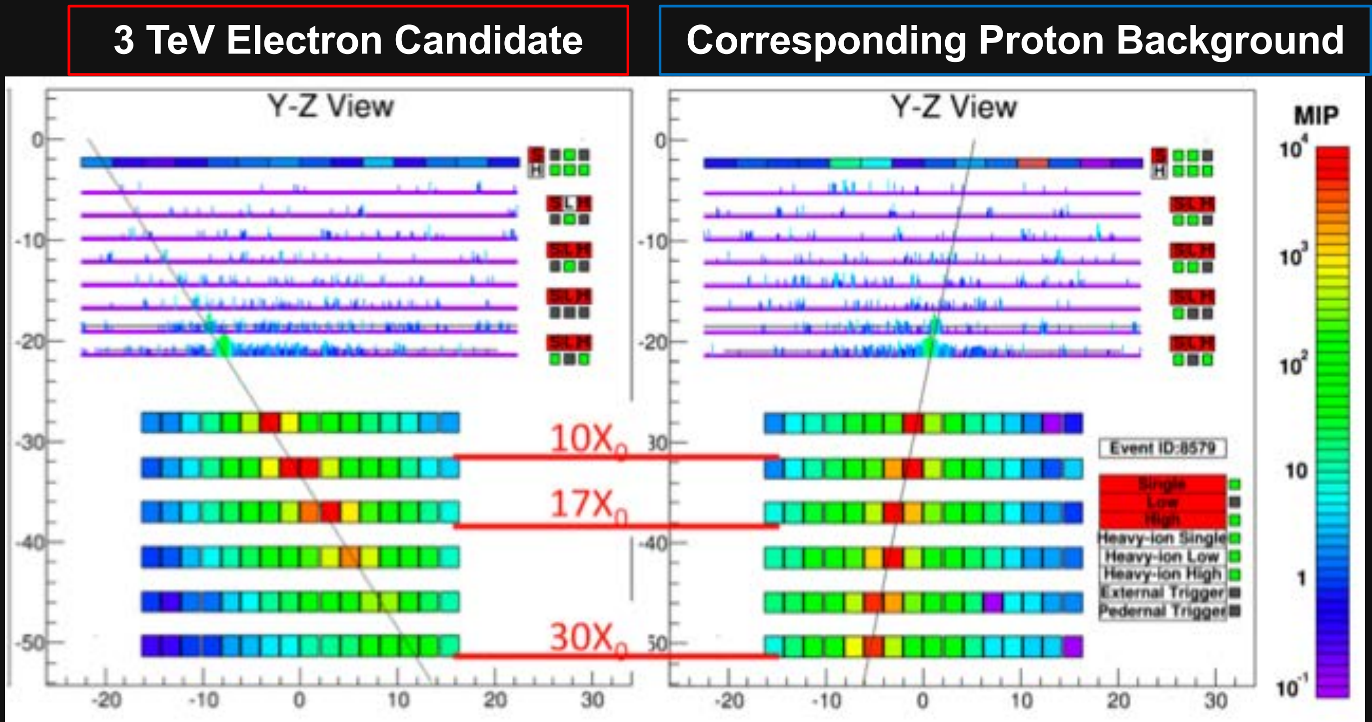


All-electron spectrum ($e^+ + e^-$)

O.Adriani et al. (CALET collaboration), PRL 119 (2017) 181101

O.Adriani et al. (CALET collaboration), PRL 120 (2018) 261102

Electron vs. proton showers

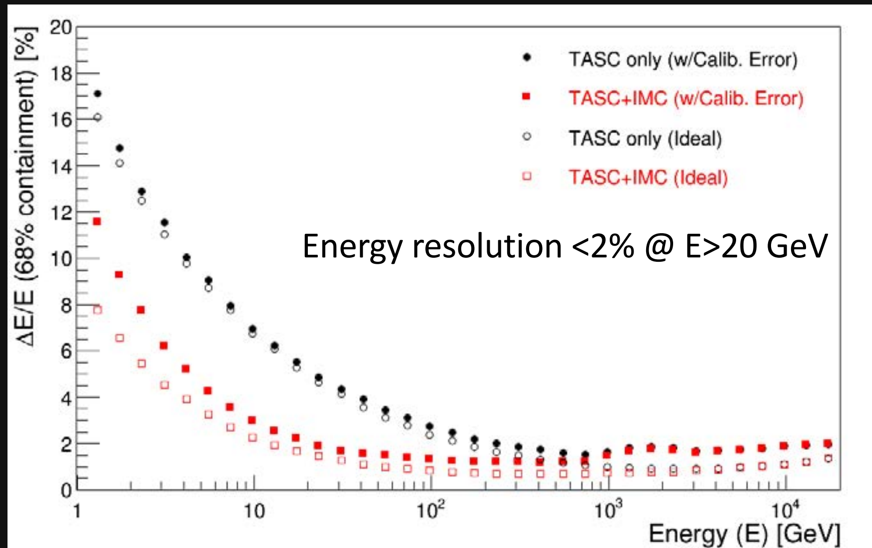


Flight data. Detector size in cm

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

CALET is an instrument optimized for all-electron spectrum measurements.

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



Event Selection

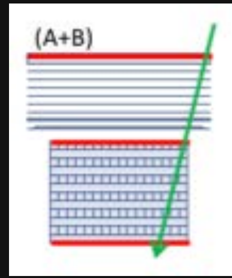
Analyzed Flight Data:

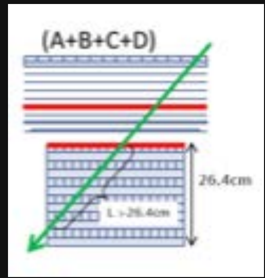
PRL 119 (2017) 181101

- 627 days (Oct.13, 2015 to June 30, 2017).
- 55% of full CALET acceptance (Acceptance A+B; 570cm^{2}sr)
- 10 GeV - 3 TeV

PRL 120 (2018) 261102

- 780 days (Oct.13, 2015 to Nov. 30, 2017)
- Full CALET acceptance at high energy (A+B+C+D~1040 cm^2 sr)
- Up to 4.8 TeV, doubled statistics at E>500 GeV





1. Offline Trigger
2. Acceptance Cut
3. Single Charge Selection
4. Track Quality Cut
5. Shower Development Consistency
6. Electron Identification
   - Simple two parameter cut (used for E<500 GeV)
   - Multivariate Analysis using Boosted Decision Trees (BDT)

Electron Identification

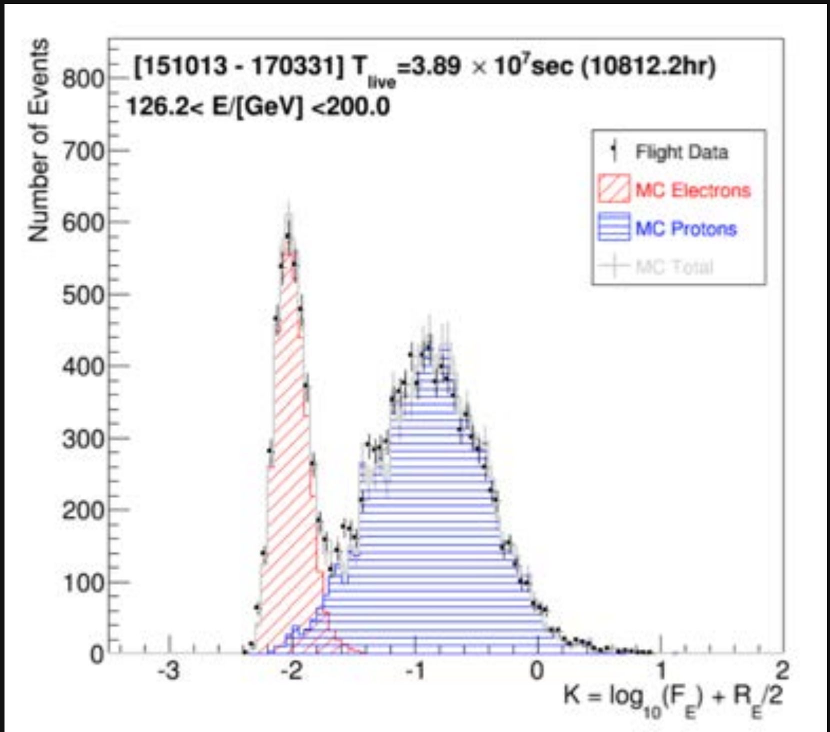
Simple Two Parameter Cut

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

R_E: Energy weighted lateral spread in TASC-X1

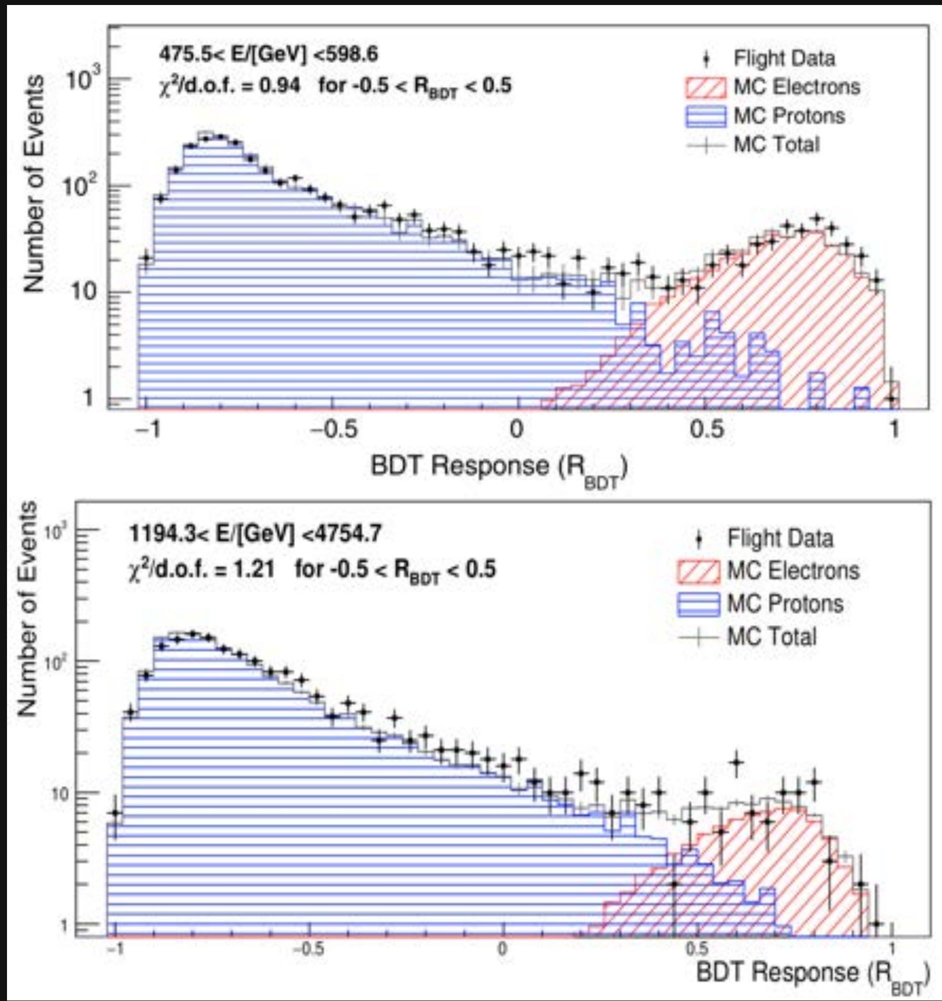
Separation Parameter K is defined as:

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

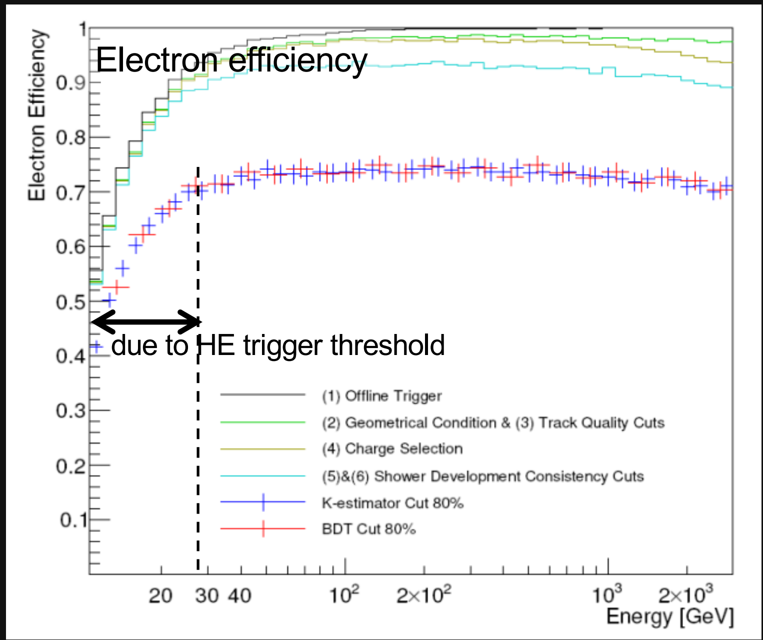


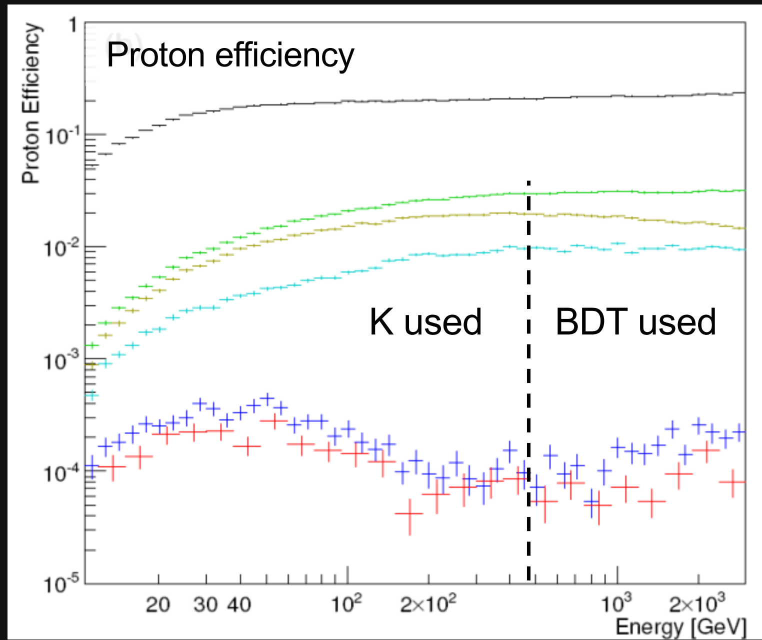
Boosted Decision Trees

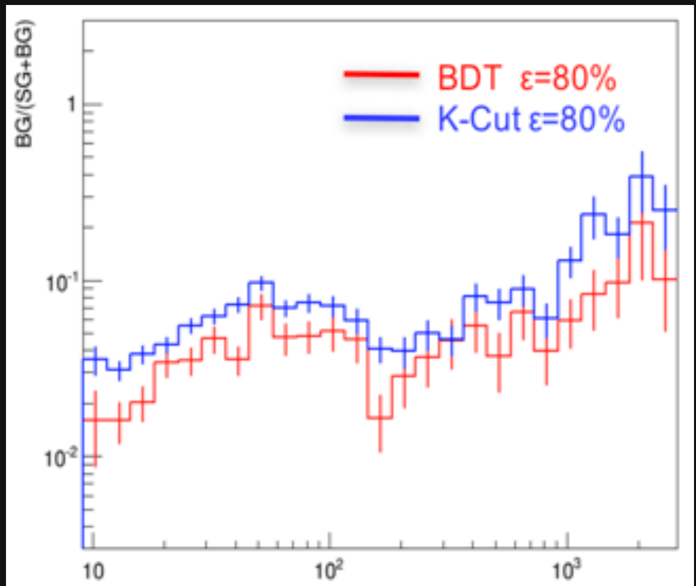
In addition to F_E and R_E , TASC and IMC shower profile fits are used as discriminating variables.



Electron Efficiency and Proton Rejection





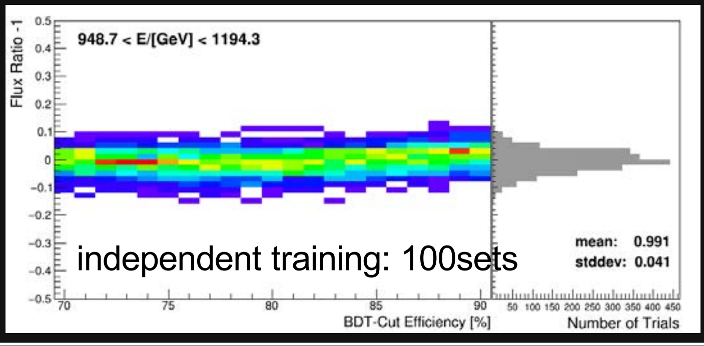


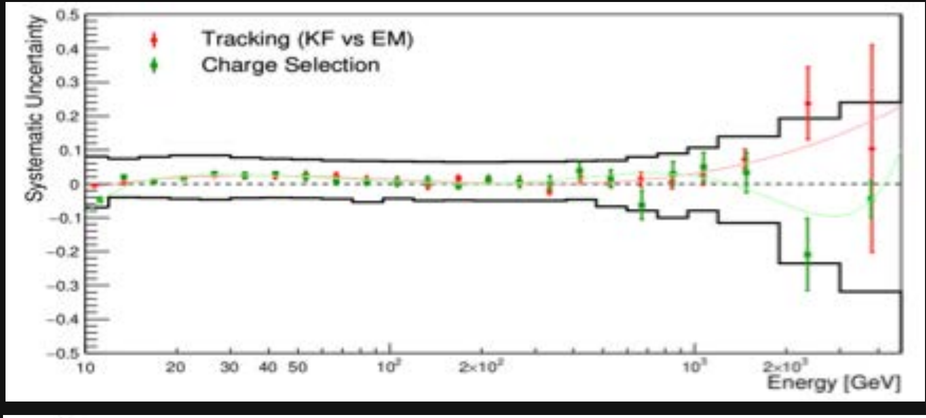
- Constant and high efficiency ~70%
- K cut is used @ E< 475 GeV
- BDT cut is used @ E>475 GeV
- Small difference between two methods are taken as systematic uncertainty.
- Proton contamination: 2-5% E<1 TeV
  10~20% 1<E<4.8 TeV

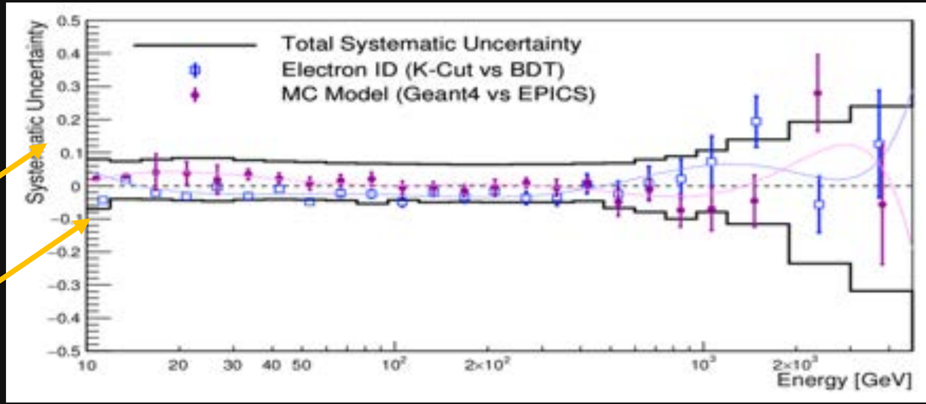
Systematic Uncertainties

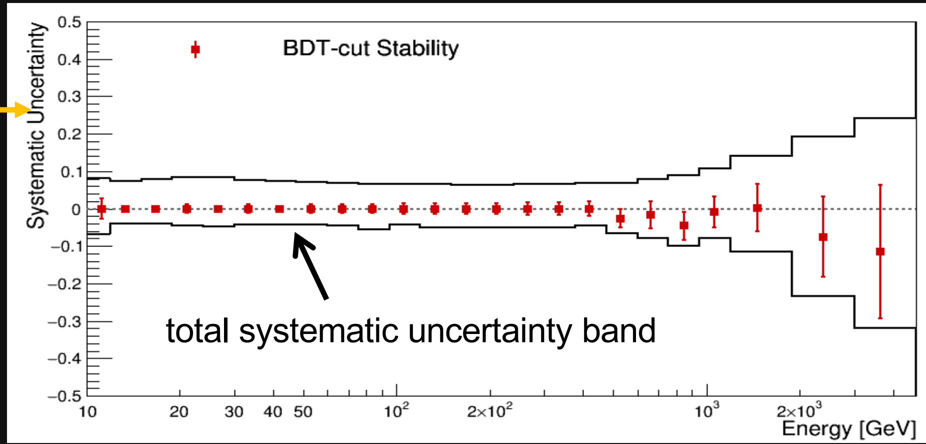
Stability of resultant flux analyzed by scanning parameter space

- **Normalization:**
  - Live time
  - Radiation environment
  - Long-term stability
  - Quality cuts
- **Energy dependent:**
  - 2 independent tracking
  - charge ID
  - electron ID (K-Cut vs BDT)
  - MC model (EPICS vs Geant4)
  - BDT stability (vs efficiency & training)

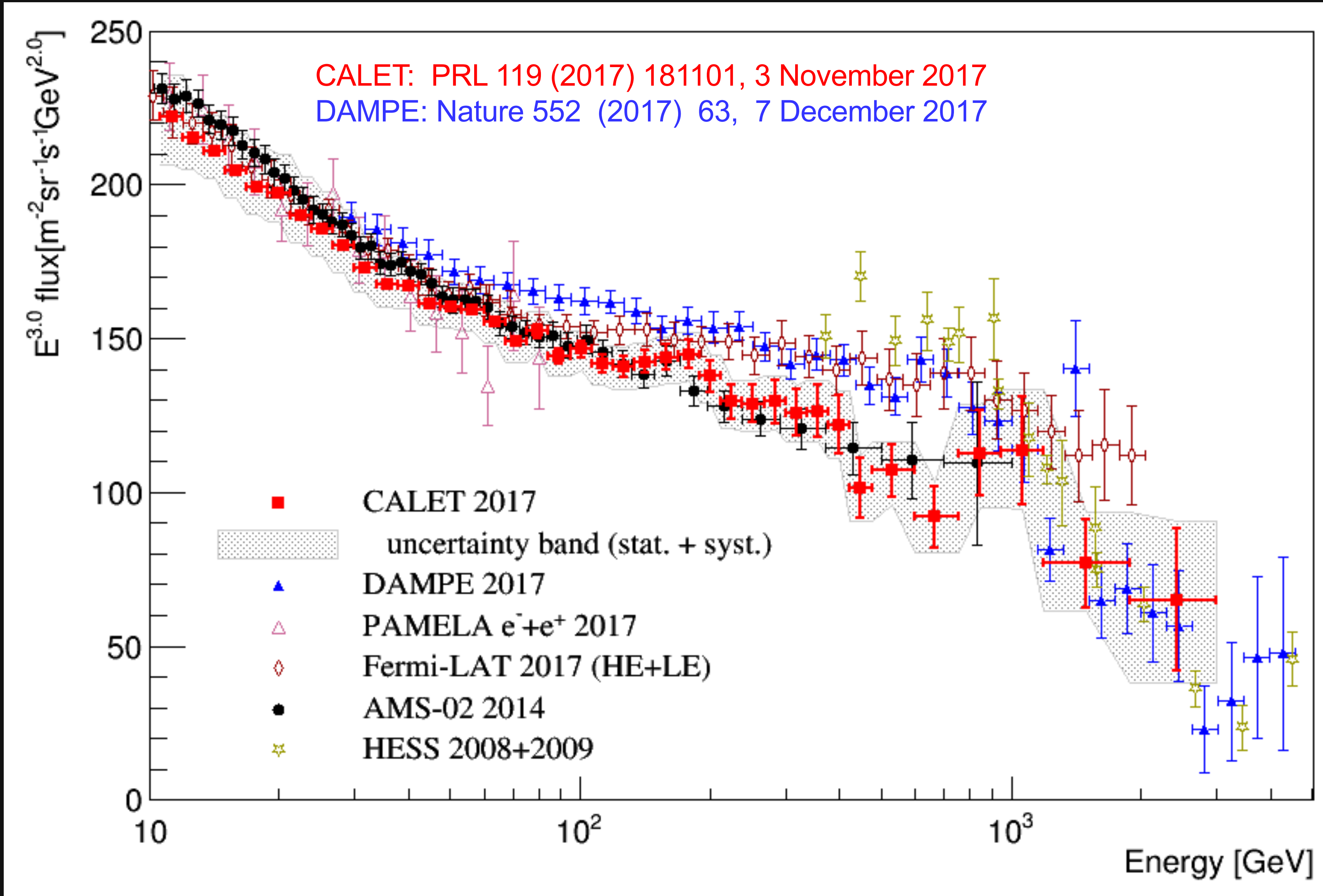




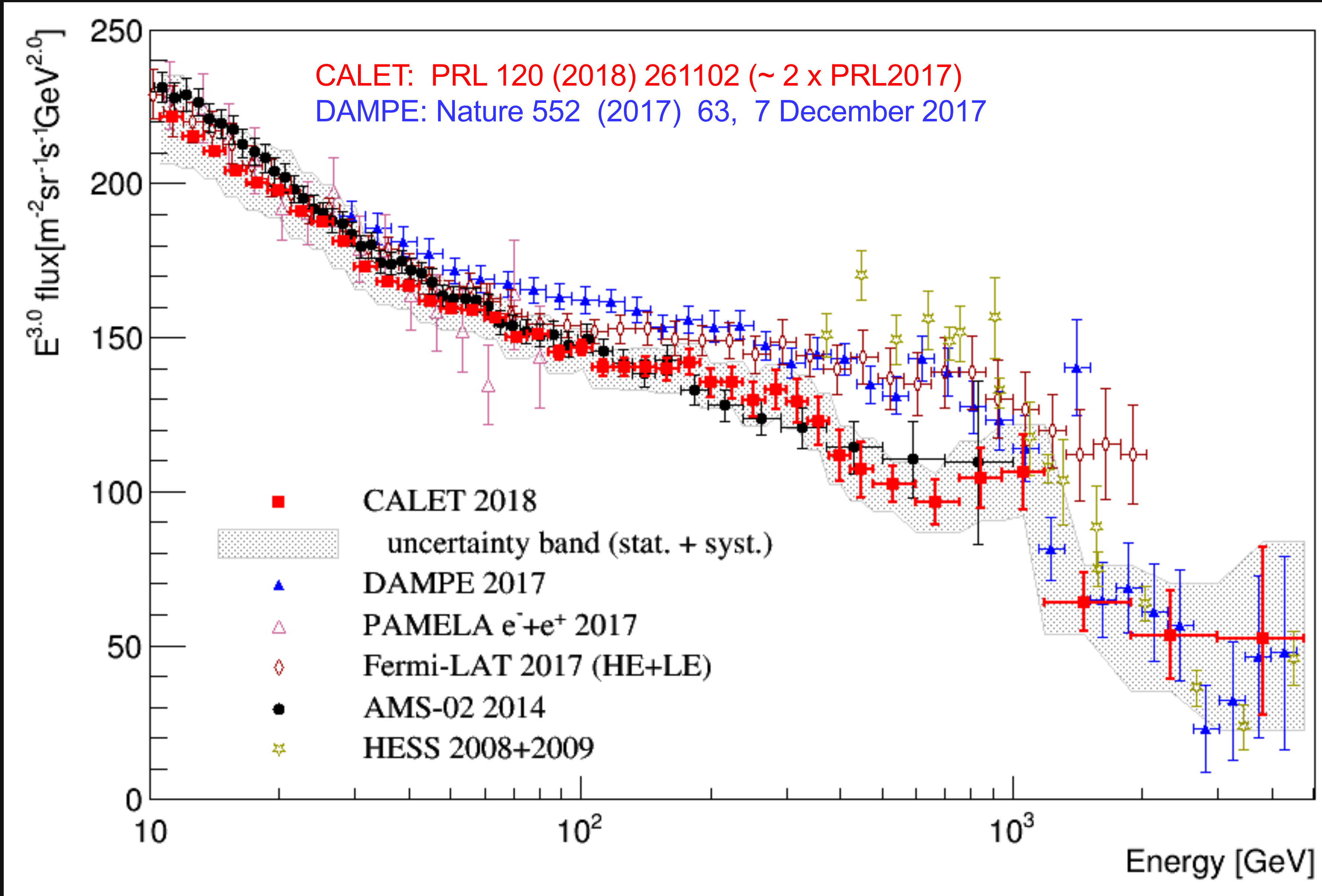




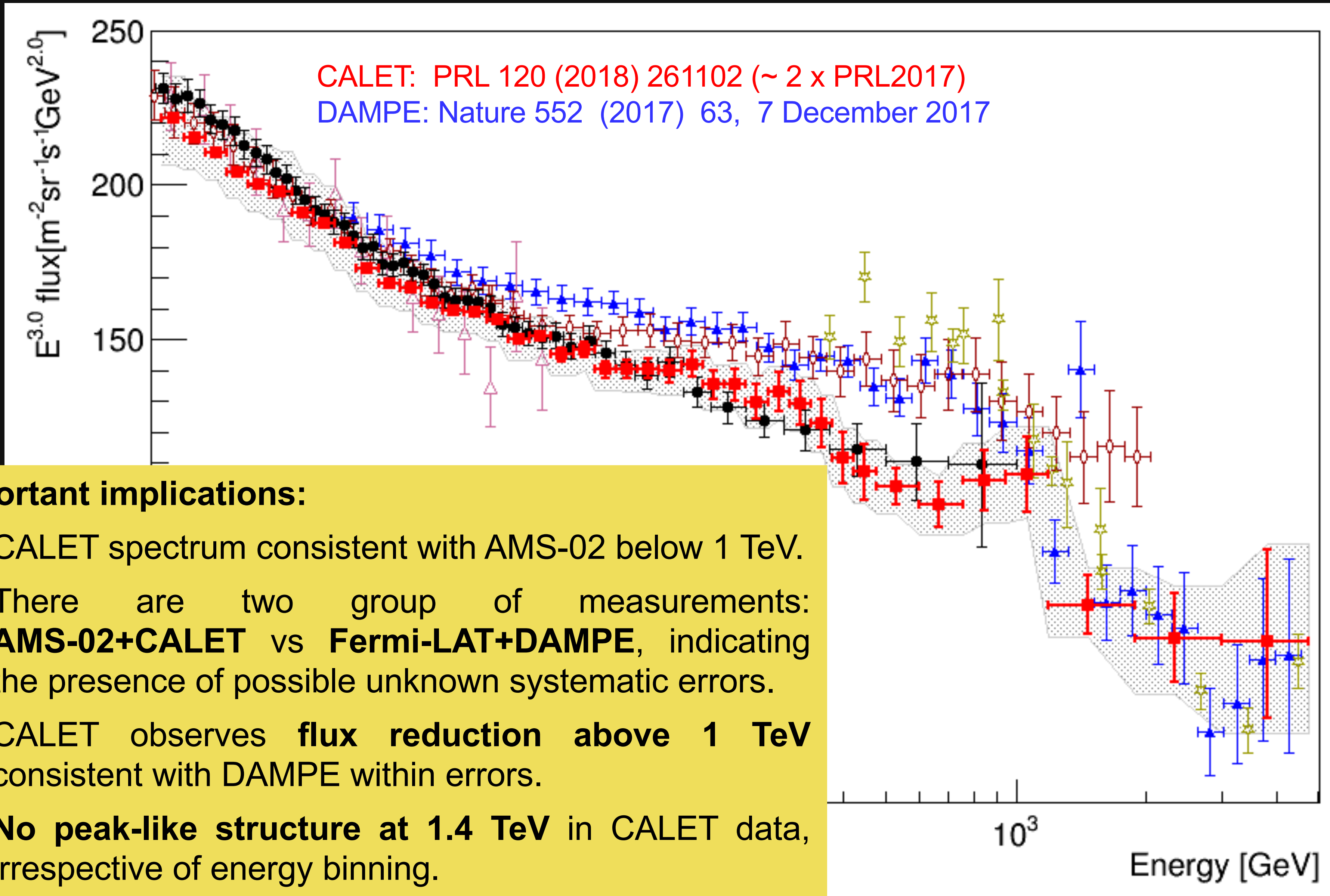
Electron spectrum



Extended measurement by CALET

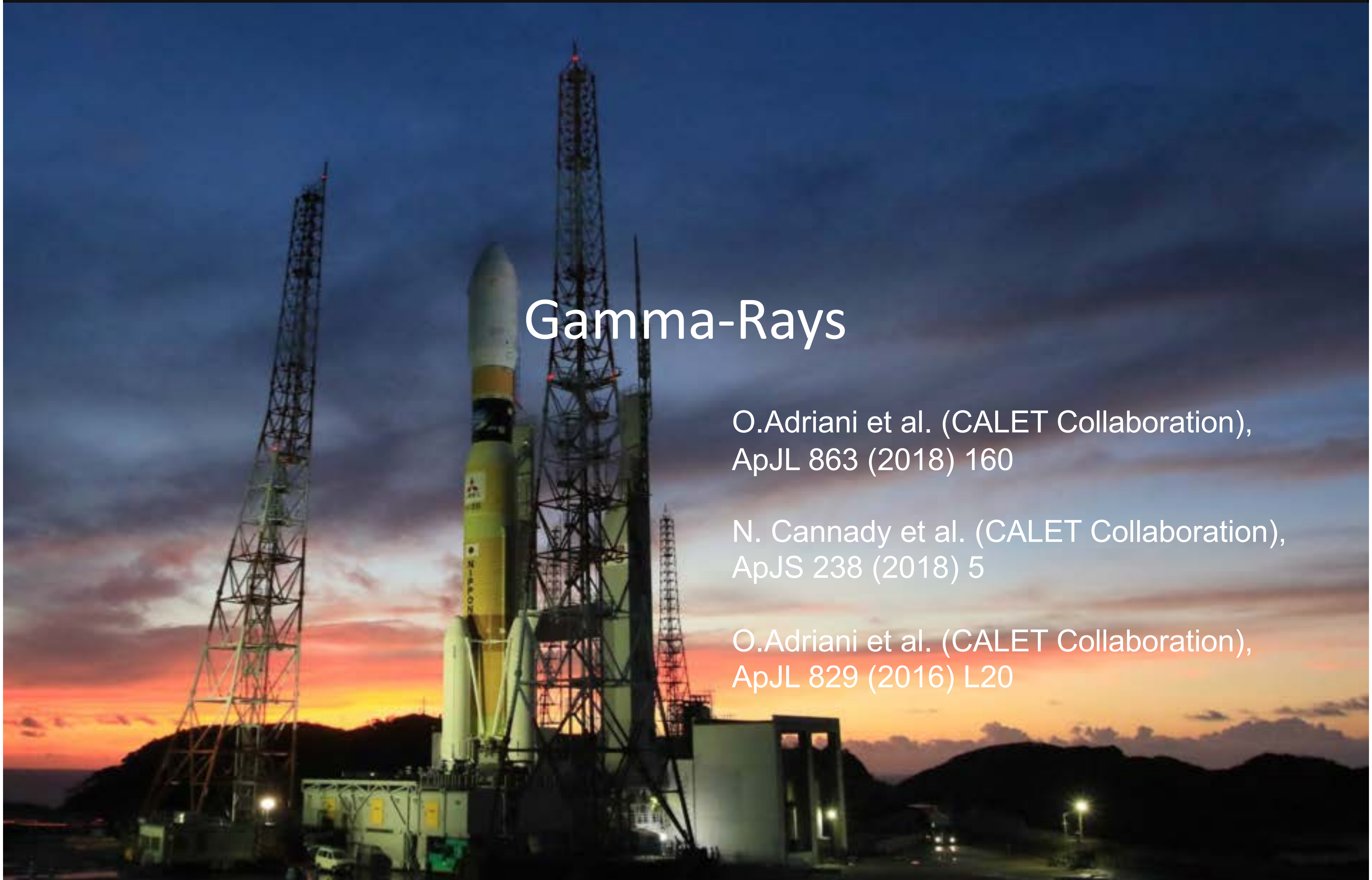


Extended measurement by CALET



Important implications:

1. CALET spectrum consistent with AMS-02 below 1 TeV.
2. There are two group of measurements: **AMS-02+CALET** vs **Fermi-LAT+DAMPE**, indicating the presence of possible unknown systematic errors.
3. CALET observes **flux reduction above 1 TeV** consistent with DAMPE within errors.
4. **No peak-like structure at 1.4 TeV** in CALET data, irrespective of energy binning.



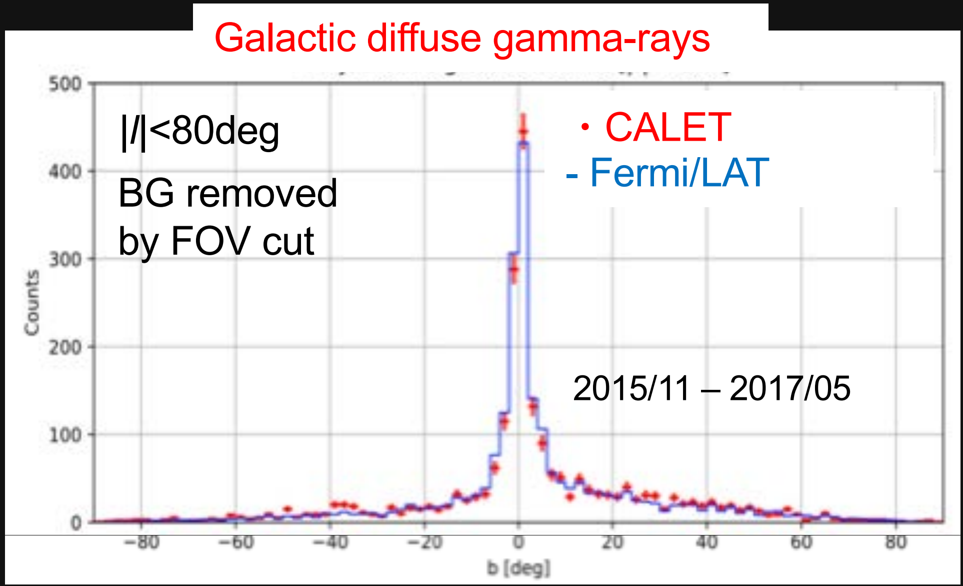
Gamma-Rays

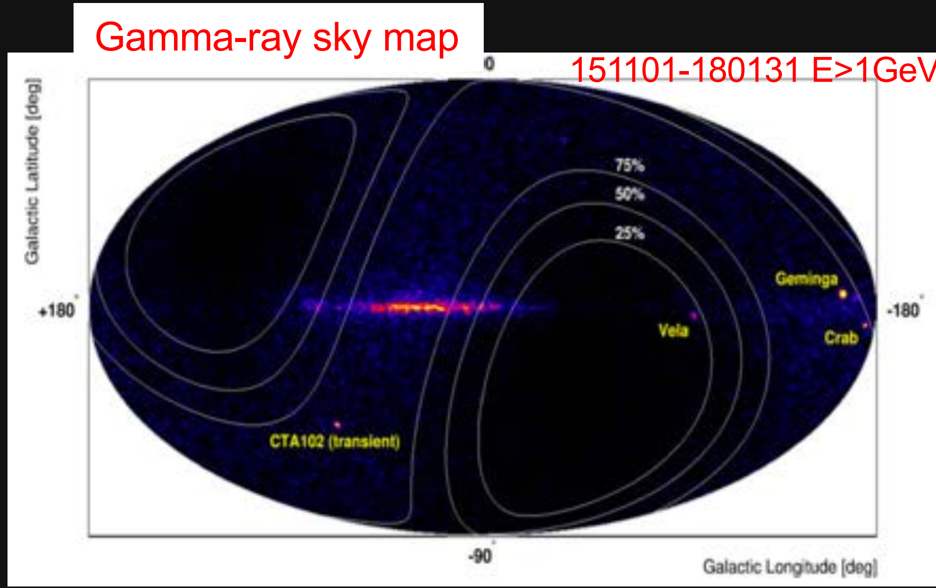
O.Adriani et al. (CALET Collaboration), ApJL 863 (2018) 160

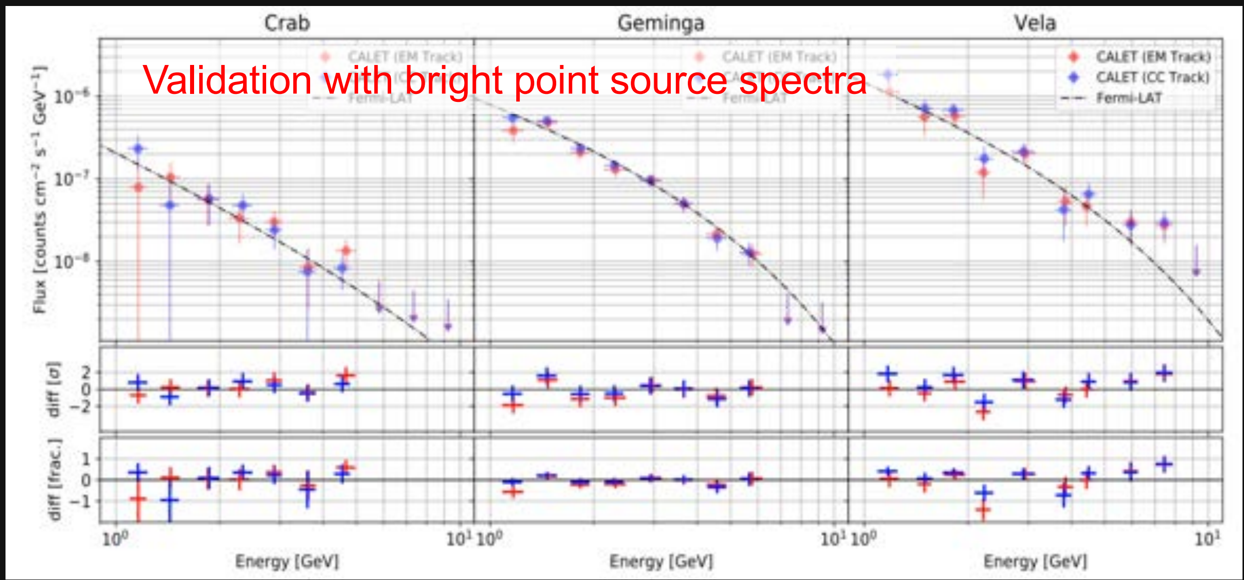
N. Cannady et al. (CALET Collaboration), ApJS 238 (2018) 5

O.Adriani et al. (CALET Collaboration), ApJL 829 (2016) L20

CALET γ–ray Sky in LE (>1GeV) trigger







Effective area ~400 cm^2 @ E> 2 GeV

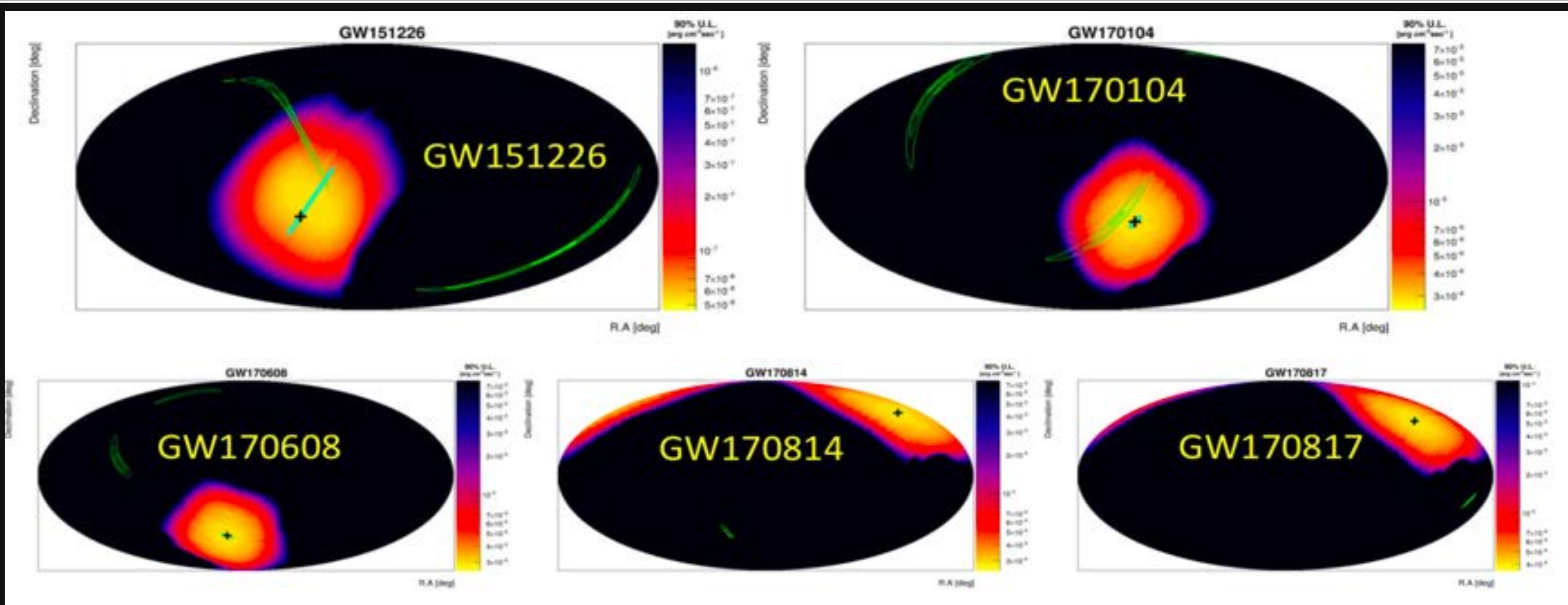
Angular resolution < 2° @ E> 1 GeV

< 0.2° @ E>10 GeV

Energy resolution ~12% at 1 GeV

~5% at 10 GeV

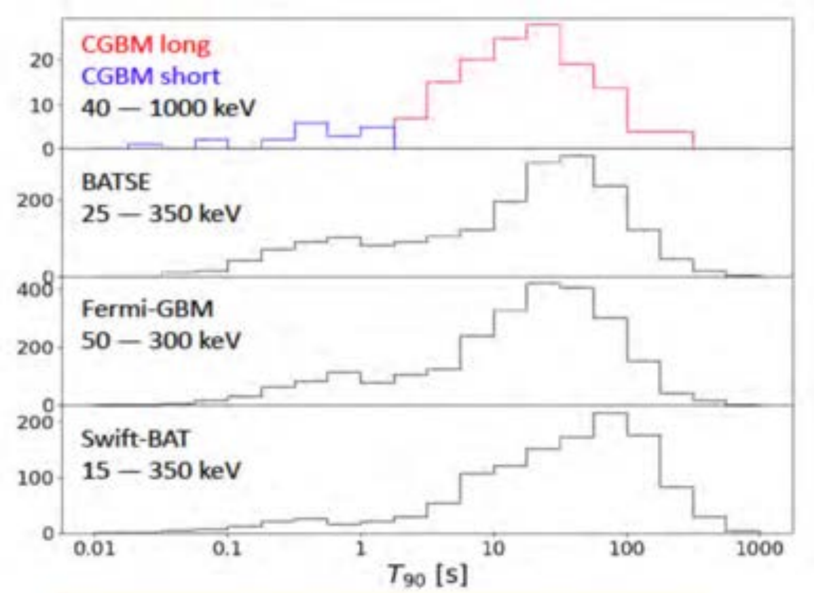
Search for X-ray and Gamma-ray counterparts of Gravitational Waves

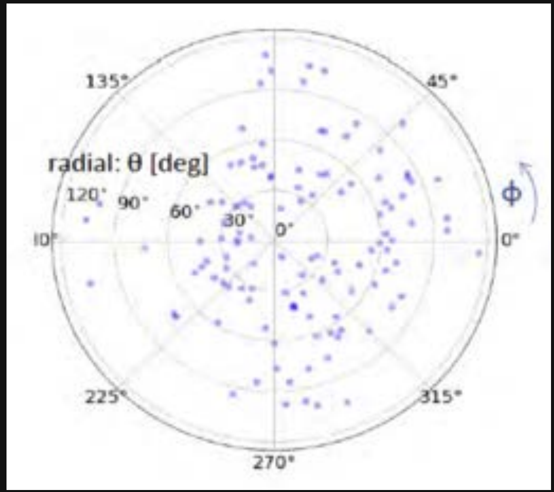


Event	Type	Mode	Sum. LIGO prob.	Obs. time	Upper limits	
					Ene. Flux erg cm^{-2} s^{-1}	Lum. erg s^{-1}
GW150914	BH-BH	Before operation				
GW151226	BH-BH	LE HXM SGM	15%	T_0-525 – T_0+211	9.3×10^{-8} 1.0×10^{-6} 1.8×10^{-6}	2.3×10^{48} $3\text{-}5 \times 10^{49}$
GW170104	BH-BH	HE	30%	T_0-60 – T_0+60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

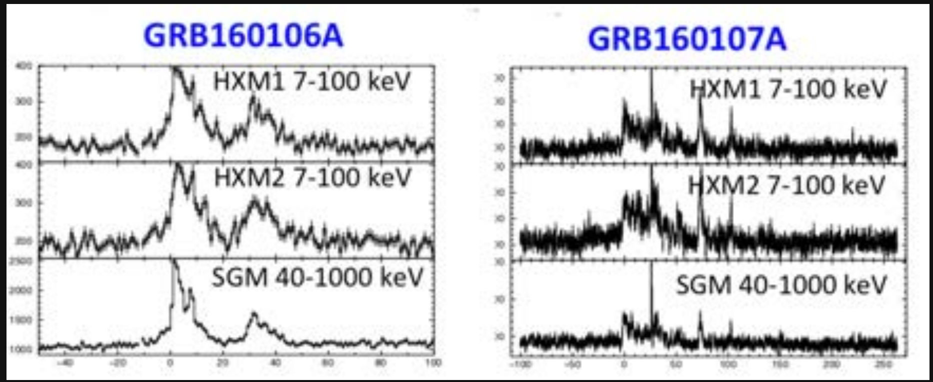
- CALET can search e.m. counterparts to LIGO/Virgo triggers
- No signal detected in CGBM and CAL for all GW events
- Upper limits set for GW151226 (CAL+CGBM) and GW170104 (CAL)
- GW170608, GW170814, GW170817 out of CALET FOV

CGBM observations summary





Examples of light curves



As of June 2019:

159 GRBs detected

140 Long (88%) 19 Short (12%)

Average rate **~43 GRBs/year**

Summary and future prospects

- CALET was successfully launched on Aug. 19, 2015, and started observations on Oct. 13, 2015. Excellent performance and remarkable stability of the instrument !
- As of May 31, 2019, total observation time is 1327 days with live time fraction to total time close to 84%. Nearly 1.8 billion events collected with high energy trigger (>10 GeV)
- Accurate calibrations have been performed with non-interacting p & He events + linearity in the energy measurements established up to 10^6 MIP's !
- Electron spectrum using full acceptance measured in energy range 11 GeV - 4.8 TeV. Observed flux reduction above 1 TeV
- Proton spectrum: single measurement from 50 GeV to 10 TeV, clear spectral hardening measured at few hundreds of GeV
- Preliminary analysis of primary heavy nuclei up to 100 TeV, B/C ratio up to 200 GeV/n
- Preliminary abundances of trans-Fe elements.
- Capability of observing diffuse gamma-rays and bright point-sources is demonstrated
- CALET's CGBM detected nearly 159 GRBs in the energy range 7 keV-20 MeV
- Follow-up observation of the GW events is carried out in X-ray and gamma-rays
- Excellent performance of CALET and data quality → extension of the mission to 5 year