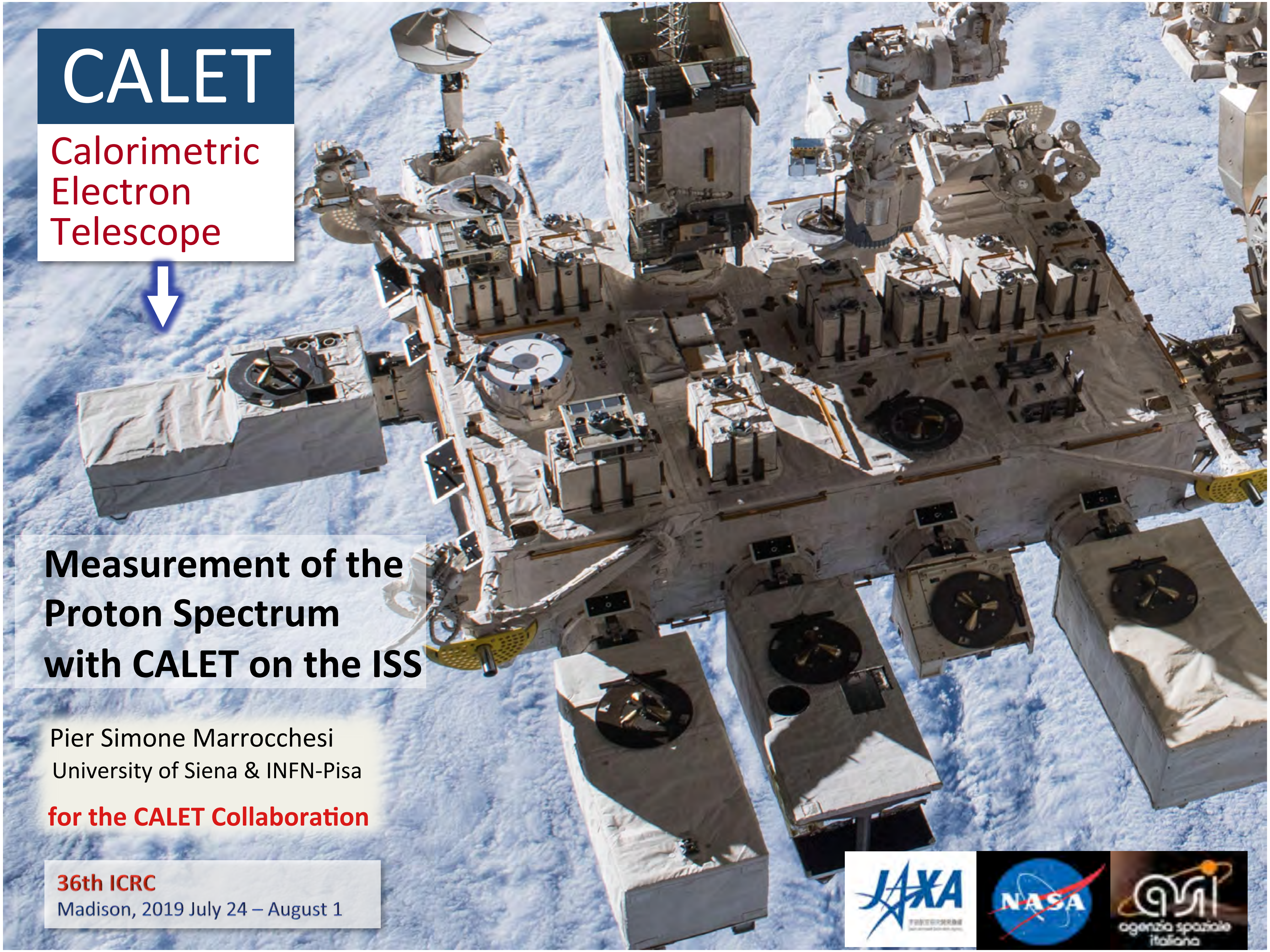
CALET

Calorimetric Electron Telescope



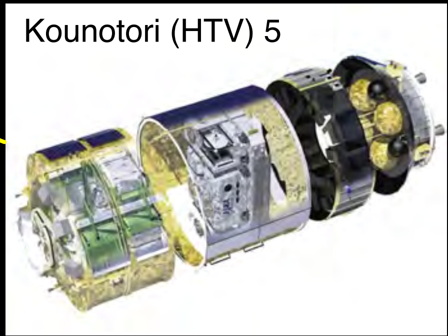
Measurement of the Proton Spectrum with CALET on the ISS

Pier Simone Marrocchesi
University of Siena & INFN-Pisa

for the CALET Collaboration

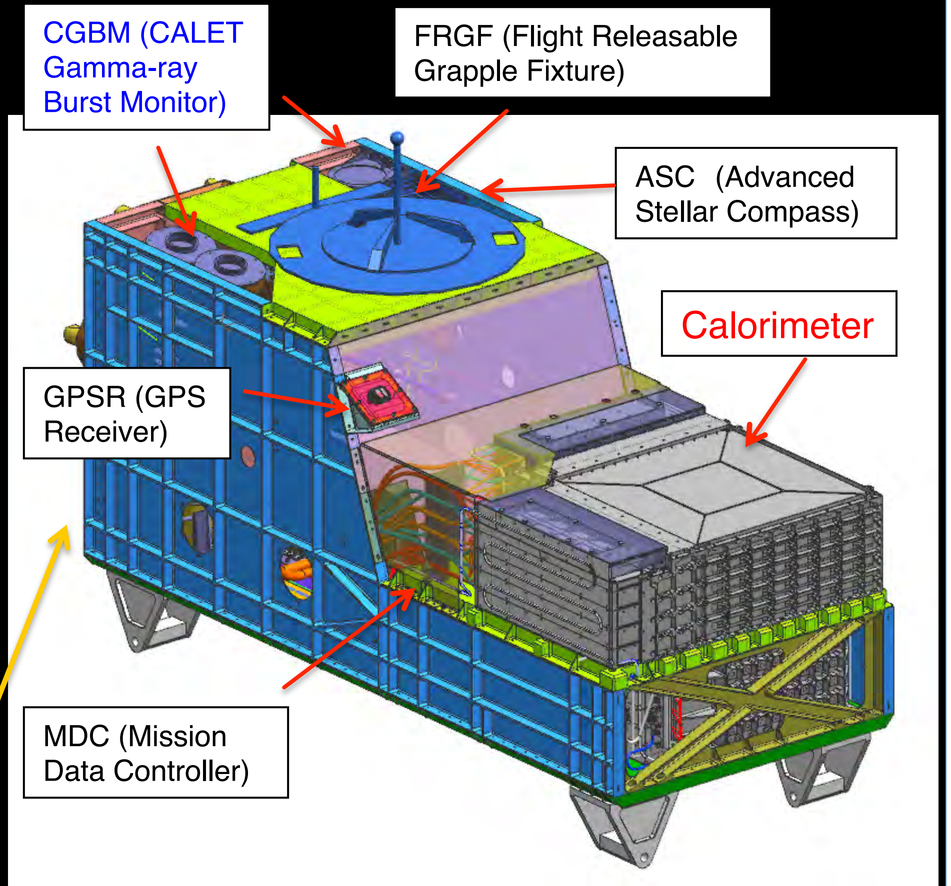
36th ICRC
Madison, 2019 July 24 – August 1

CALET Payload



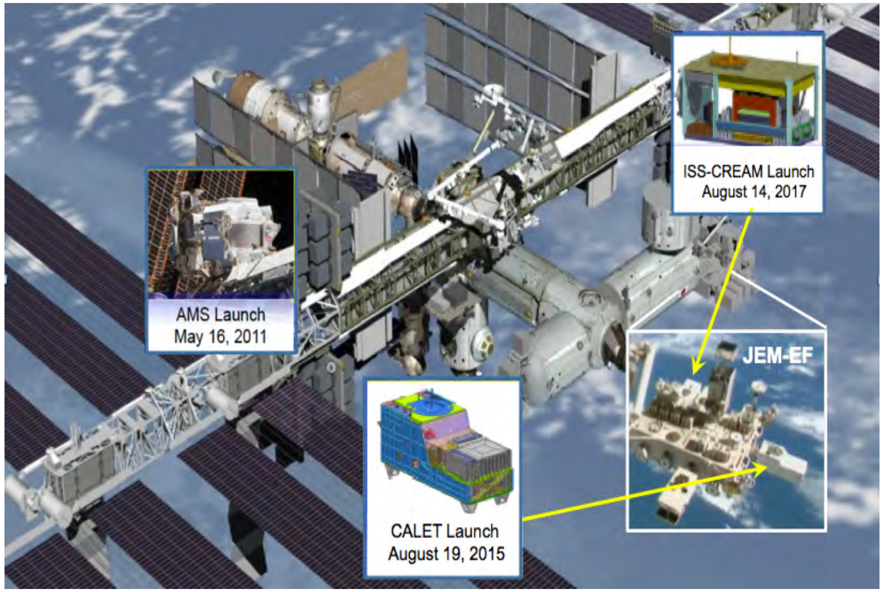
Launched on Aug. 19th, 2015
by the Japanese H2-B rocket

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



- 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)

Cosmic Ray Observations aboard the ISS and CALET program



Main CALET science objectives:

✧ **Electron observation** in 1 GeV - 20 TeV range.
Design optimized for electron detection: high energy resolution and large e/p separation power + e.m. shower containment. Detailed study of spectral shape.
Search for Dark Matter and Nearby Sources

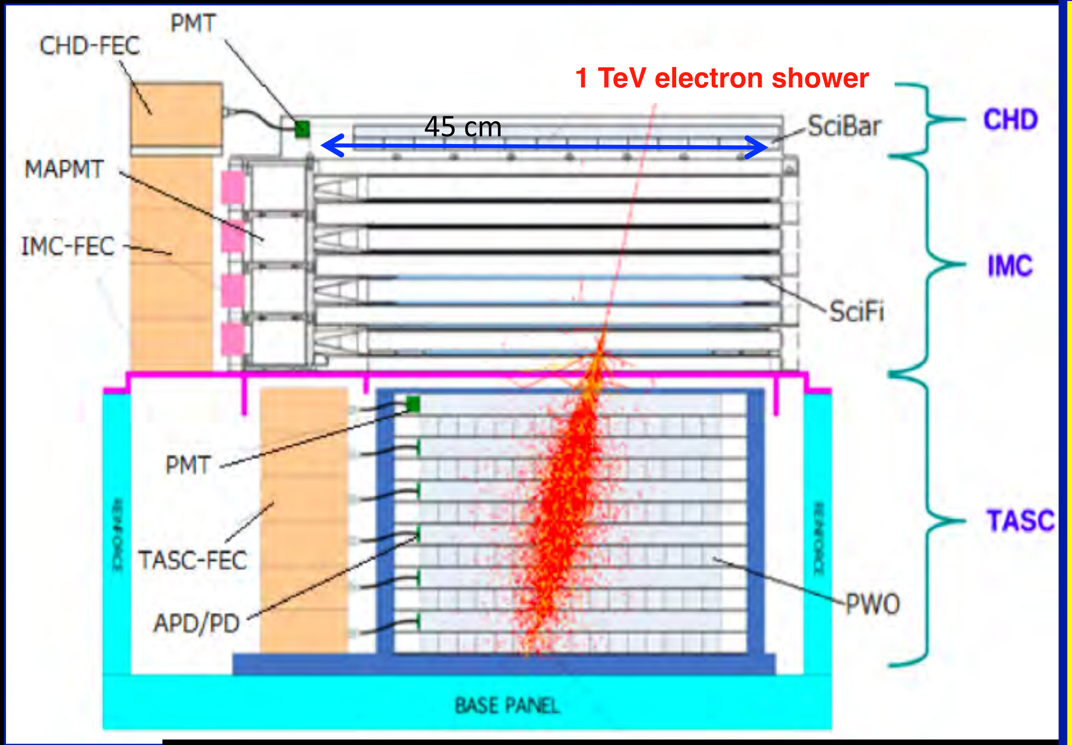
✧ **Observation of cosmic-ray nuclei** in the energy region from 10 GeV to 1 PeV.
Unravelling the CR acceleration and propagation mechanism(s)

✧ 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 ($26 < Z \leq 40$) 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

CALET instrument in a nutshell

Field of view: ~ 45 degrees (from the zenith) Geometrical Factor: ~ 1,040 $cm^2 sr$ (for electrons)

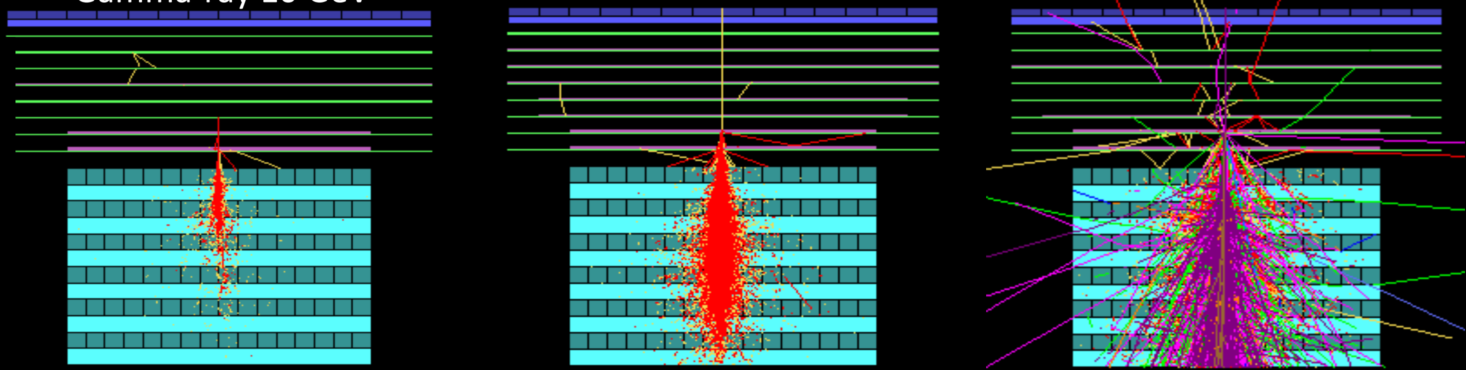


CALET: a unique set of key instruments

- **CHD**: a dedicated charge detector + multiple dE/dx sampling in the IMC allow the **identification of individual nuclear species** (charge resolution ~0.15-0.3 e).
- **IMC**: high granularity (1mm) imaging pre-shower calorimeter to accurately reconstruct **the arrival direction** of incident particles (~0.1°) and the **starting point** of electro-magnetic showers.
  Scifi + Tungsten absorbers: **3 X_0** (=0.2 X_0 x 5 + 1.0 X_0 x 2)
- **TASC**: thick (**27 X_0**) homogeneous PWO calorimeter allowing to extend electron measurements into the TeV energy region with ~2% **energy resolution**.
- **Combined** (**30 X_0, 1.2 λ_I**) they **separate electrons** from the abundant protons (rejection > 10^5).

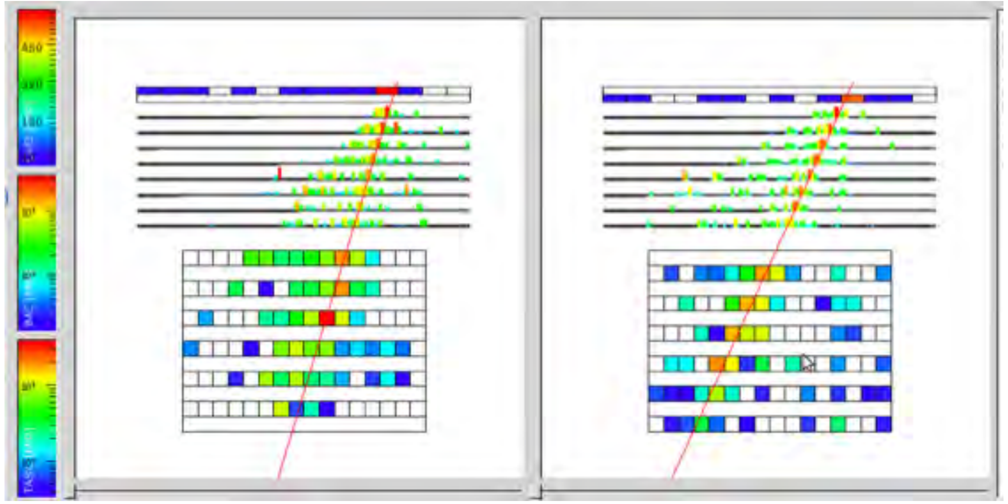
Simulated Shower Profile

Gamma-ray 10 GeV　Electron 1 TeV　Proton 10 TeV

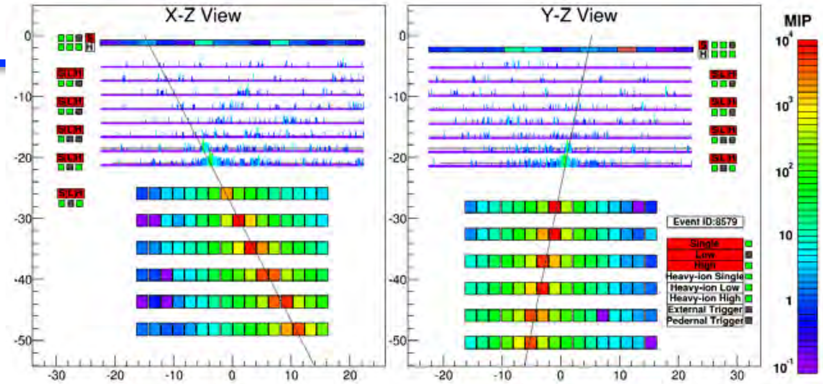


Examples of Observed Events

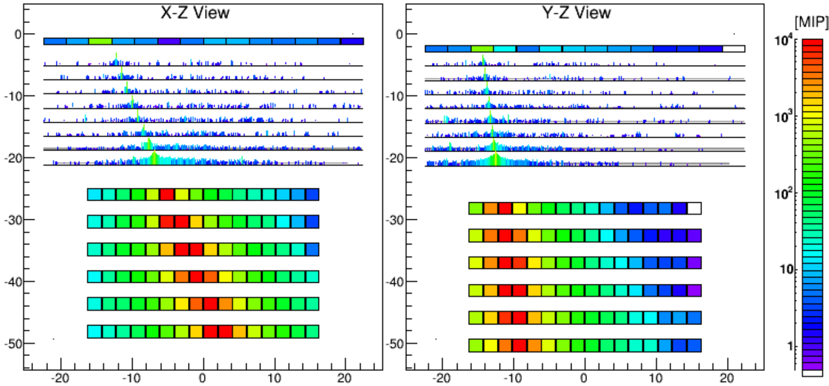
Multi-prong background event (interaction in CHD)



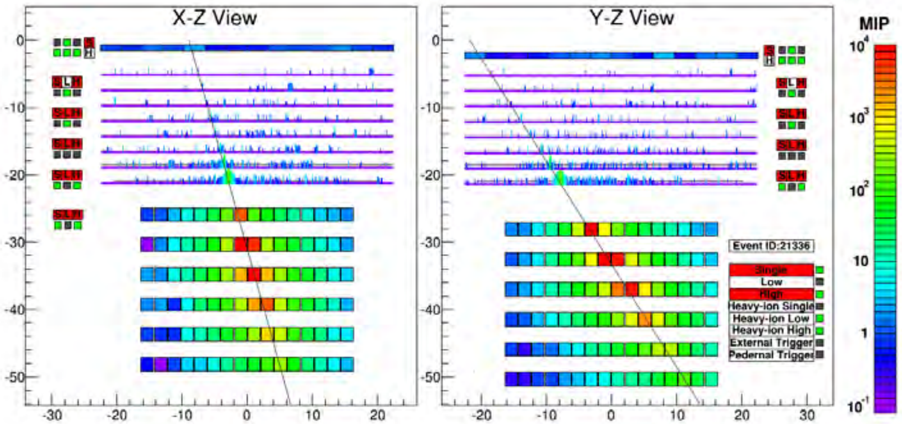
Proton, ΔE=2.89 TeV



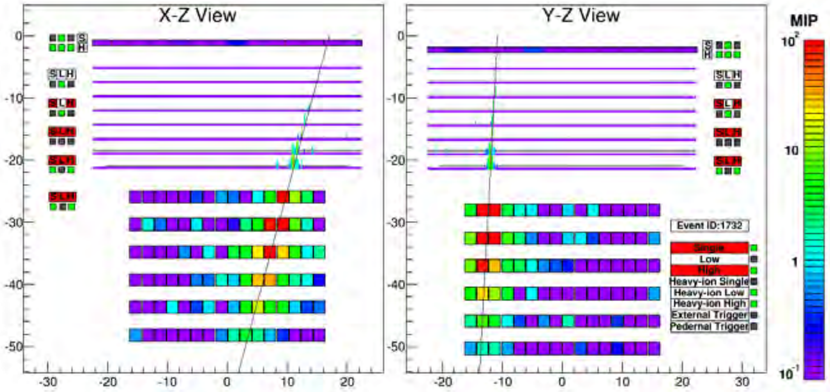
Iron, ΔE=9.3 TeV



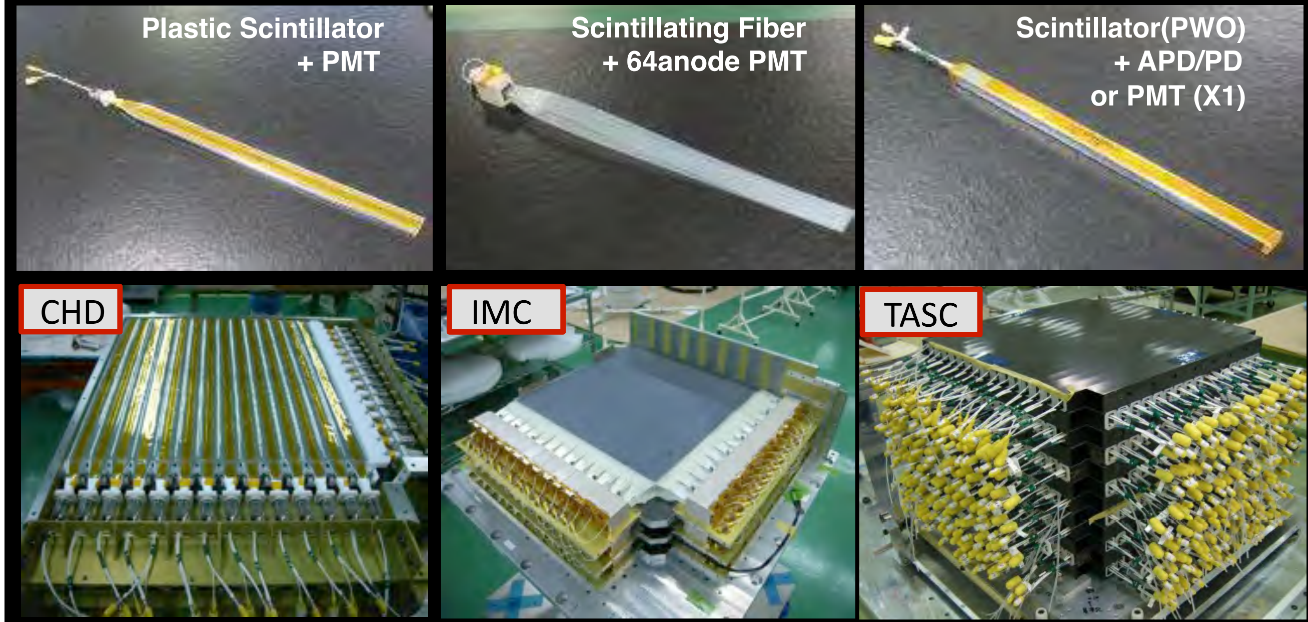
Electron, E=3.05 TeV



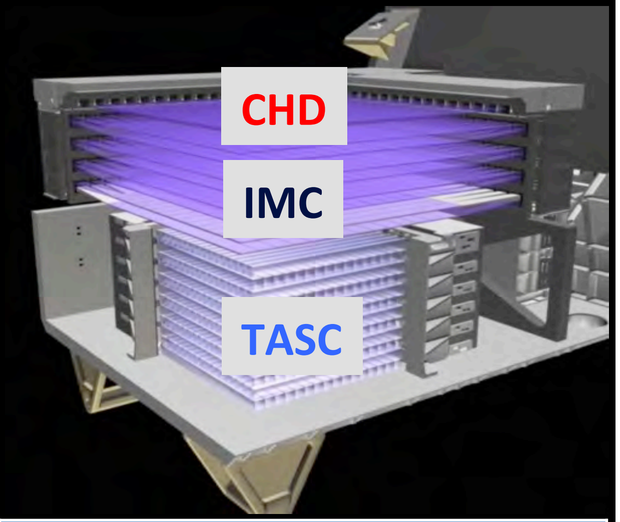
Gamma-ray, E=44.3



CALET Instrument overview



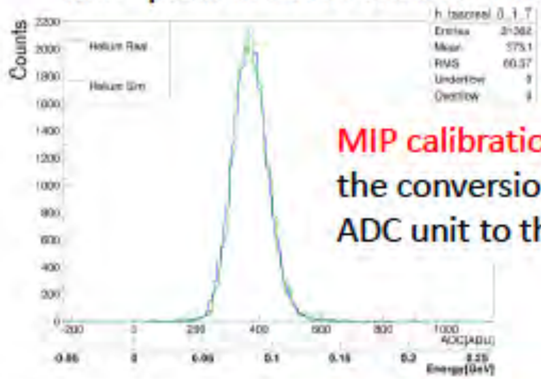
CALORIMETER



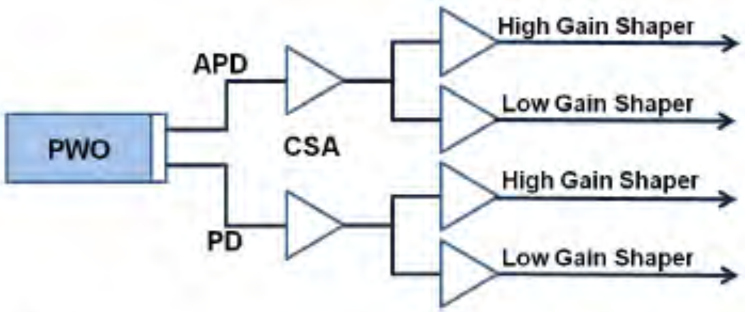
	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillators**: 28 paddles 14 paddles x 2 layers (X,Y) Paddle Size: 32 x 10 x 450 mm^3	**Scintillating Fibers**: 448 x 16 layers (X,Y) Scifi size: 1 x 1 x 448 mm^3 7 Tungsten layers : 0.2X_0 x 5 + 1X_0 x 2 Total Thickness: **3 X_0**	**PWO logs**: 16 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**

Energy Measurement in a wide dynamic range 1-10^6 MIPs

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



MIP calibration determines the conversion factor from ADC unit to the energy

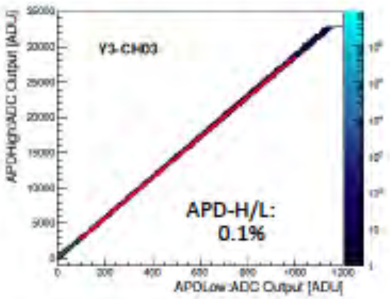


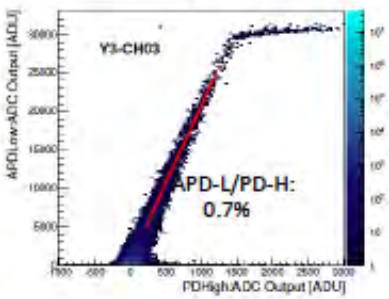
The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

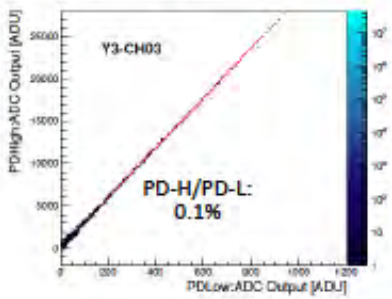
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

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

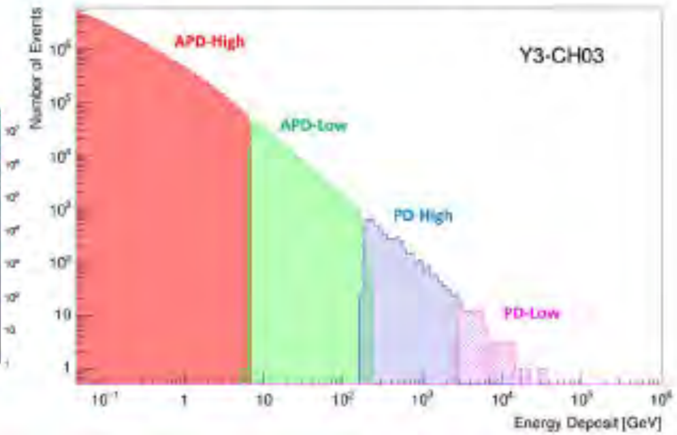
APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%







Example of energy distribution in one PWO log

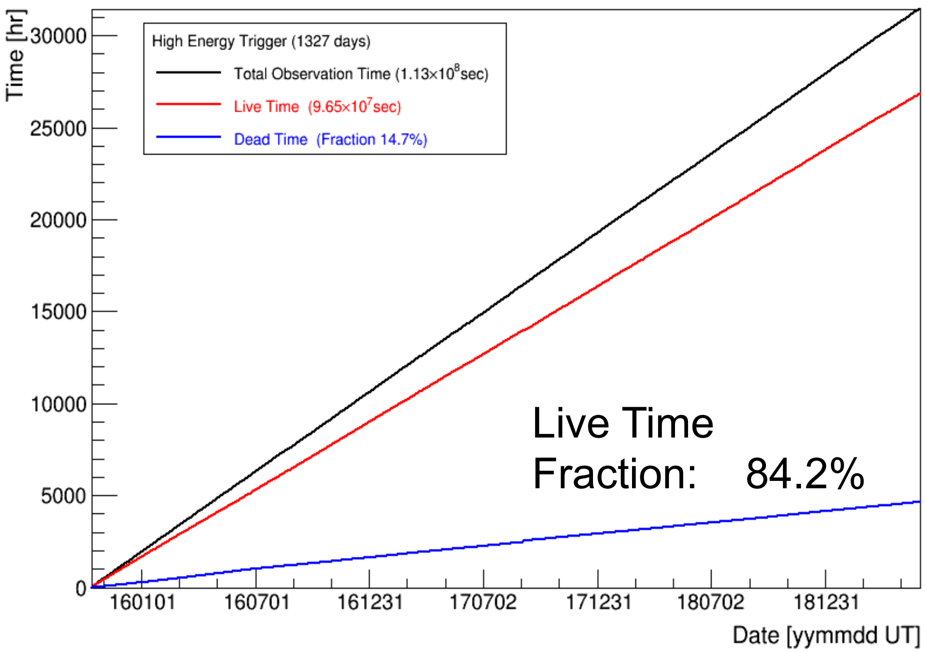


Observations with High Energy Trigger (>10GeV)

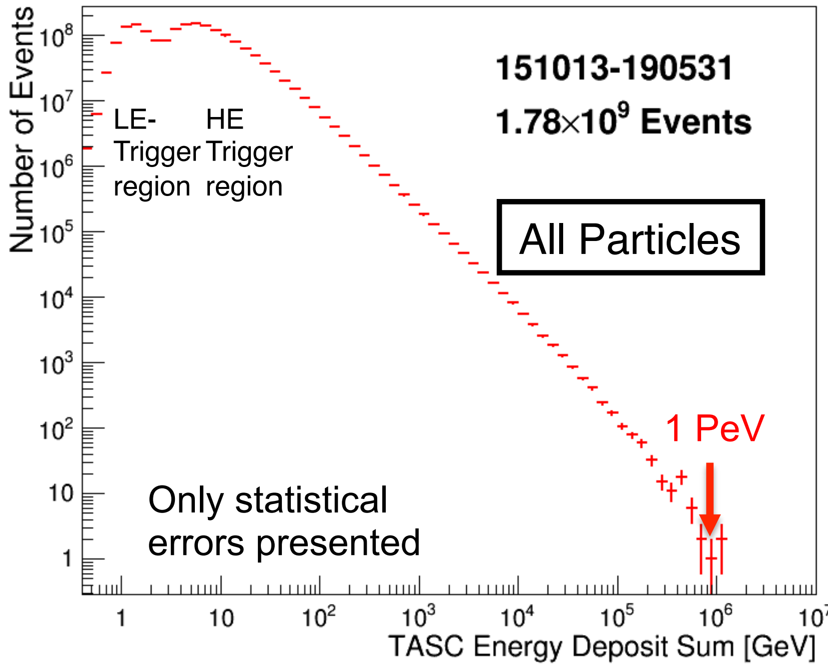
Observation with High Energy Trigger for 1327 days : Oct.13, 2015 – May 31, 2019

- 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)

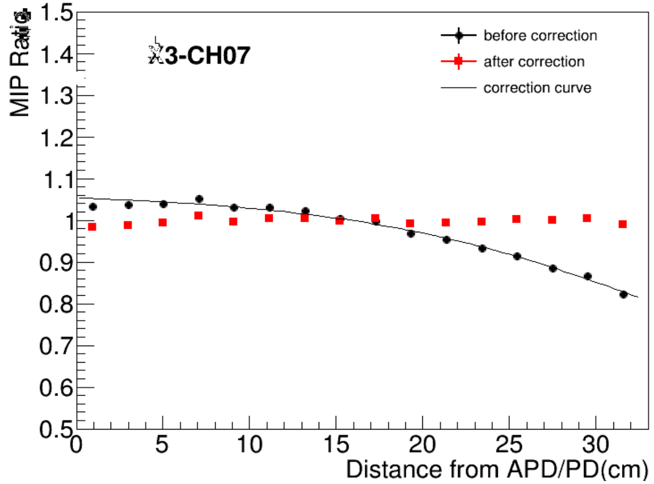


Distribution of deposit energies (ΔE) in TASC

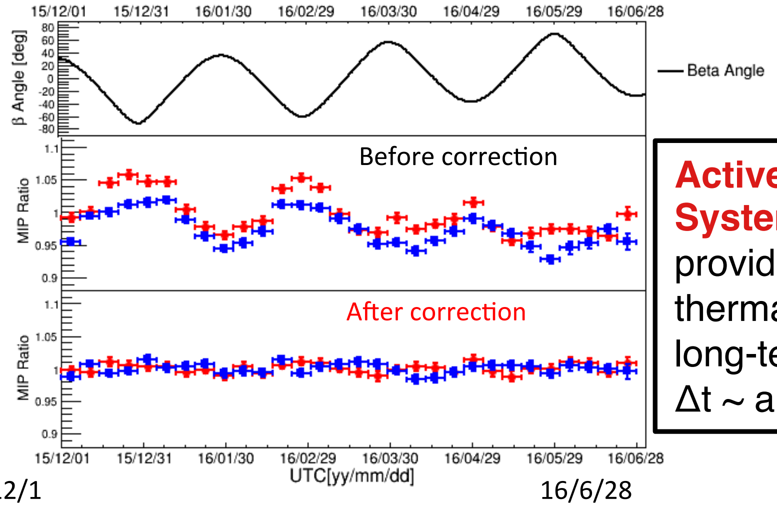


Position and Temperature Calibration + Long-term Stability

Example of position dependence correction



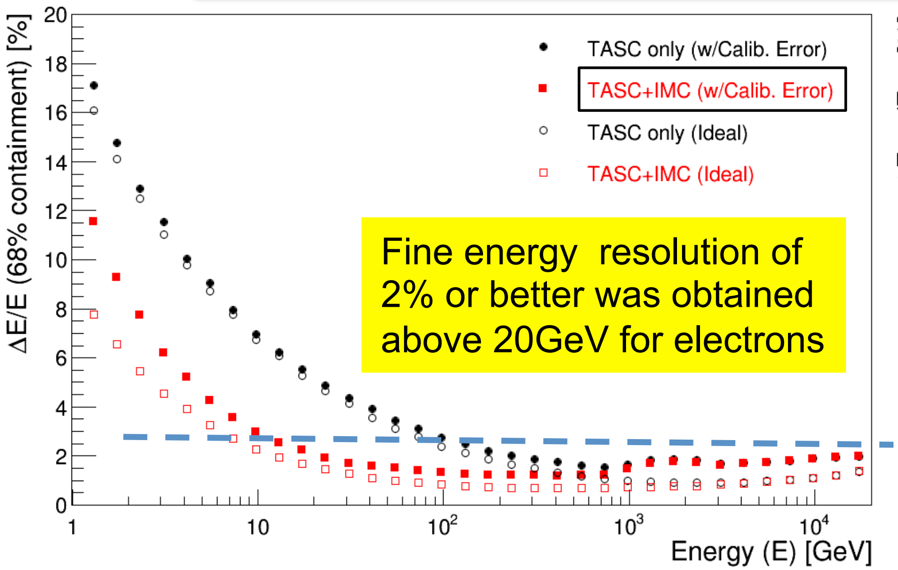
Examples of temperature change correction

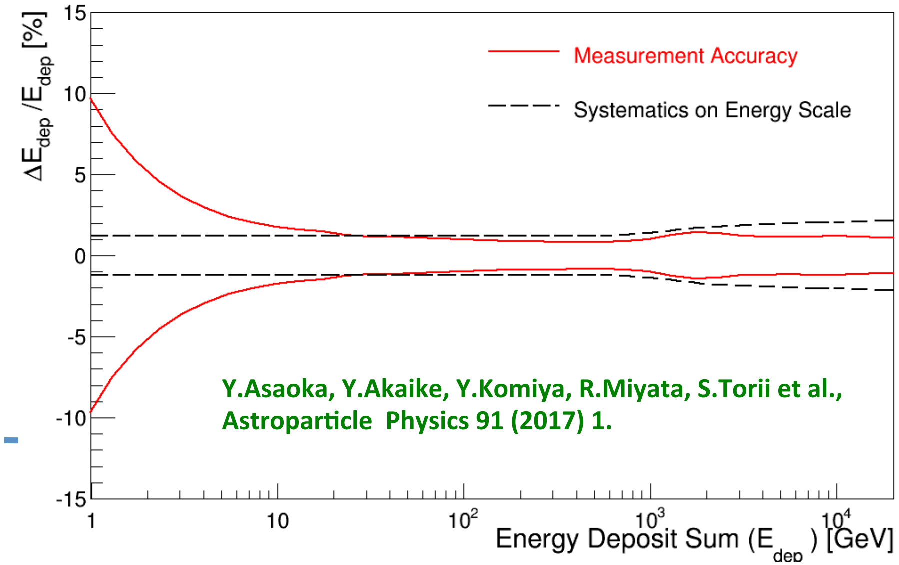


TASC

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





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

Electron / Proton Discrimination [Y.Asaoka, COSPAR 2108 E1.5-0023-18]

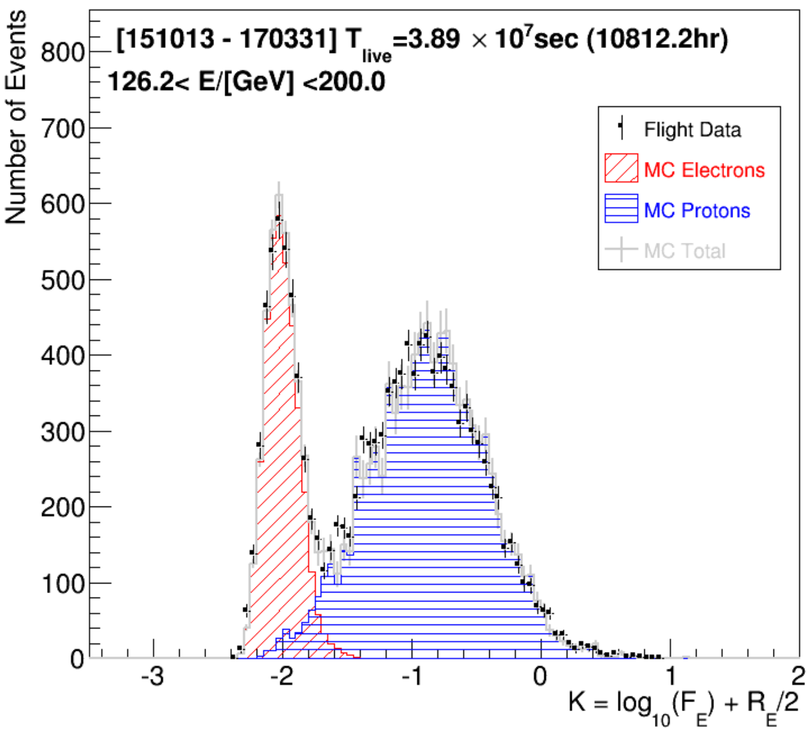
Simple Two Parameter Cut

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

R_E: Lateral spread of energy deposit in TASC-X1

Cut Parameter K is defined as follows:

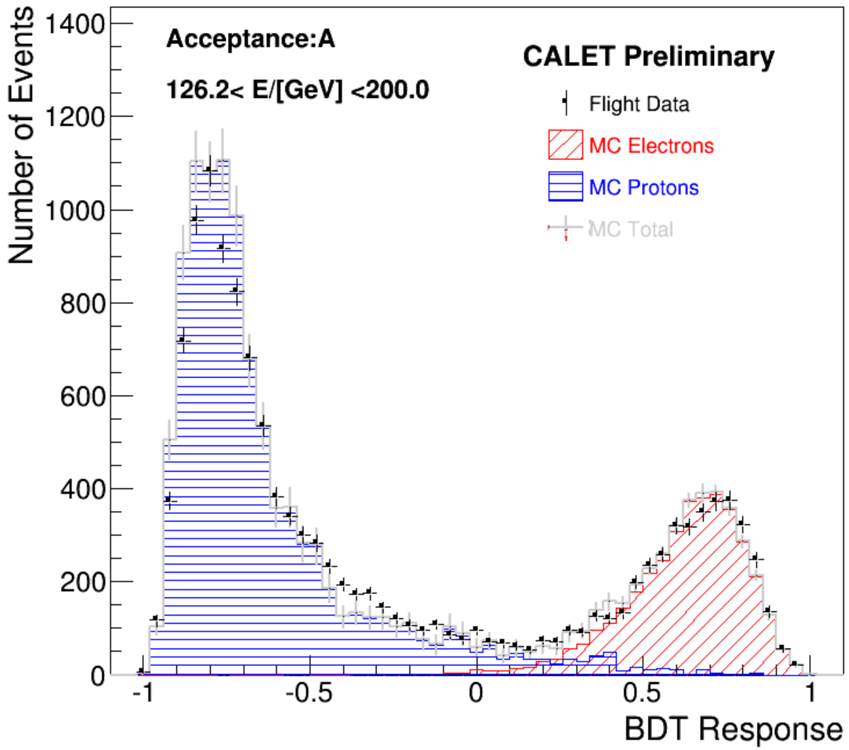
$K = \log_{10}(F_E) + 0.5\, R_E$ (/cm)



Boosted Decision Trees (BDT)

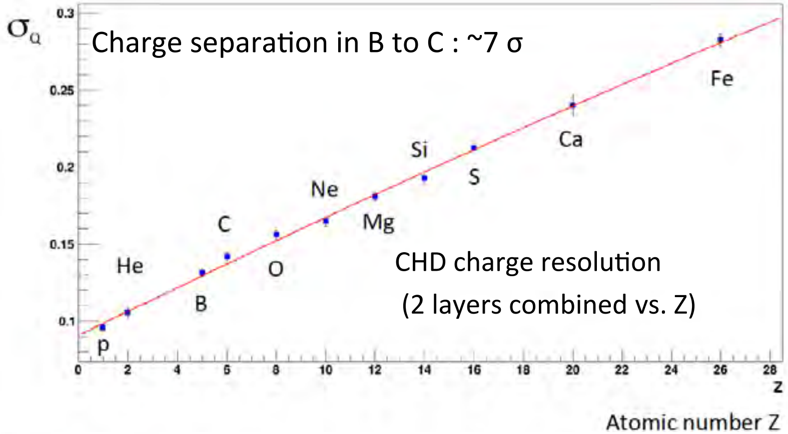
In addition to the two parameters on the left, TASC and IMC shower profile fits are used as discriminating variables

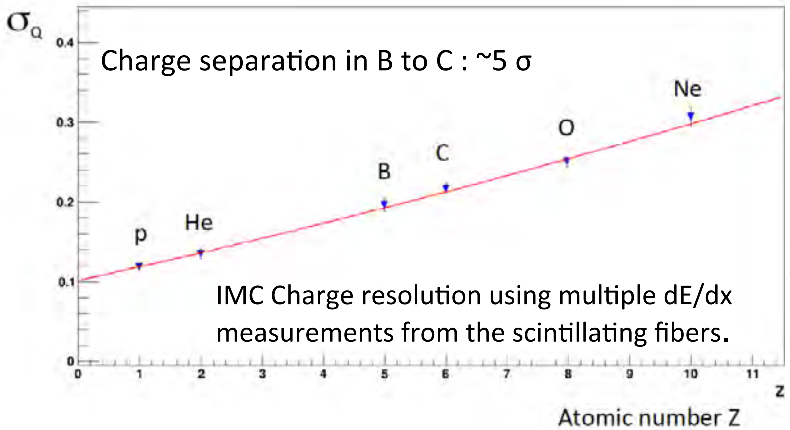
BDT Response using 9 parameters



Charge Identification of Nuclei with CHD and IMC

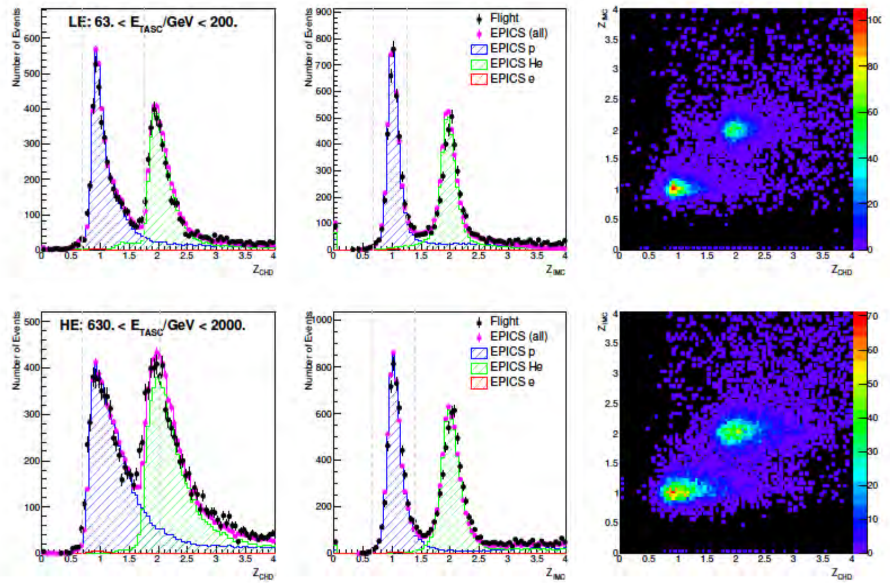
Single element selection for p, He and light nuclei is achieved by CHD+IMC charge analysis.

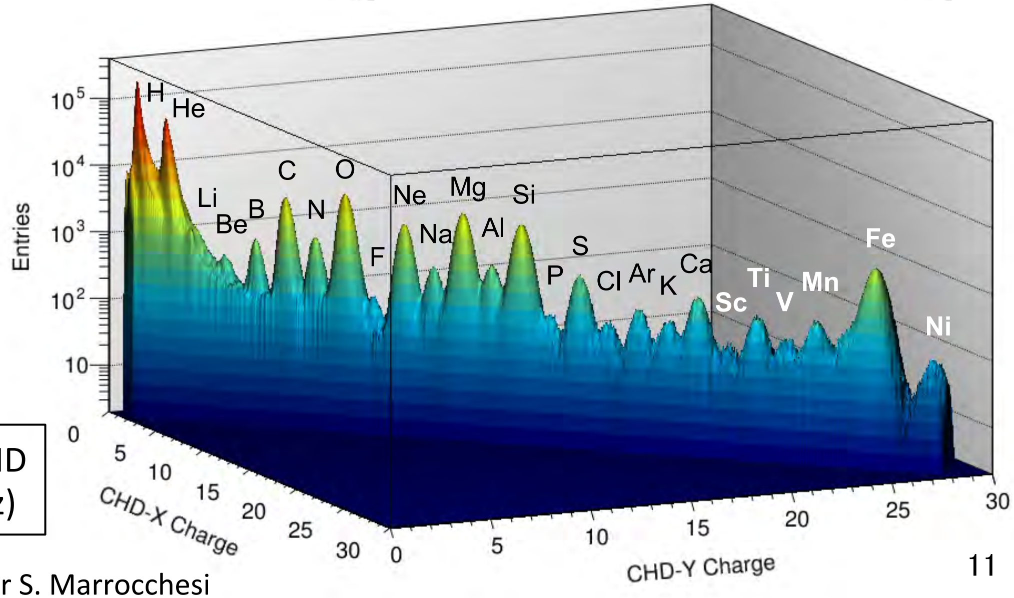




Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

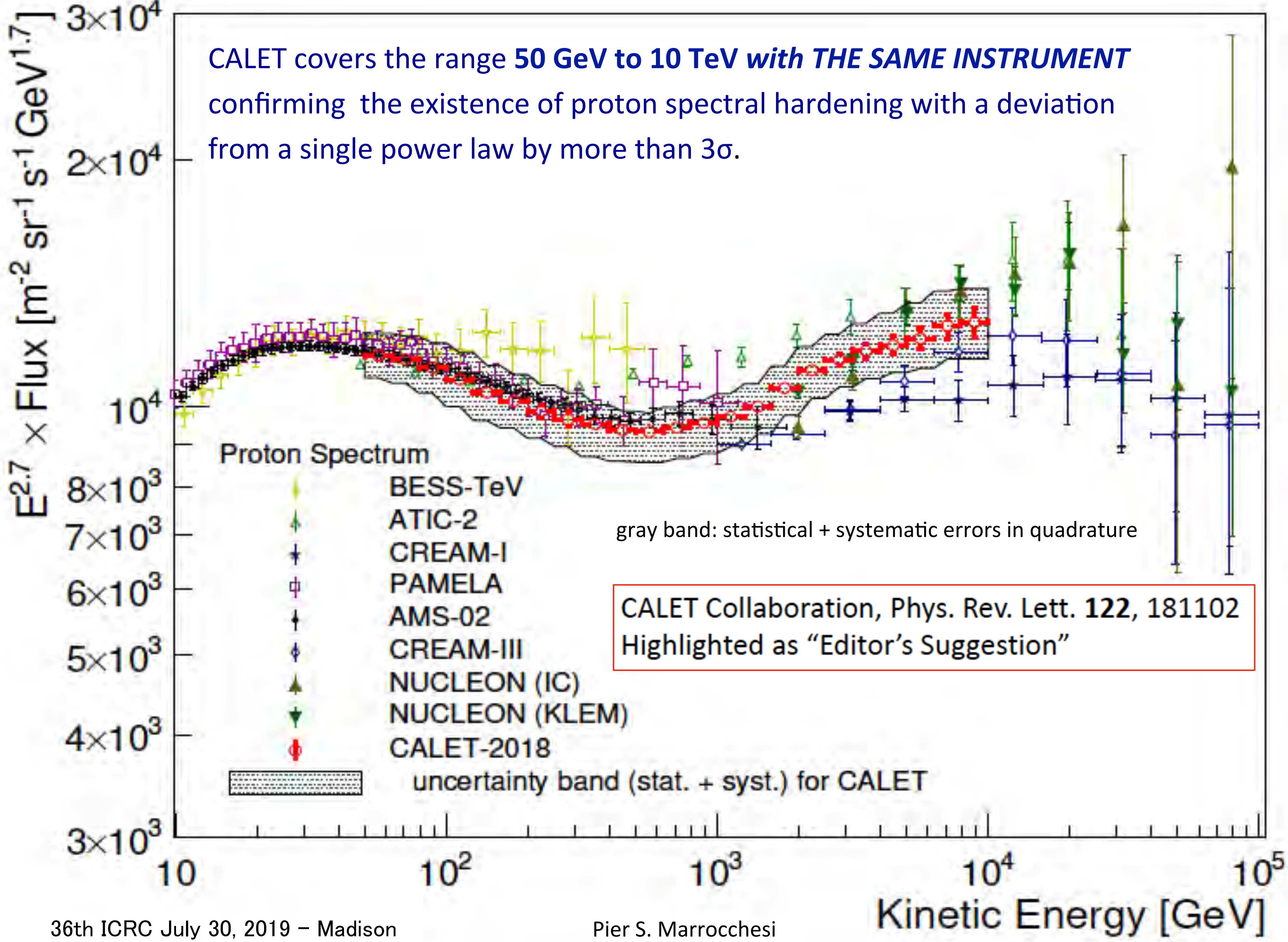
Combined CHD-IMC proton-Helium charge-ID





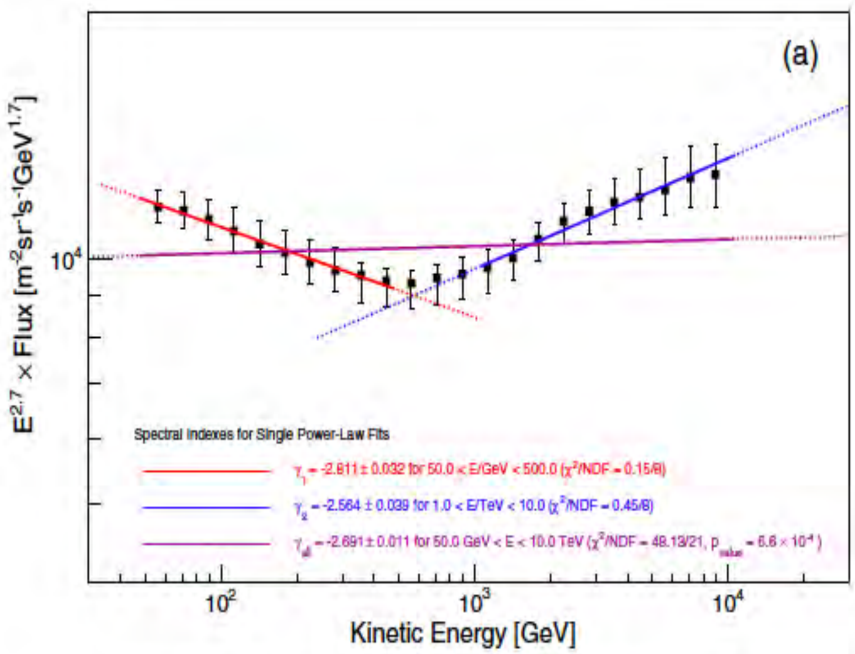
Direct measurement of proton spectrum by CALET

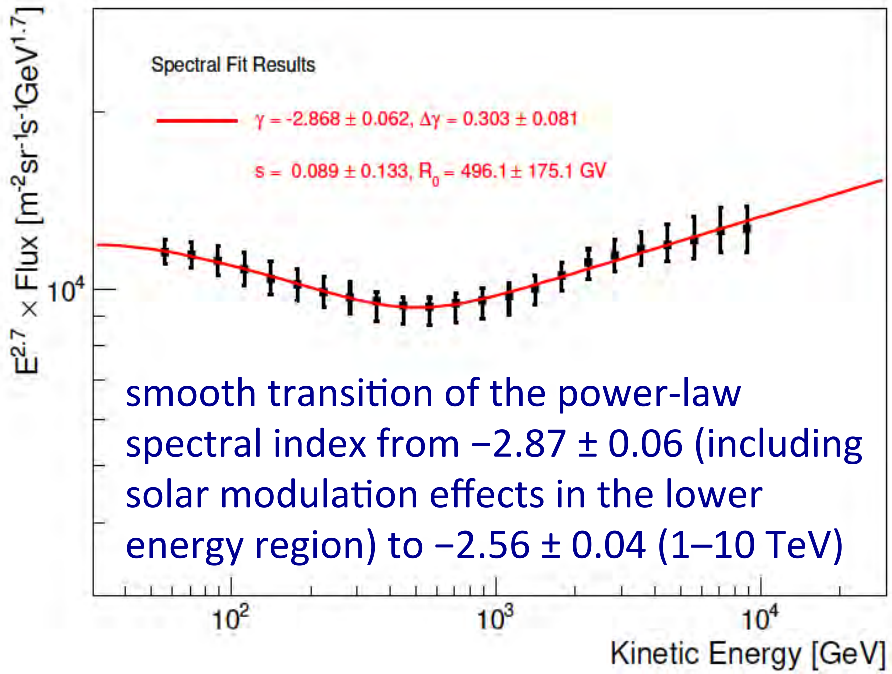
CALET covers the range **50 GeV to 10 TeV *with THE SAME INSTRUMENT*** confirming the existence of proton spectral hardening with a deviation from a single power law by more than 3σ.

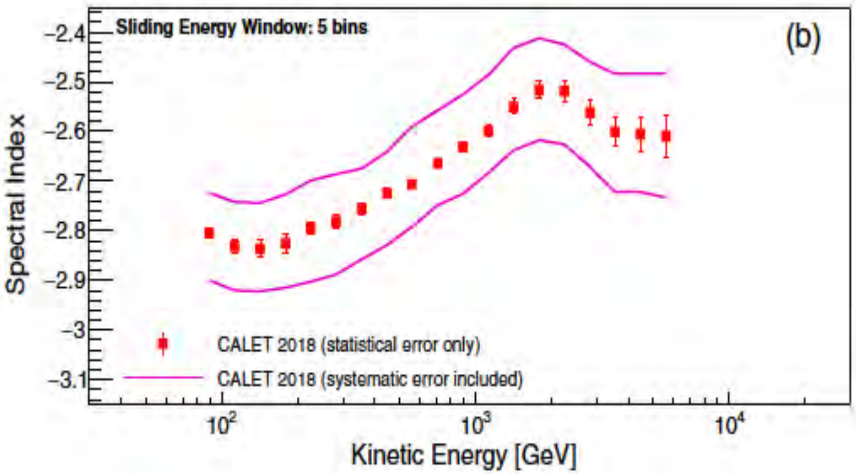


CALET Collaboration, Phys. Rev. Lett. **122**, 181102
Highlighted as "Editor's Suggestion"

Spectral Behavior of Proton Flux







1. Subranges of 50—500GeV, 1-10TeV can be fitted with single power law function, but not the whole range (significance > 3σ).
2. Progressive hardening up to the TeV region was observed.
3. "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.

Systematic Uncertainties (proton spectrum) Phys. Rev. Lett. 122, 181102 (2019)

- Study flux stability via scan of parameter space

Energy independent (normalization)

- LIve time
- Radiation environment
- Long-term stability
- Quality cuts

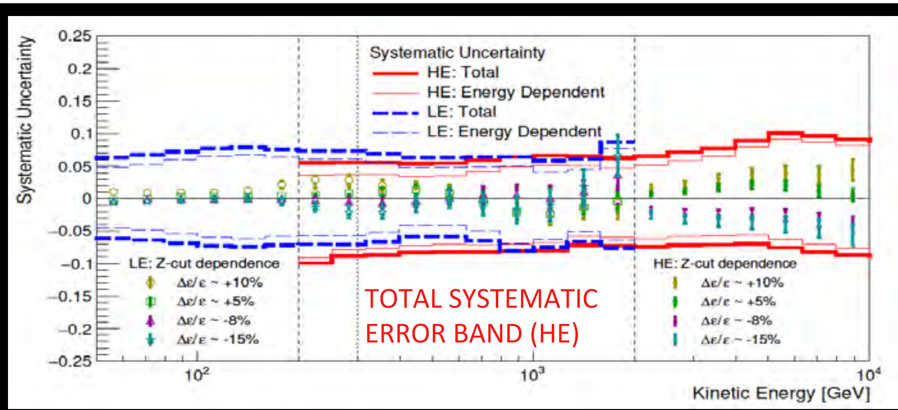
} 4.1%

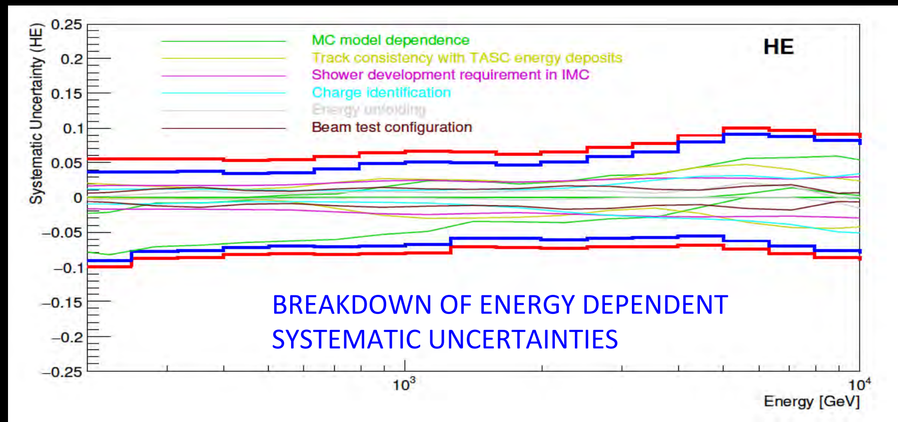
Energy dependent

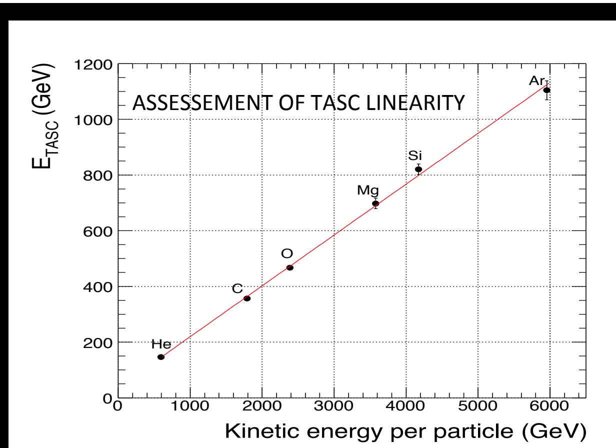
- MC model dependence
- Track consistency with TASC energy deposits
- Shower development requirement in IMC
- Charge identification
- Energy unfolding
- Beam test related uncertainties

Energy scale uncertainty

- beam test with < 400 GeV protons
- beam test with 150 GeV/n Ar fragments
- ground test with laser (response linearity)

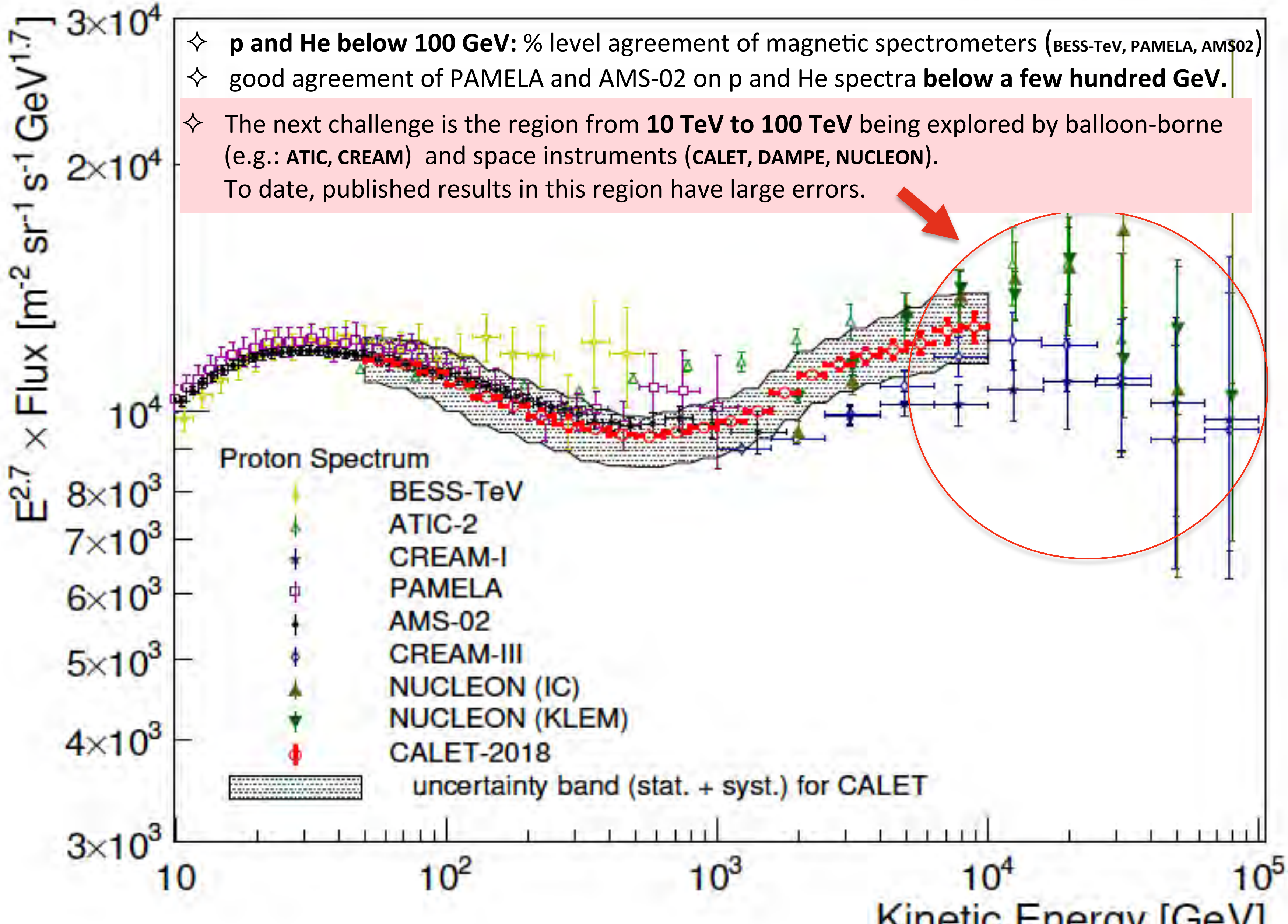






Direct measurements of proton spectrum to date

- ✧ **p and He below 100 GeV:** % level agreement of magnetic spectrometers (**BESS-TeV, PAMELA, AMS02**)
- ✧ good agreement of PAMELA and AMS-02 on p and He spectra **below a few hundred GeV.**
- ✧ The next challenge is the region from **10 TeV to 100 TeV** being explored by balloon-borne (e.g.: **ATIC, CREAM**) and space instruments (**CALET, DAMPE, NUCLEON**).
  To date, published results in this region have large errors.



CALET: Summary and Future Prospects

- CALET was successfully launched on Aug. 19th, 2015. The observation campaign started on Oct. 13th, 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 low (> 1 GeV) + high energy (>10 GeV) triggers.
- In-flight calibrations with p & 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 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.

Thank you
for your attention !

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

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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],
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