The Calorimetric Electron Telescope (CALET) on the International Space Station: Results from the First Six Years on Orbit

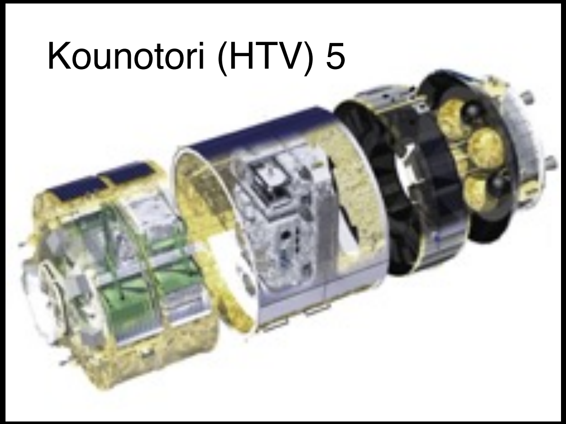
Yosui Akaike
Waseda University, Japan
for the CALET Collaboration

The CALET Collaboration Member

O. Adriani,[1, 2] Y. Akaike,[3, 4] K. Asano,[5] Y. Asaoka,[5] E. Berti,[1, 2] G. Bigongiari,[6, 7] W.R. Binns,[8] M. Bongi,[1, 2] P. Brogi,[6, 7] A. Bruno,[9] J.H. Buckley,[8] N. Cannady,[10, 11, 12] G. Castellini,[13] C. Checchia,[6, 7] M.L. Cherry,[14] G. Collazuol,[15, 16] K. Ebisawa,[17] A. W. Ficklin,[14] H. Fuke,[17] S. Gonzi,[1, 2] T.G. Guzik,[14] T. Hams,[10] K. Hibino,[18] M. Ichimura,[19] K. Ioka,[20] W. Ishizaki,[5] M.H. Israel,[8] K. Kasahara,[21] J. Kataoka,[22] R. Kataoka,[23] Y. Katayose,[24] C. Kato,[25] N. Kawanaka,[20] Y. Kawakubo,[14] K. Kobayashi,[3, 4] K. Kohri,[26] H.S. Krawczynski,[8] J.F. Krizmanic,[11] P. Maestro,[6, 7] P.S. Marrocchesi,[6, 7] A.M. Messineo,[27, 7] J.W. Mitchell,[11] S. Miyake,[28] A.A. Moiseev,[29, 11, 12] M. Mori,[30] N. Mori,[2] H.M. Motz,[31] K. Munakata,[25] S. Nakahira,[17] J. Nishimura,[17] G.A. de Nolfo,[9] S. Okuno,[18] J.F. Ormes,[32] S. Ozawa,[33] L. Pacini,[1, 2, 13] P. Papini,[2] B.F. Rauch,[8] S.B. Ricciarini,[13, 2] K. Sakai,[10, 11, 12] T. Sakamoto,[34] M. Sasaki,[29, 11, 12] Y. Shimizu,[18] A. Shiomi,[35] P. Spillantini,[1] F. Stolzi,[6, 7] S. Sugita,[34] A. Sulaj,[6, 7] M. Takita,[5] T. Tamura,[18] T. Terasawa,[5] S. Torii,[3] Y. Tsunesada,[36, 37] Y. Uchihori,[38] E. Vannuccini,[2] J.P. Wefel,[14] K. Yamaoka,[39] S. Yanagita,[40] A. Yoshida,[33] K. Yoshida,[21] and W. V. Zober[8]

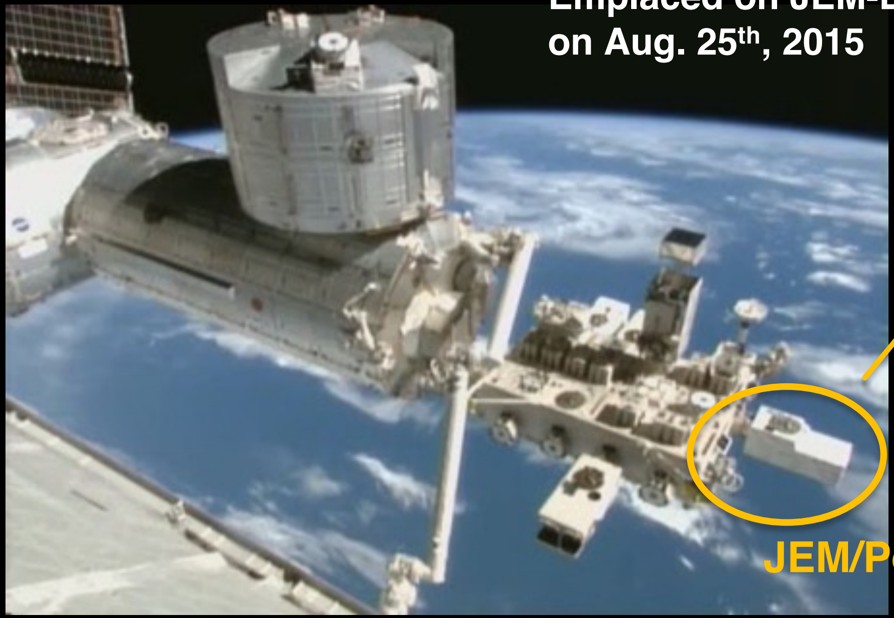
1) University of Florence, Italy
2) INFN Florence, Italy
3) WISE, Waseda University, Japan
4) JEM Utilization Center, JAXA, Japan
5) ICRR, University of Tokyo, Japan
6) University of Siena, Italy
7) INFN Pisa, Italy
8) Washington University, St. Louis, USA
9) Heliospheric Physics Laboratory, NASA/GSFC, USA
10) University of Maryland, Baltimore County USA
11) Astroparticle Physics Laboratory, NASA/GSFC, USA
12) CRESST, NASA/GSFC, USA
13) IFAC, CNR, Italy
14) Louisiana State University, USA
15) University of Padova, Italy
16) INFN Padova, Italy
17) ISAS, JAXA, Japan
18) Kanagawa University, Japan
19) Hirosaki University, Japan
20) YITP, Kyoto University, Japan
21) Shibaura Institute of Technology, Japan
22) ASE, Waseda University, Japan
23) NIPR, Japan
24) Yokohama National University, Japan
25) Shinshu University, Japan
26) IPNS, KEK, Japan
27) University of Pisa
28) NIT, Ibaraki College, Japan
29) University of Maryland, College Park, USA
30) Ritsumeikan University, Japan
31) GCSE, Waseda University, Japan
32) University of Denver, USA
33) NICT, Japan
34) Aoyama Gakuin University, Japan
35) Nihon University, Japan
36) Osaka Metropolitan University, Japan
37) NITEP, Osaka Metropolitan University, Japan
38) QST, Japan
39) Nagoya University, Japan
40) Ibaraki University, Japan

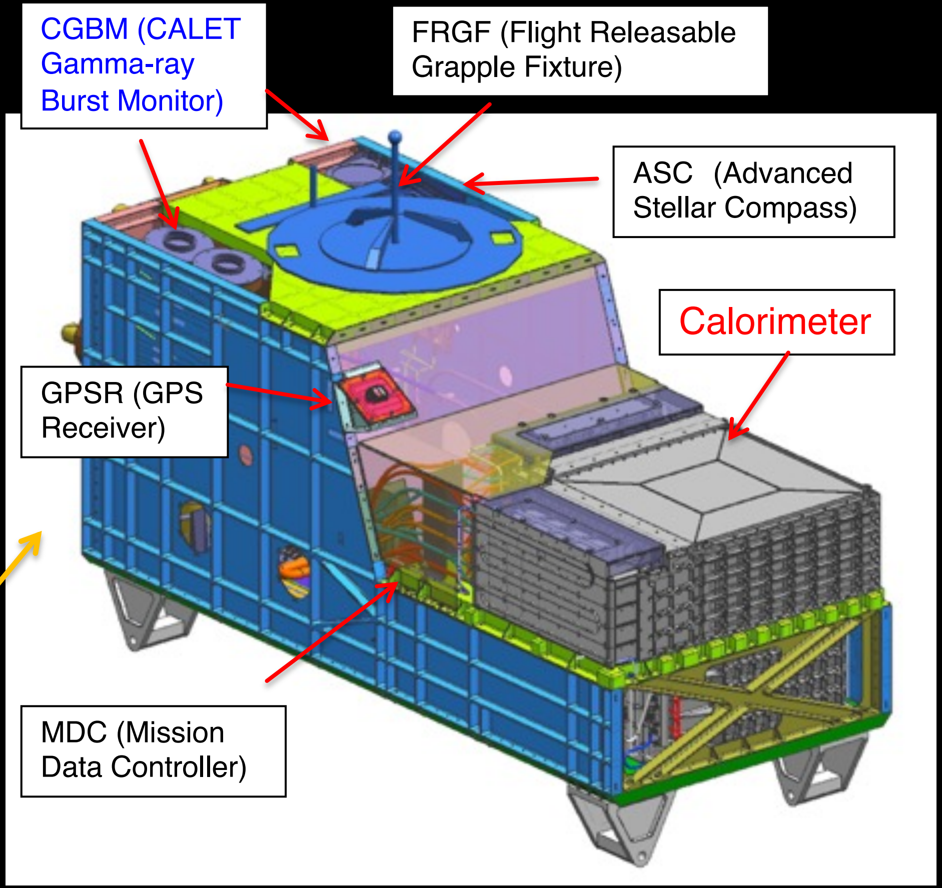
CALET Payload



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

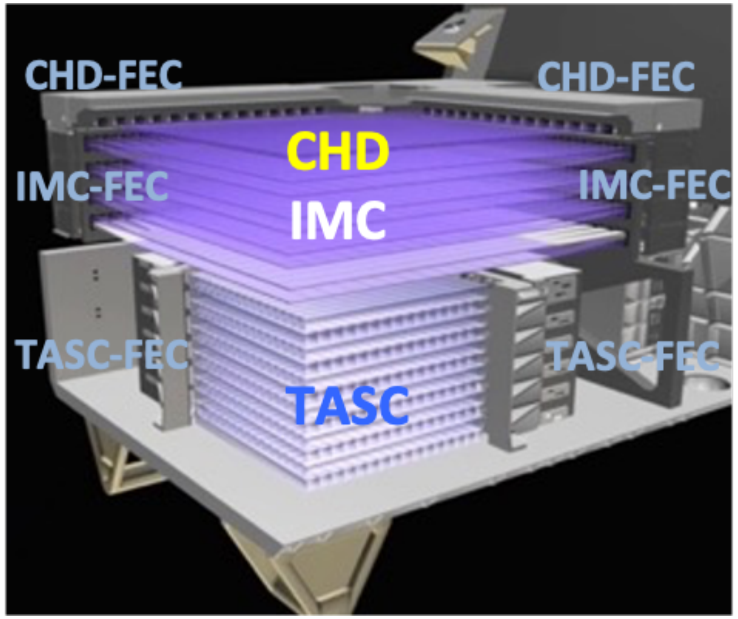
Emplaced on JEM-EF port #9 on Aug. 25th, 2015

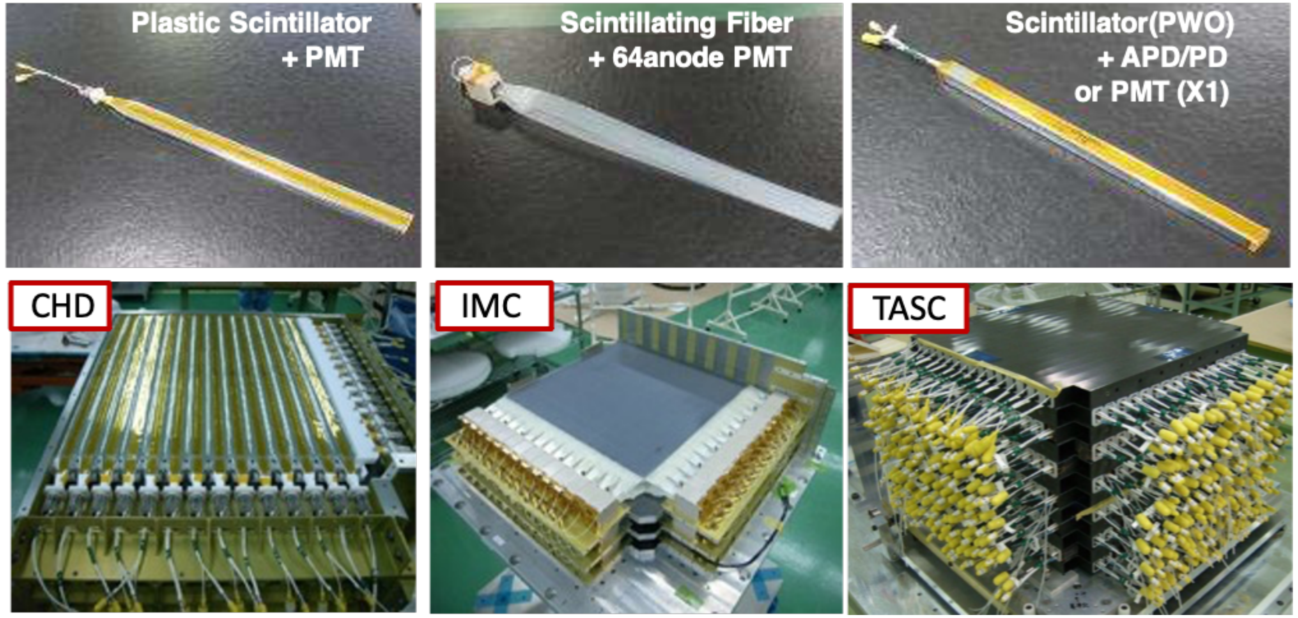




- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W (max)**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

CALET Detector: Calorimeter

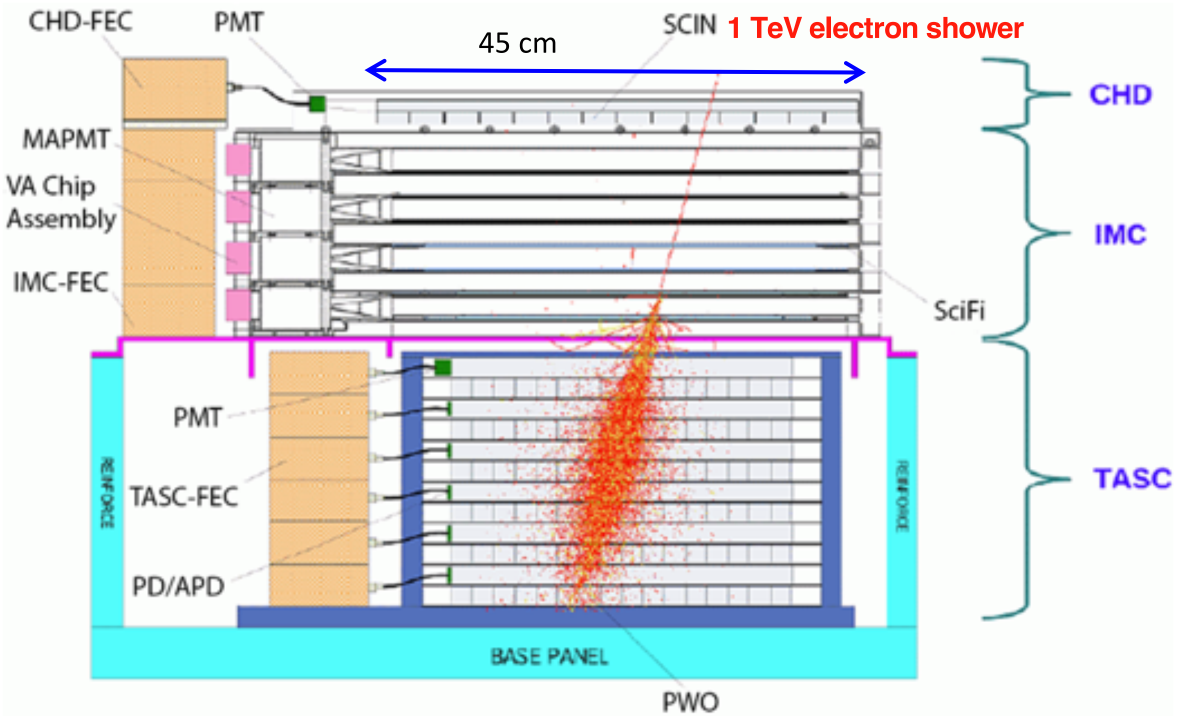




	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers (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 (VA32-HDR)**	**APD/PD+CSA PMT+CSA (for Trigger)@top layer**

CALET Calorimeter and Capability

A 30-radiation length deep calorimeter designed to detect electrons and gammas to 20 TeV and cosmic rays up to 1 PeV



CHD – Charge Detector

- 2 layers x 14 plastic scintillating paddles
- single element charge ID from p to Fe and above (Z = 40)
- charge resolution ~0.1-0.3 e

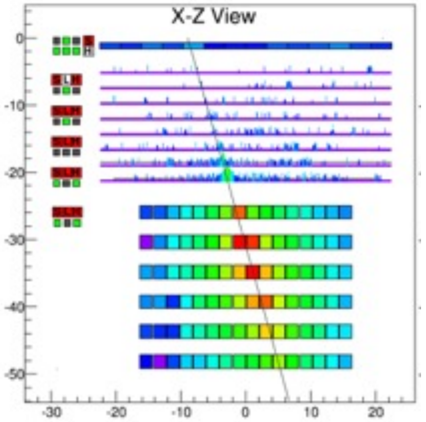
IMC – Imaging Calorimeter

- Scifi + Tungsten absorbers: $3\ X_0$ at normal incidence
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **Tracking** (~0.1° angular resolution) + **Shower imaging**

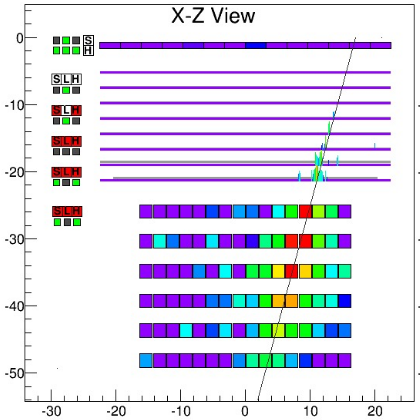
TASC – Total Absorption Calorimeter $27\ X_0$, $1.2\ \lambda_I$

- 6 x 2 x 16 lead tungstate ($PbWO_4$) logs
- **Energy resolution:** ~2 % (>10GeV) for e , γ ~30-35% for p, nuclei
- **e/p separation:** ~10^{-5}

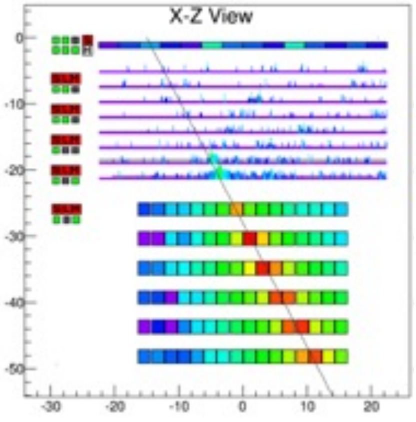
Electron, *E*=3.05 TeV



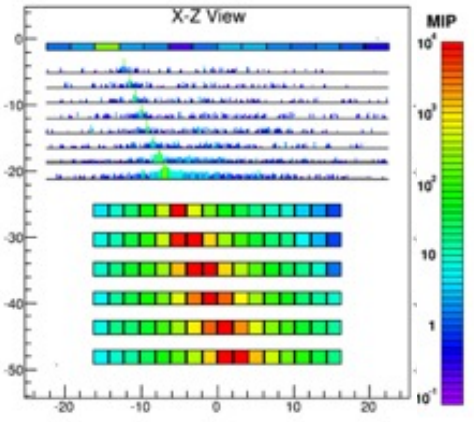
Gamma-ray, *E*=44.3 GeV



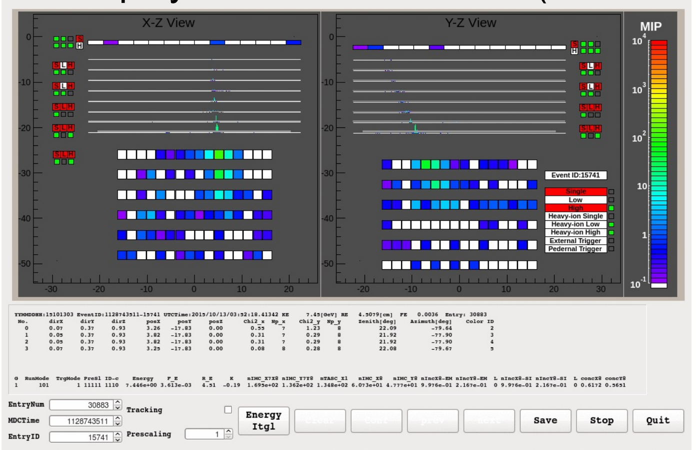
Proton, E_{TASC}=2.89 TeV



Iron, E_{TASC} =9.3 TeV

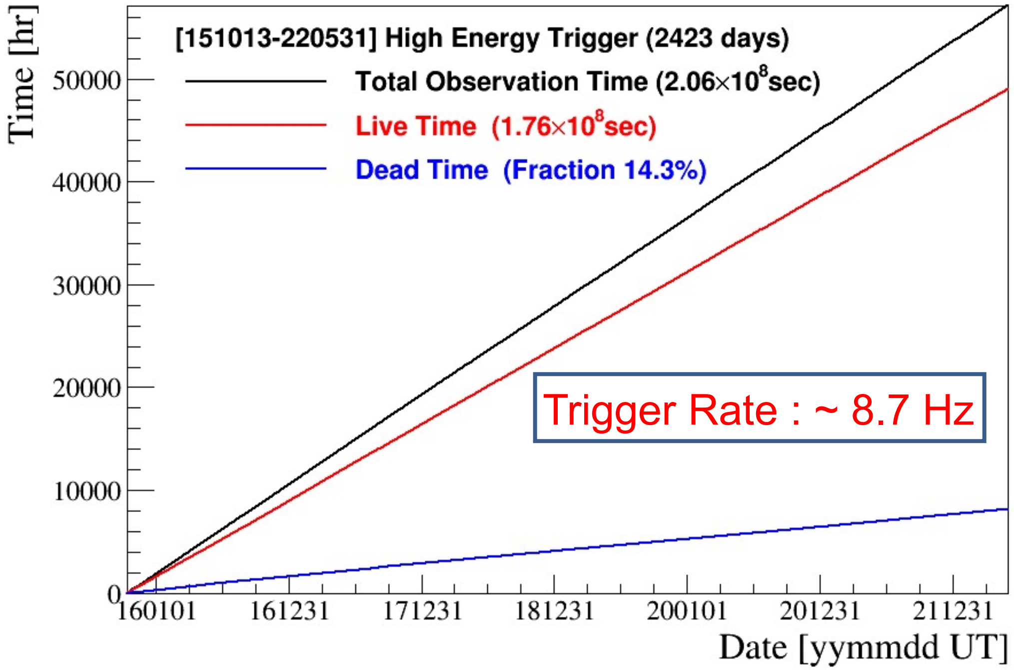


Event Display: Electron Candidate (>100 GeV)



CALET Observation on the ISS

Accumulated observation time (live, dead)



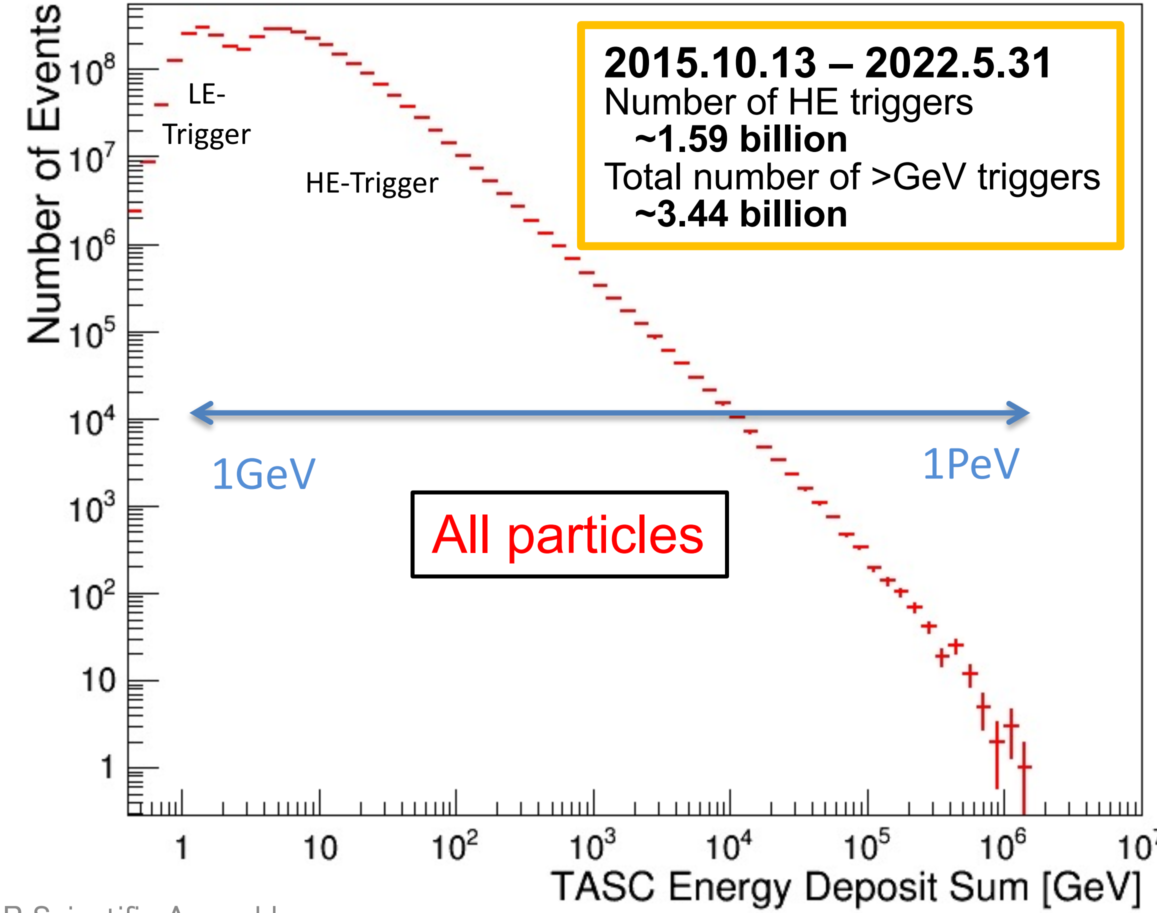
High-energy trigger (> 10 GeV) statistics:

- Operational time > **2,423 days**(*)
  (*) as of May 31, 2022
- Live time fraction **> 85%**
- Exposure of HE trigger
  ~211 m^2 sr day
- HE-gamma point source exposure
  ~4.1 m^2 day (for Crab, Geminga)

Geometrical Factor:

- 1040 cm^2 sr for electrons, light nuclei
- 1000 cm^2 sr for gamma-rays
- 4000 cm^2sr for ultra-heavy nuclei

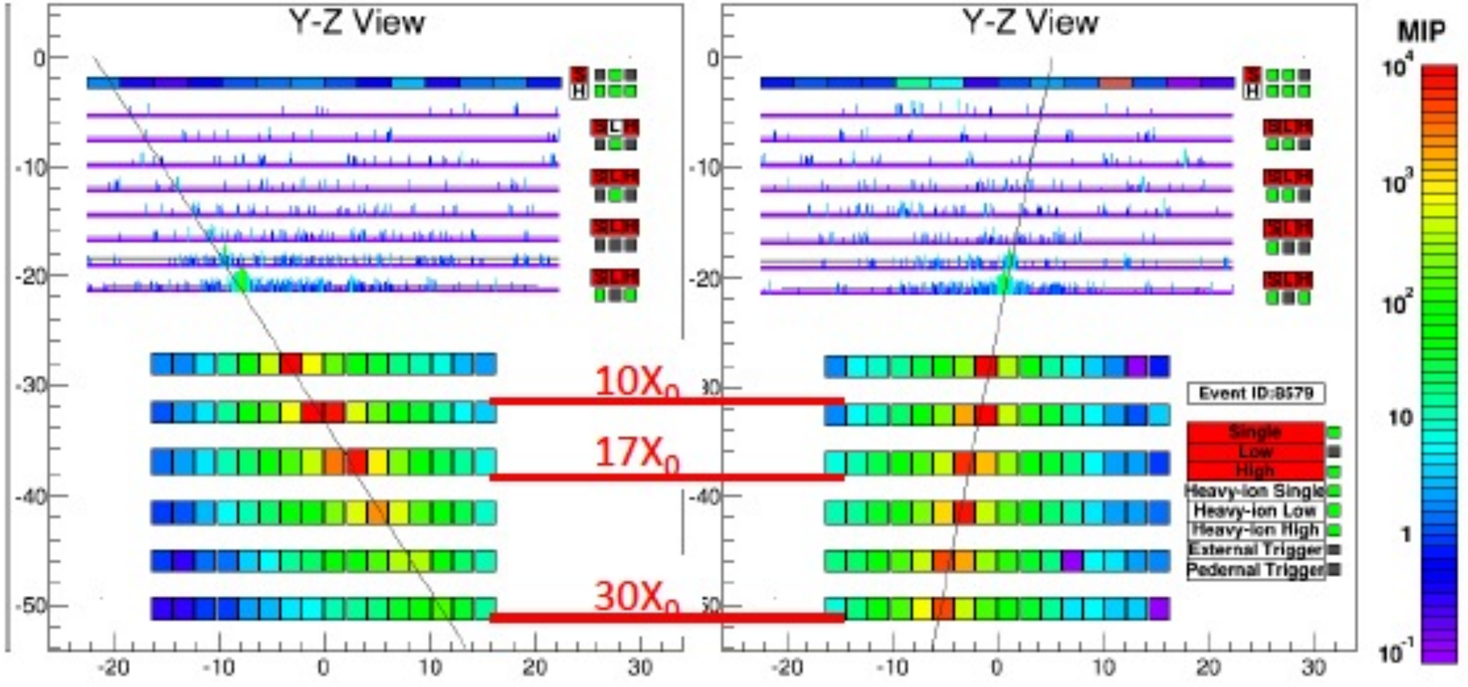
Energy deposit (in TASC) spectrum: 1 GeV-1 PeV



All-electron measurements

3TeV Electron Candidate

Corresponding Proton Background

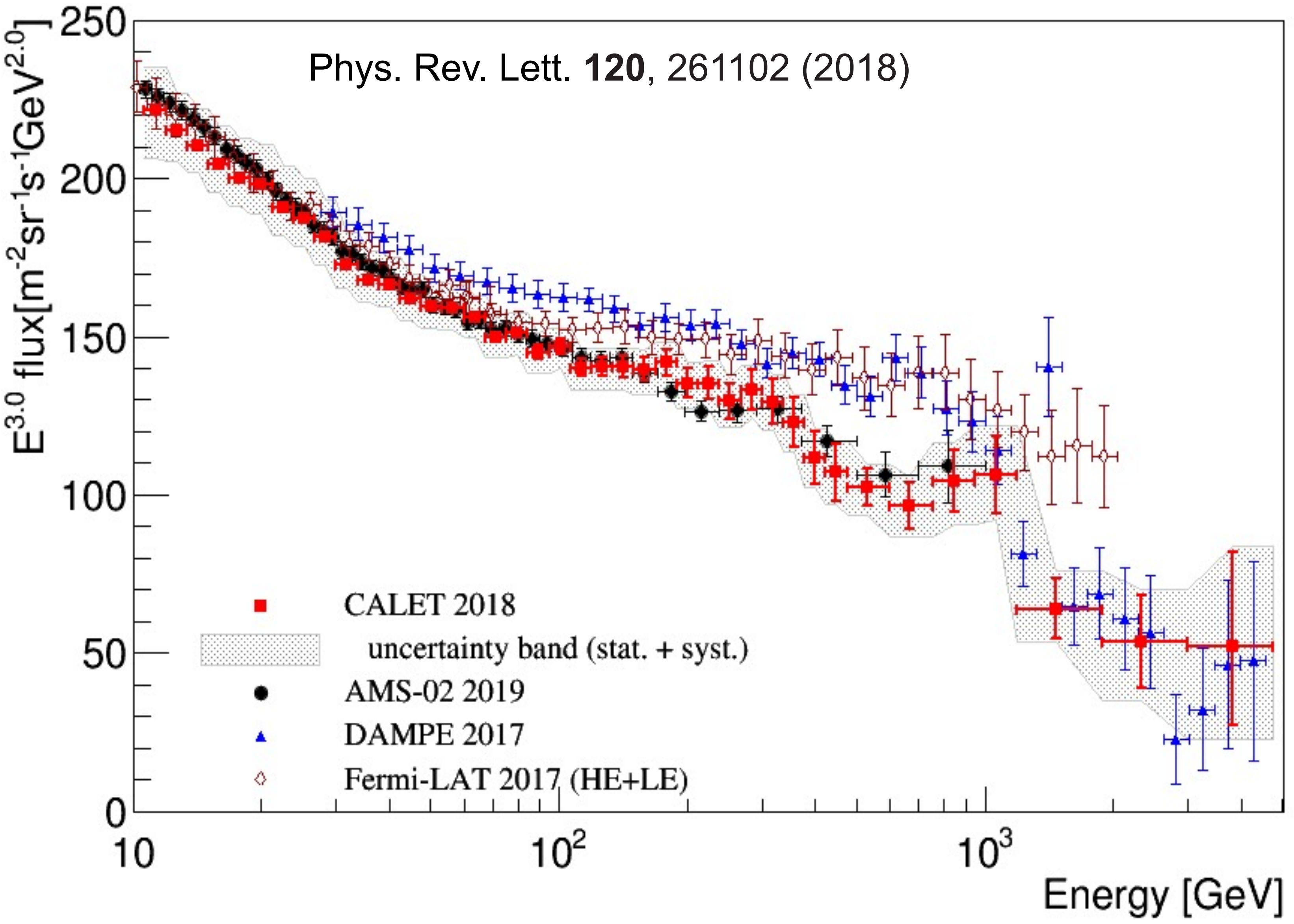


(Flight data; detector size in cm)

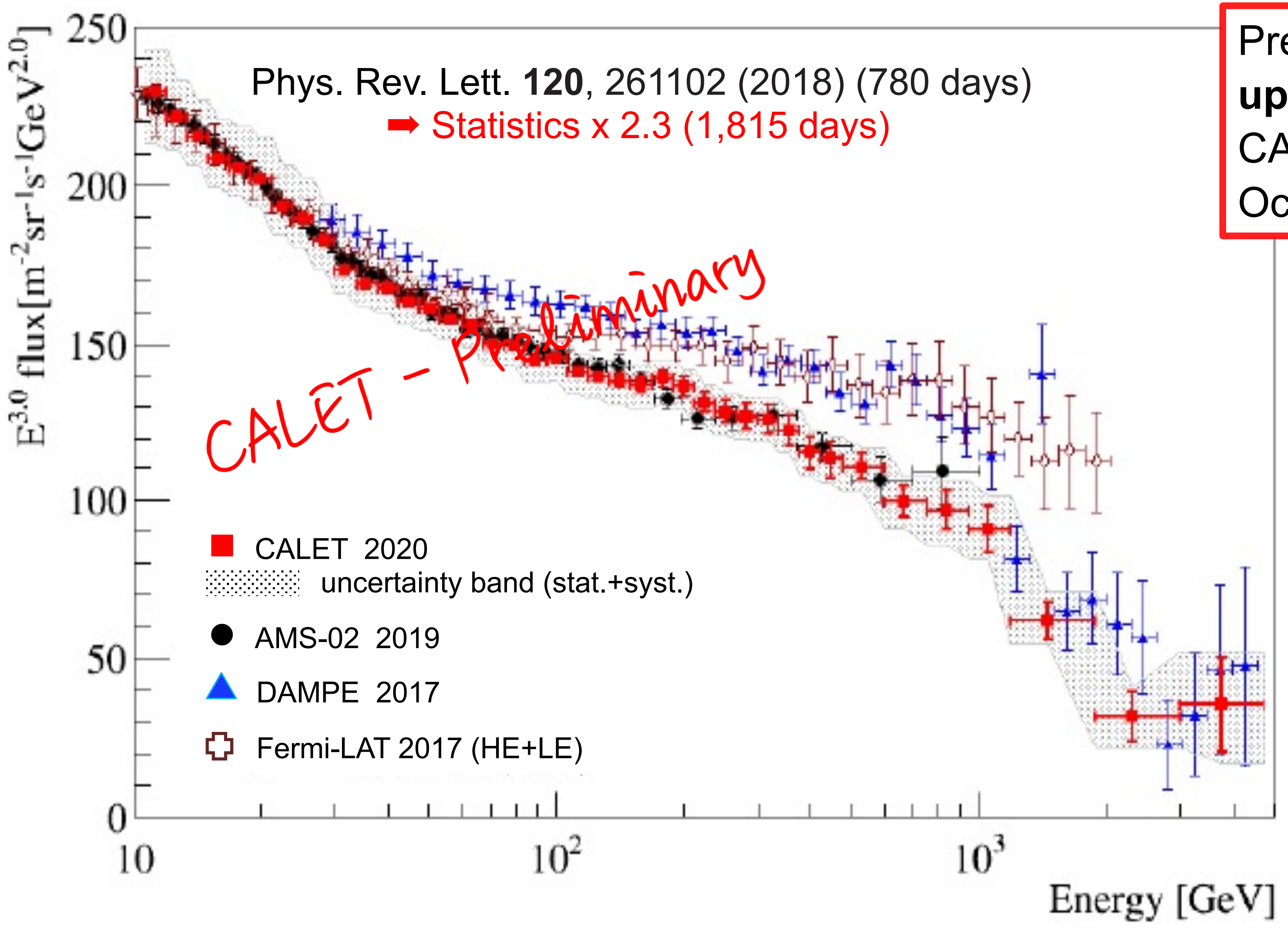
1. **Reliable tracking**
   well-developed shower core
2. **Fine energy resolution**
   full containment of TeV showers
3. **High-efficiency electron ID**
   30X$_0$ thickness, closely packed logs

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

All-electron spectrum

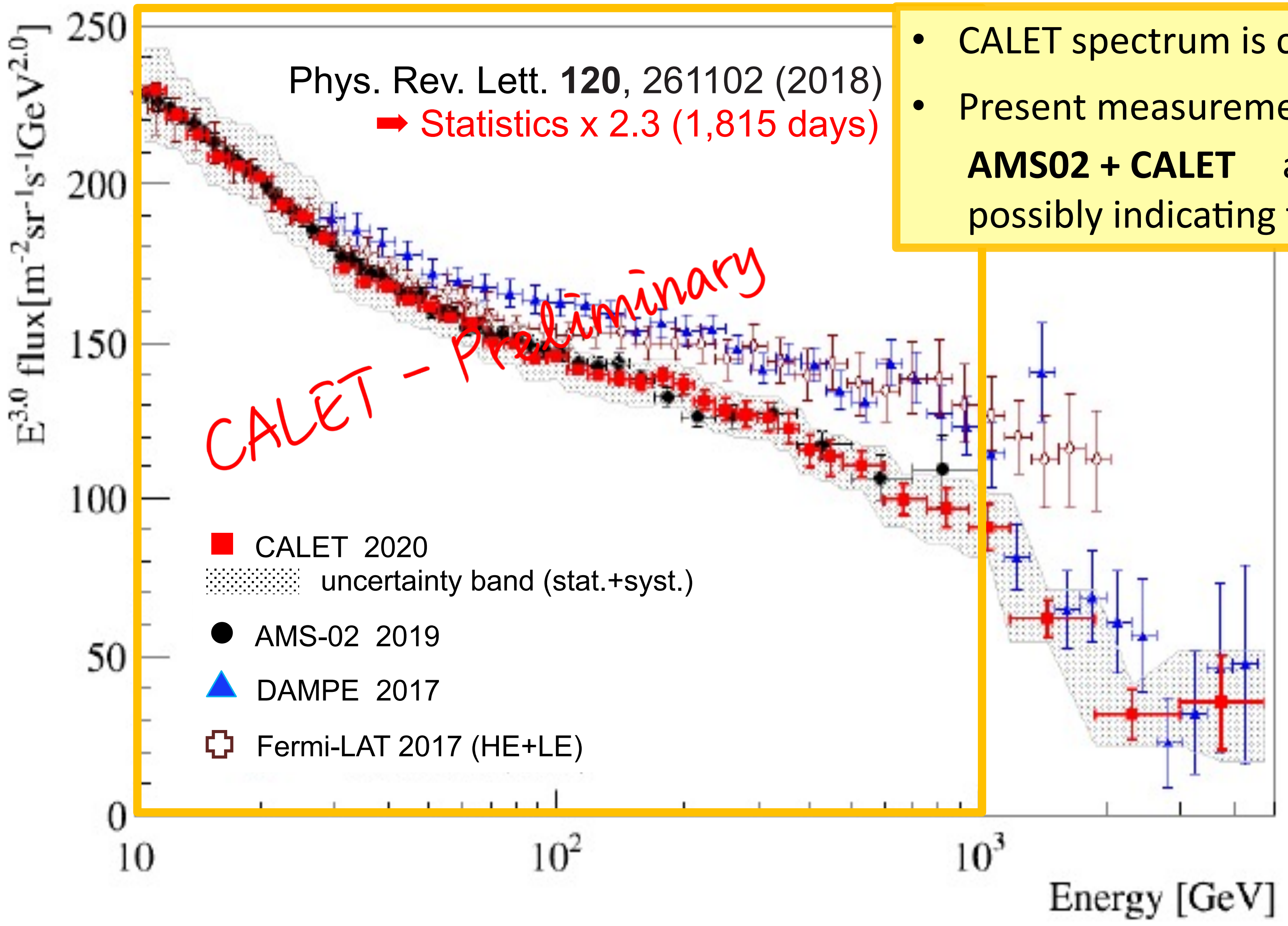


All-electron spectrum (update up to Sep.30, 2020)



Preliminary spectrum is **updated** after 1815 days of CALET observations:
Oct.13, 2015 - Sep.30, 2020

All-electron spectrum (update up to Sep.30, 2020)

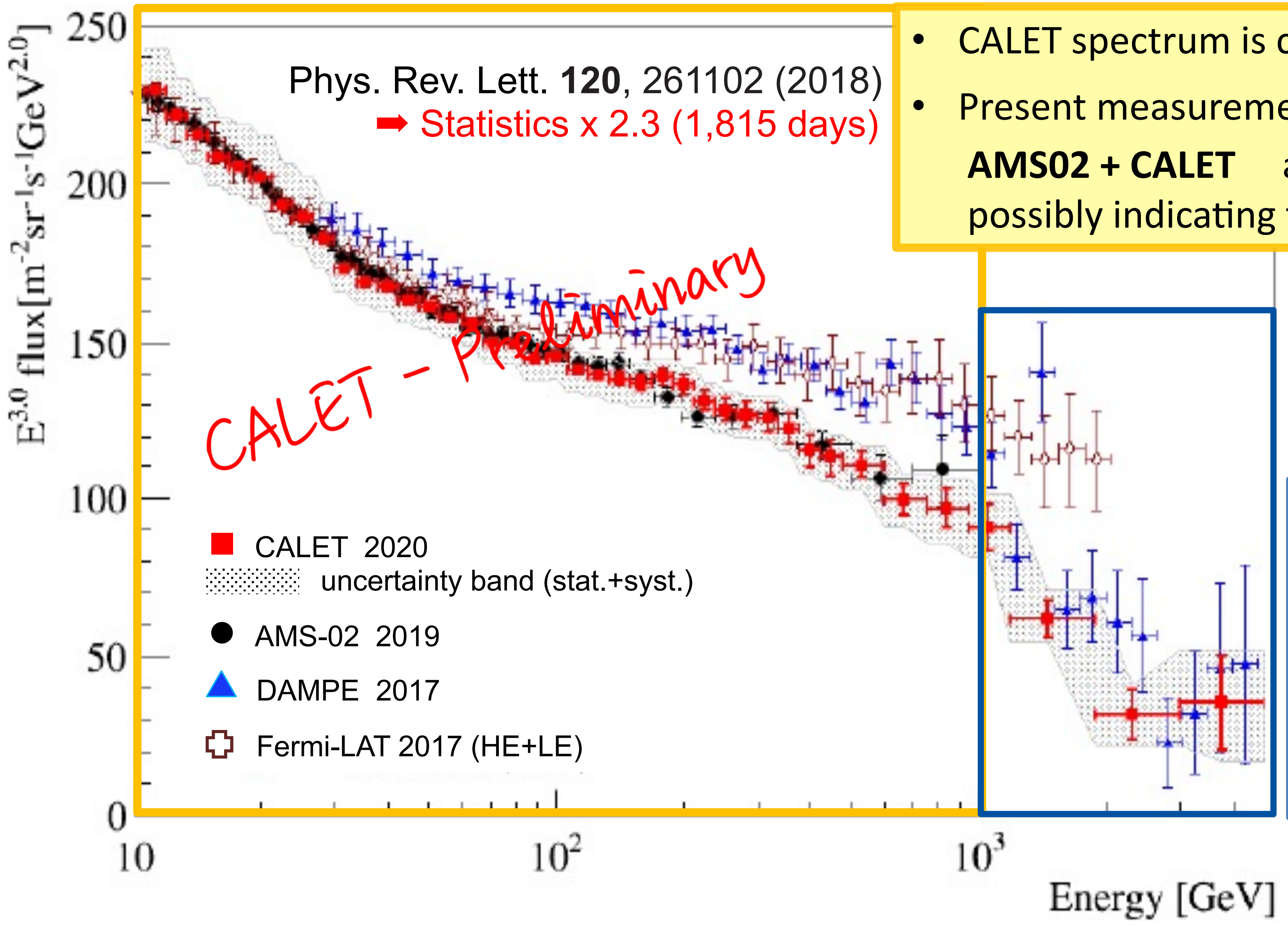


- CALET spectrum is consistent with AMS-02
- Present measurements cluster into 2 groups:

  AMS02 + CALET and **FERMI + DAMPE**

  possibly indicating the presence of unknown systematics

All-electron spectrum (update up to Sep.30, 2020)



- CALET spectrum is consistent with AMS-02
- Present measurements cluster into 2 groups:

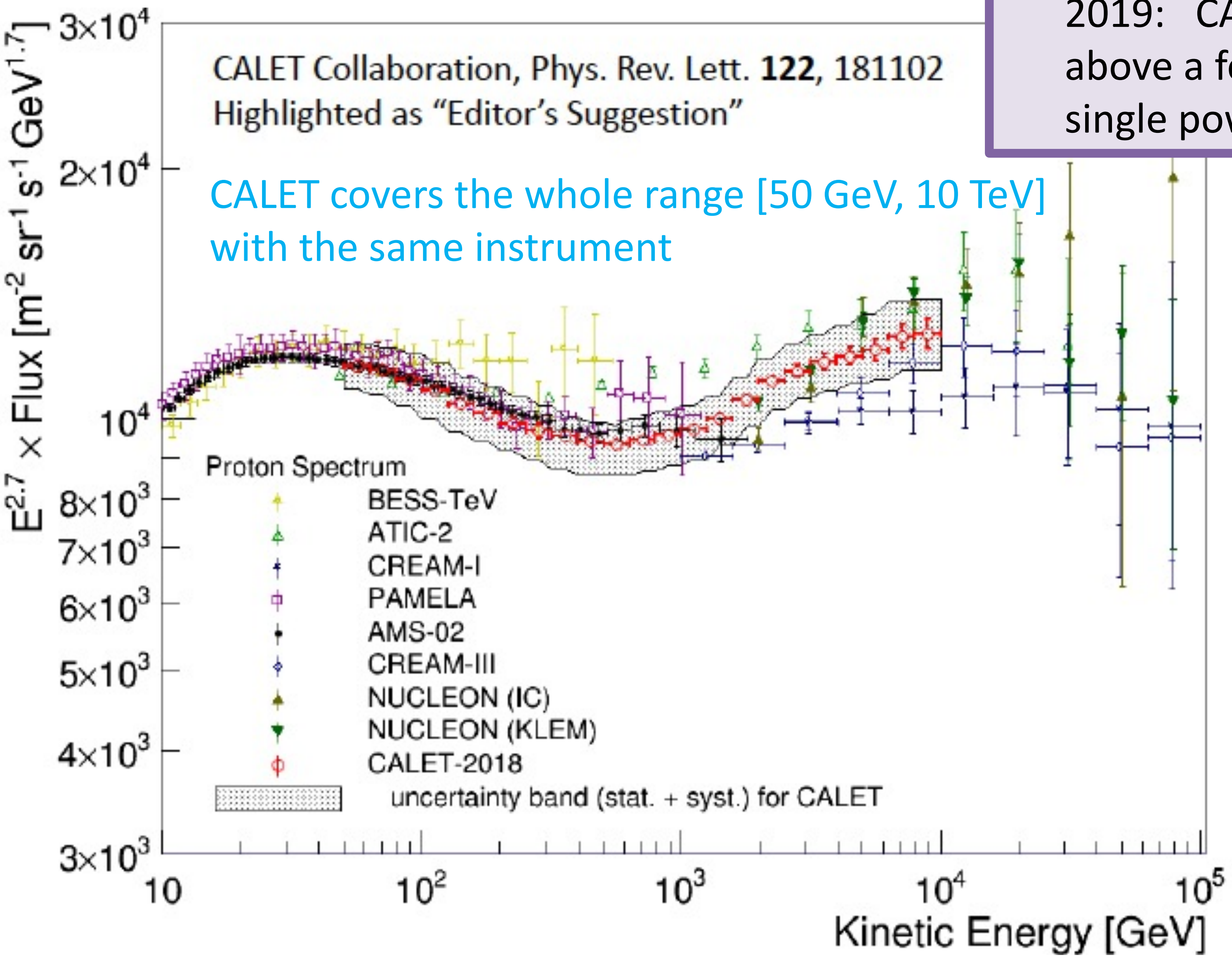
  AMS02 + CALET and **FERMI + DAMPE**

  possibly indicating the presence of unknown systematics

CALET observes a flux suppression above 1 TeV with a **significance > 6.5 σ**, a considerable improvement with respect to the result published in PRL2018 (~4 σ)

Proton spectrum

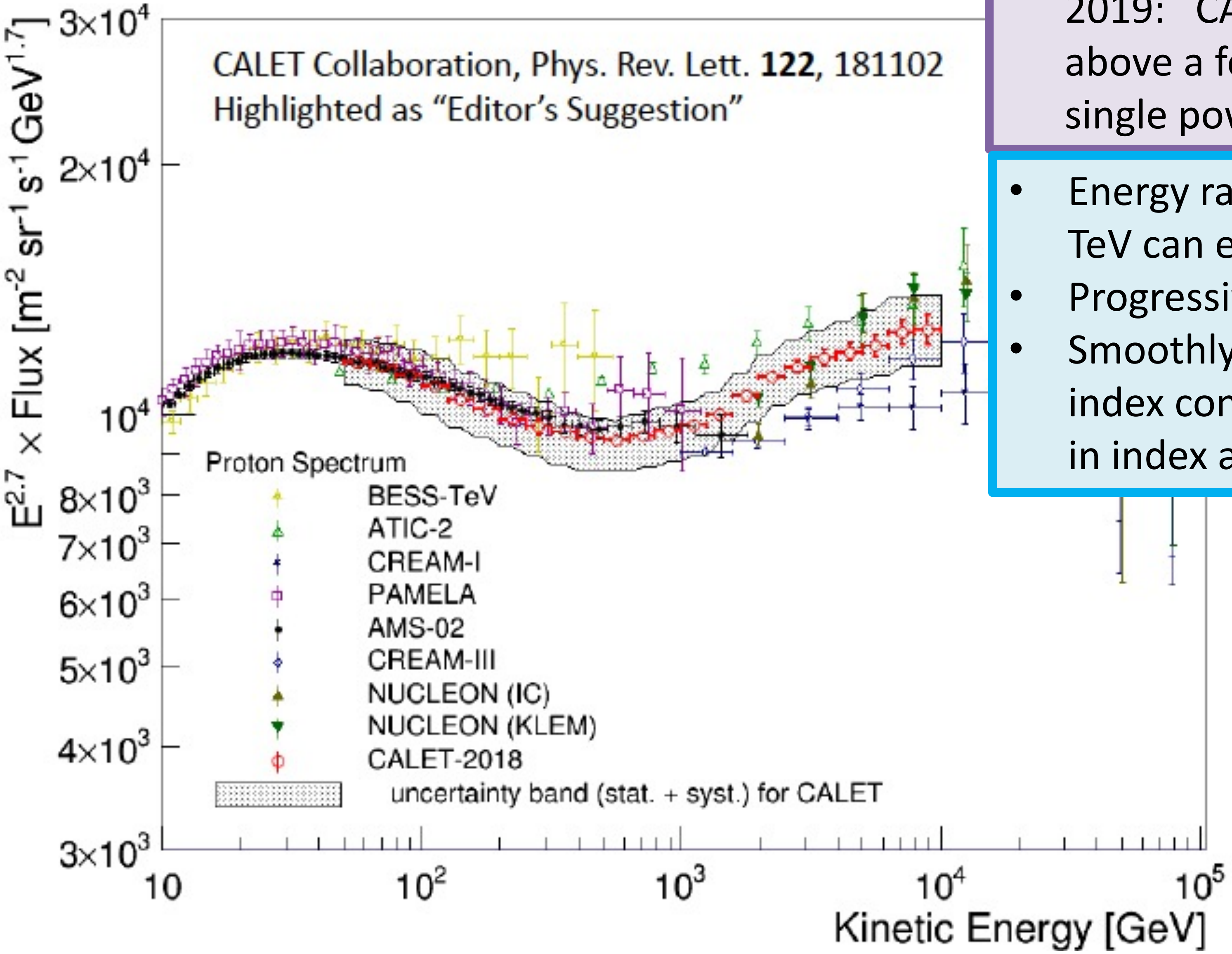
2019: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

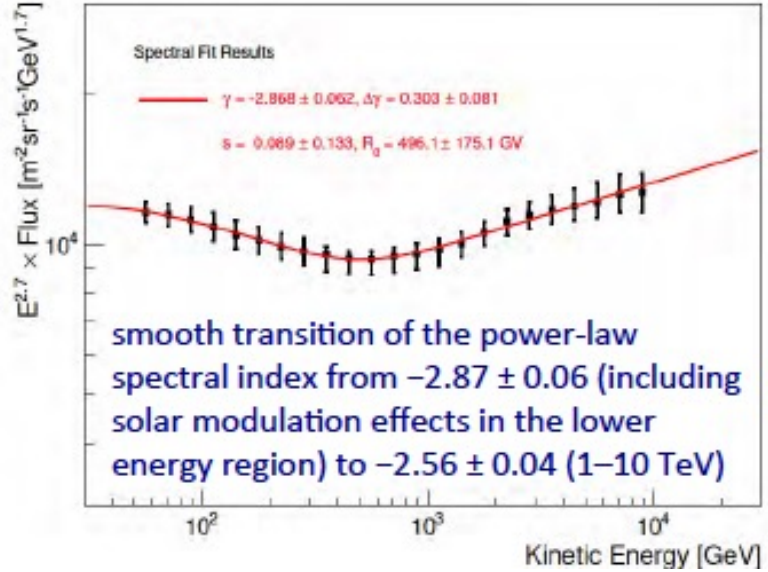


Proton spectrum

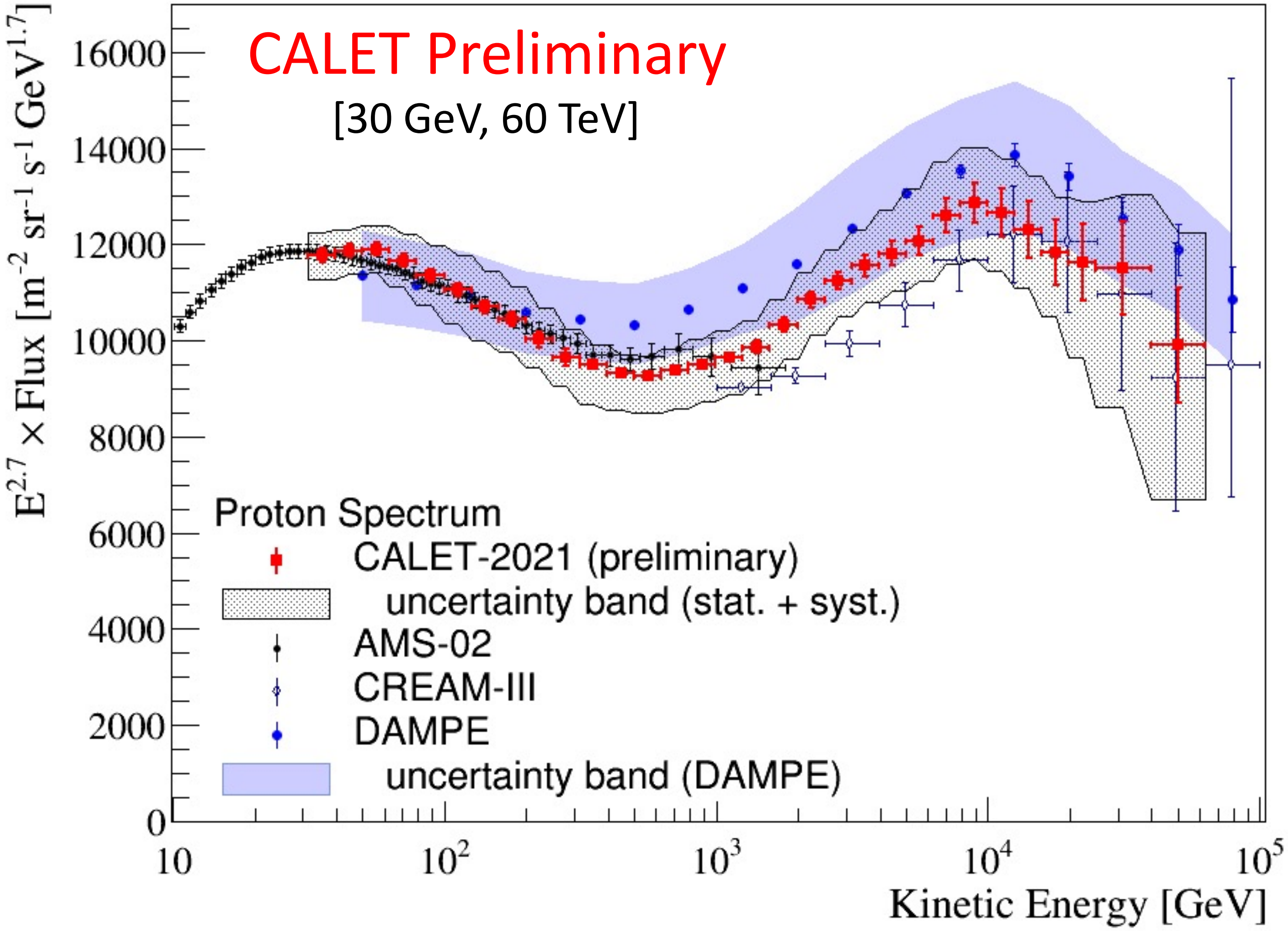
2019: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

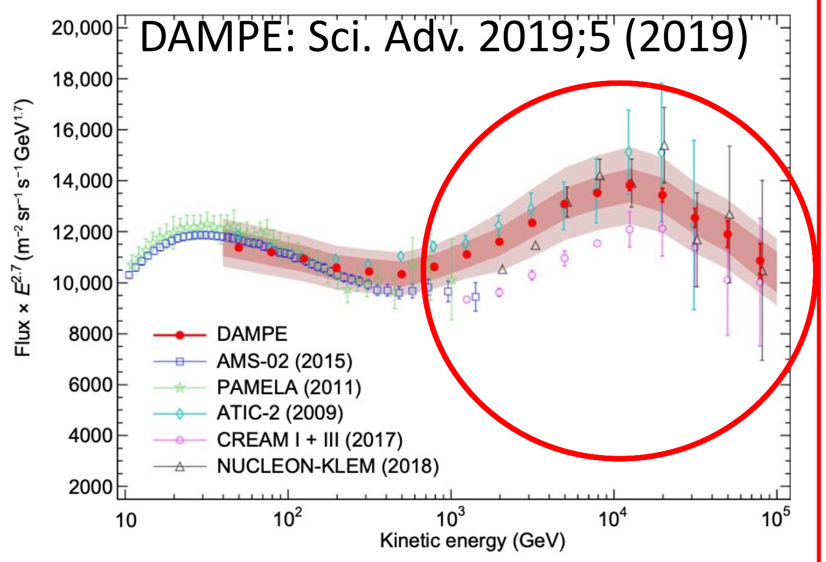
- Energy ranges 50 GeV – 500 GeV and 1 TeV – 10 TeV can each be fitted with single power laws
- Progressive hardening up to TeV energies
- Smoothly-broken power law fit gives low energy index consistent with AMS-02, but larger change in index and higher break energy





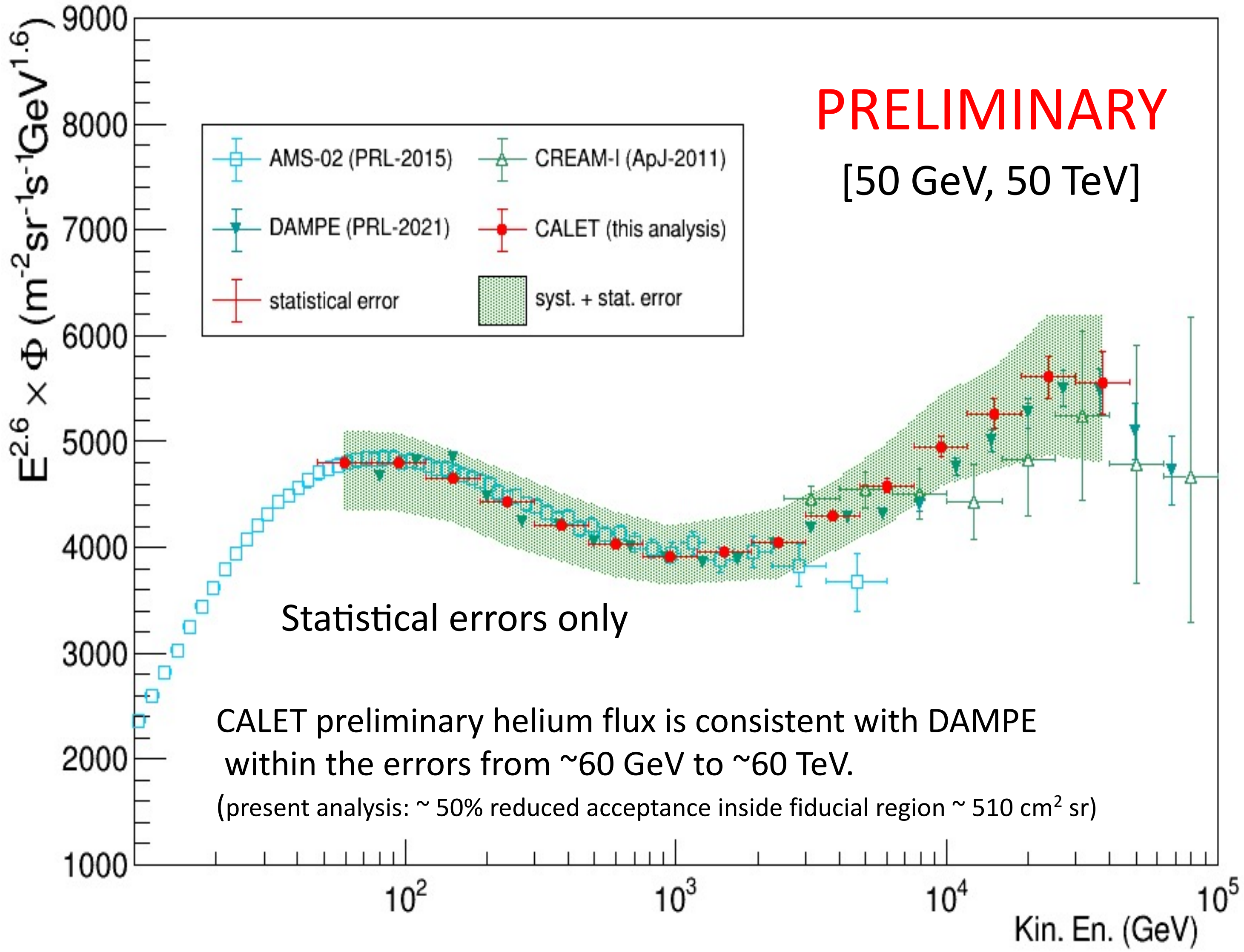
Proton spectrum (update up to Sep.30, 2020)





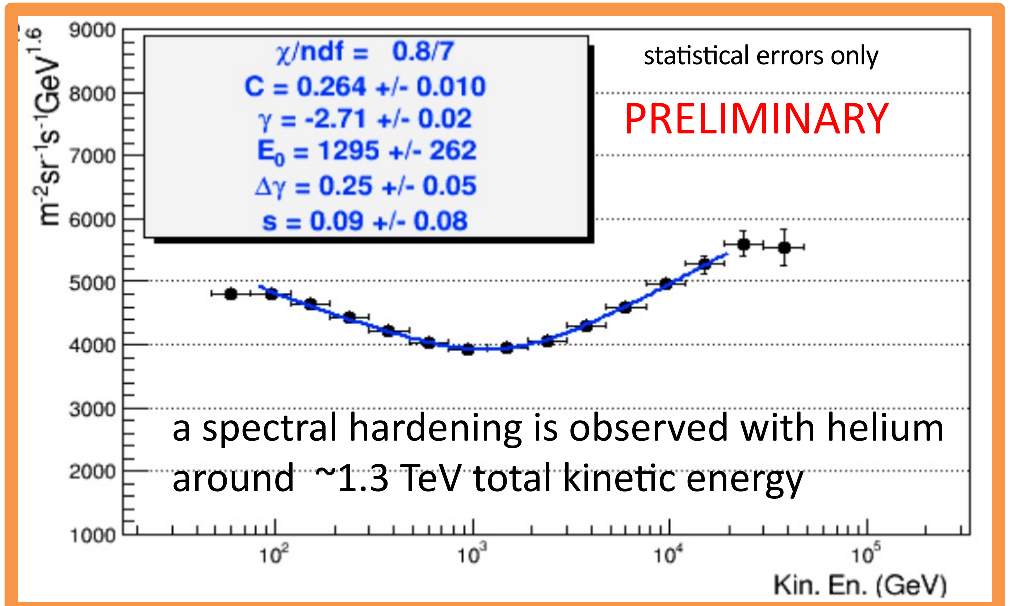
- DAMPE reported a spectral index softening $\Delta\gamma = -0.25 \pm 0.07$ from ~-2.60 to ~-2.85. above 10 TeV at E_{break} = $13.6^{+4.1}_{-4.8}$ TeV with ~30% error.
- DAMPE flux is consistent with AMS-02 and CALET up to 200 GeV. Above, the flux is higher (close to the limit of the systematic error band).

Helium spectrum (preliminary)

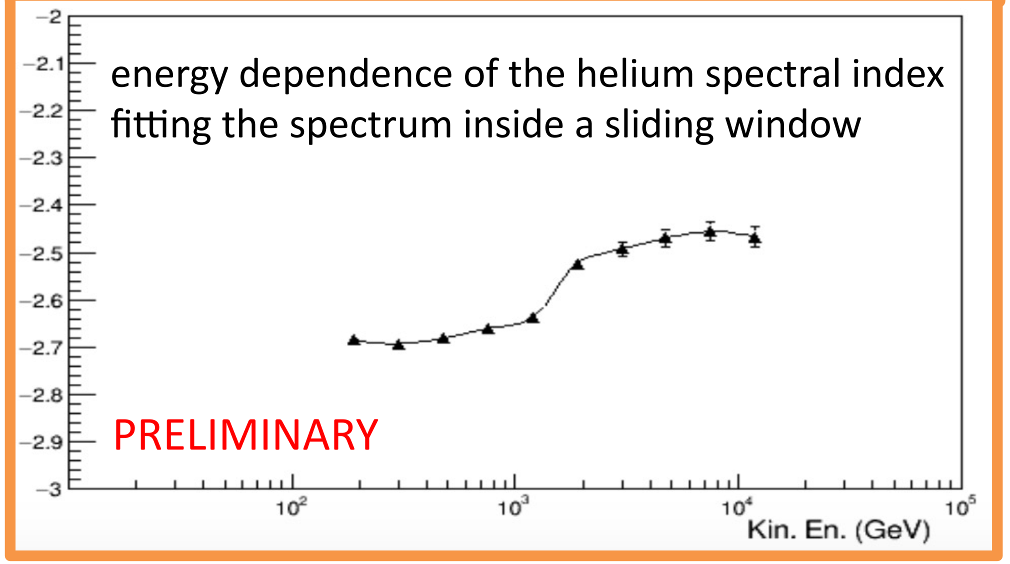


CALET preliminary helium flux is consistent with DAMPE within the errors from ~60 GeV to ~60 TeV.

(present analysis: ~ 50% reduced acceptance inside fiducial region ~ 510 cm^2 sr)

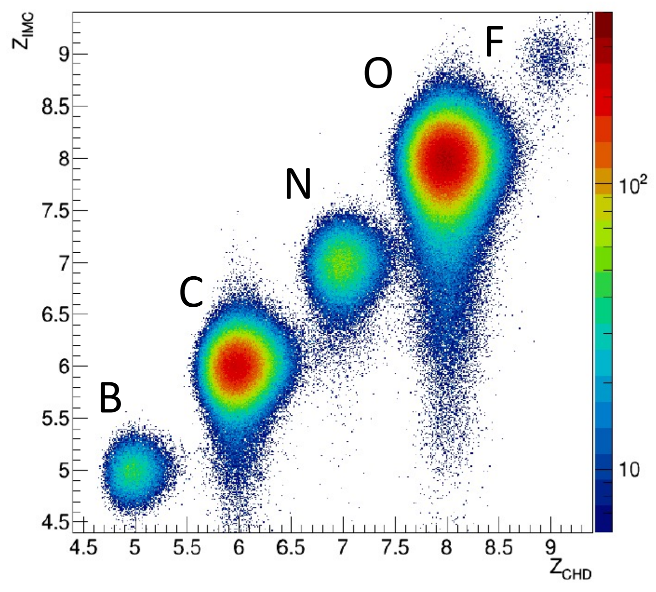


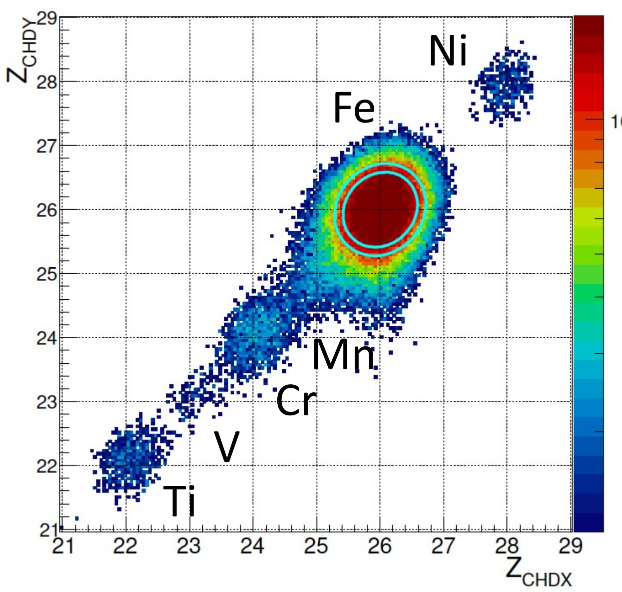
a spectral hardening is observed with helium around ~1.3 TeV total kinetic energy

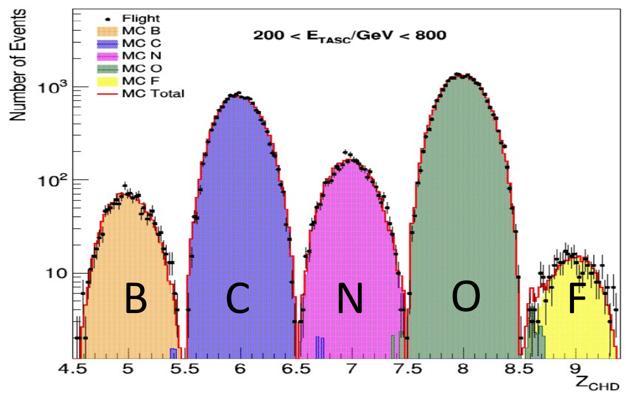


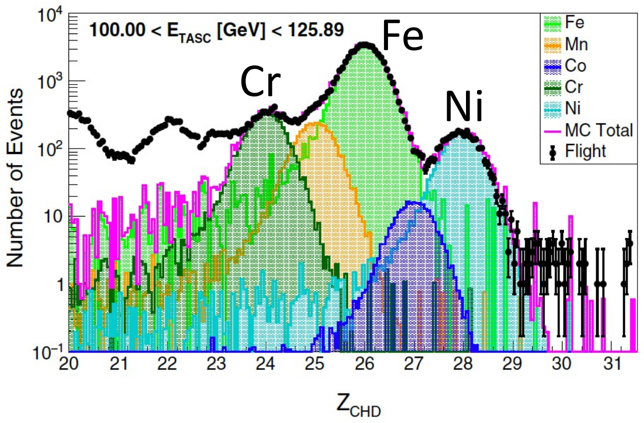
energy dependence of the helium spectral index fitting the spectrum inside a sliding window

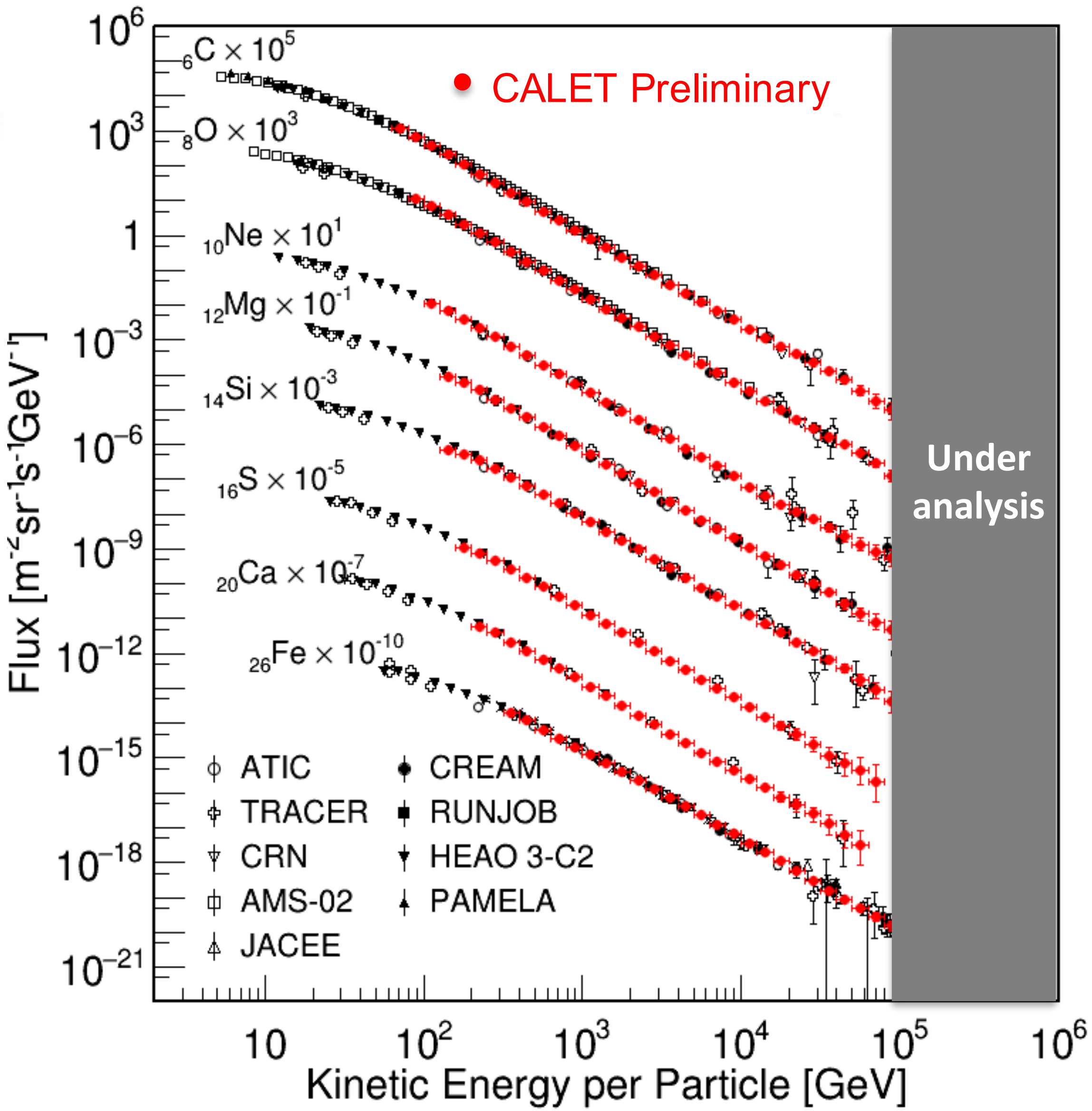
Spectra of nuclei from C to Fe





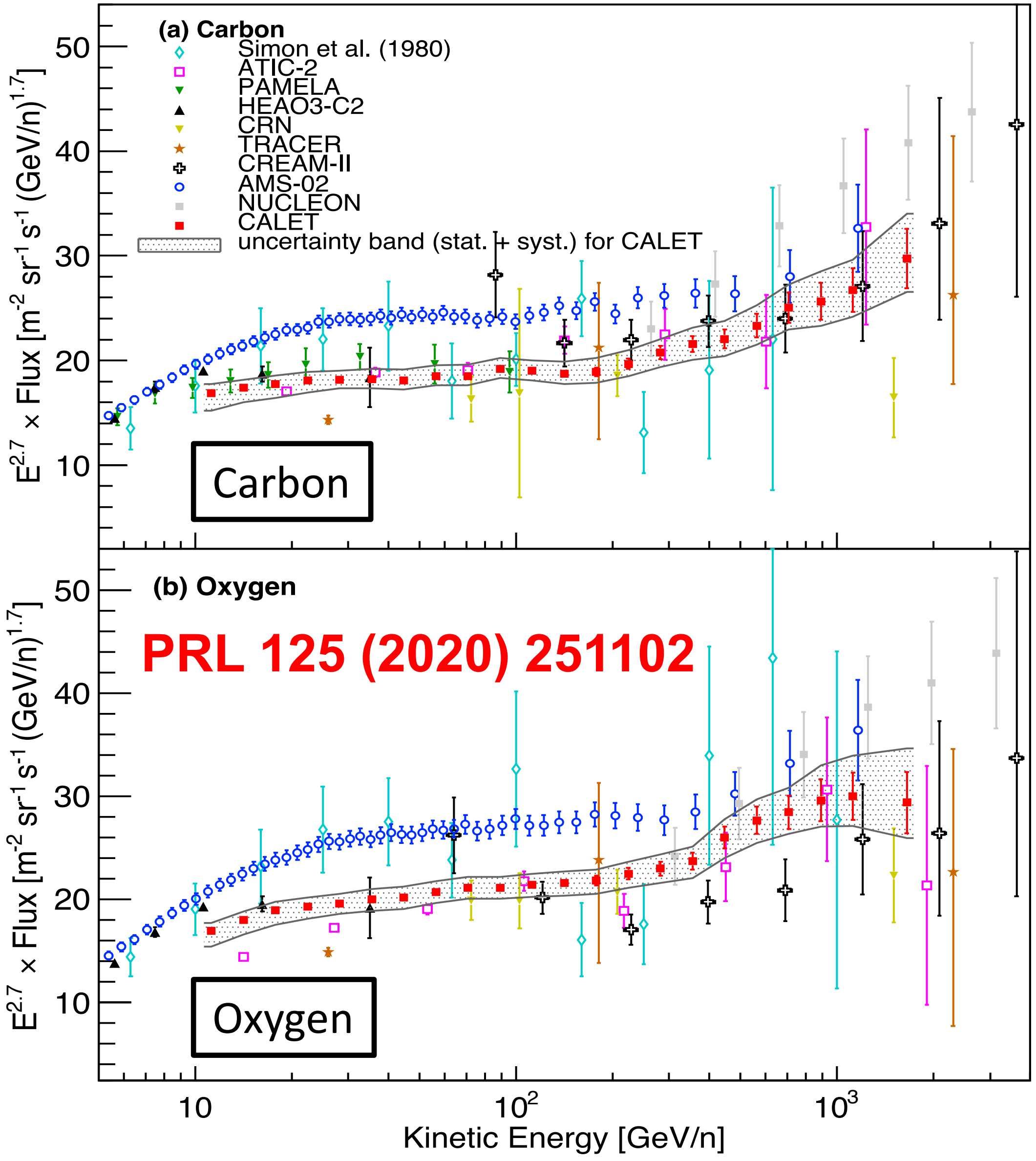






With excellent charge-ID of individual elements CALET is exploring the Table of Elements in the multi-TeV domain

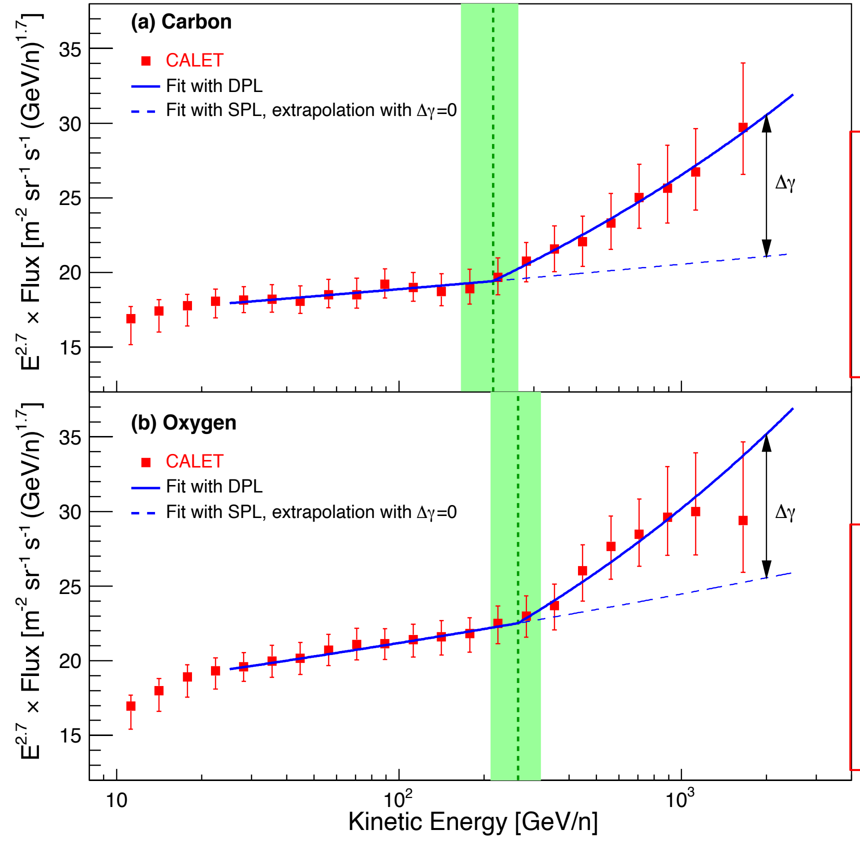
Carbon and oxygen spectra



CALET C is consistent with PAMELA and most of the previous experiments. PAMELA did not publish oxygen.

The spectra show a clear hardening around 200 GeV/n.

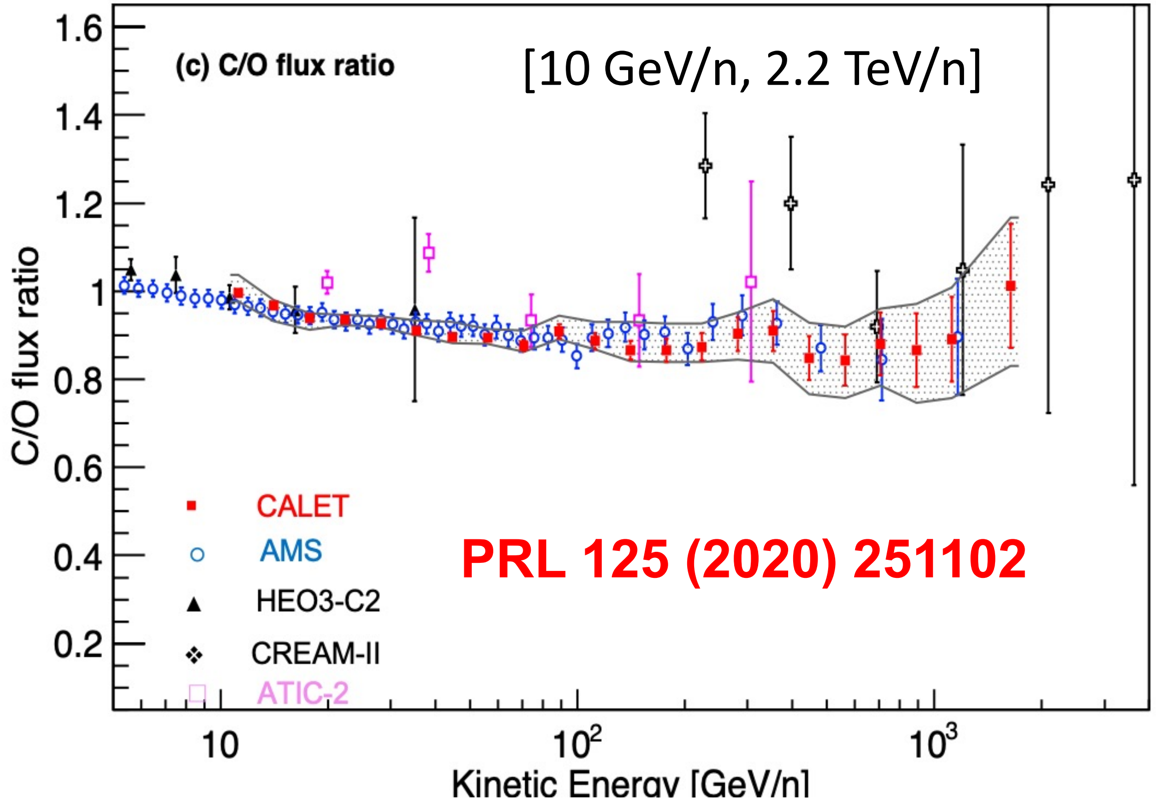
They have shapes similar to AMS-02 but the absolute normalization is significantly lower (~ 27%)

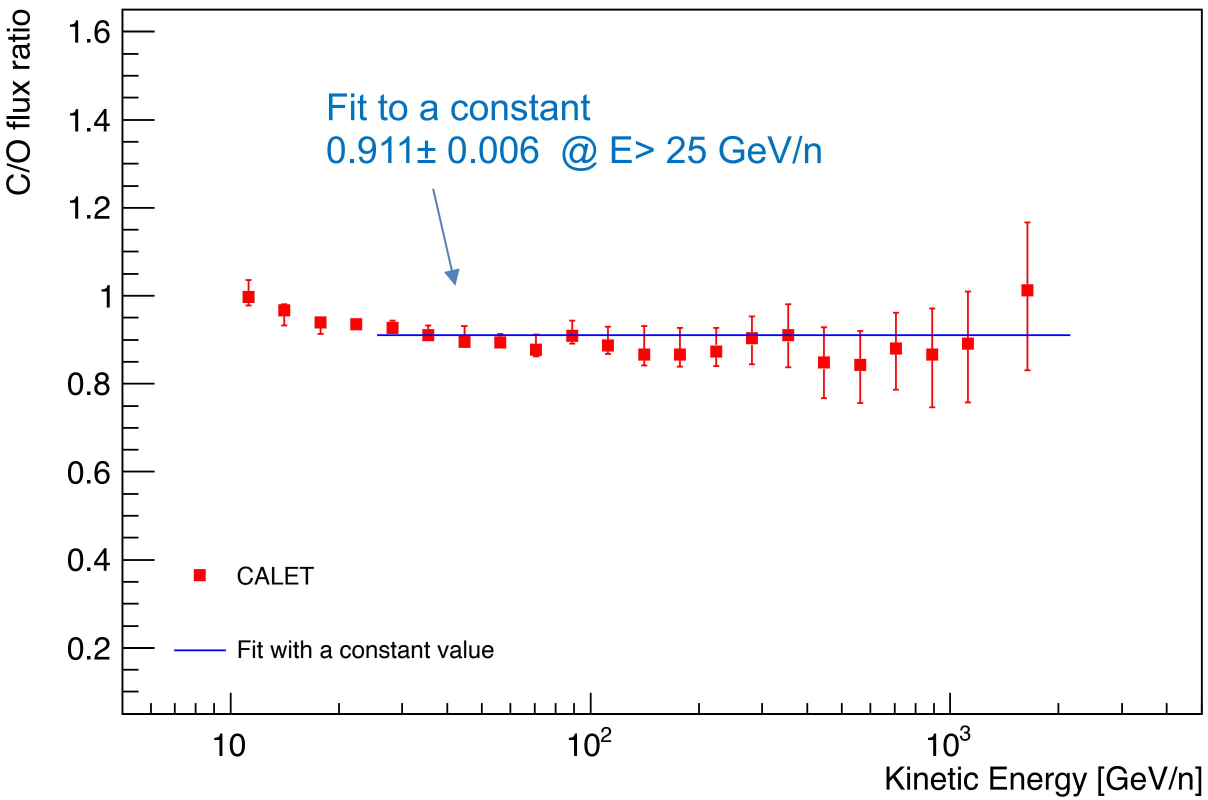


DPL fit: Carbon
$\gamma = -2.663 \pm 0.014$
$E_0 = (215 \pm 54)$ GeV/n
$\Delta\gamma = 0.166 \pm 0.042$
$\chi^2/dof = 9.0/8$

DPL fit: Oxygen
$\gamma = -2.637 \pm 0.009$
$E_0 = (264 \pm 53)$ GeV/n
$\Delta\gamma = 0.158 \pm 0.053$
$\chi^2/dof = 3.0/8$

C/O ratio





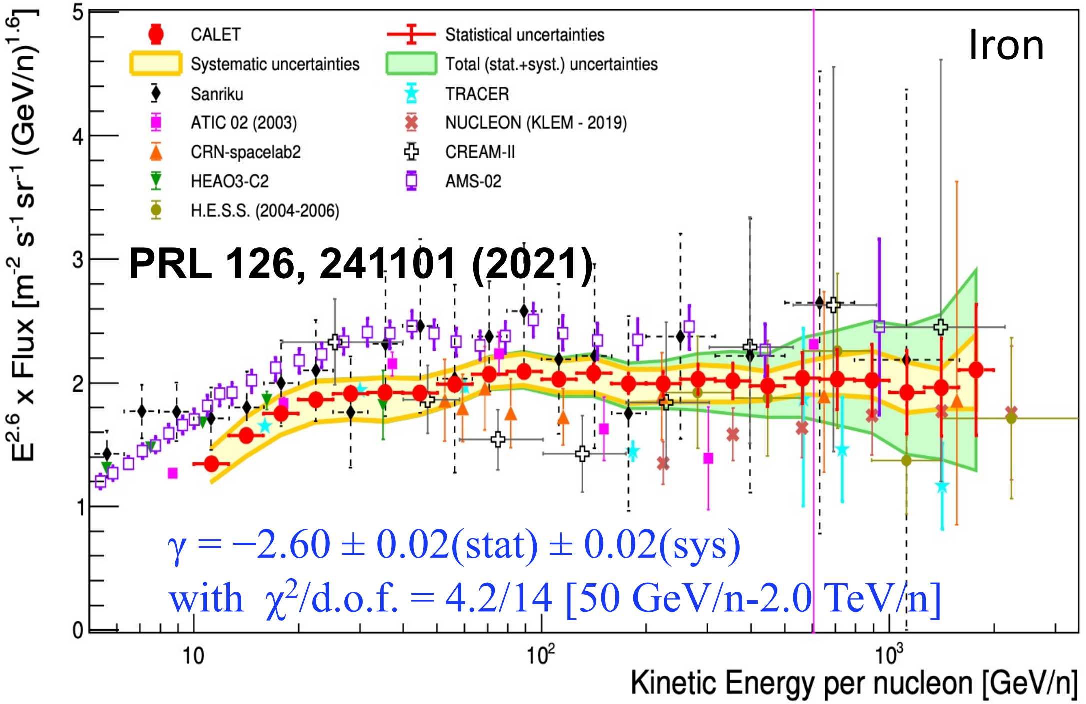
The C/O flux ratio as a function of energy is in good agreement with the one reported by AMS

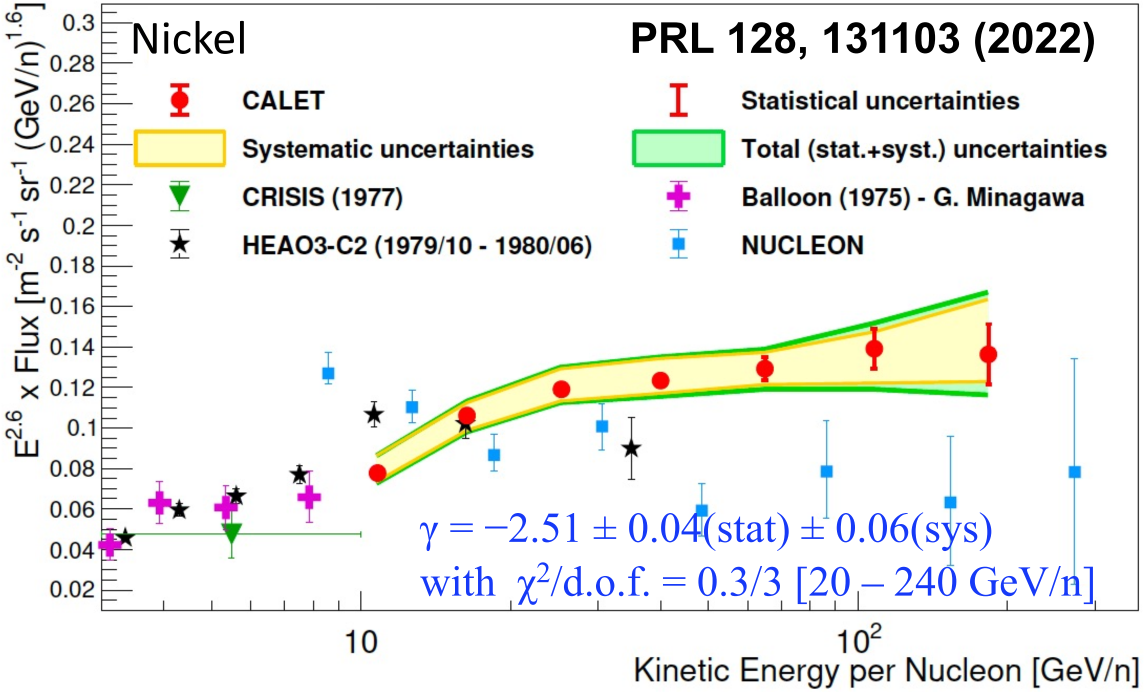
Above 25 GeV/n the C/O ratio is well fitted to a constant value of 0.911 ± 0.006 with χ^2/dof = 8.3/17

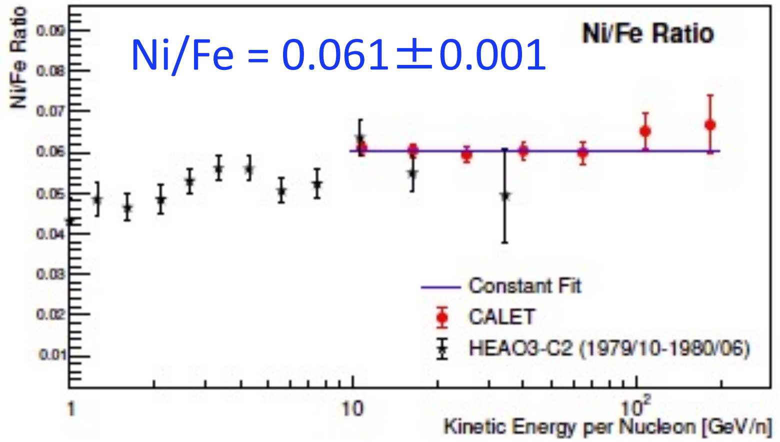
→ C and O fluxes have the same energy dependence.

Iron and Nickel Spectra

E1.3-0022-22 C. Checchia



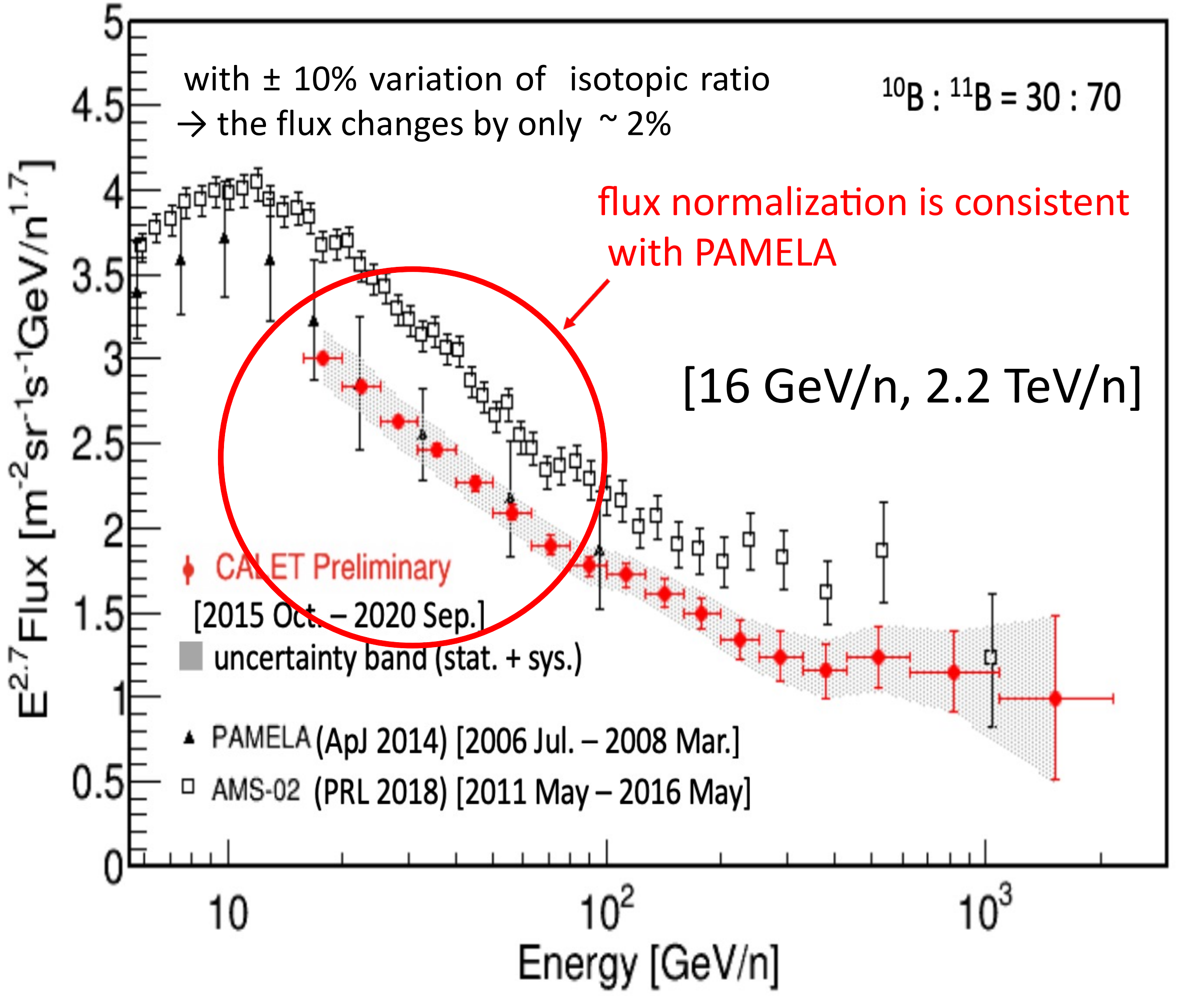




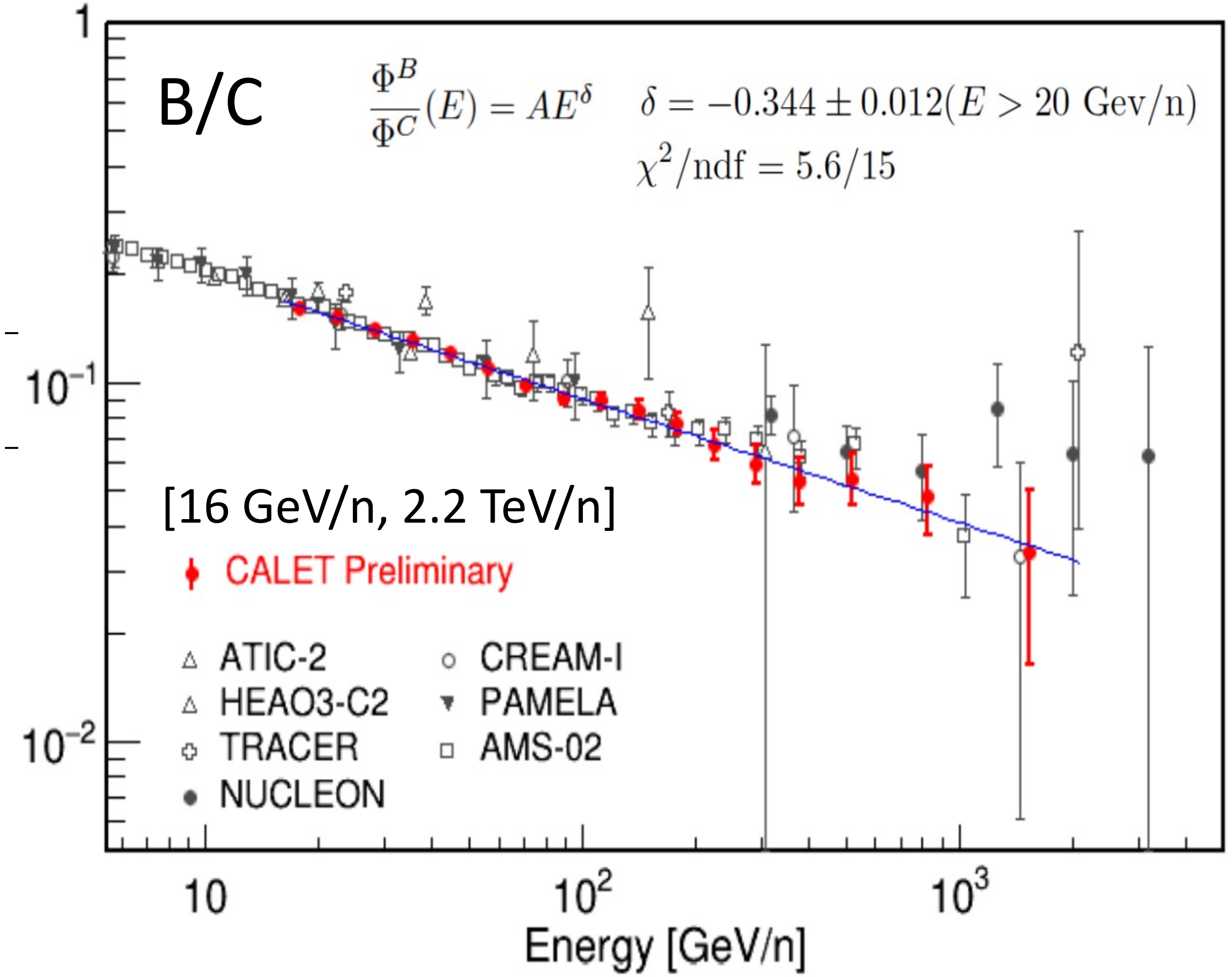
- Beyond this limit, the present statistics and large systematics do not allow to draw a significant conclusion on a possible deviation from a single power law.
- Above 10 GeV/n, the Ni/Fe ratio is well fitted to a constant value.

Boron spectrum and B/C ratio (preliminary)

Boron energy spectrum

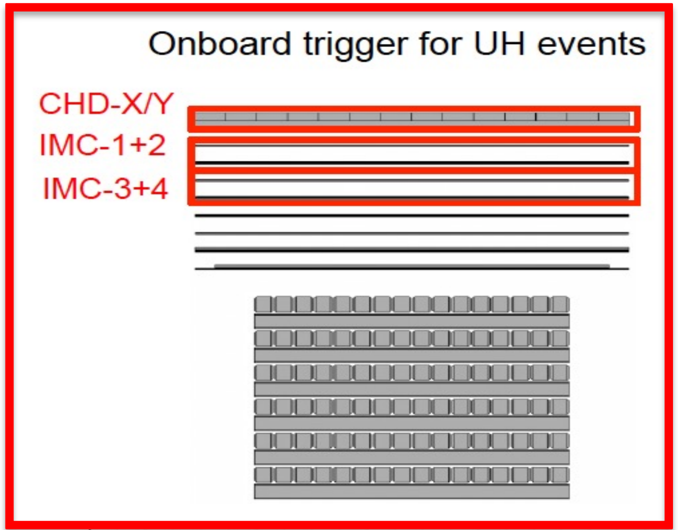


B/C ratio

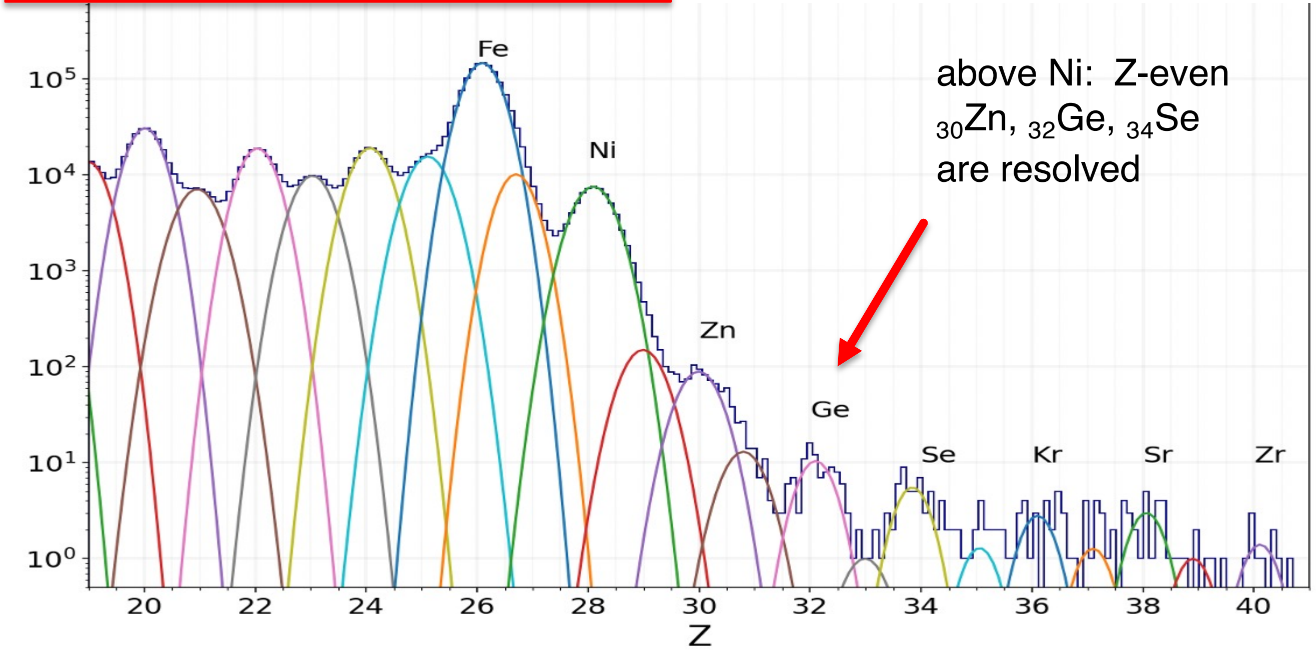


Ultra heavy nuclei (26 < Z ≦40)

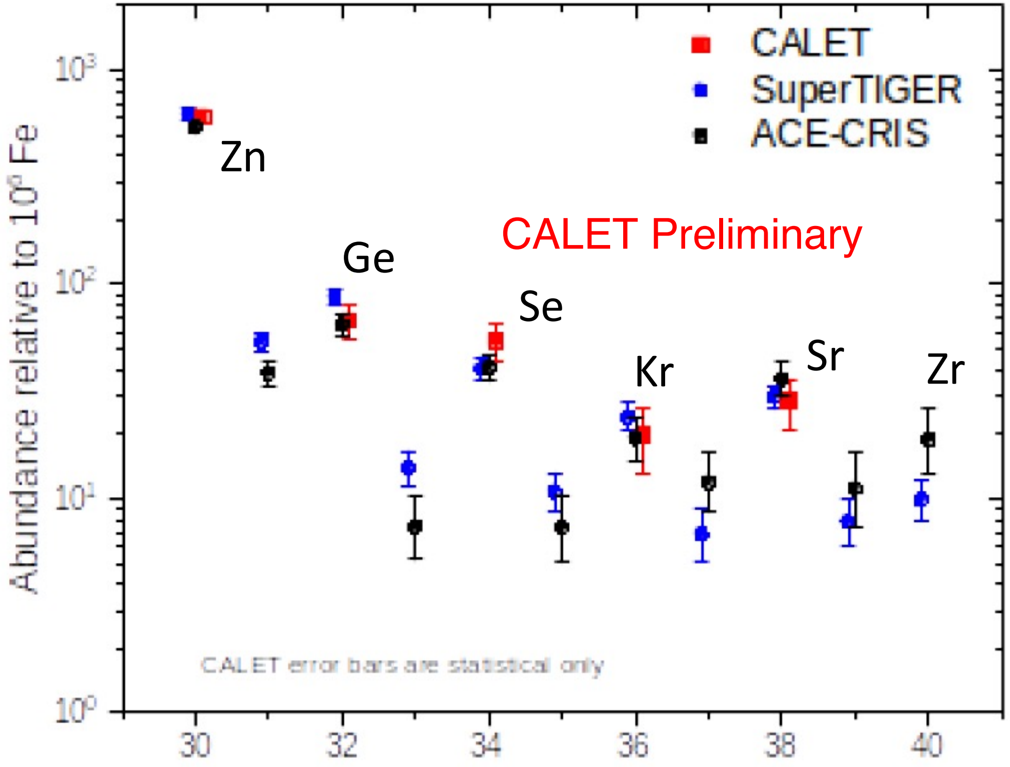
E1.3-0023-22 W. Zober



A special UH CR trigger uses the CHD and the first 4 layers of the IMC to achieve an expanded x 4 geometric factor
GF ~ 4400 cm² sr



Measurement of the relative abundances elements above Fe through $_{40}$Zr



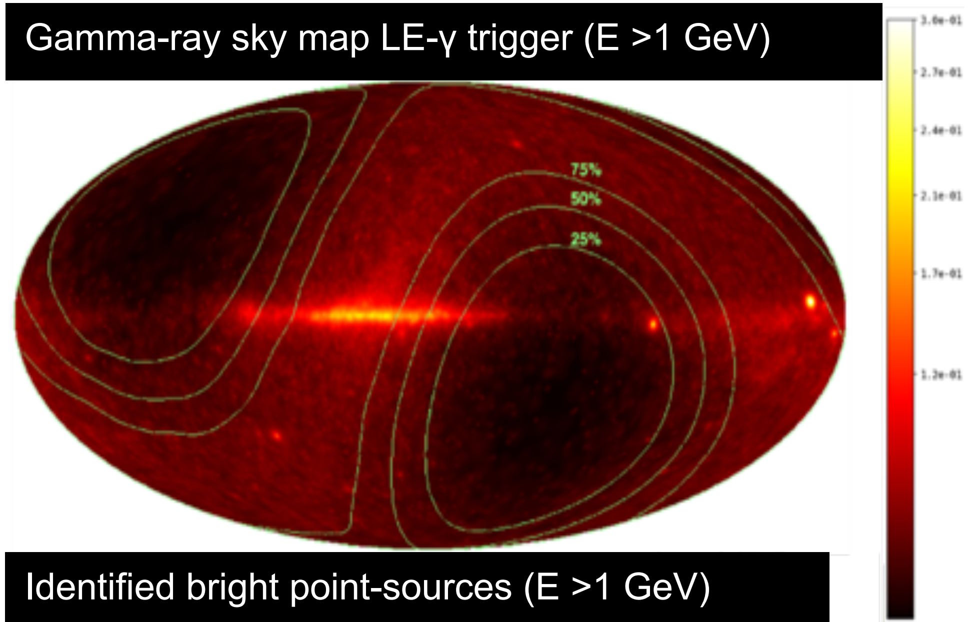
The CALET UH element ratios relative to Fe are consistent with Super-TIGER and ACE abundances.

CALET γ-ray sky, GRBs, GW follow-up, DM limits

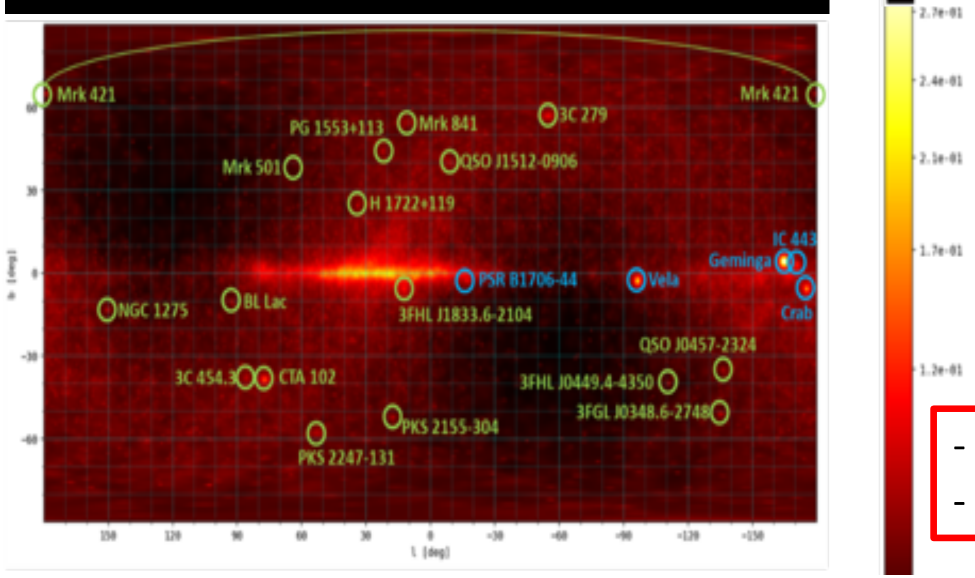
E1.16-0039-22 N. Cannady

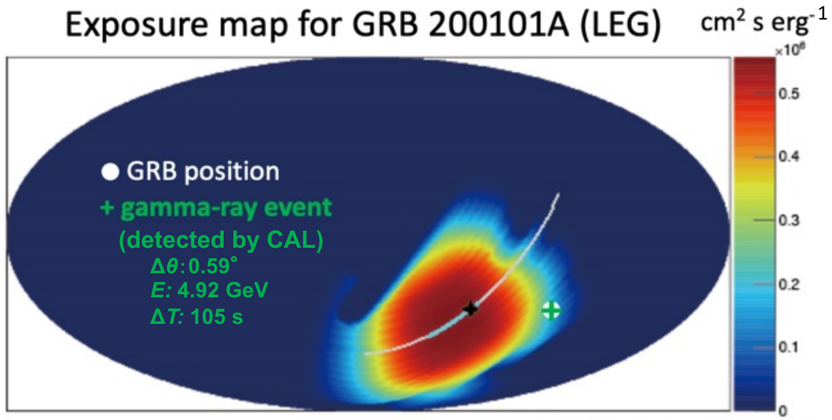
- Effective area: ~400 cm^2 above 2 GeV
- Angular resolution: < 0.2° above 10 GeV
- Energy resolution: ~5% at 10 GeV

Gamma-ray sky map LE-γ trigger (E >1 GeV)



Identified bright point-sources (E >1 GeV)





CGBM: dedicated Gammay-Ray Burst Monitor with energy range 7 keV-20 MeV

from 2015-10-05 to 2022-06-30

300 GRBs (44.5 GRBs / year)

266 Long (89%) **34 Short (11%)**

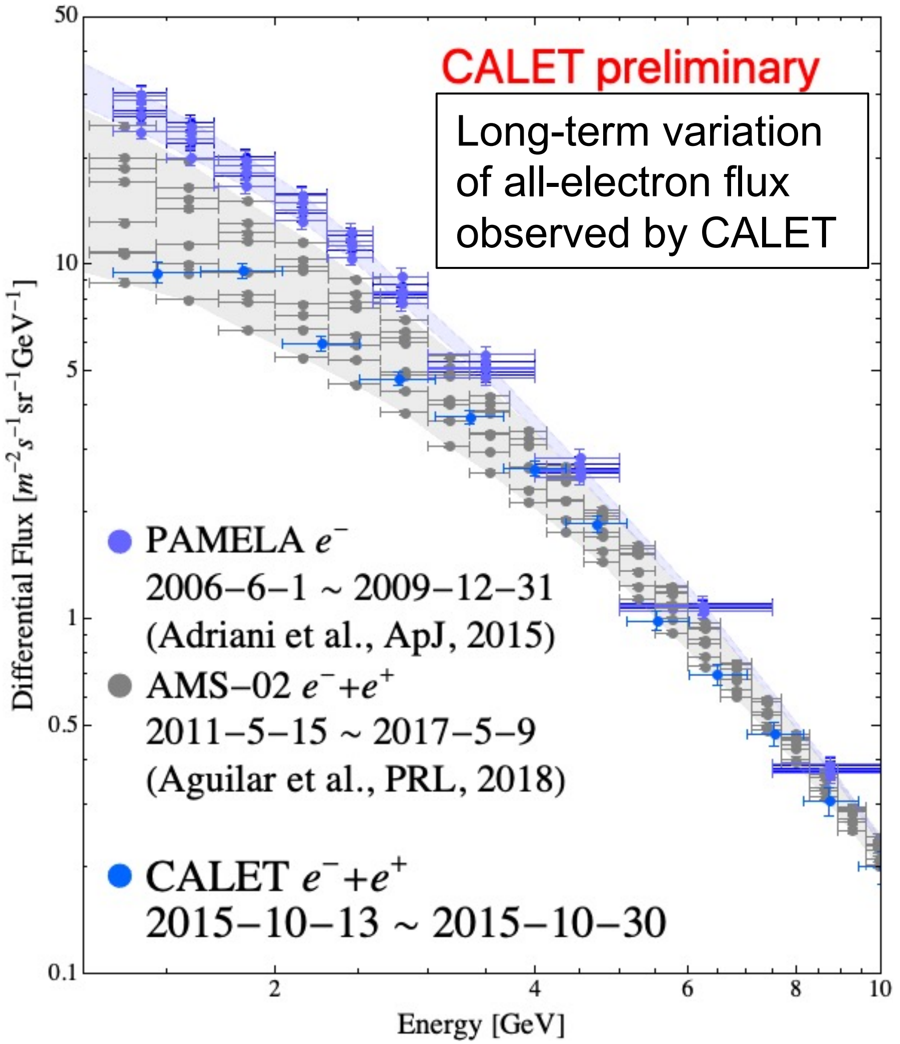
- **Follow-up** of LIGO/Virgo **GW** observations
  - X-ray and γ-ray bands
  - high-energy γ-in calorimeter

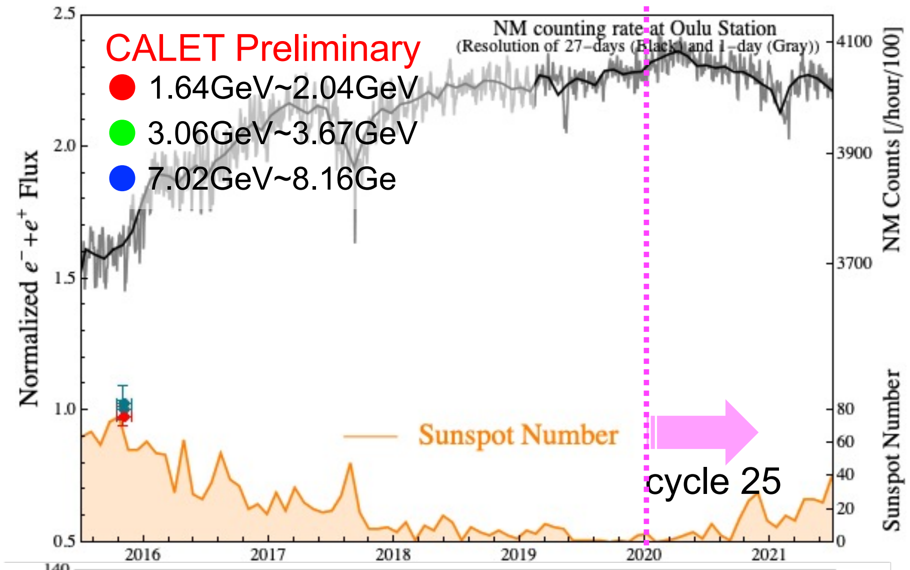
➡ ApJ 933 (2022)

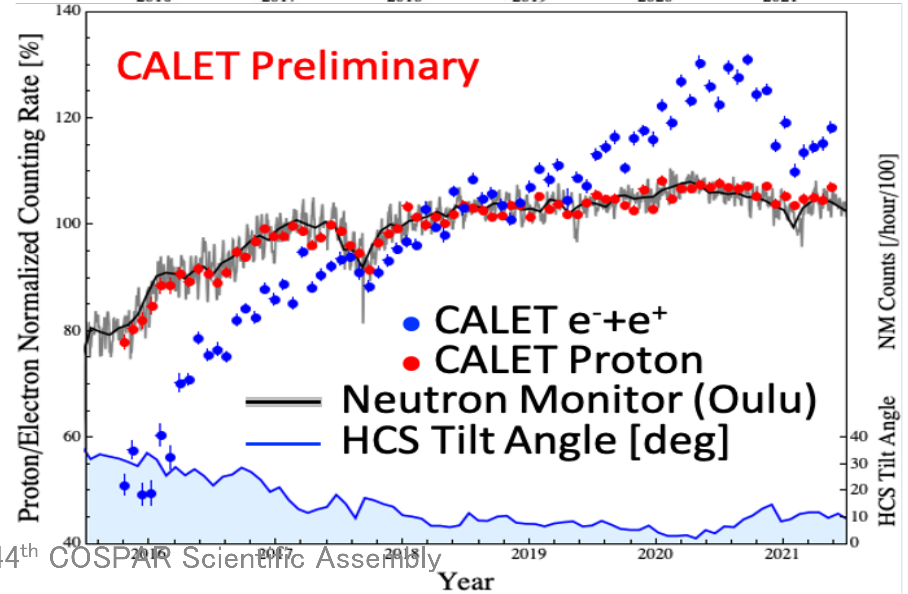
- **Limits on DM** annihilation into γγ: <σv> < 10^{-28}-$10^{-25}cm^{-3}s^{-1}$
- Limits on DM decay χ → γν etc.: $\tau_{DM} > 10^{30}$s (m_{DM}>100 GeV)

Solar modulation

- **Since the start of observations in 2015/10, a steady increase in the 1-10 GeV all-electron flux has been observed.**
- **In the past two years, the flux has reached the maximum flux observed with PAMELA during the previous solar minimum.**





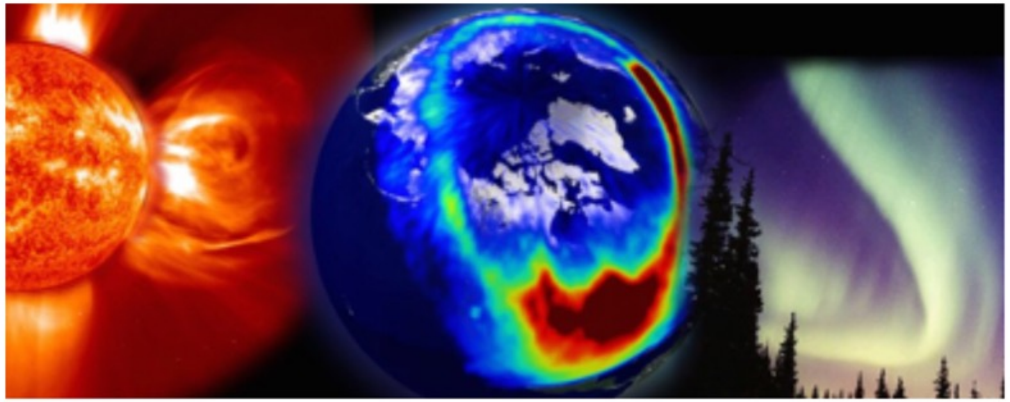


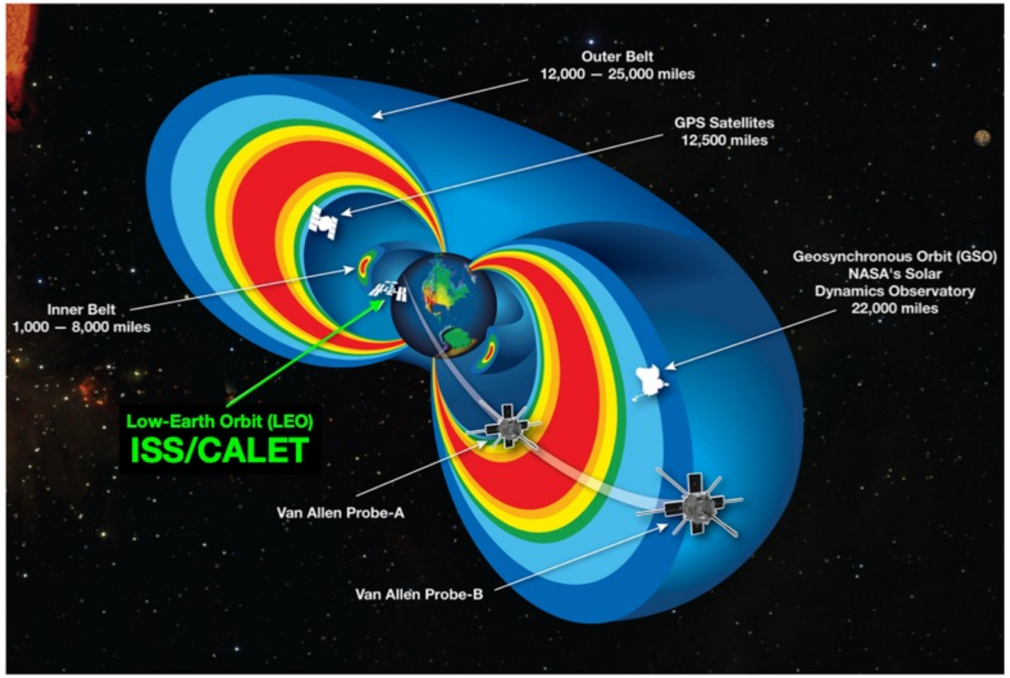
- The CR e^- + e^+ flux increases in the 1-10 GeV until ~half a year after the beginning of the new solar cycle 25. The flux has now started decreasing.

- Good correlation of the CR proton counting rate (red points) with the NM counting rate at Oulu station (black solid curve).

- The increase of CR e^- + e^+ count rate is found to be larger than that of CR protons being consistent with the expected CHARGE SIGN dependence of the solar modulation.

Space weather phenomena

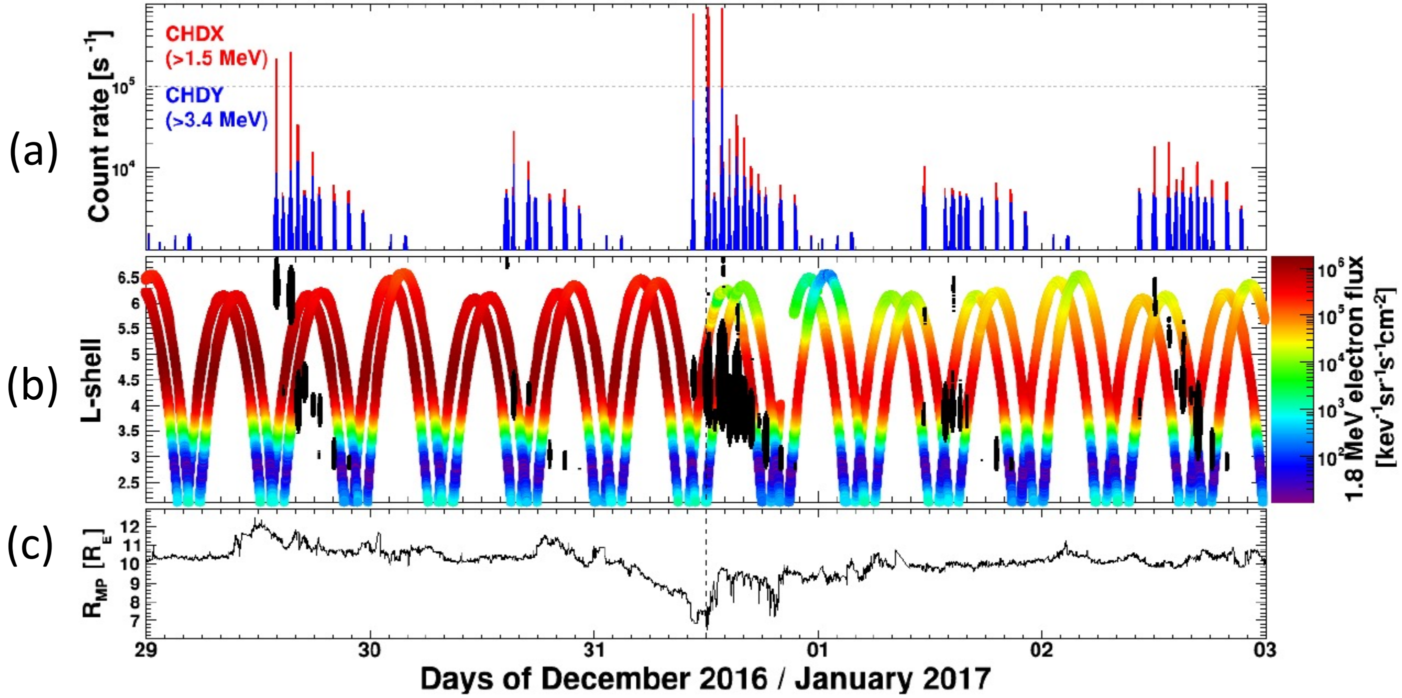




EMIC-Wave Driven Electron Precipitation observed by CALET on the International Space Station

(*Geophysical Research Letters, first published: March 07,2022*)

Observations by CALET and Van Allen Probes



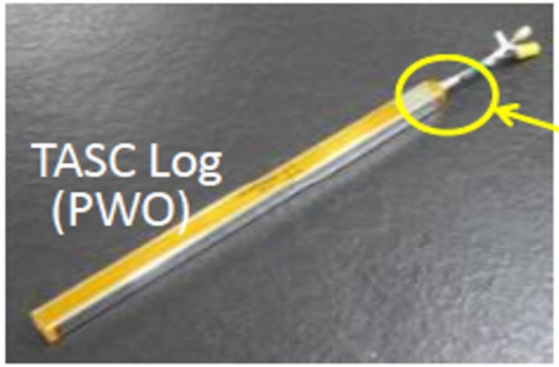
Time profile of electron, interplanetary and geomagnetic data between 29 December 2016 and 3 January 2017. From top to bottom: CHDX and CHDY count rates (a); 1.8 MeV electron intensity (color code) measured by the REPT instrument (b); the magnetopause standoff distance (c). The dashed vertical line marks the arrival of a HSS at ~12UT on December 31.

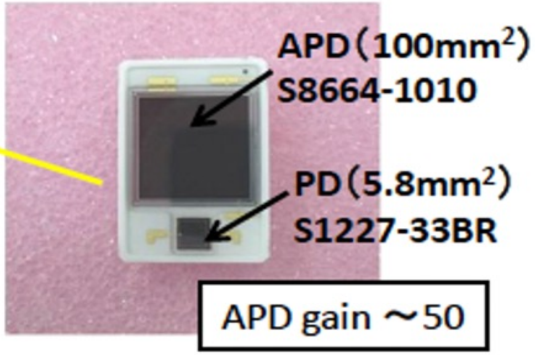
CALET: Summary and Future Prospects

- CALET was successfully launched on Aug. 19th, 2015. The observation campaign started on Oct. 13th, 2015. Excellent performance and remarkable stability of the instrument were confirmed.
- As of May. 31, 2022, total observation time is 2,423 days (> 6.5 years) with live time fraction close to 86%. Nearly 3.44 billion events collected with low (> 1 GeV) & high (> 10 GeV) energy triggers.
- Accurate calibrations have been performed with non-interacting p & He events + linearity in the energy measurements established in 1 GeV-1PeV.
- The following results have been obtained now.
  - All-electron (electron + positron) spectrum in 11 GeV - 4.8 TeV.
  - Proton and Helium spectra in 50 GeV – 60 or 50 TeV, and Carbon and Oxygen spectra in 10 GeV/n – 2.2 TeV/n: Spectral hardening observed at a few hundred GeV/n.
  - Heavy primary cosmic-ray elements up to Iron and Nickel are successfully observed: The present data are compatible within the errors with a single power law.
  - Continuous observations of gamma-ray bursts, solar modulation and REP events are successfully caried out.
- CALET observation has been carried out over 6 years and is approved to be extended for 4 years more until the end of 2024 at the JAXA review held on March 12, 2021.

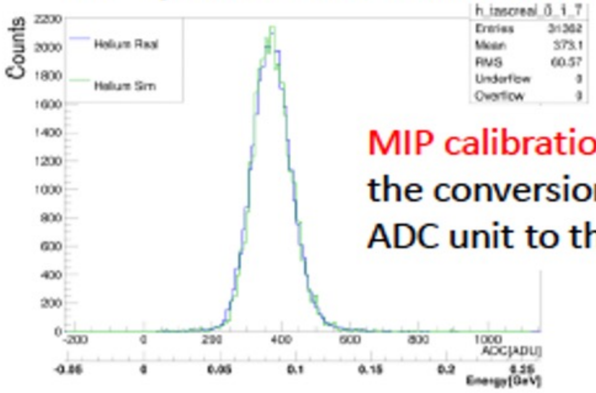
END

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

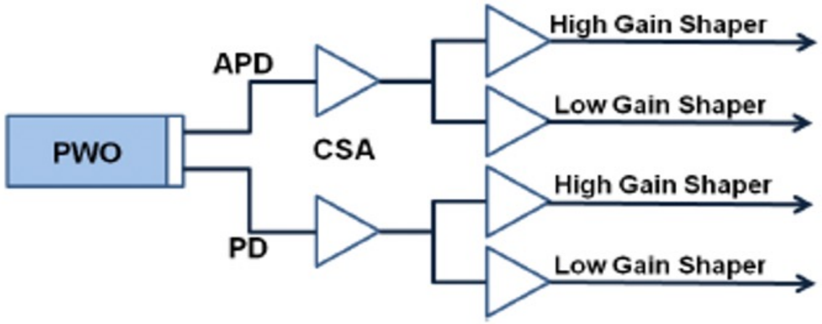




"MIP" peak in PWO: Obs. vs. MC



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

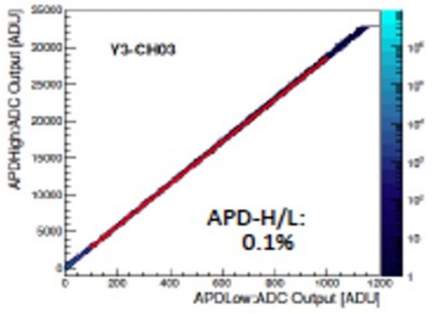


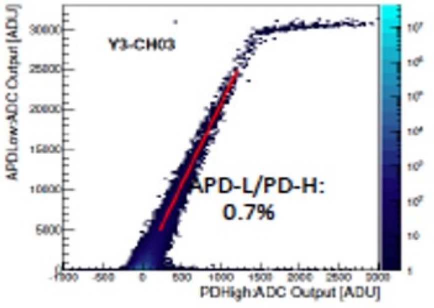
The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

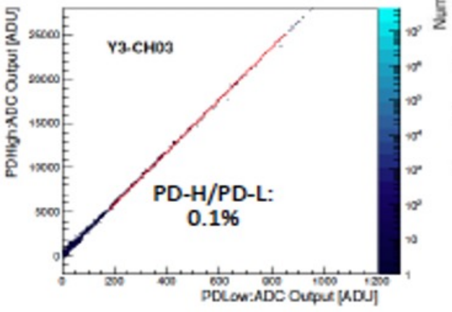
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

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

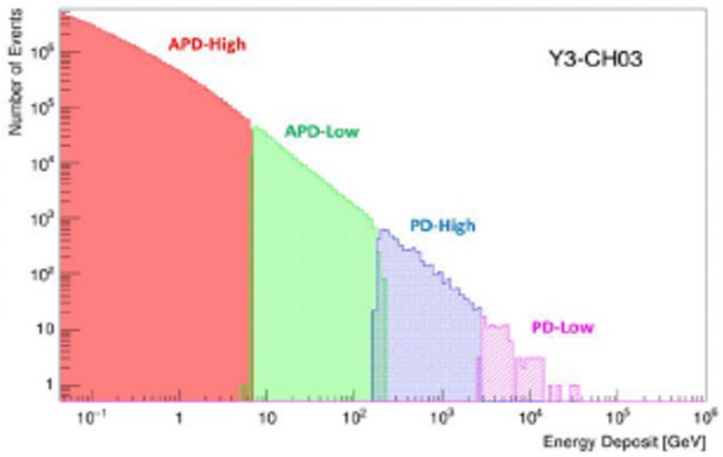
APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%



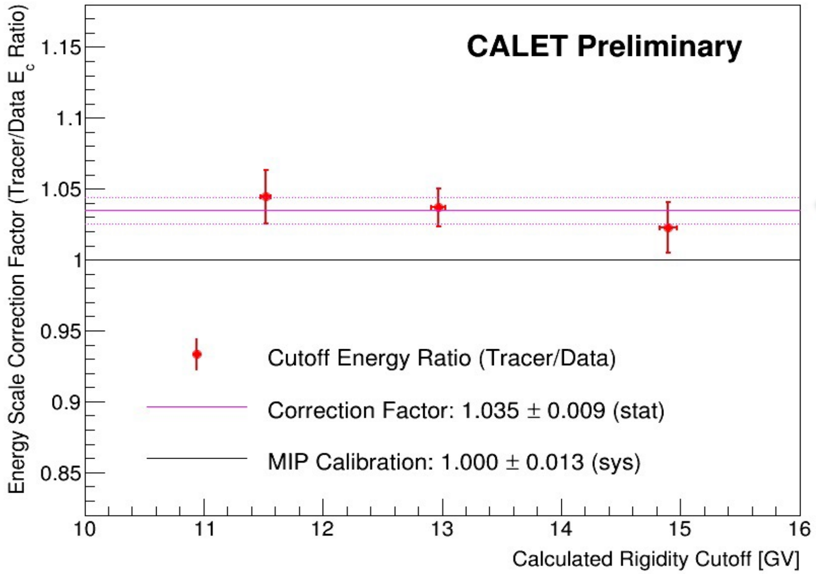




Example of energy distribution in one PWO log



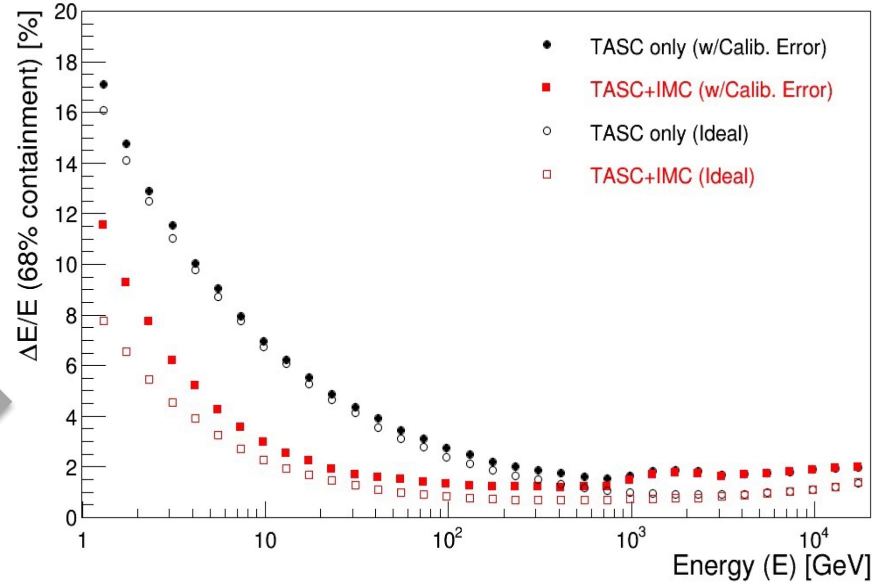
Energy Measurement: energy scale and resolution

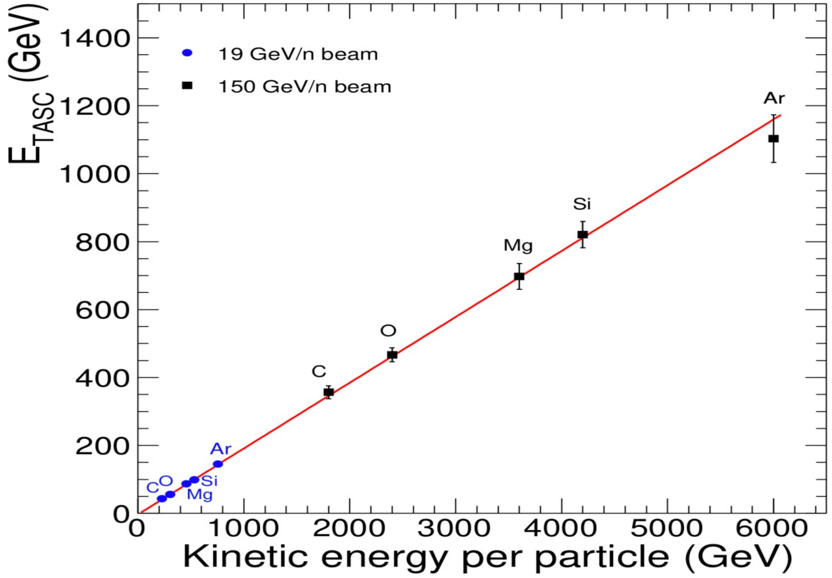


ELECTRONS

Absolute energy scale calibration for electrons using rigidity cutoff

Simulated energy dependence of electron energy resolution:
< 2% above 20 GeV
Using both TASC and IMC
Including the calibration errors



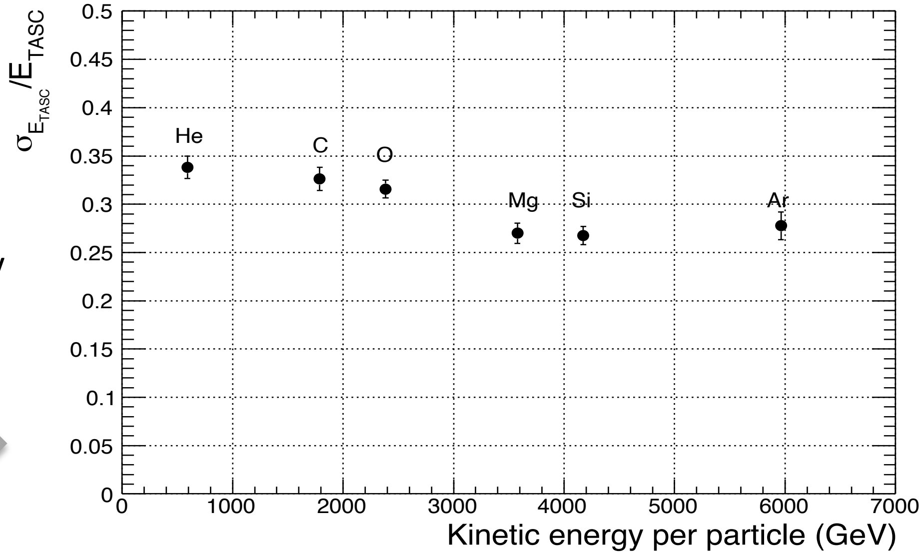


HADRONS

Beam calibration at CERN-SPS with Ion fragments at 13, 19 150 GeV/n

Linearity assessed up to ~6 TeV
With primary beam of 40Ar
at 150 GeV/n

Energy resolution ~30%



Electron identification

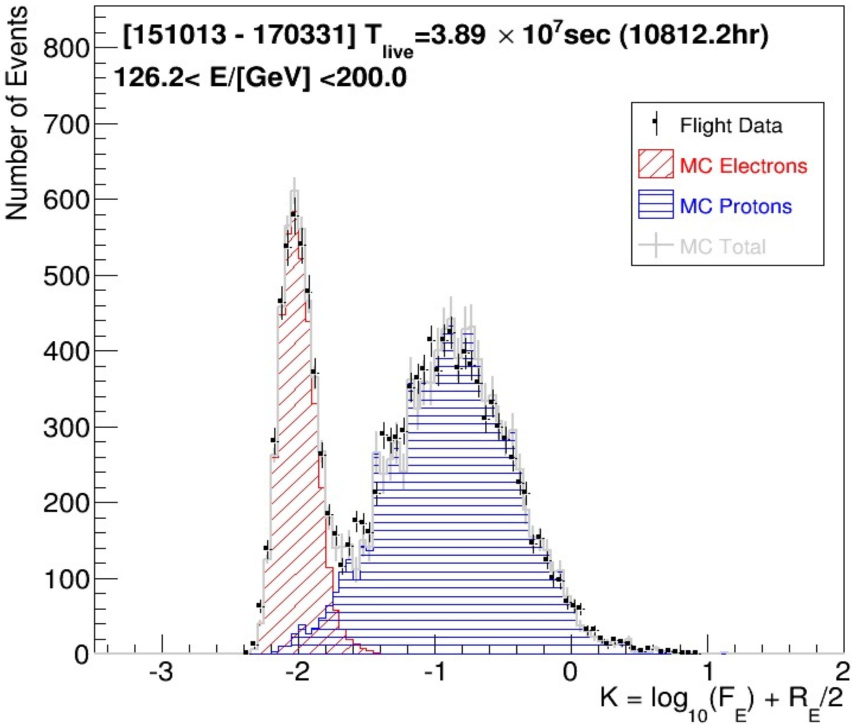
Simple Two Parameter Cut

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

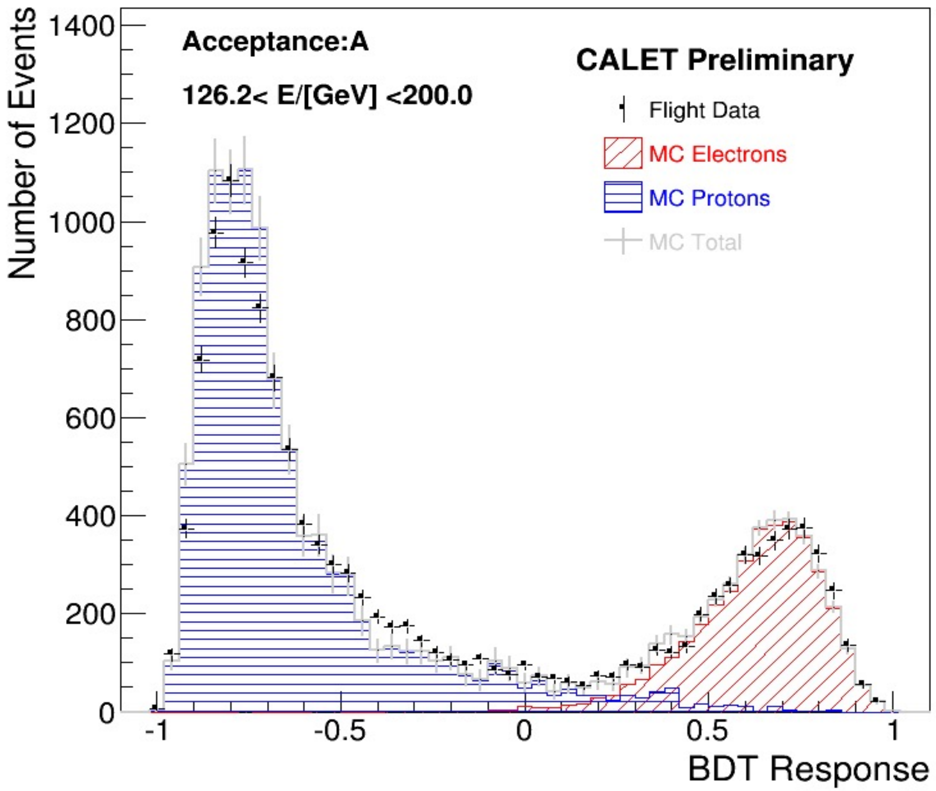
Cut Parameter K is defined as follows:

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



Boosted Decision Trees (BDT)

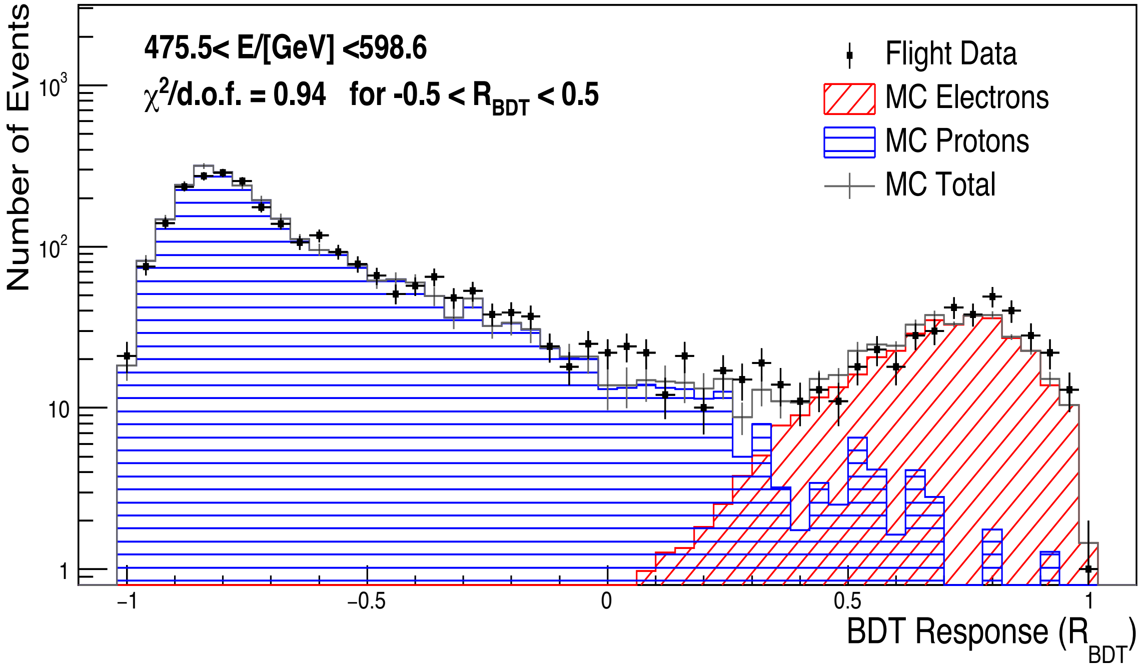
In addition to the two parameters in the left, TASC and IMC shower profile fits are used as discriminating variables.



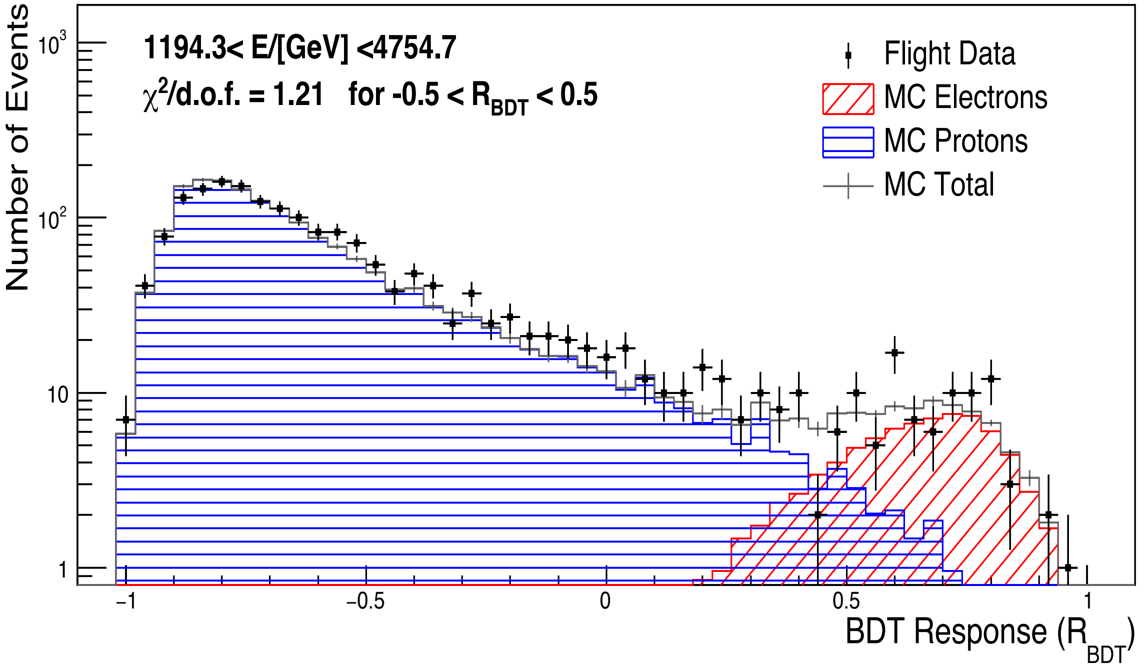
BDT response distribution at higher energies

In the final electron sample, the resultant contamination ratios of protons are:
< 5 % up to 1 TeV ; 5 % - 20 % in the 1 – 5 TeV region
, while keeping a constant high efficiency of 80 % for electrons.

476 < E < 599 GeV



1196 < E < 4755 GeV (highest energy bin)



Charge Identification with CHD and IMC