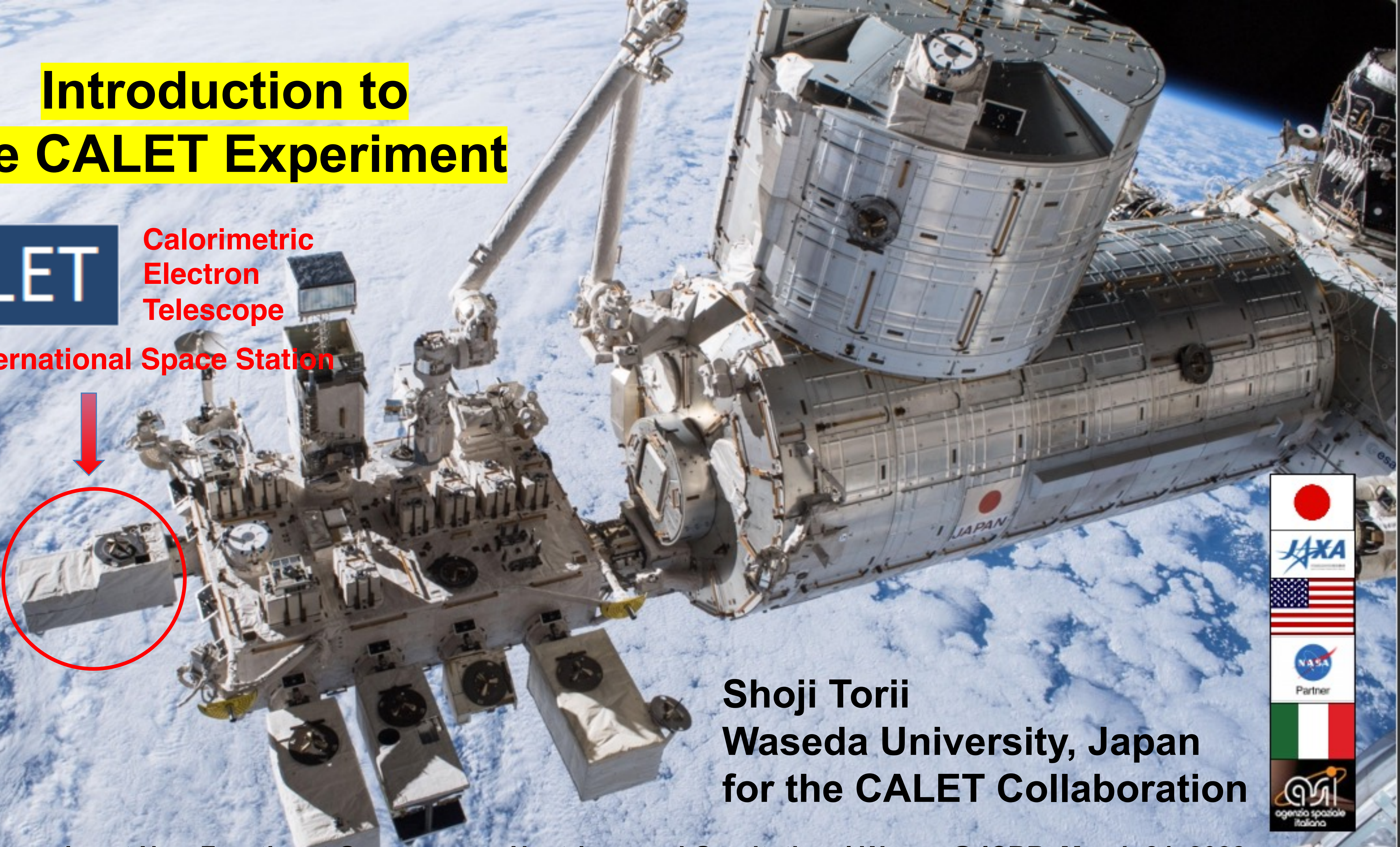
Introduction to the CALET Experiment

CALET

Calorimetric Electron Telescope

on the International Space Station



Shoji Torii
Waseda University, Japan
for the CALET Collaboration

Synergies at New Frontier at Gamma-rays, Neutrinos and Gravitational Waves @ ICRR March 24, 2022

CALET Collaboration Team

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31) Ritsumeikan University, Japan
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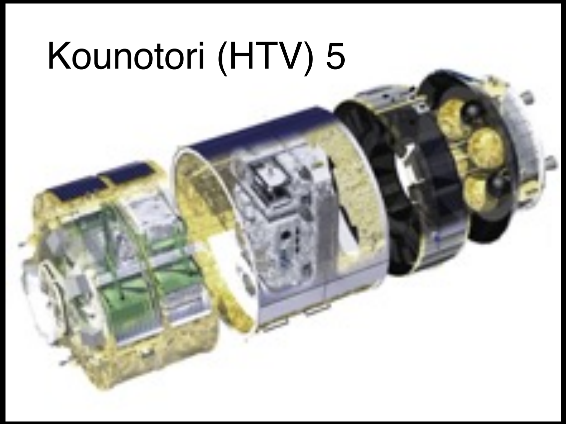
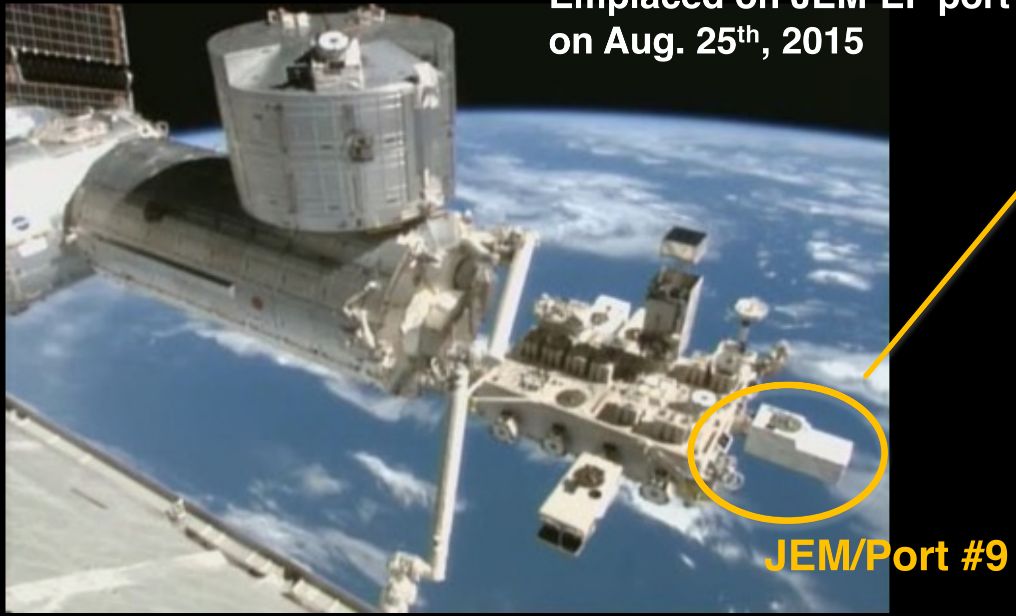
34) NICT, Japan
35) Aoyama Gakuin University, Japan
36) Nihon University, Japan
37) Osaka City University, Japan
38) QST, Japan
39) Nagoya University, Japan
40) Ibaraki University, Japan

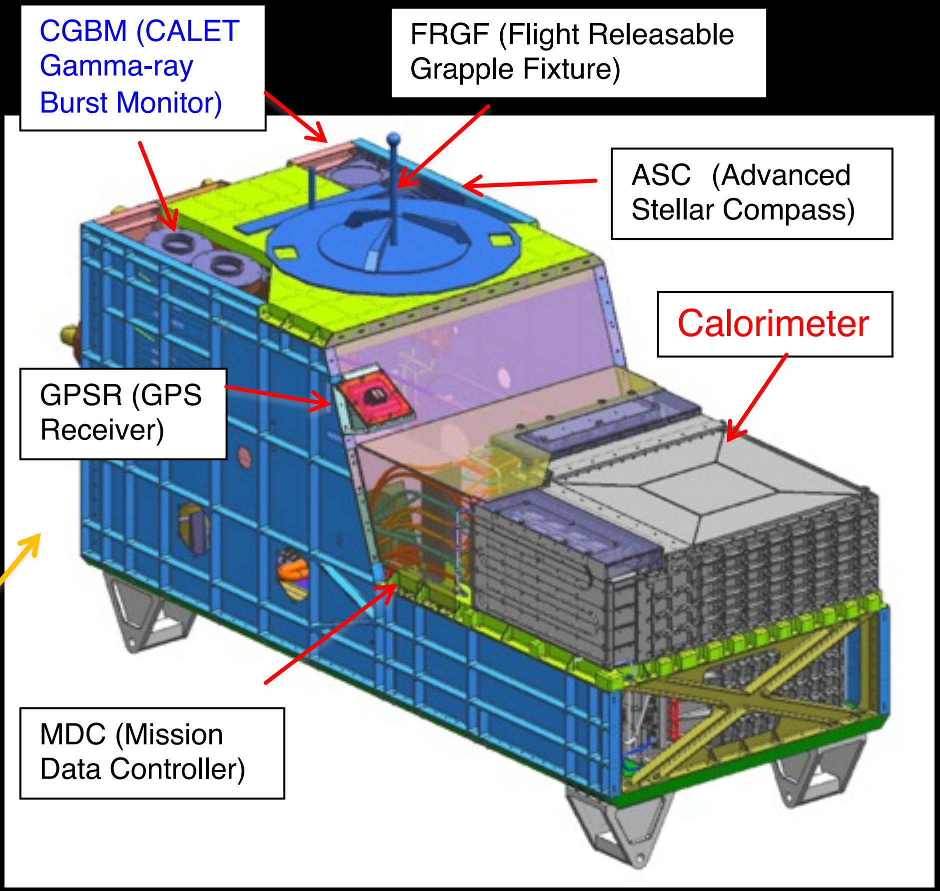
CALET Payload



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

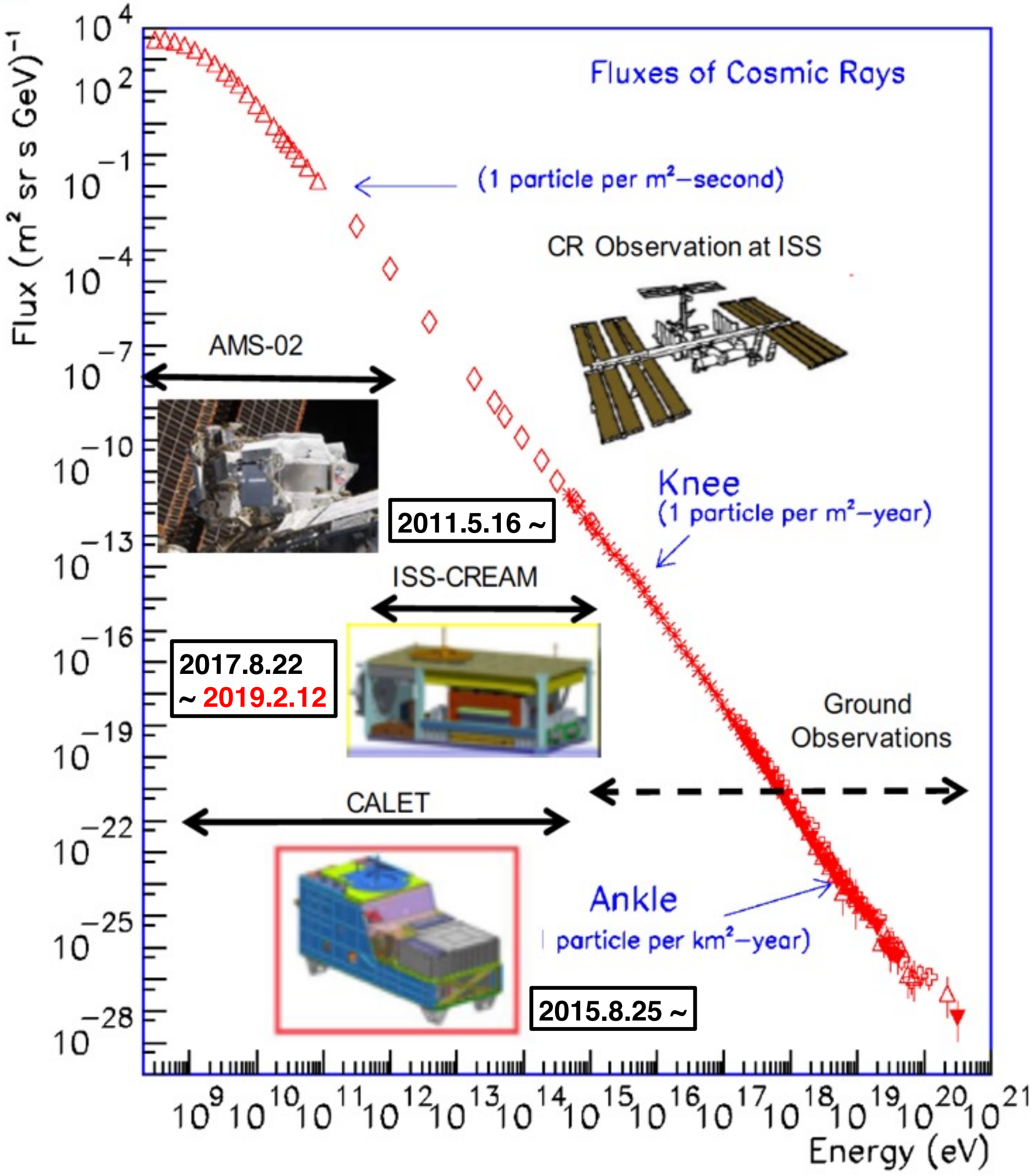
Emplaced on JEM-EF port #9 on Aug. 25th, 2015





- **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

Cosmic Ray Observations with CALET on the ISS



Overview of CALET Observations

- Direct cosmic ray observations in space at highest energy region
- Cosmic ray observation at world-record level using a large-scale detector at the ISS over a long-term more than 5 years.
- Electron observation in 1 GeV - 20 TeV is achieved with high energy resolution due to optimization for electron detection

⇨ Search for Dark Matter and Nearby Sources

- Observation of cosmic-ray nuclei will be performed in energy region from 10 GeV to 1 PeV

⇨ Unravelling the CR acceleration and propagation mechanism

- Detection of transient phenomena in space by stable observations

⇨ Gamma-ray burst, Solar flare, EM radiation from GW sources etc.

CALET Instruments

CAL

- Charge Detector (CHD)
- Imaging Calorimeter (IMC)
- Total Absorption Calorimeter (TASC)

CGBM

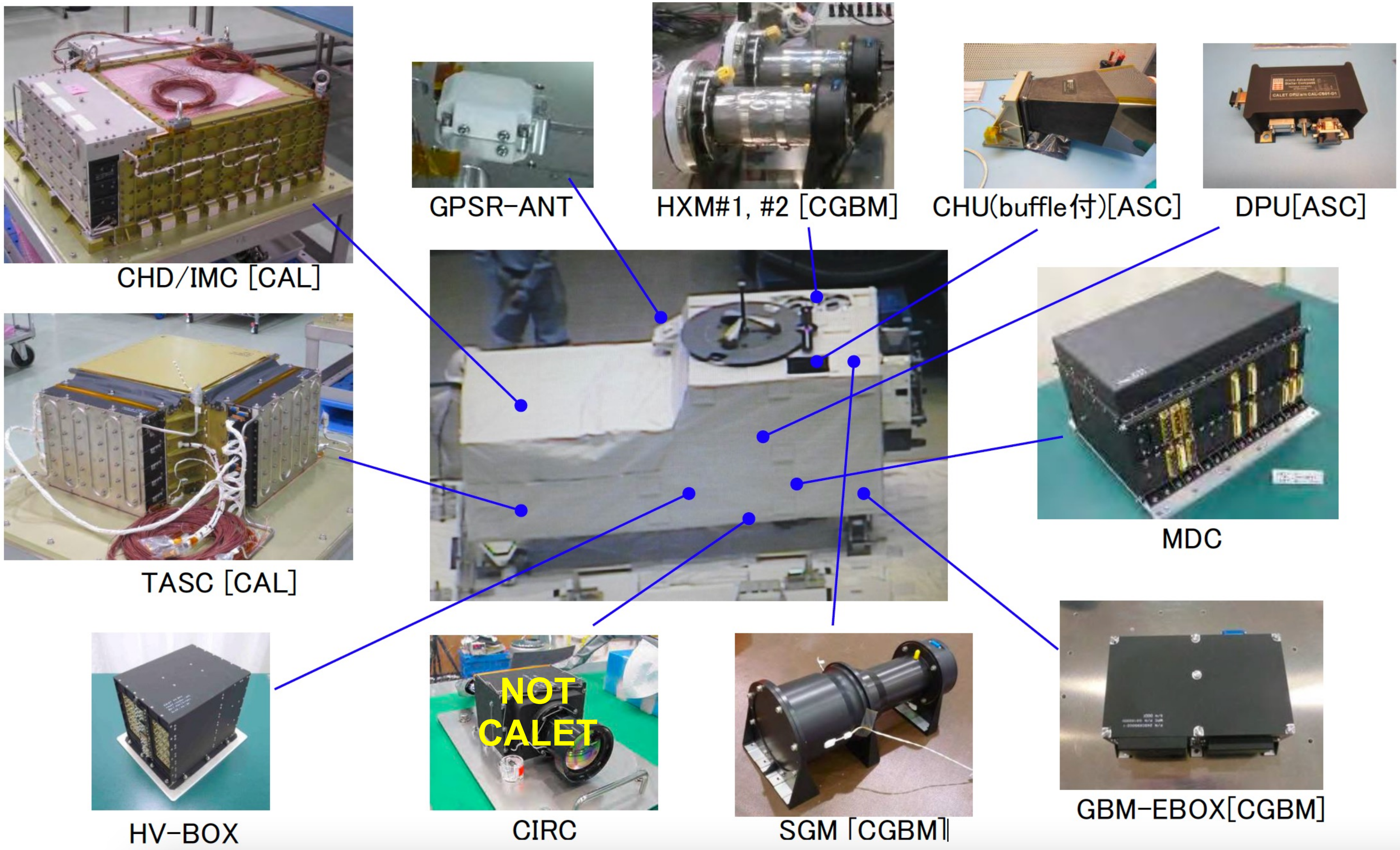
- Hard X-ray Monitor (HXM) x 2
  $LaBr_3$: 7keV～1MeV
- Soft γ-ray Monitor (SGM)
  BGO : 100keV～20MeV

Data Processing & Power Supply

- Mission Data Controller (MDC)
  CPU, telemetry, power, trigger etc.
- HV-BOX (Italian contribution)
  HV supply（PMT:68ch, APD:22ch）

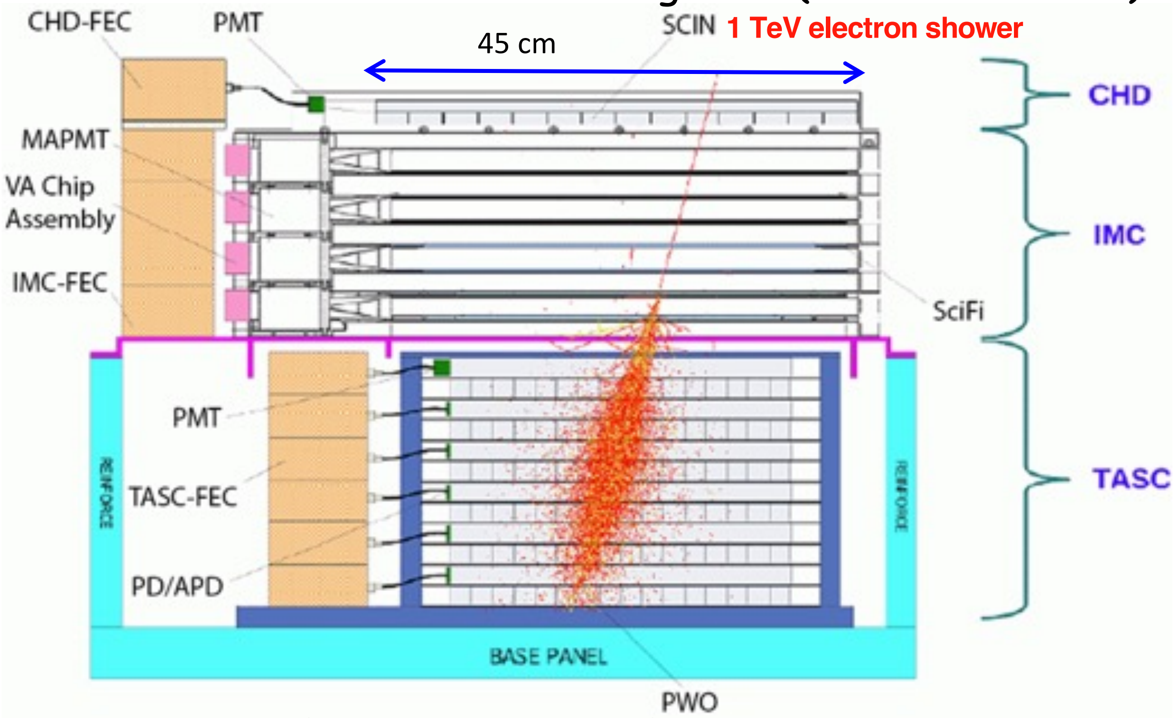
Support Sensors

- Advanced Stellar Compass (ASC)
  Directional measurement
- GPS Receiver (GPSR)
  Time stamp of triggered event (<1ms)



CALET Calorimeter and Capability

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



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

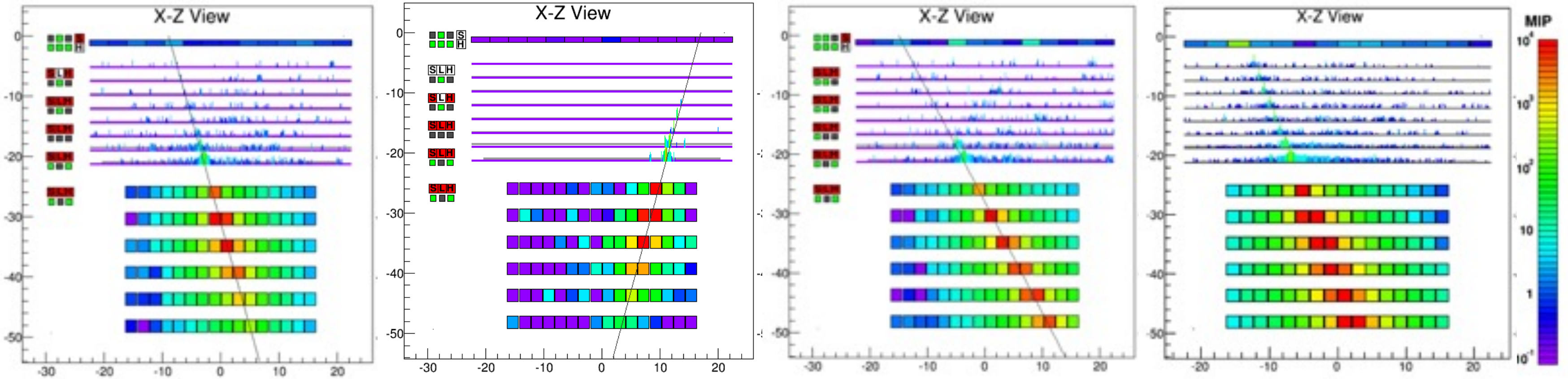
IMC – Imaging Calorimeter

- 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**

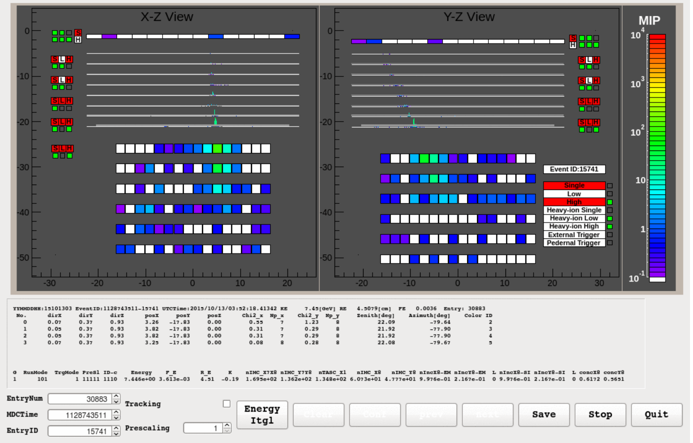
TASC – Total Absorption Calorimeter 27 X_0, 1.2 λ_I

- 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

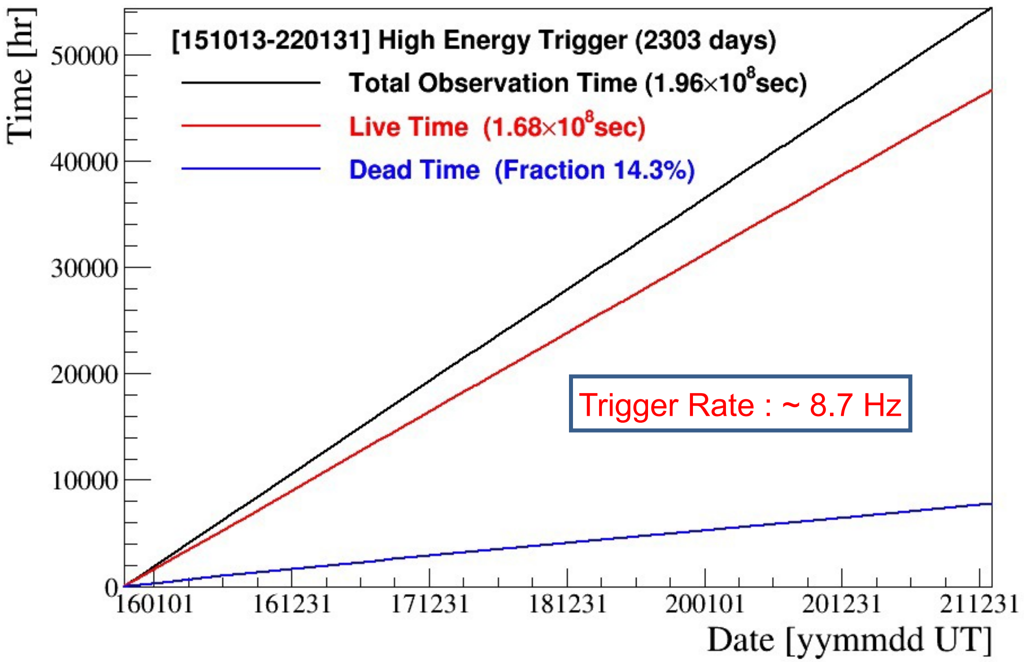


Event Display: Electron Candidate (>100 GeV)

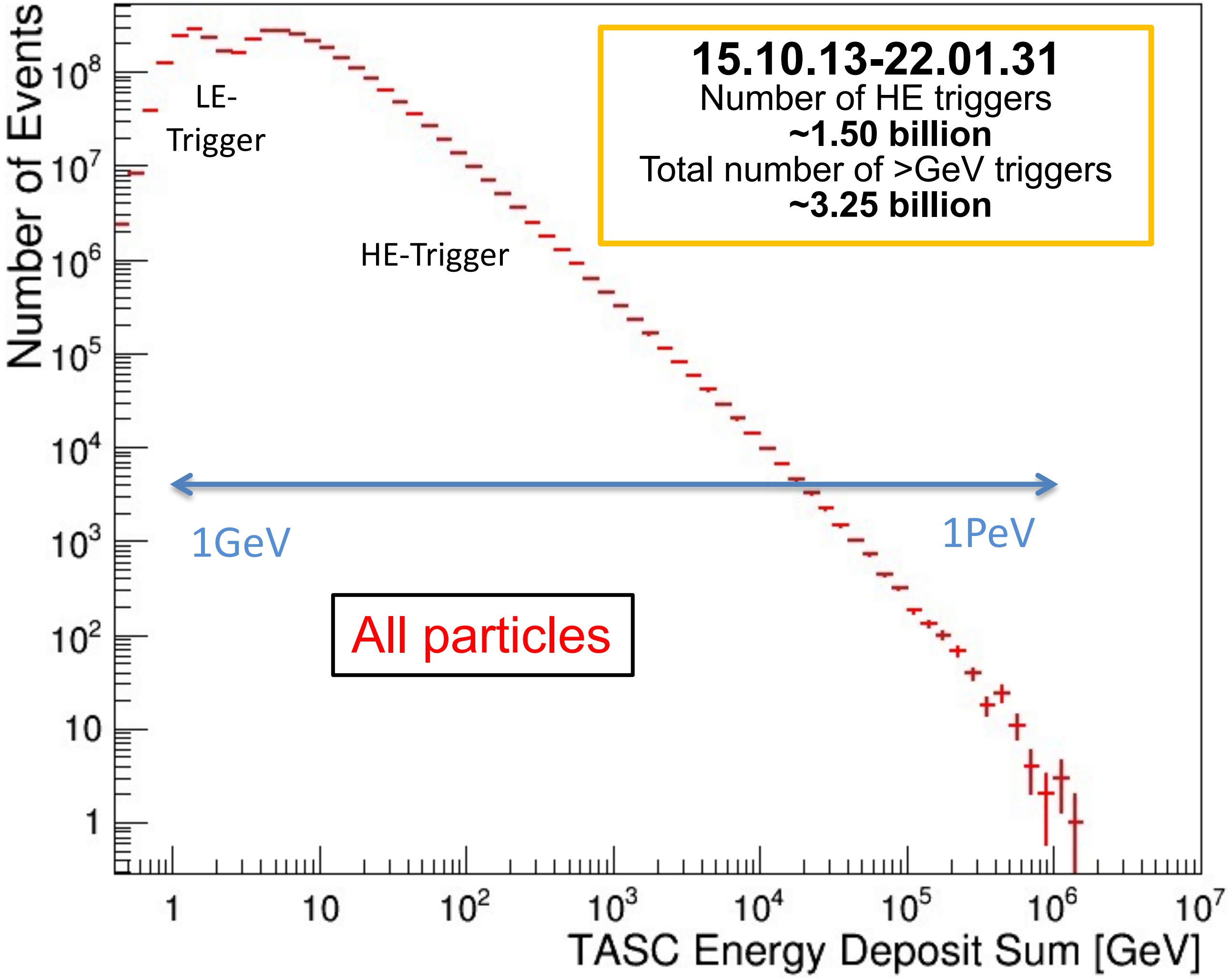


CALET Observations on the ISS

Accumulated observation time (live, dead)



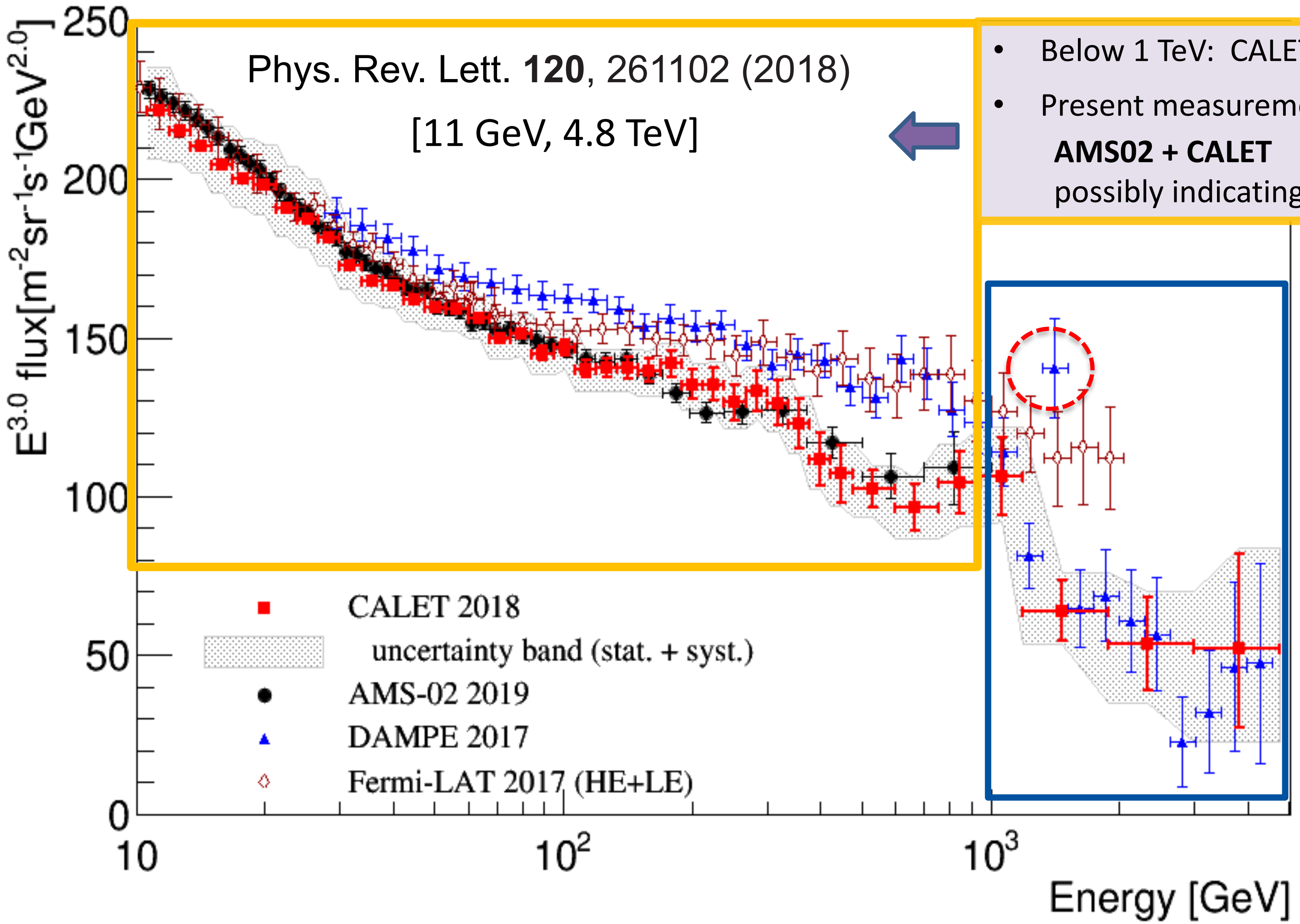
Energy deposit (in TASC) spectrum: 1 GeV-1 PeV



High-energy trigger (> 10 GeV) statistics:

- Operational time **2303 days (>6 years)**(*)
  (*) as of Jan. 31, 2022
- Live time fraction **~ 86%**
- Exposure of HE trigger
  ~200 m^2 sr day
- HE-gamma point source exposure
  ~3.6 m^2 day (for Crab, Geminga)

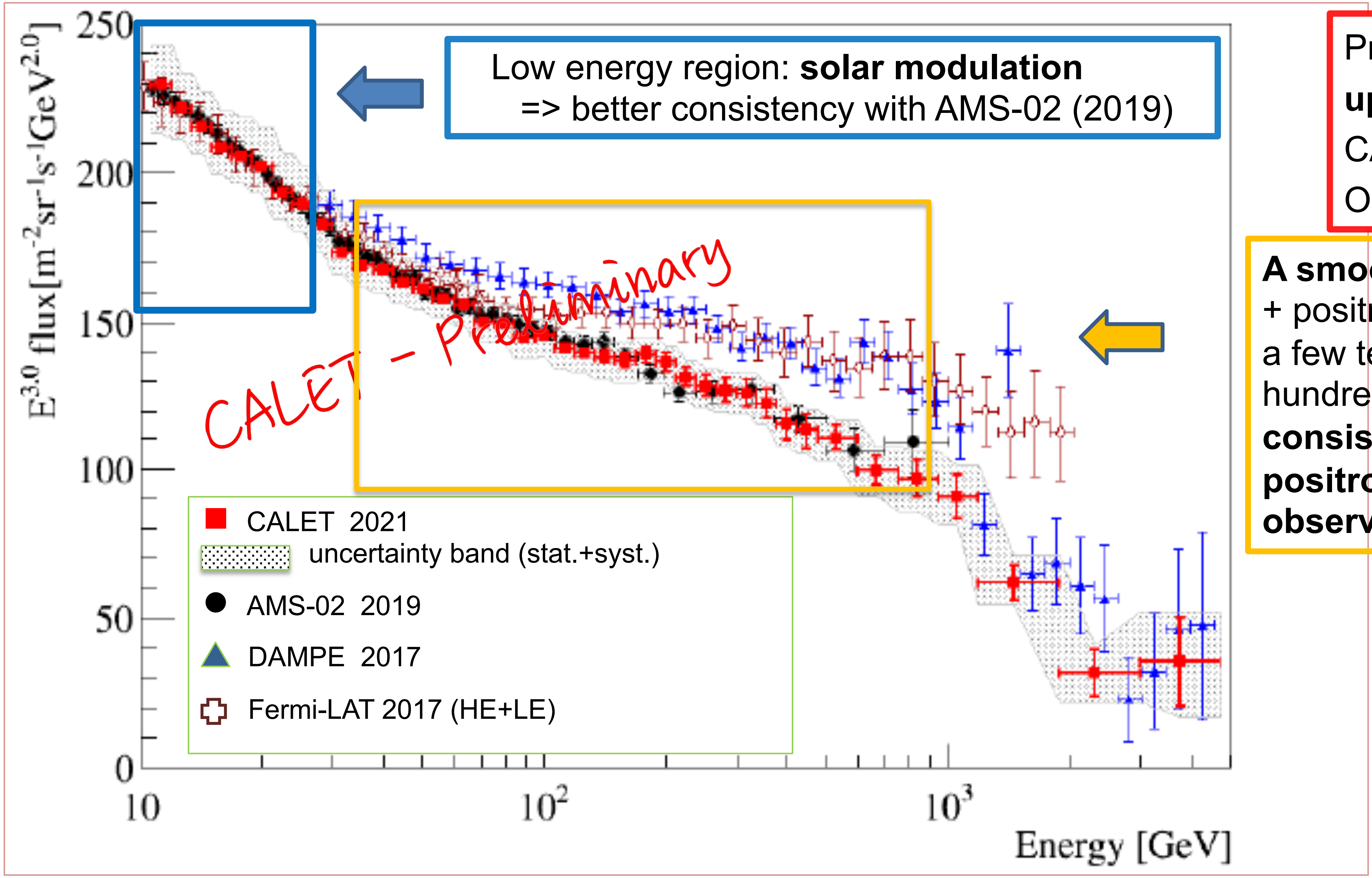
Cosmic-ray All-electron Spectrum



- Below 1 TeV: 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

- Above 1 TeV CALET observes a suppression of the flux consistent with DAMPE within errors
- No peak-like structure at 1.4 TeV in CALET measurement irrespective of binning

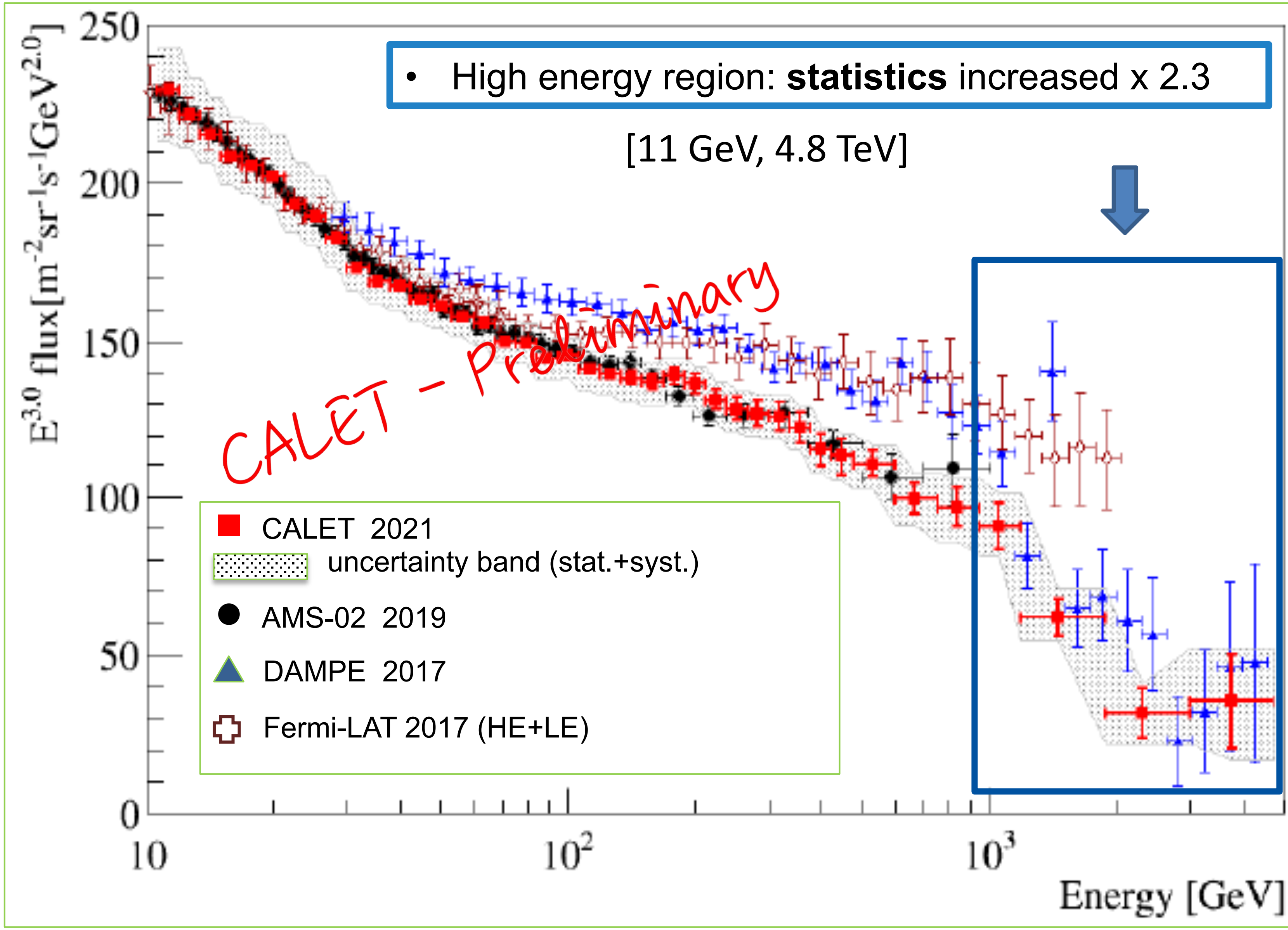
Cosmic-ray all-electron spectrum (update: as of Sep. 30, 2020)

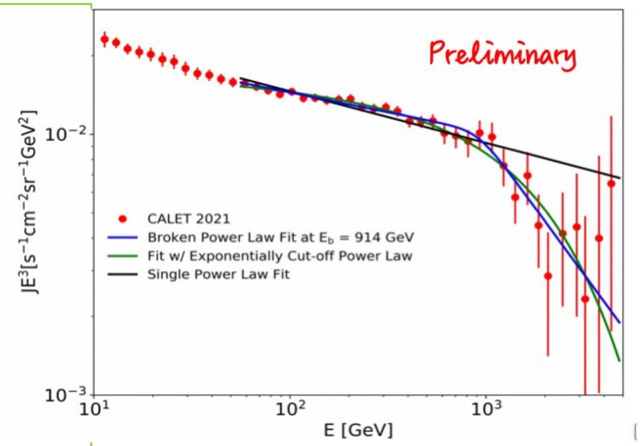


Preliminary spectrum is **updated** after 1815 days of CALET observations: Oct.13, 2015 - Sep.30, 2020

A smooth hump in the electron + positron spectrum observed in a few tens of GeV to several hundreds of GeV is **well consistent with the excess of positrons (+ electrons) observed by AMS-02.**

Cosmic-ray all-electron spectrum (update: as of Sep. 30, 2020)

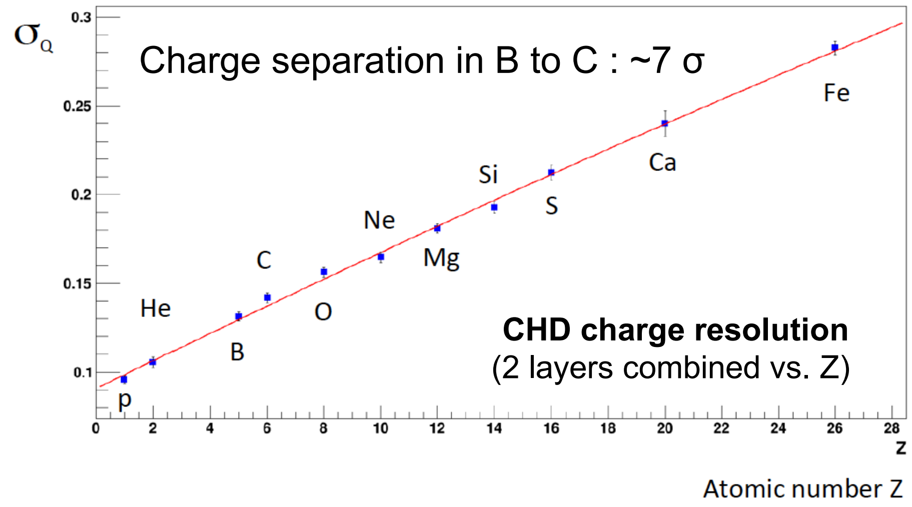


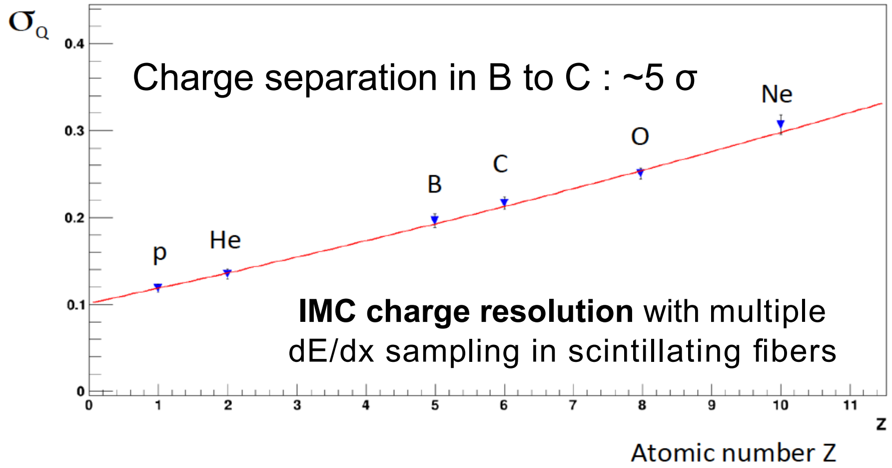


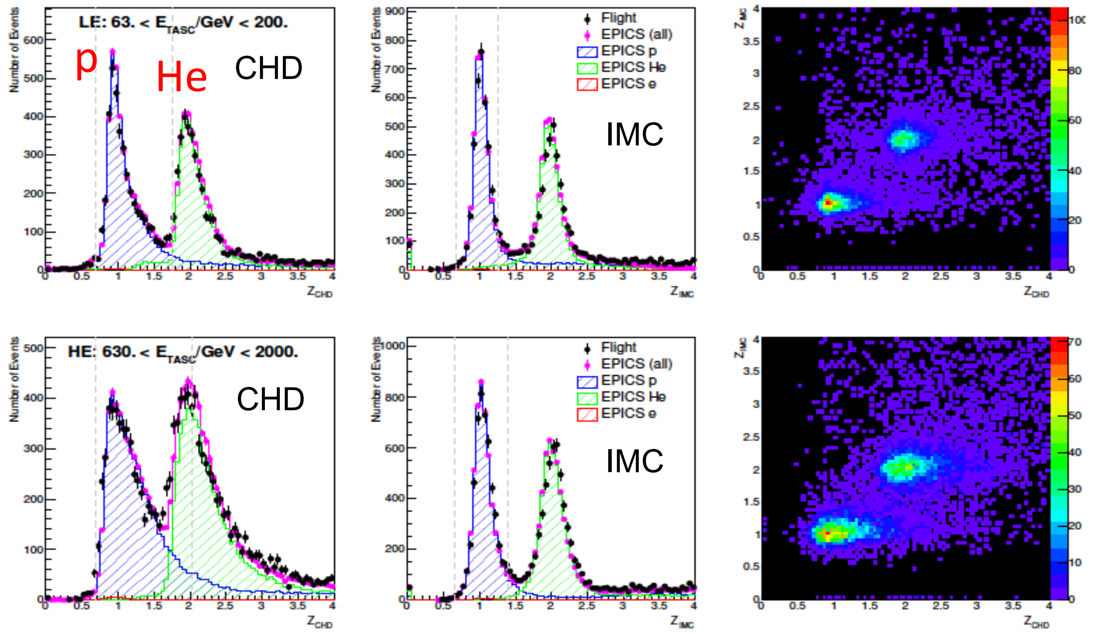
CALET observes a flux suppression above 1 TeV with a **significance > 6.5 σ**, a considerable improvement with respect to the result published in PRL2018 (~4 σ)

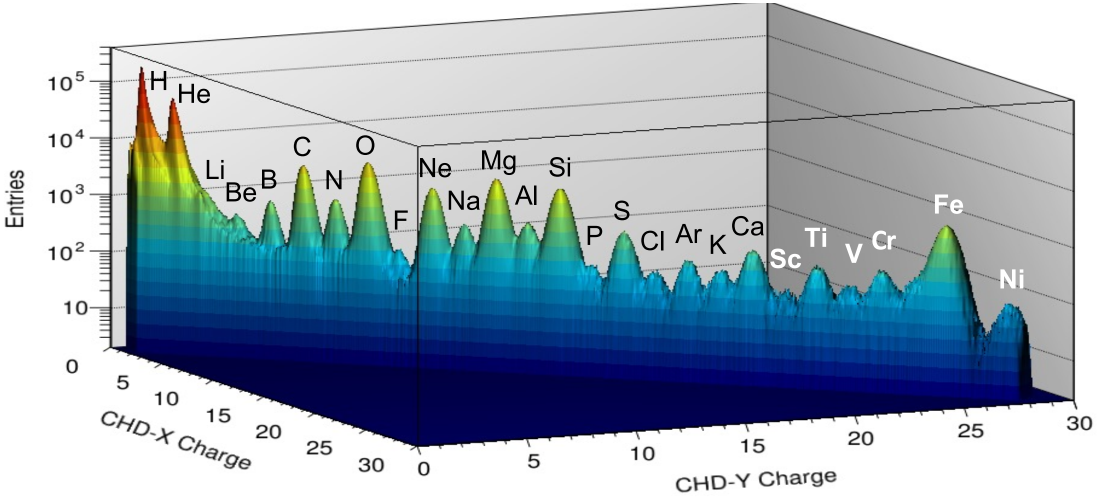
Charge Identification with CHD and IMC

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





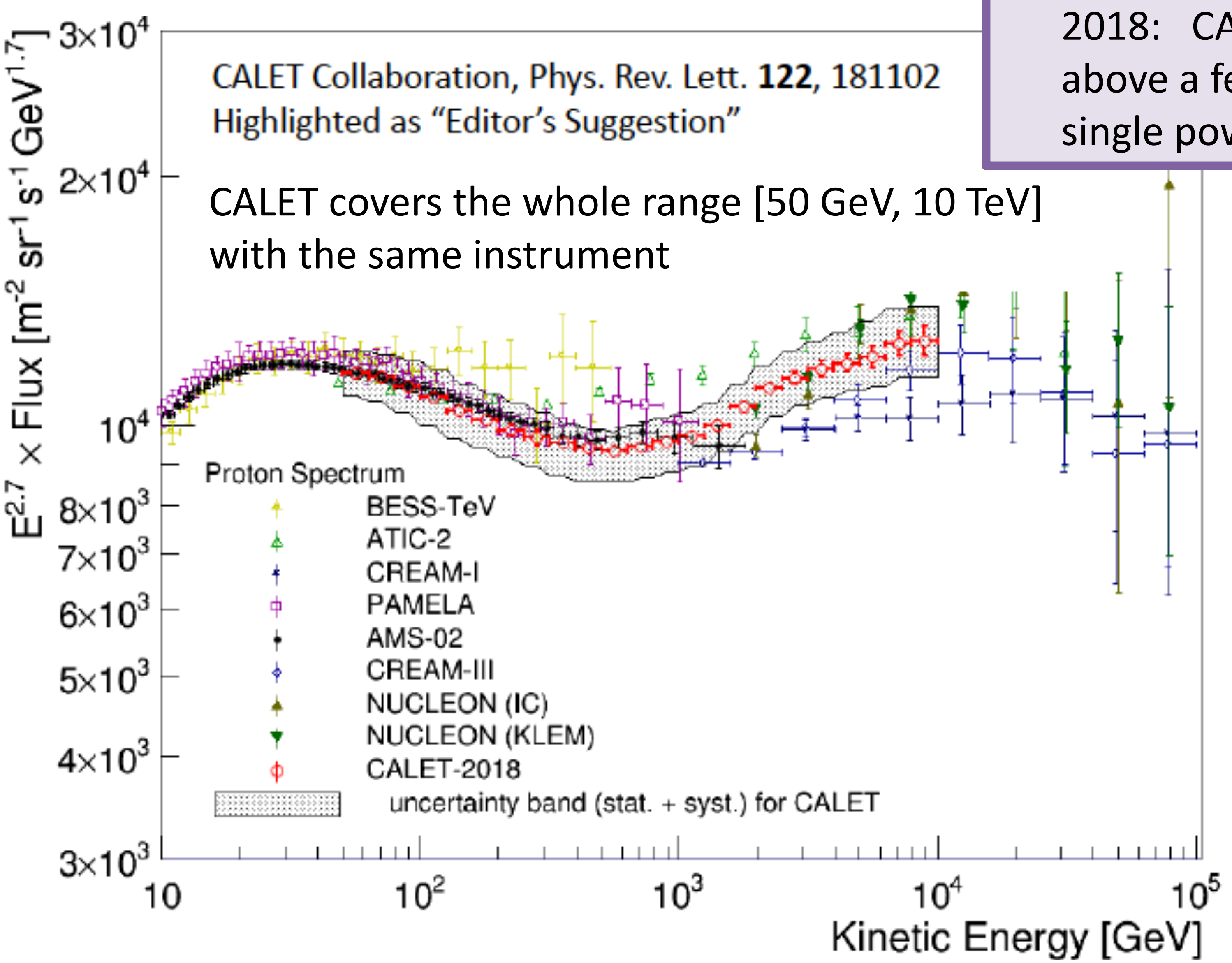




Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

Cosmic-ray proton spectrum

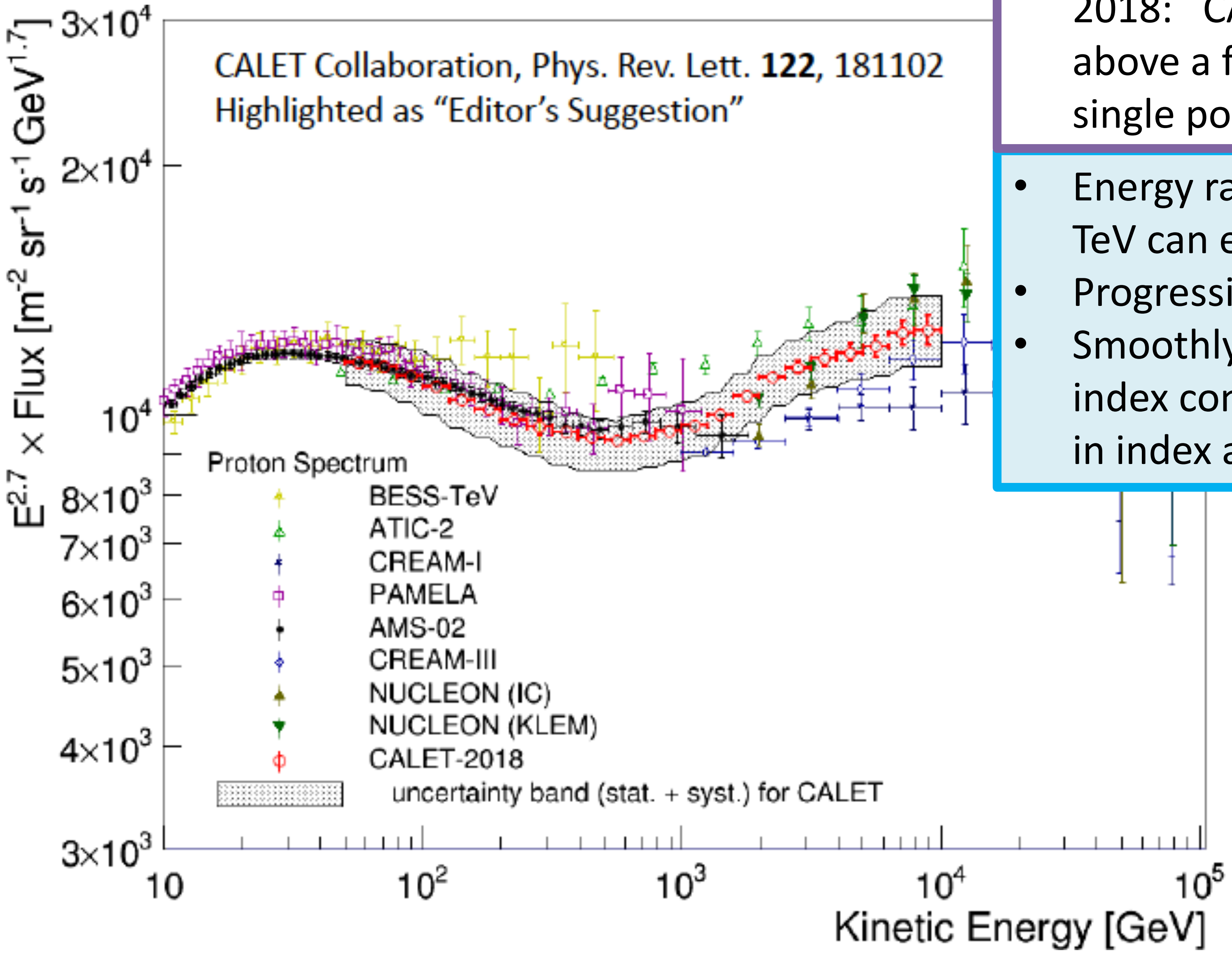
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

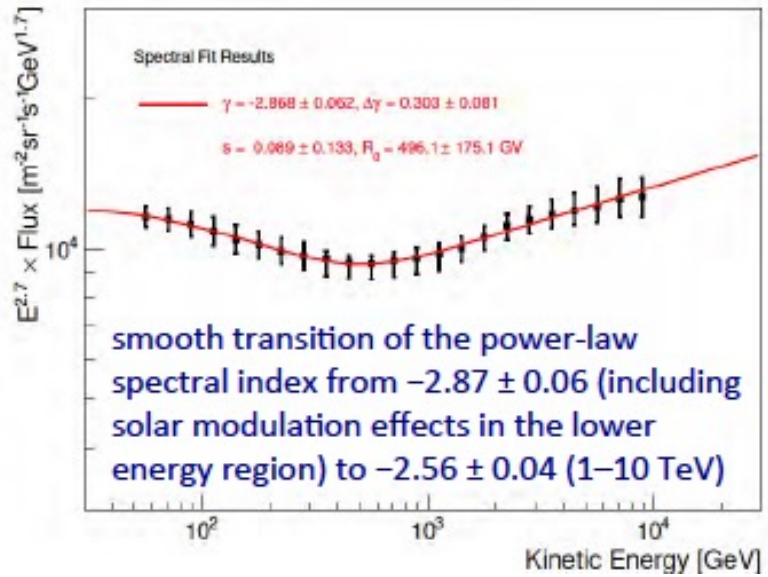


Cosmic-ray proton spectrum

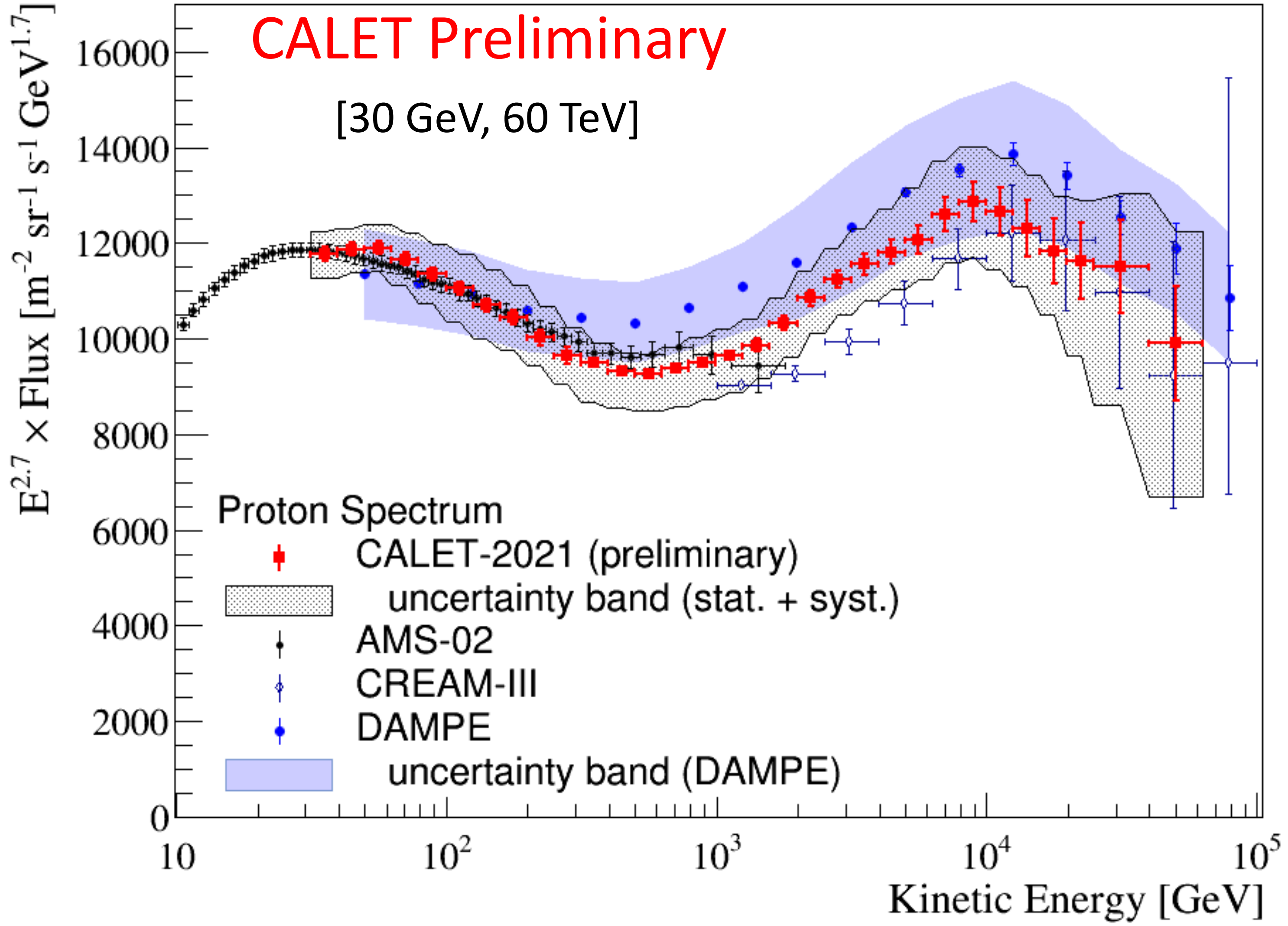
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

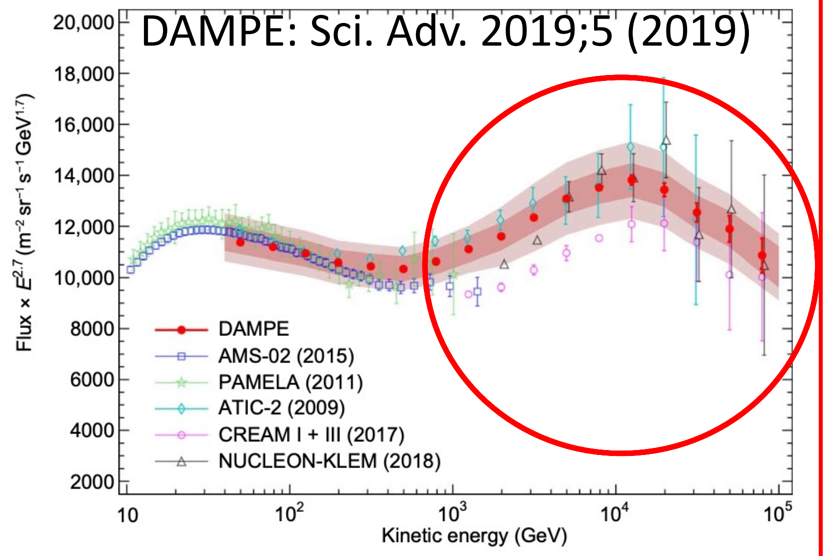
- Energy ranges 50 GeV – 500 GeV and 1 TeV – 10 TeV can each be fitted with single power laws
- Progressive hardening up to TeV energies
- Smoothly-broken power law fit gives low energy index consistent with AMS-02, but larger change in index and higher break energy





Cosmic-ray proton spectrum (update: as of Sep.30, 2020)

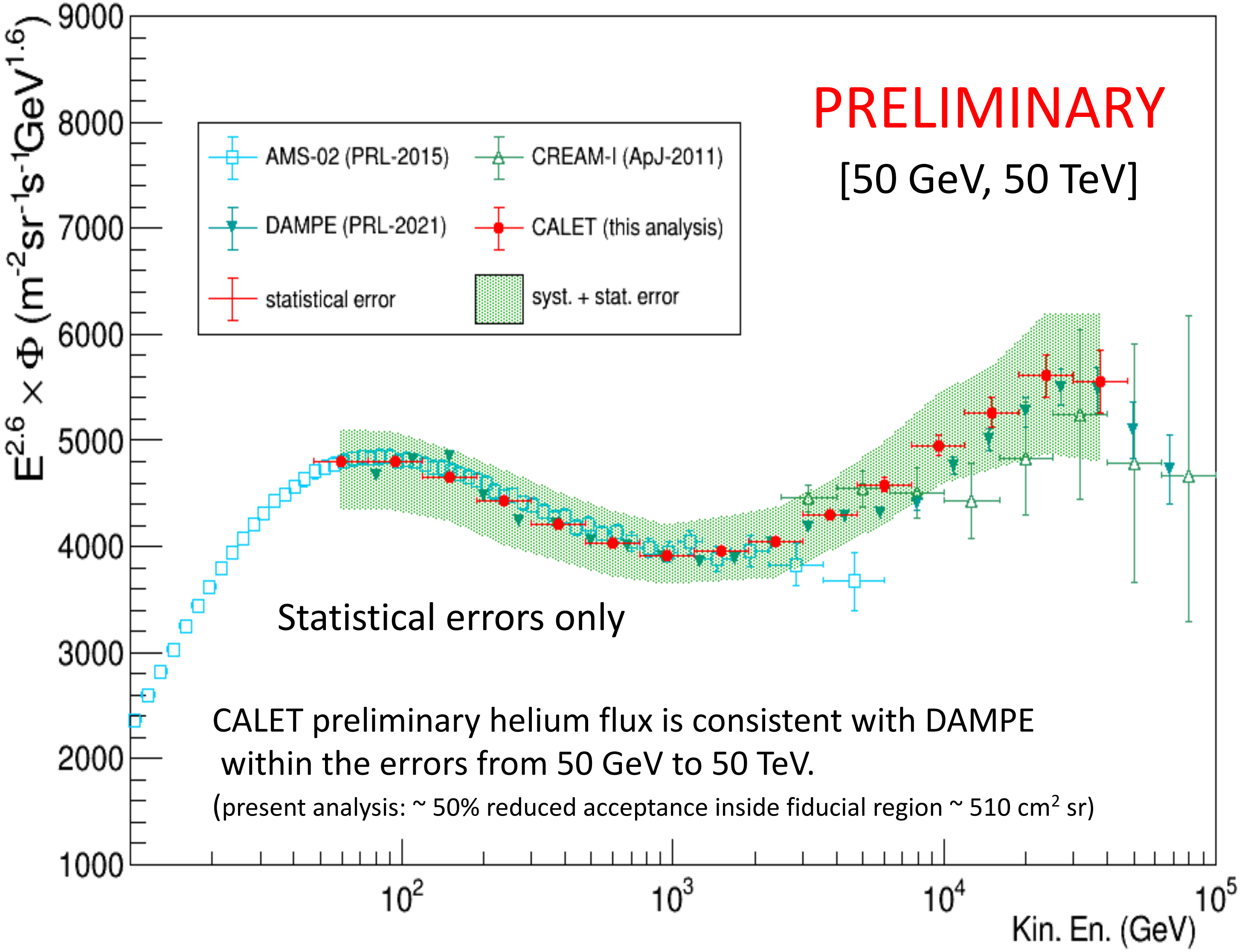




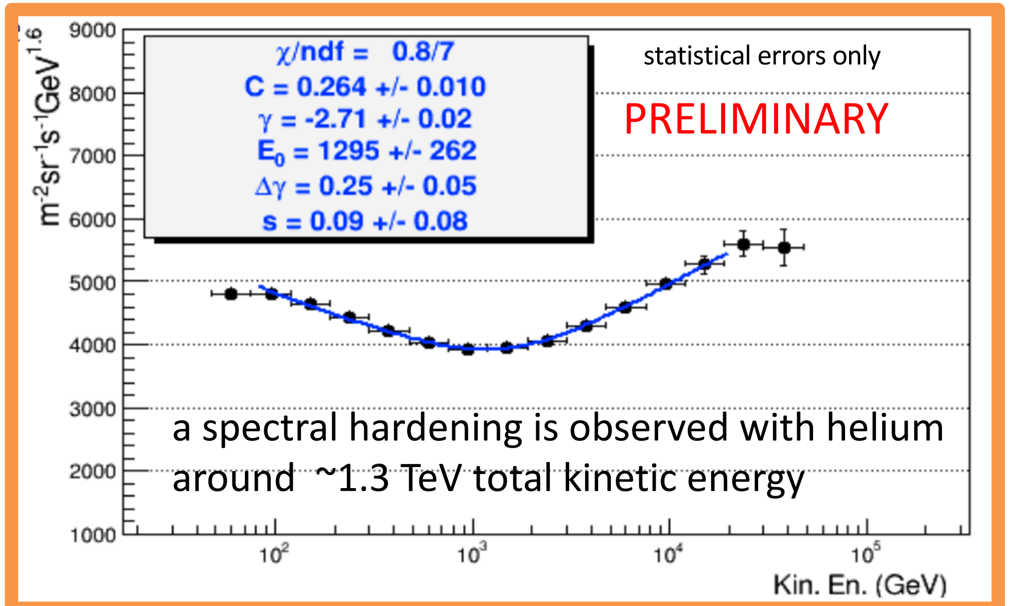
- DAMPE reported a spectral index softening $\Delta\gamma = -0.25 \pm 0.07$ from ~-2.60 to ~-2.85. above 10 TeV at E_{break} = $13.6^{+4.1}_{-4.8}$ TeV with ~30% error.

- 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).

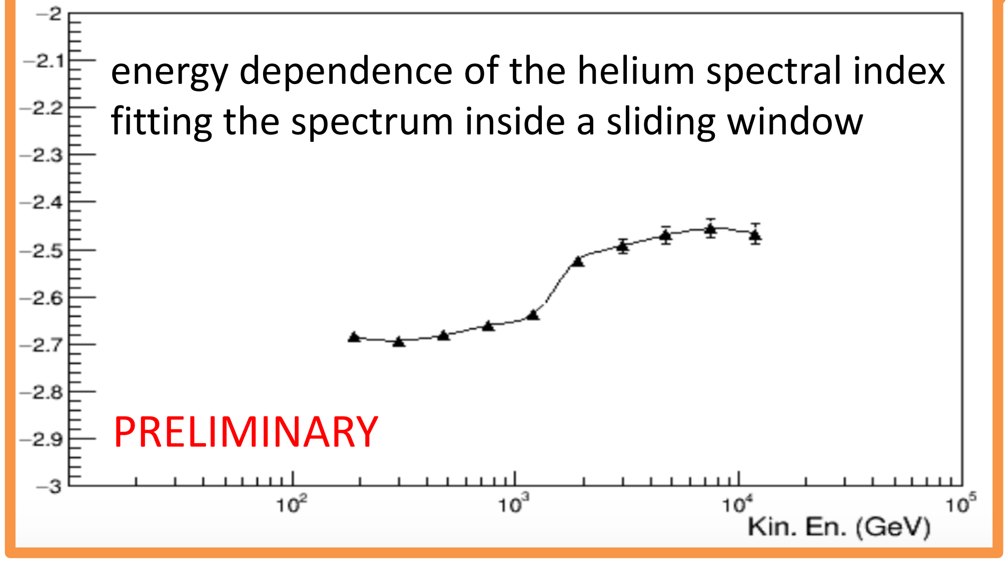
Cosmic-ray helium spectrum (preliminary)



CALET preliminary helium flux is consistent with DAMPE within the errors from 50 GeV to 50 TeV.
(present analysis: ~ 50% reduced acceptance inside fiducial region ~ 510 cm^2 sr)

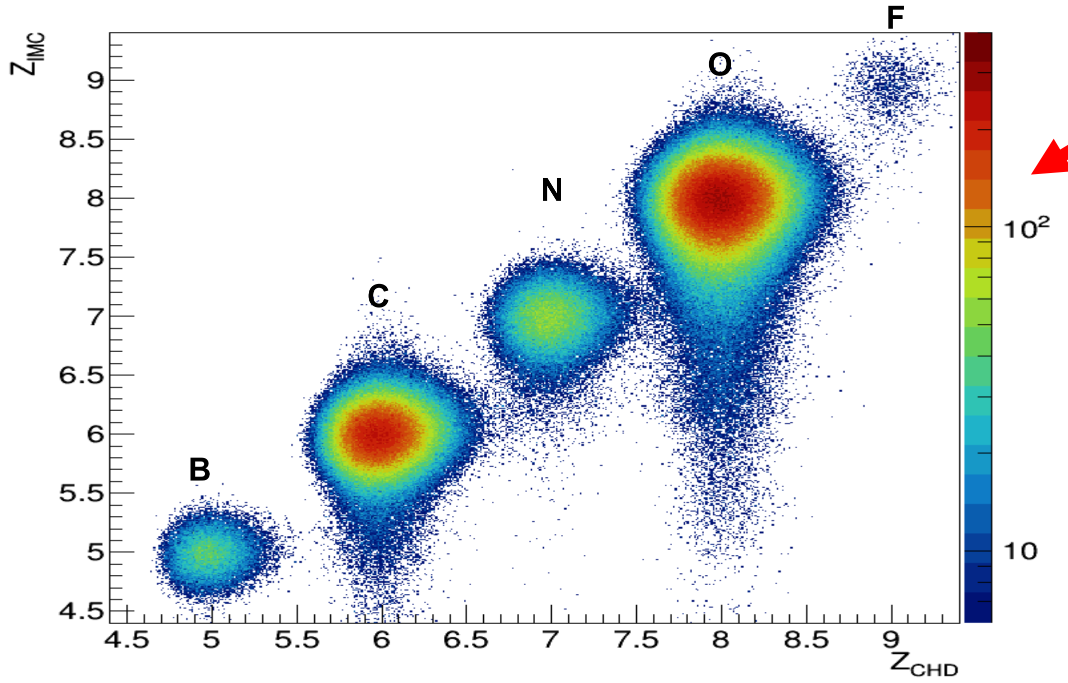


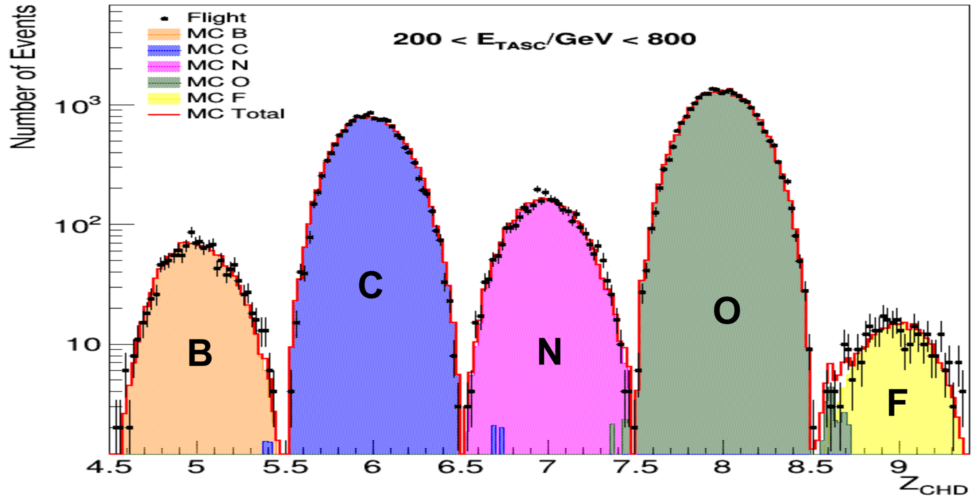
a spectral hardening is observed with helium around ~1.3 TeV total kinetic energy



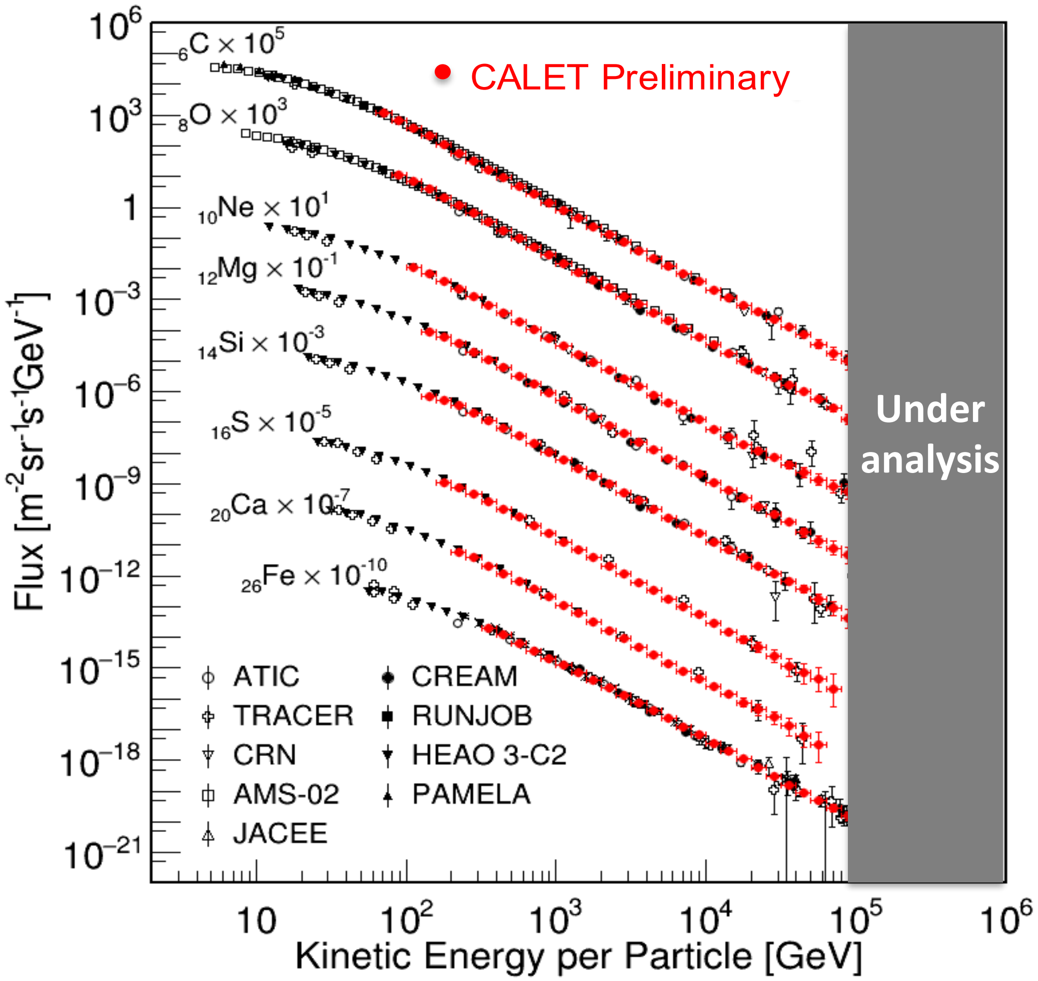
energy dependence of the helium spectral index fitting the spectrum inside a sliding window

Spectra of Cosmic-ray Nuclei from C to Fe

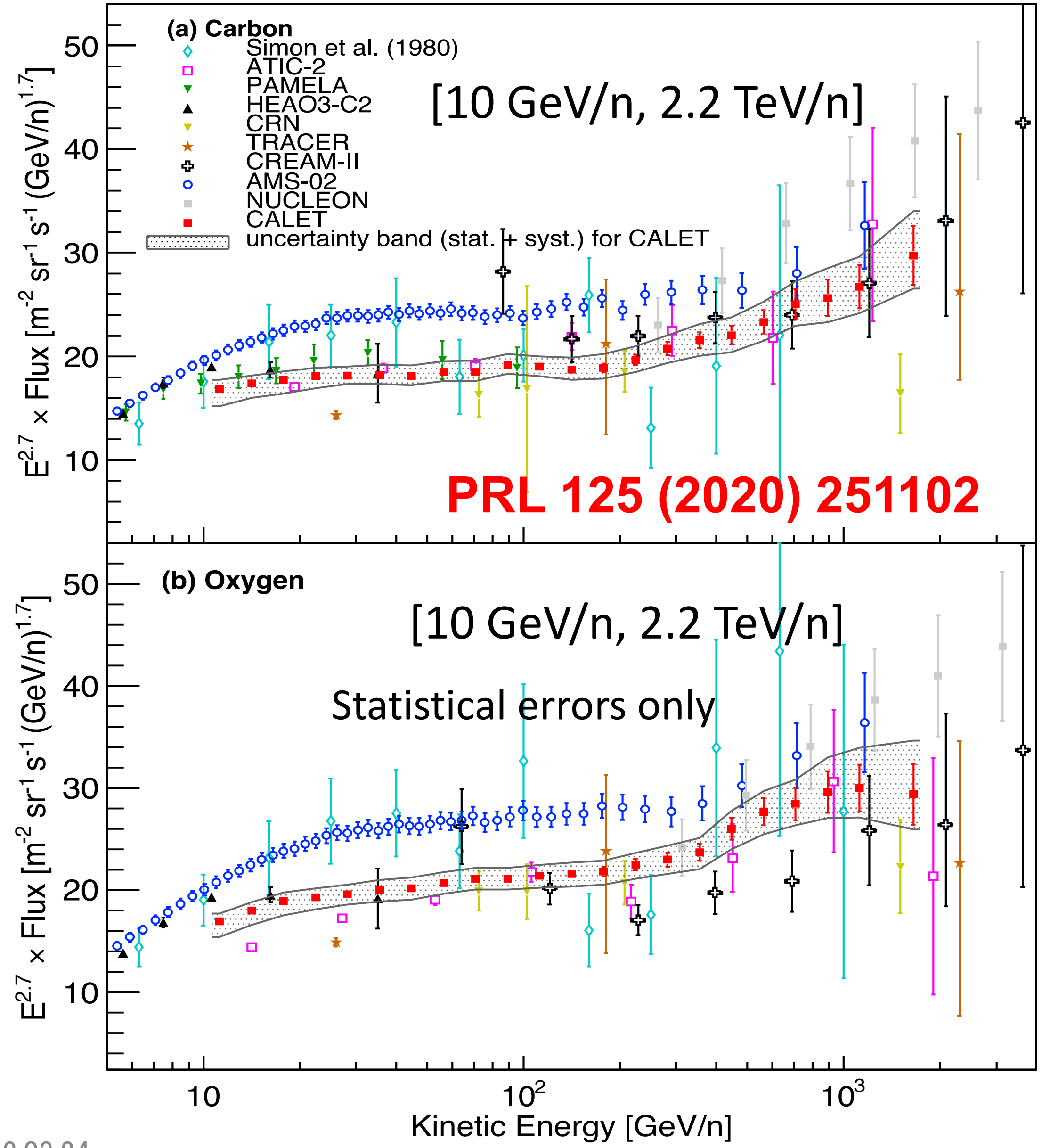




With excellent charge-ID of individual elements CALET is exploring the Table of Elements in the multi-TeV domain



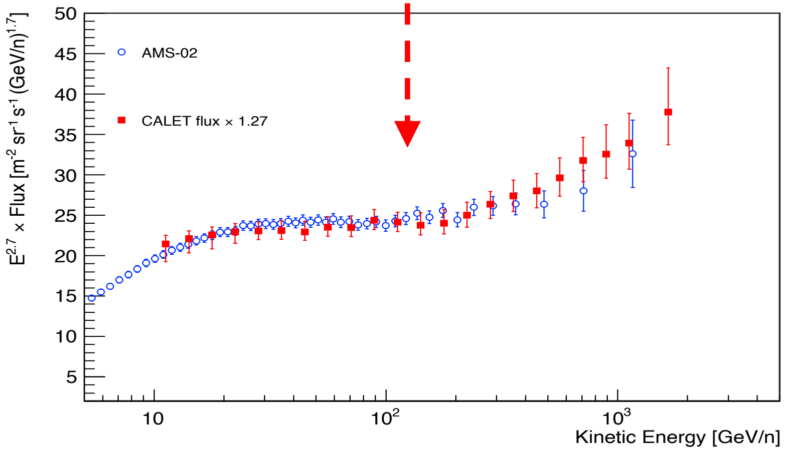
Carbon and Oxygen Energy Spectra

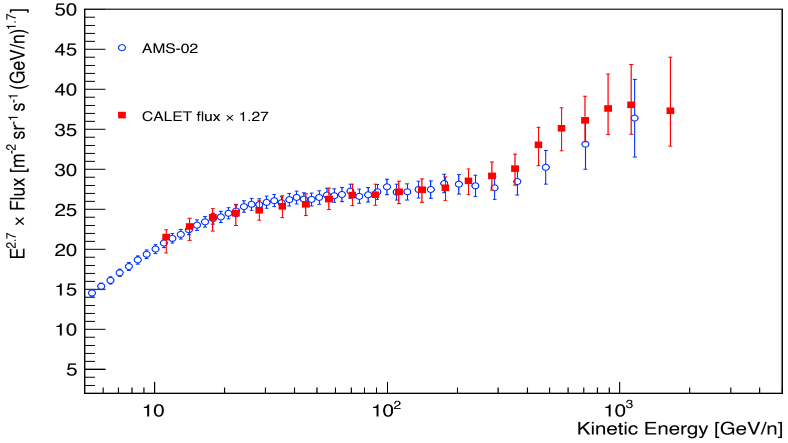


CALET C is consistent with PAMELA and most of the previous experiments. PAMELA did not publish oxygen.

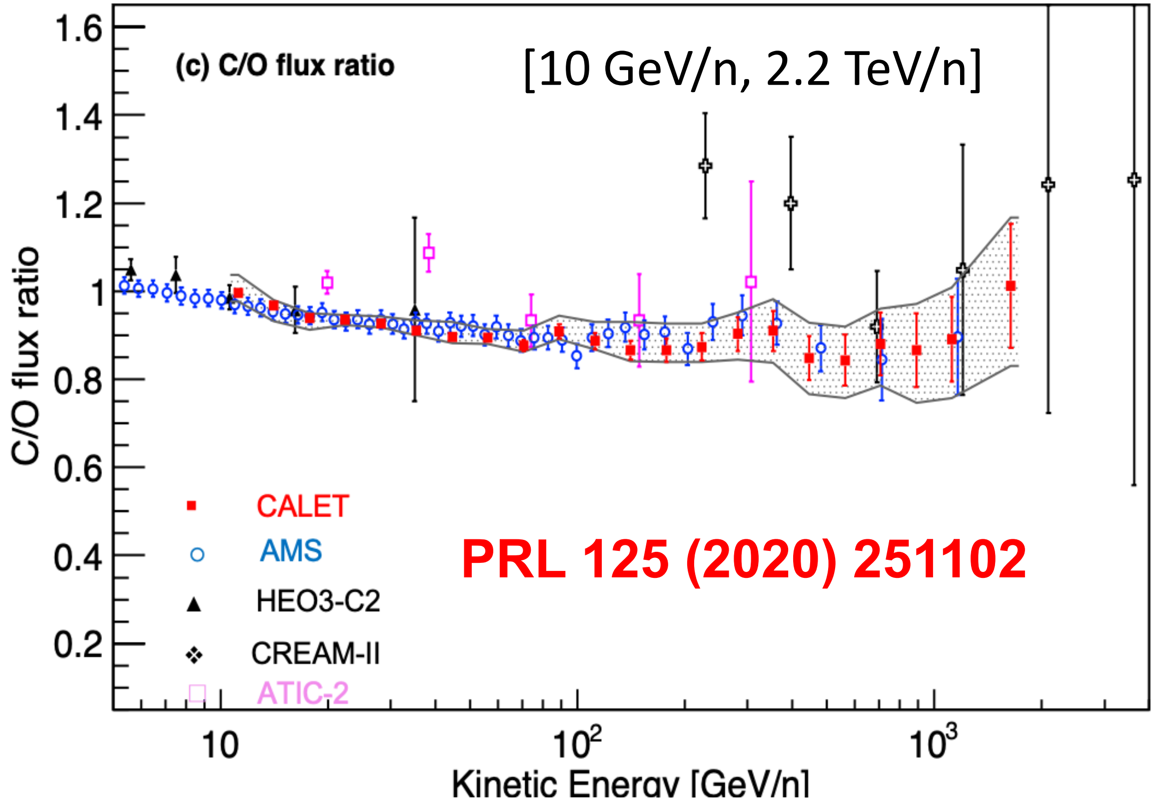
The spectra show a clear hardening around 200 GeV/n.

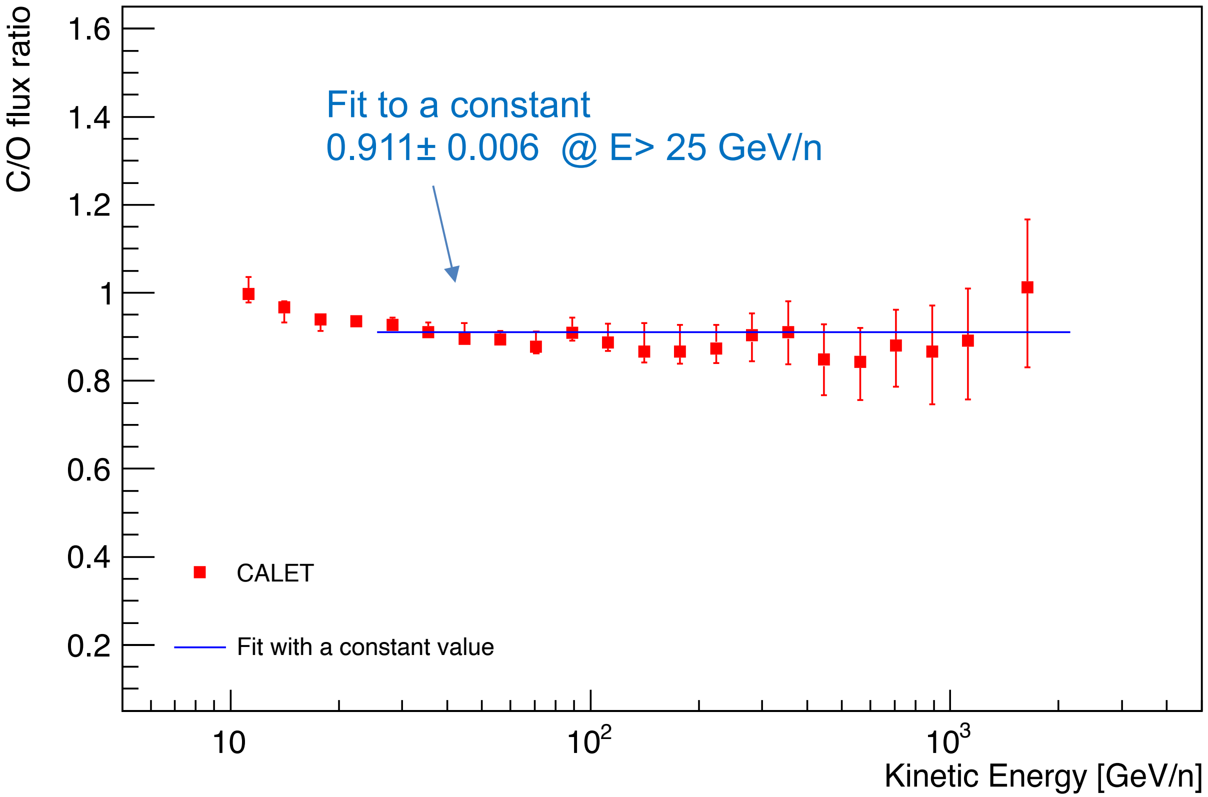
They have shapes similar to AMS-02 but the absolute normalization is significantly lower (~ 27%)





C/O flux ratio





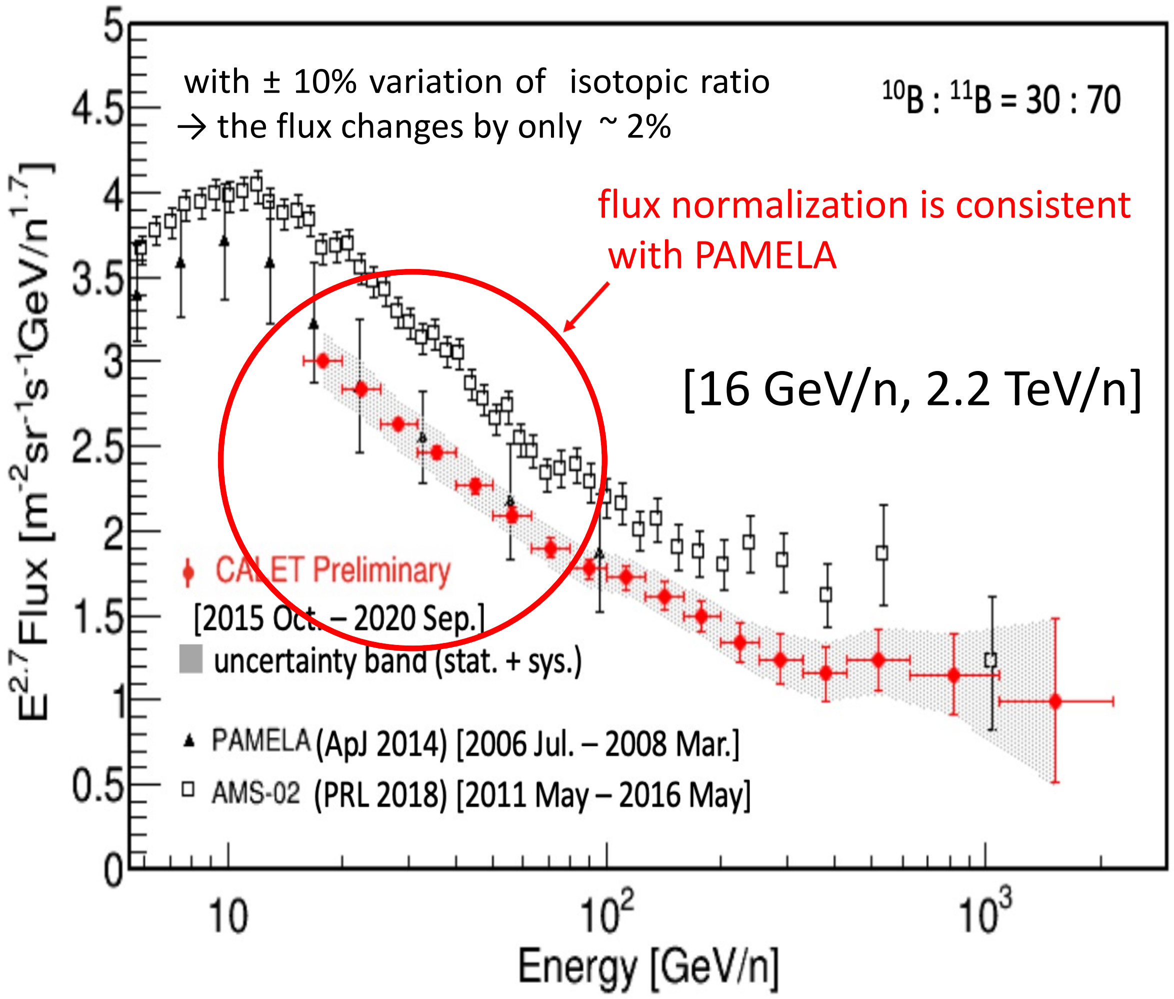
The C/O flux ratio as a function of energy is in good agreement with the one reported by AMS

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

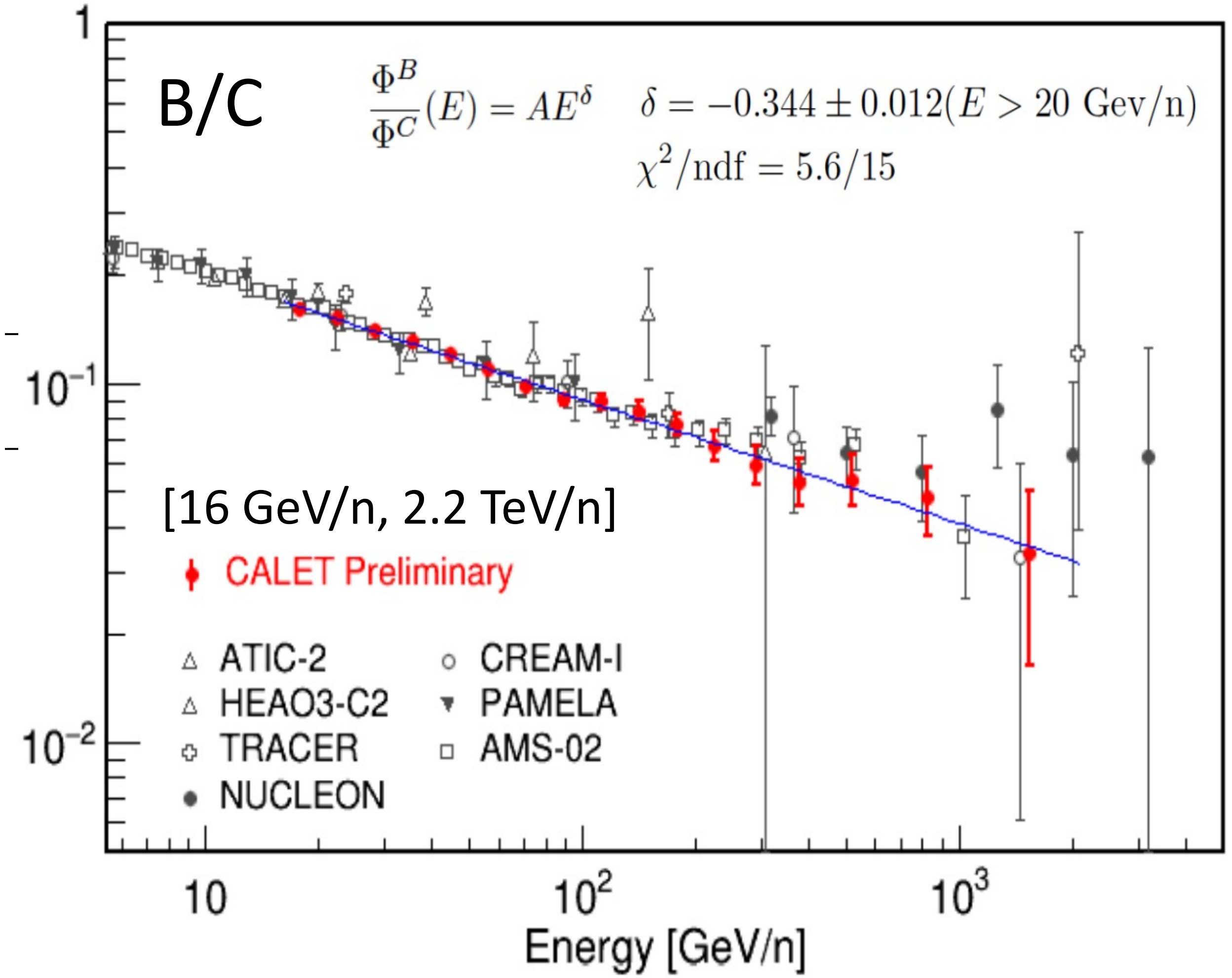
→ C and O fluxes have the same energy dependence.

Boron Spectrum and B/C Ratio (preliminary)

Boron energy spectrum

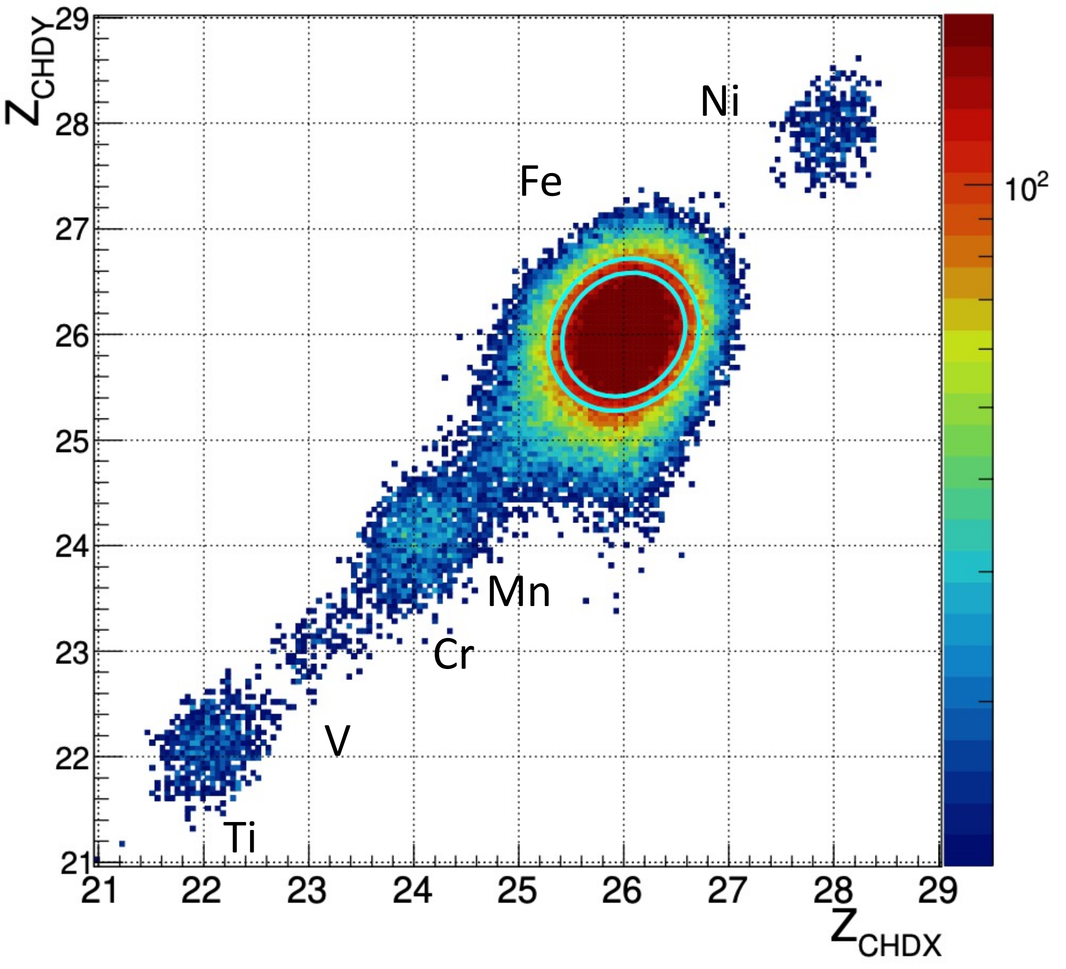


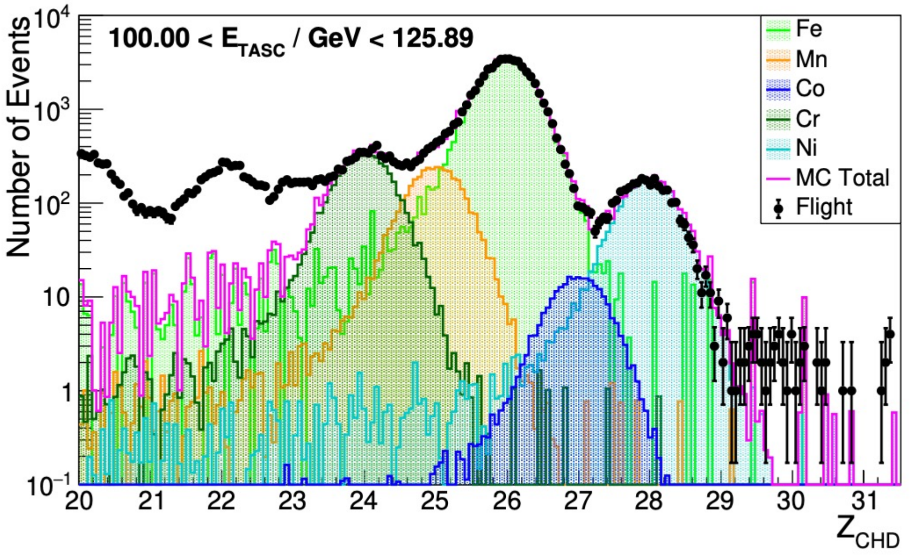
B/C ratio



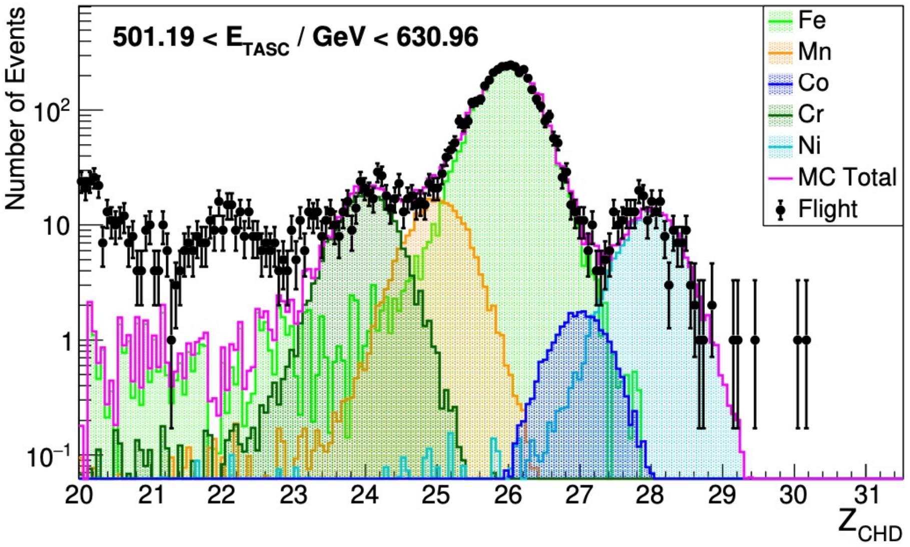
Iron – Analysis (Charge Selection)

Charge measurement with the two CHD layers





(a)



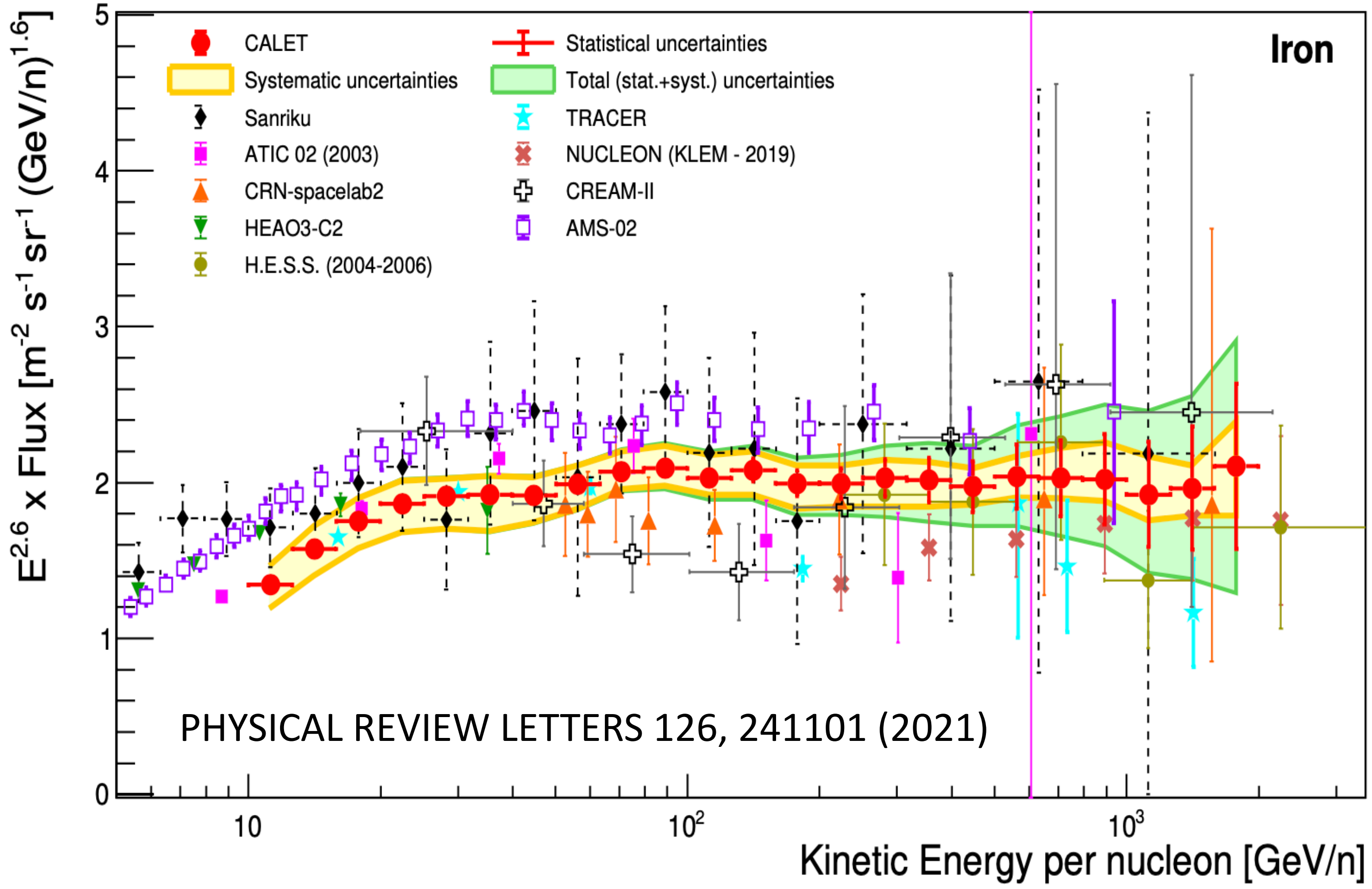
(b)

Iron Spectrum

Phys. Rev. Lett. **126**, 241101 (2021)

Flux x $E^{2.6}$ vs kinetic energy per nucleon [10 GeV/n, 2 TeV/n]

Analyzed data: Jan, 2016 – May 2020



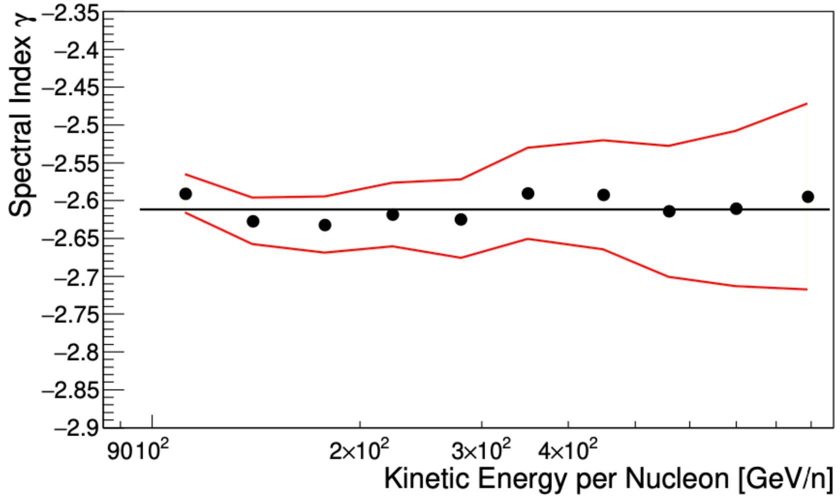
Flux normalization:
Consistent with ATIC-02 and TRACER at low energy and with CNR and HESS at high energy in tension with AMS-02 and SANRIKU (balloon)

Iron Single Power Law fit:

50 GeV/n, 2.0 TeV/n

$\gamma = -2.60 \pm 0.02(\text{stat}) \pm 0.02(\text{sys})$

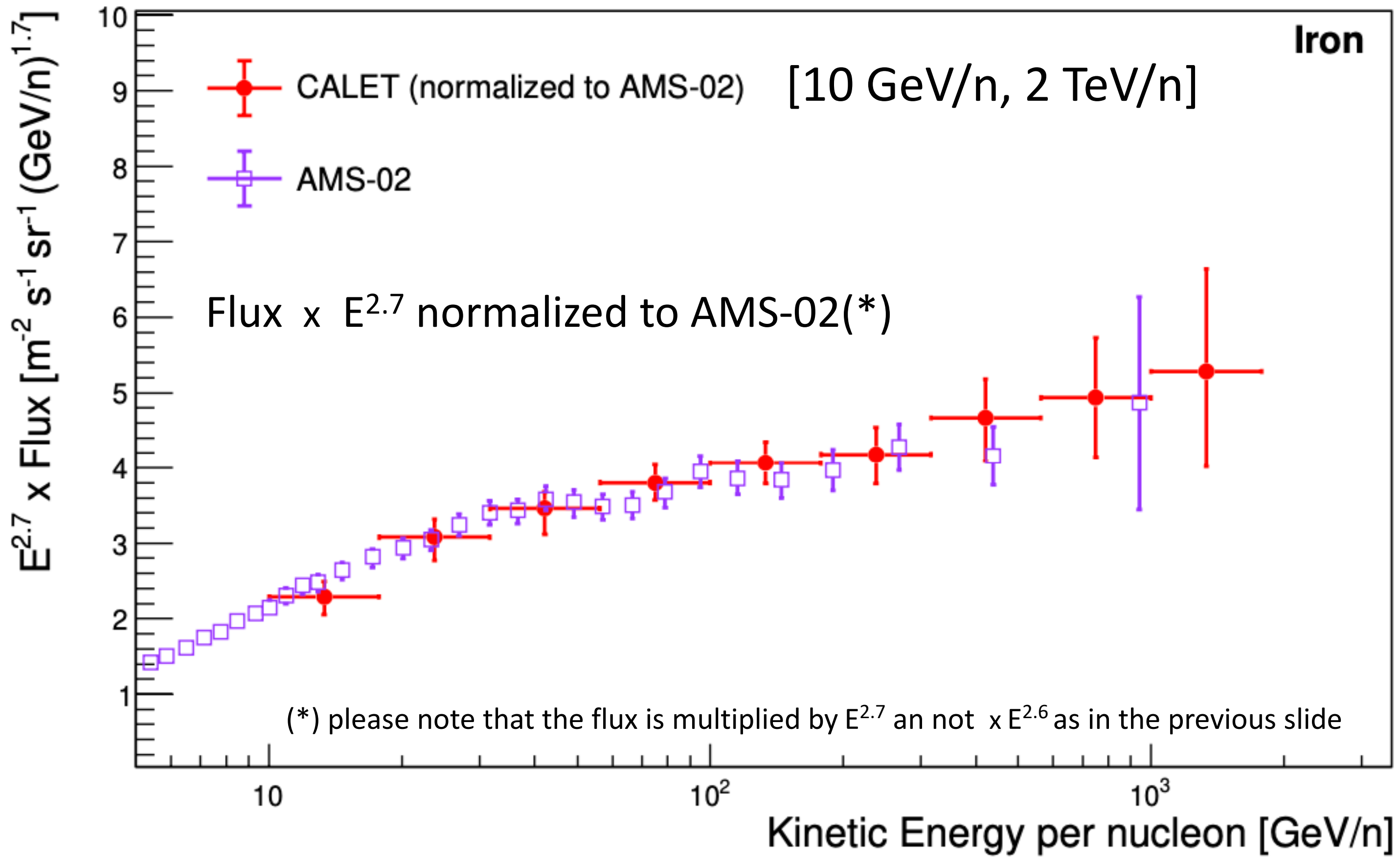
with $\chi^2/\text{d.o.f.} = 4.2/14$



Iron Spectral Shape and Normalization

AMS-02 Phys. Rev. Lett. **126**, 041104 (2021)

CALET Phys. Rev. Lett. **126**, 241101 (2021)



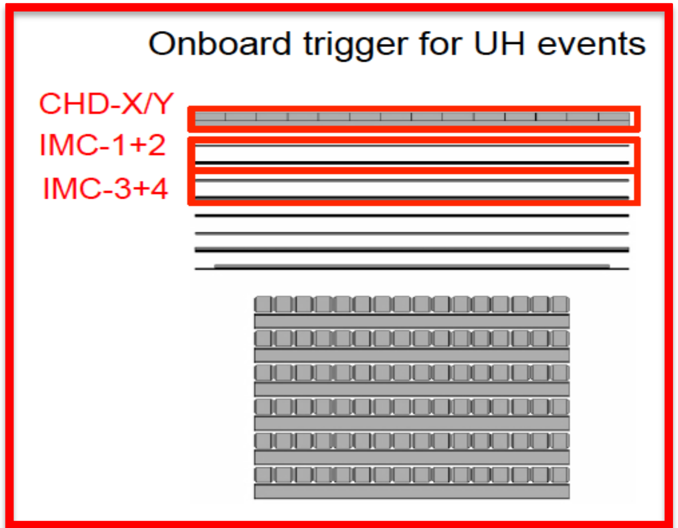
Spectral shape:

- CALET $E^{2.7}$ x Flux vs kinetic energy/n normalized to AMS-02:
  - similar spectral shape
  - comparable errors above 200 GeV/n

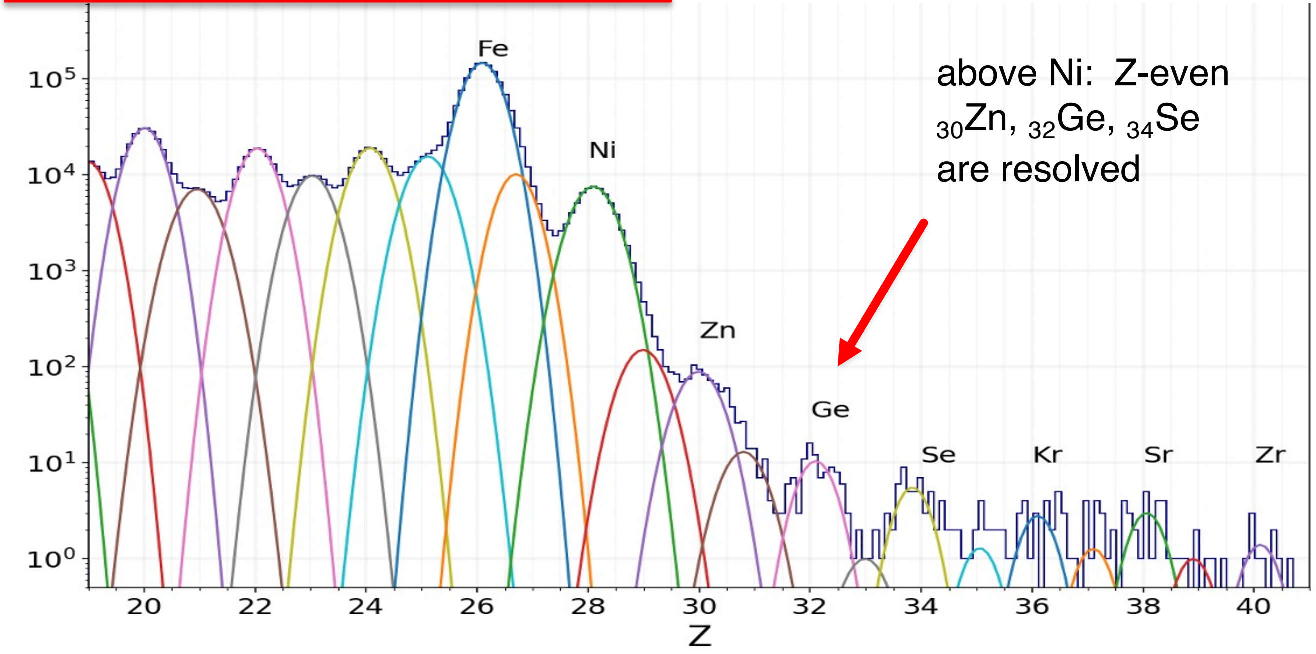
Spectral hardening:

- CALET iron data are consistent with an SPL spectrum up to 2 TeV/n.
- Beyond this limit, the present statistics and large error in systematics do not allow to draw a significant conclusion on a possible deviation from a single power law.

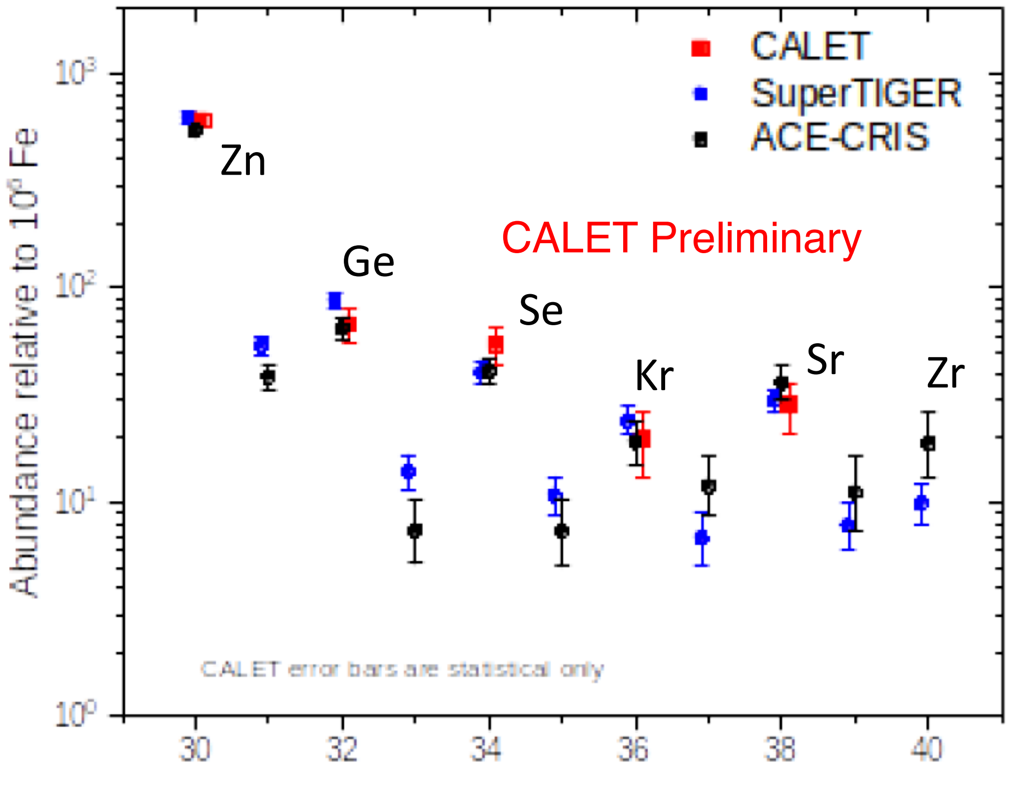
Ultra-heavy cosmic-ray nuclei (26 < Z ≤ 40)



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

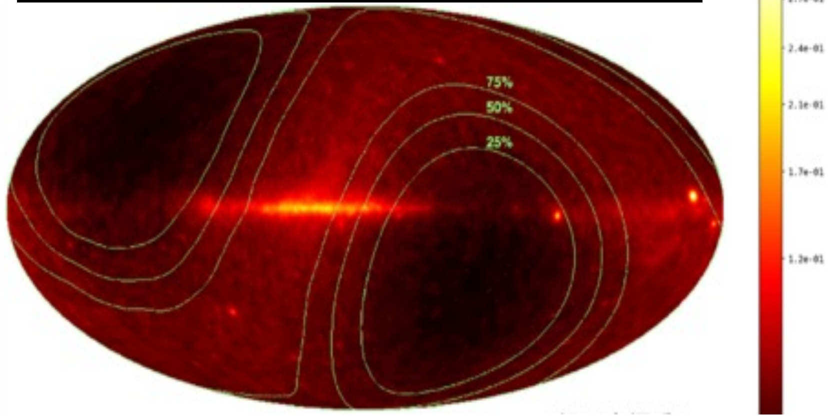


The CALET UH element ratios relative to Fe are consistent with Super-TIGER and ACE abundances.

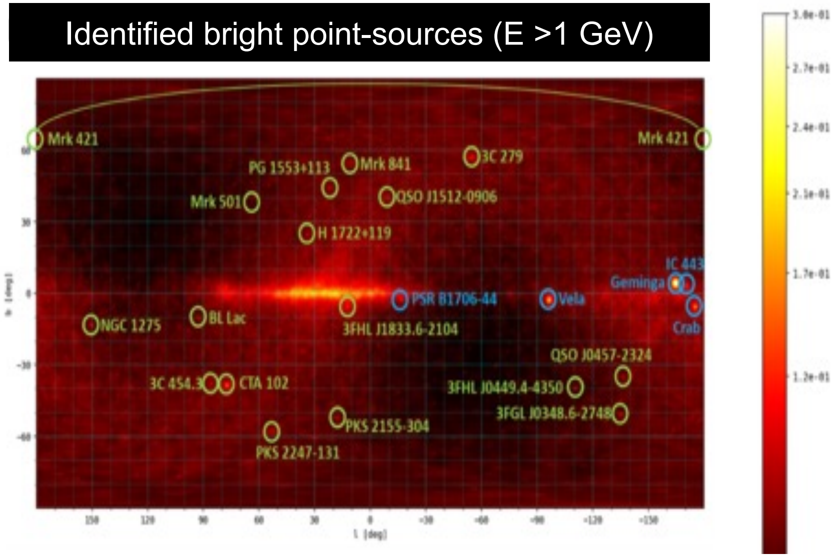
CALET γ–ray Sky (>1GeV) ,GRBs, GW follow-up, DM limits

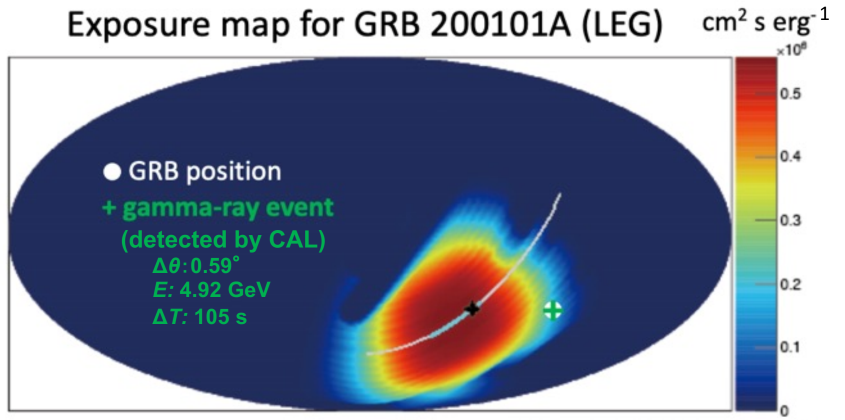
- Effective area: ~400 cm^2 (>2 GeV)
- Angular resolution: < 0.2° (> 10 GeV)
- Energy resolution: ~5% at 10 GeV

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 2022-01-31

280 GRBs (44.2 GRBs / year)

247 Long (88%) **33 Short (12%)**

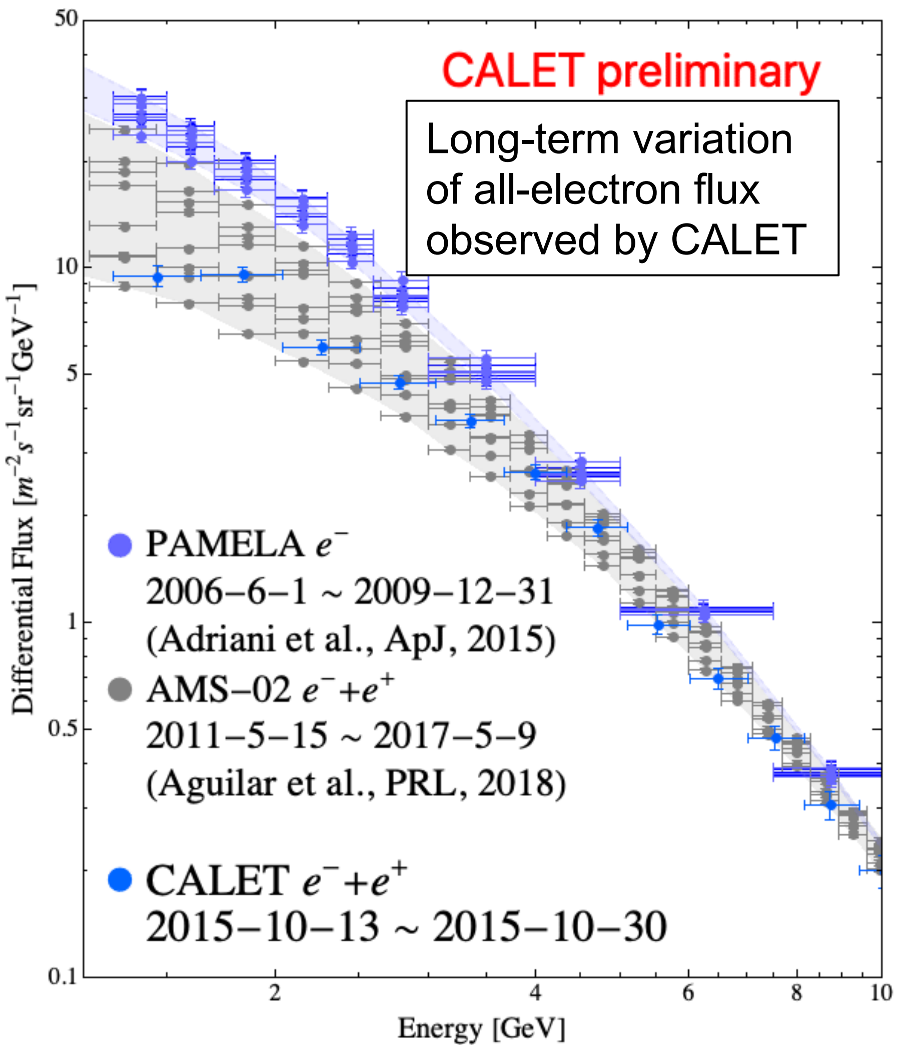
- **Follow-up** of LIGO/Virgo **GW** observations
  - X-ray and γ-ray bands
  - high-energy γ-in calorimeter

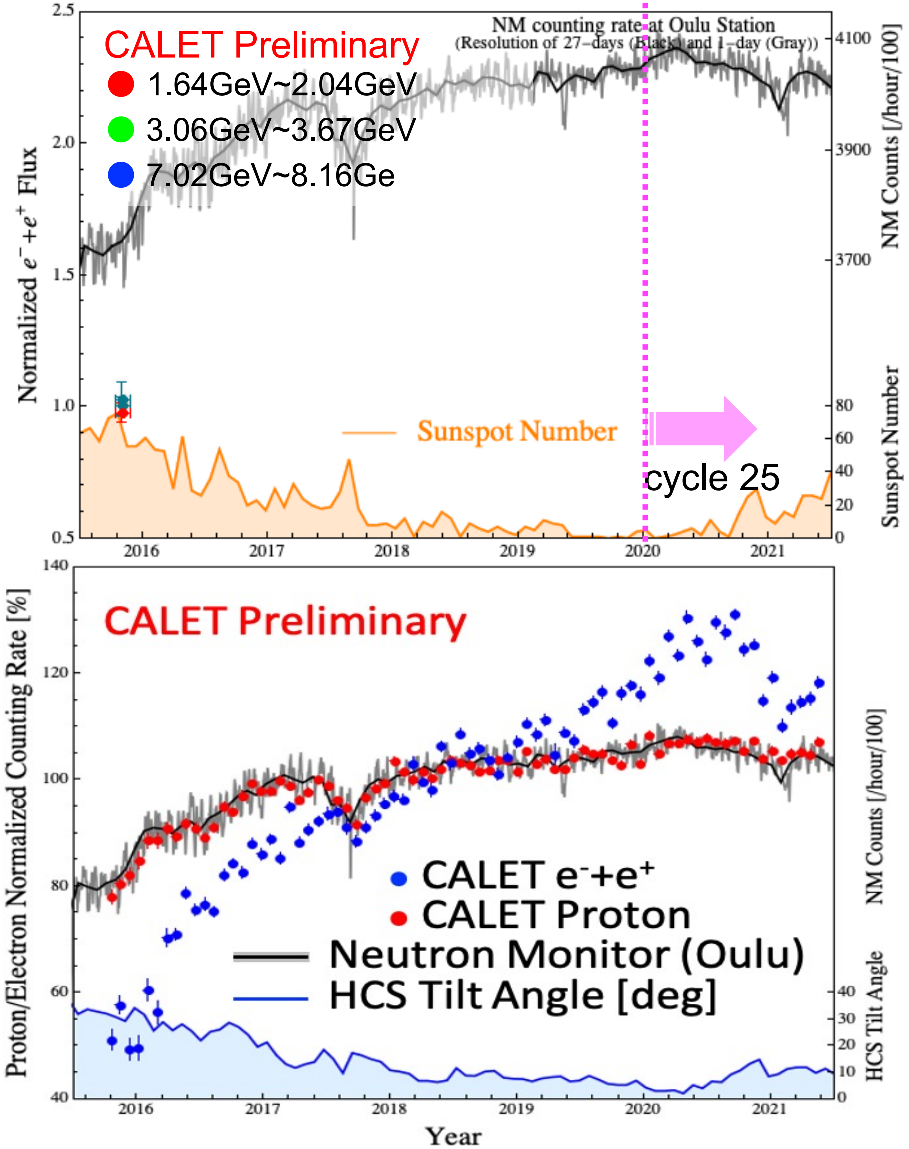
- **Limits on DM** annihilation into γγ: $<\sigma v> < 10^{-28}$-$10^{-25} cm^{-3}s^{-1}$
- Limits on DM decay $\chi \rightarrow \gamma\nu$ etc.: $\tau_{DM} > 10^{30}$s (m_{DM}>100 GeV)

See for details:
"CALET Observation of Gamma Rays" by M, Mori @ 14:00, Today
"CALET GRBs" by Y. Kawakubo @10:00, Tomorrow

Solar modulation: 1-10 GeV electrons and protons

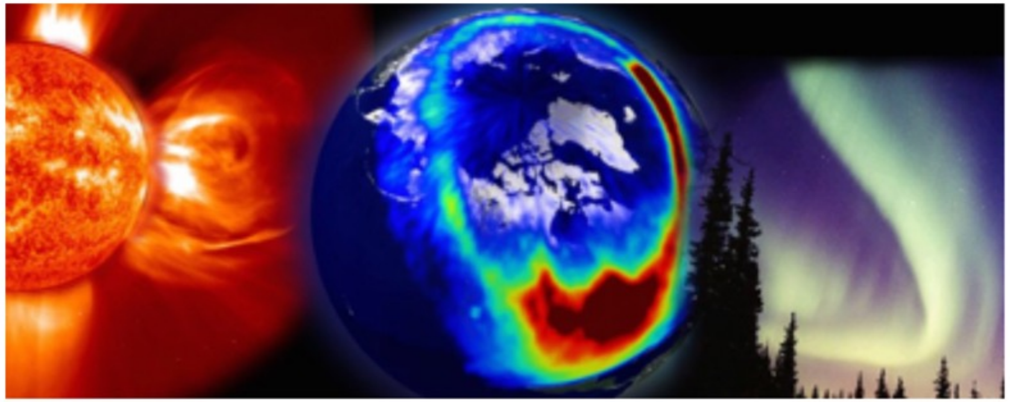
- **Since the start of observations in 2015/10, a steady increase in the 1-10 GeV all-electron flux has been observed.**
- **In the past two years, the flux has reached the maximum flux observed with PAMELA during the previous solar minimum.**

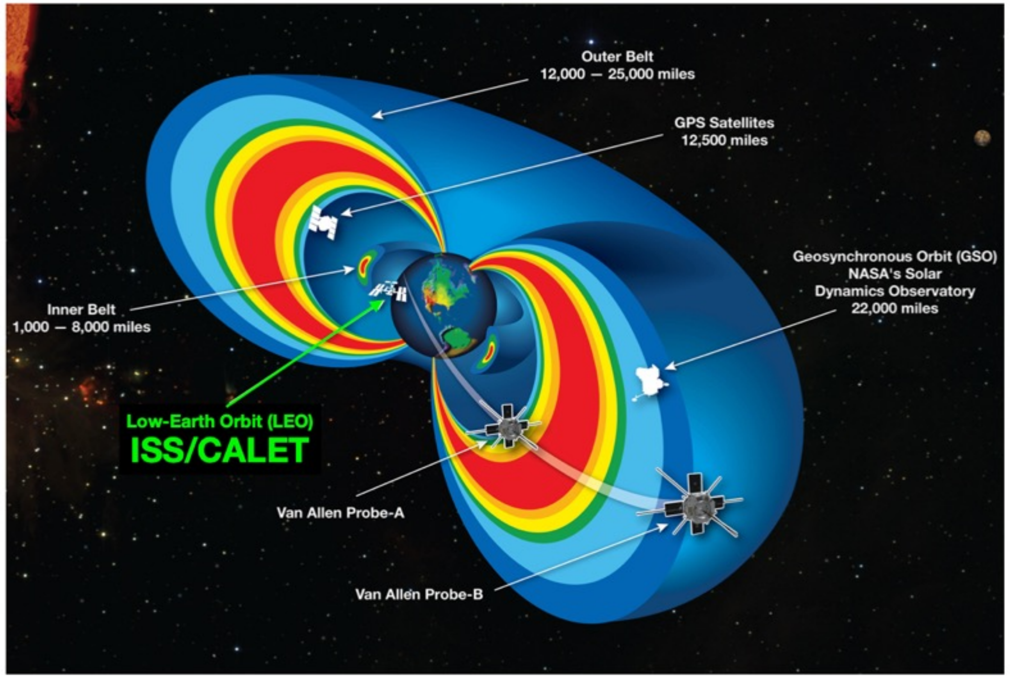




- The CR e^- + e^+ flux increases in the 1-10 GeV until ~half a year after the beginning of the new solar cycle 25. The flux has now started decreasing.
- Good correlation of the CR proton counting rate (red points) with the NM counting rate at Oulu station (black solid curve).
- The increase of CR e^- + 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 with CALET

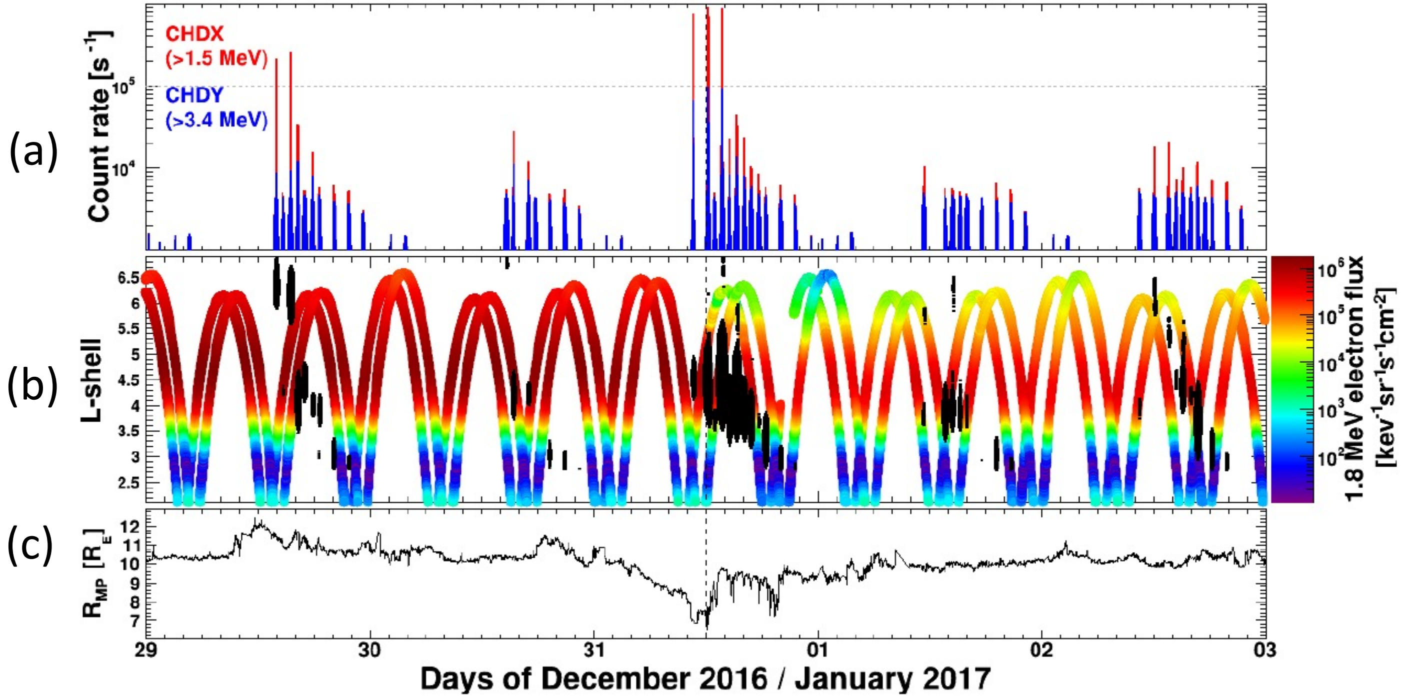




EMIC-Wave Driven Electron Precipitation observed by CALET on the International Space Station

(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 Jan. 31, 2022, total observation time is 2303 days (> 6 years) with live time fraction close to 86%. Nearly 3.25 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.
- Following results have been obtained by now.
  - Measurement of electron + positron spectrum in 11 GeV- 4.8 TeV.
  - Direct measurement of proton and Helium in 50 GeV ~60 or 50 TeV energy range, and of Carbon and Oxygen spectra in 10 GeV/n -2.2 TeV/n: Spectral hardening observed above a few hundred GeV/n.
  - Heavy primary cosmic-ray elements up to Iron and Nickel are successfully observed, and these spectra are published in PRL.
  - 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 .

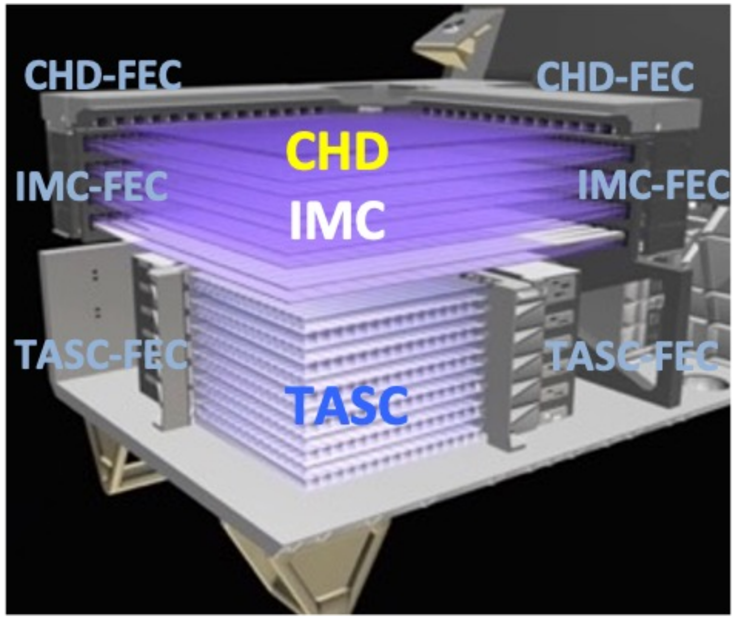
✓ We greatly appreciate JAXA staffs for perfect support of the CALET operation at the TKSC of JAXA !!
✓ **This work is partially supported by JSPS KAKENHI Kiban (S) Grant Number 19H05608 (2019-2023FY).**

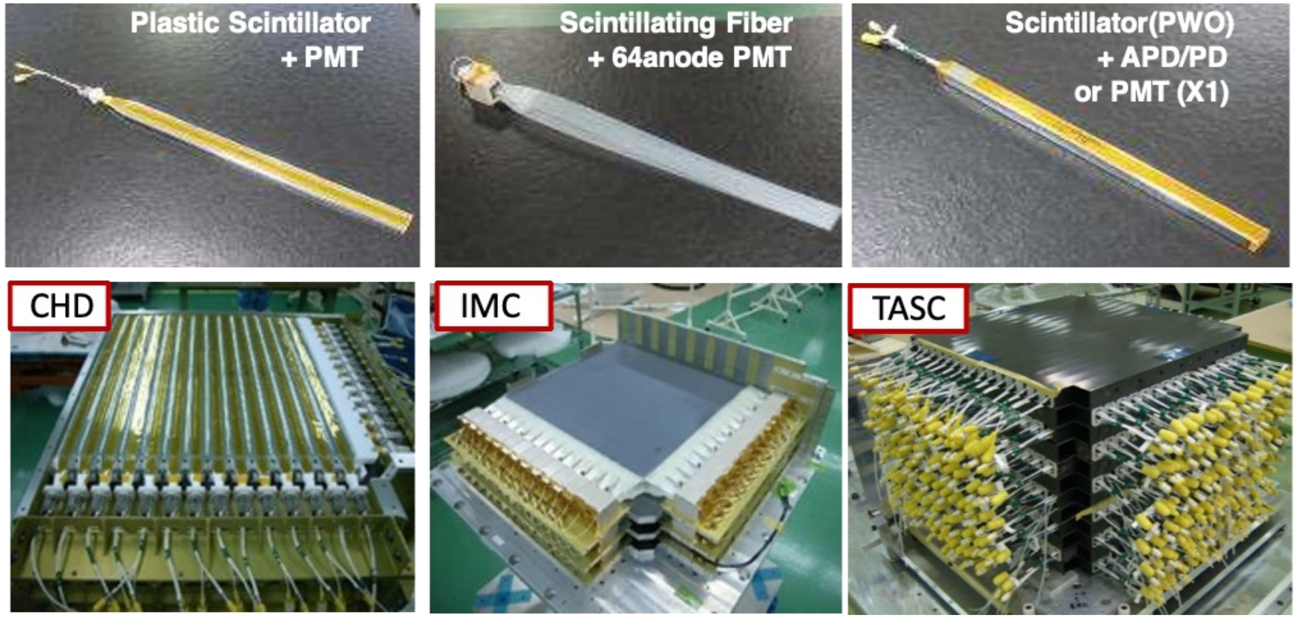
BACKUP

Main Science Goals and Status of the Analysis

Scientific Objectives	Observables	Energy Reach	Reported	Reference	Present
Cosmic-ray origin and acceleration	**Electron spectrum**	1 GeV – 20 TeV	to 4.8 TeV	PRL 120, 261102 (2018)	**11 GeV – 4.8 TeV**
	Proton spectrum	10 GeV – 1 PeV	to 10 TeV	PRL 122, 181102 (2019)	**30 GeV – 60 TeV**
	Helium spectrum	10 GeV – 1 PeV	preliminary	preliminary	**50 GeV – 50 TeV**
	Carbon and oxygen spectra	10 GeV – 1 PeV	to 2.2 TeV/n	PRL 125, 251102 (2020)	**10 GeV/n – 2.2 TeV/n**
	Iron spectrum	10 GeV – 1 PeV	to 2 TeV/n	PRL 125,241101 (2021)	**50 GeV/n – 2 TeV/n**
	Elemental spectra of primaries	10 GeV – 1 PeV	to 100 TeV	ICRC 2019, 034	10 GeV – 100 TeV
	Ultra-heavy abundances	> 600 MeV/n	> 600 MeV/n	ICRC 2019, 130	> 600 MeV/n
CR propagation	**B/C and secondary-to-primary ratios**	Up to some TeV/n	to 200 GeV/n	ICRC 2019, 034	**16 GeV/n – 2.2 TeV/n**
Nearby electron sources	**Electron spectral shape**	100 GeV – 20 TeV	to 4.8 TeV	ICRC 2019, 142	to 4.8 TeV
Dark matter	**Signatures in e/γ spectra**	100 GeV–20TeV (e) 10 GeV-10TeV (γ)	to 4.8 TeV (e) to 600 GeV (γ)	ICRC2019 , 533	to 4.8 TeV
Gamma rays	**Diffuse & point sources**	1 GeV – 10 TeV	1 GeV – 1 TeV	ApJS 238:5 (2018)	1 GeV – 1 TeV
Heliospheric physics	**Solar modulation**	1 GeV – 10 GeV	1 – 10 GeV	ICRC 2019, 1126	**1 – 10 GeV**
Gamma-ray transients	**GW follow-up and GRB analysis**	7 keV–20MeV (CGBM) 1 GeV-1TeV (ECAL)	7 KeV-20MeV	ApJL 829:L20 (2016)	7 keV–20MeV (CGBM) > 1 GeV (ECAL)
Space weather	**Relativistic electron precipitation**	> 1.5 MeV	> 1.5 MeV	Geophys.Res.Lett,43 (2016)	> 1.5 MeV

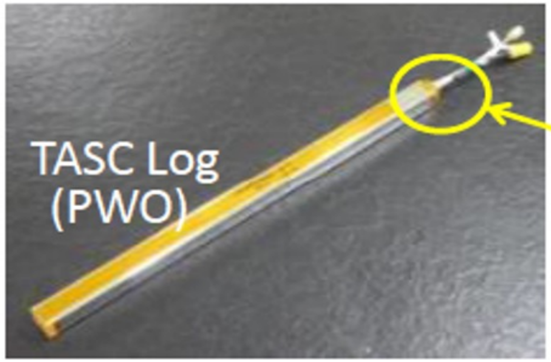
CALET Detector: Calorimeter

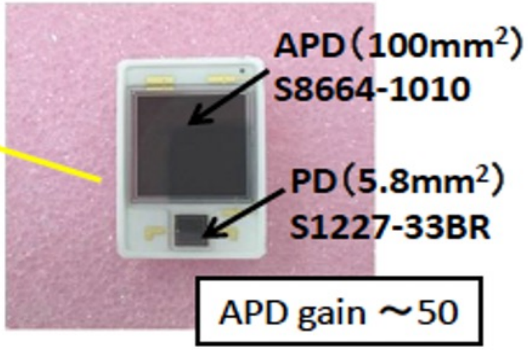




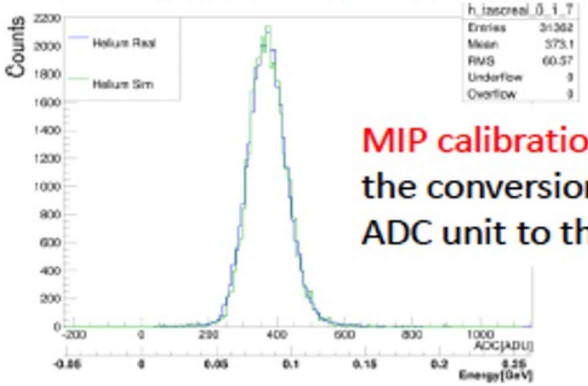
	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers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

Energy Measurement in a Wide Dynamic Range 1-10^6 MIPs

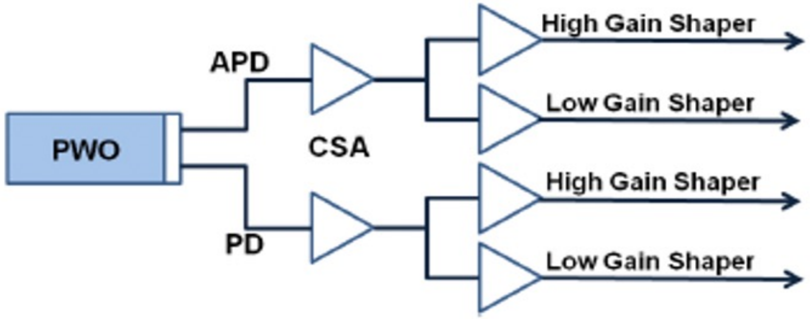




"MIP" peak in PWO: Obs. vs. MC



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

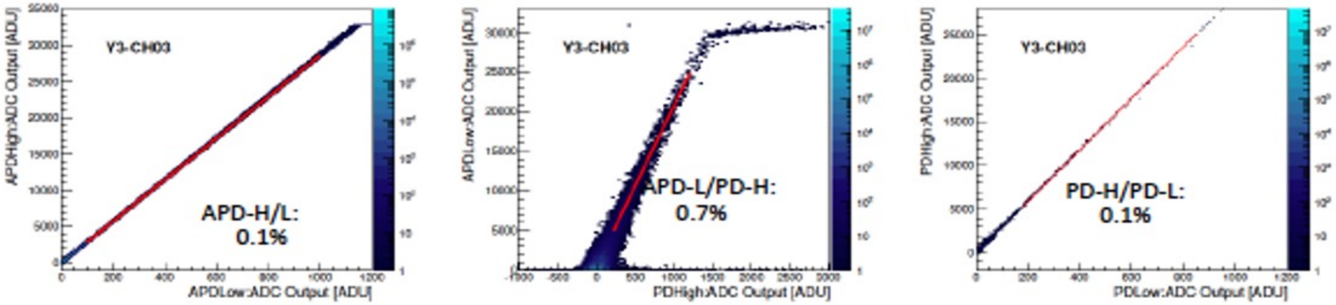


The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

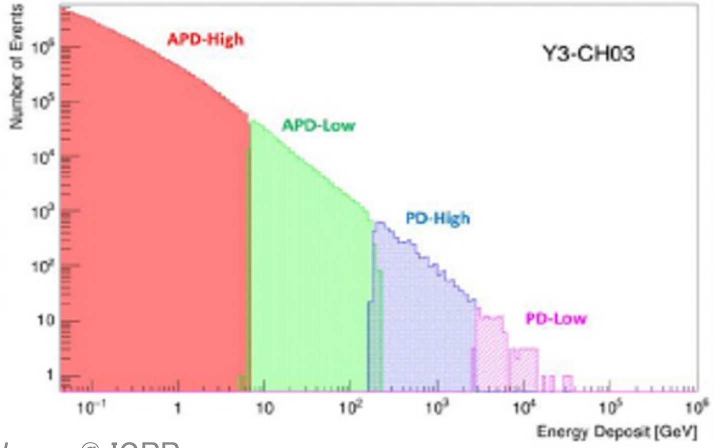
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

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



Electron Measurement with CALET: Accurate Measurements Constrain Systematics

1. Acceptance ⇨ well defined SΩ
   - Geometrical factor — because of reliable tracking

2. Detection efficiency ⇨ $\varepsilon \sim 70$ %
   - Losses in the detector — (after electron selection, E>30 GeV) keeps mostly constant up to 5 TeV

3. Energy determination ⇨ $\Delta E/E < 2\%$ (E>20 GeV)
   - Energy resolution — Absolute energy scale calibrated
   - Calibration — by beam tests and rigidity cutoff

4. Particle Identification ⇨ $P_{BG} < 5$ % (E <1 TeV)
   - Proton contamination — $P_{BG} \sim 10$ % (1 TeV<E< 5 TeV)

⇨ *Minimize the effects of unforeseen systematics,*
combined with detailed systematic studies (see PRLs and SM)

Electron Identification

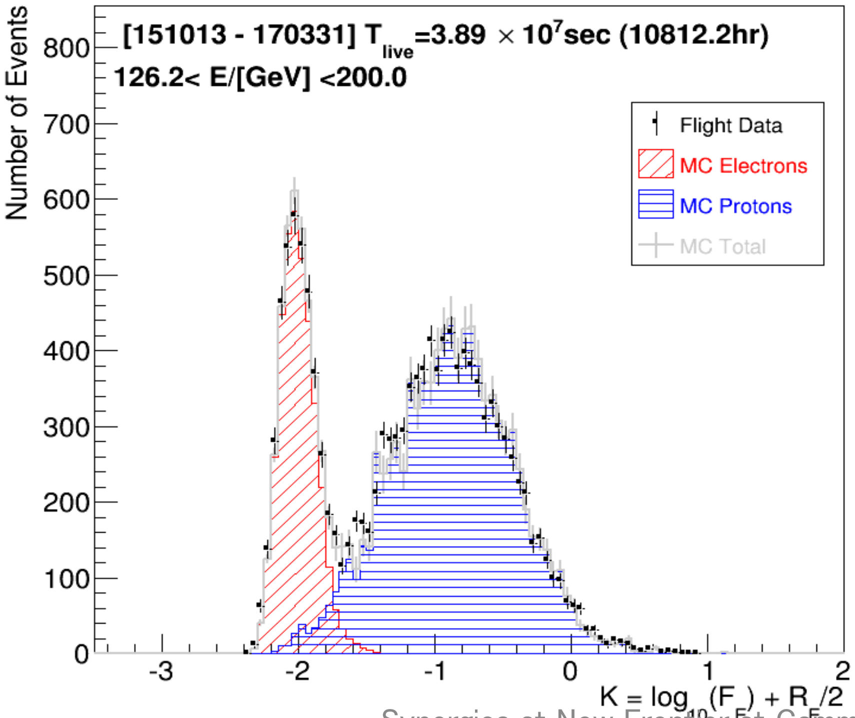
Simple Two Parameter Cut

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

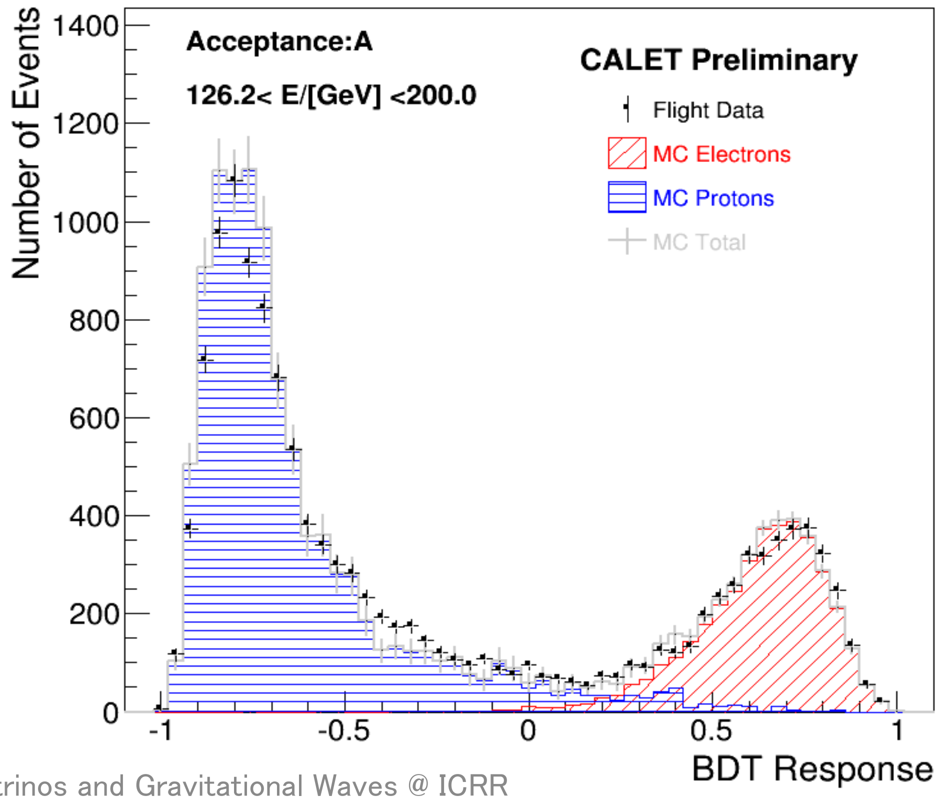
Cut Parameter K is defined as follows:

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



Boosted Decision Trees (BDT)

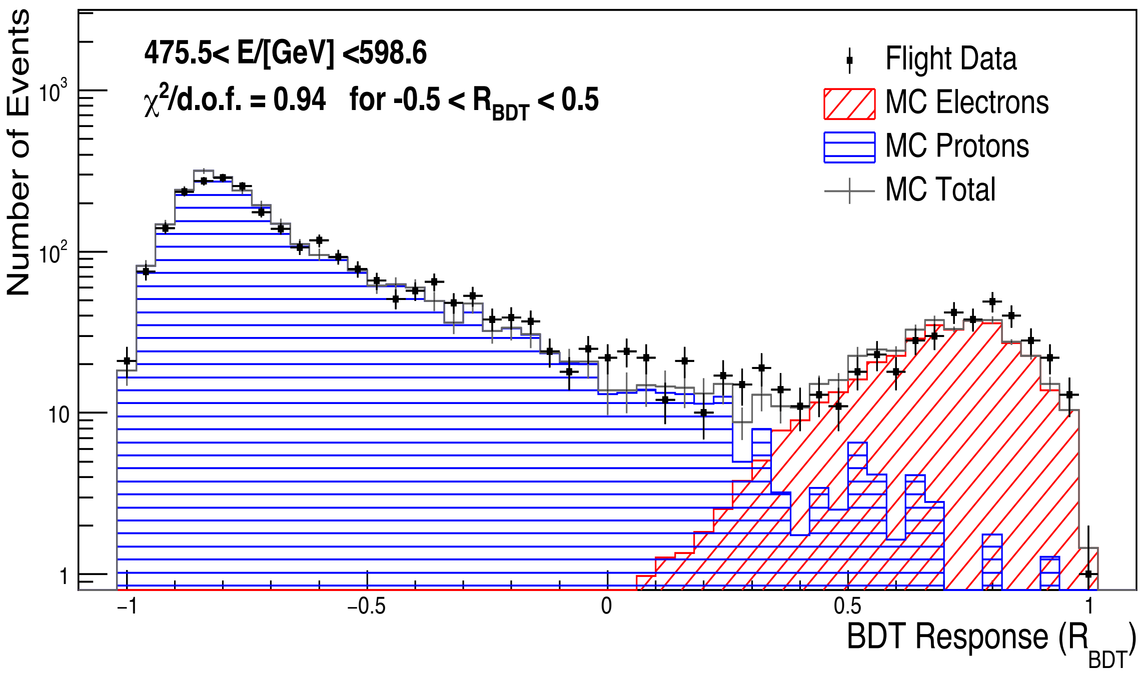
In addition to the two parameters in the left, TASC and IMC shower profile fits are used as discriminating variables.



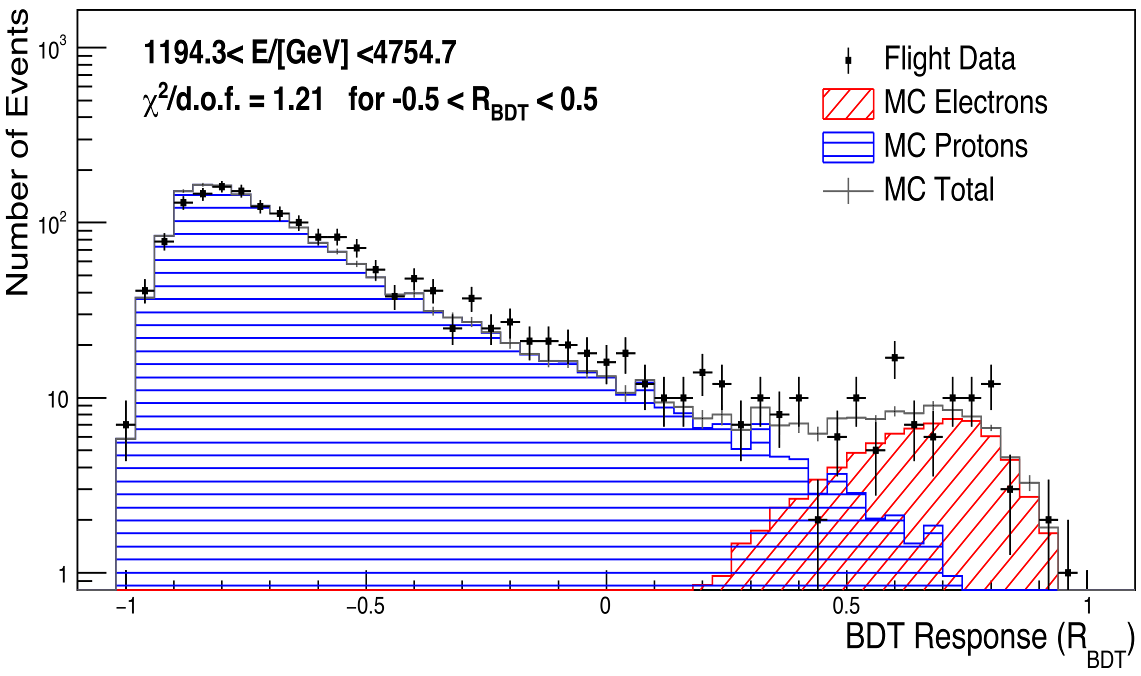
BDT Response Distribution at Higher Energies

In the final electron sample, the resultant contamination ratios of protons are:
< 5 % up to 1 TeV ; ~ 10 % in the 1 – 5 TeV region
, while keeping a constant high efficiency of 80 % for electrons.

476 < E < 599 GeV



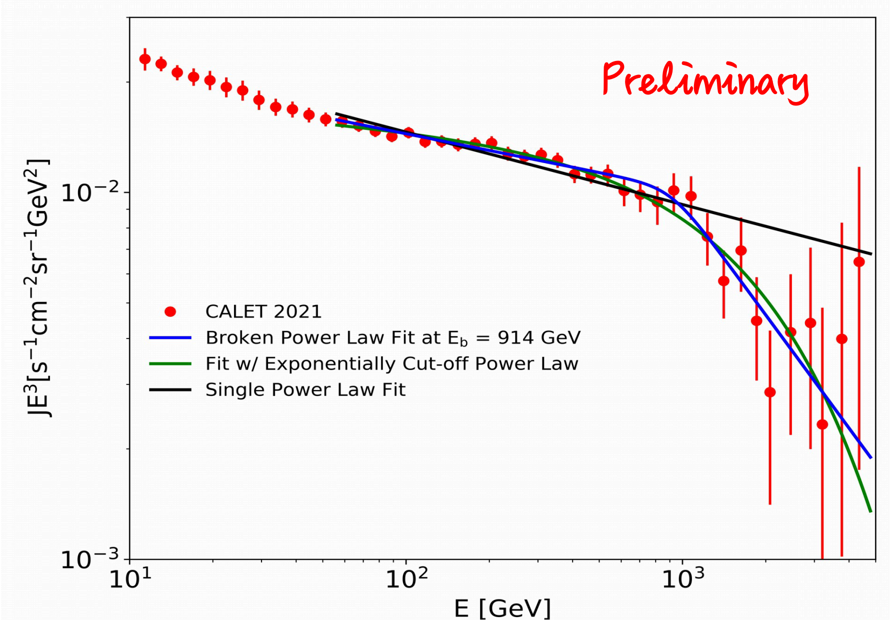
1196 < E < 4755 GeV (highest energy bin)



Towards an interpretation of the CALET all-electron spectrum

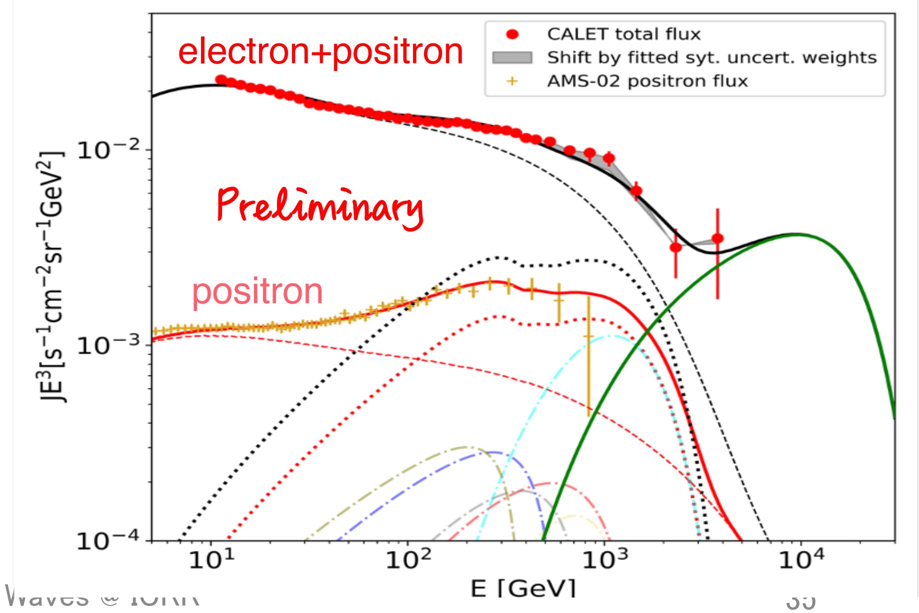
- Fits of the CALET all-electron spectrum in 55 GeV - 4.8 TeV, using the same energy binning as DAMPE [Nature, 2017]
  - Broken power law used in DAMPE
    γ= - 3.151 ⇨ - 4.024 (χ^2 /NDF=11.64/29)
  - Exponential cut-off power law [PRL, 2018]
    γ= - 3.054 with E_c= 2.17 TeV (χ^2 /NDF=11.25/29)
  - Single power law
    γ=-3.197 (χ^2 /NDF=54.50/30)

The significance of both fits of softening spectrum is considerably improved: 4 σ (PRL2018) => nearly 6.5 σ,



- Tentative spectral fit in 11 GeV-4.8 TeV including pulsars and a possible Vela SNR contribution.
  - Positron flux(AMS): secondaries+ nearby pulsars
  - Electron flux (CALET-AMS):
    Secondaries + Distant SNRs (black dashed line)
    + Vela SNR (green line).

A possible contribution from the Vela SNR:
Energy output of 2.08 x 10^{48} erg in electron CR above 1 GeV.

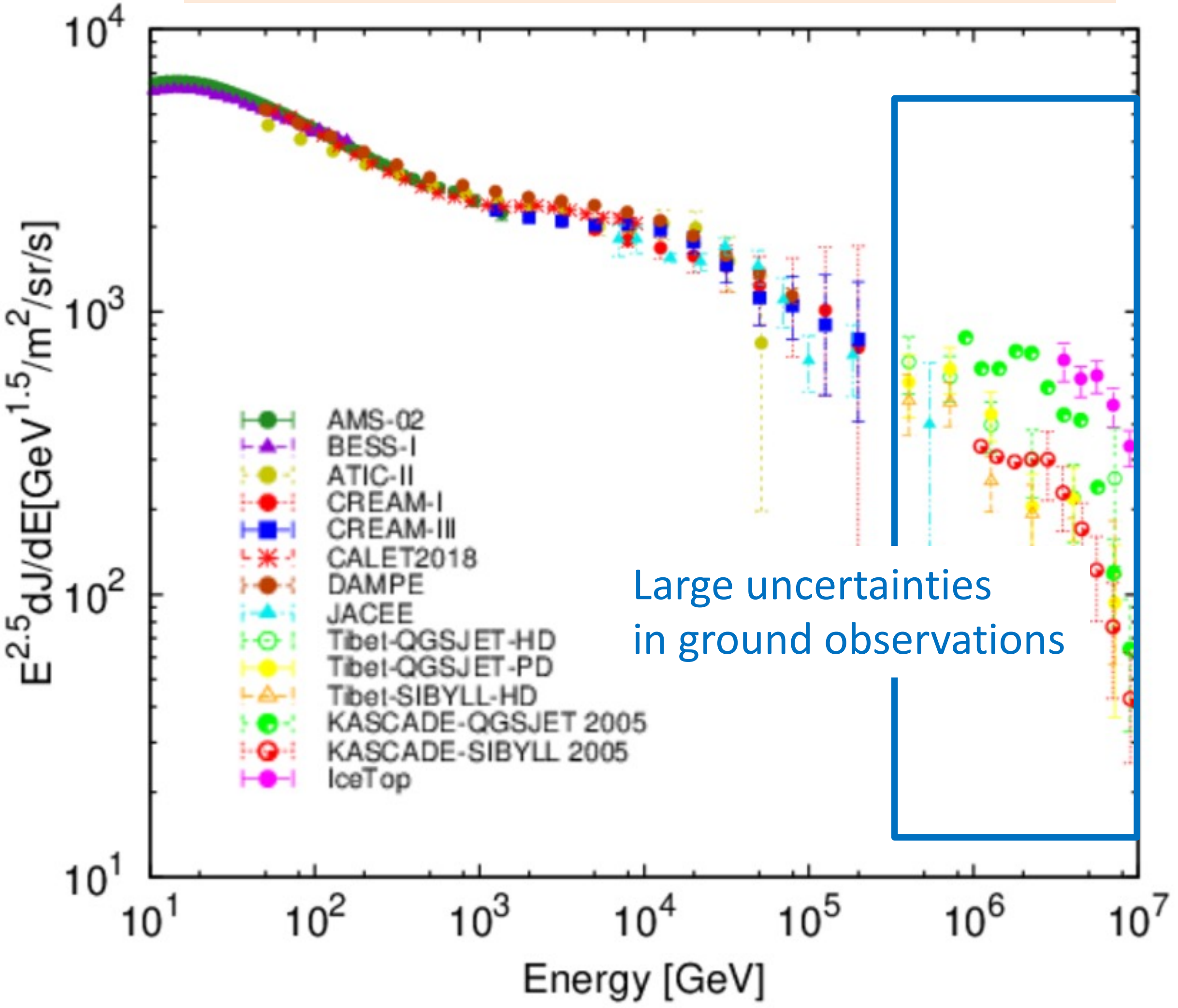


Proton spectra observed in space and on ground

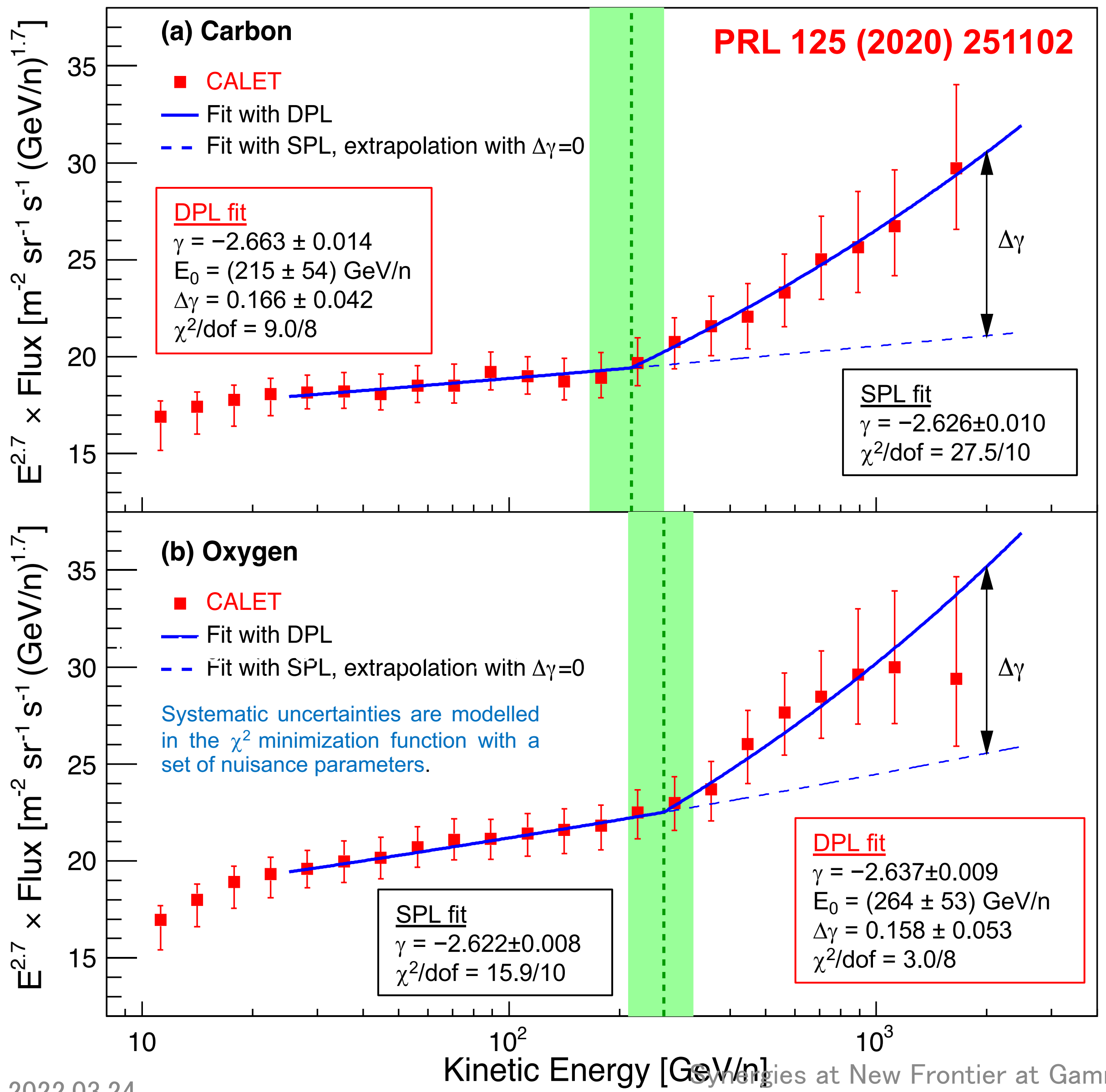
- Proton flux hardening has been observed around a few 100 GeV region. Also the softening was observed by CALET, DAMPE and Balloon Experiments around 10 TeV. It is important to determine spectrum hardening and softening parameters in order to understand cosmic ray source, acceleration mechanism, and propagation effects.

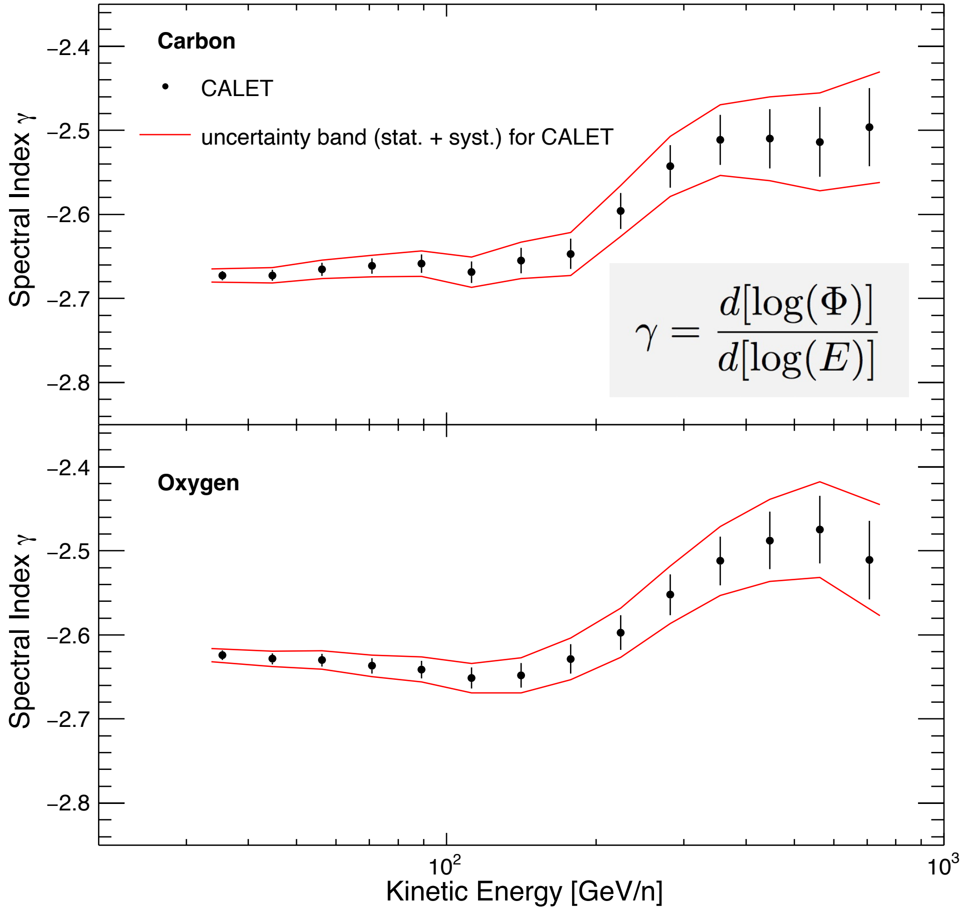
- It is also important to determine the flux up to hundreds of TeV by the direct measurements. That would also give a normalization of flux, for ground observations, and help an understanding of the origin of the KNEE in all-particle energy spectrum.

Proton flux in PRL2019 compared to other direct and ground measurements



Carbon and Oxygen: Spectral Analysis





$$\gamma = \frac{d[\log(\Phi)]}{d[\log(E)]}$$

Double power-law (DPL) fit

$$\Phi(E) = \begin{cases} C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma} & E \le E_0 \\ C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left(\frac{E}{E_0}\right)^{\Delta\gamma} & E > E_0 \end{cases}$$

Single Power Law hypothesis excluded at 3.9σ level for C and 3.2σ for O