国際宇宙ステーション搭載
CALETによる6年間観測の成果

CALET

Calorimetric
Electron
Telescope

on the International Space Station

鳥居祥二
早稲田大学理工総研
他CALET国際研究チーム

第22回　宇宙科学シンポジウム（2021年度）

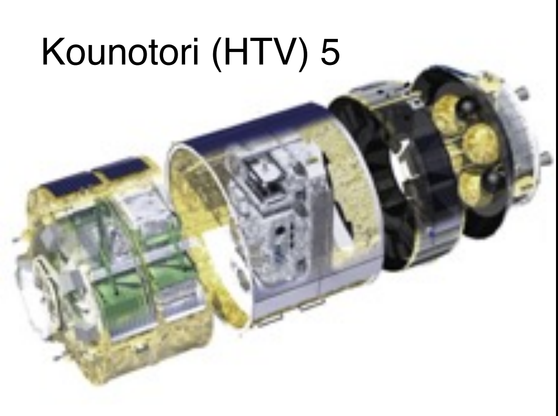
The CALET Collaboration Member

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[9,10], J.H. Buckley[8], N. Cannady[11,12,13], G. Castellini[14], C. Checchia[6], M.L. Cherry[15], G. Collazuol[16,17], K. Ebisawa[18], A.W. Ficklin[15], H. Fuke[18], S. Gonzi[1,2], T.G. Guzik[15], T. Hams[11], K. Hibino[19], M. Ichimura[20], K. Ioka[21], W. Ishizaki[5], M.H. Israel[8], K. Kasahara[22], J. Kataoka[23], R. Kataoka[24], Y. Katayose[25], C. Kato[26], N. Kawanaka[27,28], Y. Kawakubo[15], K. Kobayashi[3,4], K. Kohri[29], H.S. Krawczynski[8], J.F. Krizmanic[11,12,13], J. Link[11,12,13], P. Maestro[6,7], P.S. Marrocchesi[6,7], A.M. Messineo[30,7], J.W. Mitchell[31], S. Miyake[32], A.A. Moiseev[33,12,13], M. Mori[34], N. Mori[2], H.M. Motz[35], K. Munakata[26], S. Nakahira[18], J. Nishimura[18], G.A. de Nolfo[9], S. Okuno[19], J.F. Ormes[36], N. Ospina[16,17], S. Ozawa[37], L. Pacini[1,14,2], P. Papini[2], B.F. Rauch[8], S.B. Ricciarini[14,2], K. Sakai[11,12,13], T. Sakamoto[38], M. Sasaki[32,12,13], Y. Shimizu[19], A. Shiomi[39], P. Spillantini[1], F. Stolzi[6,7], S. Sugita[38], A. Sulaj[6,7], M. Takita[5], T. Tamura[19], T. Terasawa[40], S. Torii[3], Y. Tsunesada[41], Y. Uchihori[42], E. Vannuccini[2], J.P. Wefel[15], K. Yamaoka[43], S. Yanagita[44], A. Yoshida[38], K. Yoshida[22], and W.V. Zober[15]

1) University of Florence, Italy
2) INFN Florence, Italy
3) RISE, 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 Lab., NASA/GSFC, USA
10) Catholic University of America, Washington DC, USA
11) University of Maryland, USA
12) Astroparticle Physics Lab., NASA/GSFC, USA
13) CRESST, NASA/GSFC, USA
14) IFAC, CNR, Fiorentino, Italy
15) Louisiana State University, USA
16) University of Padova, Italy
17) INFN Padova, Italy
18) ISAS, JAXA, Japan
19) Kanagawa University, Japan
20) Hirosaki University, Japan
21) YITP, Kyoto University, Japan
22) Shibaura Institute of Technology, Japan
23) Waseda University, Japan
24) National Institute of Polar Research, Japan
25) Yokohama National University, Japan
26) Shinshu University, Japan
27) Hakubi Center, Kyoto University, Japan
28) Kyoto University, Japan
29) IPNS, KEK, Japan
30) University of Pisa, Italy
31) National Institute of Technology, Japan
33) University of Maryland, USA
34) Ritsumeikan University, Japan
35) GCSE, Waseda University, Japan
36) University of Denver, USA
37) National Institute of Information and Communications Technology, Japan
38) Aoyama Gakuin University
39) Nihon University, Japan
40) RIKEN, Japan
41) Osaka City Univiersity, Japan
42) National Institutes for Quantum and Radiation Science and Technology, Japan
43) Nagoya University, Japan
44) Ibaraki University, Japan

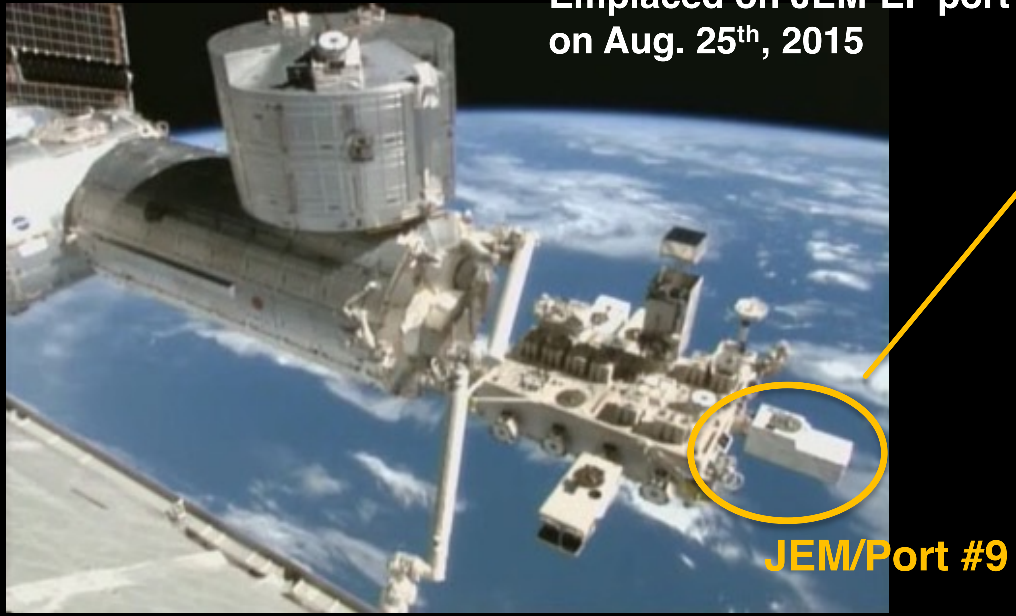
PI : Japan
Co-PI : Italy
Co-PI : USA

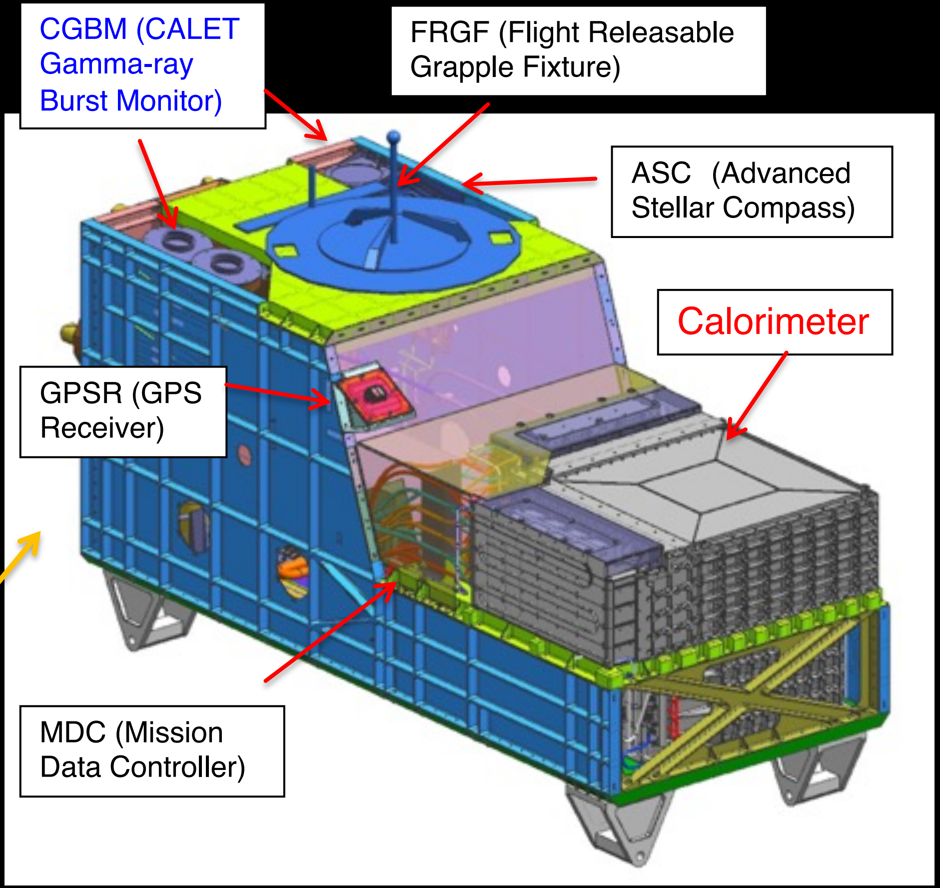
CALET Payload



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

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

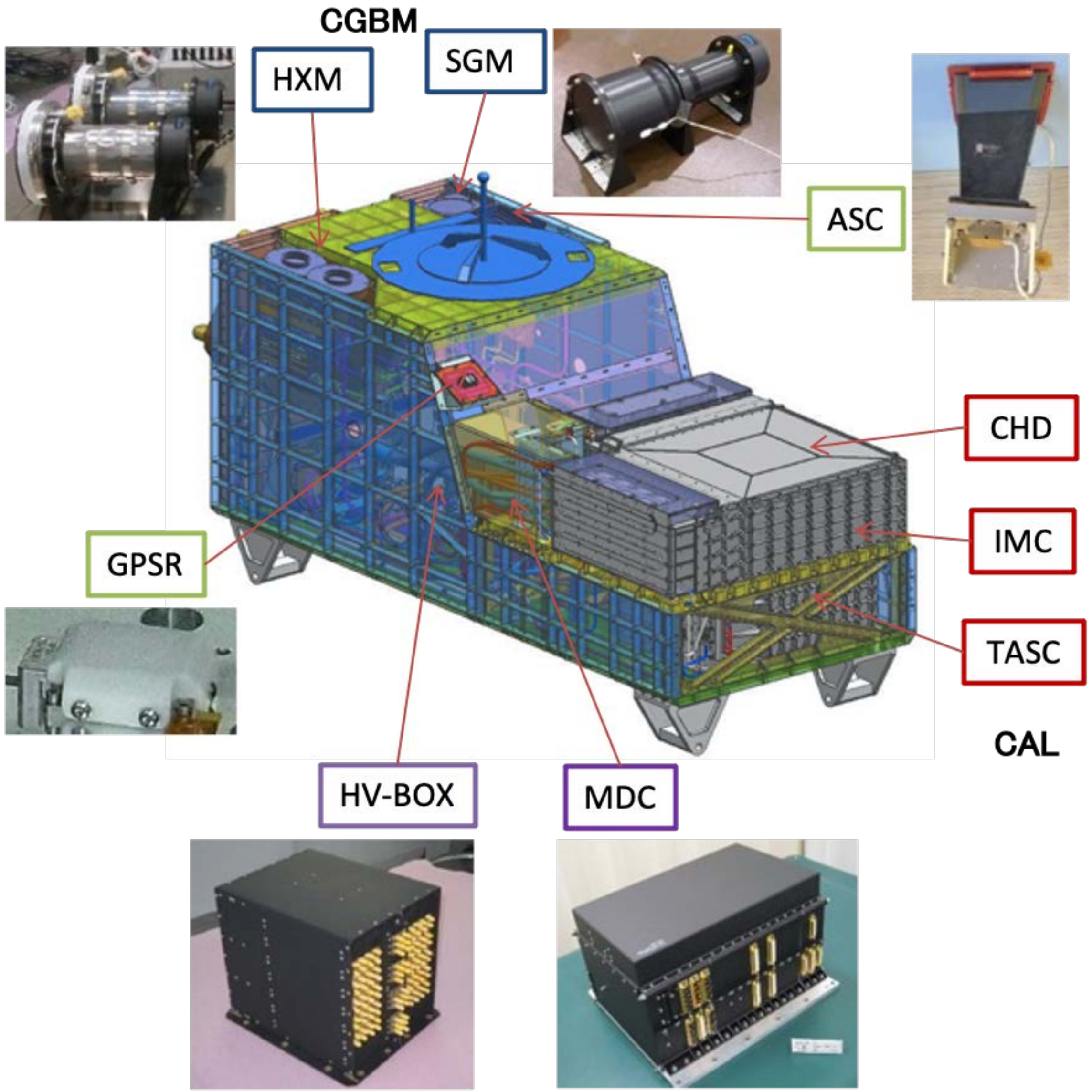




- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W (max)**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

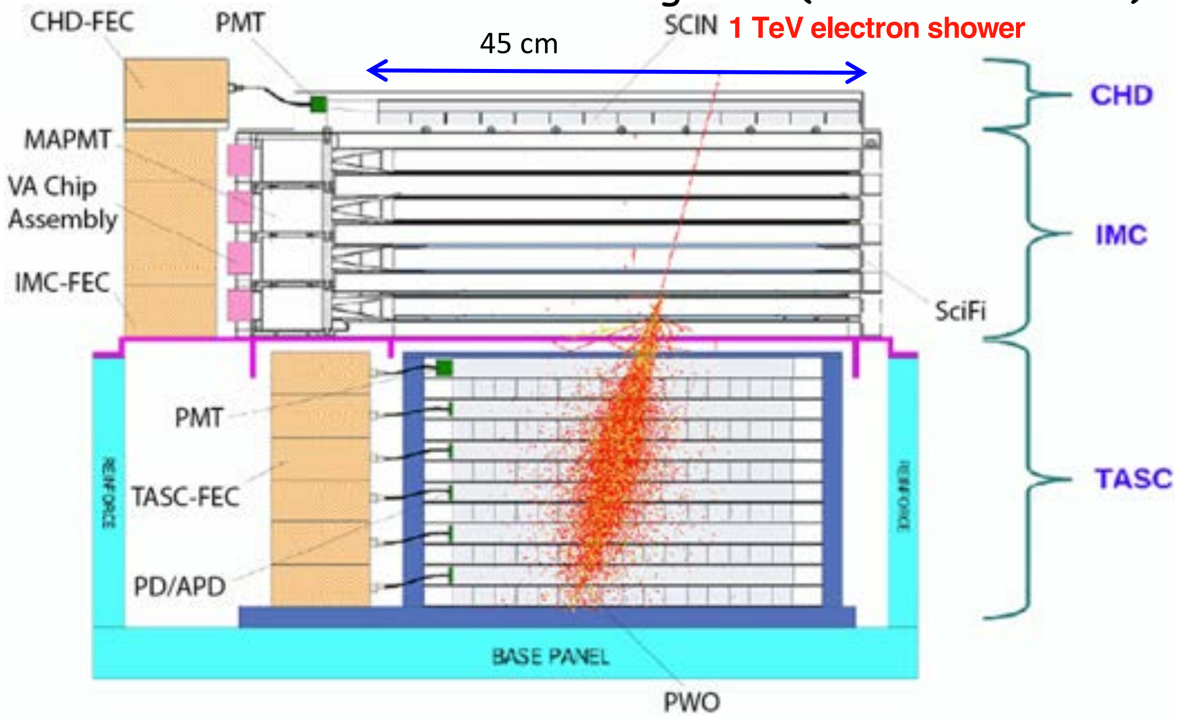
Overview of CALET Payload

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

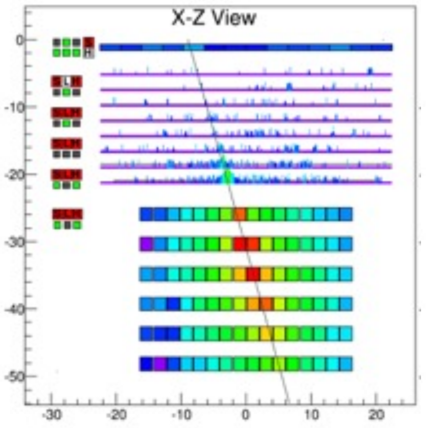
IMC – Imaging Calorimeter

- 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**

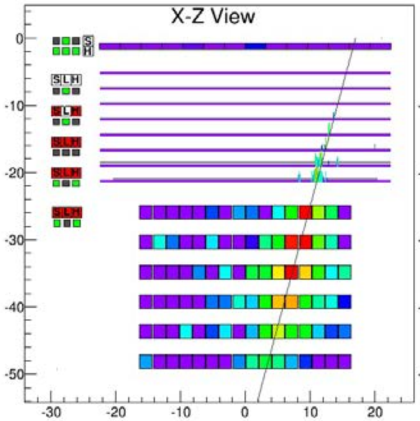
TASC – Total Absorption Calorimeter $27\ X_0,\ 1.2\ \lambda_I$

- 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}

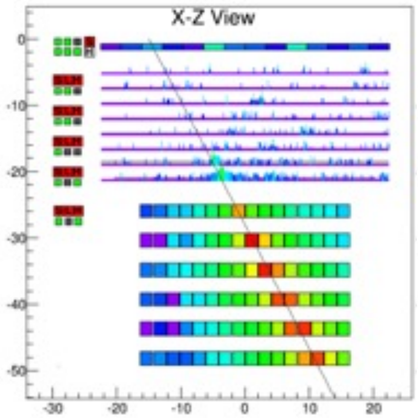
Electron, E=3.05 TeV



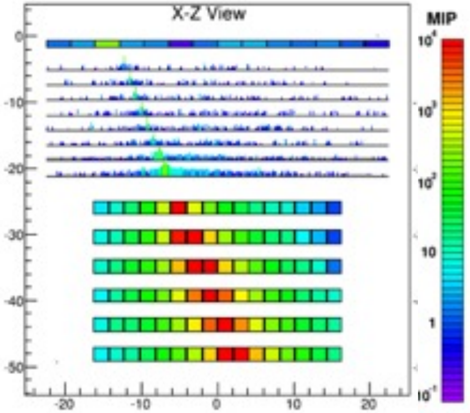
Gamma-ray, E=44.3 GeV



Proton, E_{TASC}=2.89 TeV

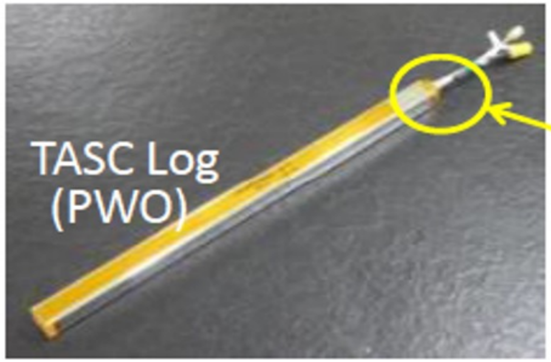


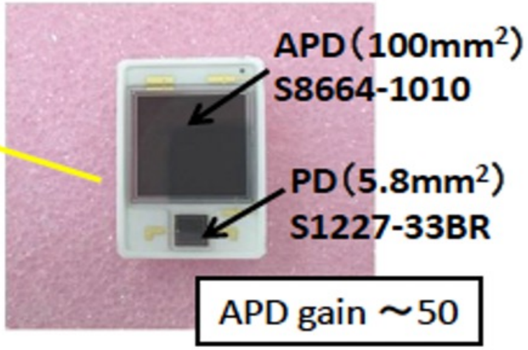
Iron, E_{TASC} =9.3 TeV



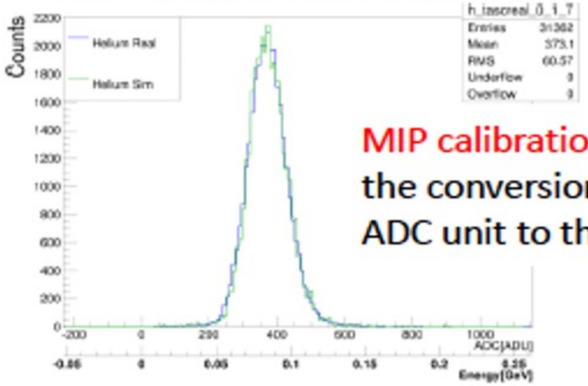
Event Display: Electron Candidate (>100 GeV)

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

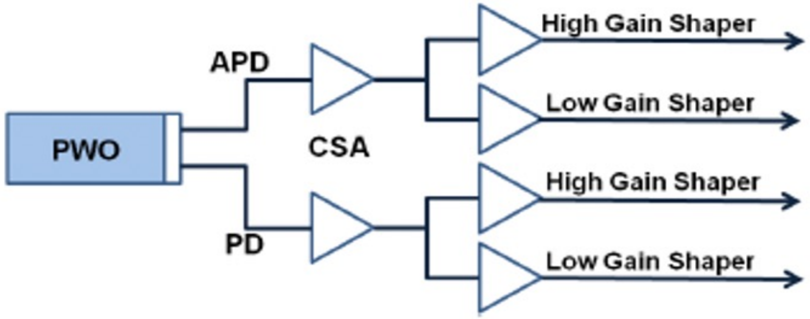




"MIP" peak in PWO: Obs. vs. MC



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

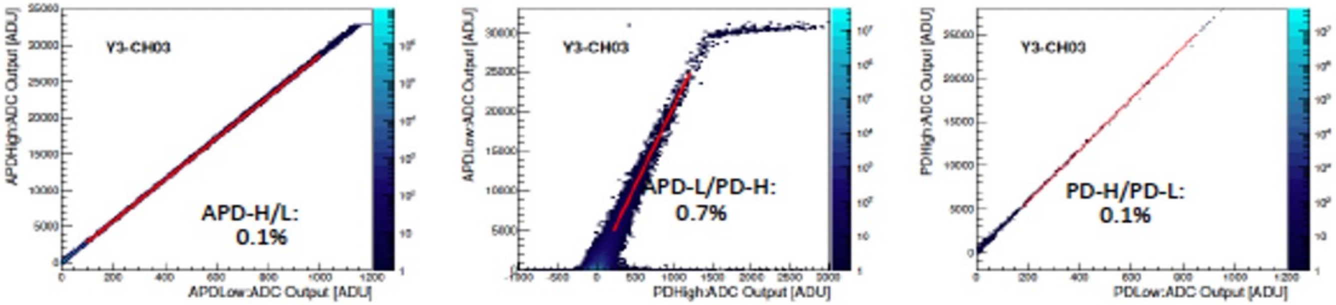


The whole dynamic range was calibrated by **UV laser irradiation** on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

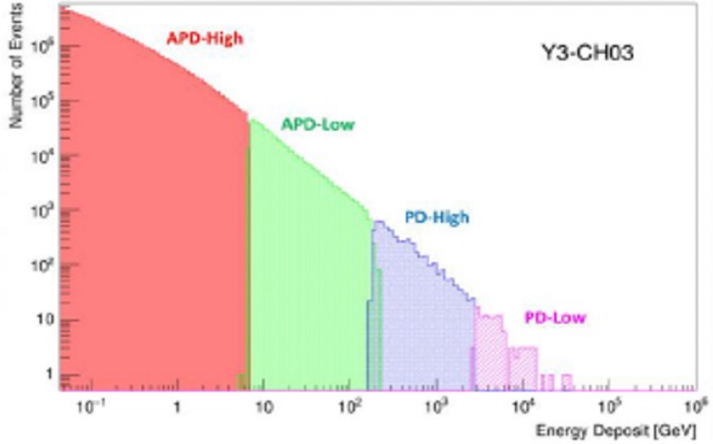
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

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%

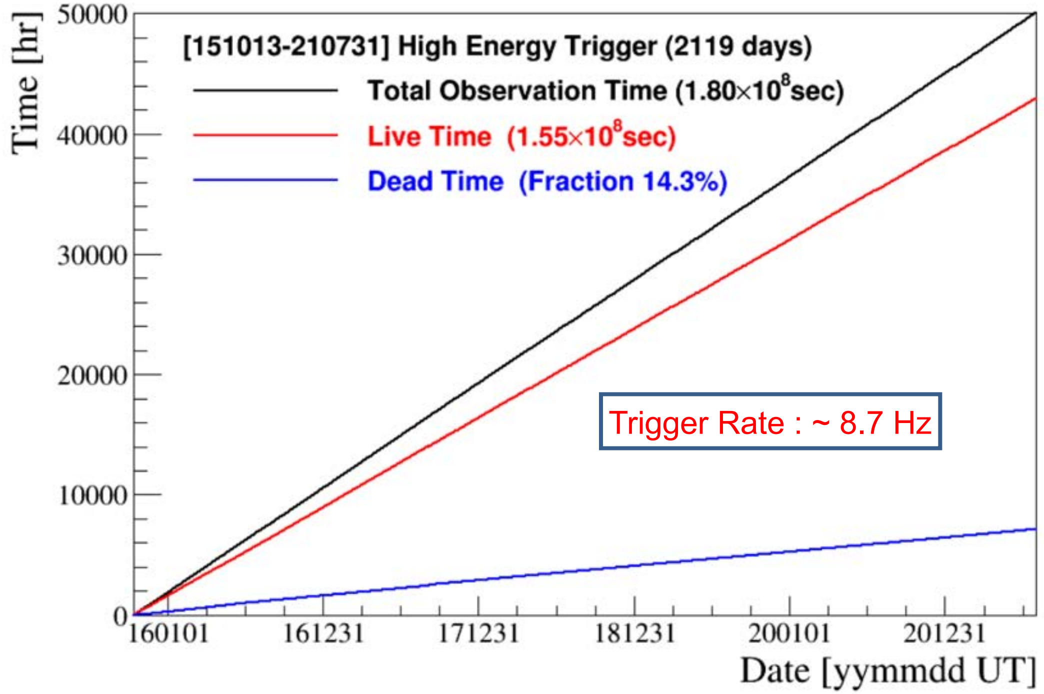


Example of energy distribution in one PWO log



CALET Observations on the ISS

Accumulated observation time (live, dead)



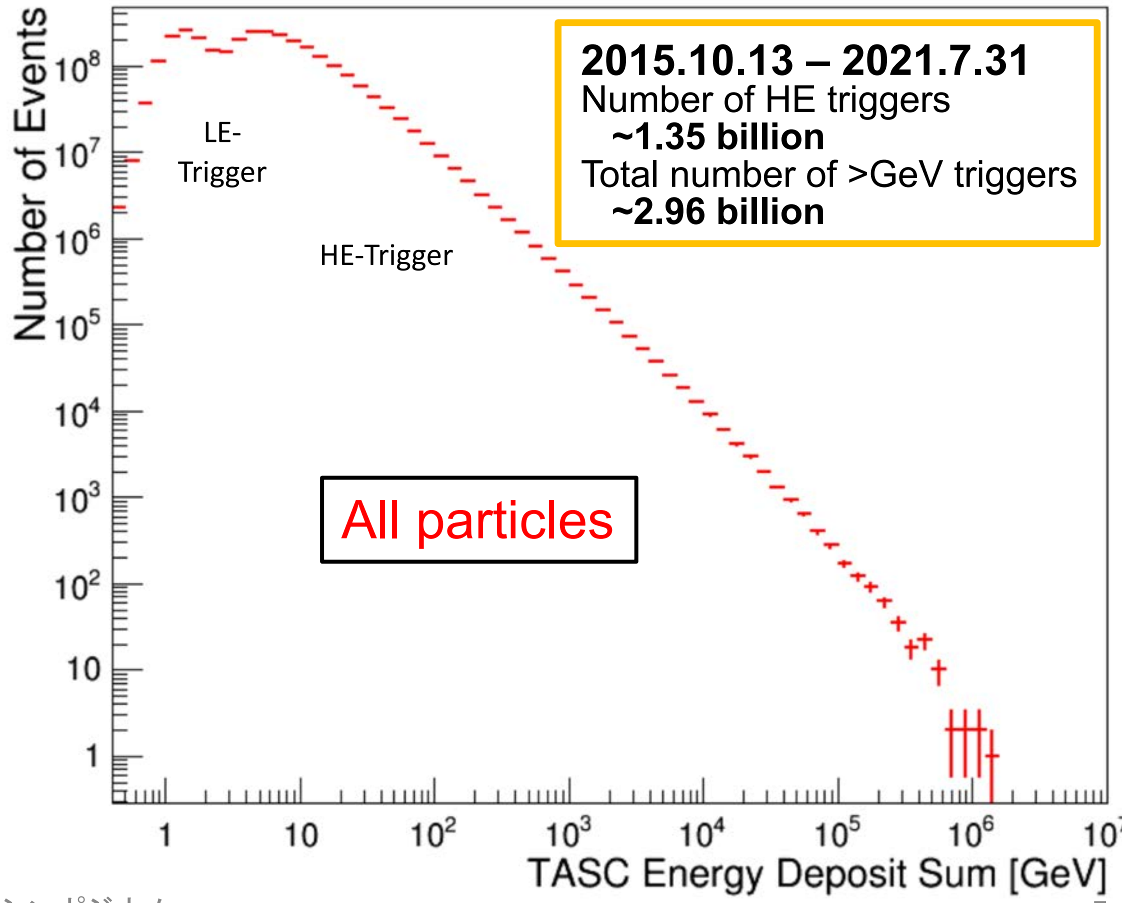
High-energy trigger (> 10 GeV) statistics:

- Operational time > **2119 days**(*)
  (*) as of July 31, 2021
- Live time fraction **> 85%**
- Exposure of HE trigger **~186 m^2 sr day**
- HE-gamma point source exposure **~3.6 m^2 day** (for Crab, Geminga)

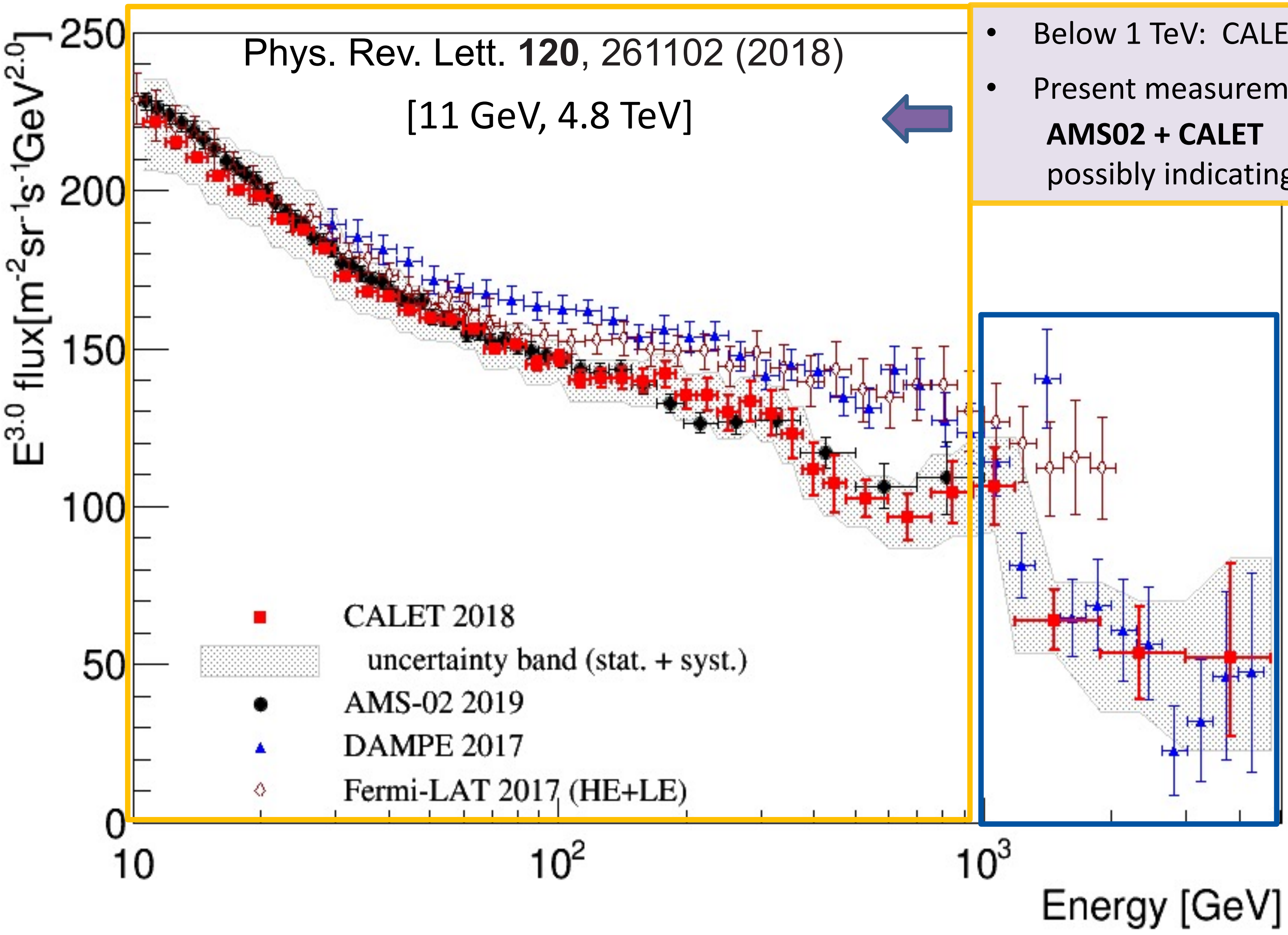
Geometrical Factor:

- 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



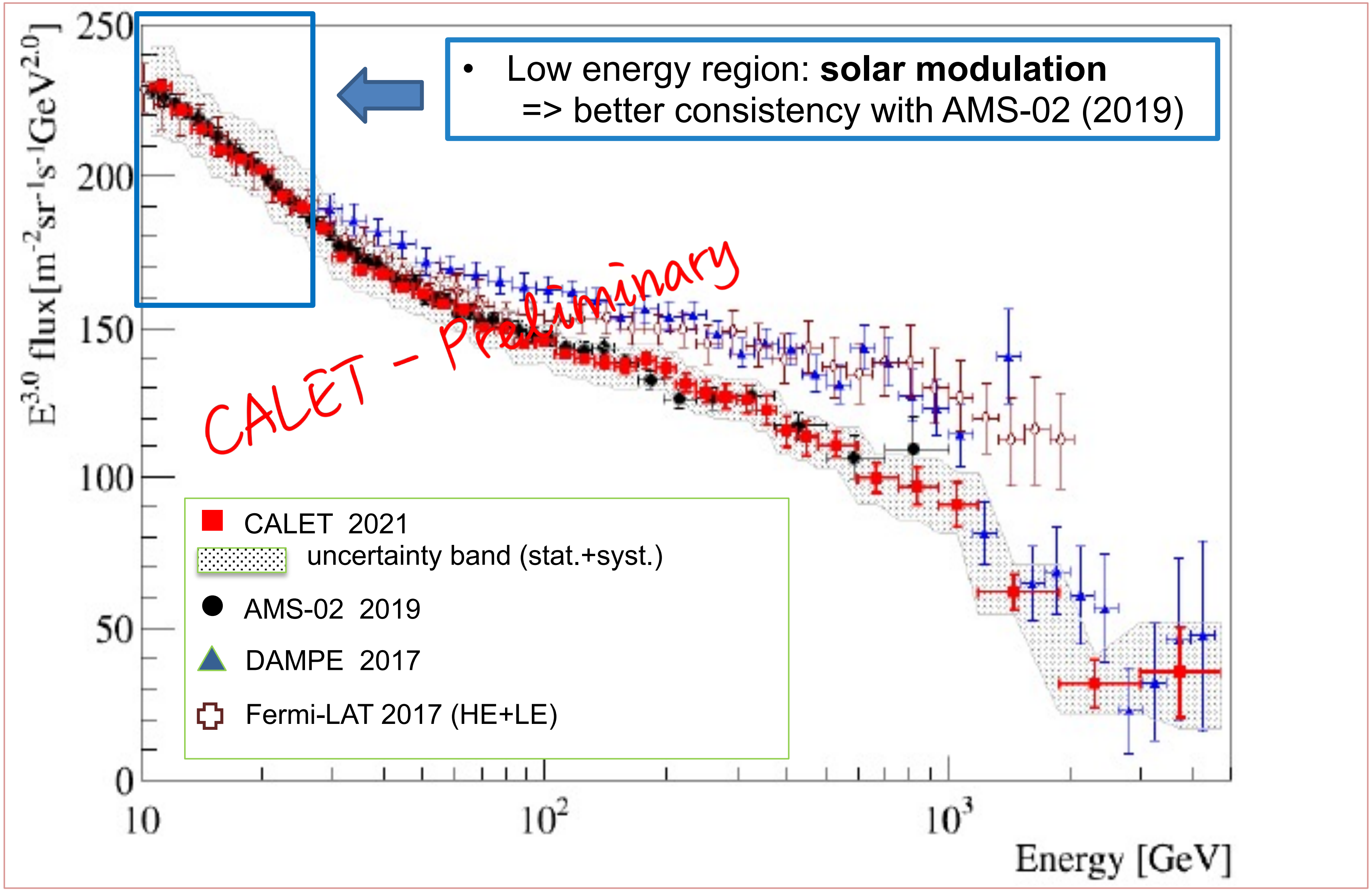
Cosmic-ray All-electron Spectrum



- 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)

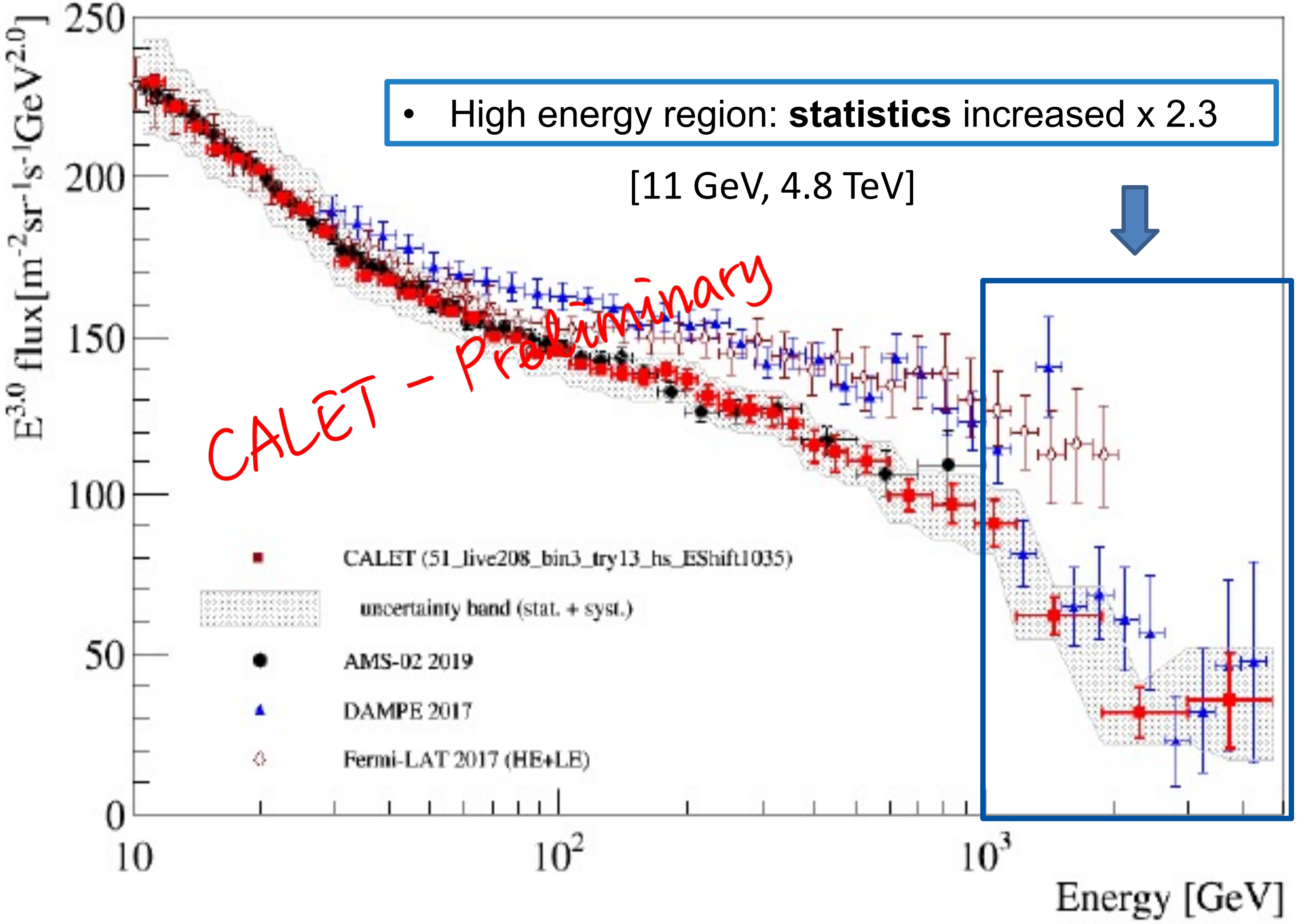


Preliminary spectrum is **updated** after 1815 days of CALET observations: Oct.13, 2015 - Sep.30, 2020

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

- High energy region: **statistics** increased x 2.3

[11 GeV, 4.8 TeV]

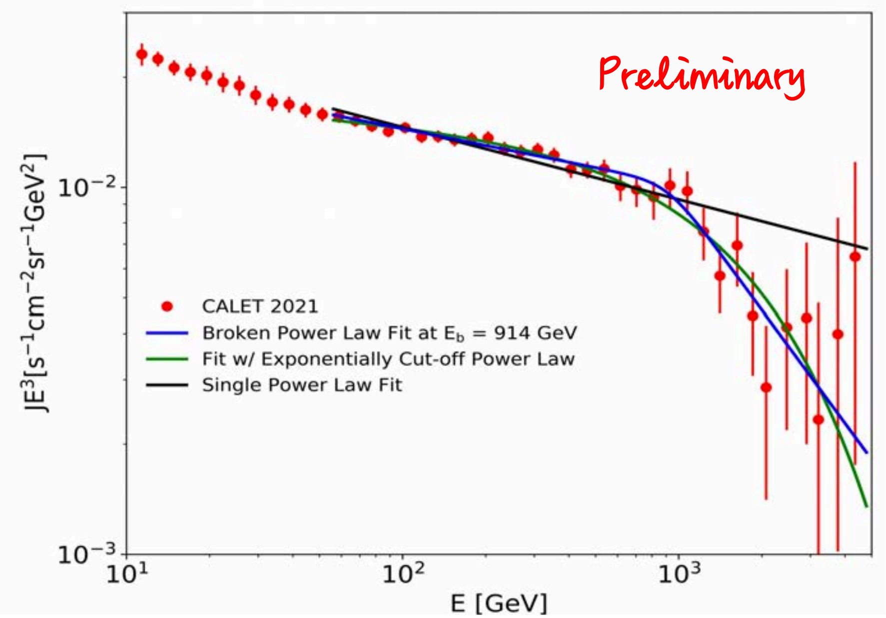


CALET observes a flux suppression above 1 TeV with a **significance > 6.5 σ**, a considerable improvement with respect to the result published in PRL2018 (~4 σ)

Towards an interpretation of the CALET all-electron spectrum

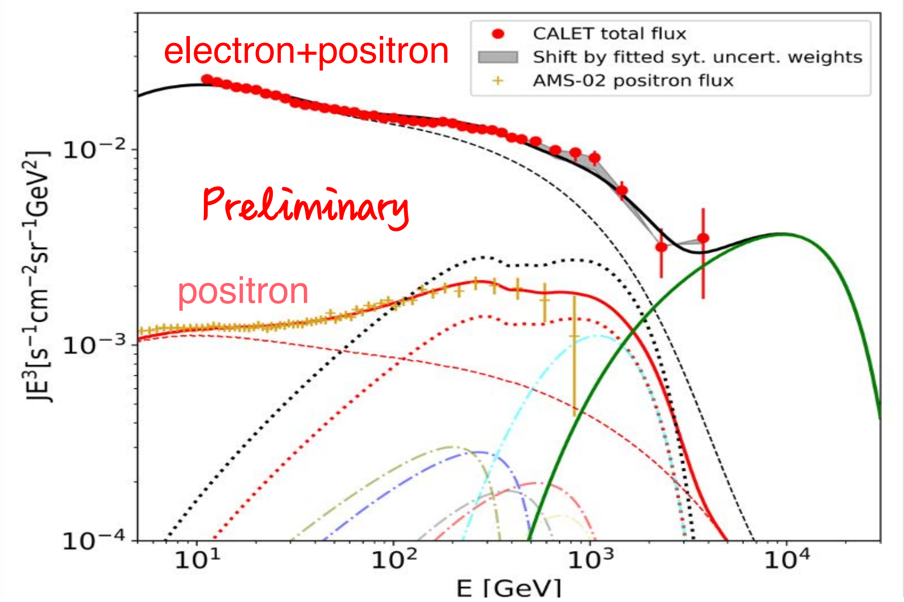
- Fits of the CALET all-electron spectrum in 55 GeV - 4.8 TeV, using the same energy binning as DAMPE [Nature, 2017]
- Broken power law used in DAMPE
  γ= - 3.151 ⇨ - 4.024 (χ^2 /NDF=11.64/29)
- Exponential cut-off power law [PRL, 2018]
  γ= - 3.054 with E_c= 2.17 TeV (χ^2 /NDF=11.25/29)
- Single power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

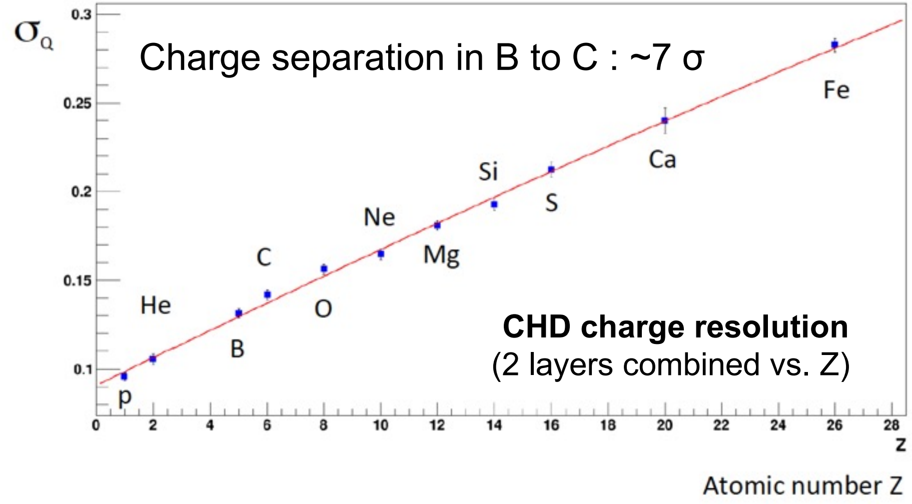
A possible contribution from the Vela SNR:
Energy output of 2.08 x 10^{48} erg in electron CR above 1 GeV.

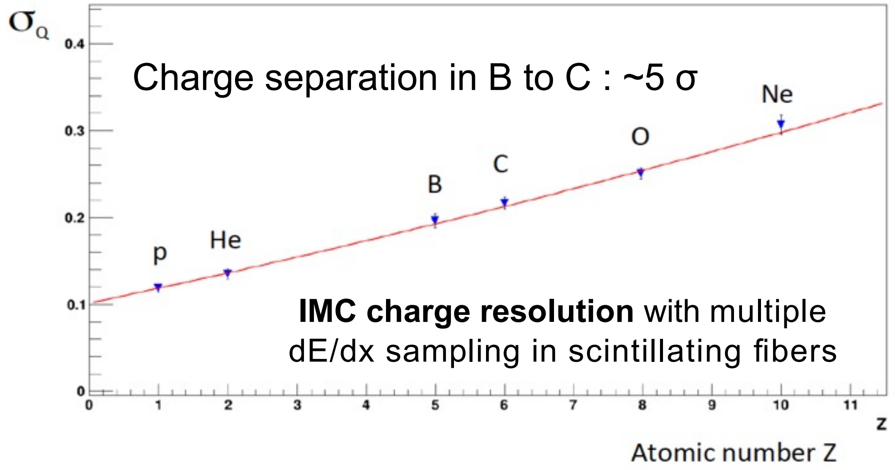


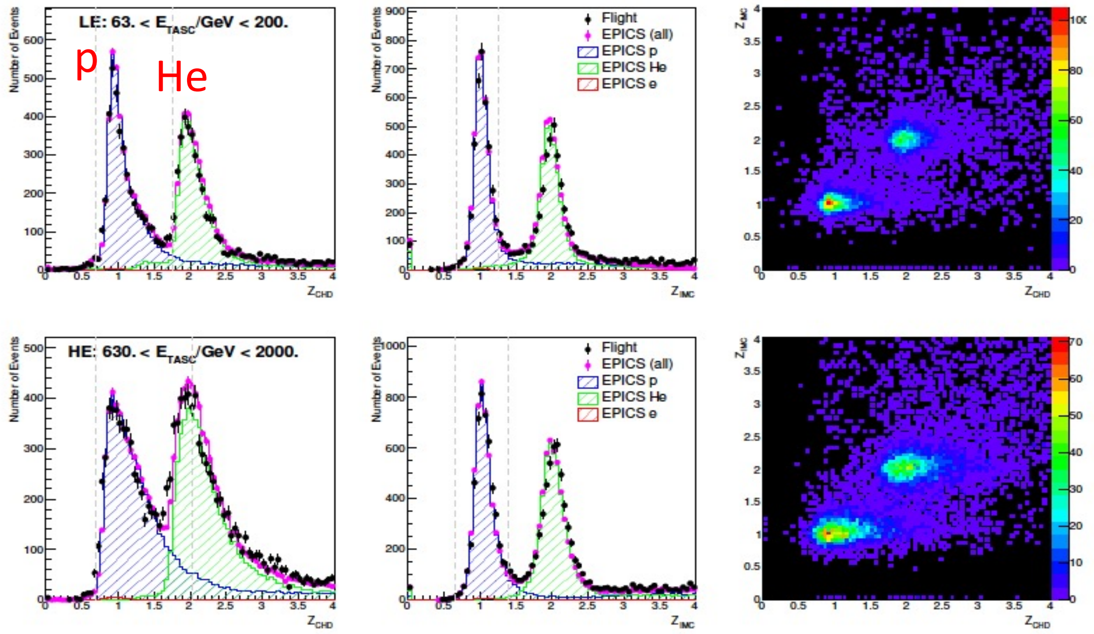
Charge Identification with CHD and IMC

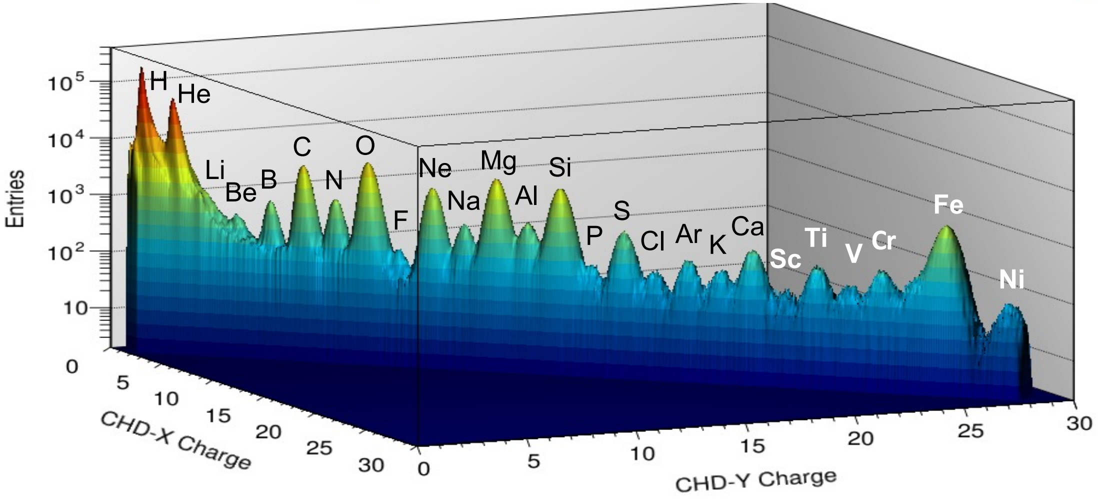
P-118

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









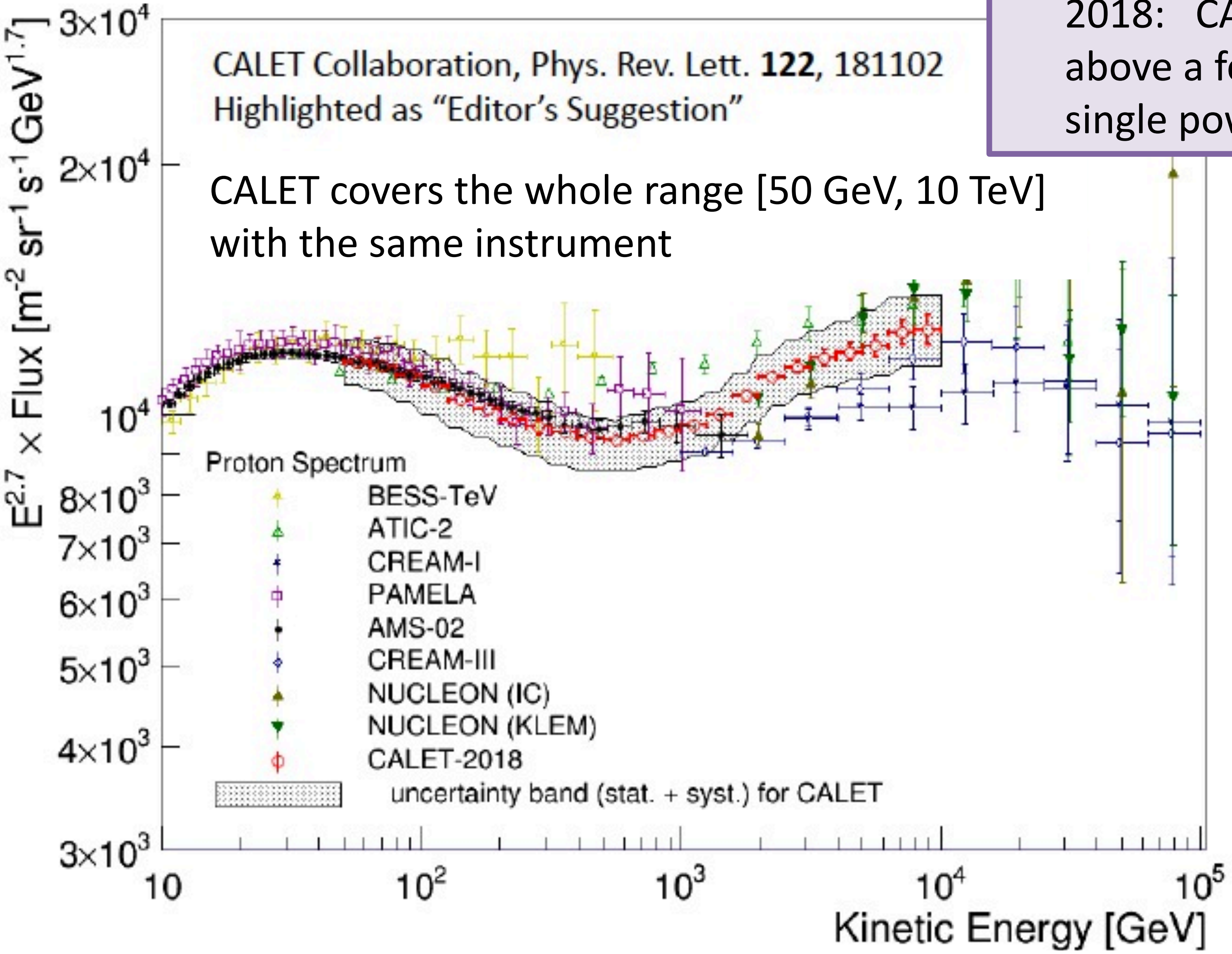
Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

Cosmic-ray proton spectrum

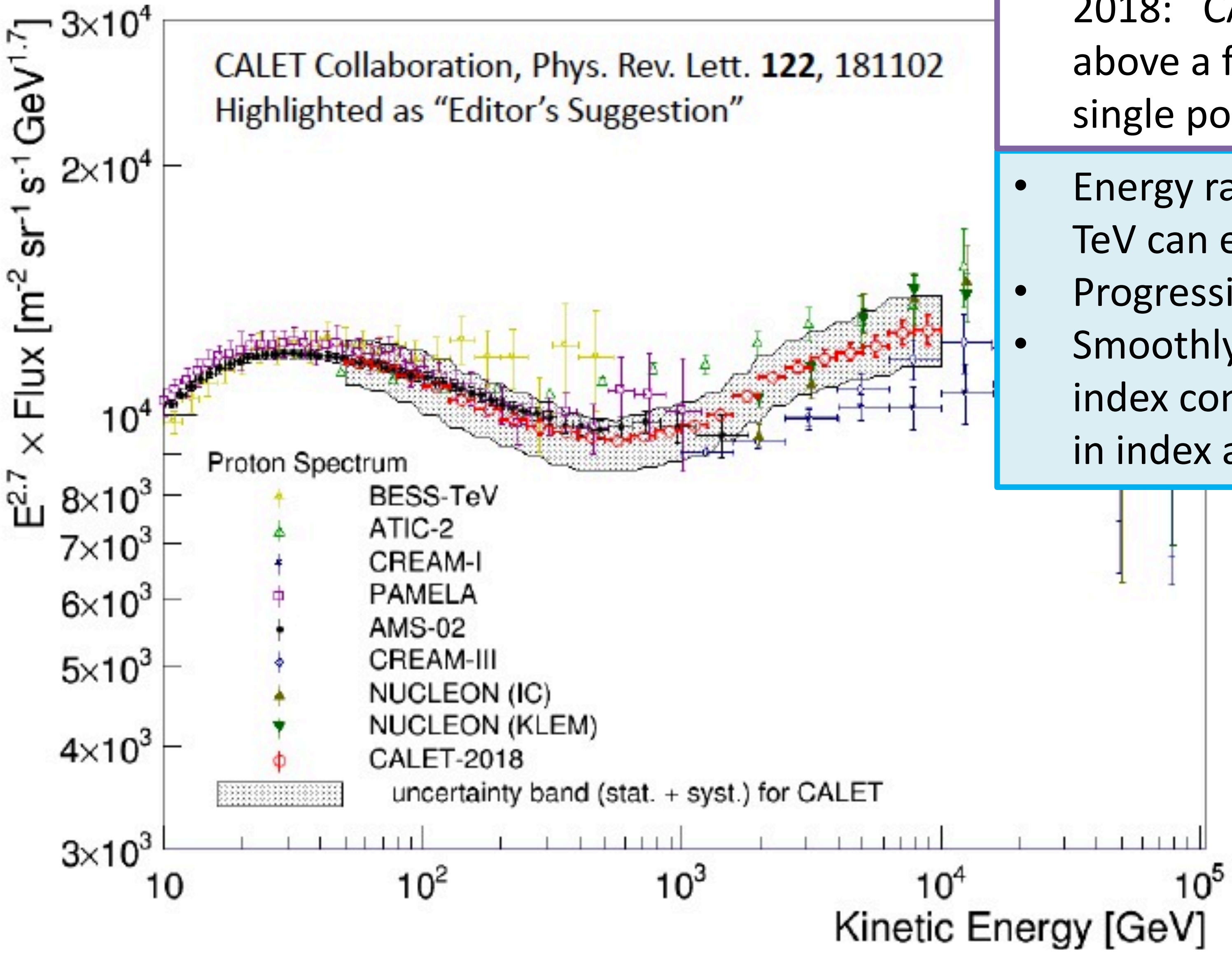
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

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

CALET covers the whole range [50 GeV, 10 TeV] with the same instrument

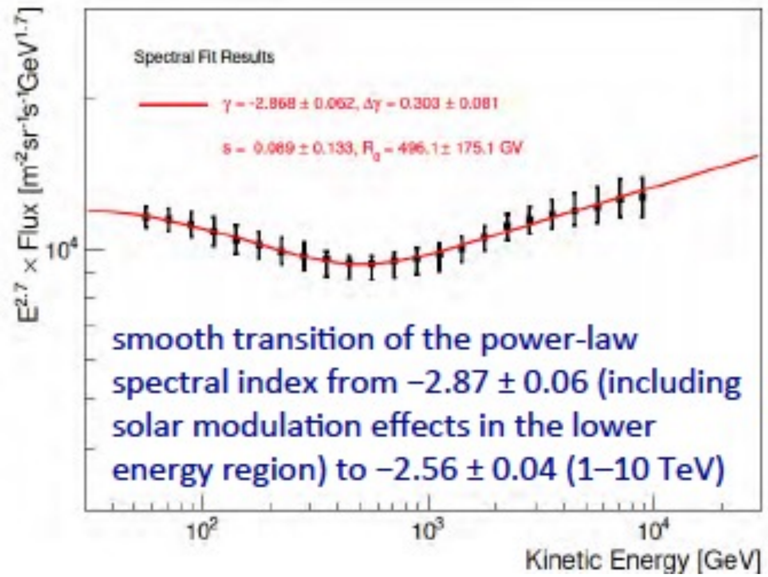


Cosmic-ray proton spectrum

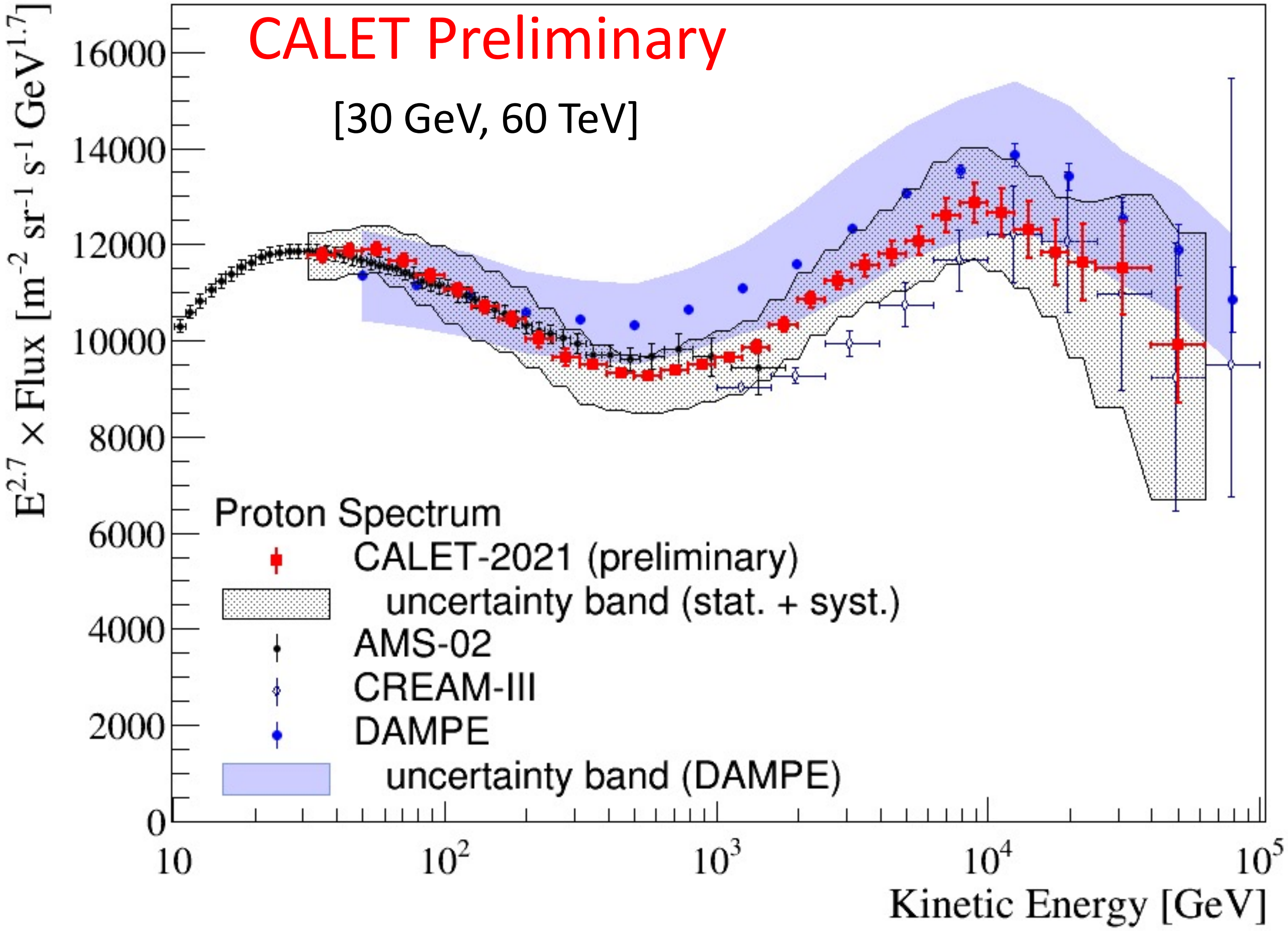


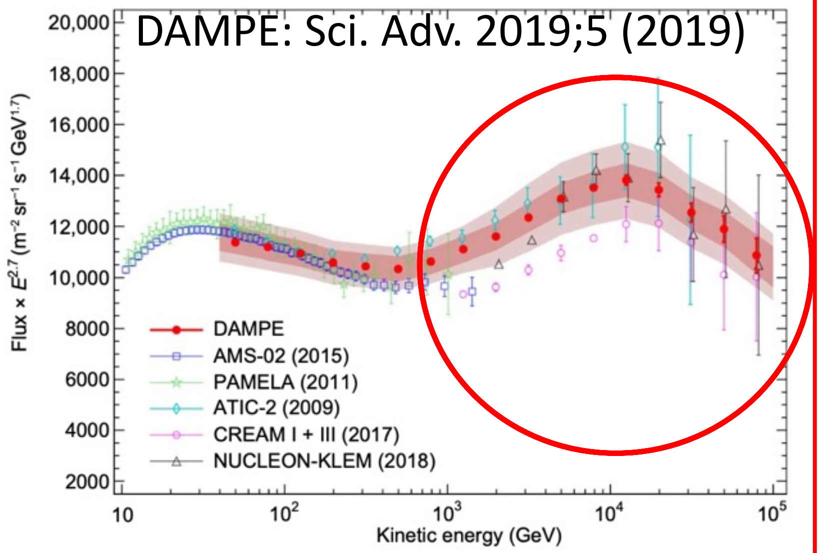
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

- 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)

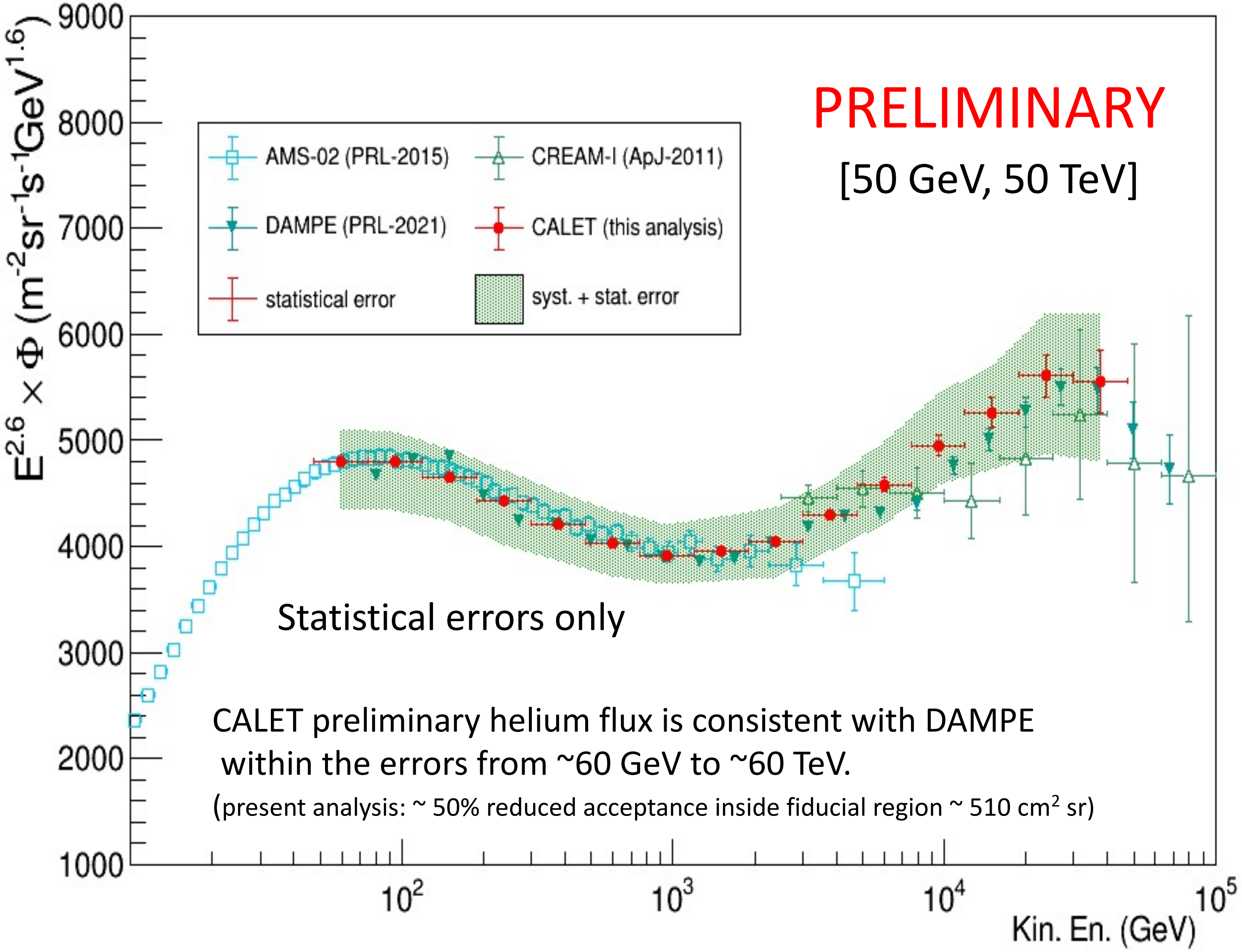


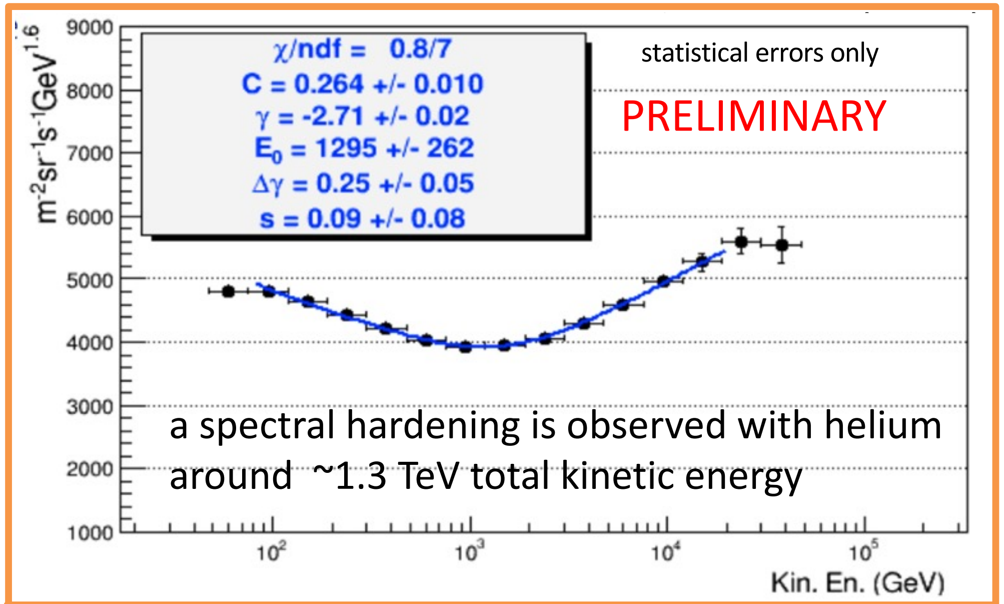


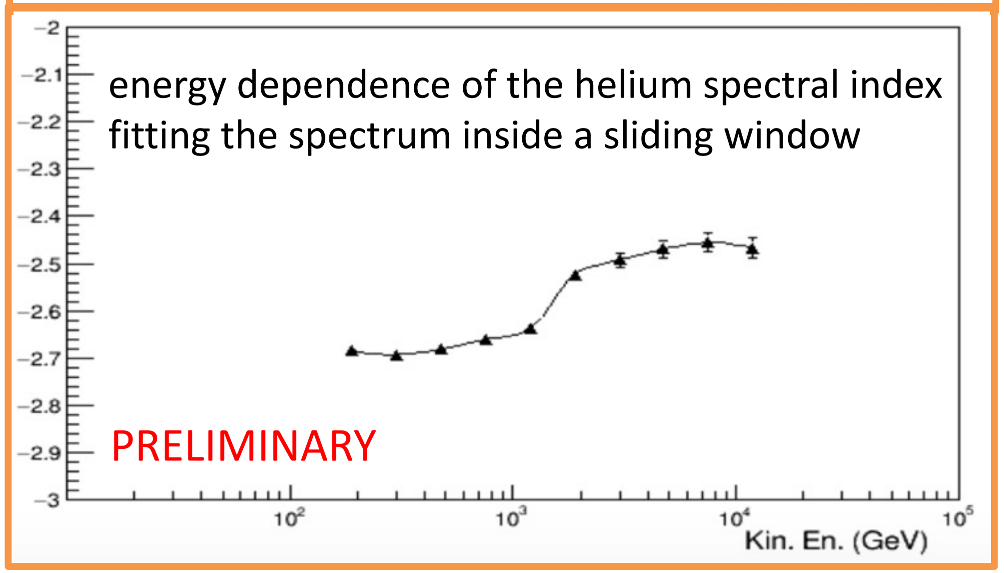
- DAMPE reported a spectral index softening $\Delta\gamma = -0.25 \pm 0.07$ from ~-2.60 to ~-2.85. above 10 TeV at E_{break} = $13.6^{+4.1}_{-4.8}$ TeV with ~30% error.

- 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)

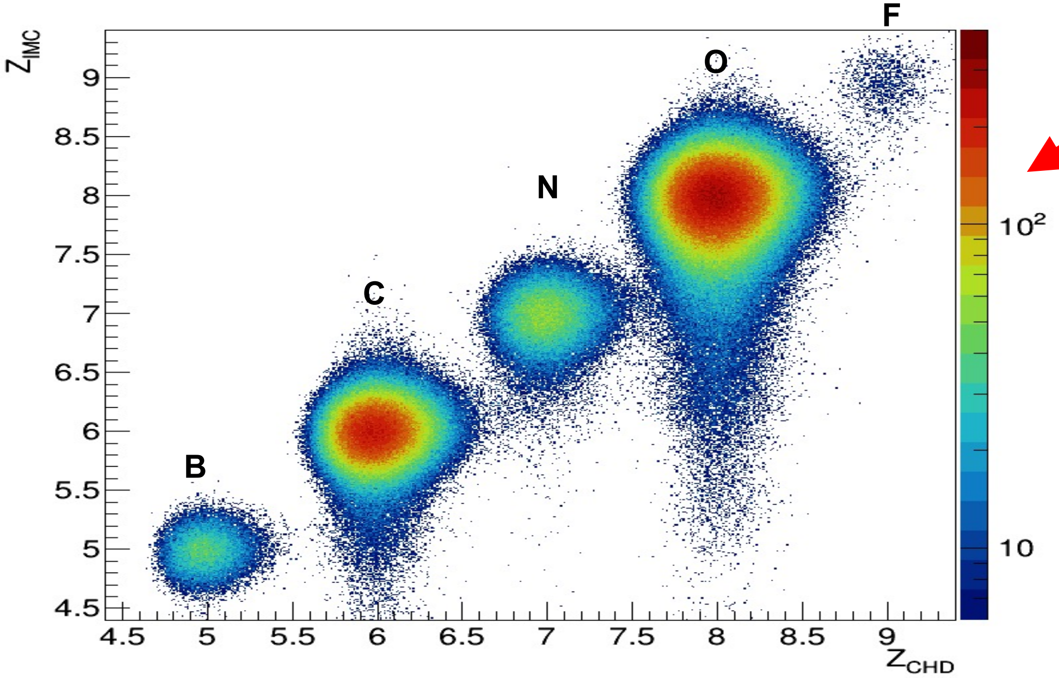




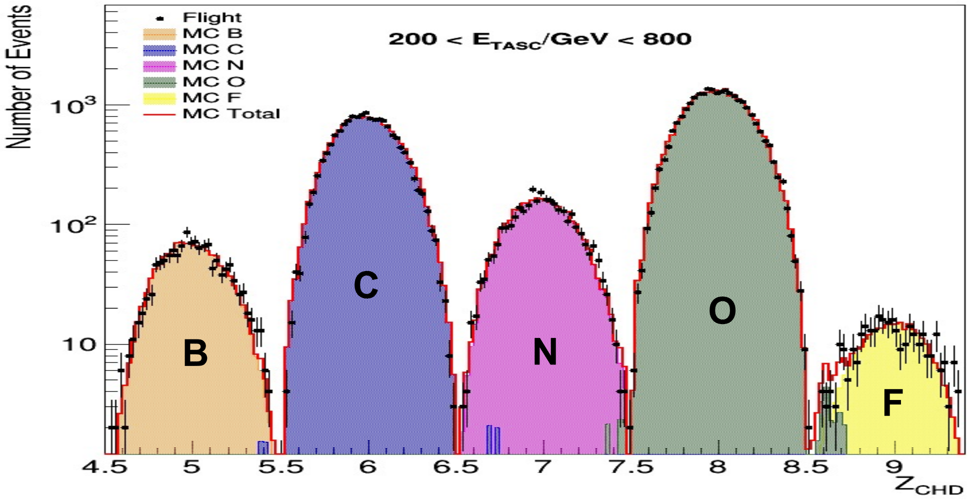


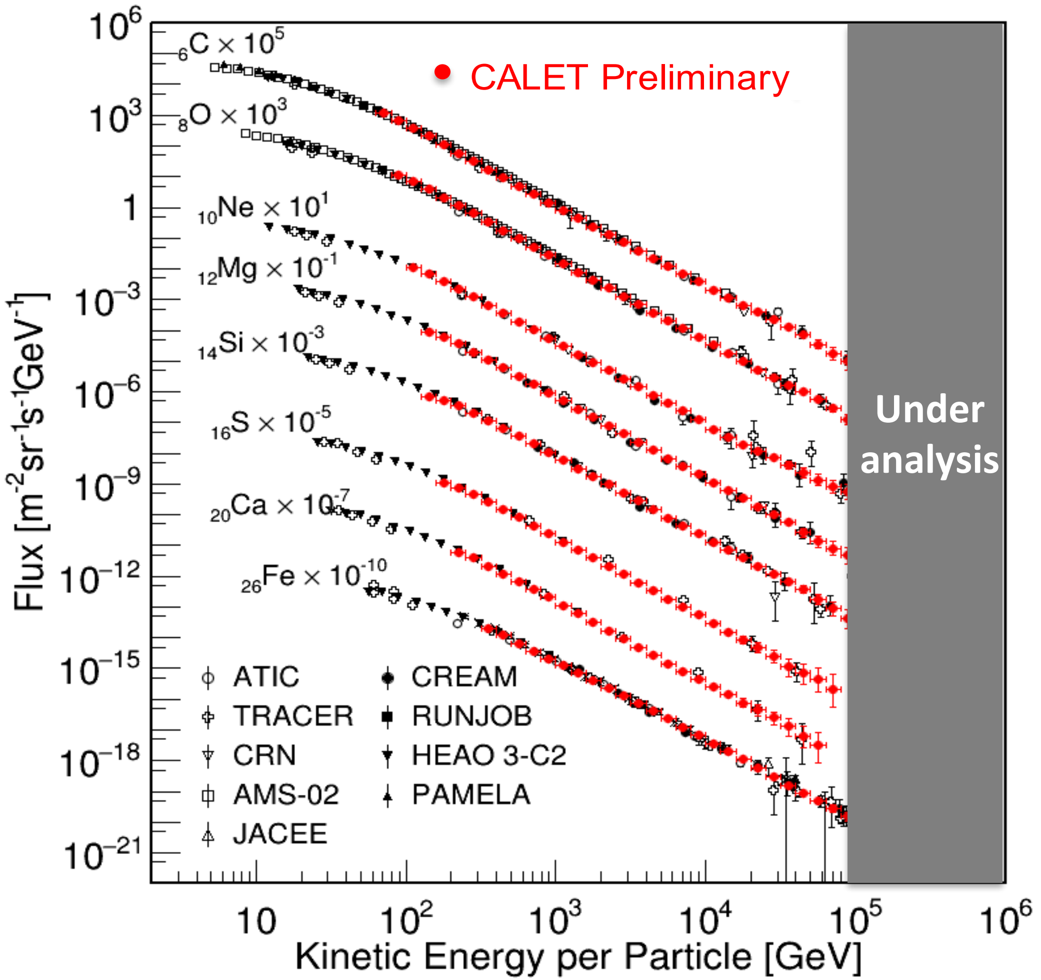
Spectra of Cosmic-ray Nuclei from C to Fe

P-118

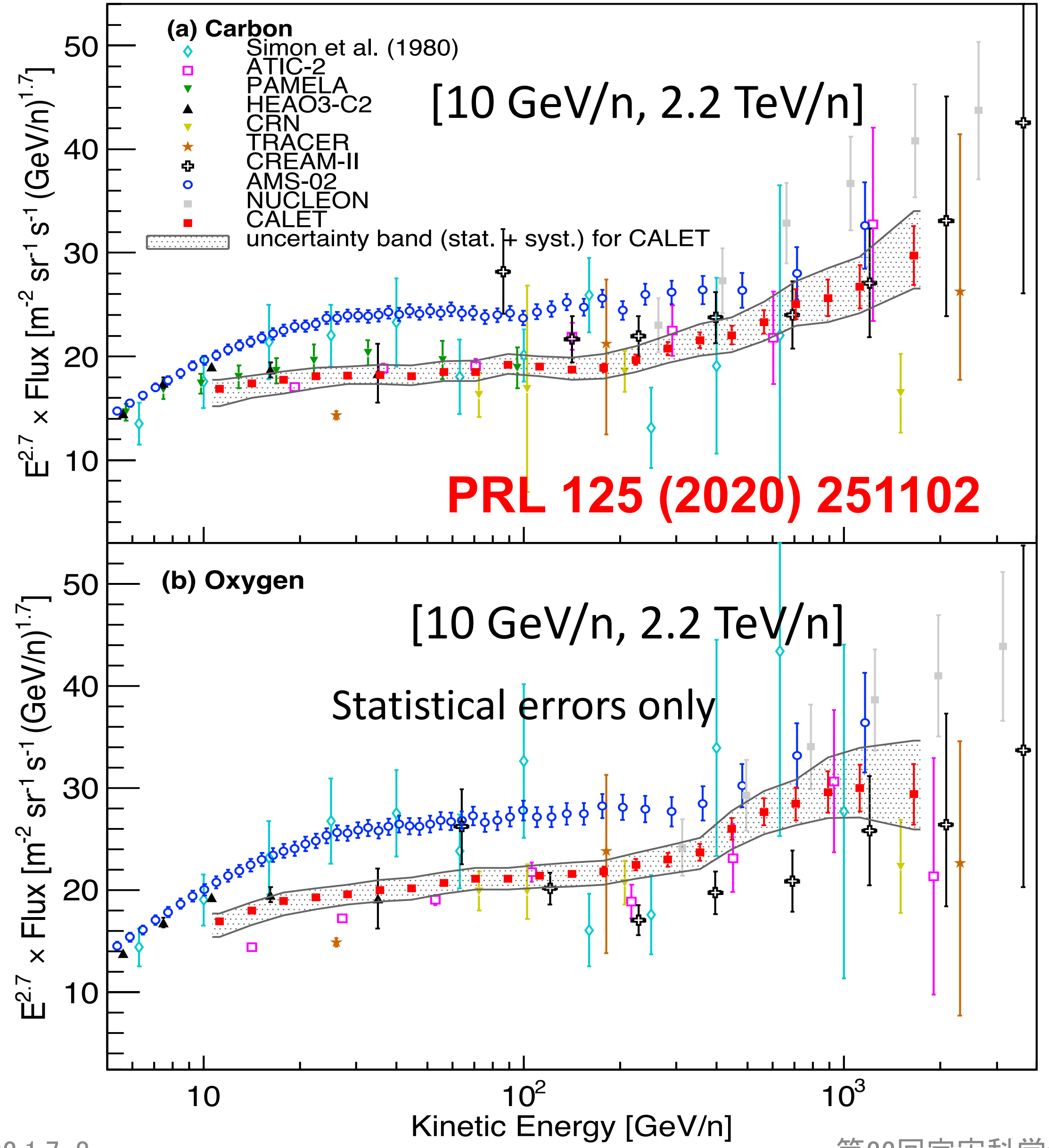


With excellent charge-ID of individual elements CALET is exploring the Table of Elements in the multi-TeV domain





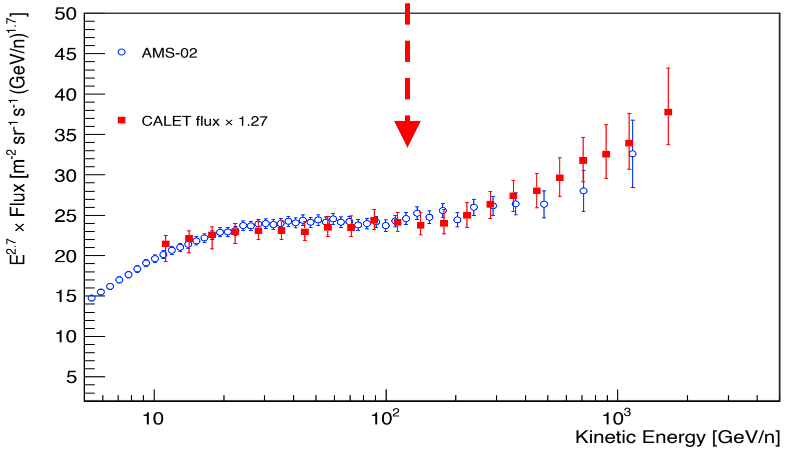
Carbon and Oxygen Energy Spectra

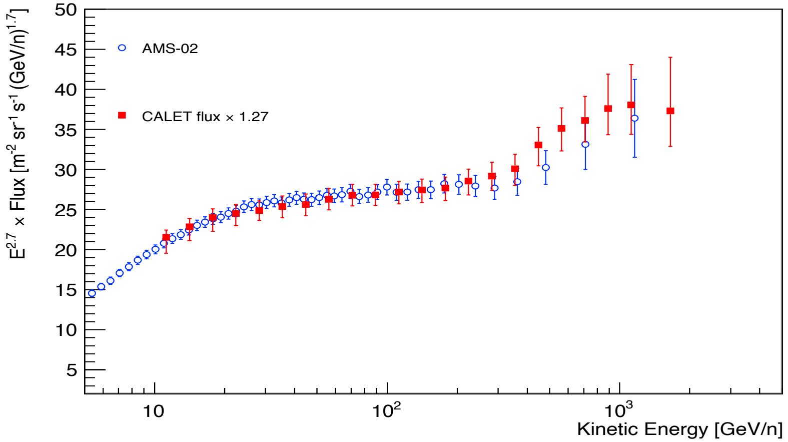


CALET C is consistent with PAMELA and most of the previous experiments. PAMELA did not publish oxygen.

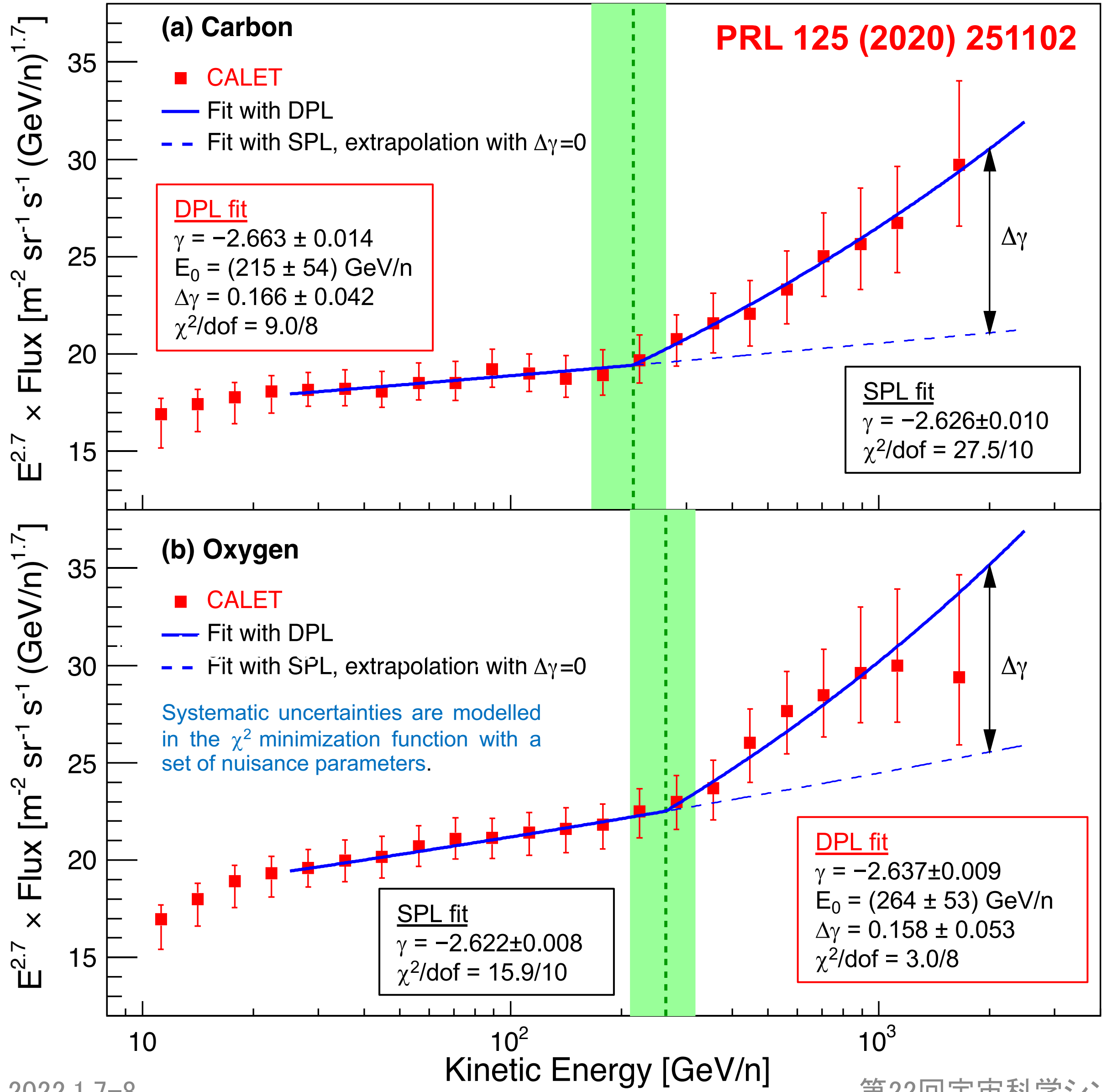
The spectra show a clear hardening around 200 GeV/n.

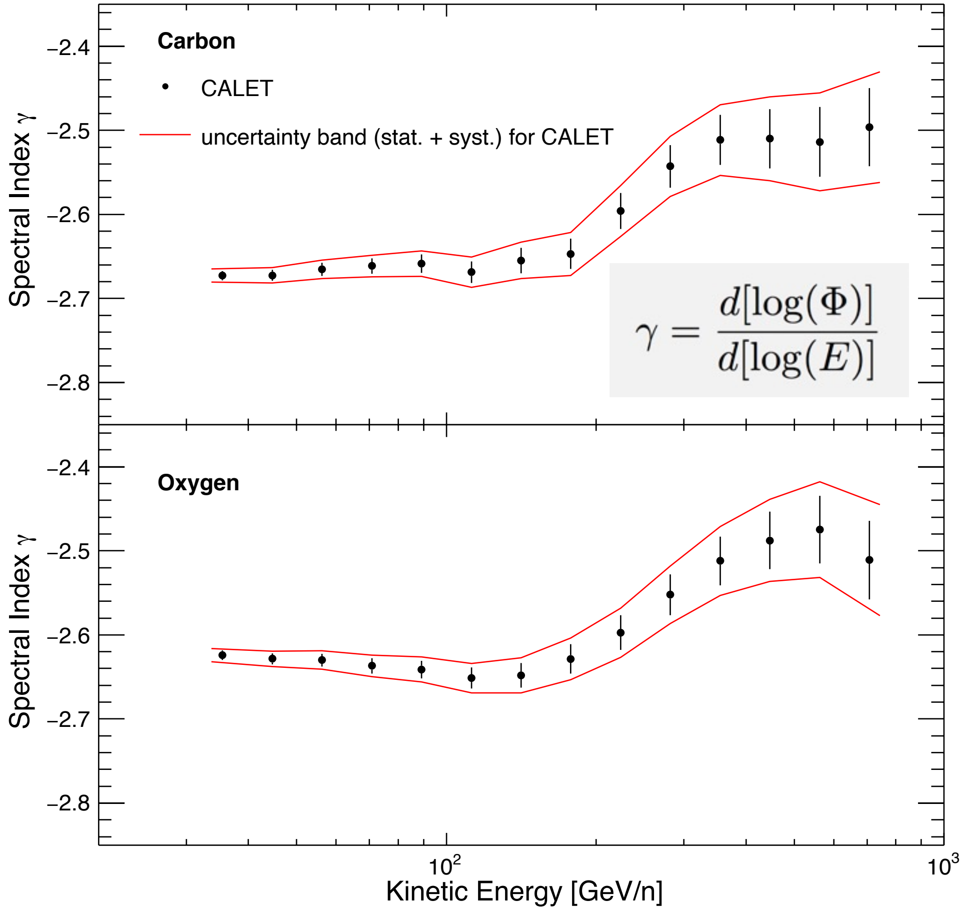
They have shapes similar to AMS-02 but the absolute normalization is significantly lower (~ 27%)





Carbon and Oxygen: Spectral Analysis



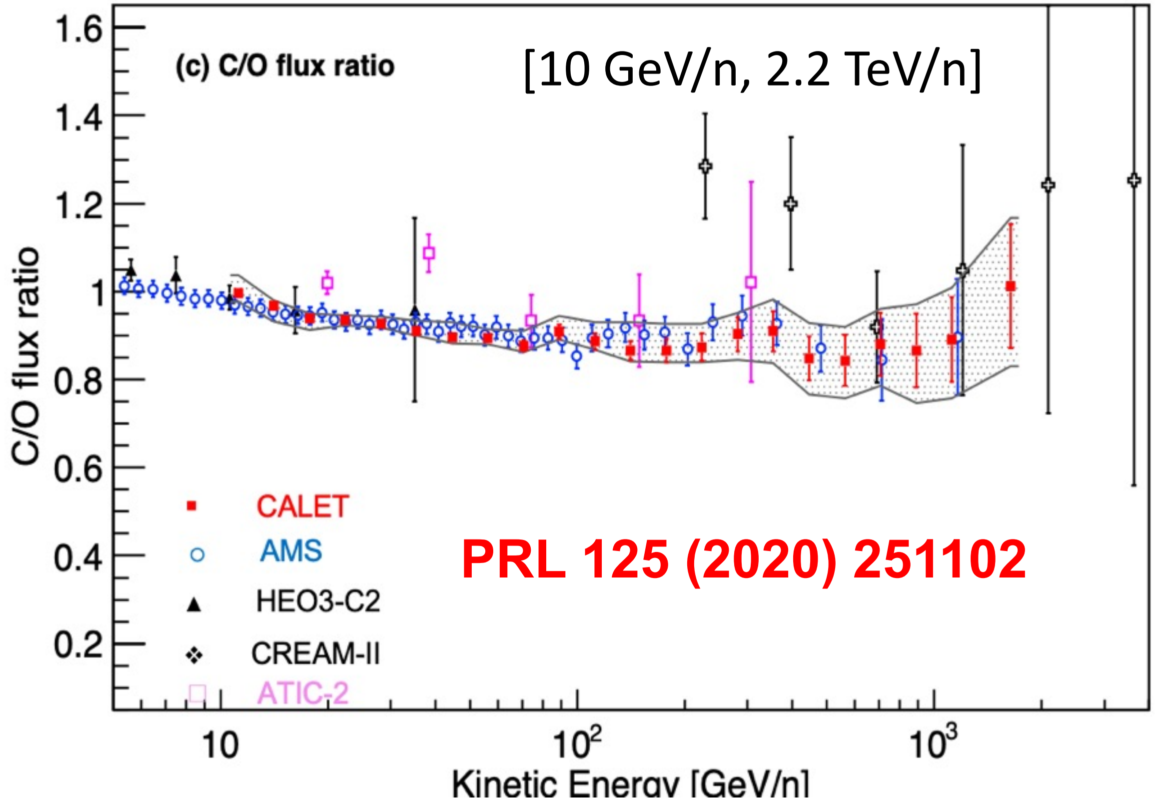


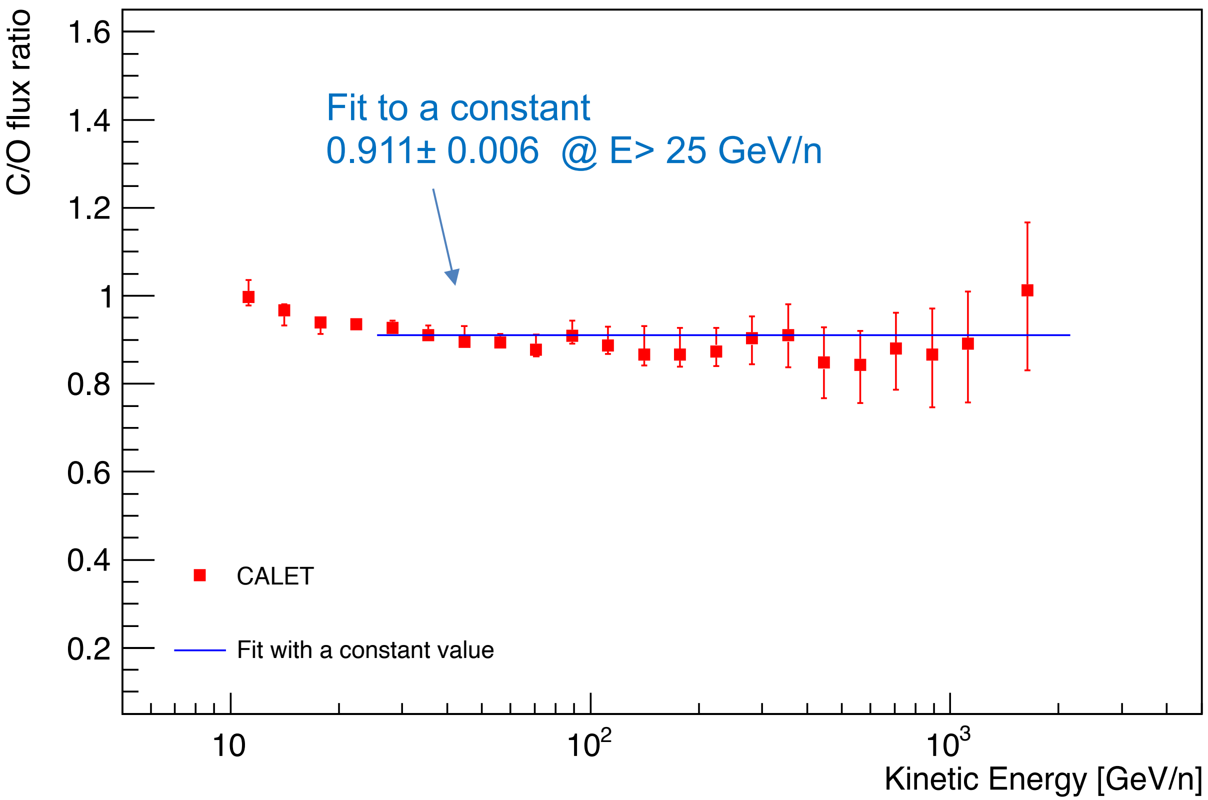
Double power-law (DPL) fit

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

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

C/O flux ratio





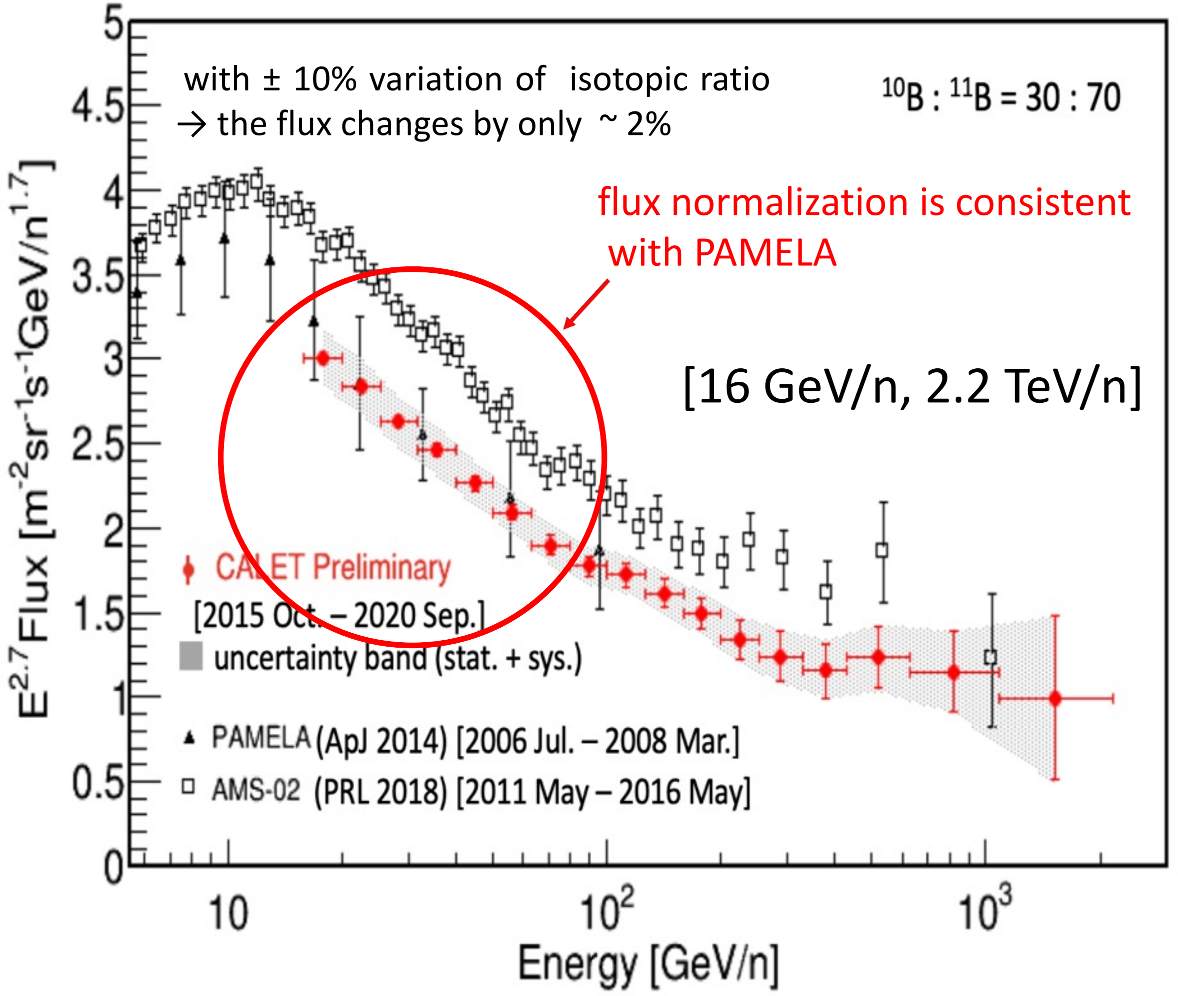
The C/O flux ratio as a function of energy is in good agreement with the one reported by AMS

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

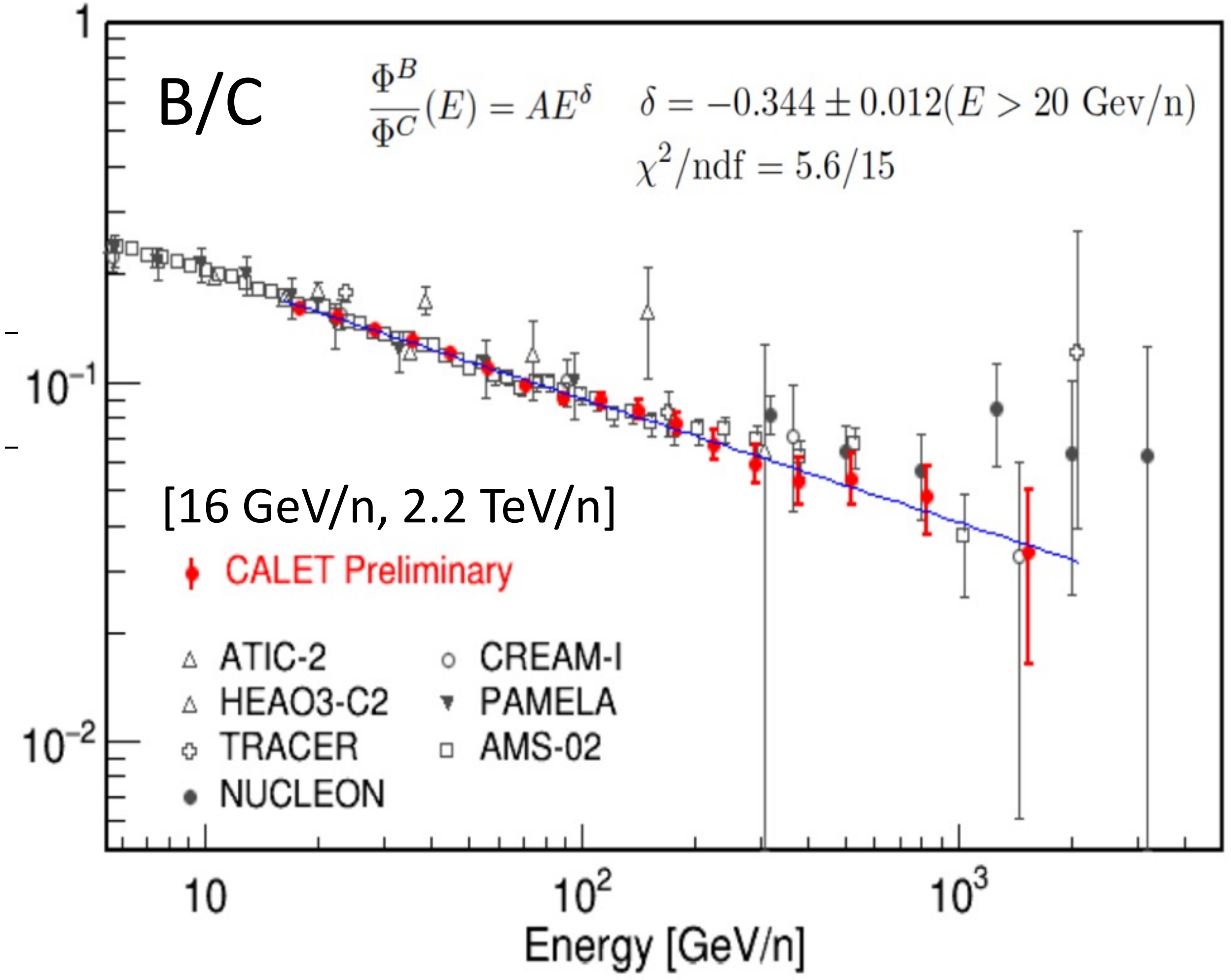
→ C and O fluxes have the same energy dependence.

Boron Spectrum and B/C Ratio (preliminary)

Boron energy spectrum

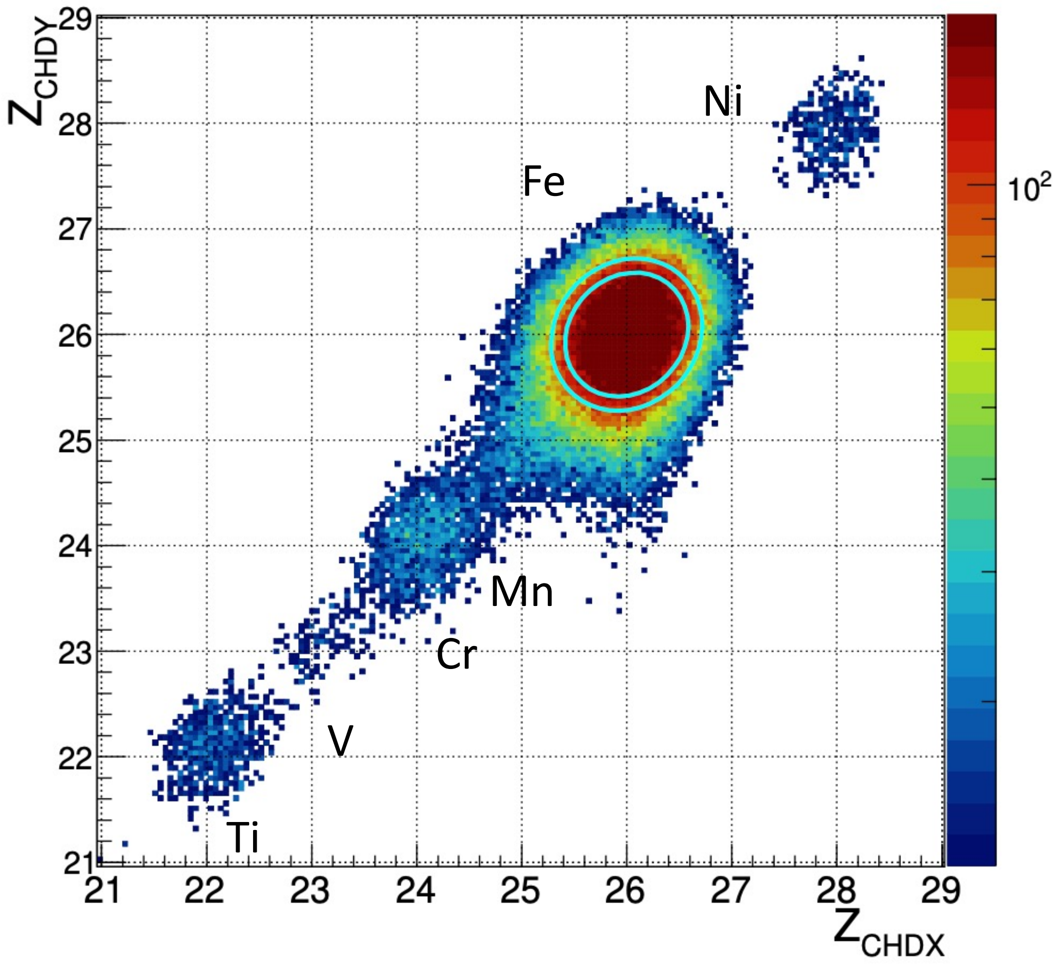


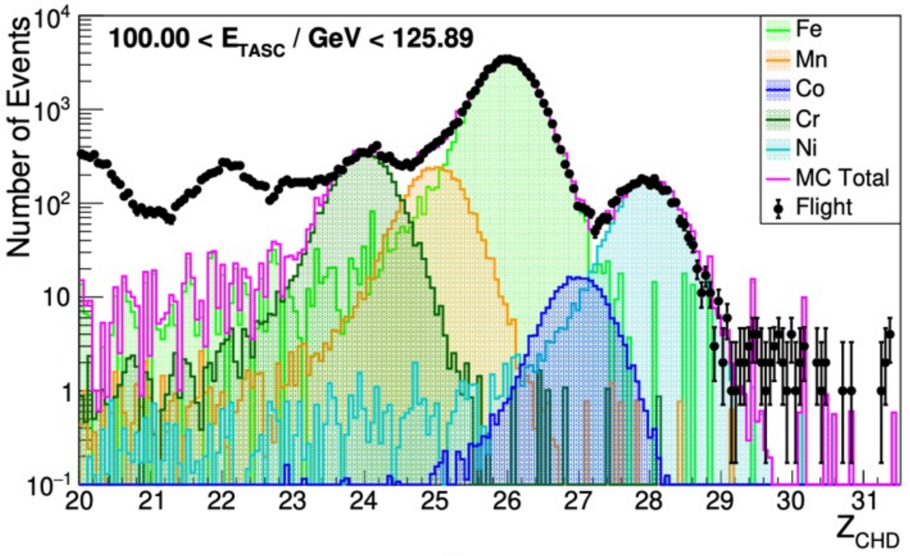
B/C ratio



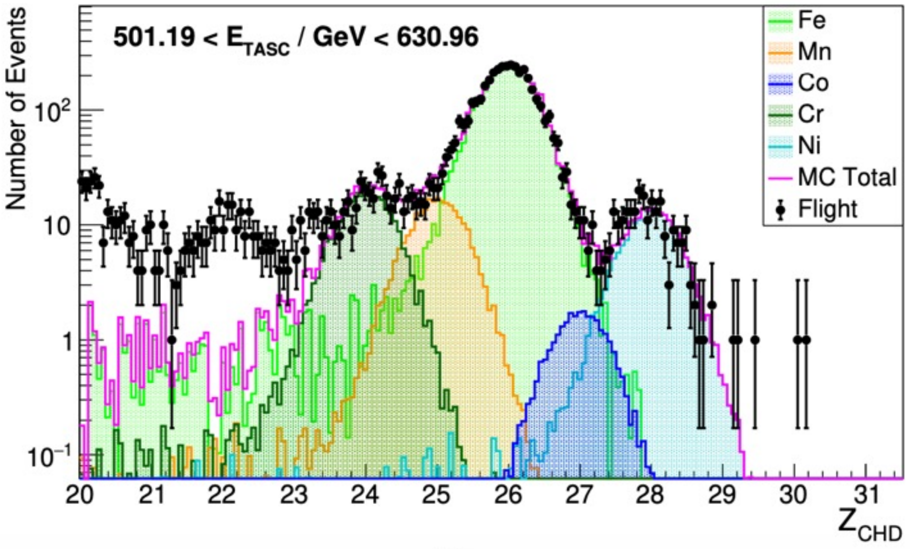
Iron – Analysis (Charge Selection)

Charge measurement with the two CHD layers





(a)

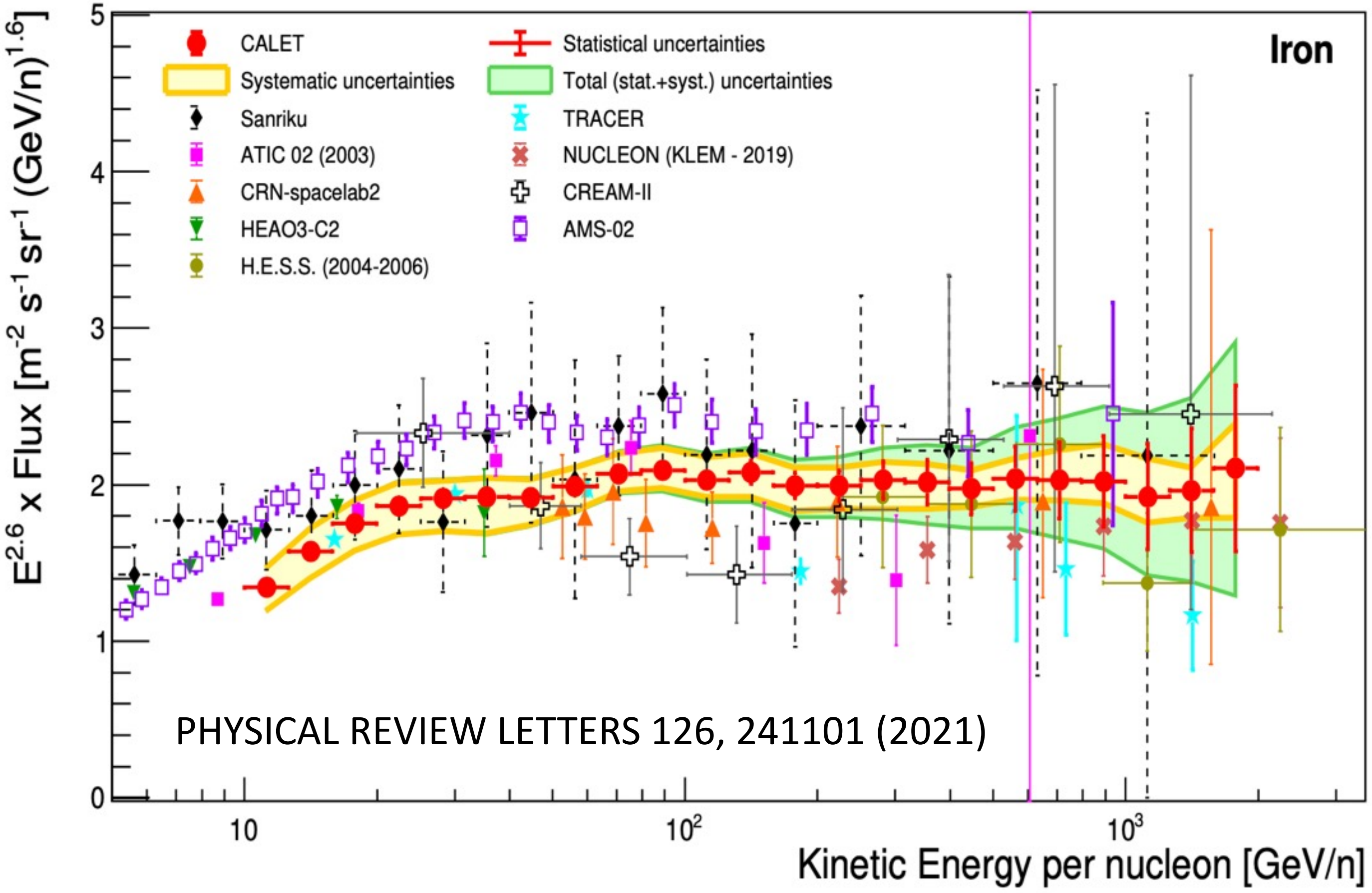


(b)

Iron Spectrum

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

analyzed data: Jan, 2016 – May 2020

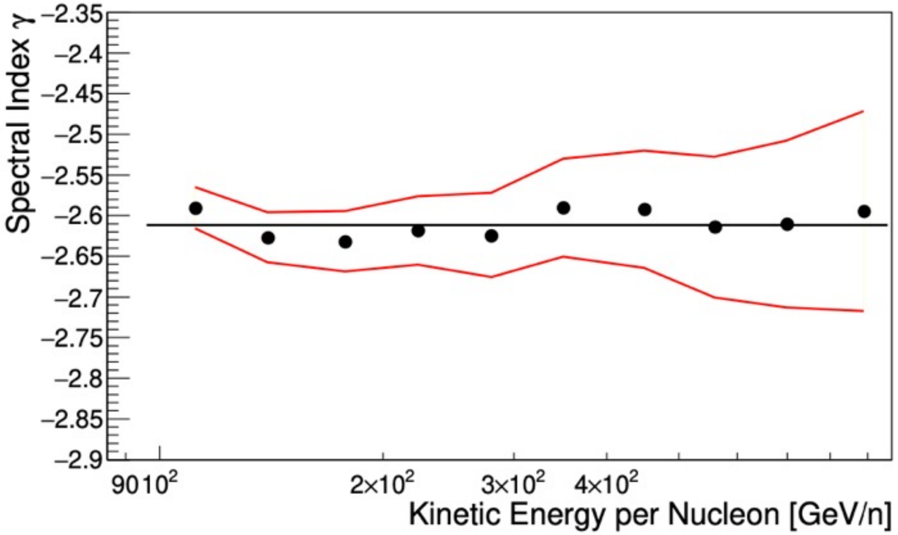


Iron Single Power Law fit:

50 GeV/n, 2.0 TeV/n

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

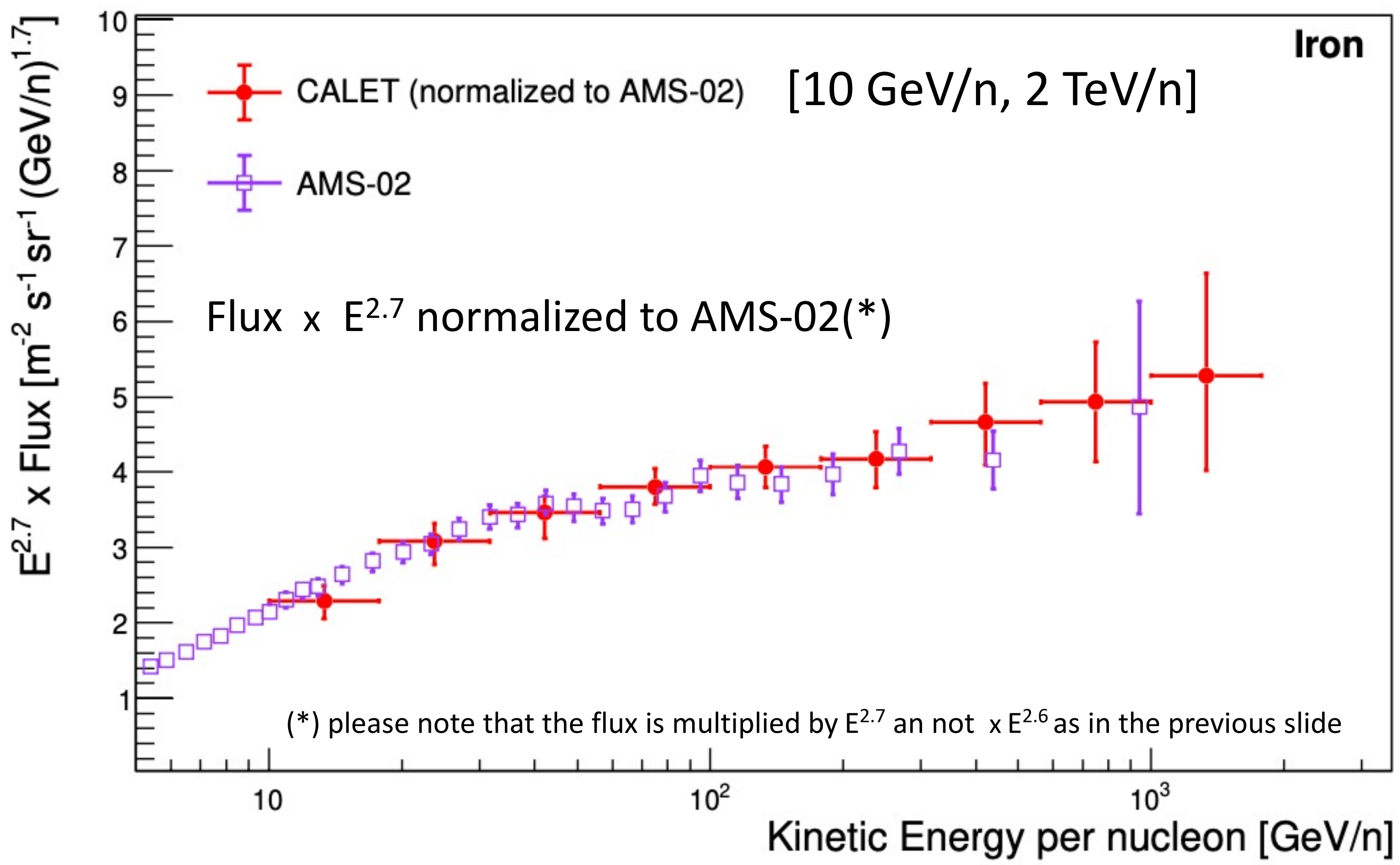
with $\chi^2/\text{d.o.f.} = 4.2/14$



Iron Spectral Shape and Normalization

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

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



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)

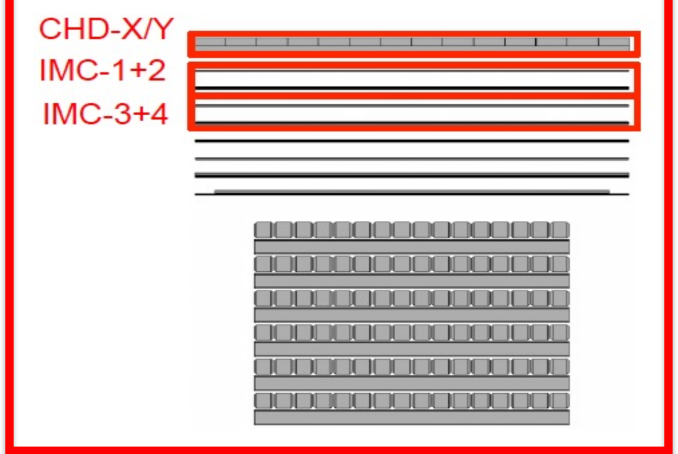
Spectral shape:

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

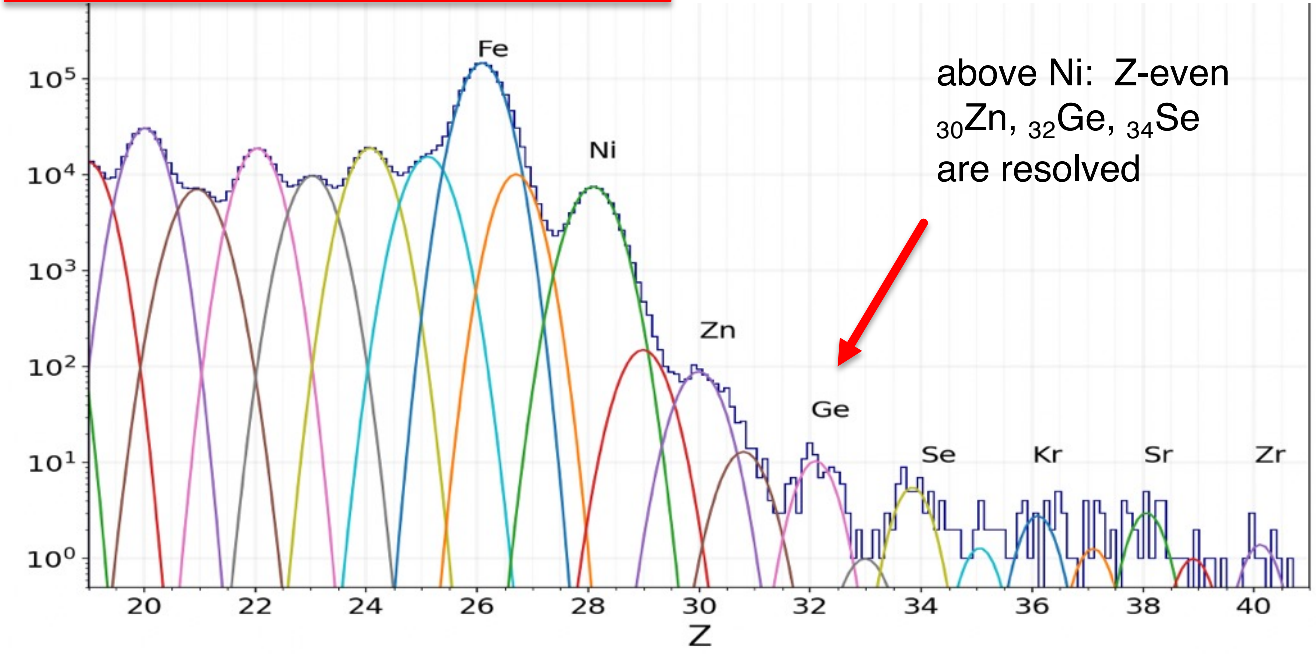
Spectral hardening:

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

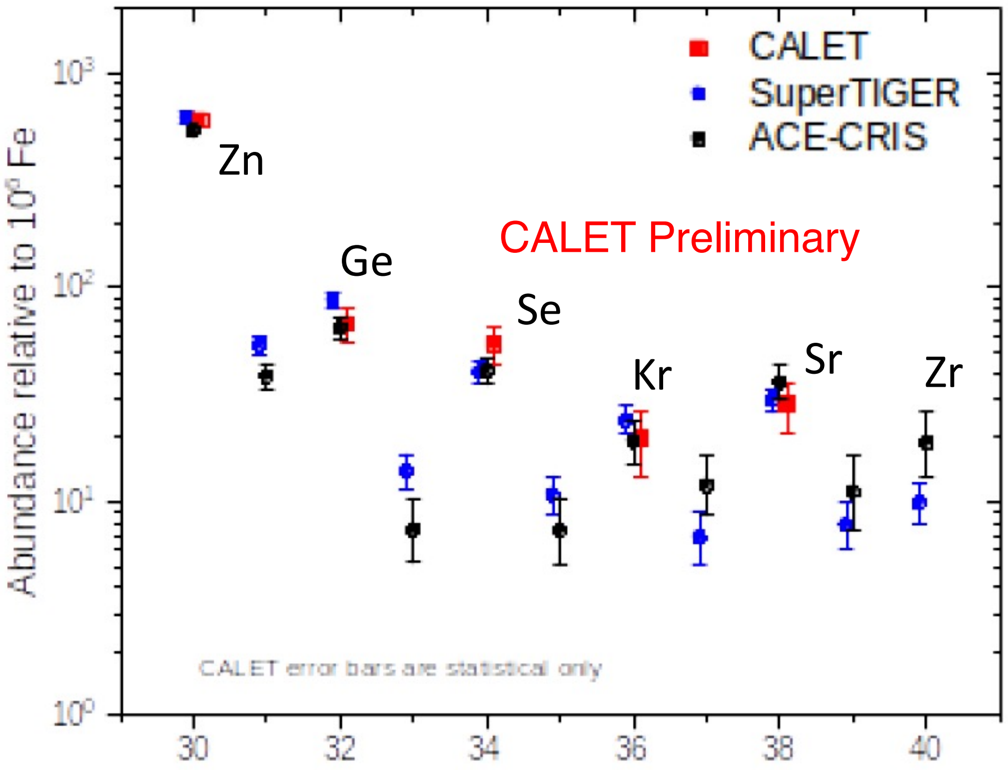
Ultra-heavy cosmic-ray nuclei (26 < Z ≤ 40)



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



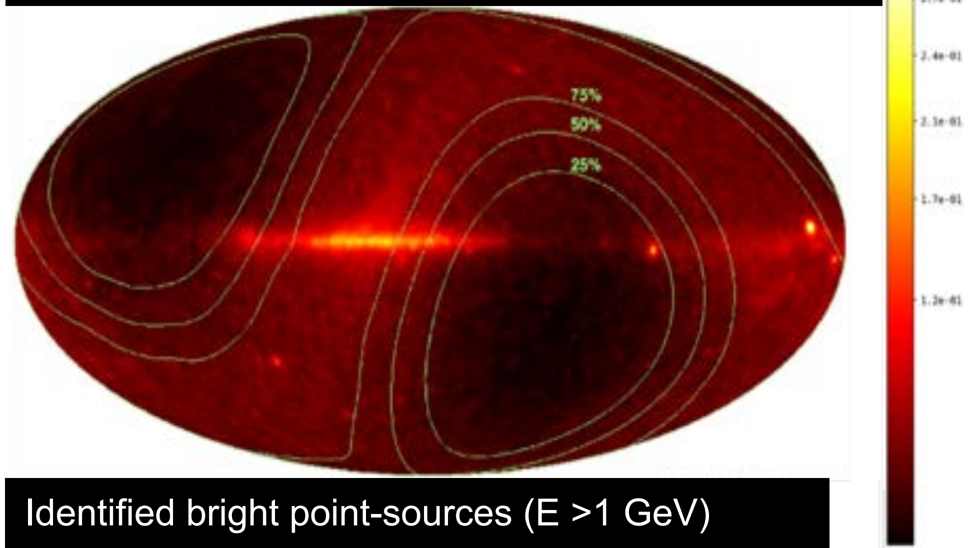
The CALET UH element ratios relative to Fe are consistent with Super-TIGER and ACE abundances.

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

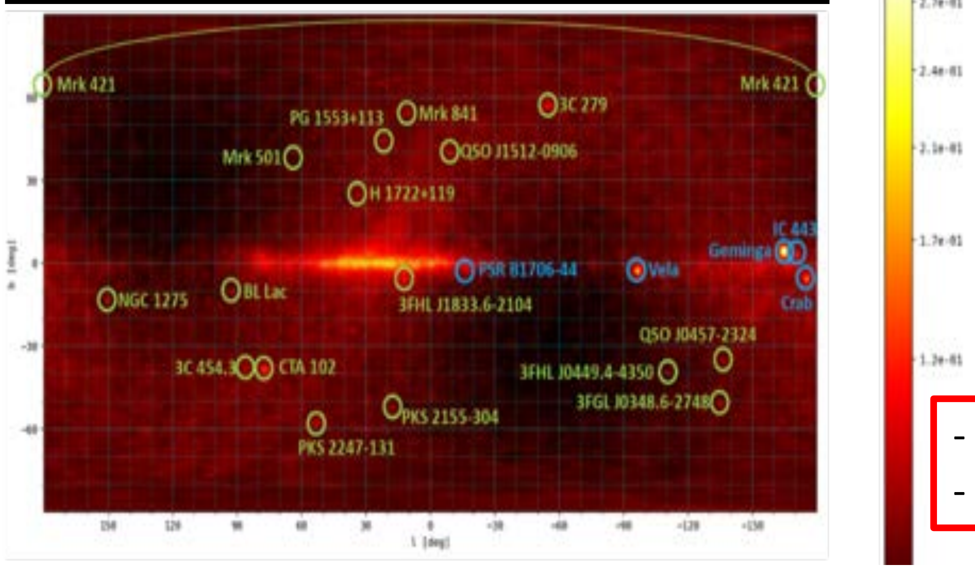
P-114
P-116

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

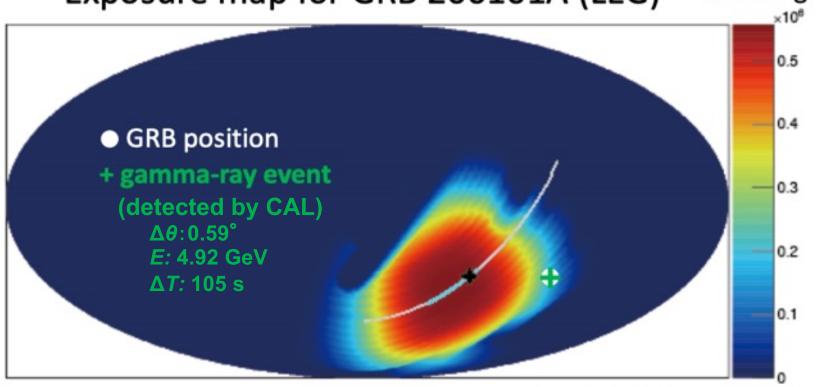
Gamma-ray sky map LE-γ trigger (E >1 GeV)



Identified bright point-sources (E >1 GeV)



Exposure map for GRB 200101A (LEG) $cm^2\ s\ erg^{-1}$



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

from 2015-10-05 to 2021-07-23

259 GRBs (44.9 GRBs / year)

228 Long (88%) **31 Short (12%)**

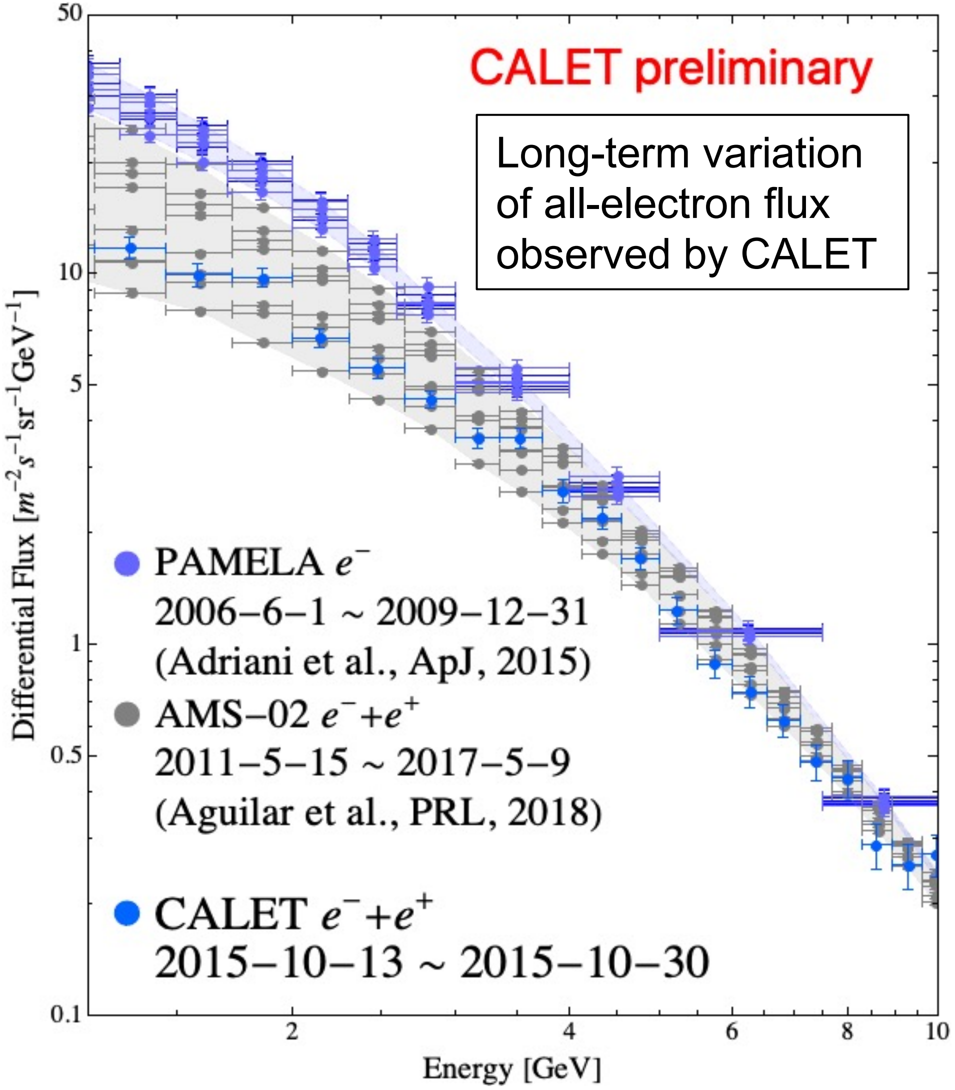
- **Follow-up** of LIGO/Virgo **GW** observations
  - X-ray and γ-ray bands
  - high-energy γ-in calorimeter

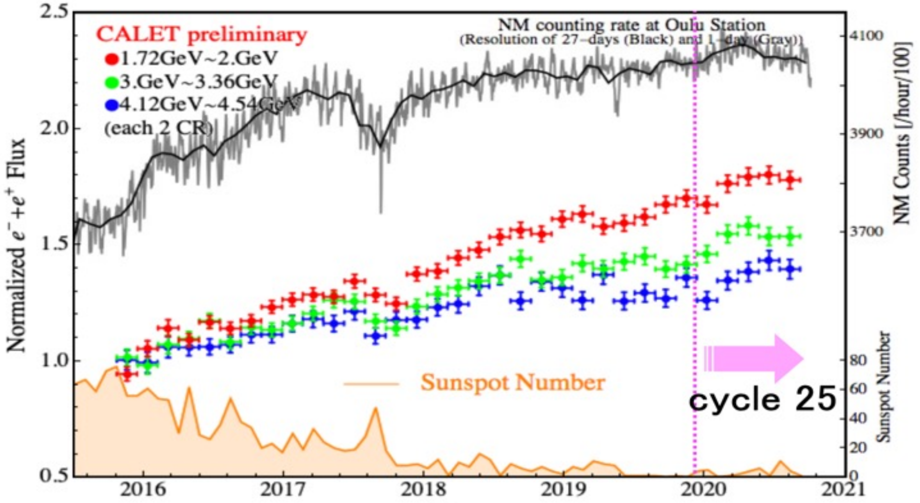
- **Limits on DM** annihilation into γγ: $\langle\sigma v\rangle < 10^{-28}$-$10^{-25} cm^{-3}s^{-1}$
- Limits on DM decay $\chi \to \gamma\nu$ etc.: $\tau_{DM} > 10^{30}$s (m_{DM}>100 GeV)

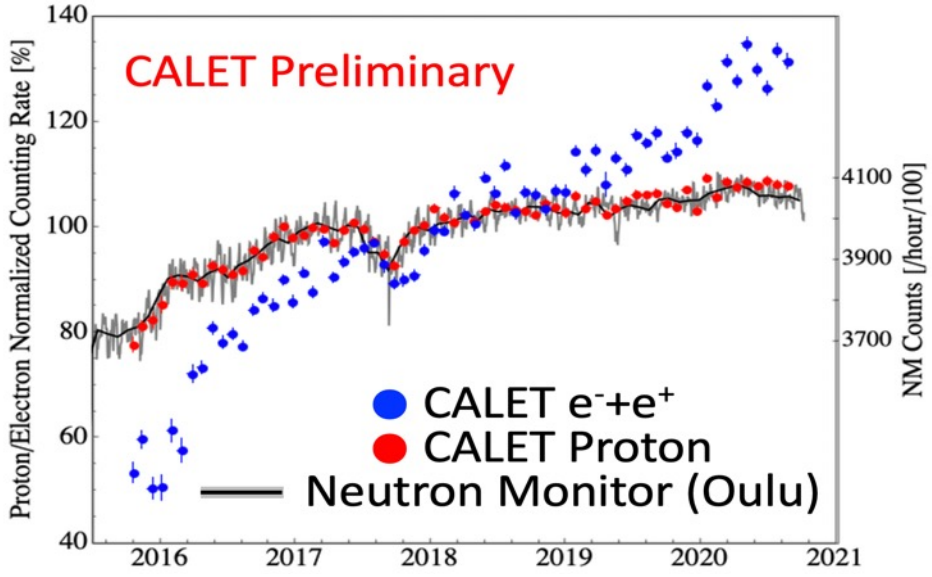
Solar modulation

P-115

- **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.**



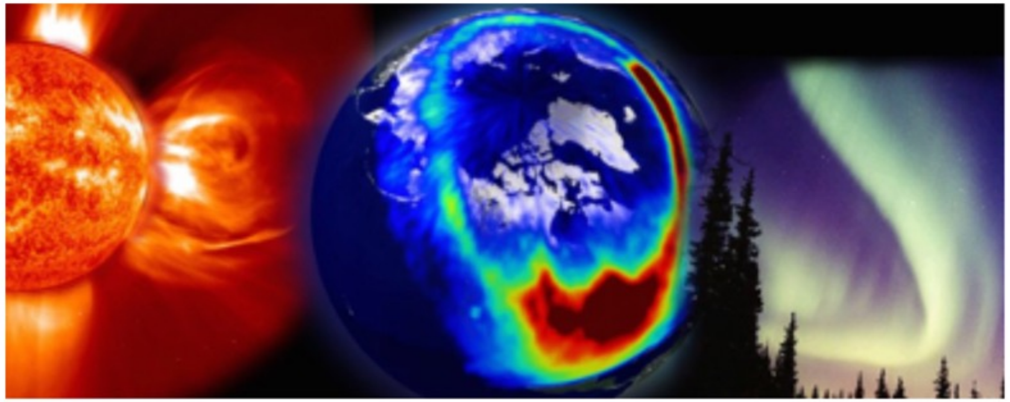


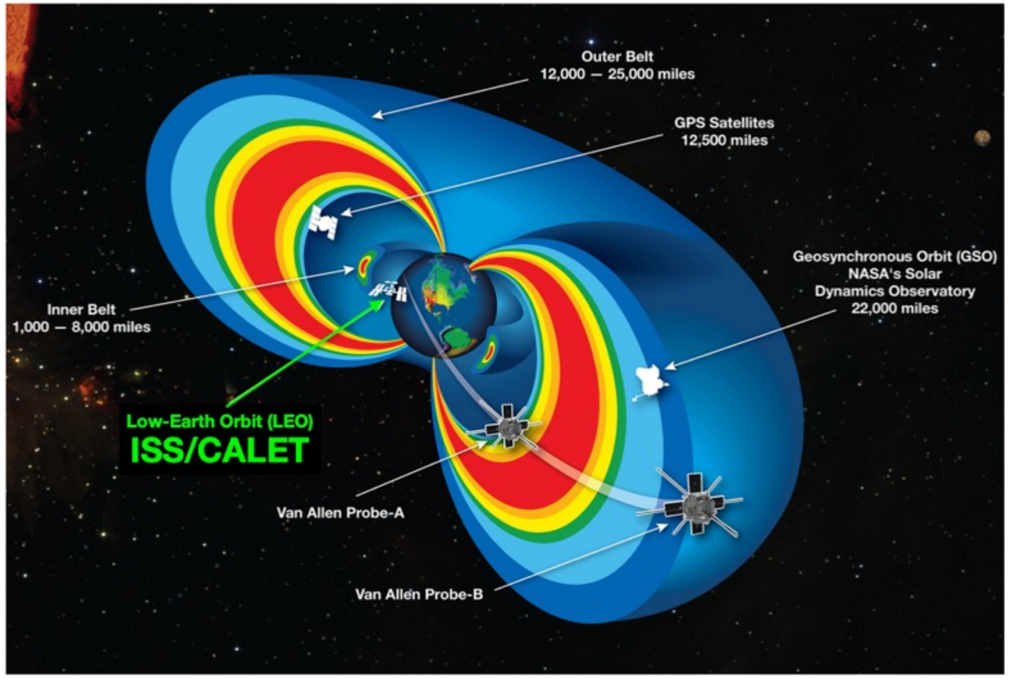


Good correlation of NM counting rate at Oulu station (black points) with the CR e^- + e^+ flux increase in the 1-10 GeV until ~half a year after the beginning the new solar cycle 25.
The flux has now started decreasing.

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

Space Weather Phenomena with CALET

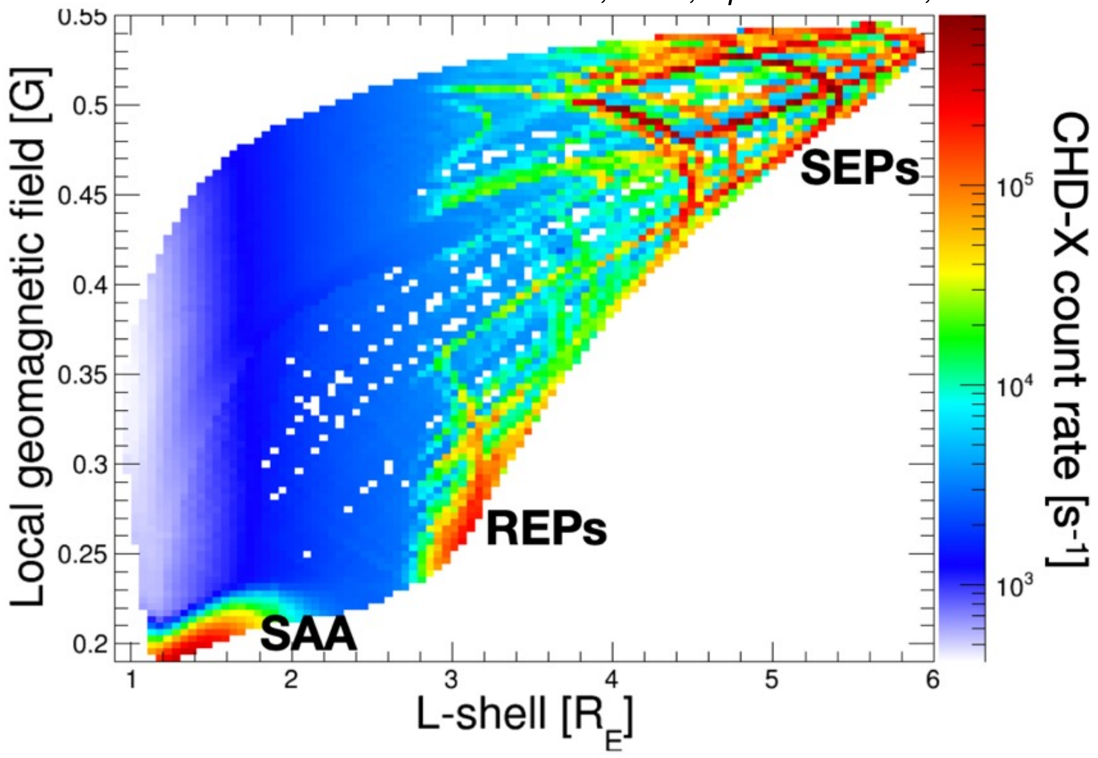




◆ In addition to the aforementioned astrophysics goals, CALET is able to provide a **continuous monitoring of space weather phenomena affecting the near-Earth environment**, including

- ☑ solar energetic particles (SEPs) at high geomagnetic latitudes
- ☑ inner-belt protons in the South-Atlantic anomaly (SAA) region
- ☑ relativistic electron precipitation (REP) events in the inner boundary of the outer radiation belt

Kataoka et al., 2016, *Geophys Res Letter, 43, 4119*
Ueno et al., 2020, Space Weather, 18



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: Summary and Future Prospects

- CALET was successfully launched in August 2015 and installed on the Japanese Experiment Module – Exposure Facility on the ISS.
- More than 6 years of excellent performance and remarkable stability of the instrument since the start of data taking on Oct. 23, 2015.
- Linearity in the energy measurements established up to 10^6 MIP
  ⇨ [Astropart. Phys. 91, 1 – 10 (2017)]
- Continuous on-orbit calibration updates
- HE trigger operational for > 2100 days with > 85% live time fraction
- Total number of > GeV triggers ~3.0 billion

Extended operations are approved by JAXA/NASA/ASI in March 2021 through the end of 2024.

＊) We greatly appreciate JAXA staffs for perfect support of the CALET operation at the Tsukuba Space Center of JAXA !!