24pW2-7

ISS搭載CALETによる7年間の軌道上観測の最新成果

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

日本物理学会2023年春季大会 (オンライン） 2023年3月24日

The CALET Collaboration Member

O. Adriani,[1, 2] Y. Akaike,[3, 4] K. Asano,[5] Y. Asaoka,[5] E. Berti,[1] 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] G.A. de Nolfo,[9] 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] 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]

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

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(KOSEN), 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

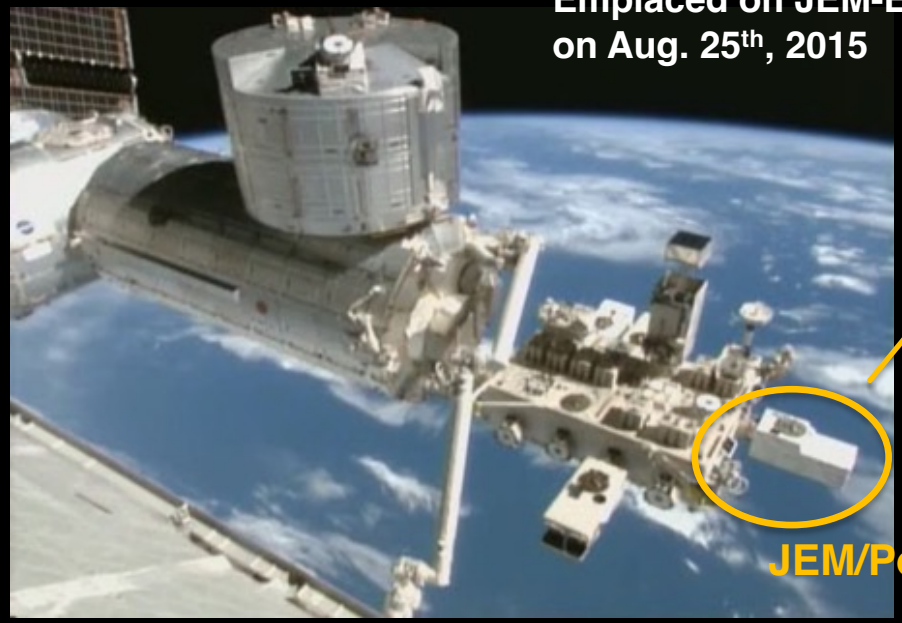
Guest Investigator: Lauren W. Blum (University of Colorado Boulder, USA), M. Teramoto (Kyushu Institute of Technology, Japan)

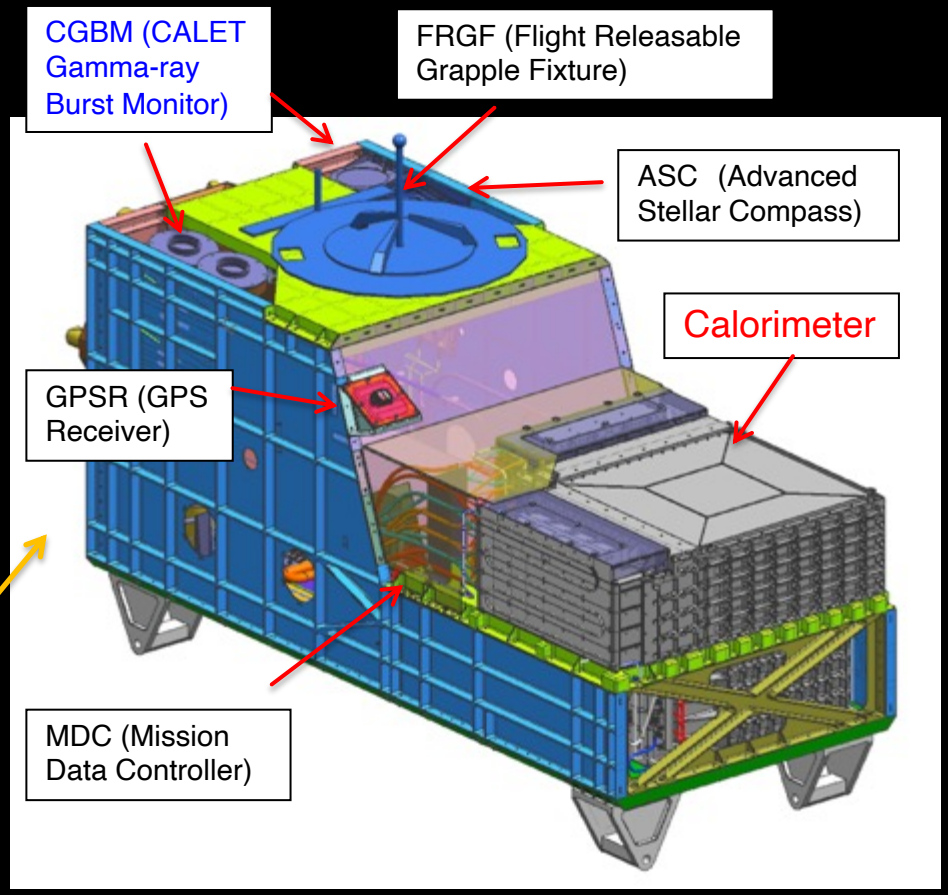
CALET Payload

Kounotori (HTV) 5

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

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

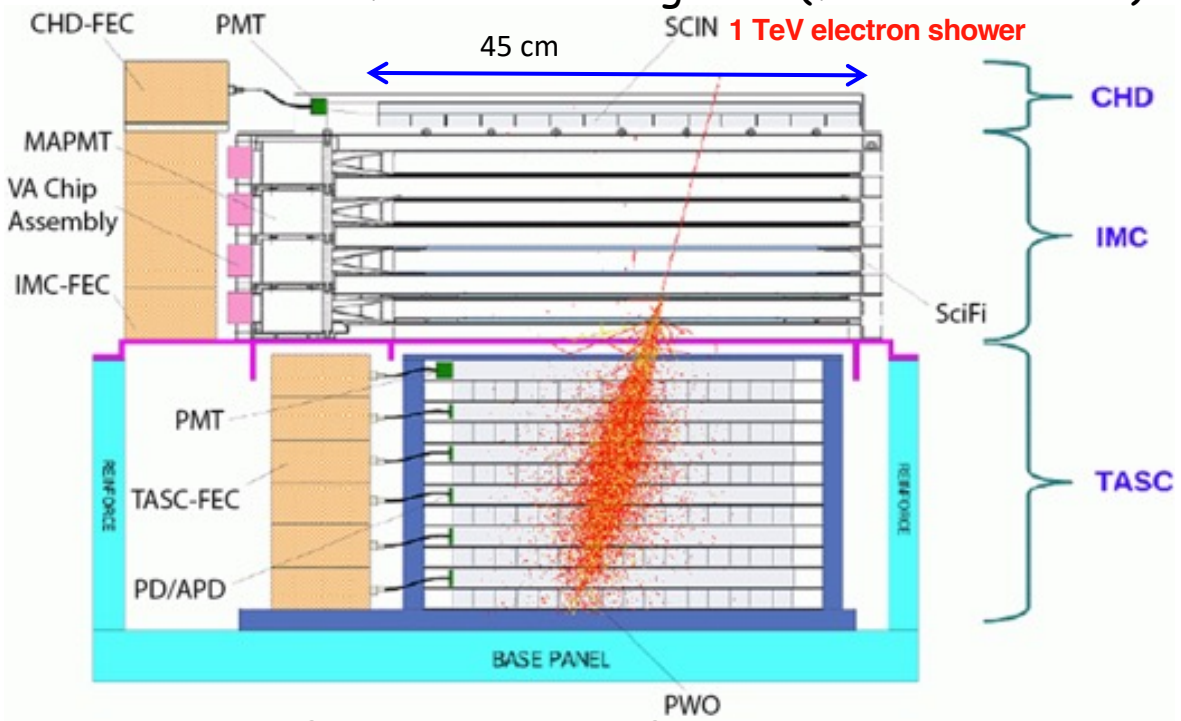




- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W（max）**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

CALET Calorimeter and Capability

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

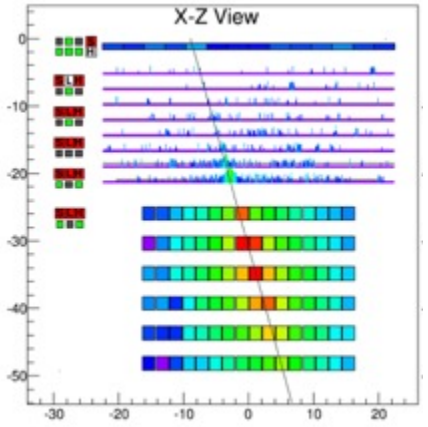
IMC – Imaging Calorimeter

- 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**

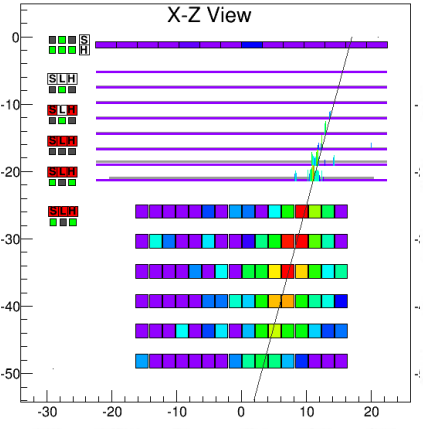
TASC – Total Absorption Calorimeter 27 X_0, 1.2 λ_I

- 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}

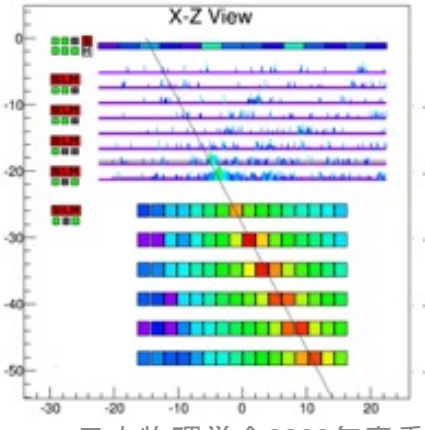
Electron, E=3.05 TeV



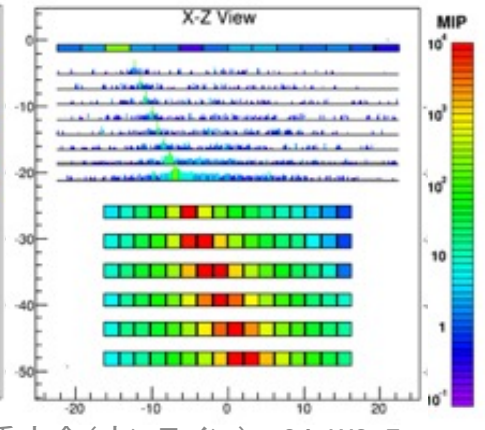
Gamma-ray, E=44.3 GeV



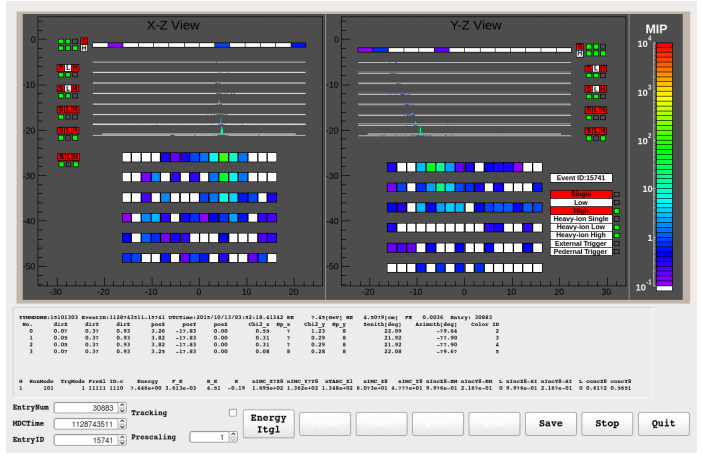
Proton, E_{TASC}=2.89 TeV



Iron, E_{TASC} =9.3 TeV

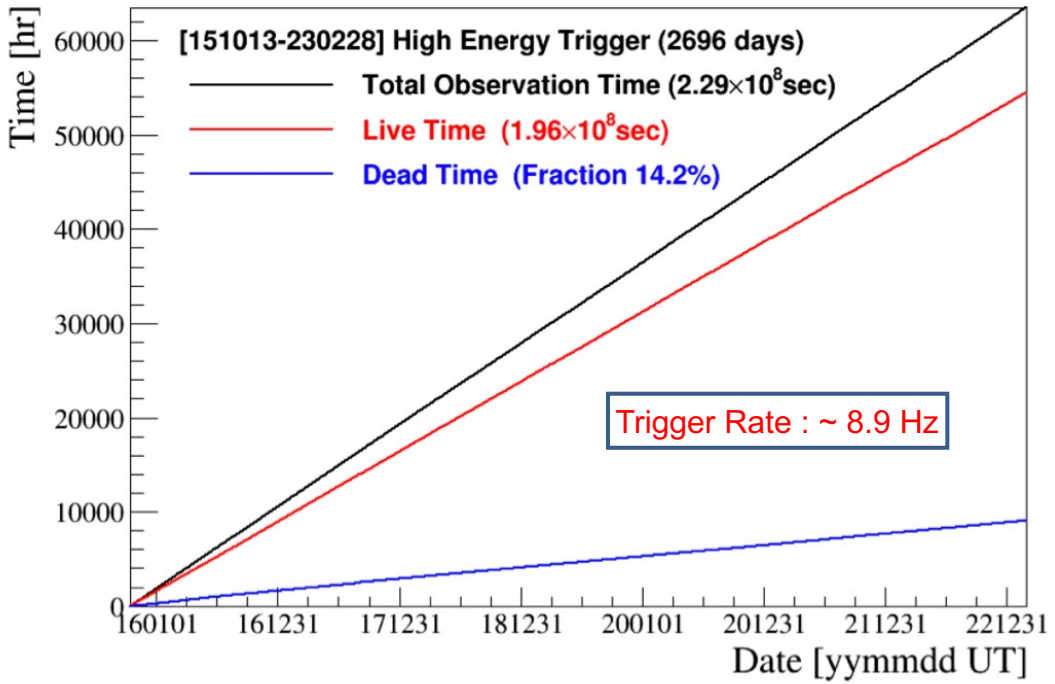


Event Display: Electron Candidate (>100 GeV)



CALET Performance of Observations on the ISS

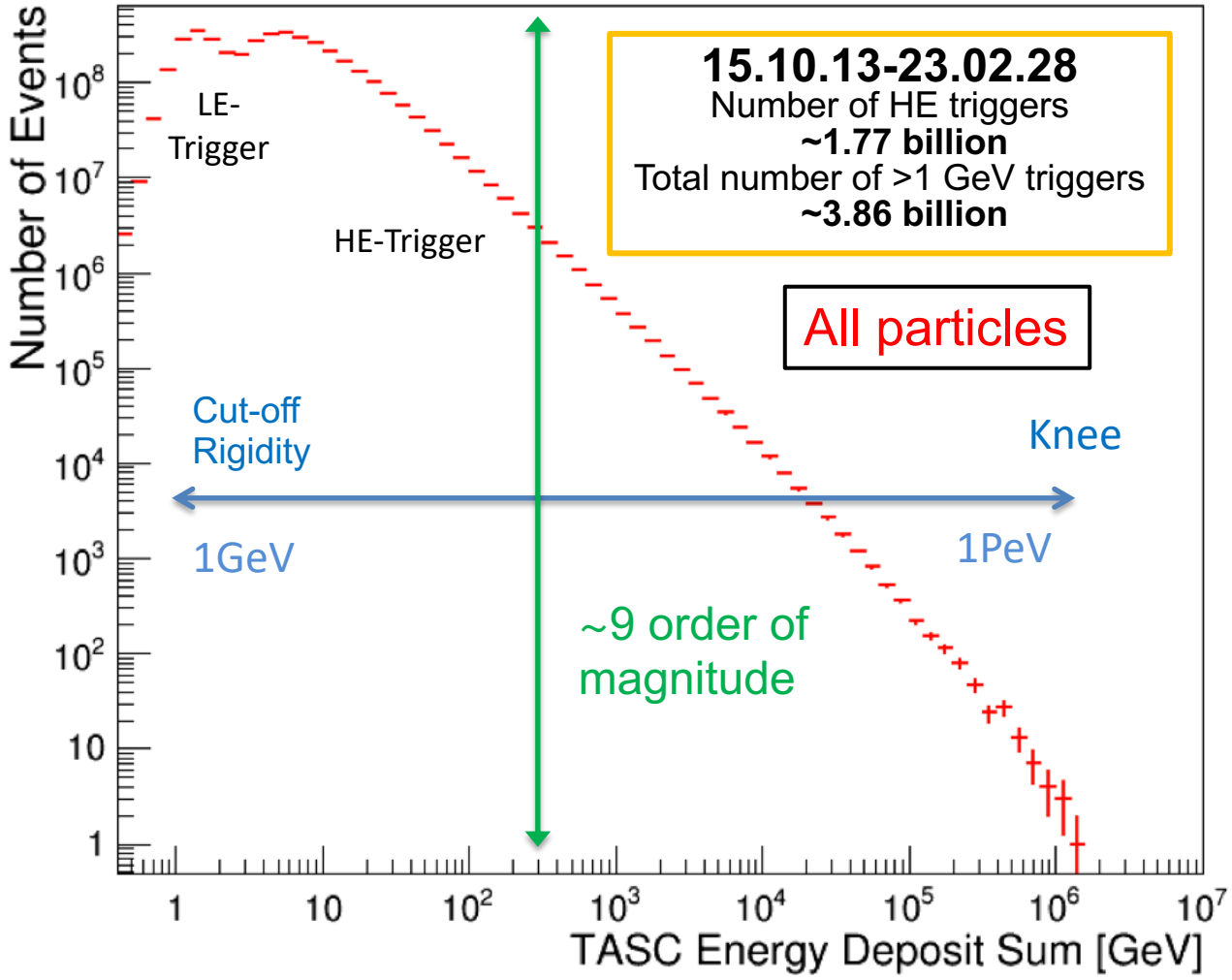
Accumulated observation time (live, dead)



High-energy trigger (> 10 GeV) statistics:

- Operational time **2696 days (> 7 years)**(*)
  (*) as of Feb. 28, 2023
- Live time fraction **~ 86%**
- Exposure of HE trigger
  ~235 m² sr day
- HE-gamma point source exposure
  ~4.2 m² day (for Crab, Geminga)

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



New Major Publications in FY2022

- Direct Measurement of the Nickel Spectrum in Cosmic Rays in the Energy Range from 8.8 GeV/n to 240 GeV/n with CALET on the International Space Station, O. Adriani et al. (CALET Collaboration), Physical Review Letters **128**, 131103 (2022)

- Observation of Spectral Structures in the Flux of Cosmic-Ray Protons from 50 GeV to 60 TeV with CALET on the ISS, O. Adriani et al. (CALET Collaboration), Physical Review Letters **129,** 101102 (2022) (highlighted by Editors' Suggestion)

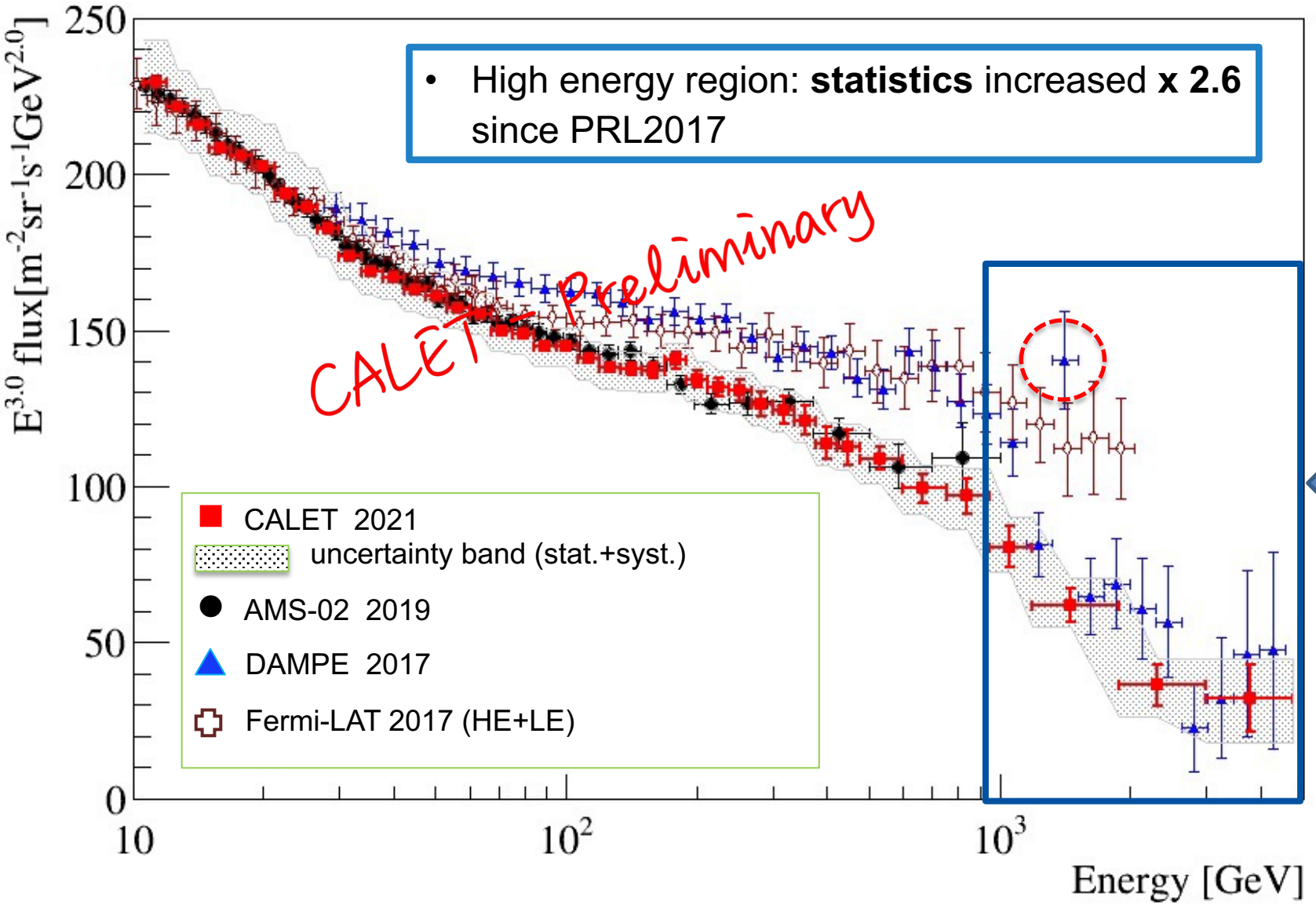
- Cosmic-ray boron flux measured from 8.4 GeV/n to 3.8 TeV/n with the Calorimetric Electron Telescope on the International Space Station, O. Adriani et al. (CALET Collaboration), Physical Review Letters **129,** 251103 (2022)

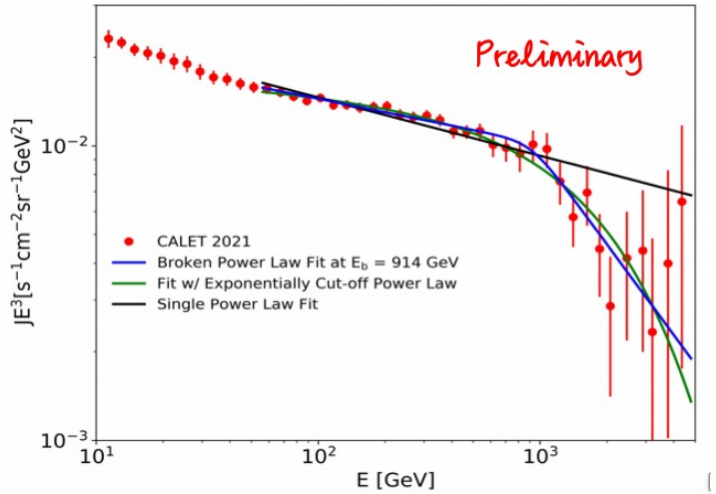
- CALET search for electromagnetic counterparts of gravitational waves during the LIGO/Virgo O3 run, O. Adriani et al. (CALET Collaboration) , The Astrophysical Journal, 933:85 (16pp) , 2022 July 1

- EMIC-Wave Driven Electron Precipitation observed by CALET on the International Space Station, A.Bruno, L. W. Blum, G. A. de Nolfo, R. Kataoka, S. Torii, A. D. Greeley, S. G. Kanekal, A. W. Ficklin, T. G. Guzik and S. Nakahira, Geophysical Research Letter 49, e2021GL097529

Cosmic-ray All-electron Spectrum (update: as of May 30, 2021)

- High energy region: **statistics** increased **x 2.6** since PRL2017





- 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).
- No peak-like structure at 1.4 TeV in CALET measurement irrespective of binning.

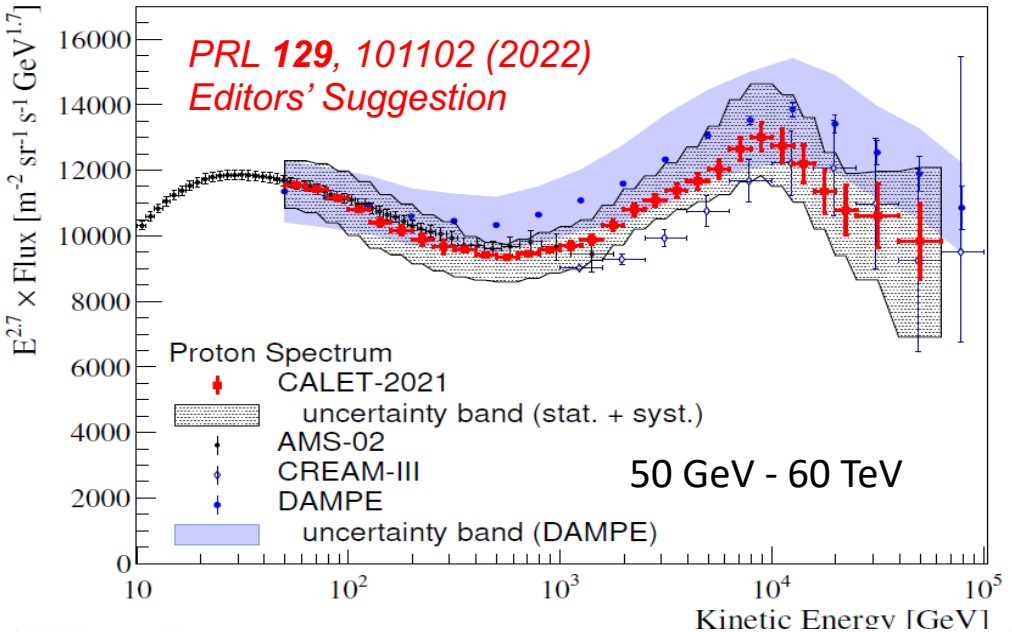
Statistics x 3.4 as of Dec. 2022
=> Updated results coming soon...

Cosmic-ray Proton & p/He Spectrum

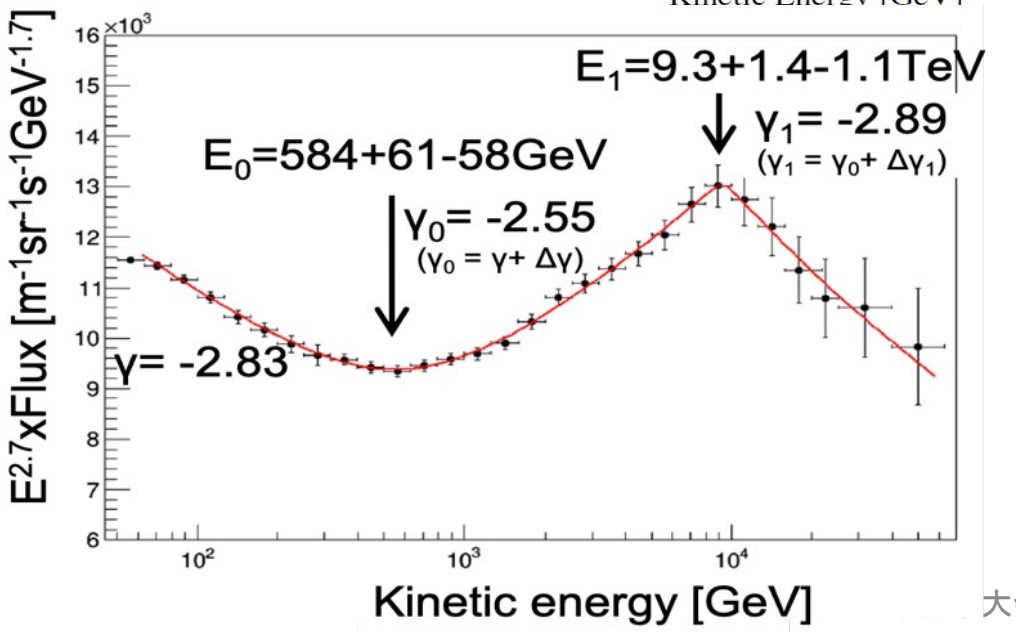
24pW2-8: K.Kobayashi

Proton

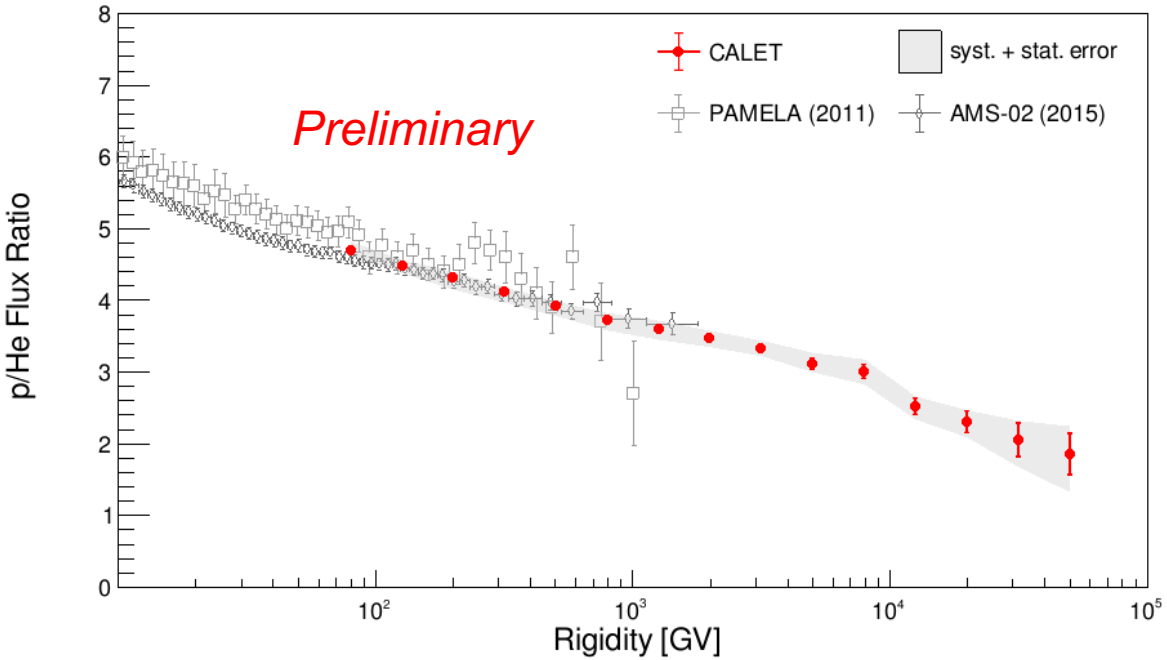
Energy Spectrum



Fitting Results



Proton/Helium ratio vs Rigidity



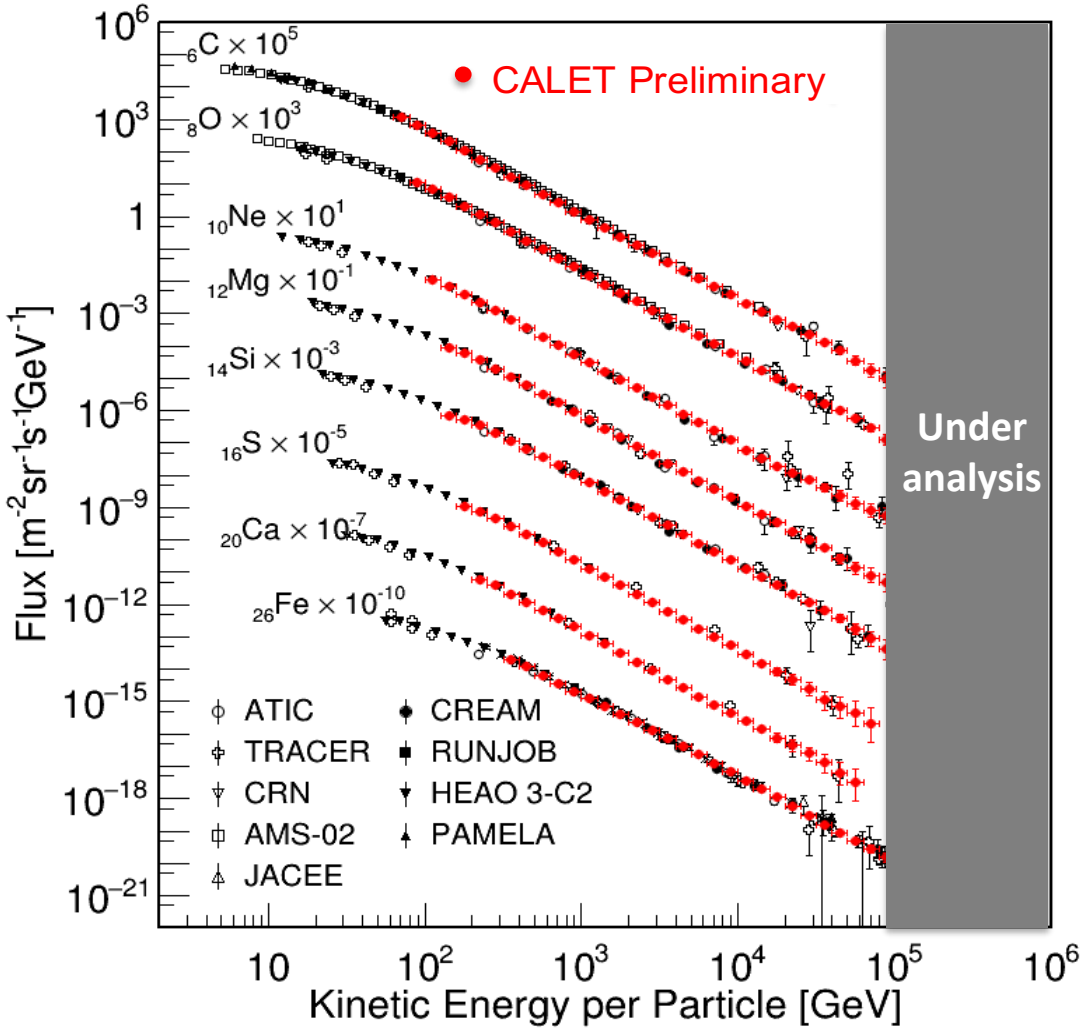
The relative flux of proton to helium decrease with rigidities, and no clear structure is not seen in the flux.

⇒ The helium spectrum seems to have a similar structure with the proton spectrum.

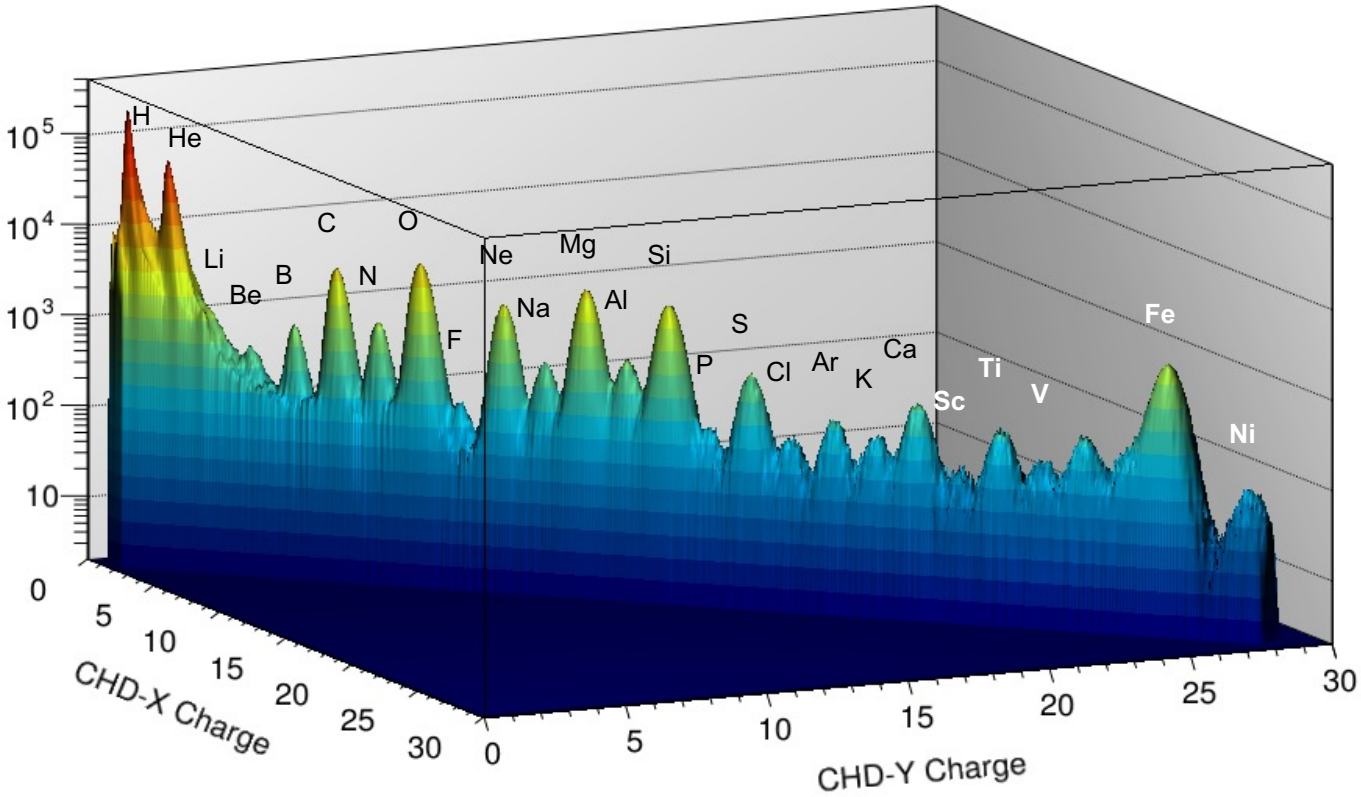
The helium energy spectrum will be published soon.

Observations of Cosmic-ray Nuclei from C to Fe

Preliminary Spectra of Carbon – Iron



Charge Distribution from Proton to Nickel (periodic table of elements by CALET)

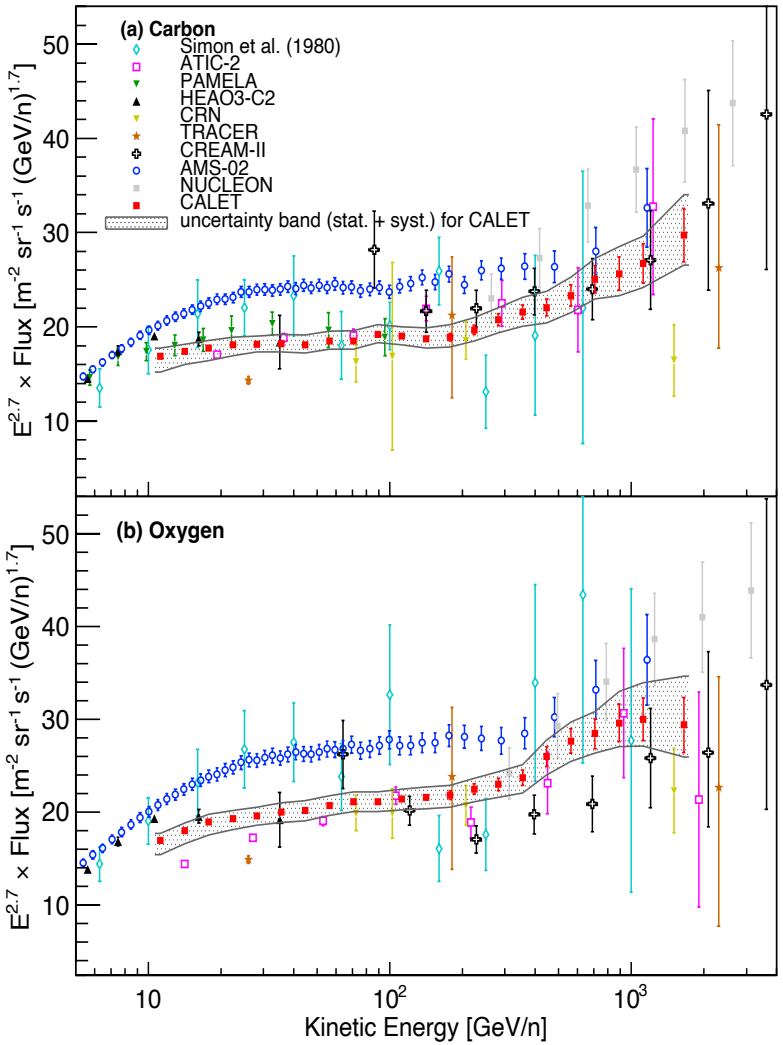


Spectra of Cosmic-ray Nuclei from C to Ni

24pW2-9: Y.Akaike

Carbon and Oxygen energy spectra

PRL **125**, 251102 (2020) [10 GeV/n, 2.2 TeV/n]

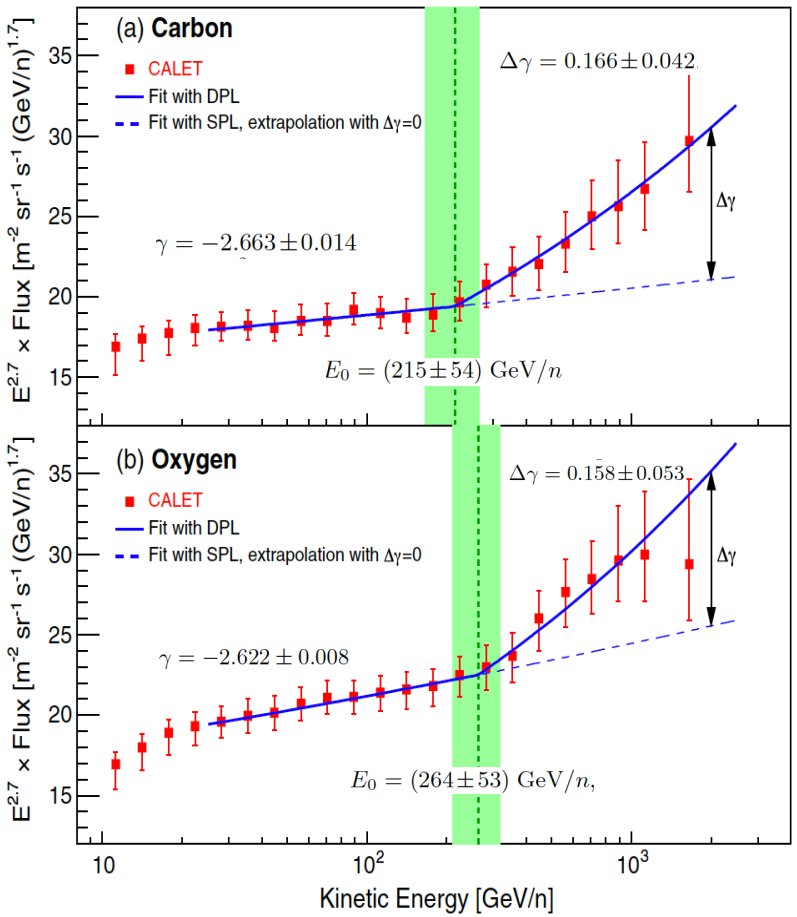


Spectra of Cosmic-ray Nuclei from C to Ni

24pW2-9: Y. Akaike

Carbon and Oxygen energy spectra

PRL **125**, 251102 (2022) [10 GeV/n, 2.2 TeV/n]



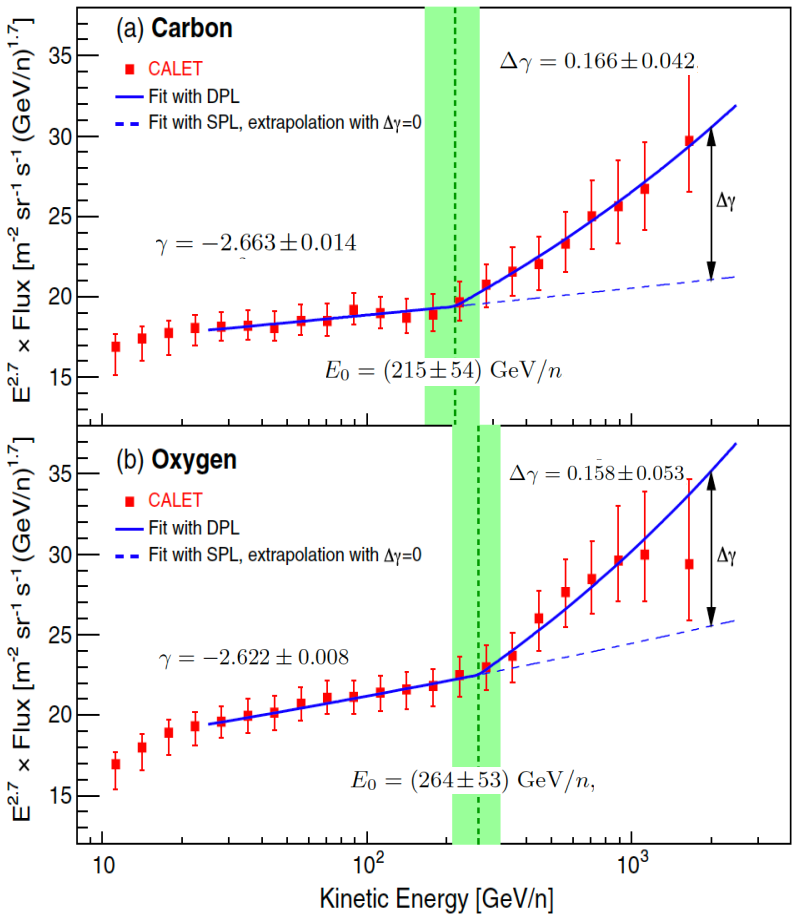
- The spectra of Carbon and Oxygen show a clear hardening around 200-300 GeV/n.
- It is consistent with hardening observed in p and He within errors, in the energy (per charge) region of 400-600 GeV/z.

Spectra of Cosmic-ray Nuclei from C to Ni

24pW2-9: Y.Akaike

Carbon and Oxygen energy spectra

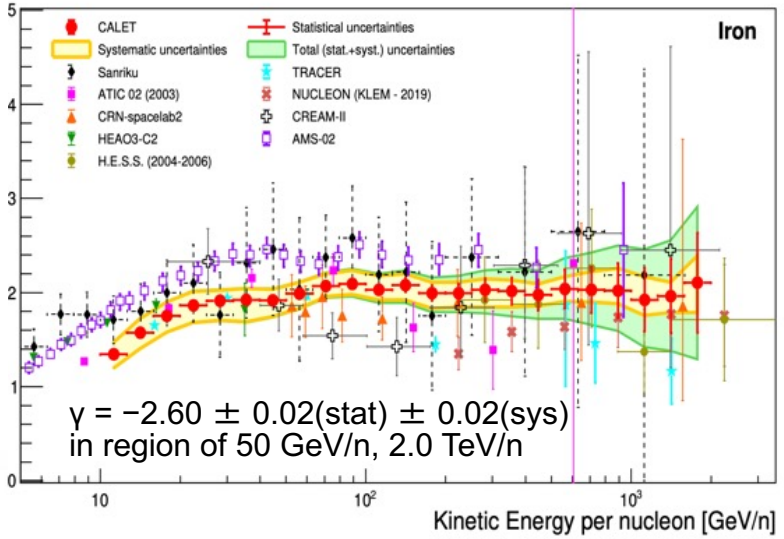
PRL **125**, 251102 (2020) [10 GeV/n, 2.2 TeV/n]



- The spectra of Carbon and Oxygen show a clear hardening around 200-300 GeV/n.
- It is consistent with hardening observed in p and He within errors, in energy region of 400-600 GeV/Z.
- However, the hardening is not observed in Iron spectrum, and Nickel spectrum shows a similar structure up to 240GeV/n.

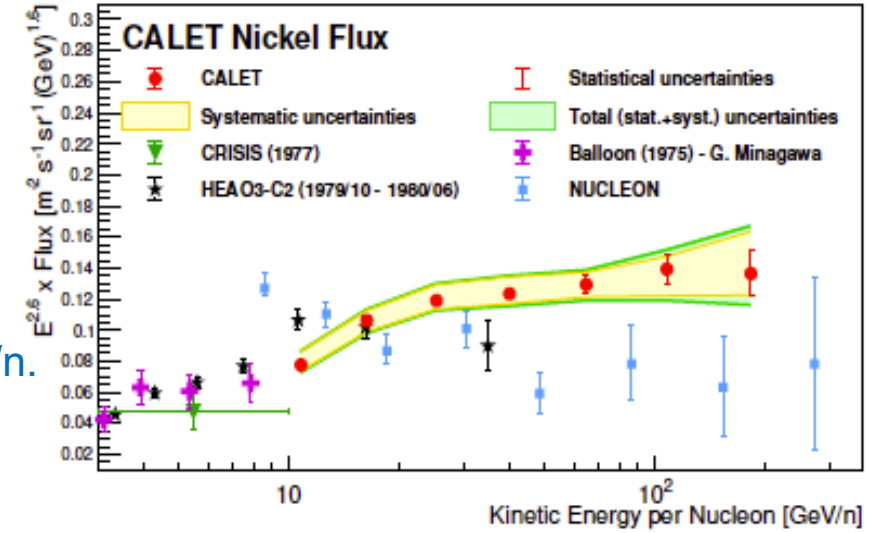
Iron energy spectrum

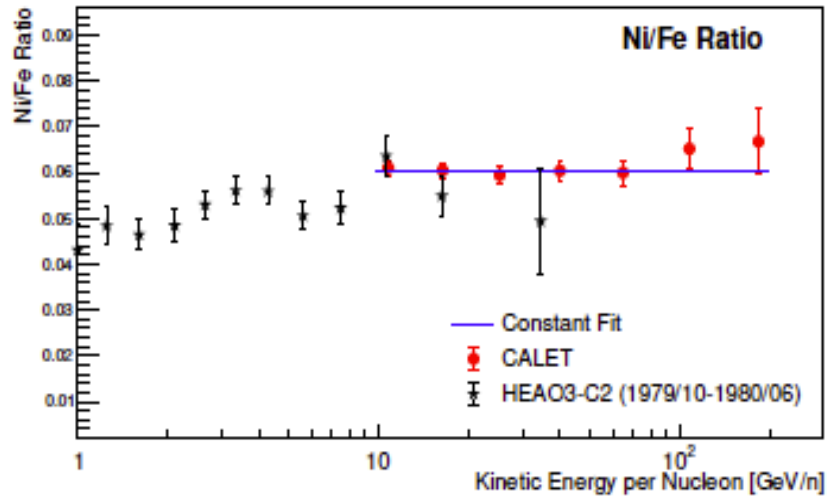
PRL ***126***, 241101(2021) [10 GeV/n, 2 TeV/n]



Nickel energy spectrum

PRL **126**,131103 (2022) [8.8 GeV/n, 240 GeV/n]



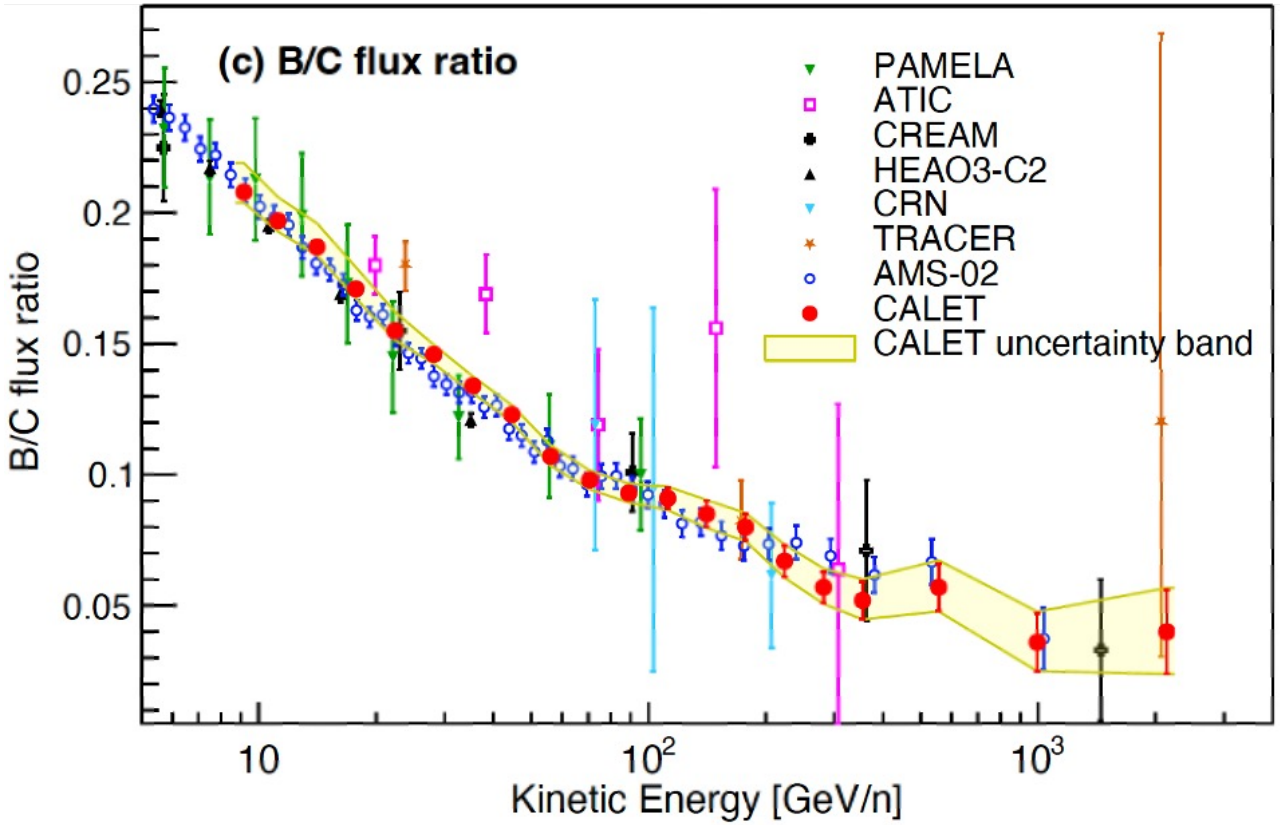


Boron/Carbon Ratio from 8.5 GeV/n to 3.8 TeV/n

24pW2-9: Y. Akaike

PRL **129**, 251103 (2022)

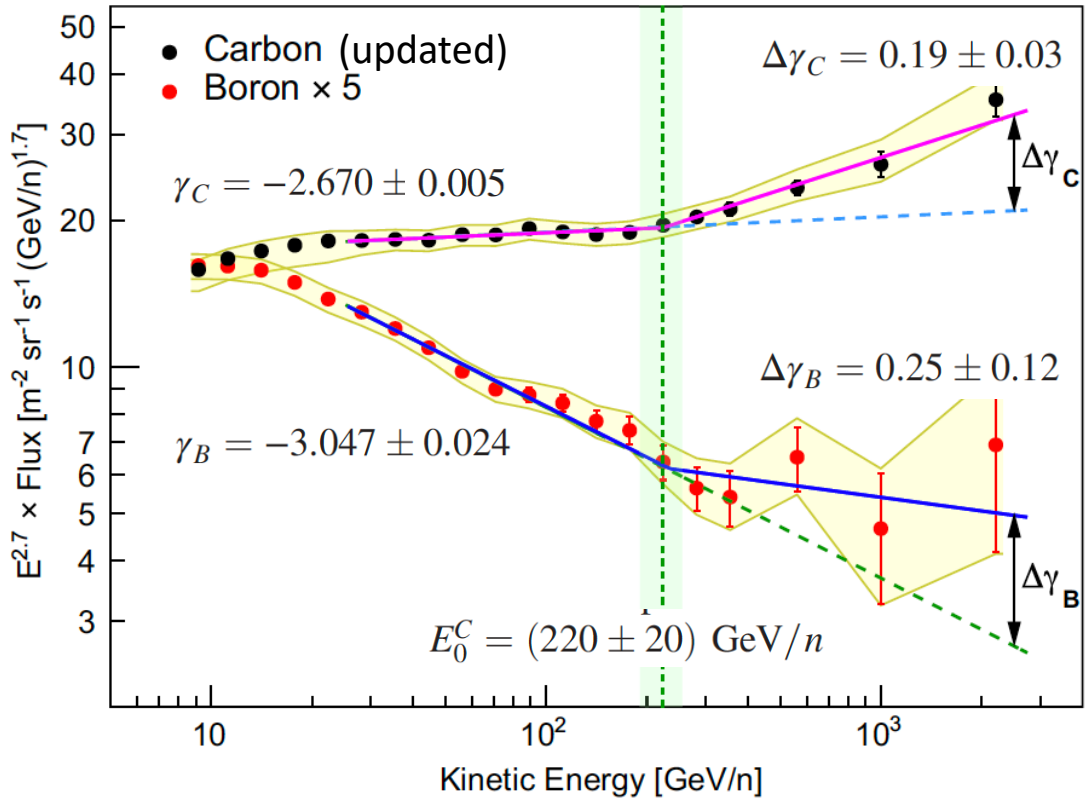
B/C ratio as a function of kinetic energy per nucleon



First precise measurements of B/C ratio up to the TeV region.

*) DAPME published a similar result at same timing.

Comparison of energy spectra of Boron and Carbon



Boron and Carbon energy spectra are fitted by Double Power Law functions. Δγ is the change of spectral index above the transition energy of Carbon, E_0^C.

Energy Spectrum of Diffuse Component

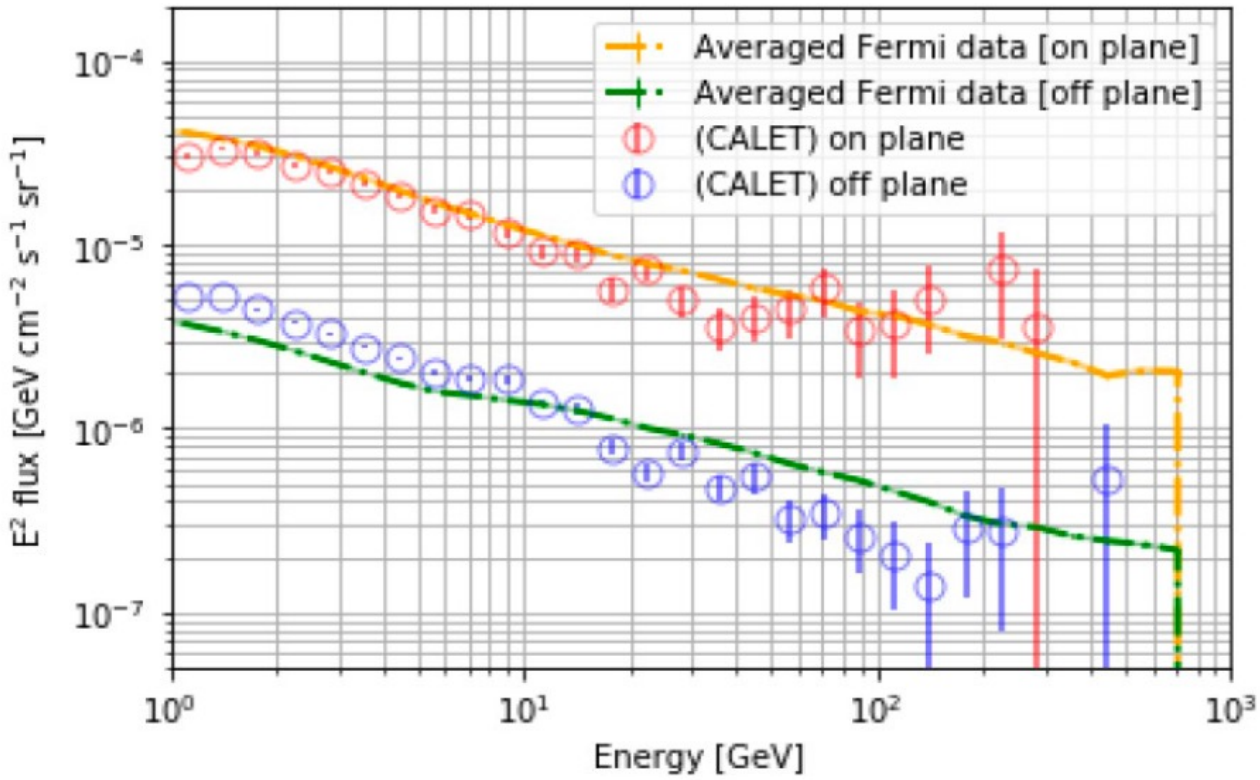
- Effective area: ~400 cm^2 above 2 GeV, decreases above 100 GeV => Improvement by 24pW2-10: M. Mori
- Angular resolution: < 0.2° above 10 GeV ・ Energy resolution: ~5% at 10 GeV

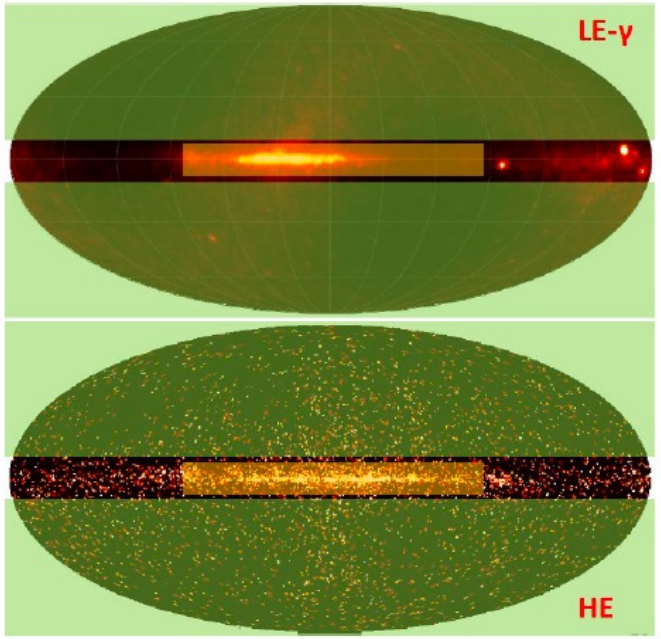
Diffuse Gamm-ray Spectrum Compared with Fermi-LAT

Preliminary

LE-γ + HE November 2015 – February 2022

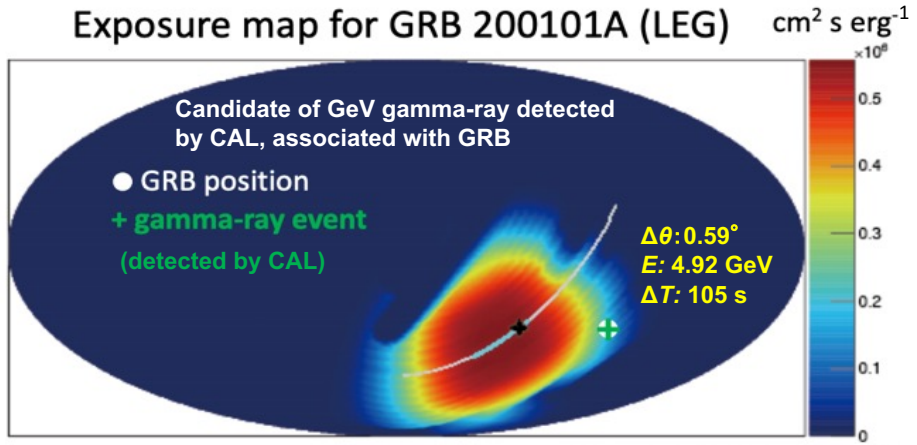
(Fermi data: analyzed from public data





"On-plane": $|l| < 80°$ & $|b| < 8°$, "Off-plane": $|b| > 10°$

Gamma-ray Bursts and GW Follow-up



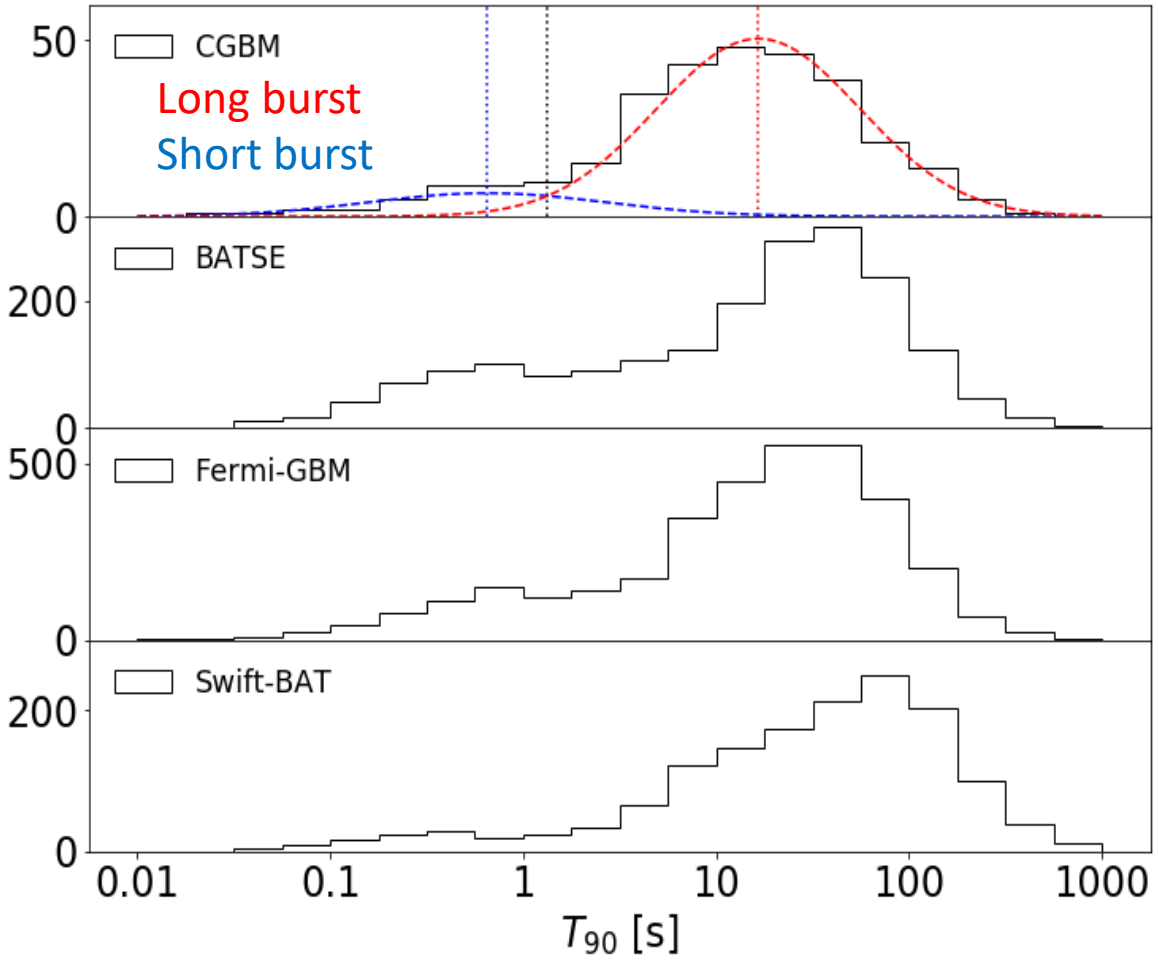
CGBM: dedicated Gammay-Ray Burst Monitor with energy range 7 keV-20 MeV

from 2015-10-05 to 2022-1-31

314 GRBs (~44 GRBs / year)

247 Long (89%) **33 Short (11%)**

Time distribution (T_{90}) of GRB durations



- **Follow-up** of LIGO/Virgo **GW** observations during O3
- X-ray and gamma-ray bands
- high-energy gamma-ray in the calorimeter

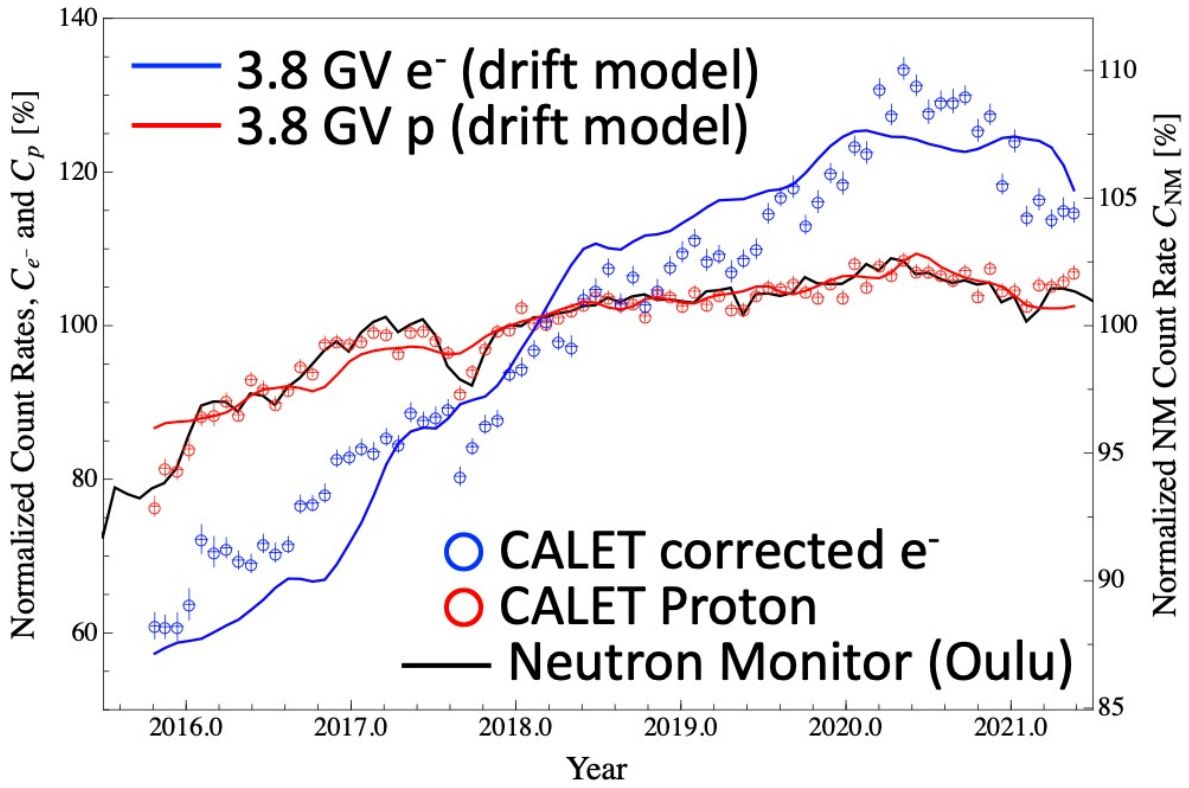
published in Astrophysical Journal **933**:85 (2022)

Solar Modulation

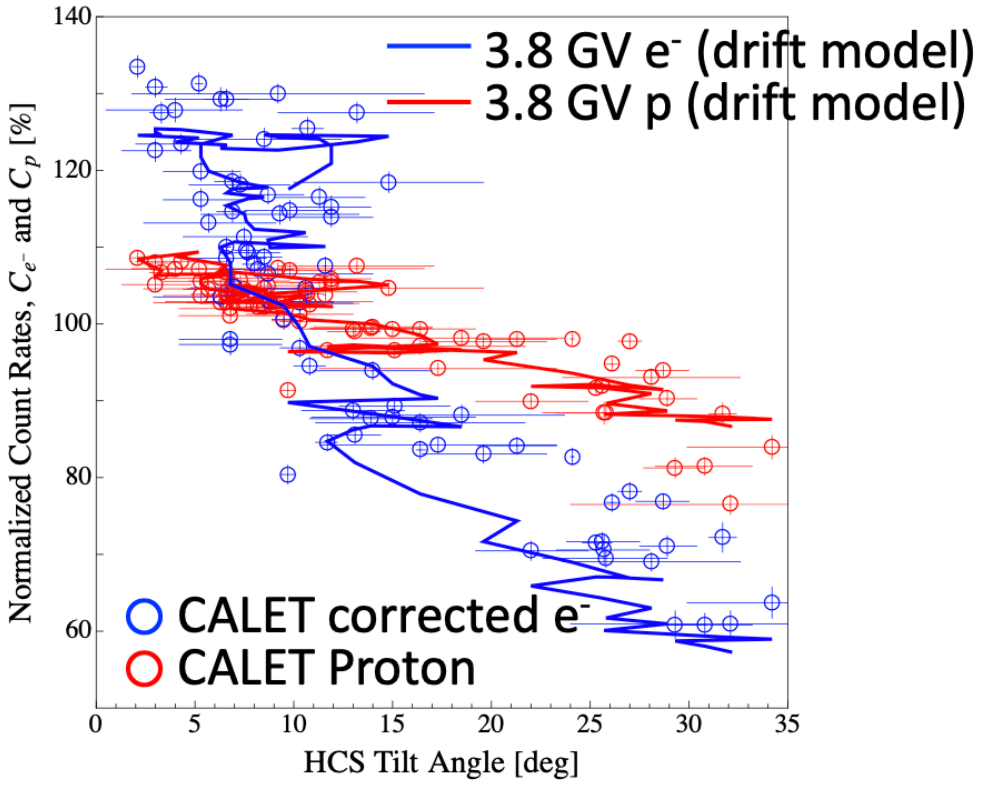
24pW2-11: S. Miyake

- The low energy (<10GeV) electron and proton observations have being carried out since the start of CALET operations (Oct., 2015) on the International Space Station.
- The results for solar modulation are now interpreted by a drift model by S. Miyake (ICRC2017).

Time profile of the count rate of CR protons and corrected e⁻



Correlation with count rate of CR protons/corrected e⁻ and HCS tilt angle



Space Weather Phenomena with CALET

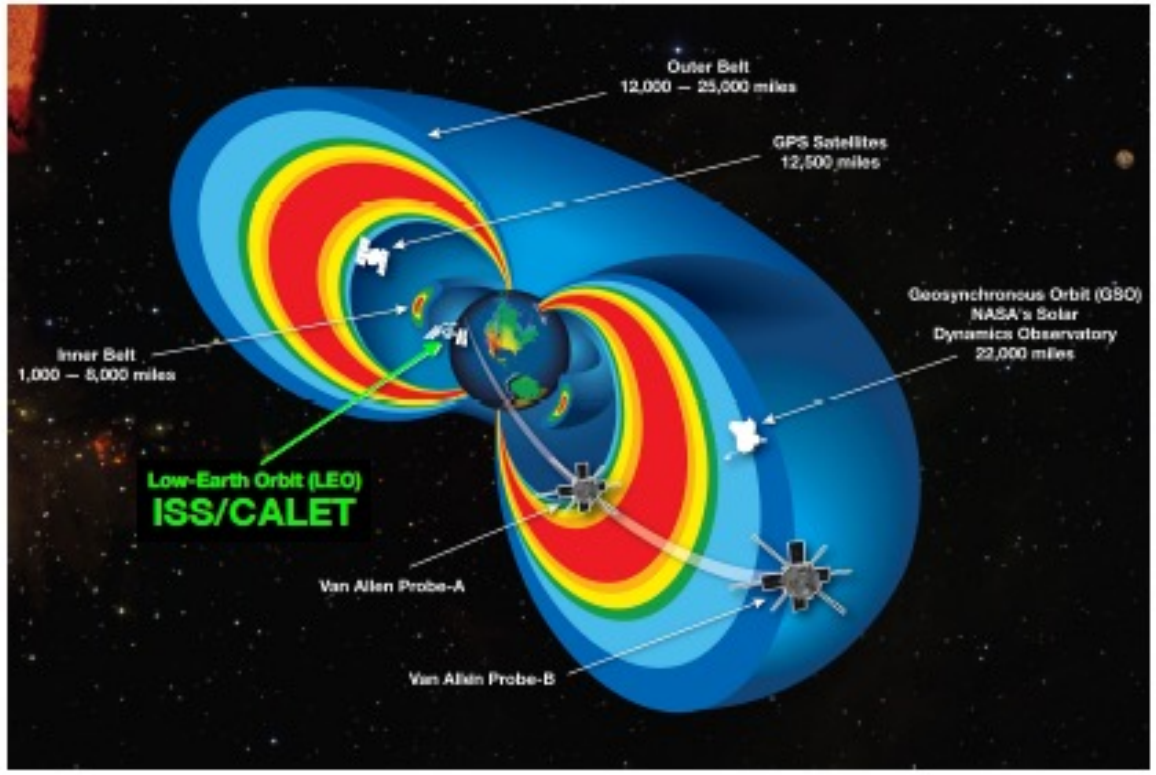
Research using the public data archived at ISAS/DARTS

https://data.darts.isas.jaxa.jp/pub/calet/cal-v1.1/CHD/level1.1/obs/

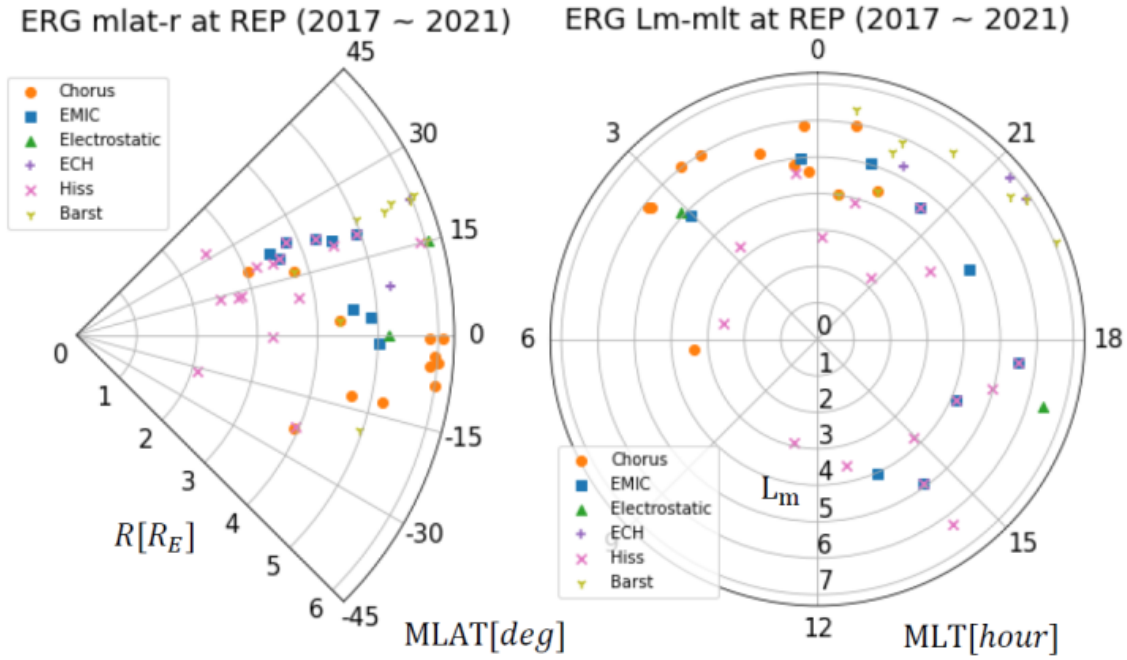
EMIC-Wave Driven Electron Precipitation observed by CALET on the International Space Station

(*Geophysical Research Letters* **49,** e2021GL097529)

Observations by CALET and Van Allen Probes



The REP events observed simultaneously by CALET and the Arase satellite (ERG)



24pW2-12: M. Teramoto

CALET: Summary and Future Prospects

- CALET was launched on Aug. 19th, 2015. The observation campaign started on Oct. 13th, 2015. Excellent performance and remarkable stability of the instrument have been confirmed.
- As of Feb. 28, 2023, total observation time is 2969 days (> 7 years) with live time fraction close to 86%. Nearly 3.86 billion events collected with low energy trigger (> 1 GeV) and 1.77 billion events with high energy trigger (> 10 GeV).
- Accurate calibrations have been performed in the energy measurements established in 1 GeV-1PeV.
- Following results of the cosmic-ray spectra 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 was consistently observed around a few hundred GeV/n. B/C flux is precisely measured up to 3.8 TeV/n.
  - Iron and Nickel spectra were measured to energies beyond those covered by previous experiments.
- Continuous observations of GRBs, Solar Modulation and REP events have being carried out.
- CALET observation has successfully been carried out over 7 years, and is approved to be extended for further 4 years (at least) until the end of 2024 (or more).

✓ 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).**

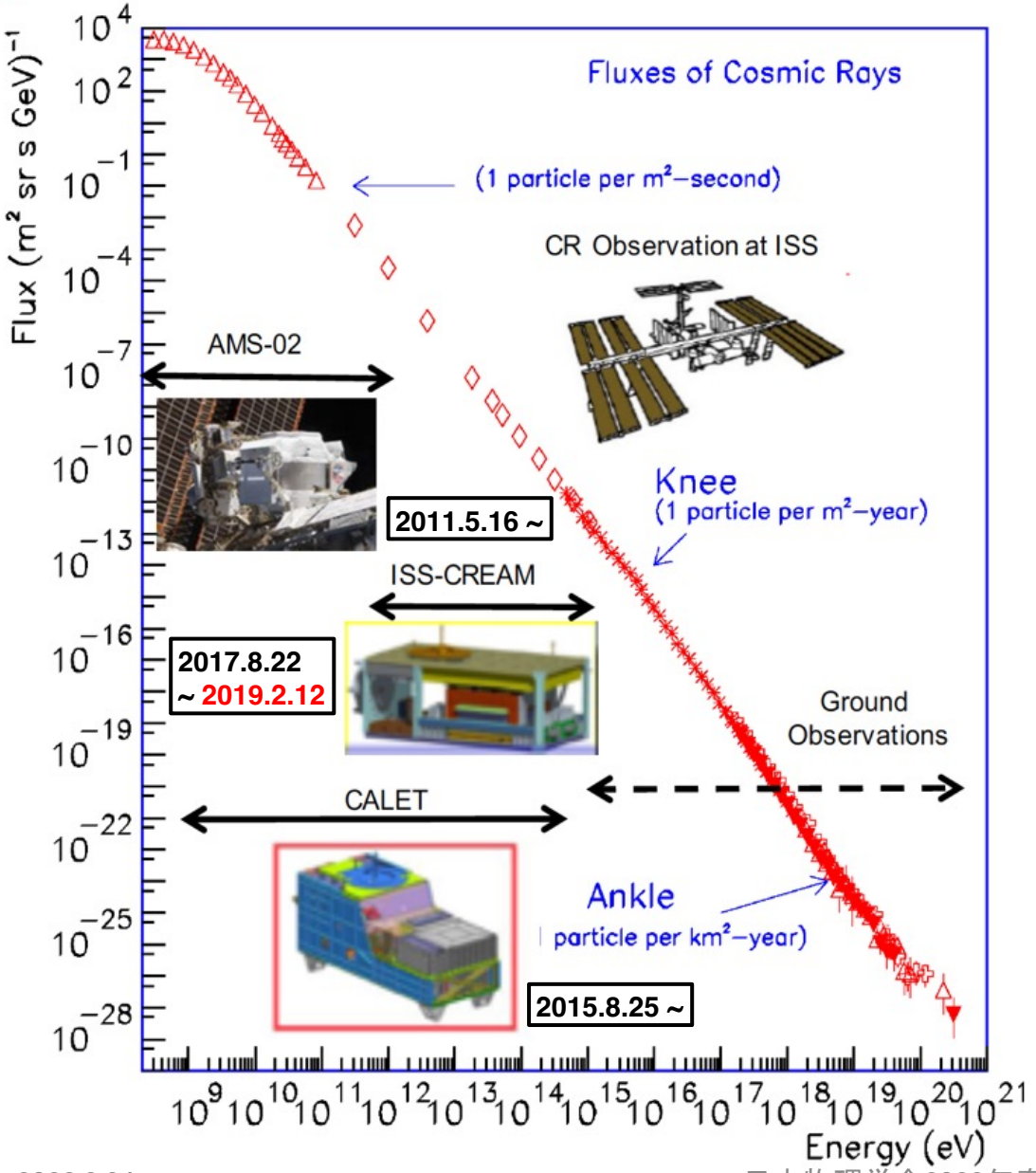
Main Science Goals and Status of the Analysis

Scientific Objectives	Observables	Energy Reach	Reported	Reference (Latest)	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 60 TeV	PRL 129, 101102 (2022)	**50 GeV – 60 TeV**
	Helium spectrum	10 GeV – 1 PeV	To 50 TeV	PoS (ICRC2021), 101	**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/Nickel spectrum	10 GeV – 1 PeV	to 2 TeV/n	PRL 125,241101 (2021) PRL 128,131103 (2022)	**50 GeV/n – 2 TeV/n** **8.8GeV/n – 240GeV/n**
	Elemental spectra of primaries	10 GeV – 1 PeV	to 100 TeV	PoS (ICRC2019), 034	10 GeV – 100 TeV
	Ultra-heavy abundances (< z=40)	> 600 MeV/n	> 600 MeV/n	PoS (ICRC2021), 124	> 600 MeV/n
CR propagation	**B/C and secondary-to-primary ratios**	Up to some TeV/n	to 3.8 TeV/n	PRL 129,251103 (2022)	**8.4 GeV/n – 3.8 TeV/n**
Nearby electron sources	**Electron spectral shape**	100 GeV – 20 TeV	to 4.8 TeV	PRL 120, 261102 (2018)	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)	Proc. of IDM2022 (e) PoS (ICRC2021), 619 (γ)	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	PoS (ICRC2021), 1270	**1 – 10 GeV**
Gamma-ray transients	**GW follow-up and GRB analysis**	7 keV–20MeV (CGBM) 1 GeV-1TeV (ECAL)	7 KeV-20MeV	ApJ 933:85 (2022)	7 keV–20MeV (CGBM) > 1 GeV (ECAL)
Space weather	**Relativistic electron precipitation**	> 1.5 MeV	> 1.5 MeV	Geophys.Res.Lett,49 (2022)	> 1.5 MeV

CALETの軌道上運用に関するJAXAによる審査経過と今後の計画

時期	経過状況
2015年 11月	チェックアウトフェーズ完了 通常観測開始
2015年 12月	CALET 定常運用移行審査
2016年 1月	CALET 定常運用移行審査　デルタ審査
2017年 11月	CALET 定常運用終了審査 (後期運用(1) への移行が承認された)
2018年 4月	後期運用(1) へ移行
2019年 3月	CALET 後期運用(1) 延長審査 (後期運用(2) への以降が承認された。後期運用(1) と併せて、2018年4月～2021年3月の3年間 運用する)
2019年 4月	CALET プロジェクト終了審査
2021年3月	後期運用（2）終了審査／後期運用（3）計画審査会（2024年12月まで運用する）
2022年3月	後期運用（3）中間確認会
2023年3月	後期運用（3）中間確認会（その2）

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

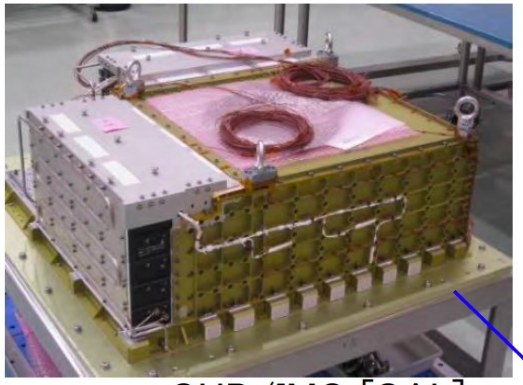
- Observation of cosmic-ray nuclei will be performed in energy region from 10 GeV to 1 PeV

⇨ Unravelling the CR acceleration and propagation mechanism

- Detection of transient phenomena in space by stable observations

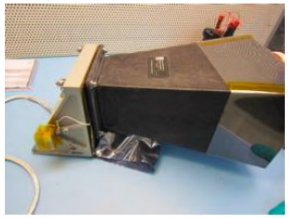
⇨ Gamma-ray burst, Solar flare, EM radiation from GW sources etc.

CALET Instruments

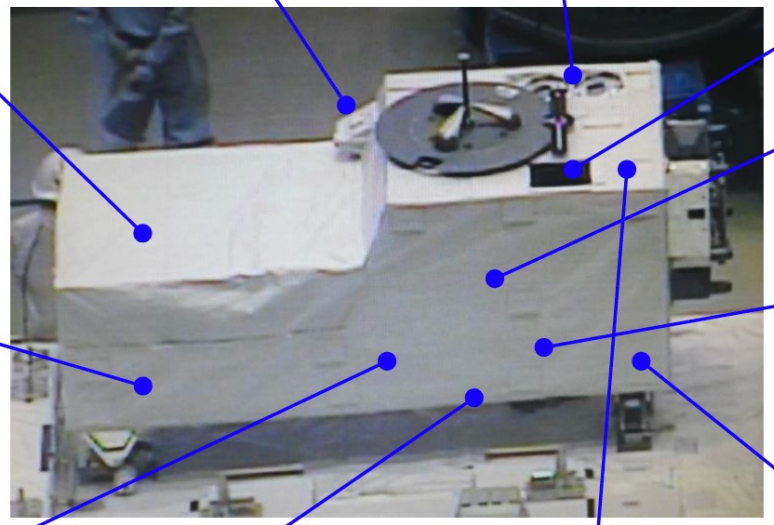

CHD/IMC [CAL]

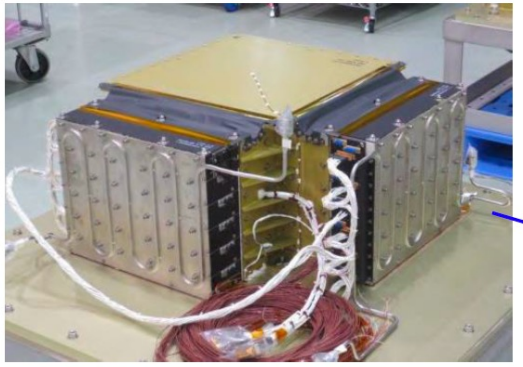

GPSR-ANT


HXM#1, #2 [CGBM]

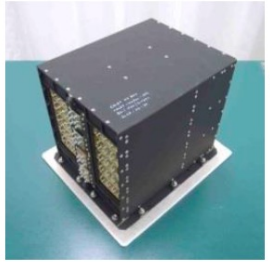

CHU(buffle付)[ASC]


DPU[ASC]




TASC [CAL]


MDC

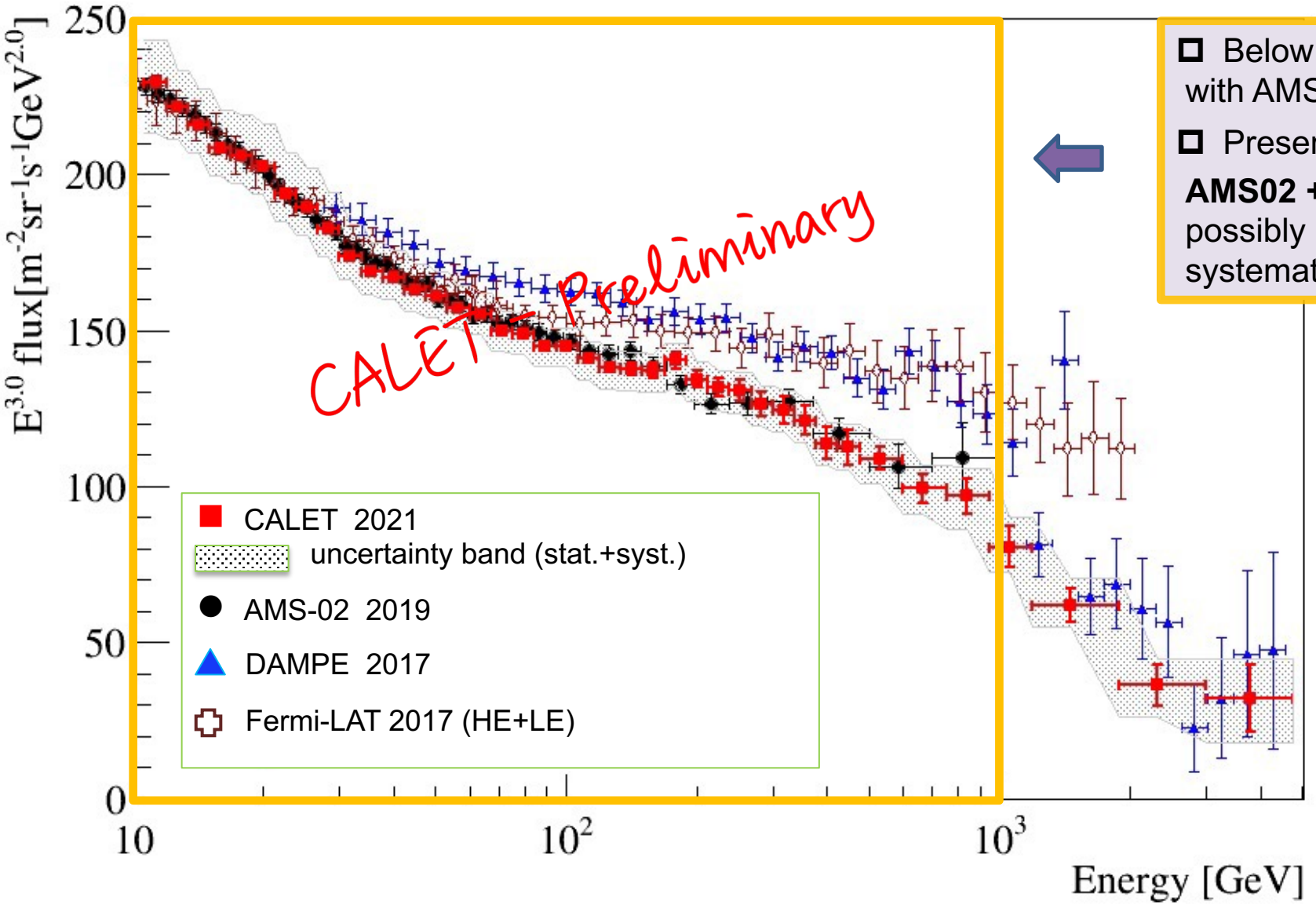

HV-BOX

CIRC


SGM [CGBM]


GBM-EBOX[CGBM]

Cosmic-ray all-electron spectrum (update: as of May 30, 2021)



- 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 unkown systematics

Preliminary spectrum is **updated** after 2057 days of CALET observations:
Oct.13, 2015 – May 30, 2021