13aW3-5

CALETによる5年間の軌道上観測の成果と展望

CALET

Calorimetric Electron Telescope on the International Space Station

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他　CALETチーム

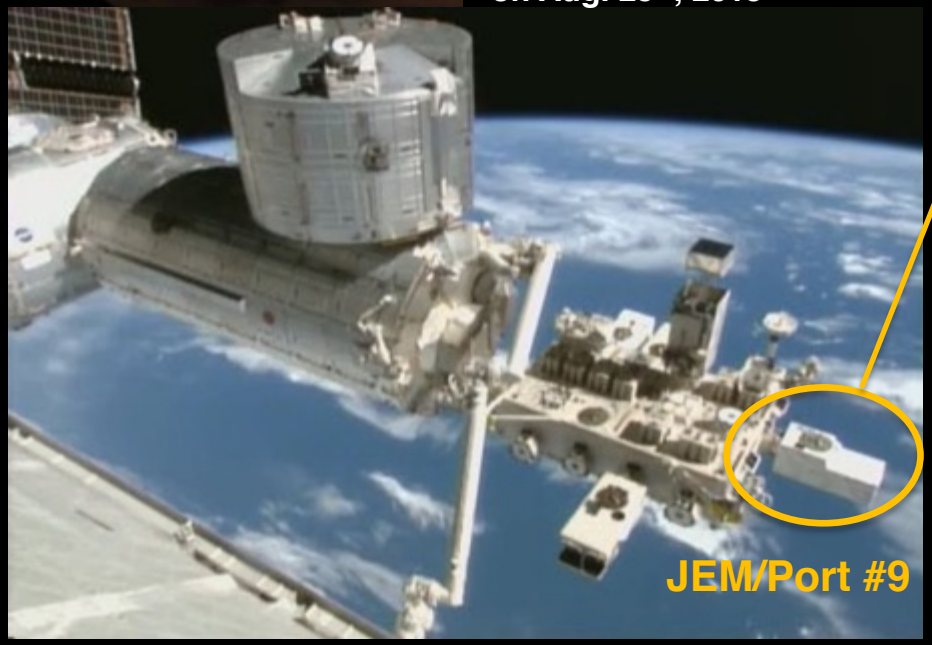
日本物理学会第76回年次大会　2021年3月13日

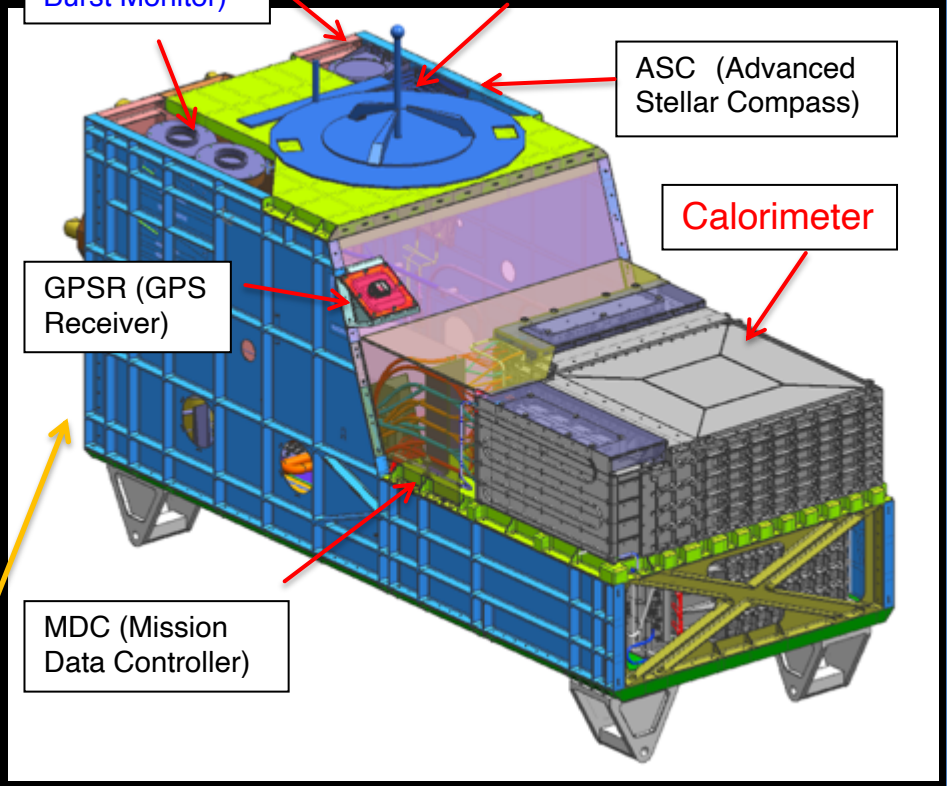
CALET Payload

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 Overview

Main CALET scientific objectives

- **Electron observation in 1GeV-20TeV**
  Design optimized for electron detection:
  high energy resolution and large e/p separation power
  + e.m. shower containment
  Search for Dark Matter and Nearby Sources
- **Observation of cosmic-rays in 10 GeV-1 PeV**
  Unraveling the CR acceleration and propagation mechanism(s)
- **Detection of transient phenomena in space:**
  - Gamma-ray burst
  - GW e.m. counterparts
  - Solar modulation
  - Space weather

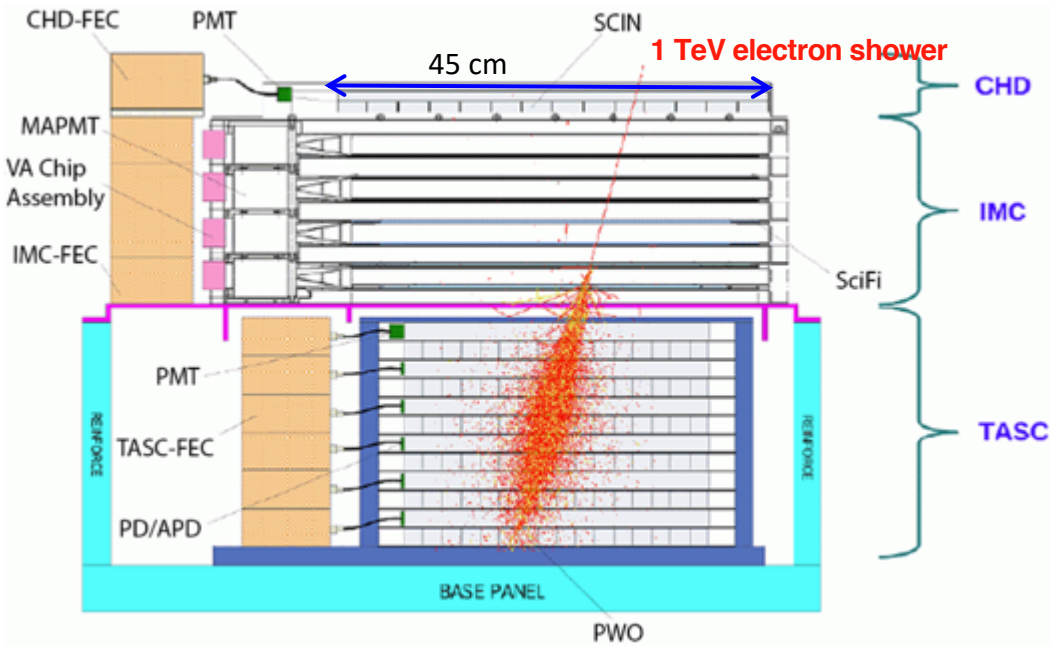
Detector performance

- **Geometrical Factor:**
  1040 cm^2 sr for electrons, light nuclei
  1000 cm^2 sr for gamma-rays
  4000 cm^2sr for ultra-heavy nuclei
- **ΔE/E:**
  ~2 % (>10GeV) for e , γ
  ~30-35% for protons, nuclei
- **e/p separation:** ~10^5
- **Charge resolution:** 0.15-3 e (p-Fe)
- **Angular resolution:**
  0.2° for gamma-rays > 10 GeV

Scientific Objectives	Observation Targets	Energy Range
CR Origin and Acceleration	Electron spectrum Individual spectra of elements from proton to Fe Ultra Heavy Ions (26<Z≤40) Gamma-rays (Diffuse + Point sources)	1GeV - 20 TeV 10 GeV - 1000 TeV > 600 MeV/n 1 GeV - 1 TeV
Galactic CR Propagation	B/C and sub-Fe/Fe ratios	Up to some TeV/n
Nearby CR Sources	Electron spectrum	100 GeV - 20 TeV
Dark Matter	Signatures in electron/gamma-ray spectra	100 GeV - 20 TeV
Solar Physics	Electron flux (1GeV-10GeV)	< 10 GeV
Gamma-ray Transients	Gamma-rays and X-rays	7 keV - 20 MeV

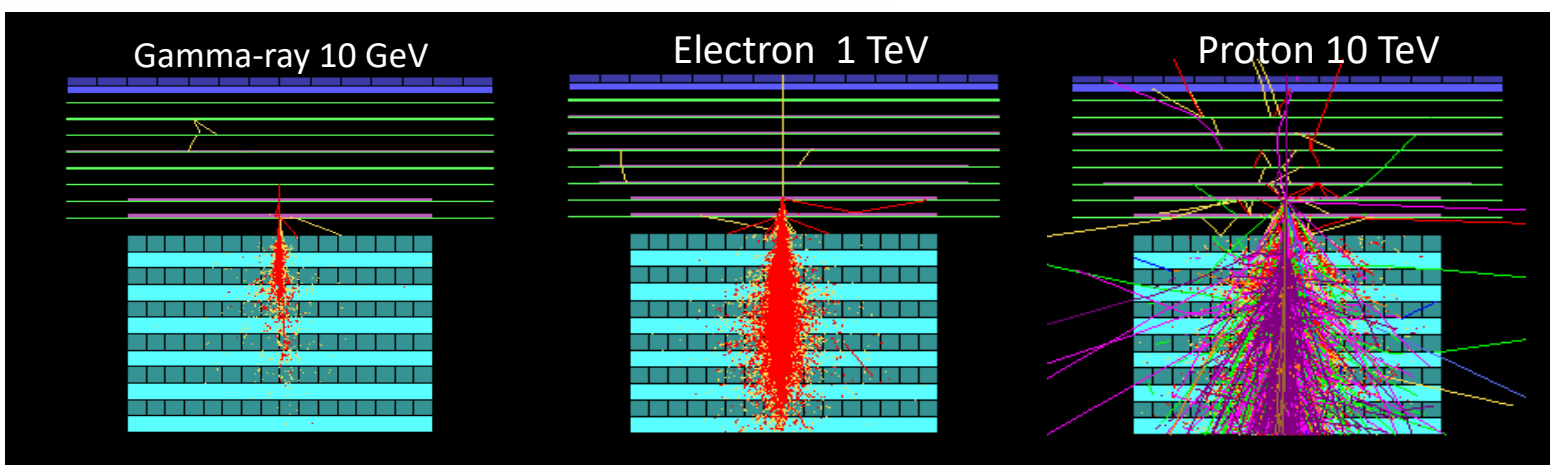
CALET Capability

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



Unique features of CALET

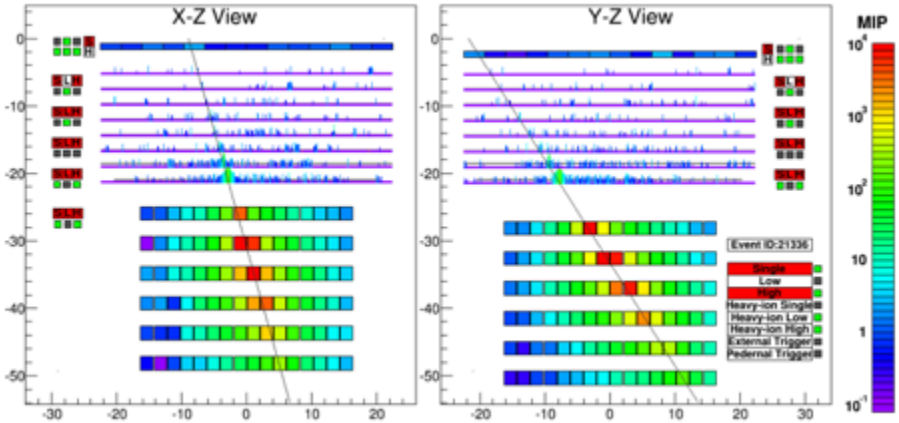
- A dedicated charge detector + multiple dE/dx track sampling in the IMC allow to identify individual nuclear species（Δz~0.15-0.3 e).
- Thick(~30 X_0), fully active calorimeter allows measurements well into the TeV energy region with excellent energy resolution (~2-3%)
- High granularity imaging calorimeter to accurately identify the arrival direction of incident particles (~0.2°) and the starting point of electromagnetic showers.
- ➢ Combined, they powerfully separate electrons from the abundant protons: contamination is much less than 10 % up to the TeV region.



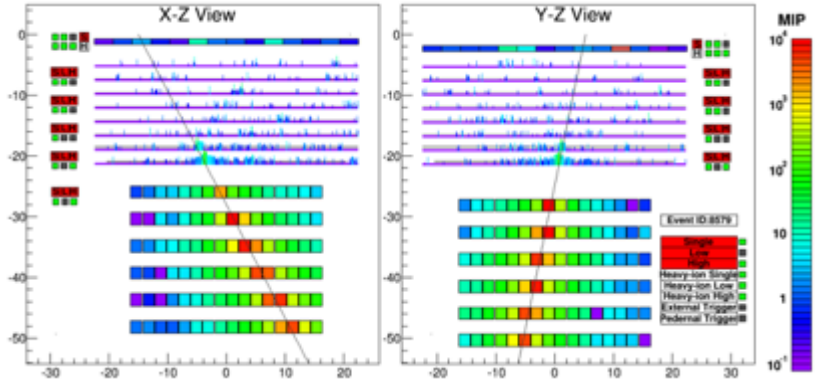
Examples of Observed Events

Event Display: Electron Candidate (>100 GeV)

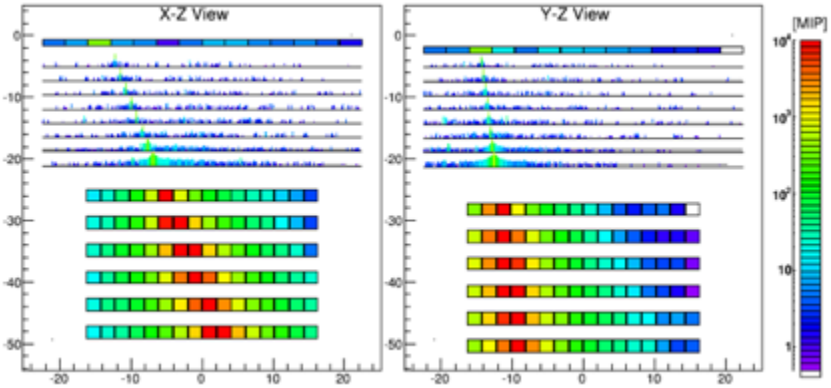
Electron, E=3.05 TeV



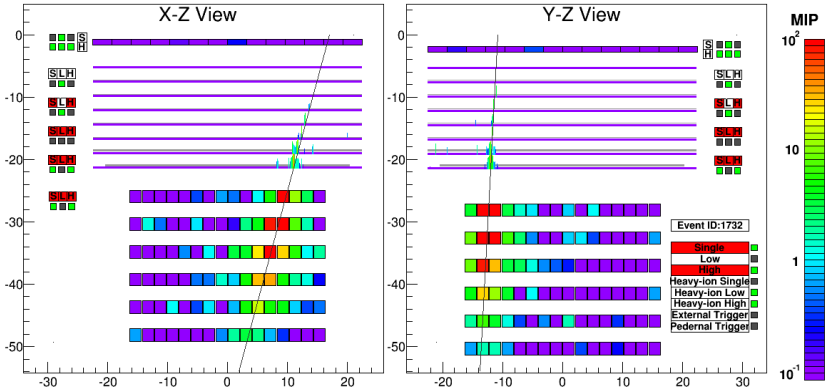
Proton, E_{TASC}=2.89 TeV



Fe, E_{TASC} =9.3 TeV



Gamma-ray, E=44.3 GeV



Unit in MIP

Observations with High Energy Trigger (>10GeV)

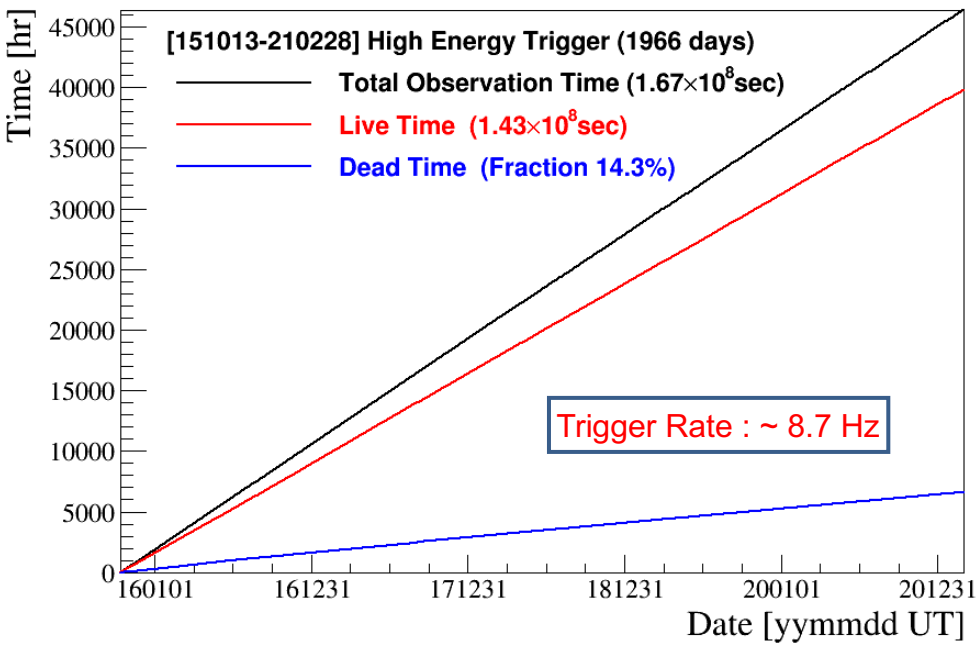
13aW3-6 (Tamura)

Observation by High Energy Trigger over 1966 days : Oct.13, 2015 – Feb. 28, 2021

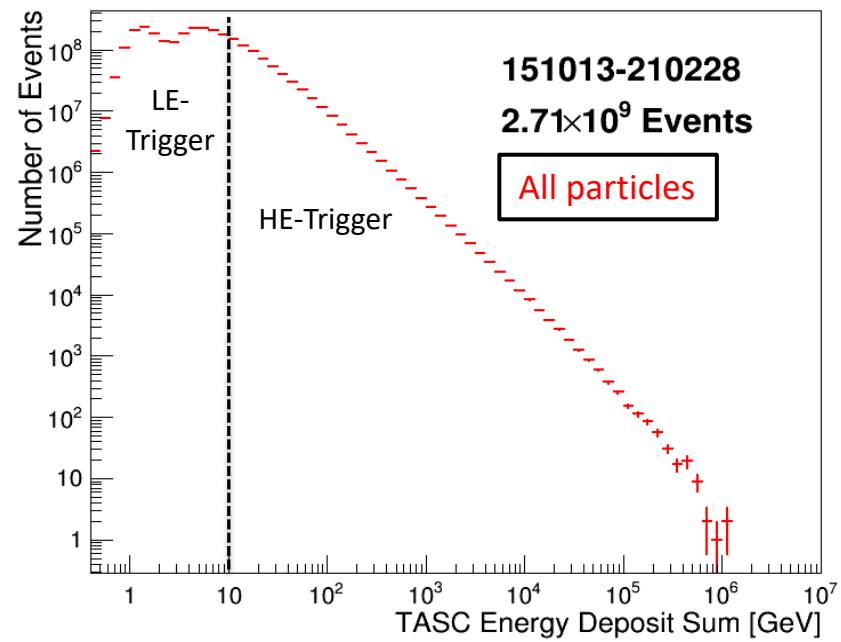
Over five-years observations have already been achieved !!

- The exposure, SΩT, has reached to ~174 m^2 sr day for electron observations by continuous and stable operations.
- Event number of HE triggered events (>10 GeV) is ~1.27 billion with a live time fraction of about 86 %. Total event number triggered over 1 GeV is ~2.71 billion.

Accumulated observation time (live, dead)

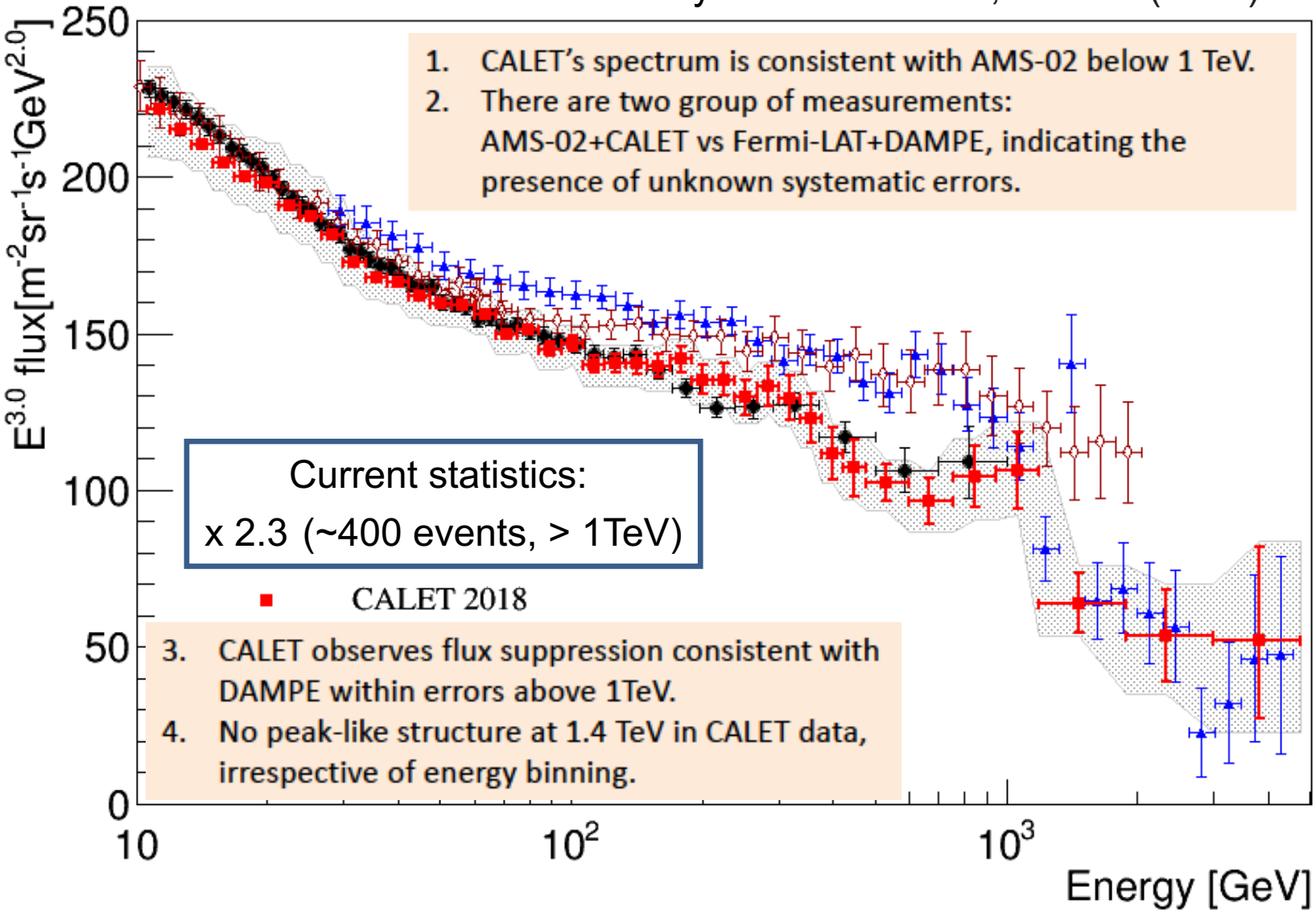


Energy deposit (in TASC) spectrum: 1 GeV-1 PeV

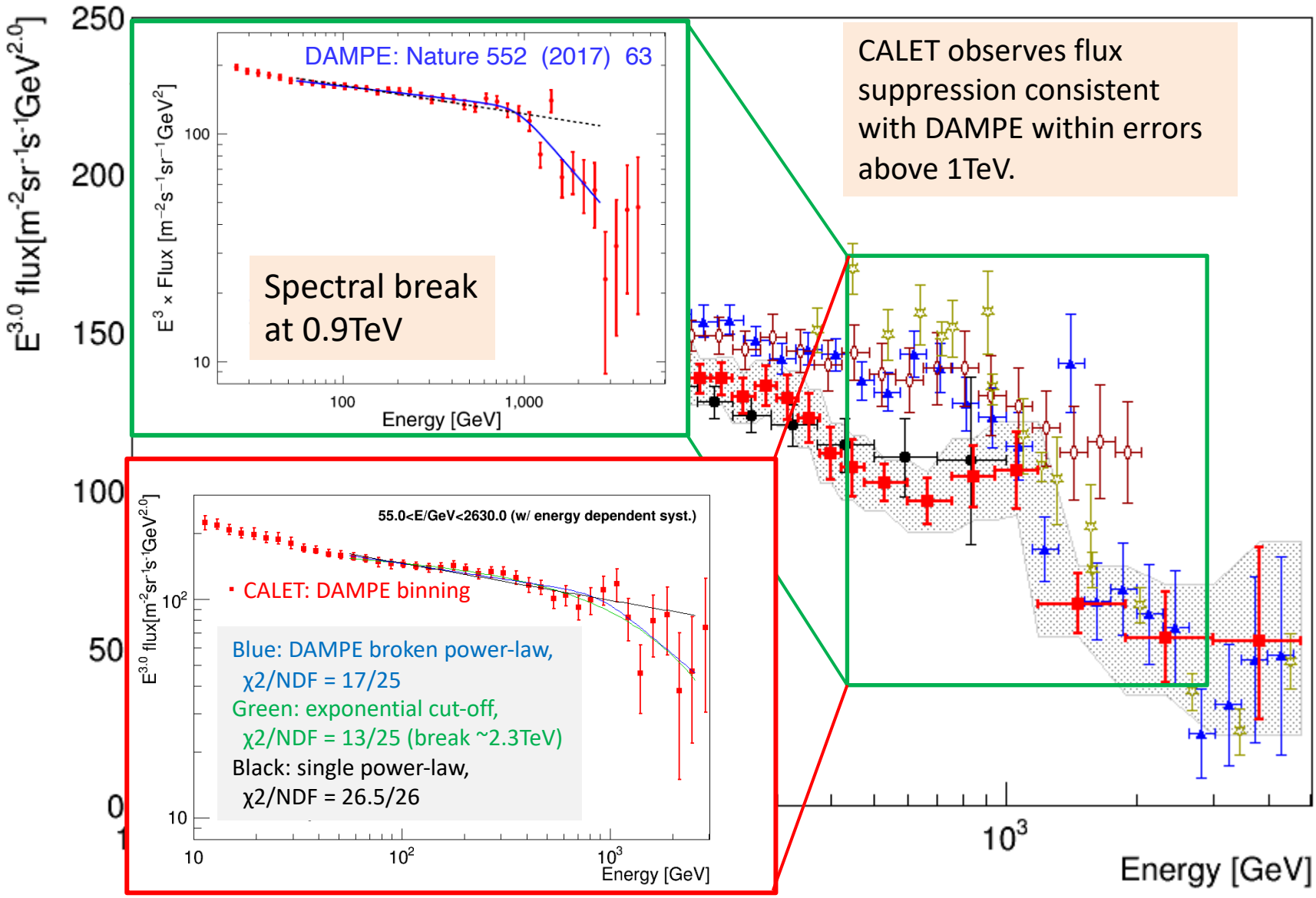


Direct Measurement of All-Electron Spectrum

Phys. Rev. Lett. **120**, 261102 (2018)

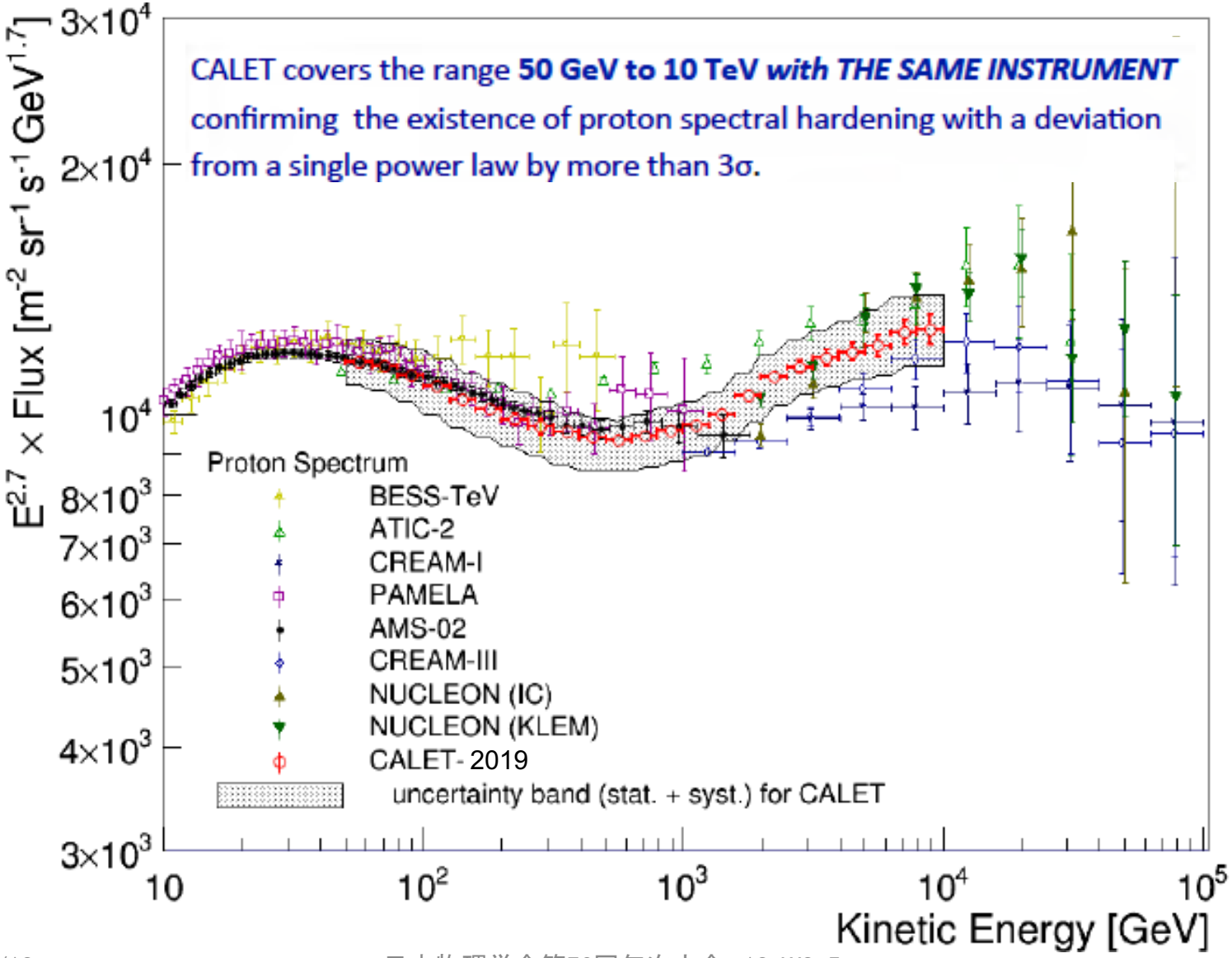


CALET All-Electron Spectrum : sub-TeV to TeV region



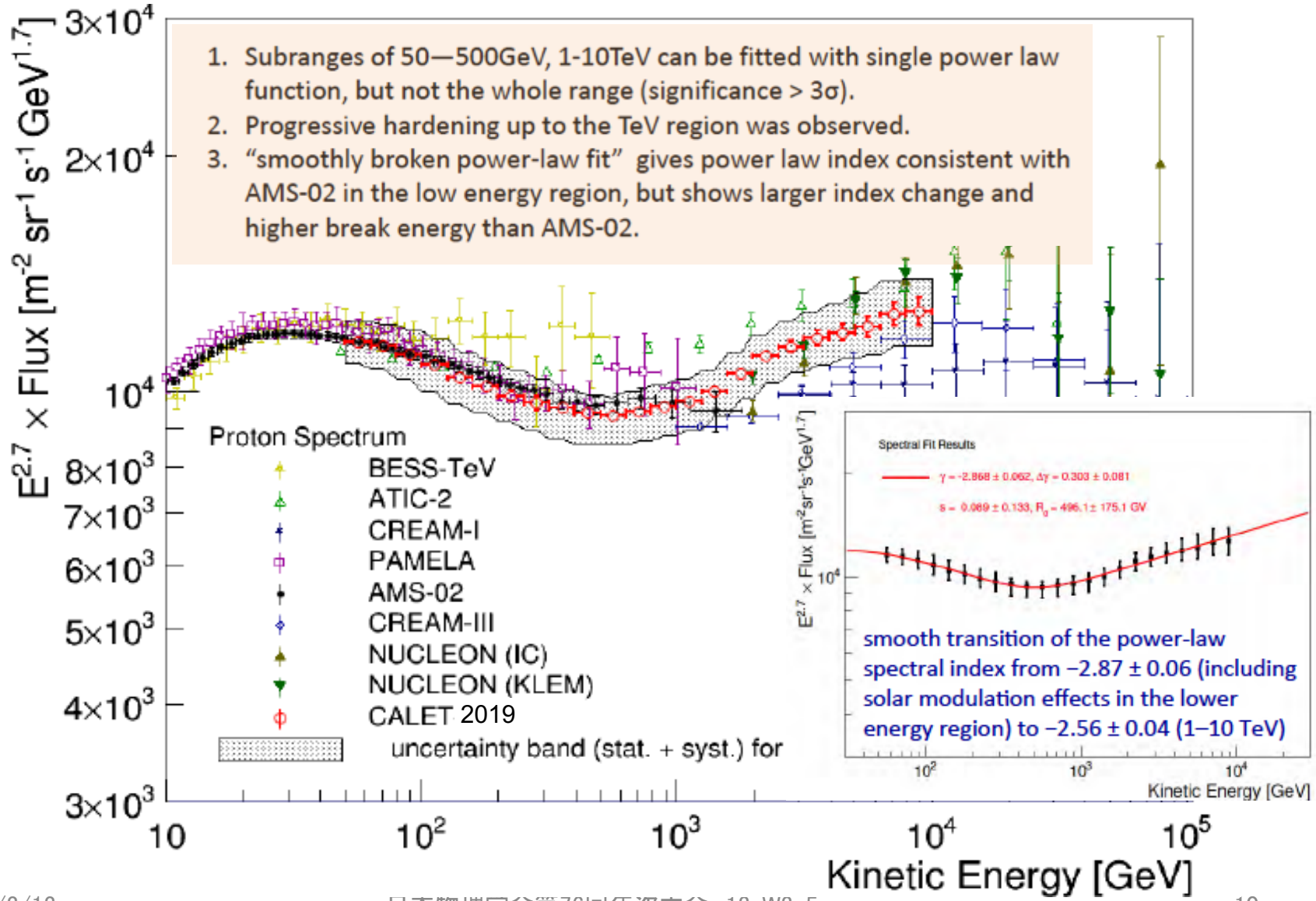
Direct Measurement of Proton Spectrum

Phys. Rev. Lett. **122**, 181102 (2019) Highlighted as " Editor's Suggestion"

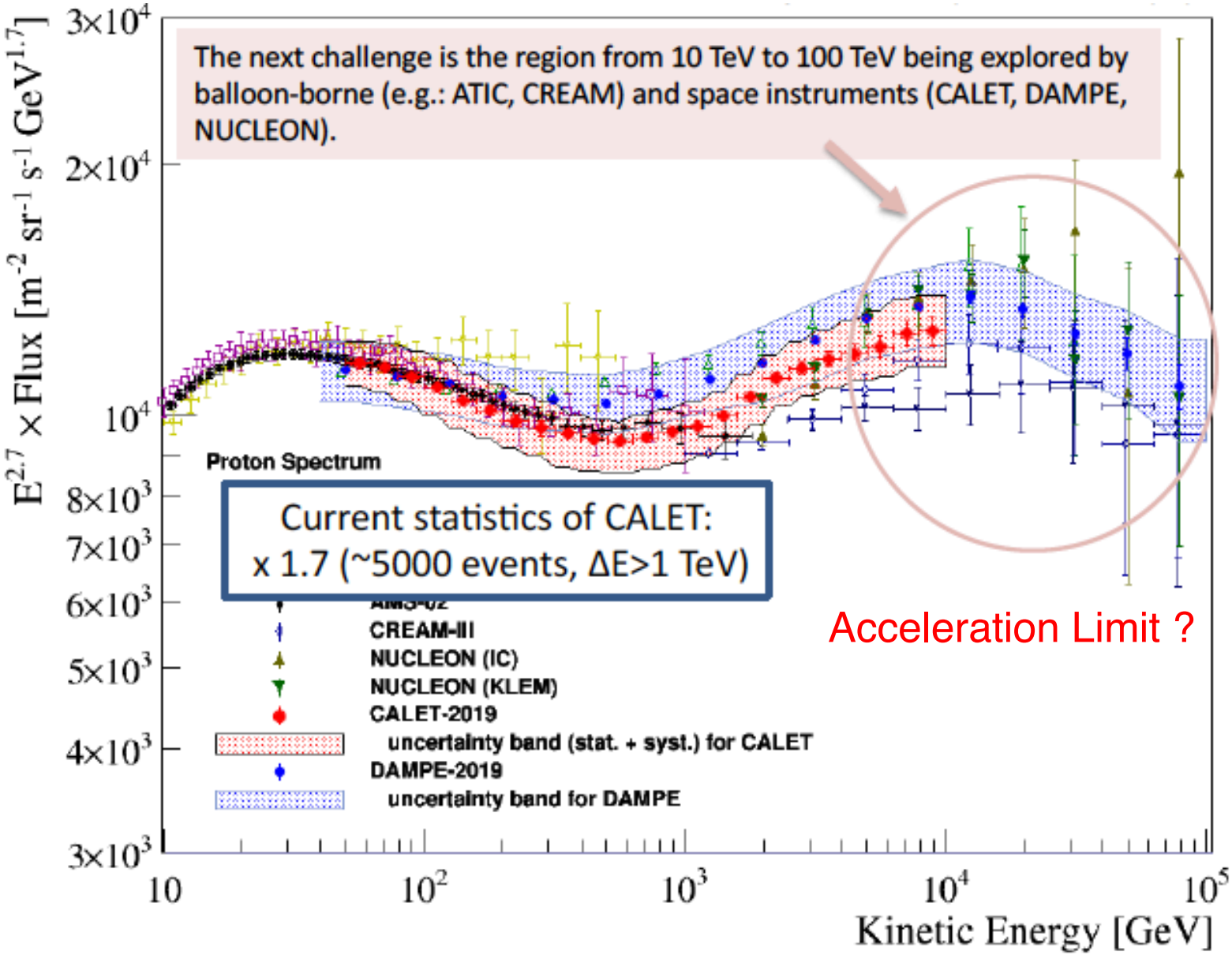


Proton Spectrum: Comparison between Recent Direct Measurements

Phys. Rev. Lett. **122**, 181102 (2019) Highlighted as " Editor's Suggestion"



Proton Spectrum: Next Challenge and Current Status

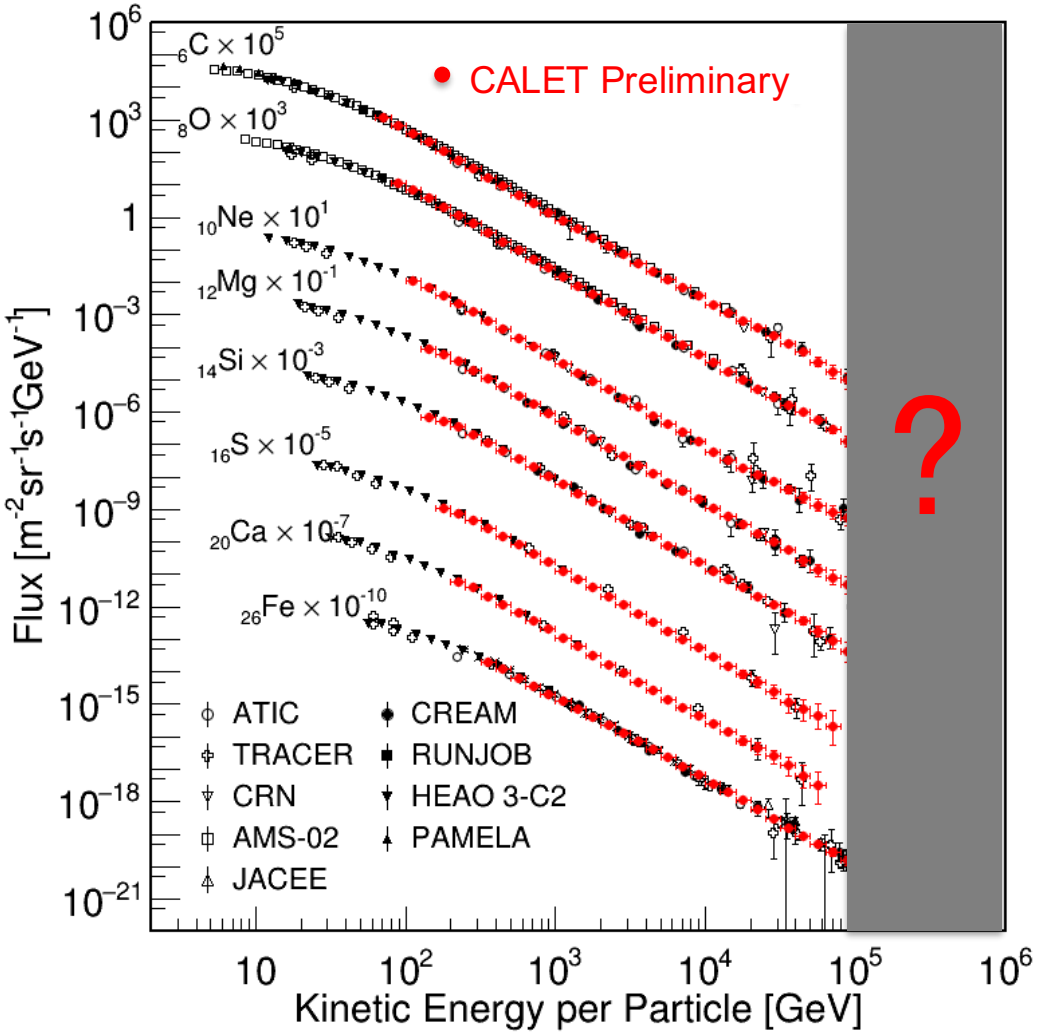


Energy Spectra of Heavy Nuclei

13aW3-7 (Akaike)

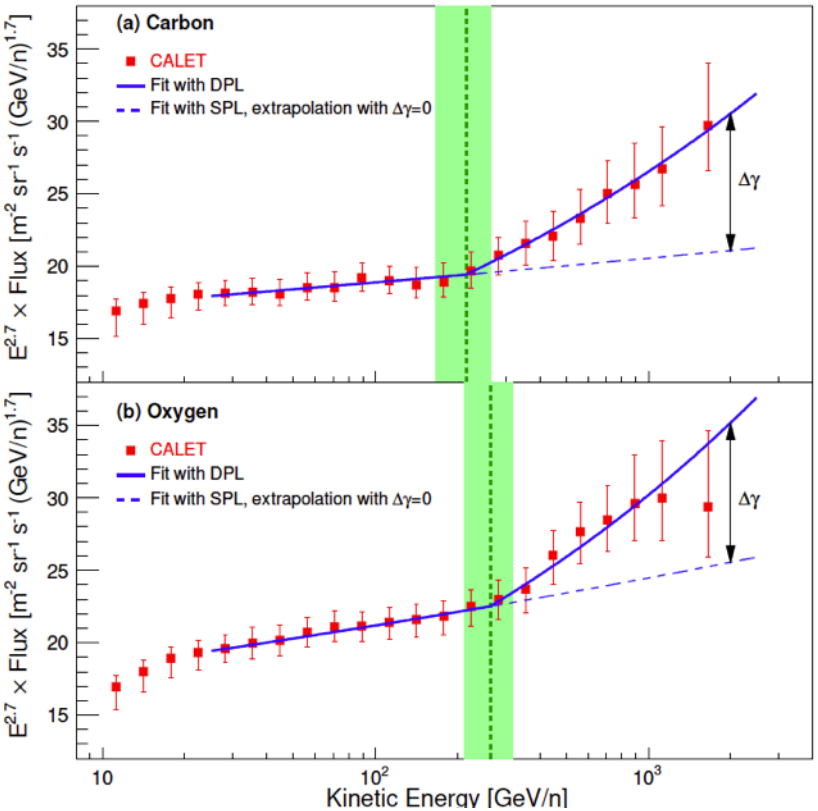
Spectra of Carbon – Iron

Oct.13, 2015 – Sep.30, 2020 (for 1818 days)



Spectra of Carbon and Oxygen

Oct.13, 2015 – Oct.31, 2019 (for 1,480 days)



Carbon

$$\begin{cases} \gamma = -2.663 \pm 0.014 \\ E_0 = 215 \pm 54\,\mathrm{GeV/n} \\ \Delta\gamma = 0.166 \pm 0.042 \quad (4.0\,\sigma) \\ \text{with } \chi^2/\mathrm{d.o.f.} = 9.0/8 \end{cases}$$

Oxygen

$$\begin{cases} \gamma = -2.637 \pm 0.009 \\ E_0 = 264 \pm 53\,\mathrm{GeV/n} \\ \Delta\gamma = 0.158 \pm 0.053 \quad (3.0\,\sigma) \\ \text{with } \chi^2/\mathrm{d.o.f.} = 3.0/8 \end{cases}$$

Ultra Heavy CR Nuclei

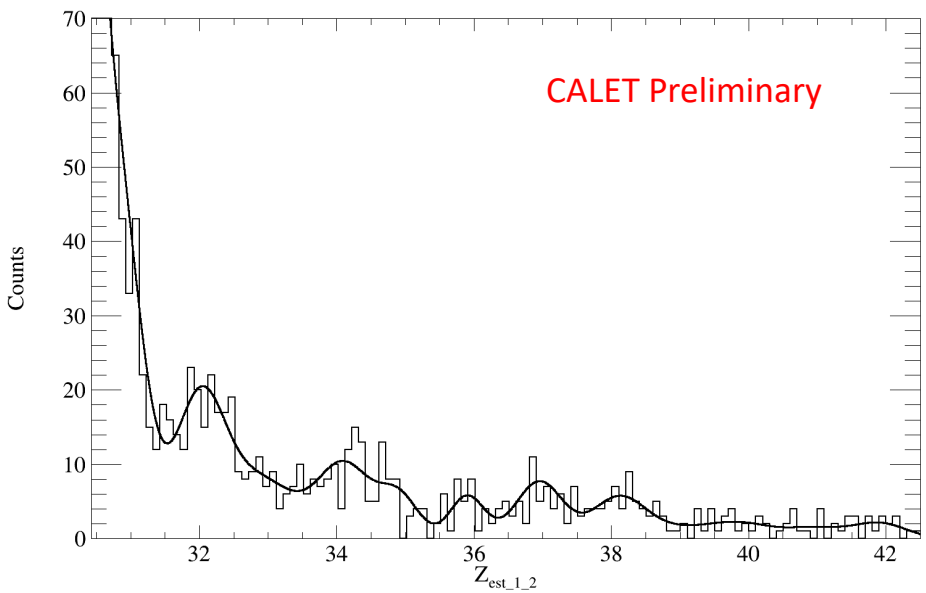
Using ~60 months of CALET UH-trigger data with ~4 × the geometry factor of the standard nuclei trigger (0.44 m^2 sr).

Rigidity dependence of number of the observed UH events with Z≥30

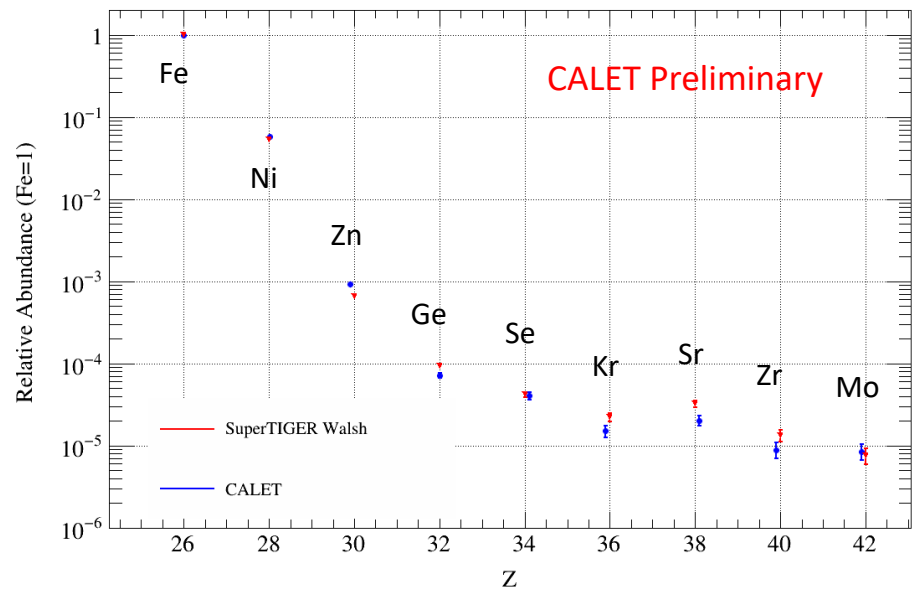
Rigidity	2.0 GV	2.5 GV	3.0 GV	3.5 GV	4.0 GV
Z≥30	8,550	6,231	4,593	3,669	3,122

- CALET and SuperTIGER cover similar energy ranges with different systematics
- Improved charge assignment and data selections can improve agreement

UHCR (>4 GV) flux with linear scale



Comparison of CALET abundances with SuperTIGER



Gamma-Ray Observations : Sky Map

13aW3-8 (Mori)

Instrument characterized using EPICS simulations

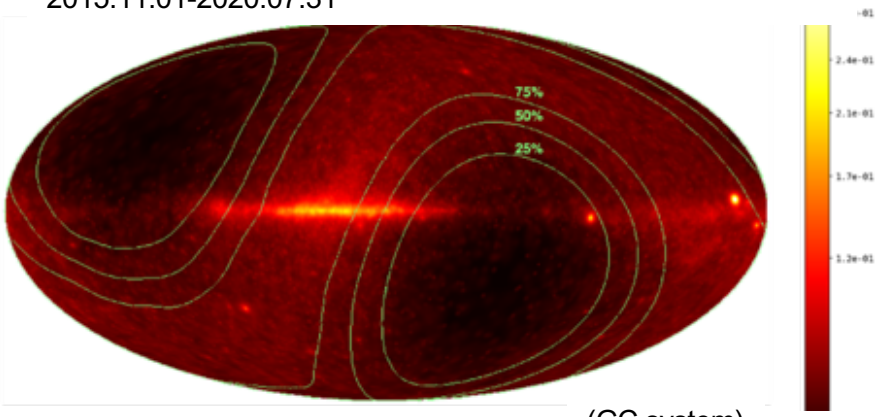
- Effective area ~400 cm² above 2 GeV
- Angular resolution < 2° above 1 GeV (< 0.2° above 10 GeV)
- Energy resolution ~12% at 1 GeV (~5% at 10 GeV)

Simulated IRFs consistent with 2 years of flight data

Consistency in signal-dominated regions with Fermi-LAT

Residual background in low-signal regions

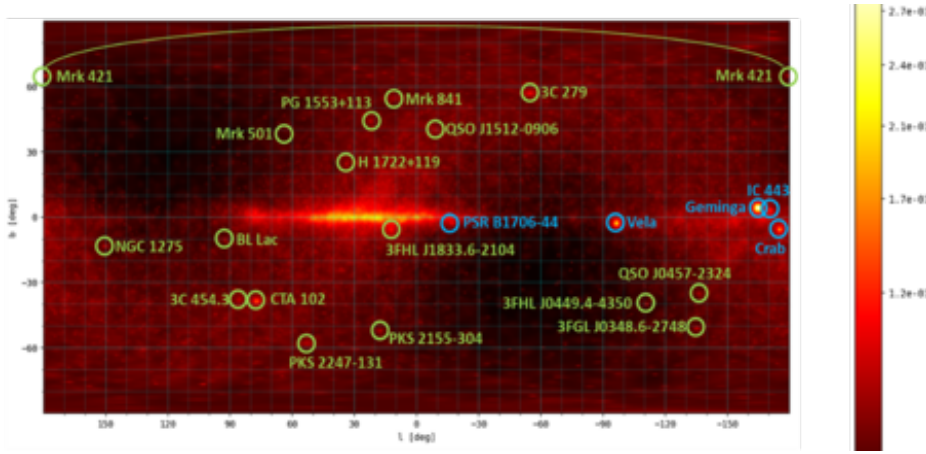
Gamma-ray sky map w/LE-γ trigger (E >1 GeV)
2015.11.01-2020.07.31



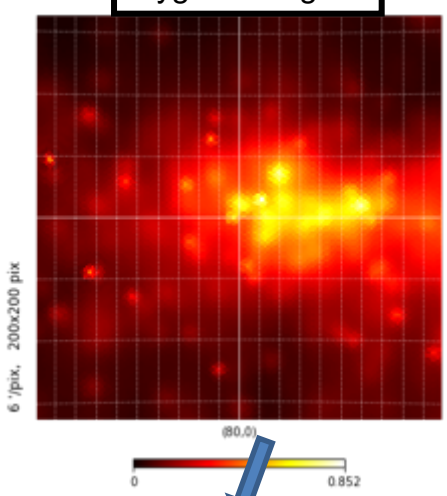
Contours: Exposure ratio to max.

(GC system)

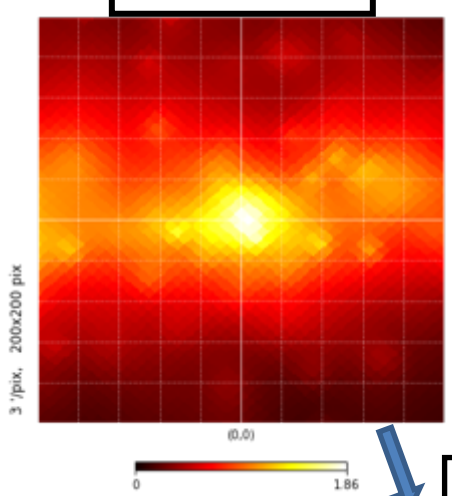
Identified bright point-sources (E >1 GeV)
2015.11.01-2020.07.31



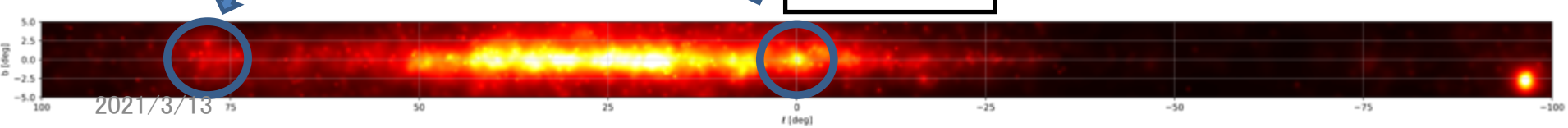
Cygnus Region



Galactic Center



Galactic Plane

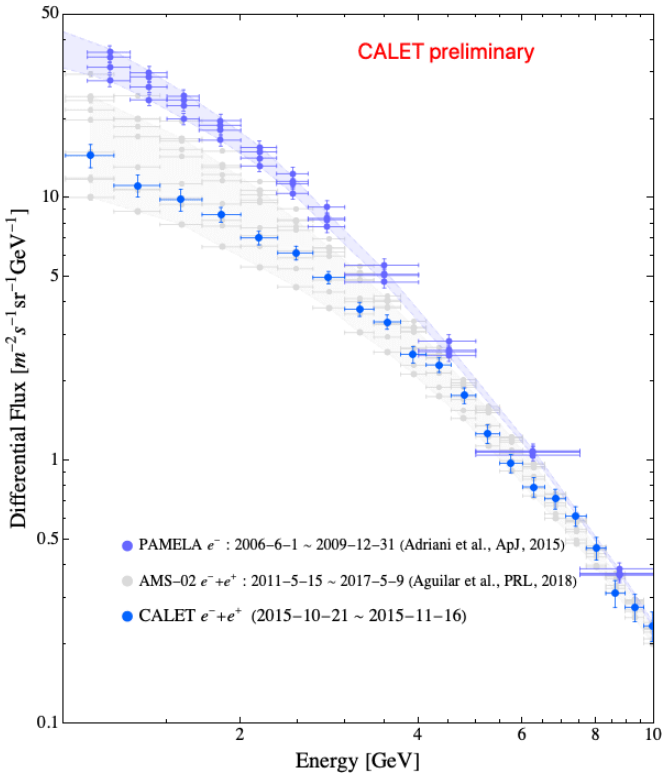


Observations of Solar Modulation during 2015 - 2020

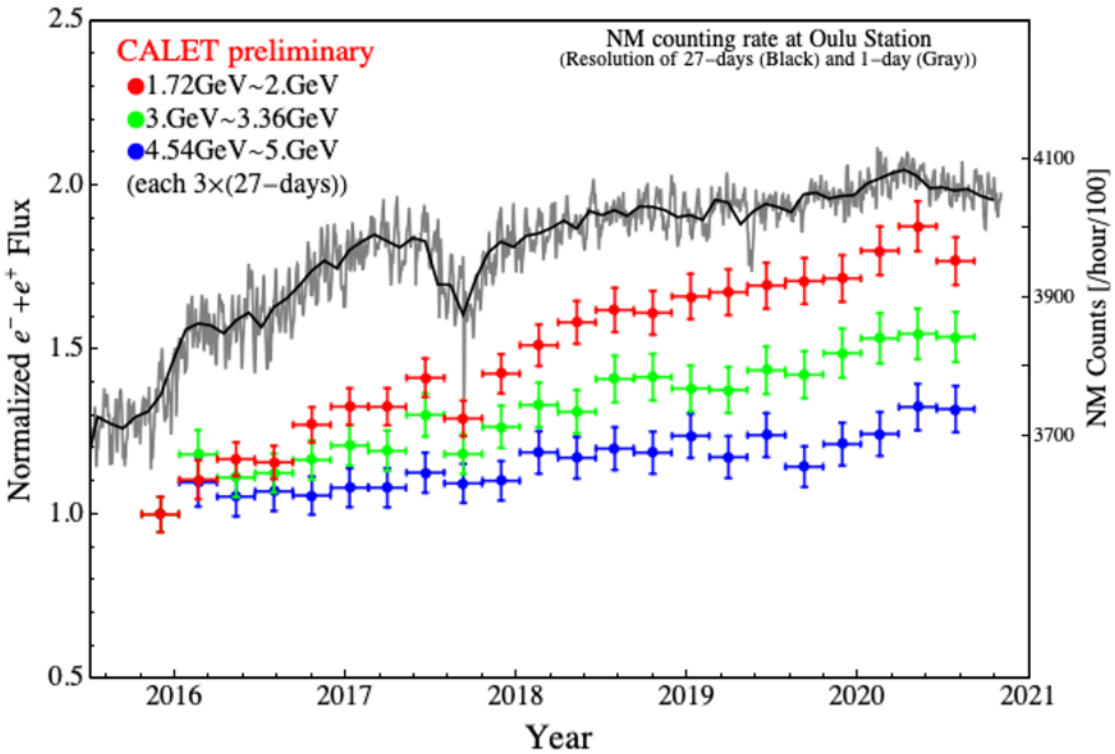
13aW3-9 (Ko) 13aW3-10 (Miyake)

- Since the start of observations in October, 2015, a steady increase in the 1-10 GeV all-electron flux has been observed up to the present time.
- Especially, the flux in the most recent two years has reached the maximum flux observed with PAMELA during the last solar minimum period.

Long-term variation of all-electron energy spectrum observed with CALET (animation)



Long-term variation of the all-electron flux compared with NM count rate at Oulu and sun spot number



CALET: Summary and Future Prospects

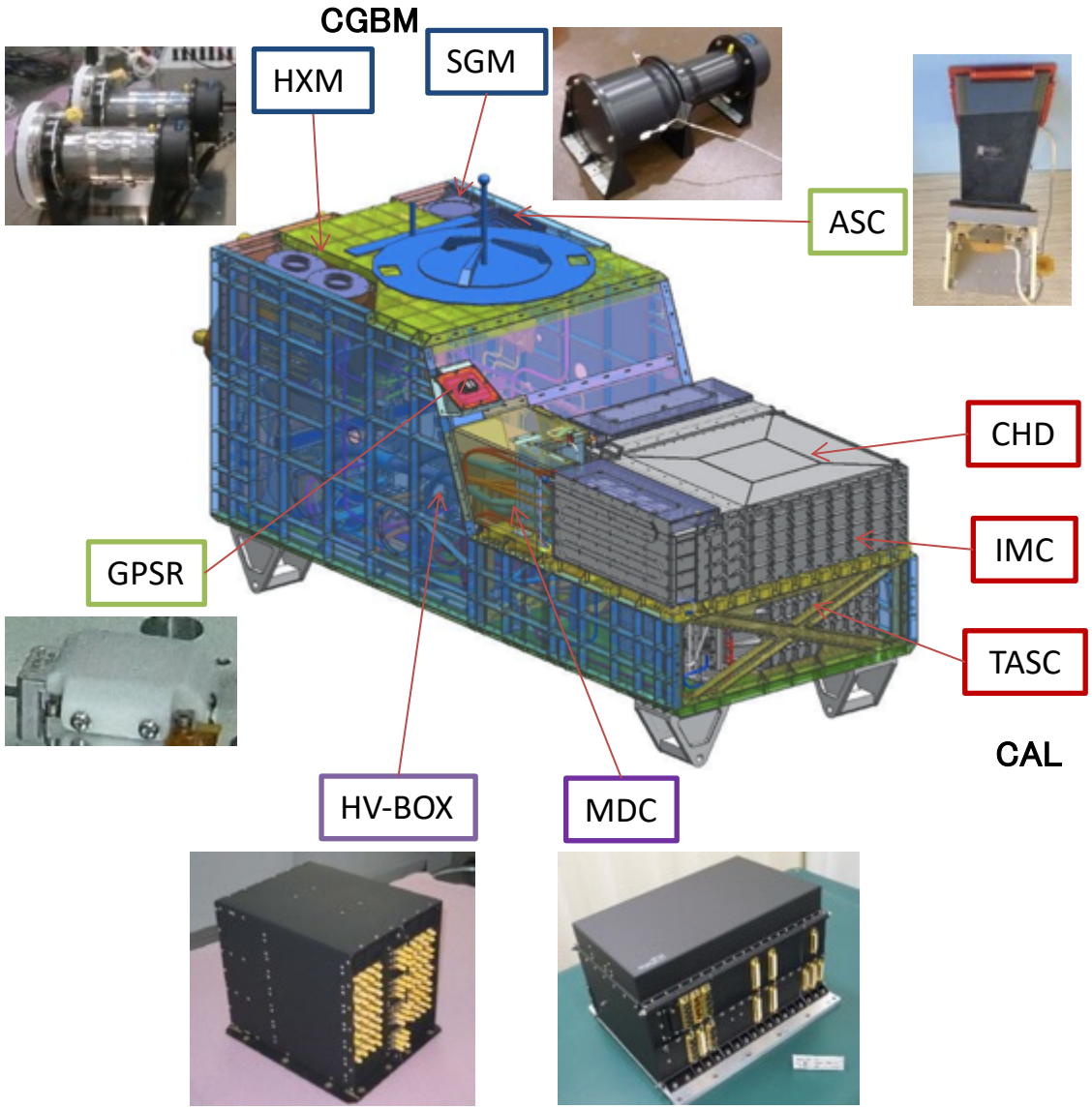
- CALET was successfully launched on Aug. 19th, 2015. The observation campaign started on Oct. 13th, 2015. Excellent performance and remarkable stability of the instrument were confirmed.
- As of Feb. 28, 2021, total observation time is 1966 days with live time fraction close to 86%. Nearly 2.7 billion 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 up to 10^6 MIPs.
- Following results have been obtained by now.
  - Measurement of electron + positron spectrum in 11 GeV- 4.8 TeV.
  - Direct measurement of proton spectrum in 50 GeV- 10 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.
  - Preliminary analysis of primary cosmic-ray elements up to Iron.
  - Study of diffuse and point sources (+ Sun) of gamma-rays.
  - Follow-up observations of GW events in X-ray and gamma-ray bands.
  - Continuous observations of gamma-ray bursts, solar modulation and REP events are successfully caried out.
- CALET observation has been carried out over 5 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 .

※ This work is partially supported by JSPS KAKENHI Kiban (S) Grant Number 19H05608 (2019-2023FY).

BACKUP

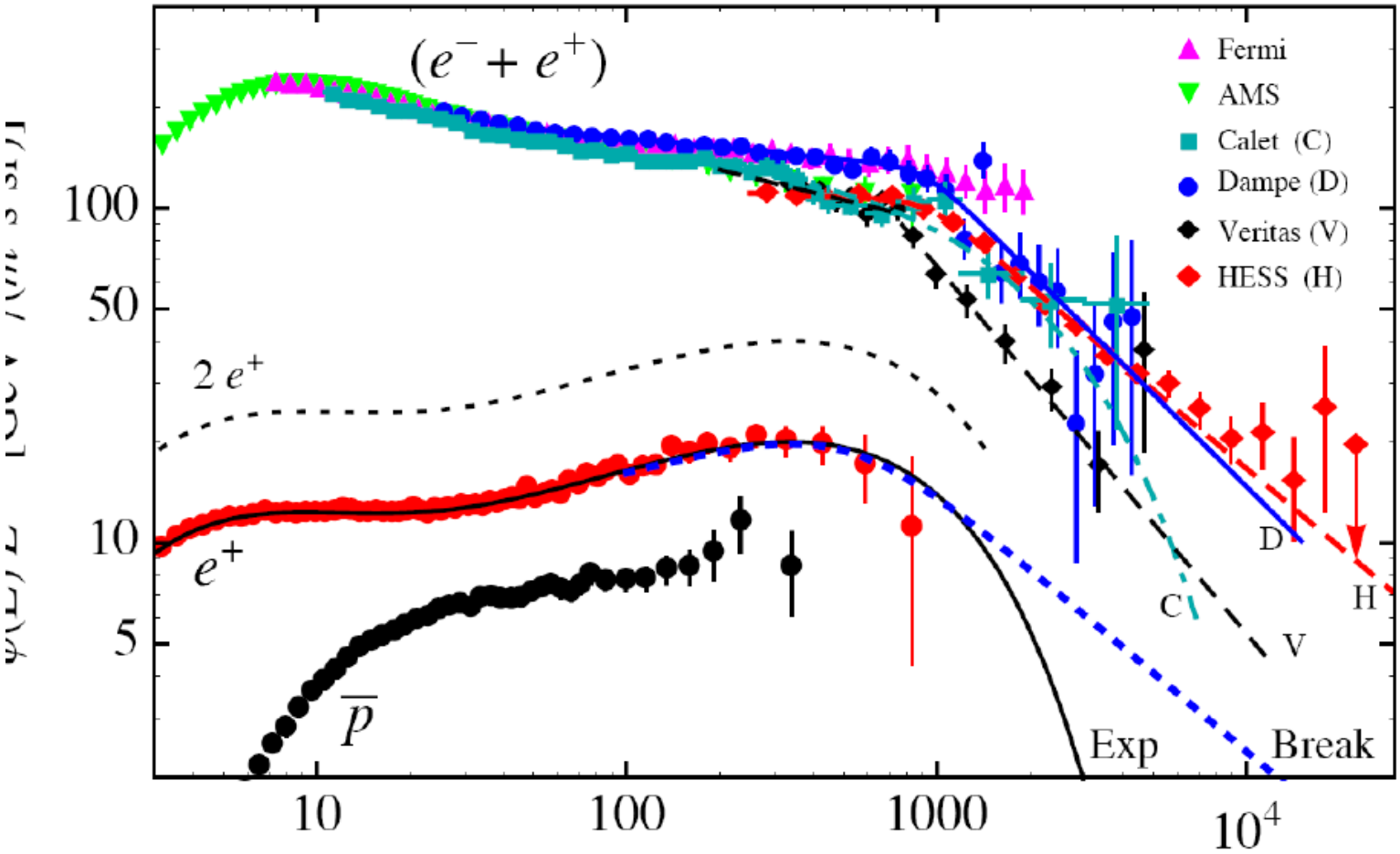
Overview of CALET Payload

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)



All Electron Spectrum:
Comparison between Direct & Ground Measurements

P. Lipari arXiv:1902.06173



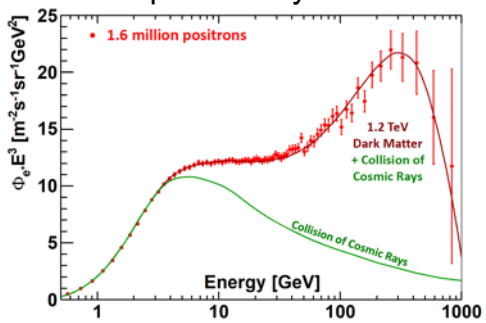
HESS: ICRC2017, unpublished

Future prospects: Search for new sources

- Search for Dark Matter signature in the electron spectrum structure
  - Detection of unknown primary source of electron and positron: Pulsar(s) or Dark Matter ?

- Investigation of CR nearby sources by electron observations at the TeV region
  - Direct detection of nearby sources
  - Acceleration limit and escape process from SNR

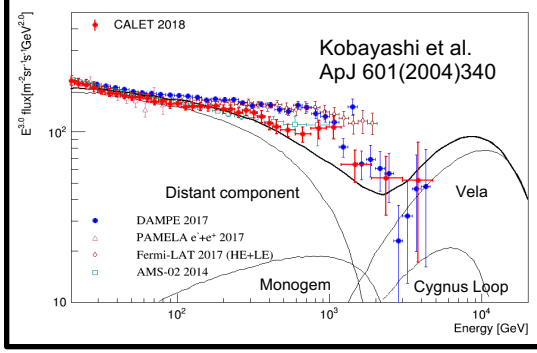
e^+ spectrum by AMS-02



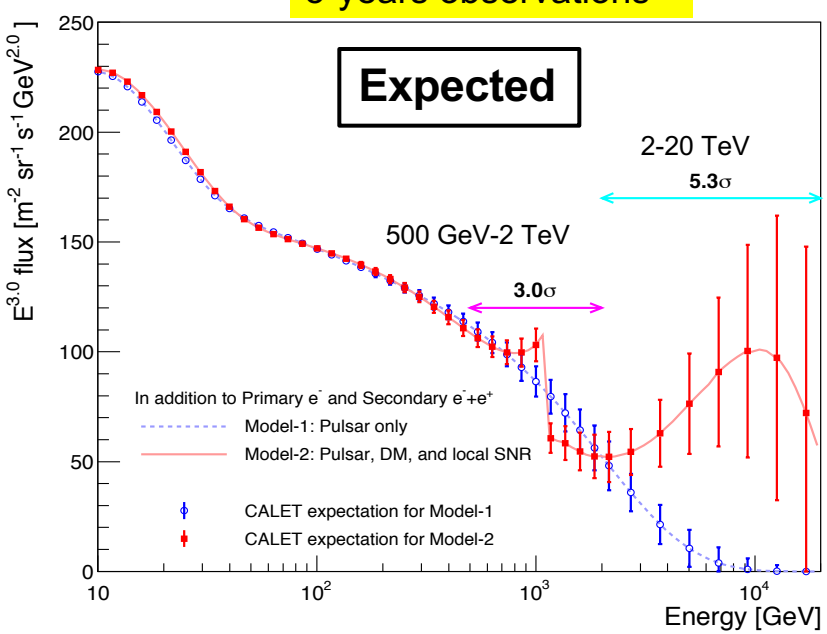
Detection of new primary sourcea of e+ & e- in 500GeV-2 TeV

Search for nearby source(s) In 2-20 TeV

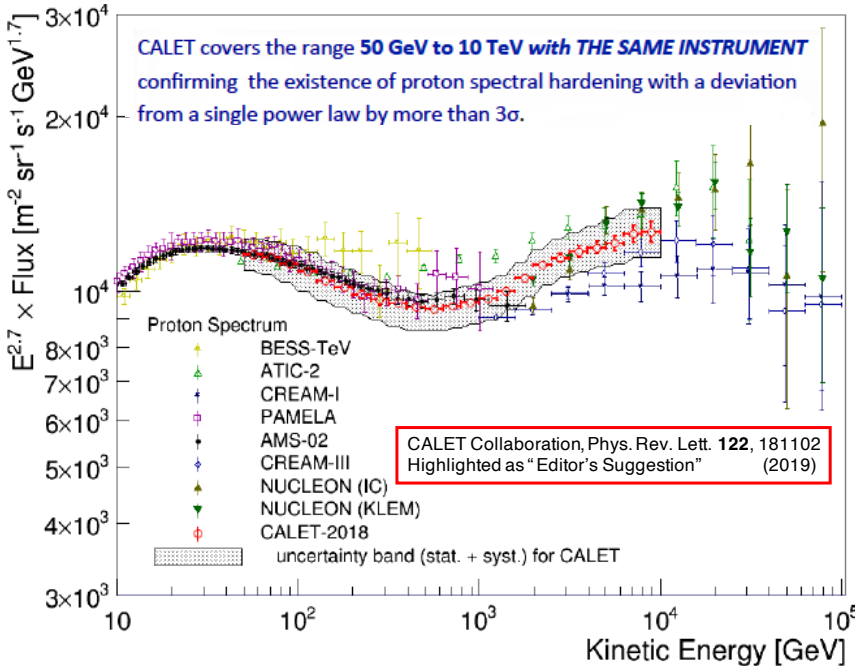
e^-+e^+ spectrum & nearby sources



5-years observations

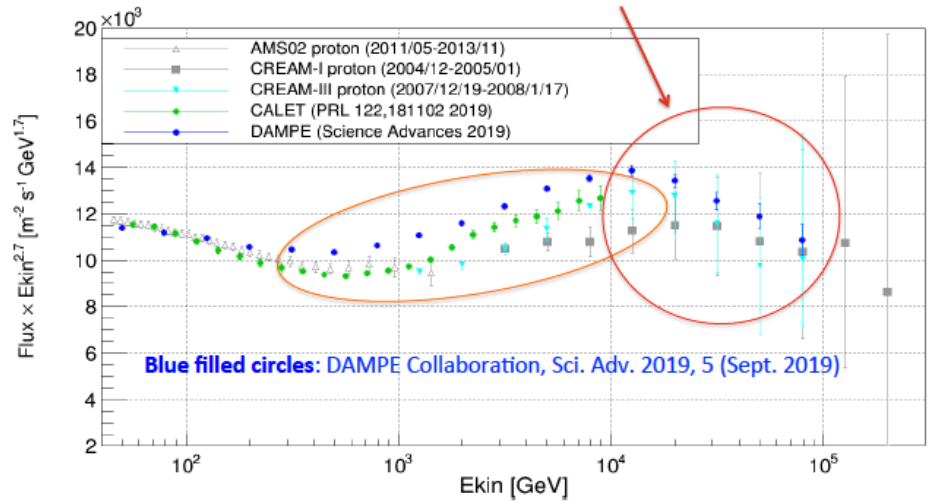


Direct Measurement of Proton Spectrum by CALET

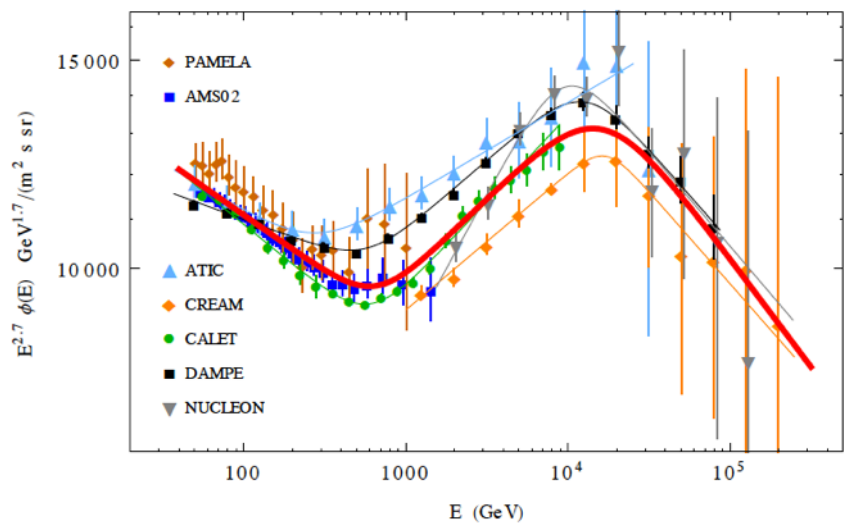


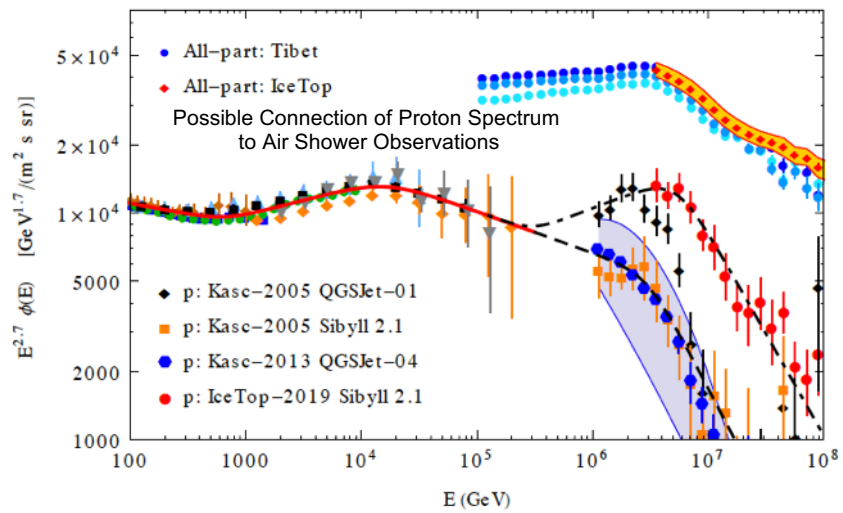
Recent paper by DAMPE collaboration (Sept 2019) from 40 GeV to 100 TeV:

- flux higher than AMS02 and CALET above 200 – 300 GeV
- flux higher than CREAM-III (and CREAM-I) in the region 1 TeV to 10 TeV approx.
- flux reduction above 13.6 TeV (spectral index changes from ~2.60 to ~2.85)



Paolo Lipari and Silvia Vernetto arXiv:1911.01311v1[astro-ph.HE] 4 Nov 2019





Space Weather: Recent Publication of REP Observations

Plasma Waves Causing Relativistic Electron Precipitation Events at International Space Station: Lessons From Conjunction Observations With Arase Satellite

Ryuho Kataoka, Yoichi Asaoka, Shoji Torii, Satoshi Nakahira, Haruka Ueno, Shoko Miyake , Yoshizumi Miyoshi , Satoshi Kurita, Masafumi Shoji ,Yoshiya Kasahara8 , Mitsunori Ozaki , Shoya Matsuda , Ayako Matsuoka ,Yasumasa Kasaba , Iku Shinohara , Keisuke Hosokawa, Herbert Akihito Uchida , Kiyoka Murase, and Yoshimasa Tanaka

JGR Space Physics, 125, e2020JA027875

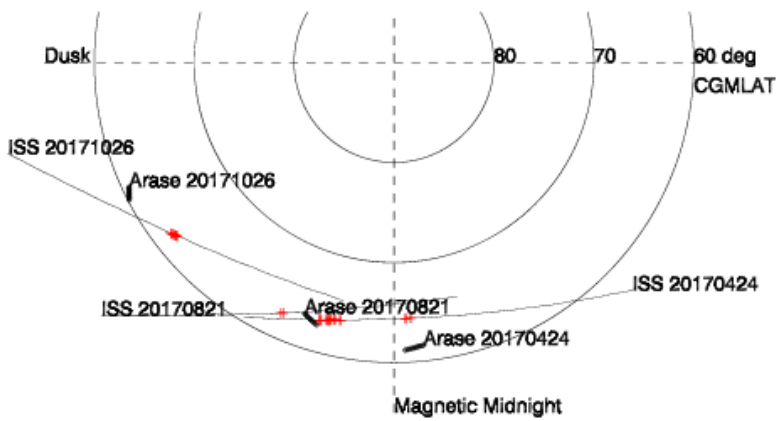


Figure 1. The ISS orbit (black curves) and the Arase footprint (diamonds) during the 10 min time intervals of three selected REP events. The AACGM coordinate system was used to show the polar map, center is the south pole (CGMLAT = −90°), 12 MLT is to the top, and 18 MLT is to the left. The red plus signs indicate the large count rate (>5 × 10^4 Hz) of CHD-X.

a. EMIC Event on 21 August 2017
b. Chorus Event on 24 April 2017
c. Electrostatic Whistler Event on 26 October 2017

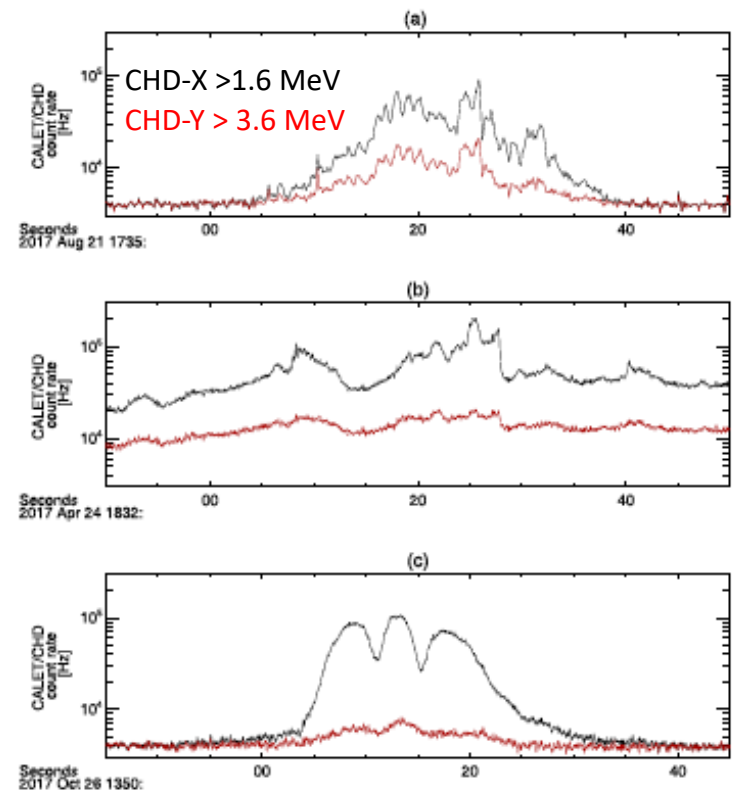


Figure 2. High time cadence count rate data of CHD-X (black) and CHD-Y (red) at 0.1 s time cadence; (a) quasiperiodic variation associated with EMIC waves, (b) irregular variation associated with chorus waves, and (c) smooth and quasiperiodic variation associated with electrostatic whistler waves.