ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

Precise Measurement of the Electron plus Positron Spectrum with CALET on the International Space Station

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The primary objectives of the CALorimetric Electron Telescope (CALET) mission are to search for possible nearby cosmic-ray sources and dark matter signatures through the precise measurement of the electron plus positron (all-electron) spectrum. The instrument is optimized to measure the all-electron spectrum well into the TeV region, with a total thickness of 30 radiation lengths at normal incidence and fine shower imaging capability. These capabilities provide an excellent energy resolution of 2\% over a wide energy range from 20~GeV to 20~TeV, and enable highly precise measurements by suppressing hadron contamination to below a few percent. CALET has been accumulating scientific data for more than nine years on the International Space Station without major interruption.
In this study, we will present the latest results of the all-electron spectrum with high-statistics data, and briefly discuss its interpretation regarding nearby electron sources at the TeV region.

Introduction

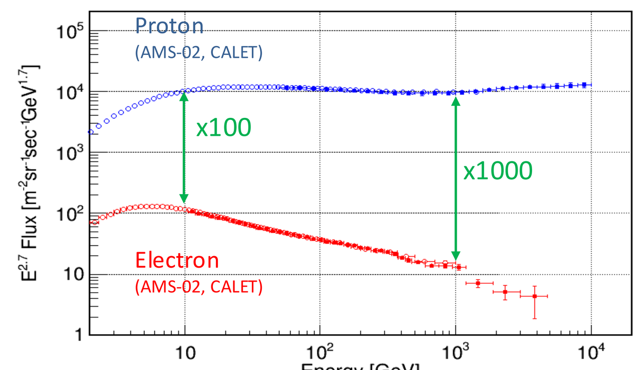
Scientific objectives of the electron plus positron (all-electron) spectrum

- ➢ Search for nearby cosmic-ray sources
- High-energy electrons lose energy rapidly via synchrotron and inverse Compton scattering.
  ⇨ TeV-scale electrons probe nearby (<1kpc) and recent (<10^5yr) astrophysical sources.
- Since the number of such candidates are limited,
  measurements of the all-electrons may identify the sources such as nearby SNRs (e.g., Vela)

- ➢ Constrain dark matter Signatures
- A positron excess has been reported by PAMELA and AMS-02.
  Various models have been proposed, including astrophysical sources (e.g., PWNe) and dark matter.
  Precise measurement at high energies are crucial to constrain these scenarios.

Observation of the all-electron spectrum

- ➢ Challenges in electron measurements
- **Low flux**: Only a few events per $m^{-2}sr^{-1}s^{-1}$above 1 TeV
- **Large proton** background:
  ~10× higher than electron at 10 GeV,
  ~1000× higher at 1 TeV
- **High energy resolution** is essential to distinguish spectral features and constrain models.



Electron and proton fluxes

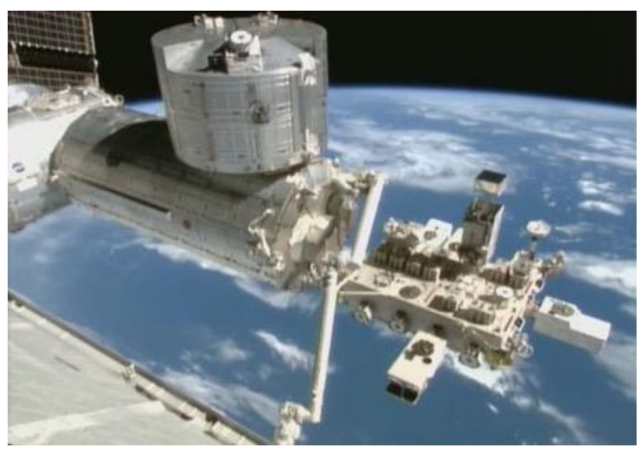
CALET: CALorimetric Electron Telescope

Mission overview

- Launched in August 2015 and installed on the ISS Japanese Experiment Module "Kibo"
- Continually operating for over 9 nears

Scientific objectives:

- Search for nearby sources of high-energy electrons
- Investigate possible signatures of dark matter
- Study cosmic-ray acceleration and propagation
- Search for the counter parts of γ-ray burst and GWs
- Monitor the solar modulation, space weather, etc.

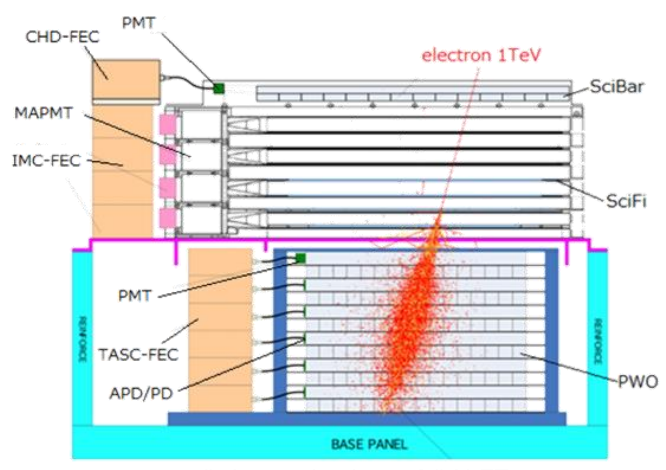

Japanese Experiment Module

Targets

- Electrons (1 GeV – 20 TeV)
- Proton and Nuclei (a few 10 GeV – 1 PeV)
- Gamma-rays (1 GeV – 10 TeV)

CALET Calorimeter

- Consists of
  - **CHD** (Charge Detector): charge identification (Z=1 – 40)
  - **IMC** (Imaging Calorimeter): shower tracking and PID
  - **TASC** (Total Absorption Calorimeter): energy measurement



Schematic view of CALET

Key Features of CALET Calorimeter

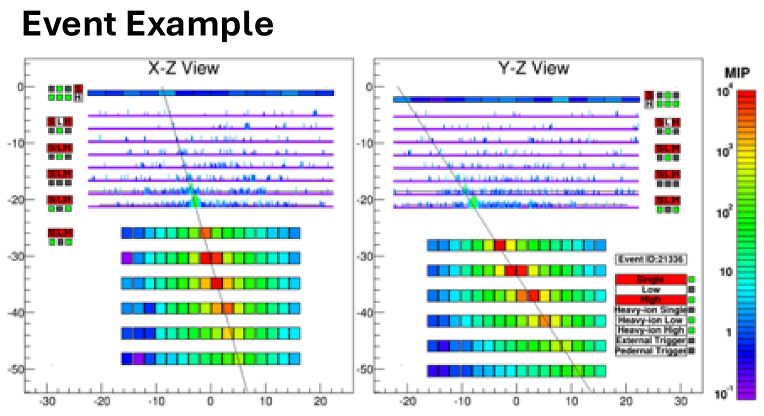
- **High energy resolution:** ~2% above 20 GeV for electrons and gamma-rays
- **Excellent proton rejection power**: >105 using imaging capability
- **Wide dynamic range**: from MIP to ~ PeV
- **Precise charge resolution**: 0.15 – 0.3e (p– Fe)
- **Stable operation** and calibration verified via cosmic-ray MIP and beam test data

Data analysis I

Observation period

- Oct. 13, 2015 – Dec. 31, 2024 (9.2 years, 3368 days)
- High-energy (HE) trigger: $E > 10$ GeV
- Continually operating for over 9 nears

Event Example



3 TeV electron candidates

Detector simulation

- EPICS with DPMJET-III validated by beam test
- Used to derive efficiency, correction factors, and background estimates.

Calibration

- MIP-based, time-dependent gain correction for each detector component
- Absolute energy scale adjusted by +3.5% from geomagnetic cutoff analysis

Track reconstruction

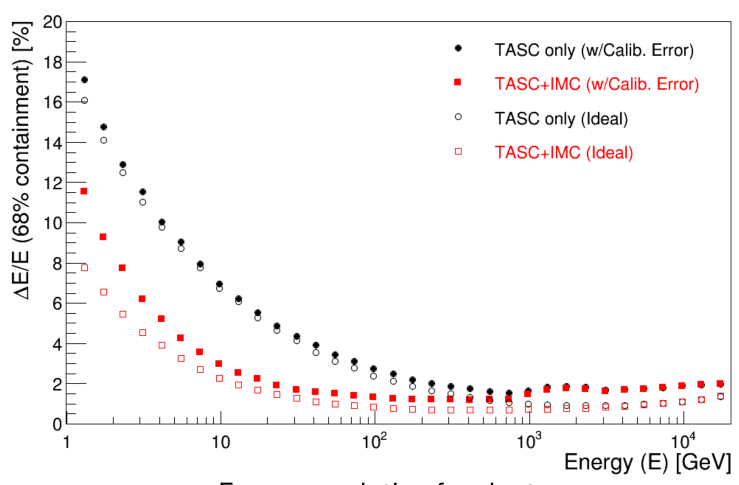
- Electromagnetic shower tracking algorithm
- Energy-independent high efficiency and reliability

Pre-selection criteria

- Offline trigger confirmation with stricter threshold
- Geometrical acceptance & track quality cut
- $E < 1.25$ using CHD
- EM-like longitudinal & lateral shower profiles
- ~90% efficiency after pre-selection

Energy reconstruction

- Sum of energy in TASC and IMC with small correction
- Correction < 5% up to TeV region



Energy resolution for electrons

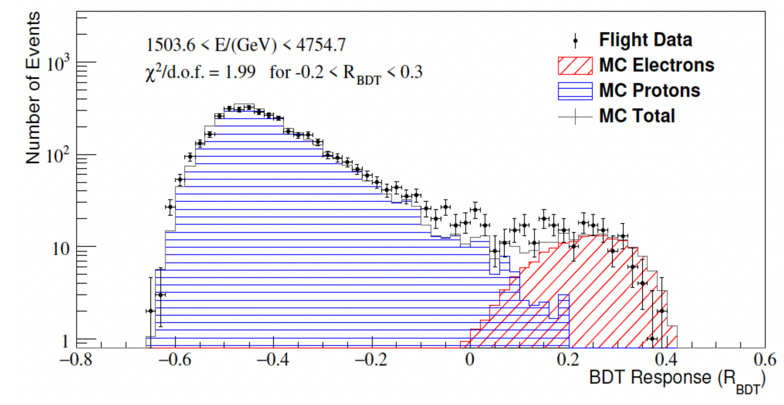
Data analysis II

Electron identification

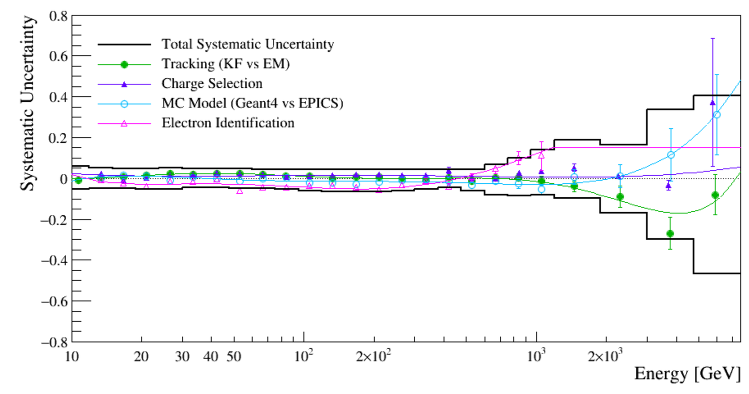
- Below 476 GeV: K-estimater (2-parameter cut)
- Above 476 GeV: Boosted Decision Tree (BDT)
- Residual proton contamination: a few % to TeV
- 80% constant efficiency after pre-selection

Systematic uncertainties

- Sources: trigger efficiency, tracking, charge & electron ID, BDT stability, MC model.
- BDT stability: evaluated from 100 training with varying cut efficiency (70-90%)
- All components integrated for total systematic error estimate



BDT distributions in 1.5 TeV to 4.8 TeV

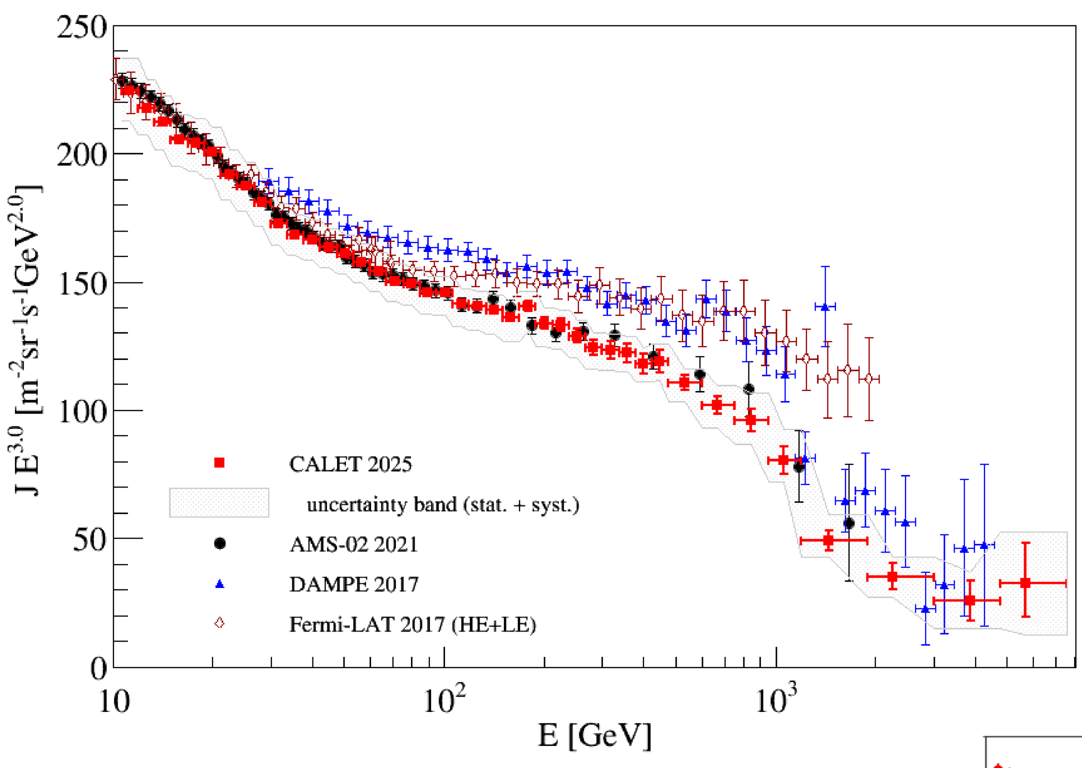


Systematic Uncertainties

Results

All-electron spectrum: energy range from 10 GeV to 7.5 TeV

- Data set increased by 27% compared to previous publication [PRL **131**, 191001 (2023)]



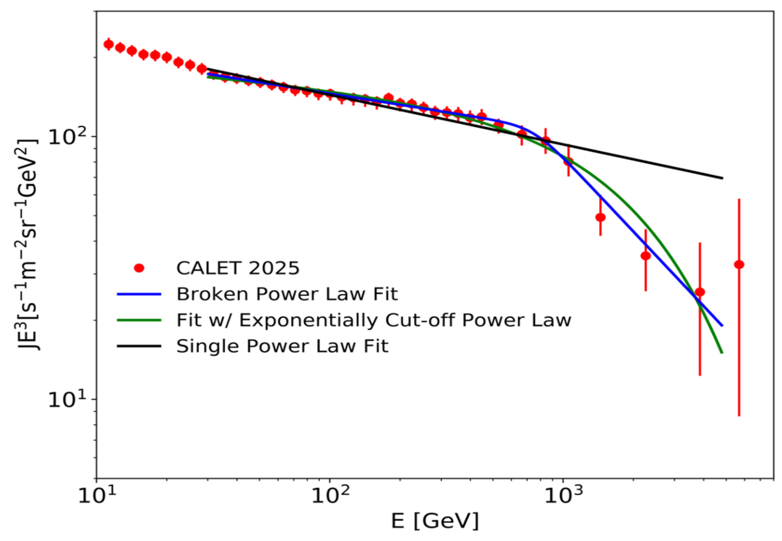
The electron plus positron spectrum

- Good agreement with AMS-02 up to ~2 TeV
- CALET shows slightly softer spectrum than Fermi-LAT and DAMPE from 60 GeV to ~1TeV.

Spectral fit

- Fit with smoothly broken power law (SBPL):
  - Break energy: $E_b = 752 \pm 140$ GeV
  - Spectral change: $\Delta\gamma = -0.80 \pm 0.25$
  - Reduced $\chi^2/\mathrm{NDF} = 1.7/28$
- Exponentially cutoff power law also fits well:
  - Cutoff energy: $E_c = 2385 \pm 299$ GeV
  - Index: $\gamma = -3.08 \pm 0.01$
  - Reduced $\chi^2/\mathrm{NDF} = 6.1/28$

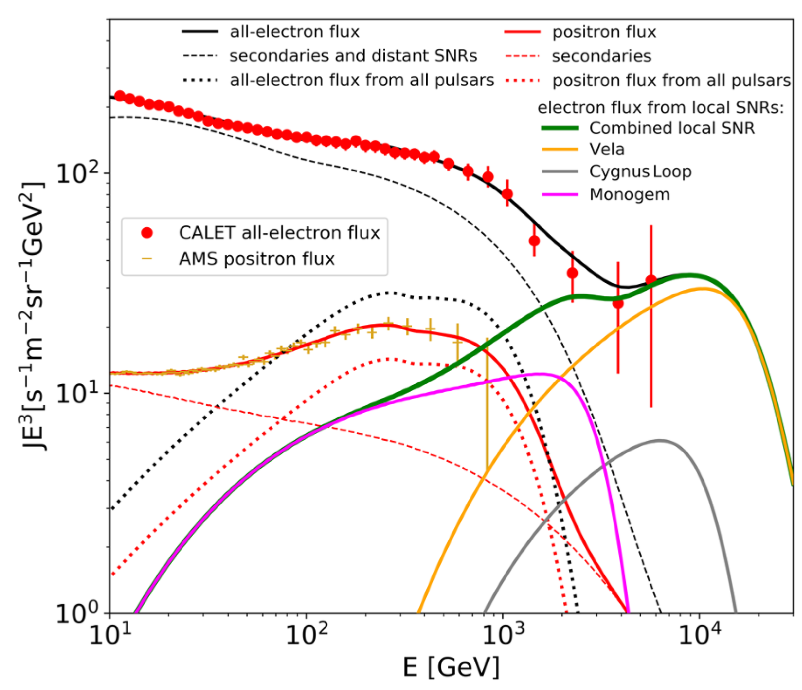
⇨ Significance over single power law: **6.7 σ**.



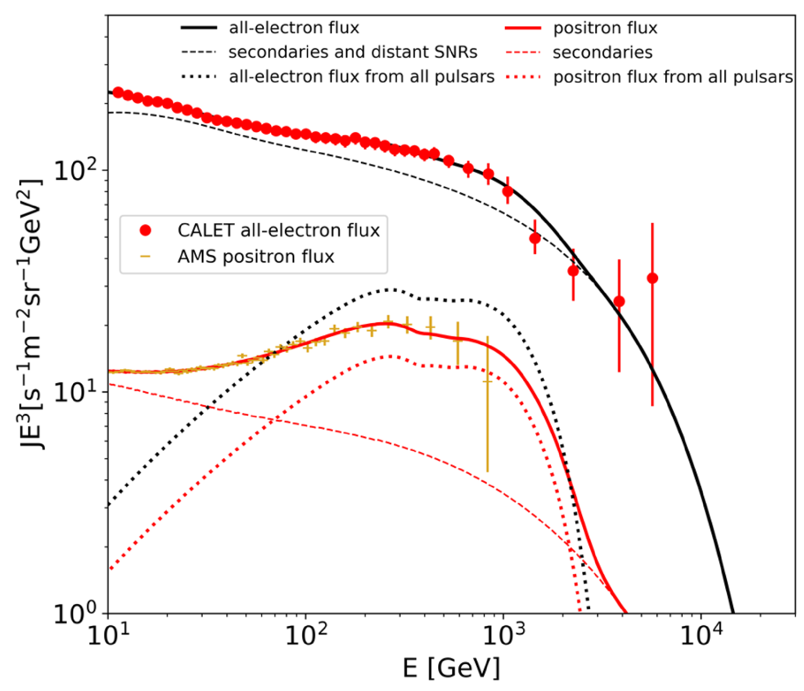
The fitted results in the range from 30 GeV to 4.8 TeV

Interpretation of the CALET all-electron spectrum with AMS-02 positron spectrum

- The spectrum is modeled using DRAGON propagation code[], incorporating AMS-02 positron data and parameters from prior studies.
- Below ~1 TeV, the spectrum including the positron excess is explained by secondaries and primary $e^{\pm}$ pairs from distant SNRs and pulsars.
- Above 1 TeV, nearby SNRs (Vela, Cygnus Loop, Monogem) are required to reproduce the observed spectrum.
- The combined contribution from these SNRs corresponds to an energy output of ~0.65 × 10^{48} erg in electrons above 1 GeV per source.
- Fits with and without nearby sources show similar χ^2/NDF (35/80 vs. 33/80), but the inclusion provides better spectral agreement in the TeV region.



Possible spectral fit over the whole energy region of CALET, Including pulsars and nearby SNR sources as individual sources, with the Vela SNR dominating in the TeV region.



Spectral fit over the whole energy region of CALET and AMS-02 positrons data, but without the contribution from nearby SNRs.

Summary

- We updated the CALET all-electron spectrum with two more years of data, confirming a spectral break in the TeV region consistent with DMAPE.
- The extended statistics improve precision in spectral shape and break characterization.

Acknowledgement: We gratefully acknowledge JAXA's contributions to the development of CALET and to the operations aboard the JEM-EF on the ISS. This work was supported in part by JSPS Grant-in-Aid for Scientific Research (S) No. 26220708, No. 19H05608, and No. 24H00025, JSPS Grant-in-Aid for Scientific Research (B) No. 24K00665, and by the MEXT Supported Program for the Strategic Research Foundation at Private Universities (2011-2015) (No. S1101021) at Waseda University. The CALET effort in Italy is supported by ASI under Agreement No. 2013-018-R.0 and its amendments. The CALET effort in the United States is supported by NASA through Grants No. NNX16AB99G, No. NNX16AC02G, and No. NNH14ZDA001N-APRA-0075.