Highlights from 10 years observations with CALET on the International Space Station

CALET

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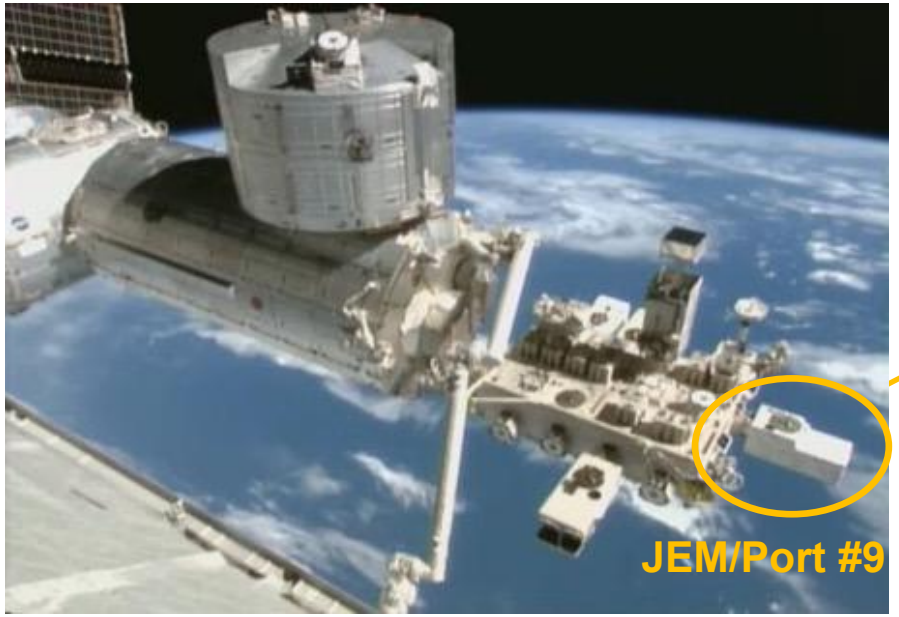
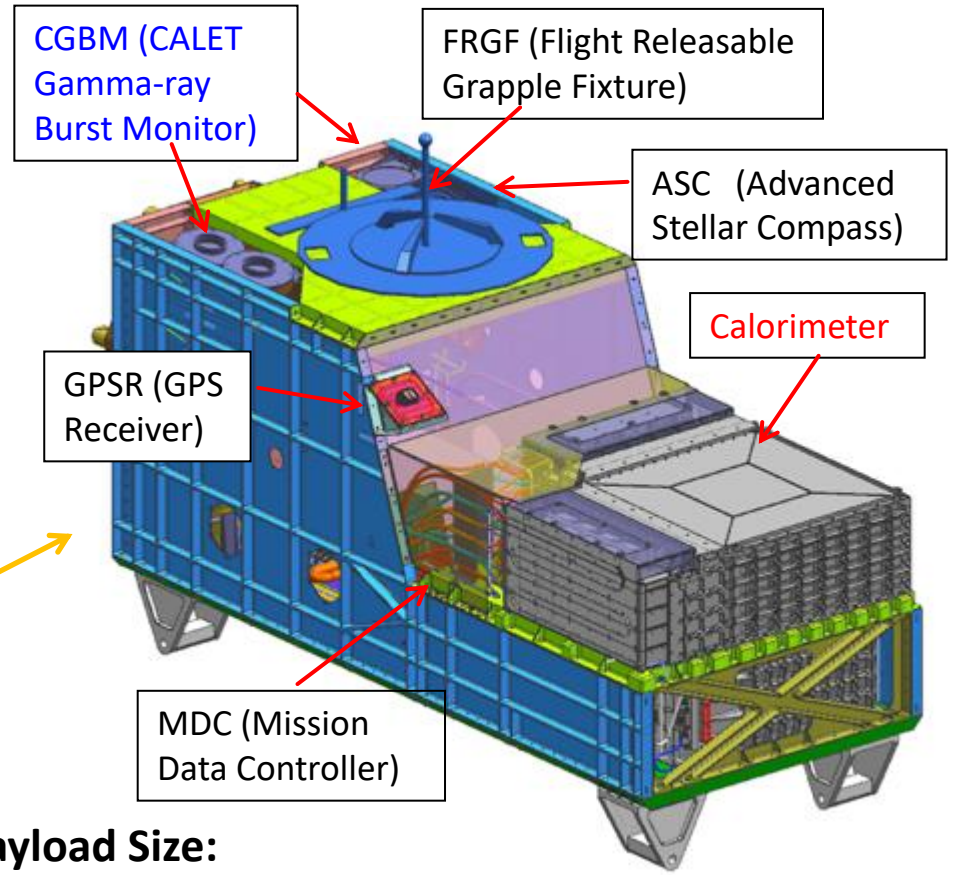
CALET Payload

Kounotori (HTV) 5

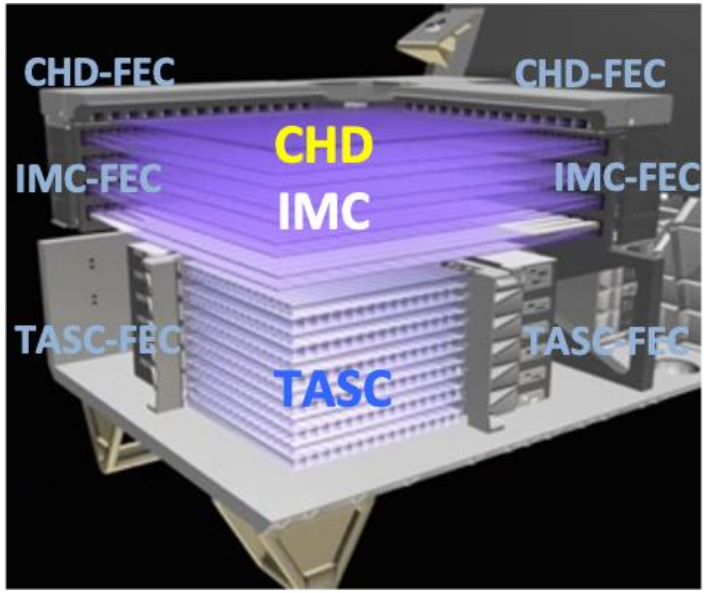
- **Launched on Aug. 19th, 2015 by the Japanese H2-B rocket.**
- **Emplaced on JEM-EF port #9 on Aug. 25th, 2015**

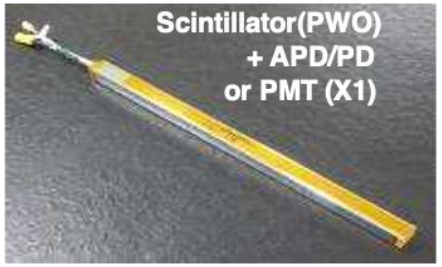


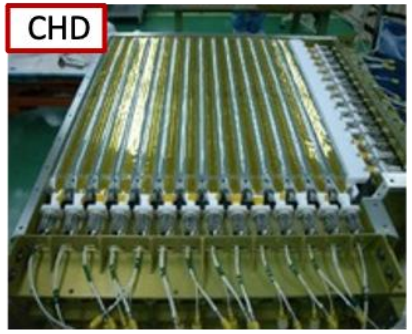


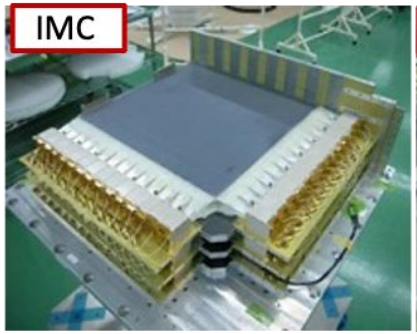
- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W（max）**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

CALET Detector: Calorimeter





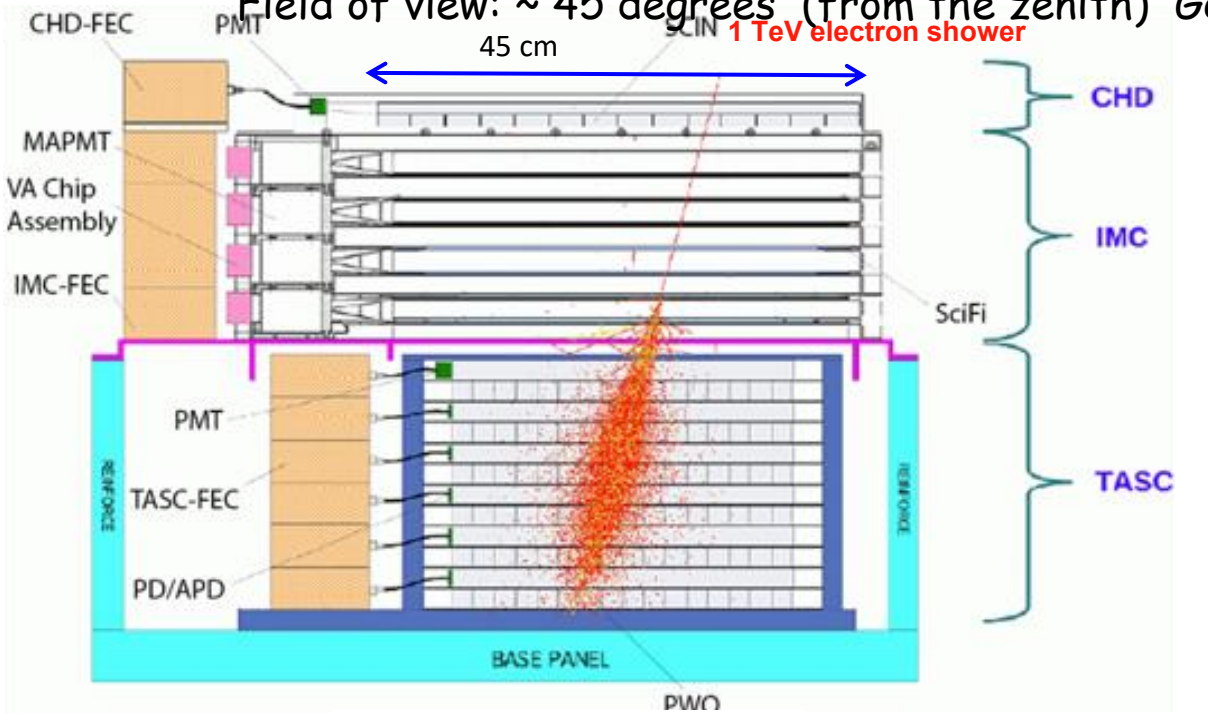




	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers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

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

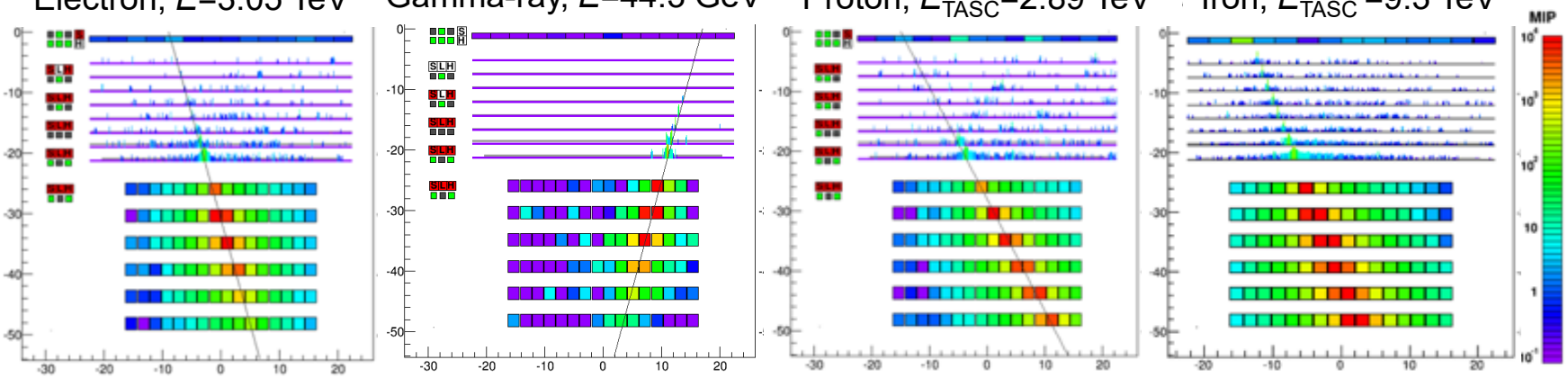
IMC – Imaging Calorimeter

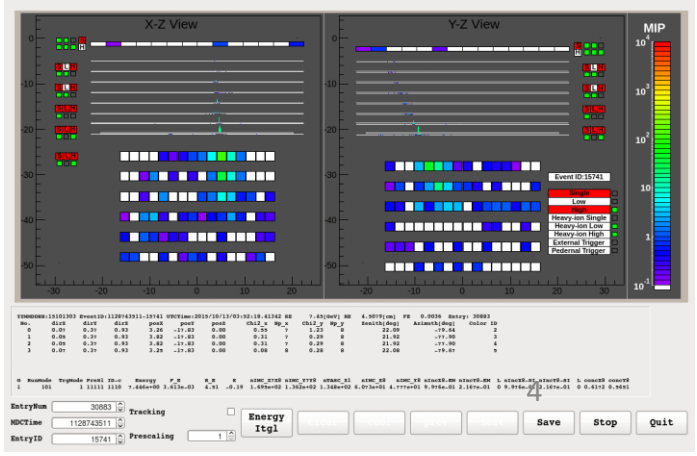
- Scifi + Tungsten absorbers: 3 X_0 at normal incidence
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **Tracking** (~0.1° angular resolution) + **Shower imaging**

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}

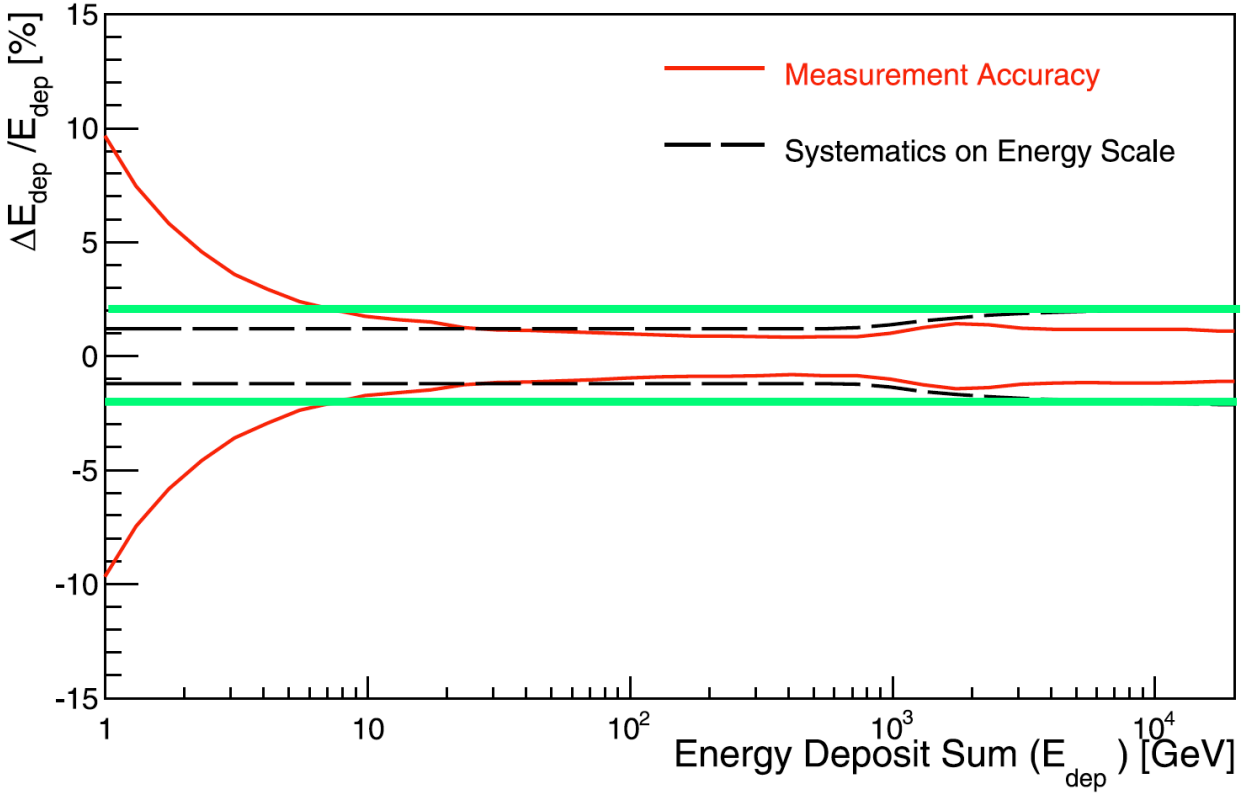
Electron, E=3.05 TeV | Gamma-ray, E=44.3 GeV | Proton, E_{TASC}=2.89 TeV | Iron, E_{TASC} =9.3 TeV



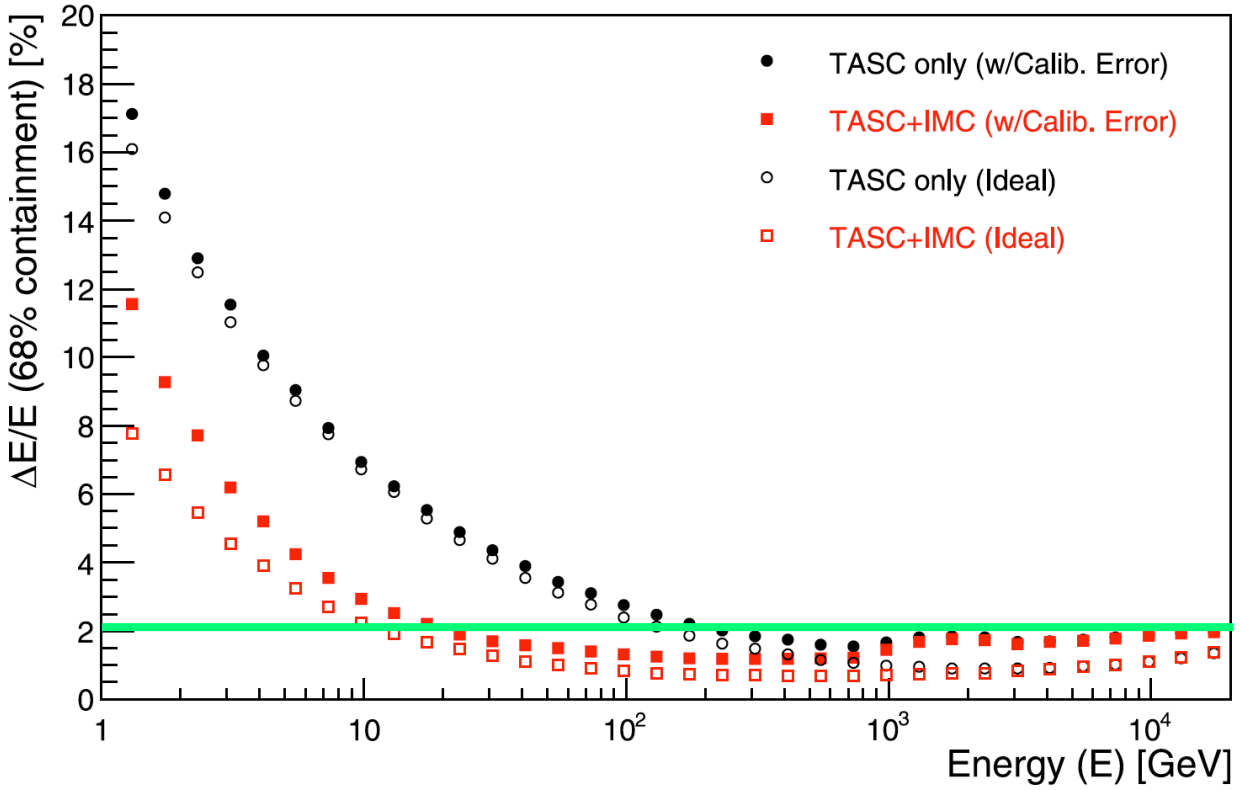


Energy Deposit Resolution in the Calorimeter

Asaoka et al. 2017, Astropart. Phys. 91, 1-10



Energy deposit resolution in the TASC is better than 2% above ~8 GeV



Reconstructed energy resolution is better than 2% for electrons above ~20 GeV

CALET Scientific Goal

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 > ~50 GeV

Scientific objectives

◆ **Electron observation in 1GeV-20TeV**
Design optimized for electron detection:
high energy resolution and large e/p separation power
+ electromagnetic shower containment
Search for Dark Matter and Nearby Sources

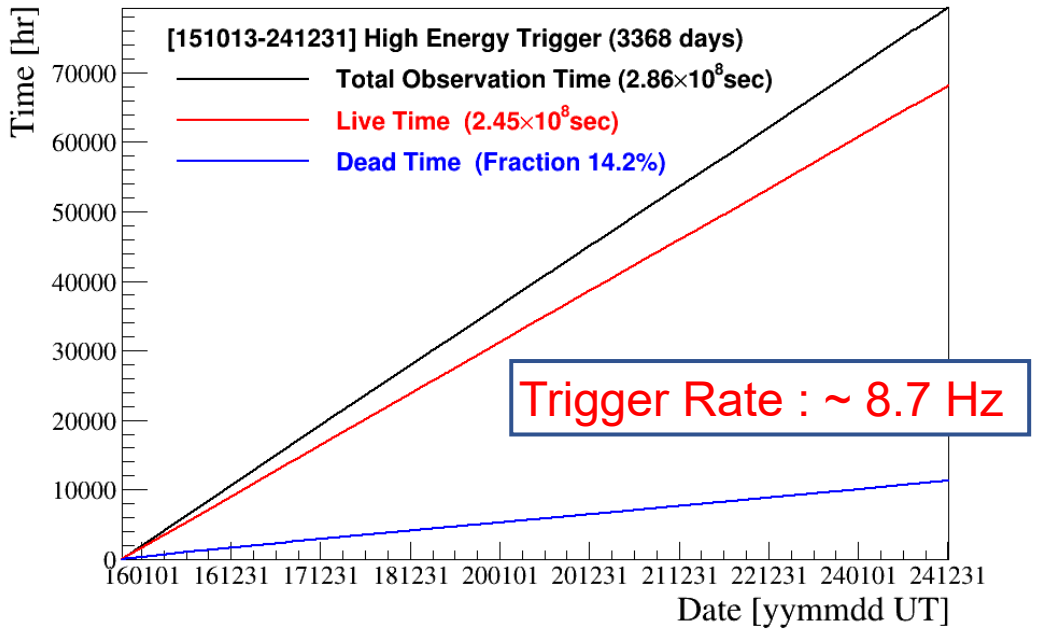
◆ **Observation of cosmic-rays in 10 GeV-1 PeV**
CR acceleration and propagation mechanism(s)

◆ **Detection of transient phenomena in space:**
- Gamma-ray burst
- GW e.m. counterparts
- Solar modulation
- Space weather

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 Observation on the ISS

Accumulated observation time (live, dead)

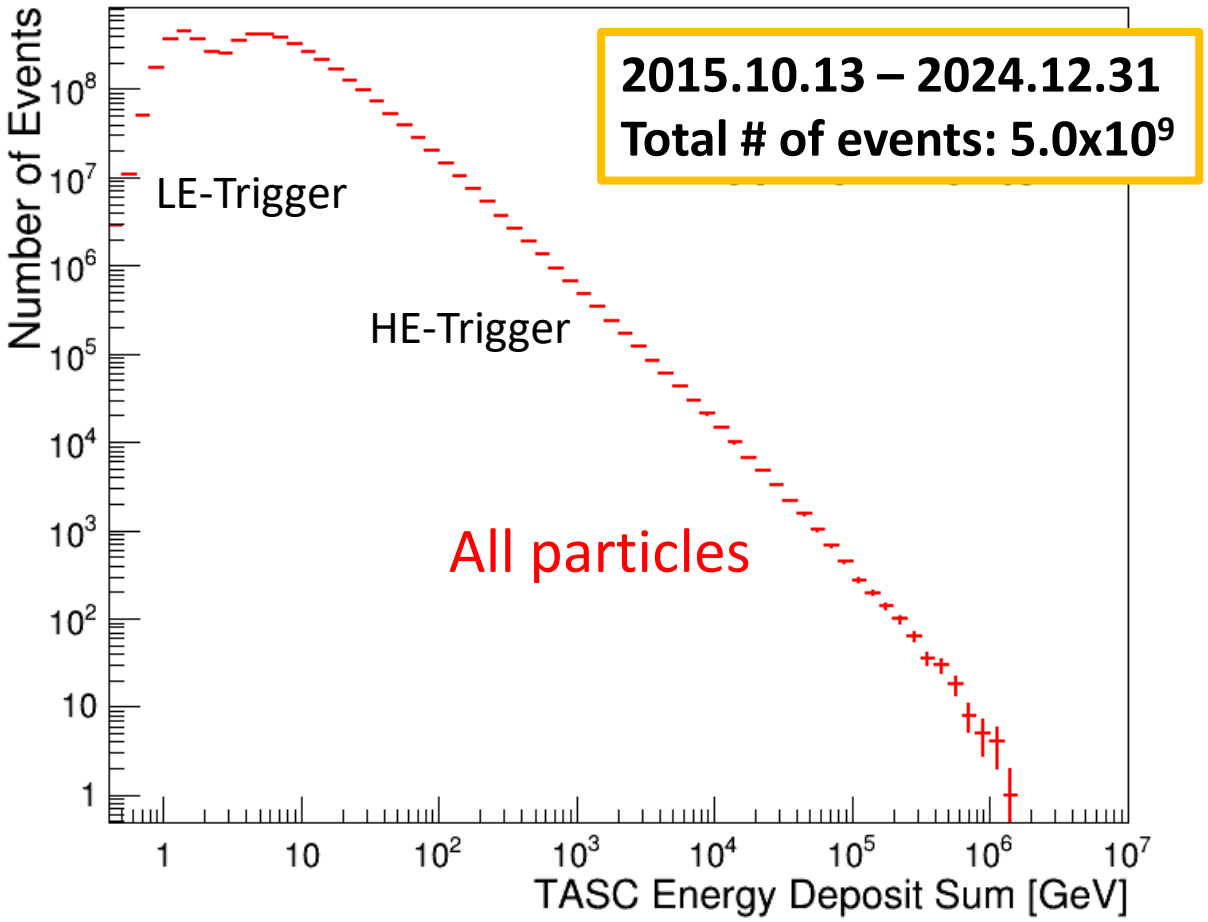


Trigger Rate : ~ 8.7 Hz

High-energy trigger (> 10 GeV) statistics:

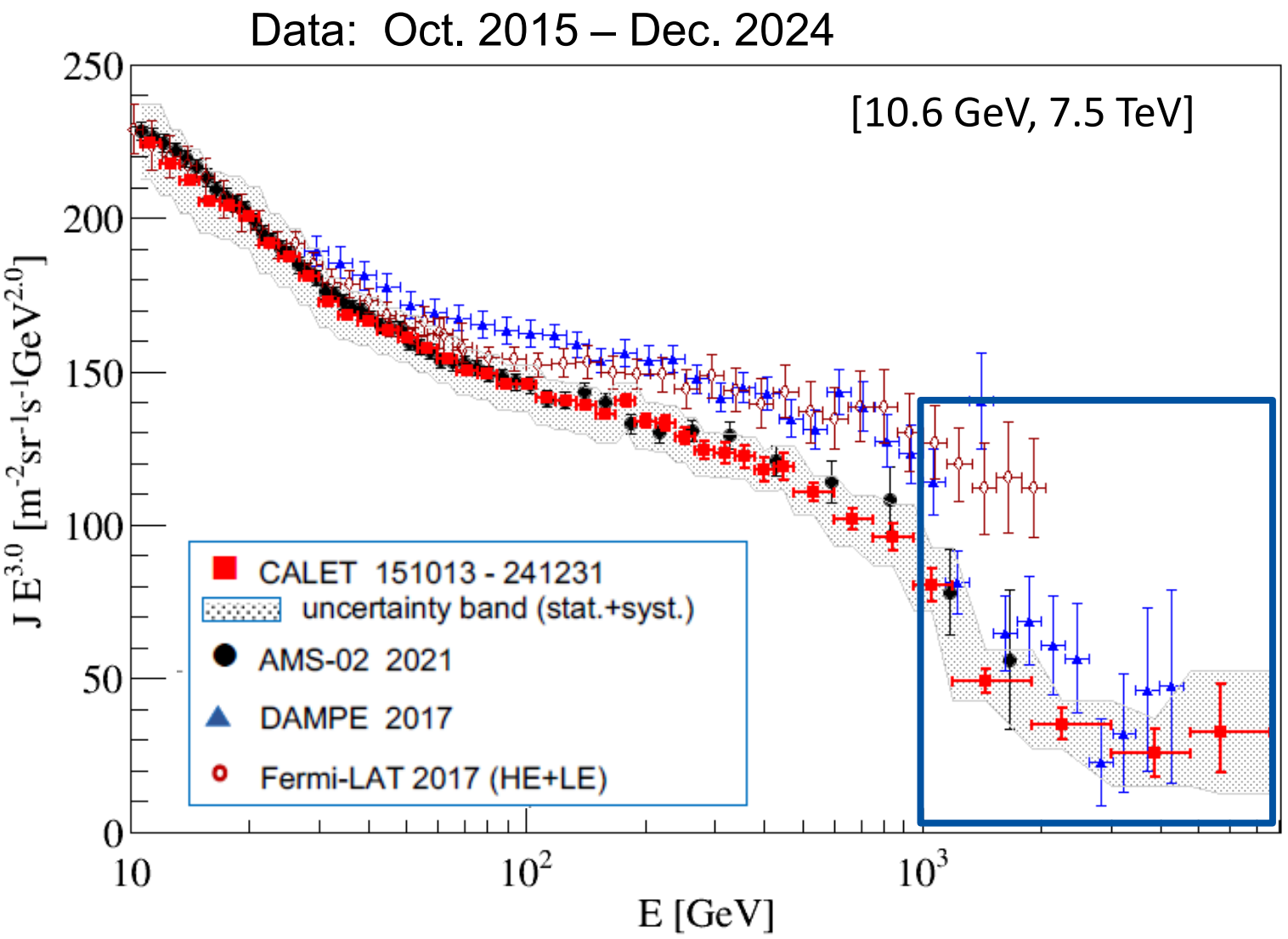
- Operational time: **3368 days** as of Dec. 31, 2024
- Live time fraction: **>85%**
- Exposure of HE trigger: **~300 m^2 sr day**

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



Cosmic-ray all-electron spectrum

PRL 131, 191001 (2023)
ICRC2025 update

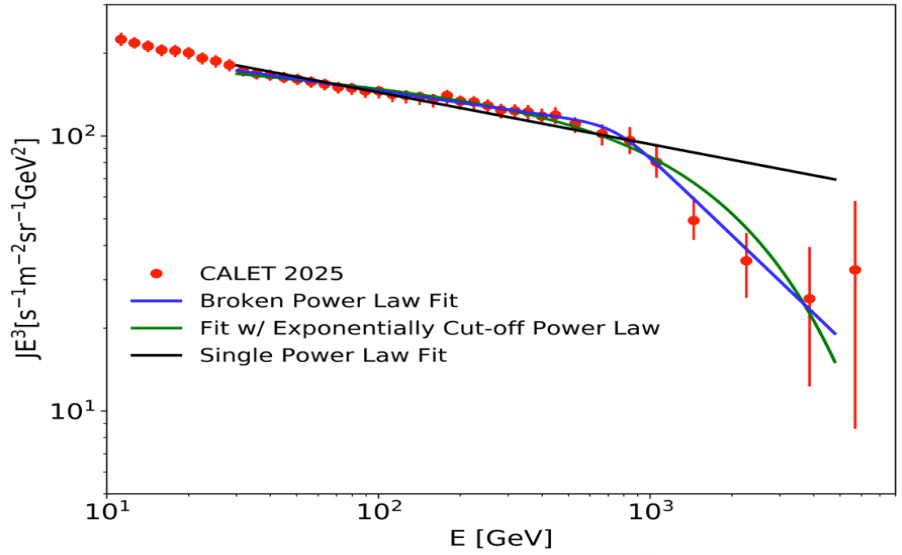


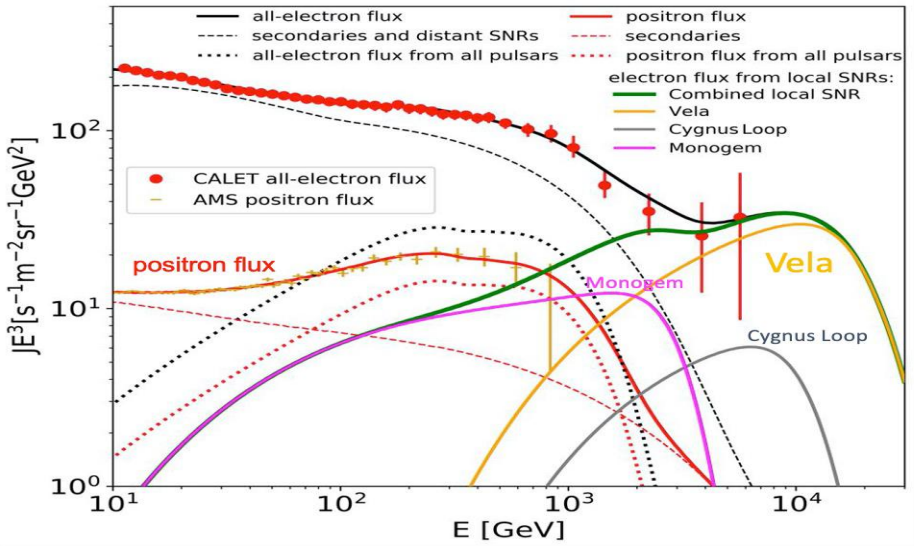
- More than 9 years observation has reduced statistics and systematic errors.
- Statistics has increases by 27% from PRL 2023.
- Systematic discrepancy between CALET/AMS-02 and DAMPE/Fermi-LAT remains.

CALET observes a flux suppression above 1 TeV with a **significance of 6.7 σ**.

Towards an Interpretation of the CALET All-electron Spectrum

- Fit in 30-4.8TeV
  - Single power law is suppressed above 1 TeV with a significance ~6.7σ.
  - Broken power law
    - γ= -3.14±0.01 -> 3.92 at 752±140GeV
    (χ^2/NDF=1.7/28)
  - Exponentially cut-off power law
    - γ= -3.10±0.01 at 2854± 304GeV
    (χ^2/NDF=6.1/28)
- Possible spectral fit in whole energy region
  - Positron contribution is fitted using AMS flux with secondaries + pulsers.
  - CALET electron+positron flux is fitted with secondaries + pulsers + SNRs.

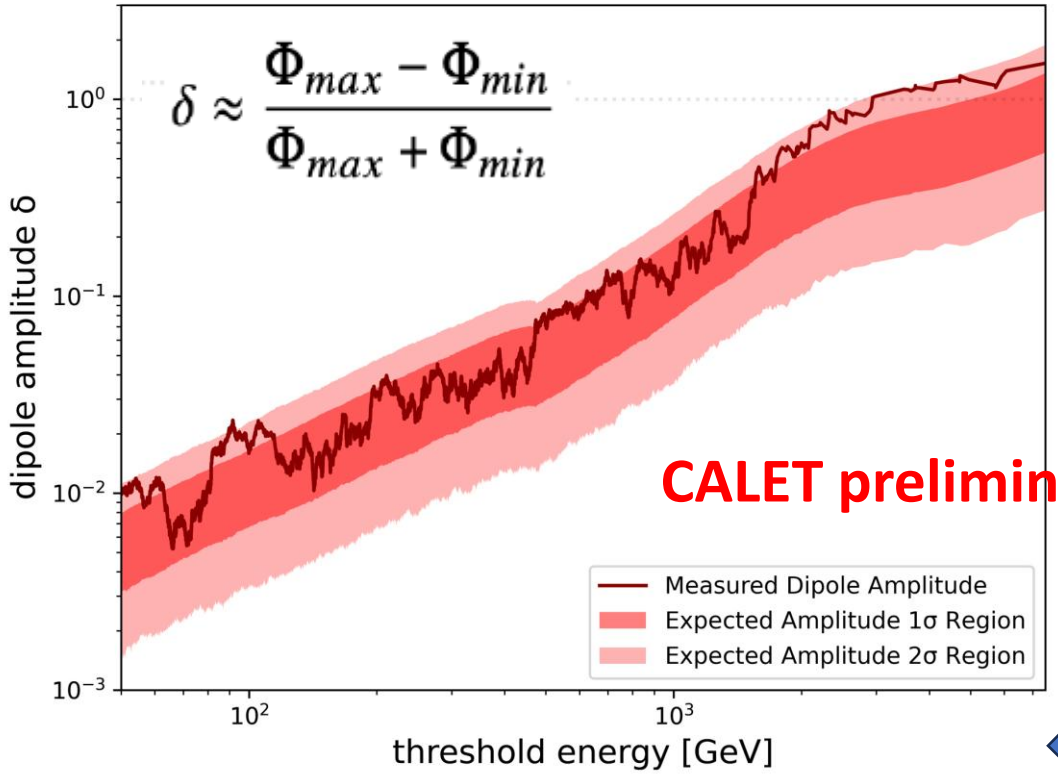




Dipole Anisotropy Measurement

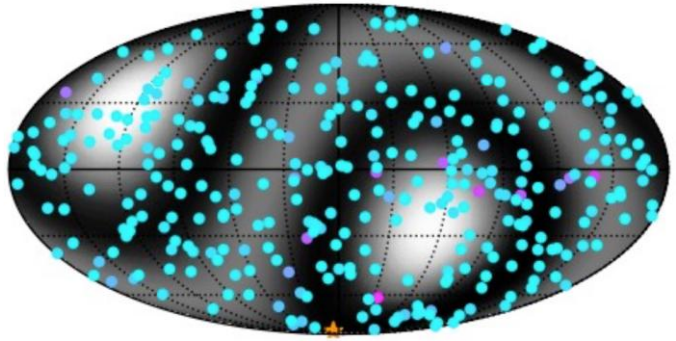
ICRC2025

Data sample: 3x10^5 electrons above 50GeV
(Oct. 2015 – Dec. 2024)

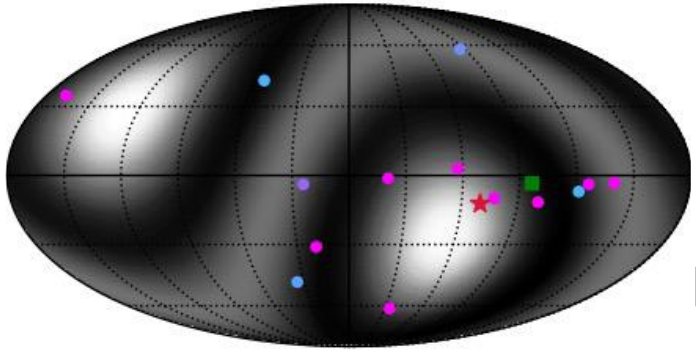


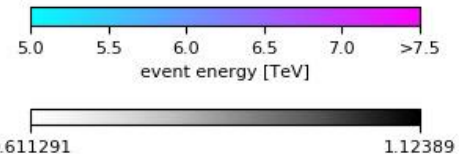
CALET preliminary

event map in E>1 TeV



event map in E>5 TeV



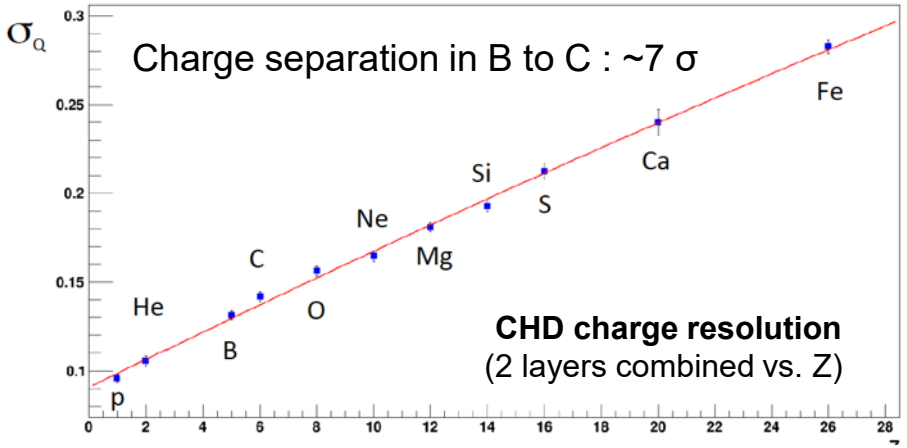


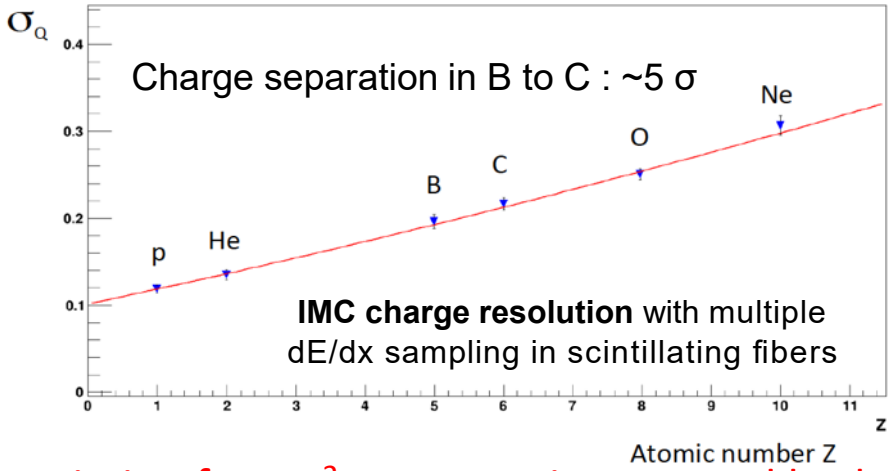
In E>5 TeV, event cluster close to the direction toward the Vela SNR.

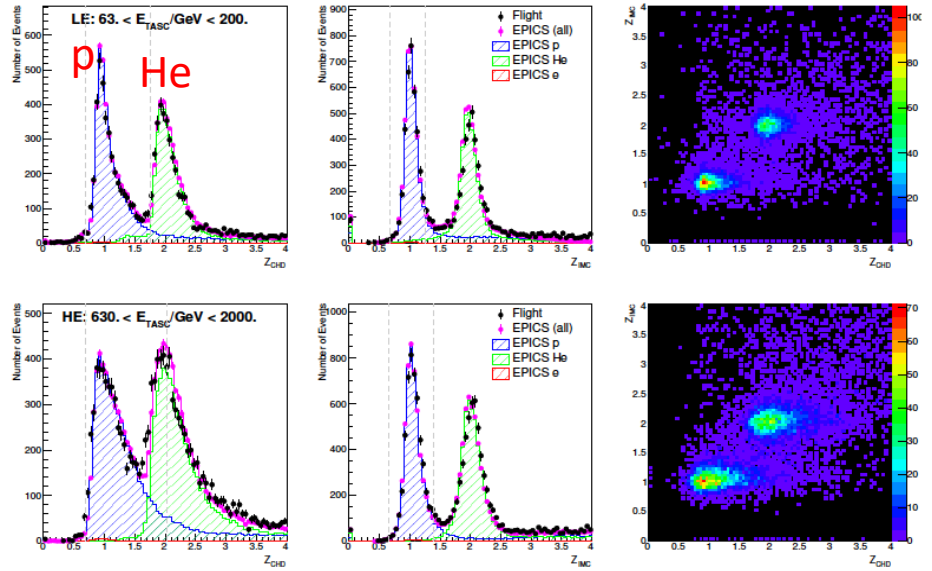
Dipole amplitude is within 2σ band. But the amplitude above ~2TeV is close to the upper boundary.

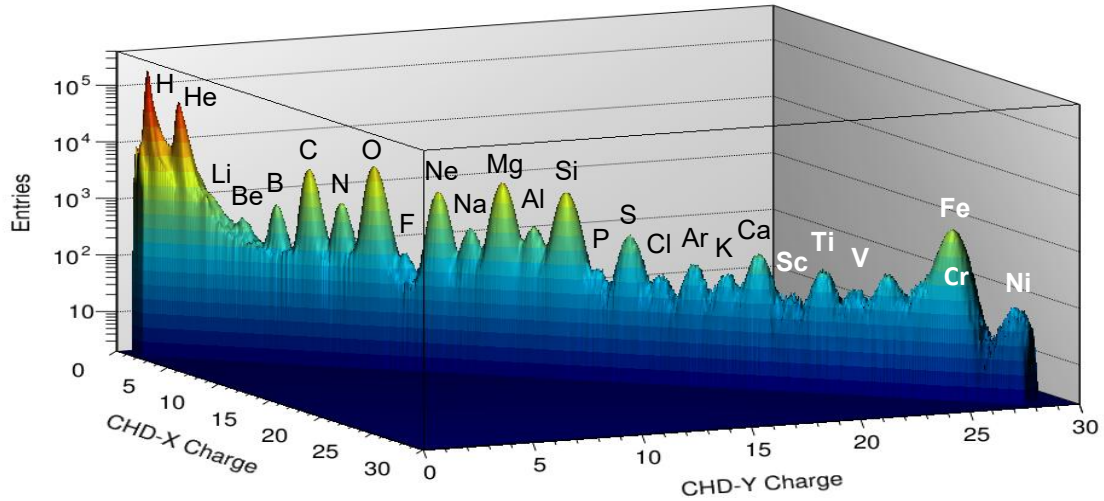
Charge Identification with CHD and MC

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





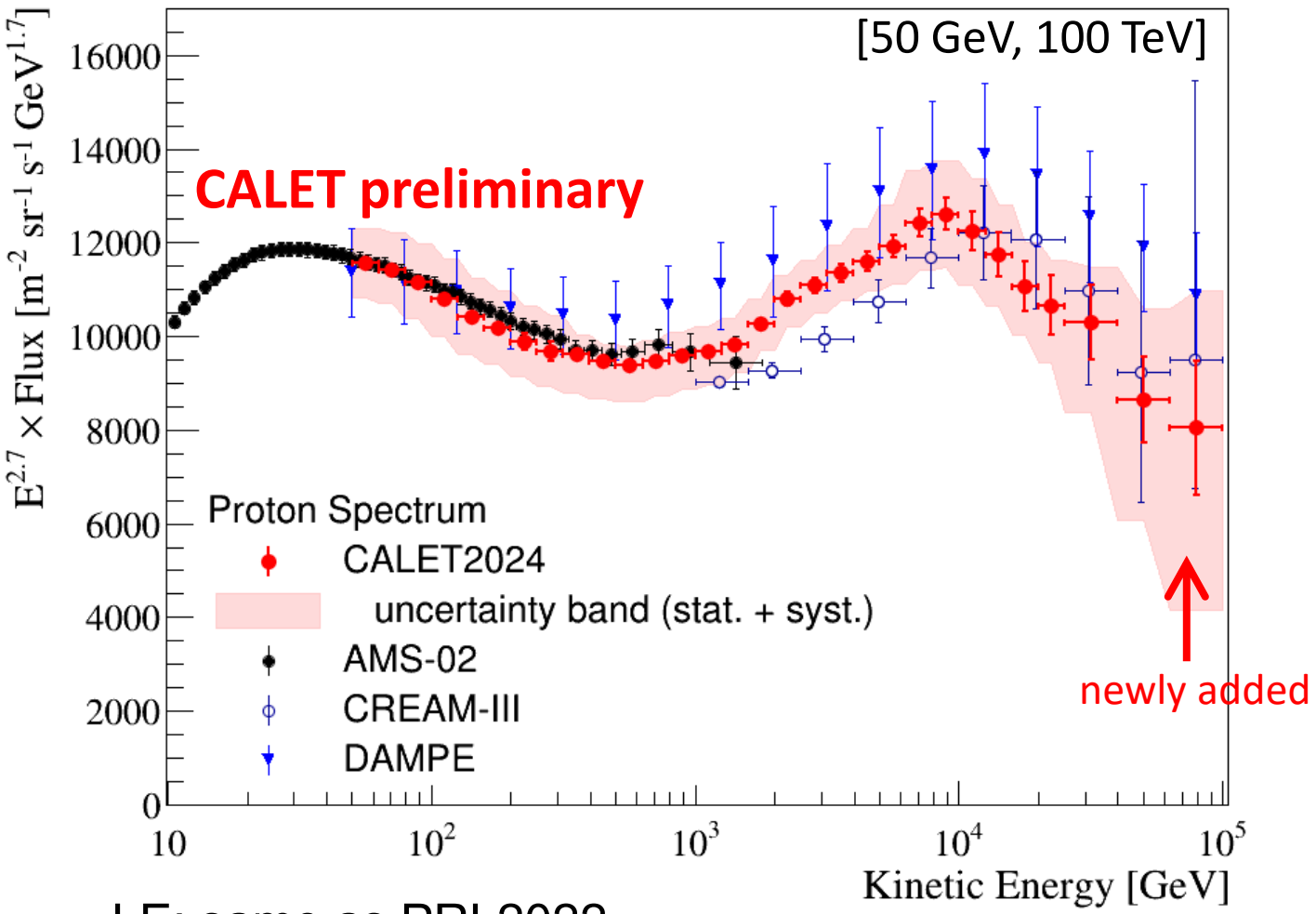




Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

Proton Energy Spectrum

PRL 129, 101102 (2022)
ICRC 2025 update

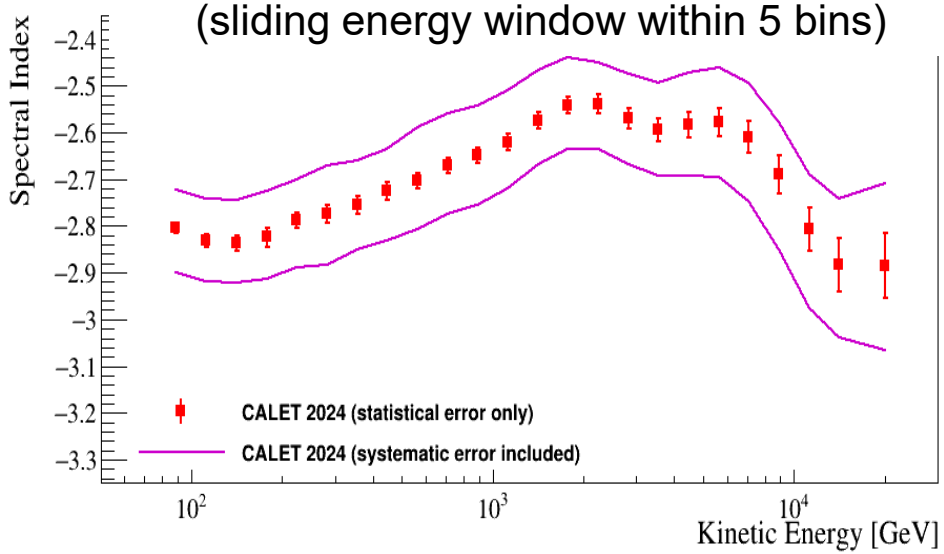


LE: same as PRL2022
HE: 2850 days of live time (Oct. 2015 – Dec. 2024)

$$\Phi(E) = \frac{N(E)}{S\Omega T \Delta E \varepsilon(E)}$$

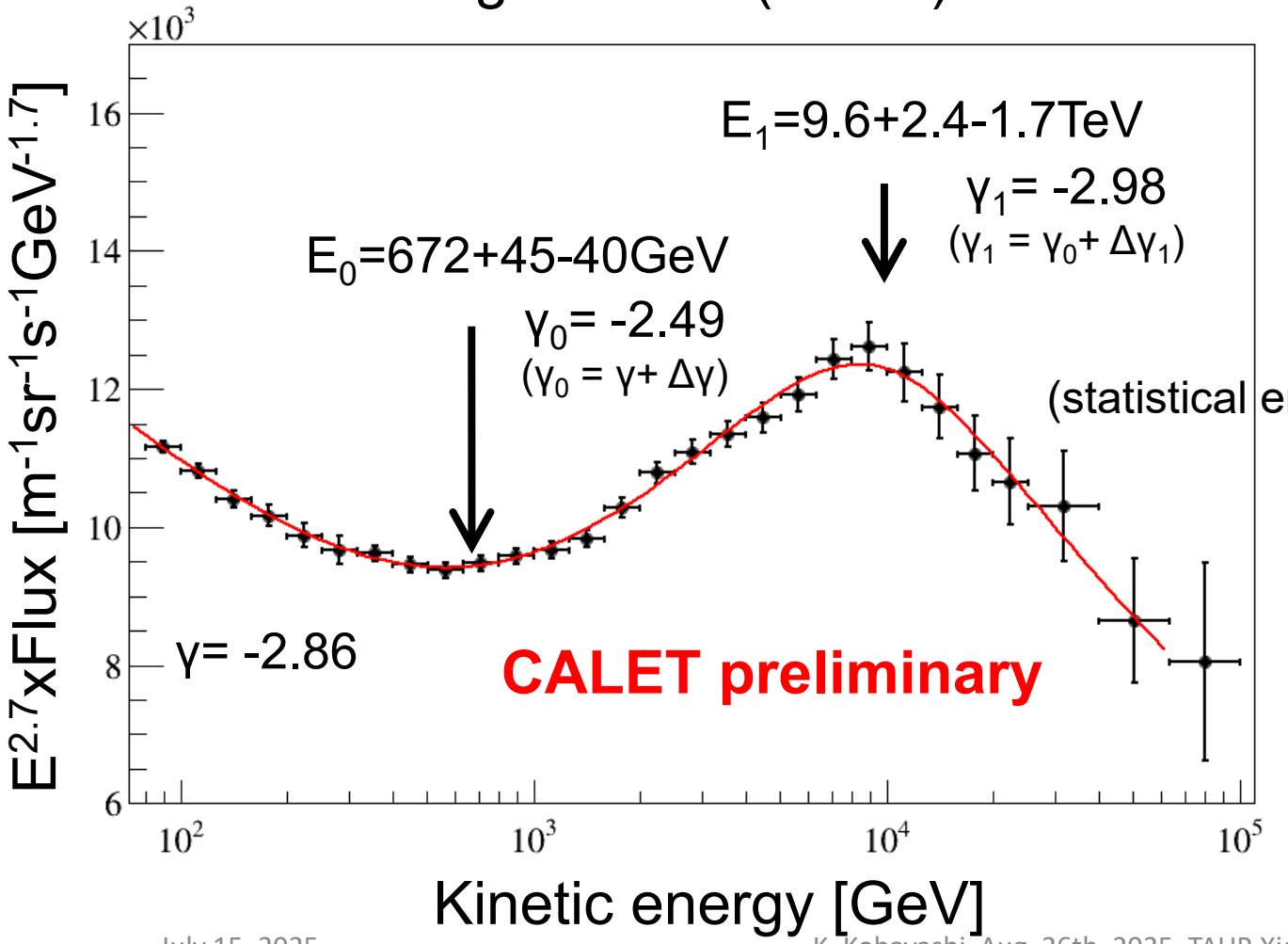
$\Phi(E)$: proton flux
$N(E)$: number of events in ΔE bin (after background subtraction)
$S\Omega$: geometrical acceptance (510cm^{2}sr)
T: livetime
ΔE: energy bin width
$\varepsilon(E)$: detection efficiency

Energy dependence of spectral index
(sliding energy window within 5 bins)



Spectral Fit with Double Broken Power Law (DBPL)

Fitting function (DBPL): $\Phi = E^{2.7} \times C \times \underbrace{\left(\frac{E}{1GeV}\right)^{\gamma}}_{\text{Low energy}} \times \underbrace{\left(1+\left(\frac{E}{E_0}\right)^{s}\right)^{\frac{\Delta\gamma}{s}}}_{\text{hardening}} \times \underbrace{\left(1+\left(\frac{E}{E_1}\right)^{s_1}\right)^{\frac{\Delta\gamma_1}{s_1}}}_{\text{softening}}$



(statistical error only)

$\chi^2 = 6.8/20$

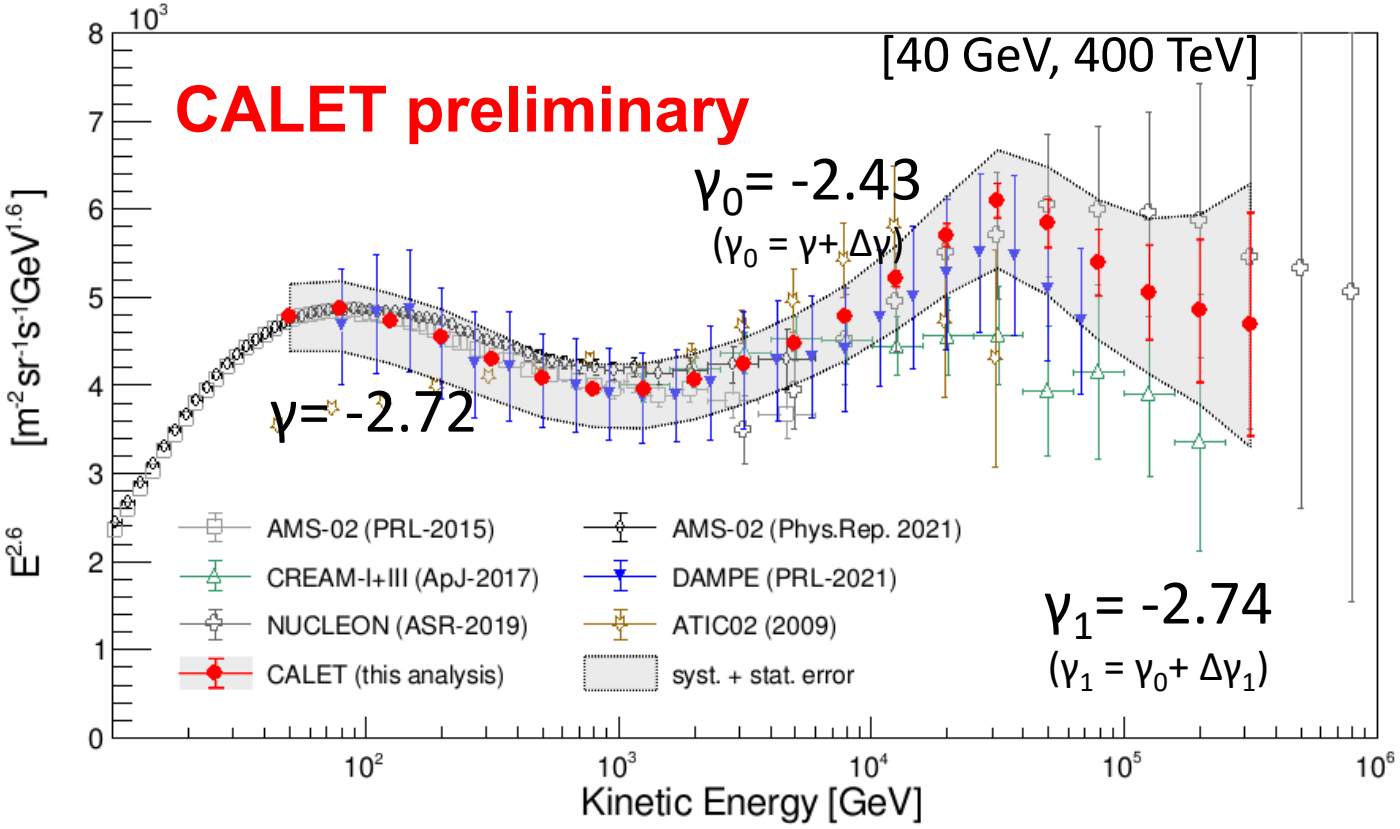
γ	-2.858+0.005-0.005
s	1.6±0.2
Δγ	(3.7±0.1)x10^{-1}
E_0	(6.72+0.45-0.40)x10^2
$\Delta\gamma_1$	(-4.9+1.2-1.3)x10^{-1}
E_1	(9.6+2.4-1.7)x10^3
s_1	2.7+3.5-0.5

The s_1 becomes smoother, but s_1 is larger than s.

Helium Energy Spectrum

PRL 130, 171002 (2023)
ICRC2025 update

Data: Oct. 2015 – Sep. 2020

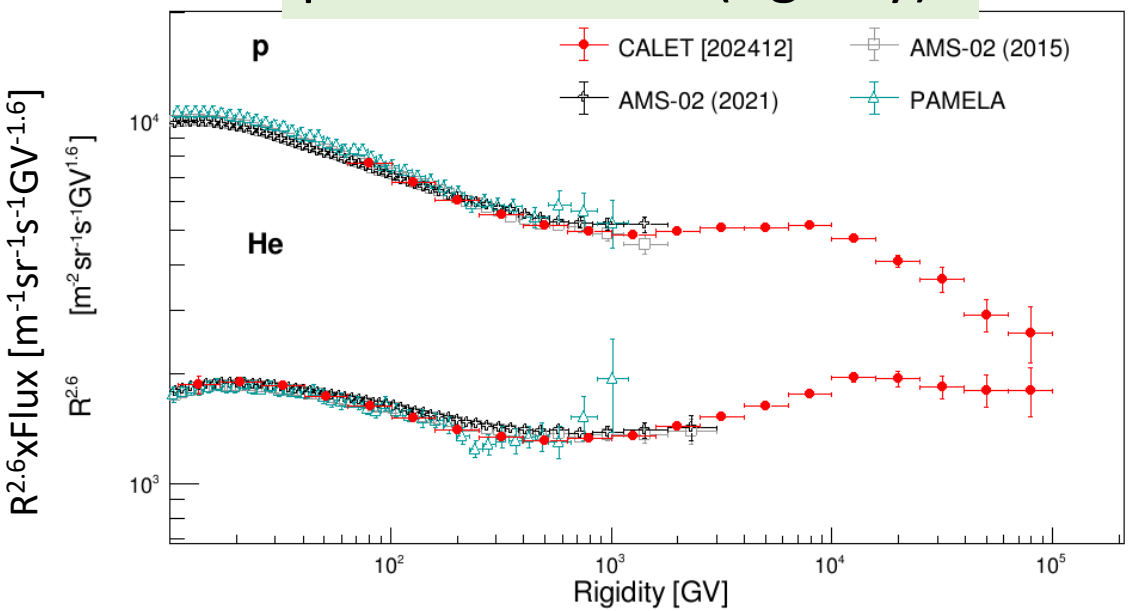


$$\Phi'(E) = C \times \left(\frac{E}{1\ \mathrm{GeV}}\right)^{\gamma} \times \left[1 + \left(\frac{E}{E_0}\right)^{s}\right]^{\frac{\Delta\gamma}{s}} \times \left[1 + \left(\frac{E}{E_1}\right)^{s_1}\right]^{\frac{\Delta\gamma_1}{s_1}}$$

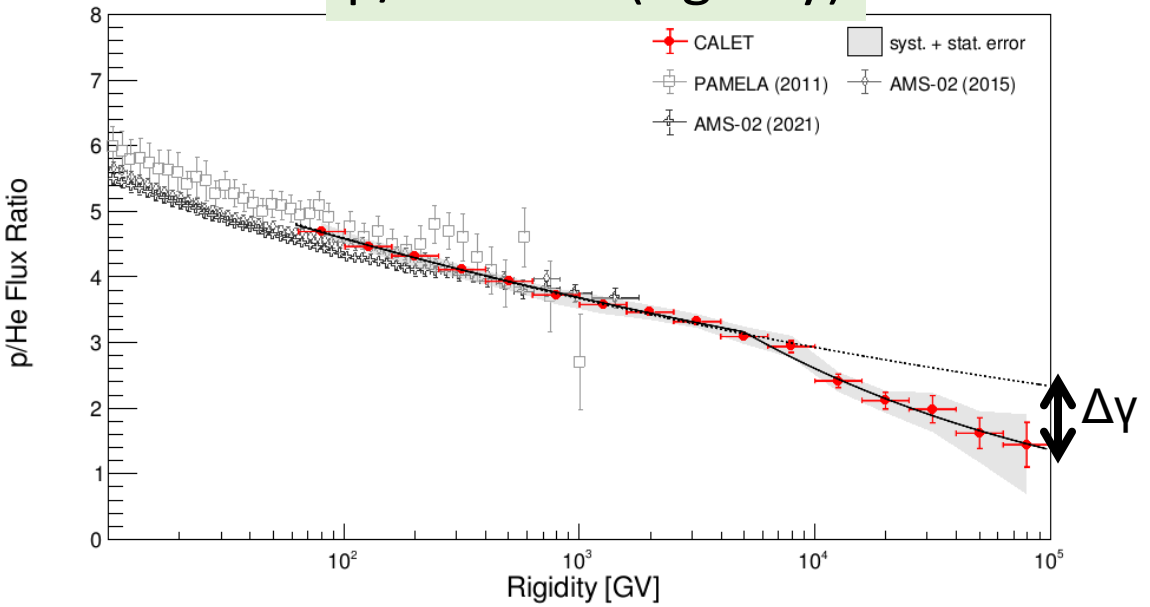
- We observe the spectral hardening starting at
  $E_0 = 1.276^{+0.111}_{-0.094}(stat)^{+0.250}_{-0.198}(sys)\mathrm{TeV}$
  This is consistent with DAMPE result (PRL 2021).
- We also observe spectral softening starting at
  $E_1 = 34.6^{+7.2}_{-5.5}(stat)^{+1.6}_{-6.1}(sys)\mathrm{TeV}$

Proton/He ratio

p and He fluxes (rigidity)



p/He ratio (rigidity)

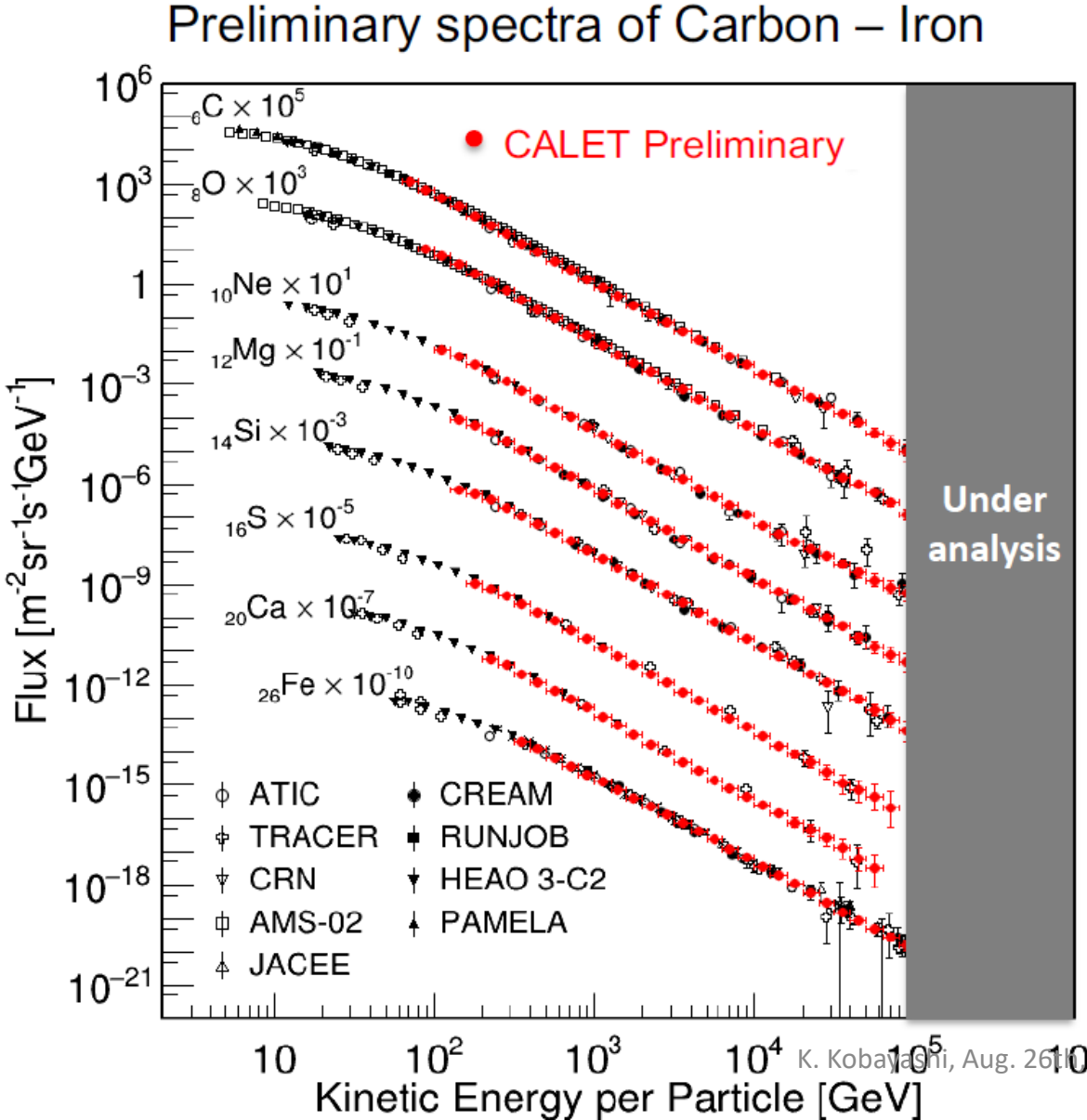


- Spectral hardening in rigidity are consistent between proton and helium.
- p/He ratio from tens GV to 10 TV is well described by SPL ($\Phi(R)$ =A × R^{γ}, γ=-0.097±0.005).
- DPL is favored with a significance of 4.8σ compared to SPL from 60 GV to 100 TV.

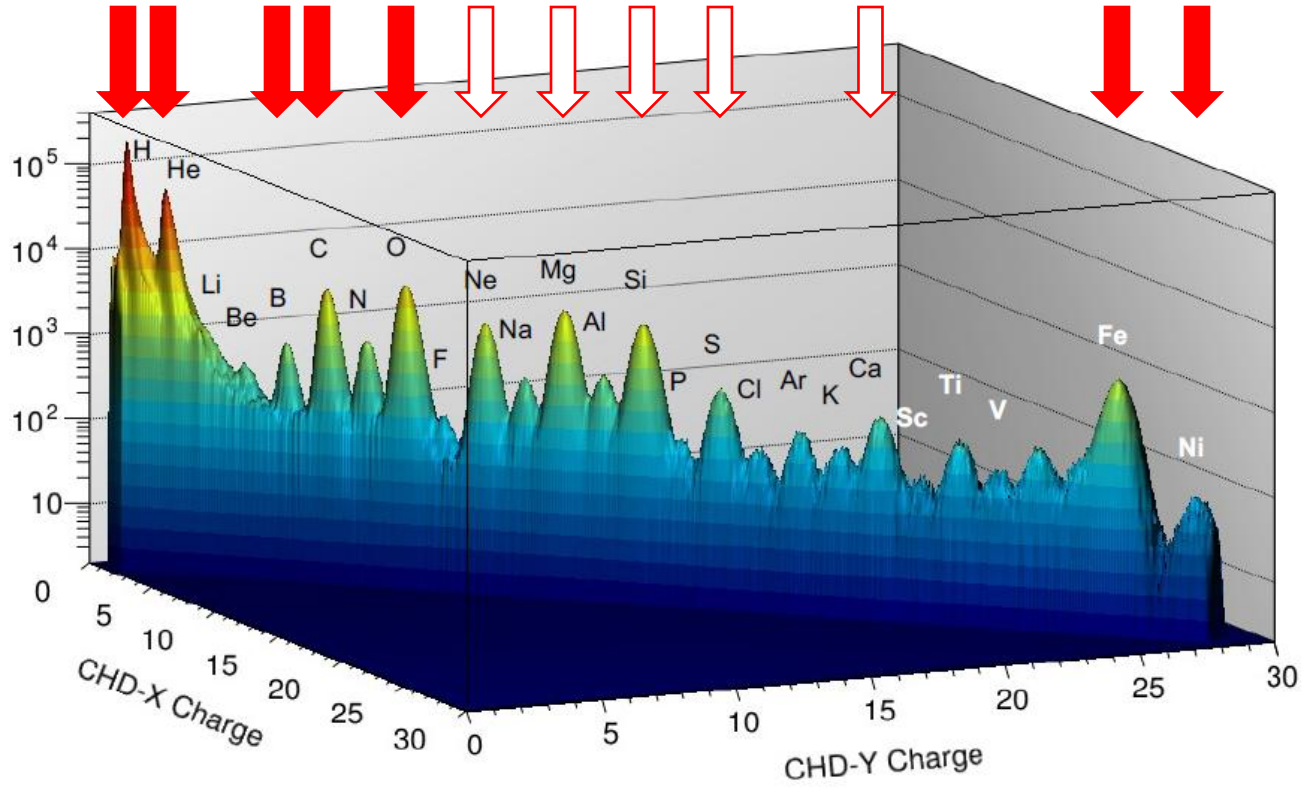
DPL: $\Phi(R) = \begin{cases} C \times \left(\frac{R}{1GV}\right)^{\gamma} & (R > R_0) \\ C \times \left(\frac{R}{1GV}\right)^{\gamma} \times \left(\frac{R}{R_0}\right)^{\Delta\gamma} & (R > R_0) \end{cases}$

γ	-0.097±0.006
R_0	6.60±1.87 TV
Δγ	-0.23±0.08

Observations of Cosmic-ray Nuclei



Dedicated analysis of cosmic-ray nuclear fluxes and flux ratios into the TeV region ongoing.

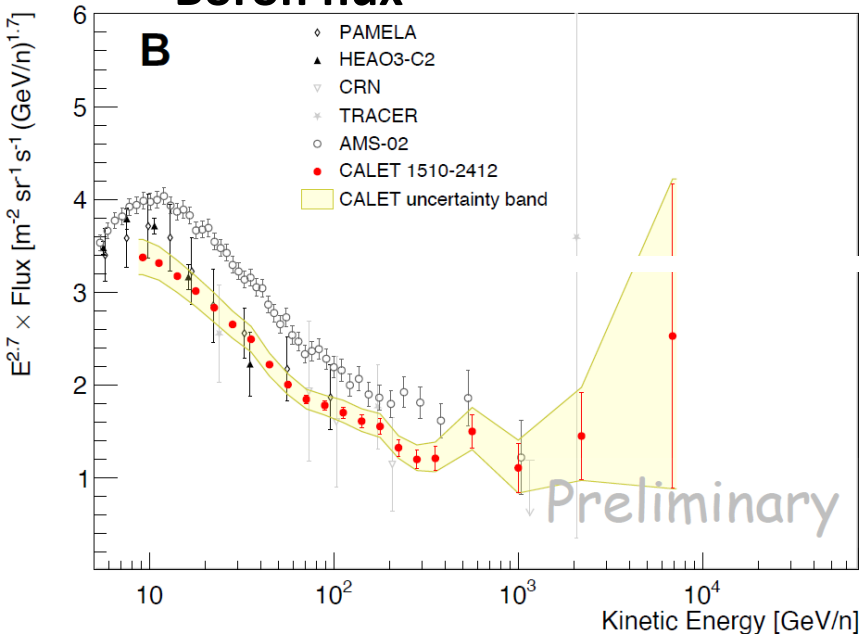


Energy Spectra of Cosmic-ray BCO

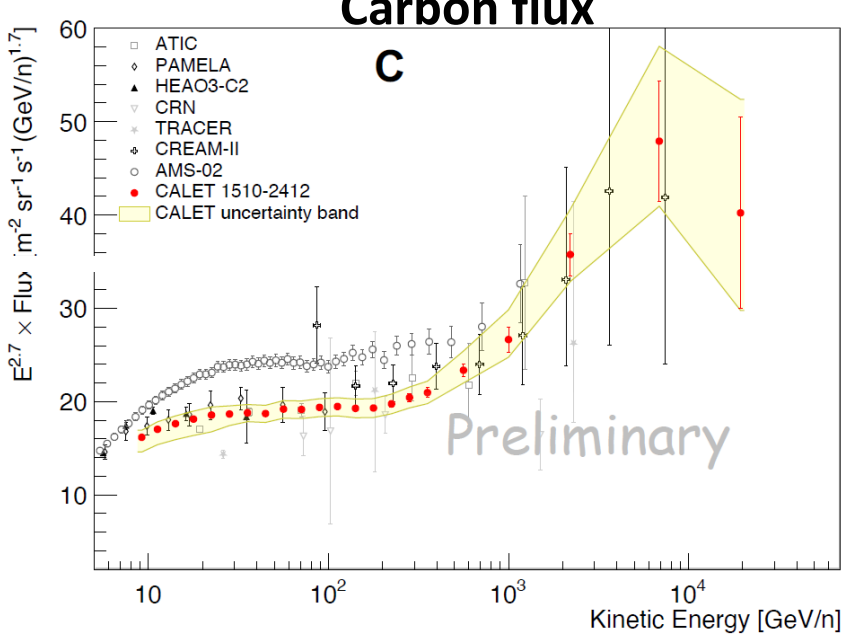
C&O: PRL 125, 251102 (2020)
B: PRL 129, 251103 (2022)
ICRC 2025 update

[8.4 GeV/n, 19 TeV/n]

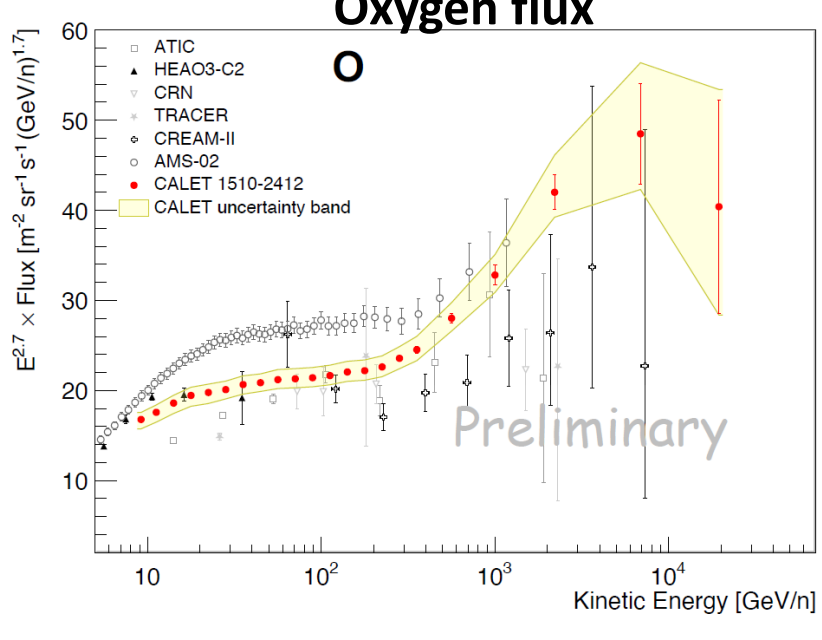
Boron flux



Carbon flux



Oxygen flux

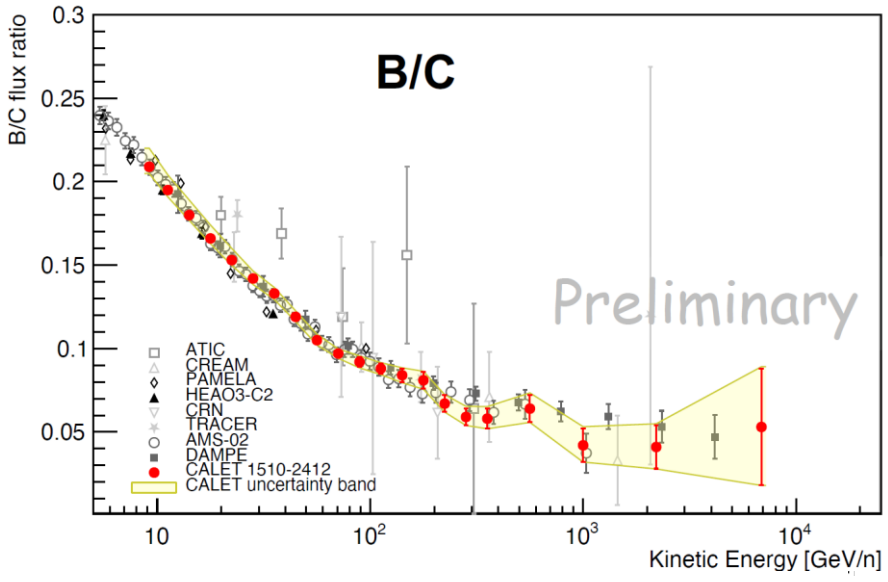


- CALET B,C are consistent with PAMELA and most of the previous experiments (PAMELA did not publish oxygen).
- CALET B,C,O absolute normalization are lower than AMS-02.
- The C, O spectra show a clear hardening around 200 GeV/n and hint of a softening around 10 TeV/n.

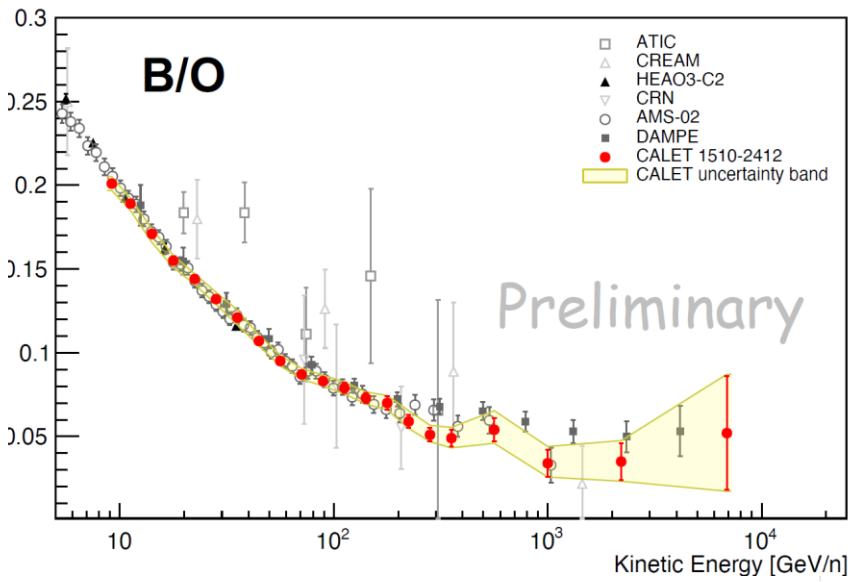
BCO flux ratio

ICRC 2025

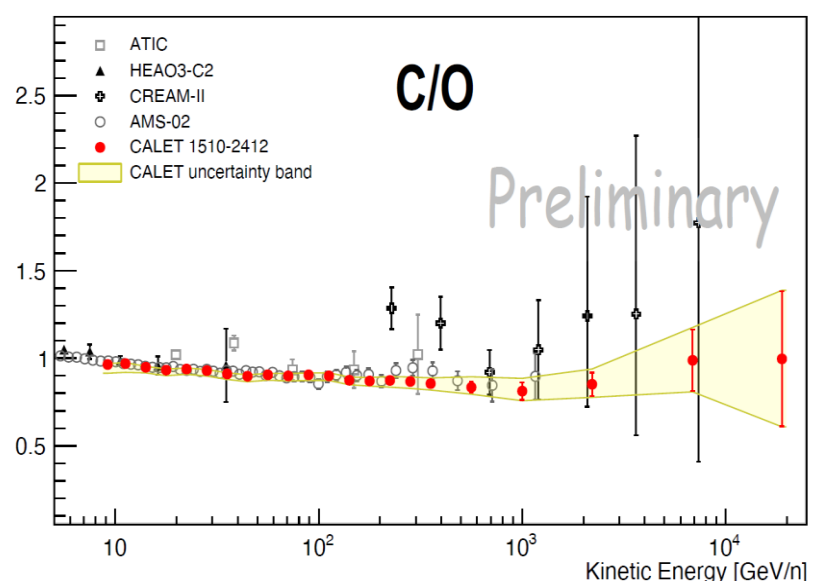
Boron / Carbon



Boron / Oxygen



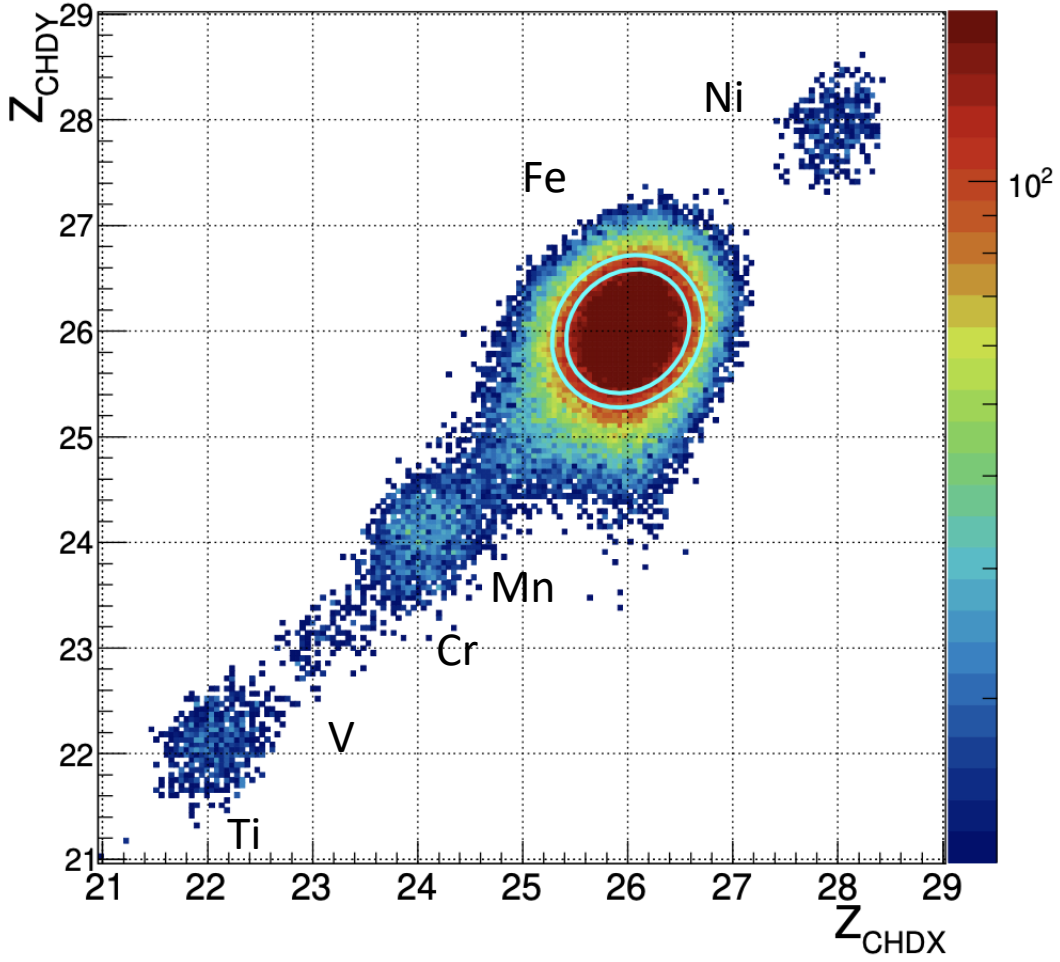
Carbon / Oxygen

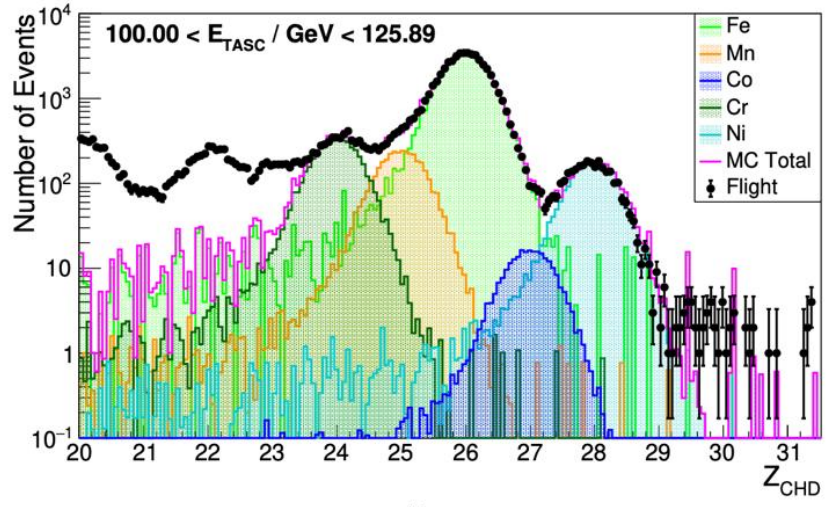


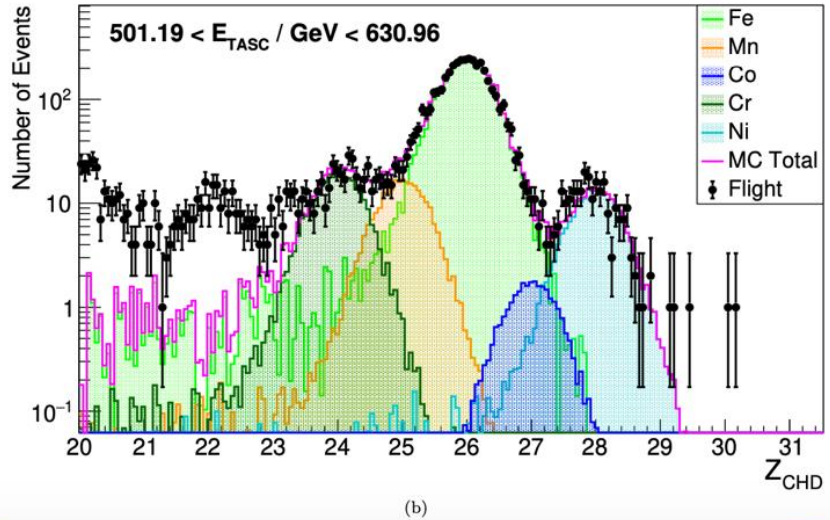
- Cosmic ray Boron are entirely produced by the collision with the interstellar matter, though carbon are thought to be mainly produced and accelerated in astrophysical sources. Therefore, B/C ratio directly measures the average amount of interstellar material traversed by cosmic rays.
- B/C, B/O, and C/O ratio are consistent to AMS-02.

Iron – Analysis (Charge Selection)

Charge measurement with the two CHD layers





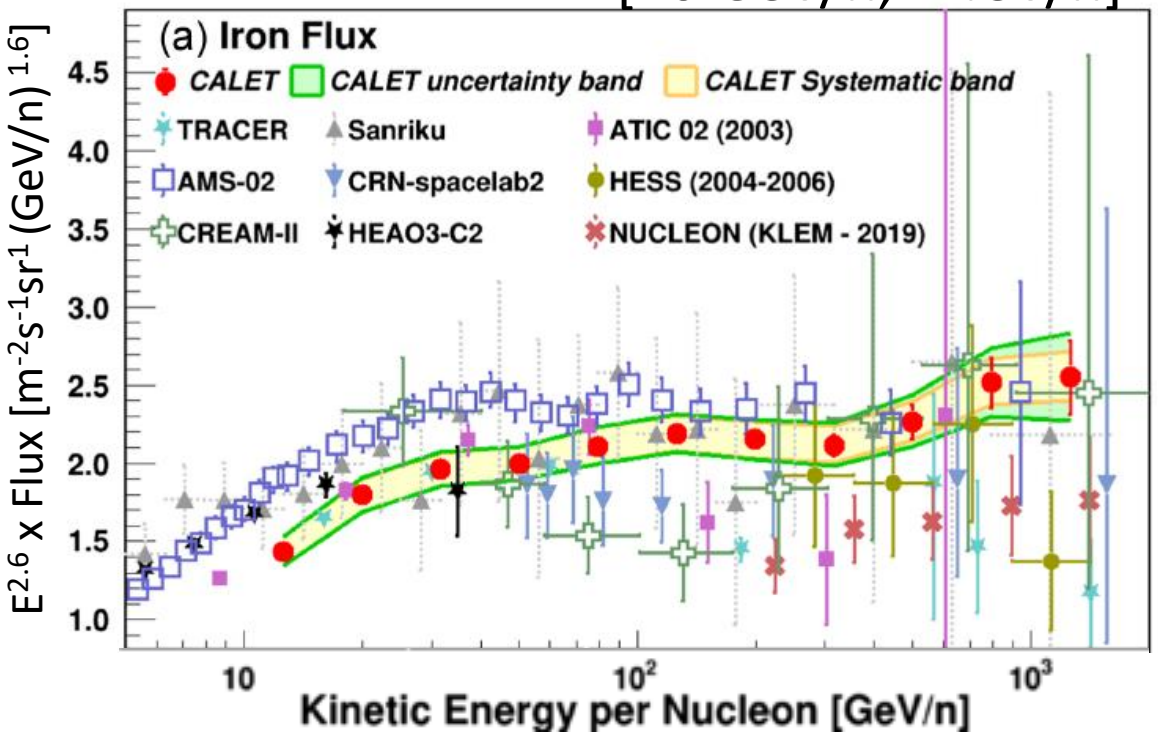


Iron and Sub-Iron Energy Spectrum

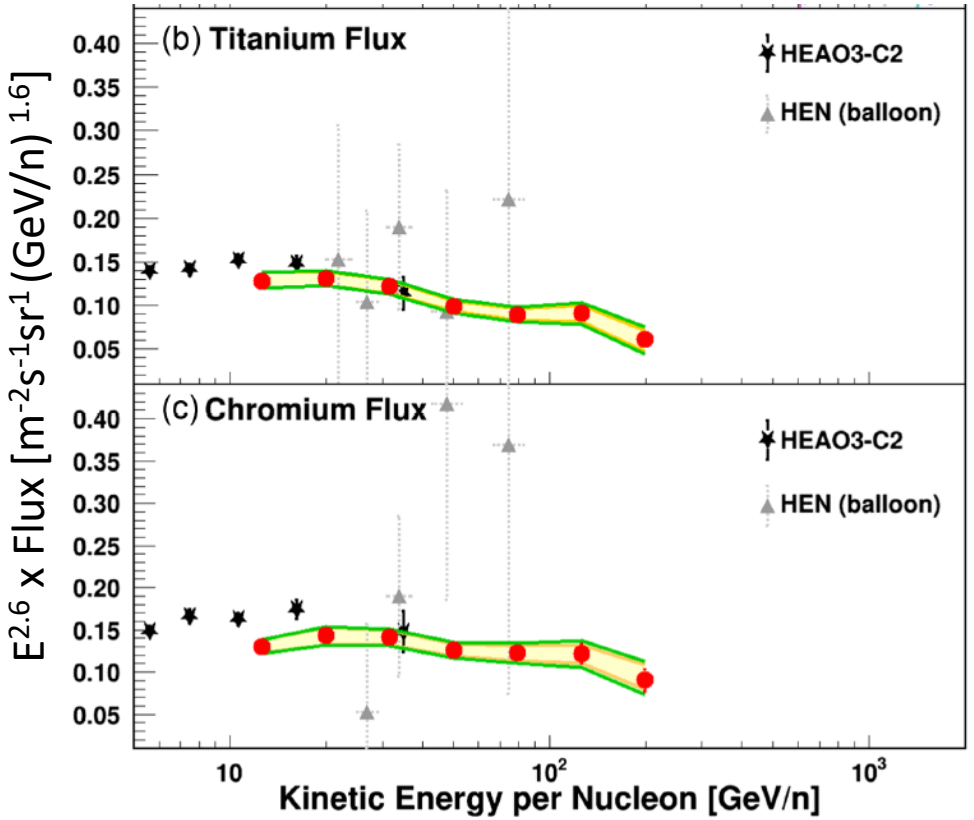
PRL 135, 021002 (2025)

Data: Nov. 2015 – Oct 2023

[10 GeV/n, 1 TeV/n]



[10 GeV/n, 100 GeV/n]



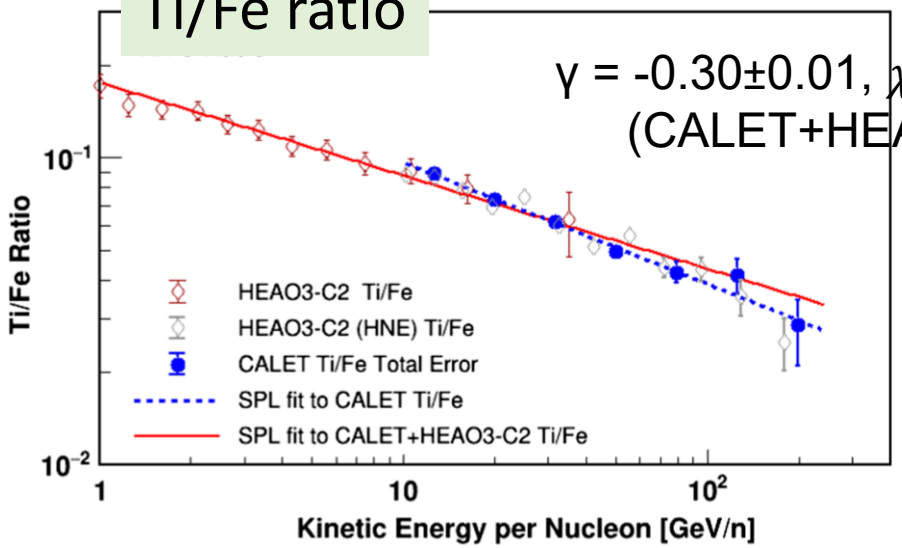
- Iron spectrum was updated with 2 times larger statistics than PRL 2020.
- Possible hardening of iron spectrum above a few hundred GeV/n.
- New measurement on Ti and Cr spectrum.

Sub-Iron to Iron Ratios

PRL 135, 021002 (2025)

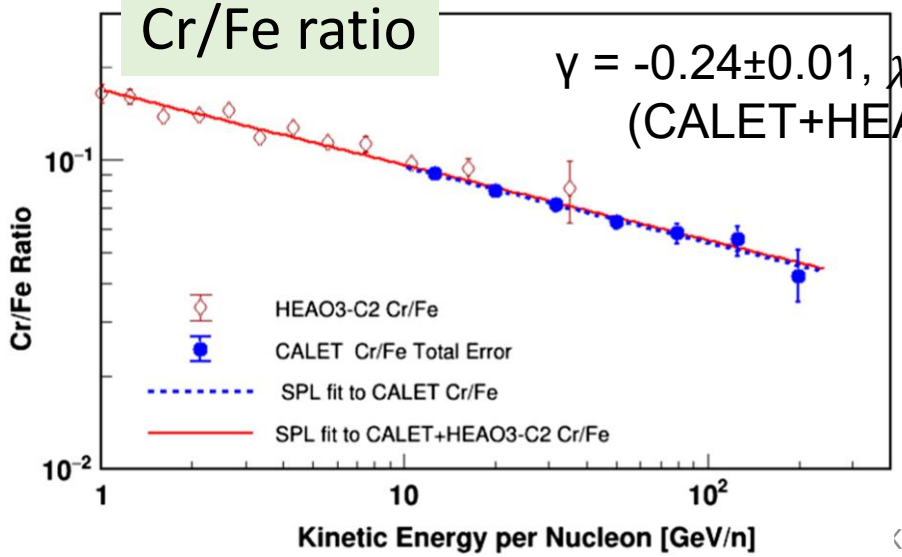
Ti/Fe ratio

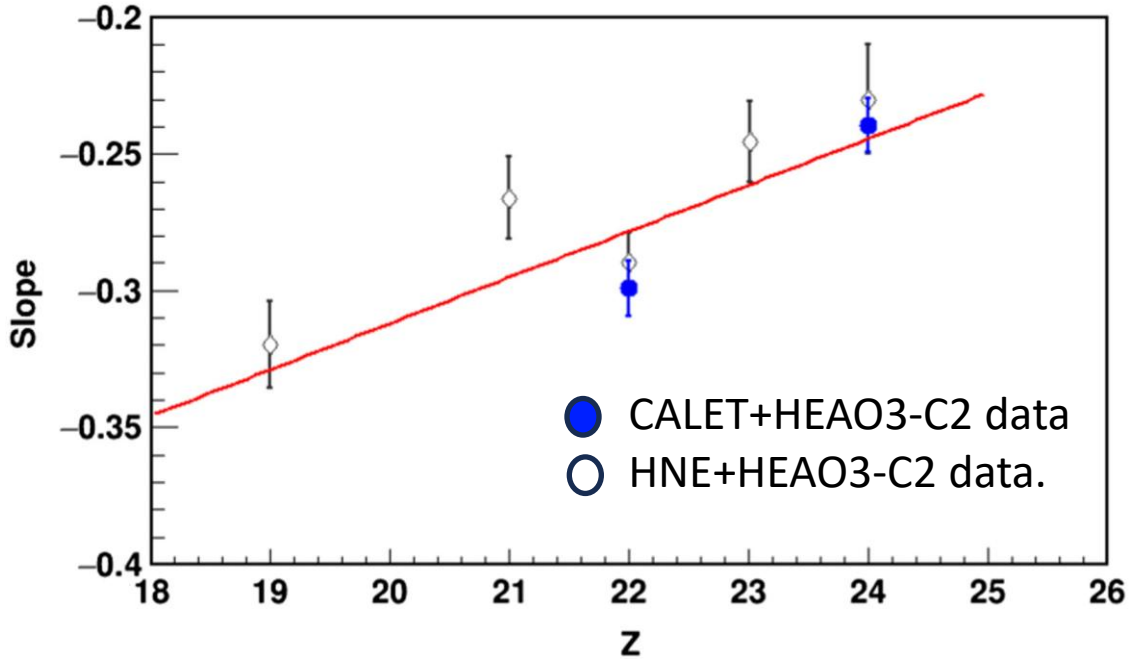
γ = -0.30±0.01, χ^2/n = 15/17
(CALET+HEAO3-C2)



Cr/Fe ratio

γ = -0.24±0.01, χ^2/n = 17/17
(CALET+HEAO3-C2)





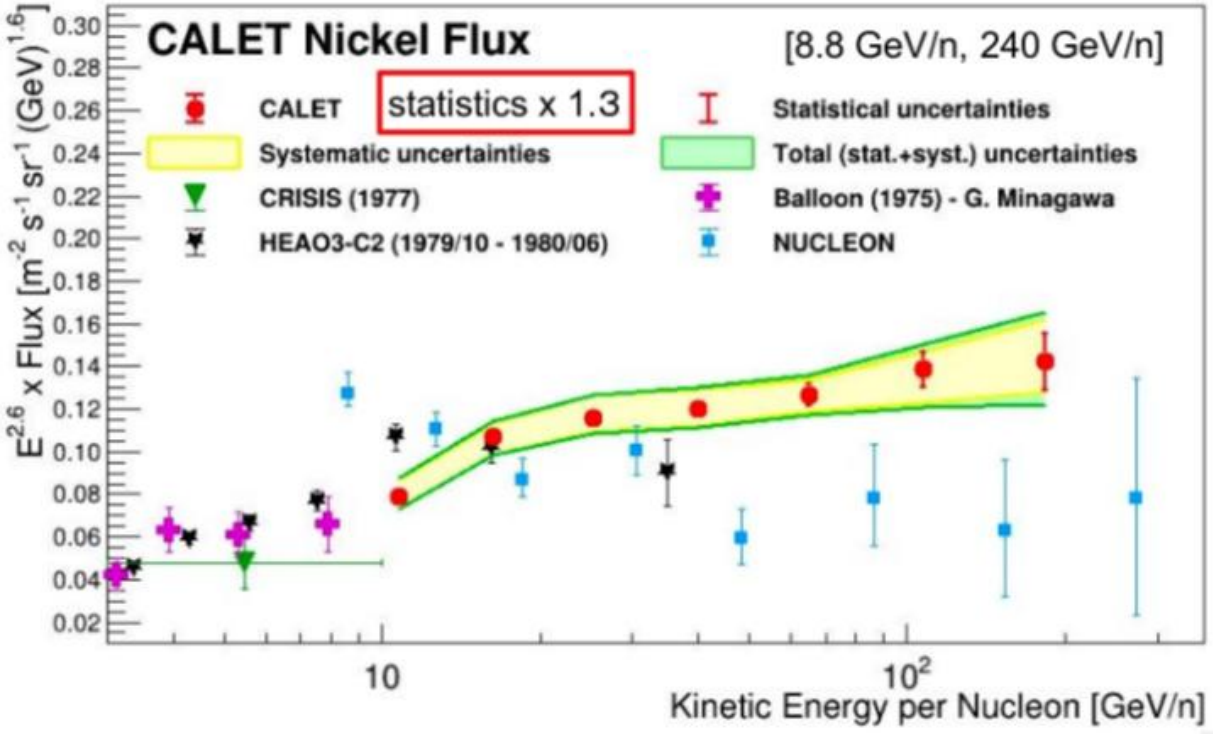
- Ti/Fe and Cr/Fe ratios are well fitted with SPL.
- Z dependence of the Index of flux ratio is found to be consistent with the CALET + HEAO3-C2 data.

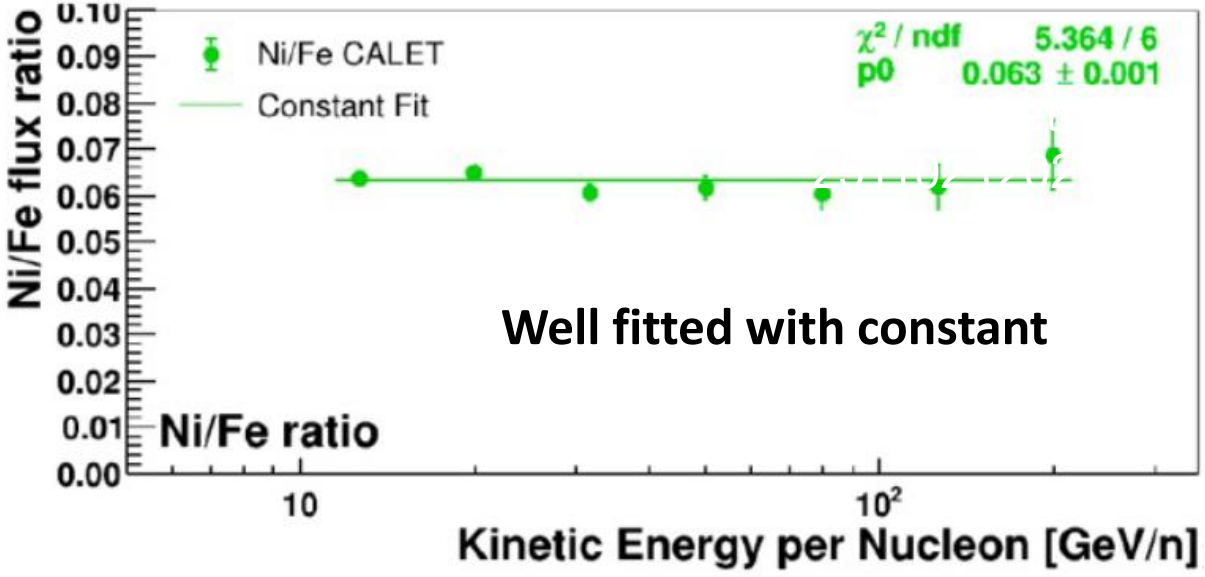
Nickel Energy Spectrum

PRL 128, 131103 (2022)
ICRC 2023 Update

Flux x $E^{2.6}$ vs kinetic energy per nucleon [8.8 GeV/n, 240 GeV/n]

Data: Nov. 2016 – Dec 2022



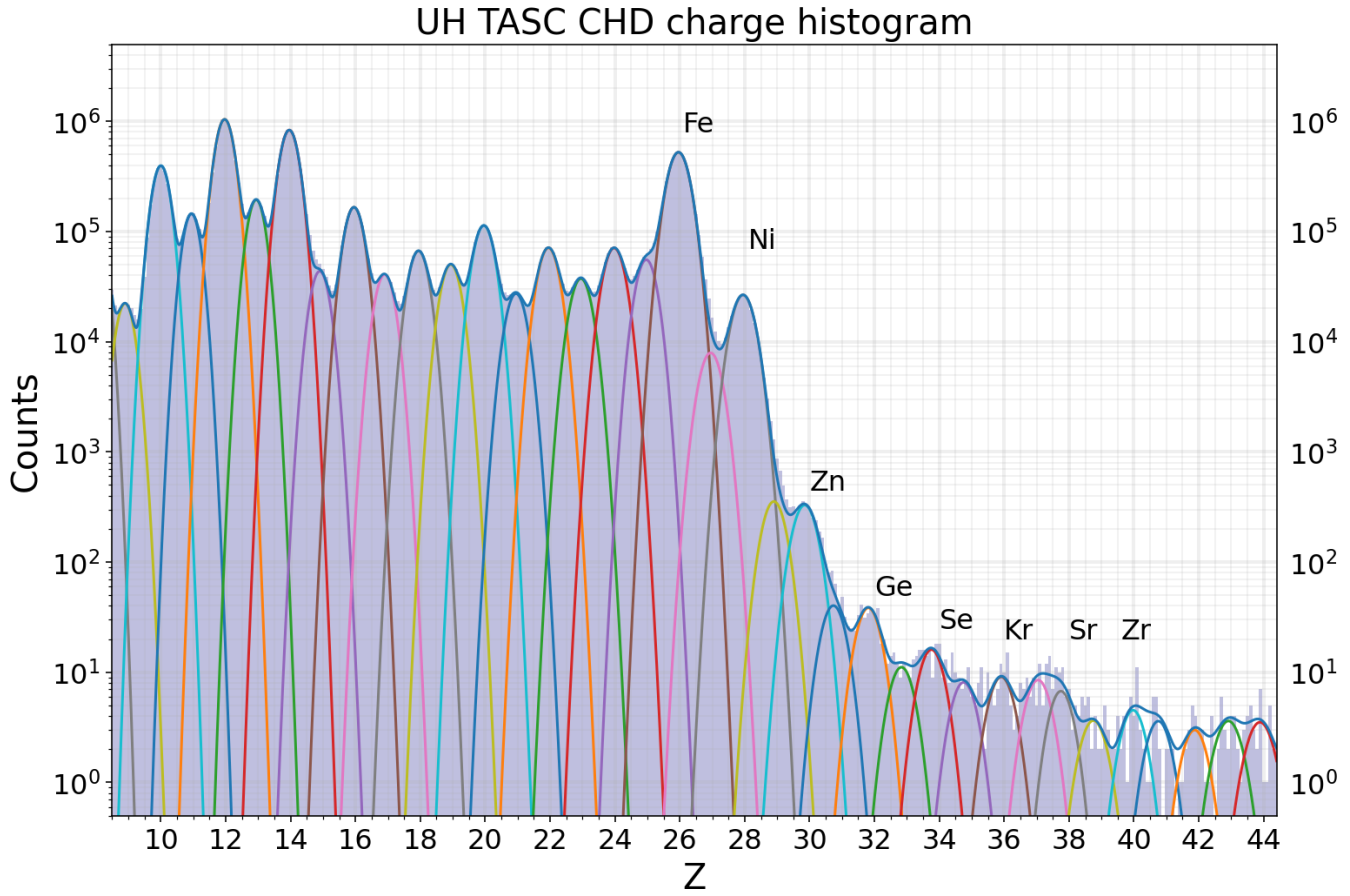


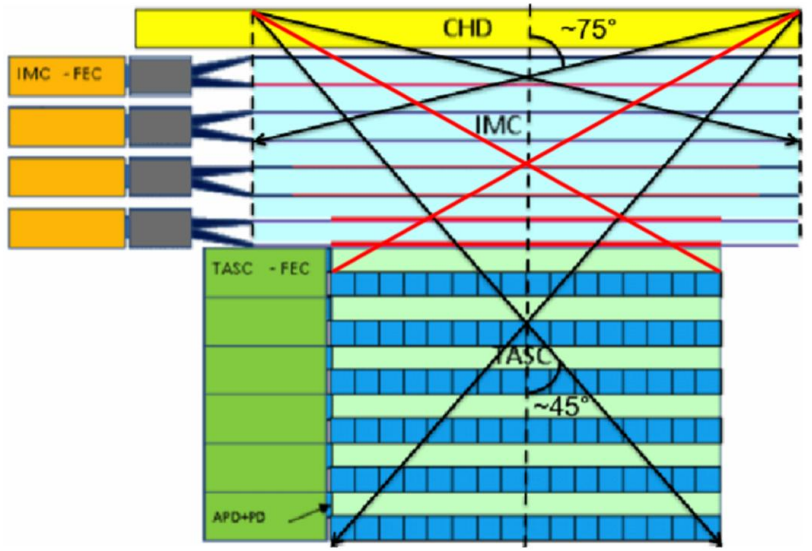
Ni and Fe fluxes have the same energy dependence.

Ultra Heavy Nuclei (14<=Z<=44)

APJ 988:148 (2025)

- Data: 7.5years of CALET UH-trigger from Oct. 2015 to Nov. 2023.

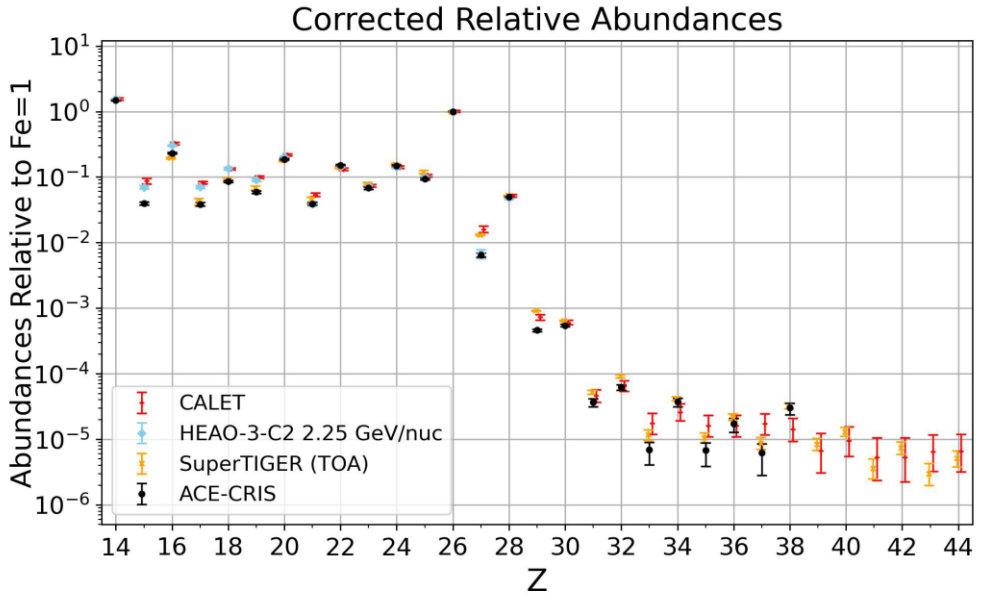


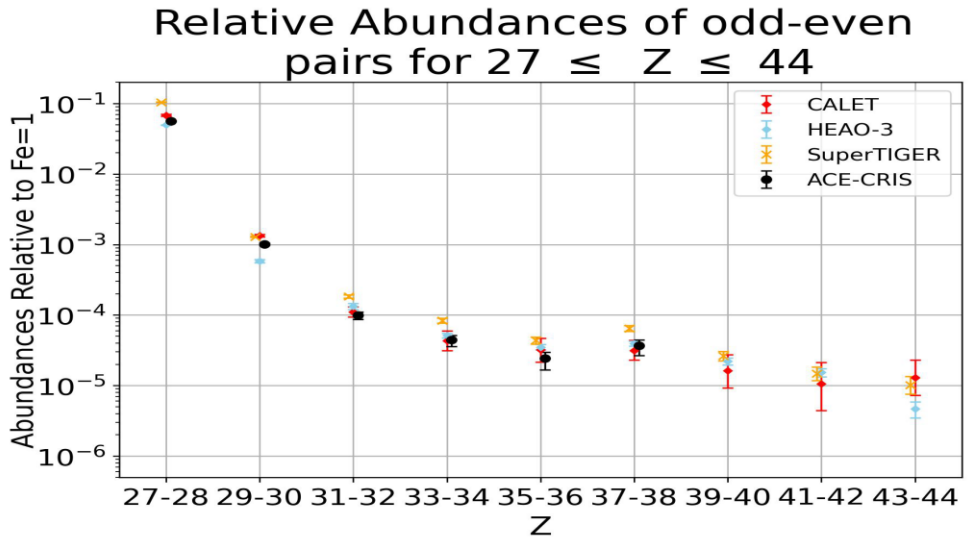


A special UH CR trigger uses the CHD and the first 4 layers of the IMC to achieve an expanded x 4 geometric factor, GF ~ 4400 cm^2 sr.

Ultra Heavy Nuclei (14<=Z<=44)

APJ 988:148 (2025)

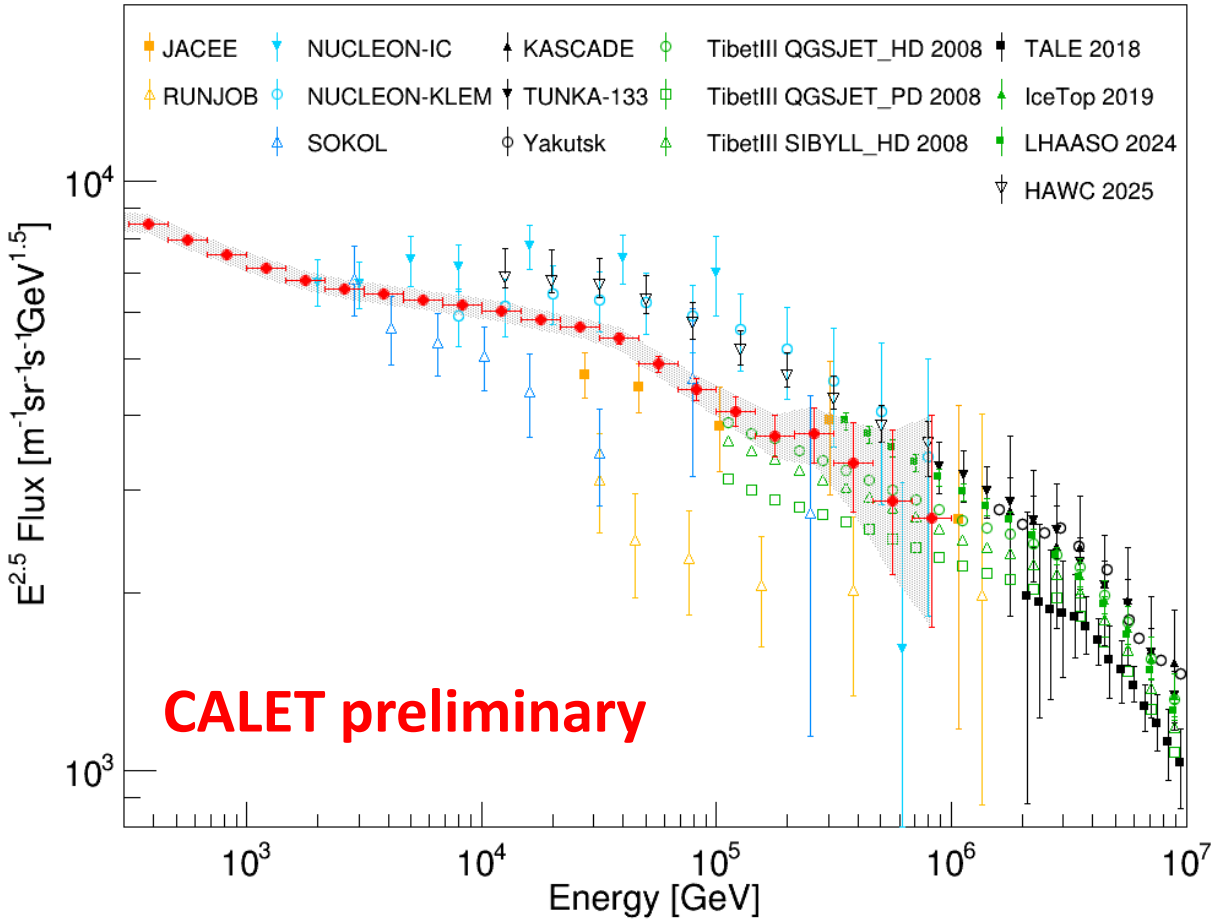




- We measure the relative abundances to Fe for 14<=Z<=44.
- The CALET UH element ratios are consistent with Super-TIGER, ACE_CRIS, and HEAO-3 abundances.
- For Z>26, odd peaks are higher than that of other experiments. However, relative abundance of odd-even elements pairs (lower figure) shows excellent agreement.

All-particle Spectrum from 31.6 GeV to 1 PeV ICRC2025

Data: Oct. 2015 – Dec. 2024



- Simple selection criteria are applied.
- MC (EPICS with DPMJET-III) are weighted to reproduce the fitted results of the observed CALET spectra.
- The spectrum is reconstructed using the unfolding response matrix from MC based on a weighted mixture of nuclei (Z=1~28).
- CALET spectrum is close to the indirect measurements from ground experiments.

CALET GeV-energy Gamma Rays

Effective area: ~400 cm2 (>2 GeV)

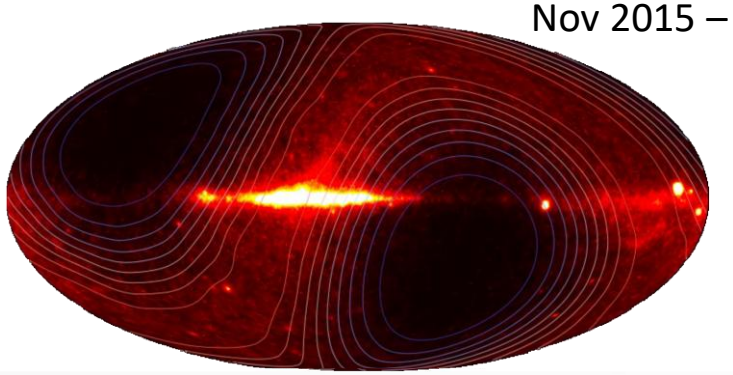
LE-γ trigger (E > 1 GeV)

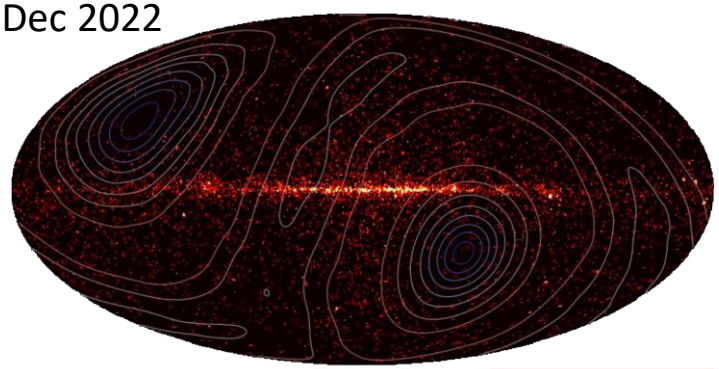
- Angular resolution: < 0.2° (> 10 GeV)

HE trigger (E > 10 GeV)

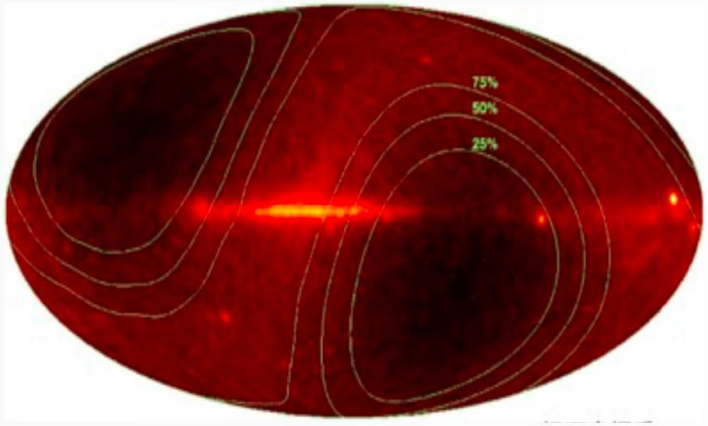
- Energy resolution: ~2% (> 10 GeV)

Nov 2015 – Dec 2022

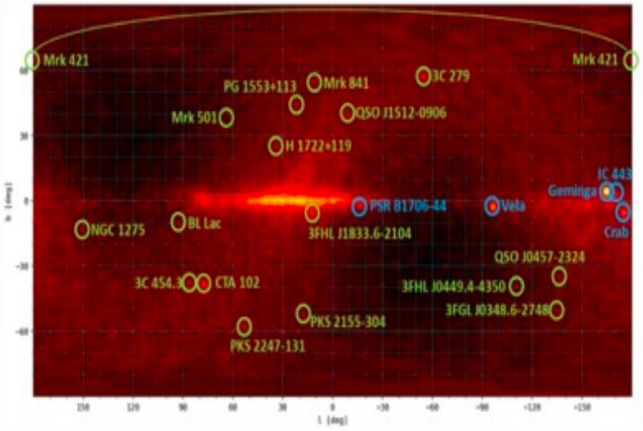




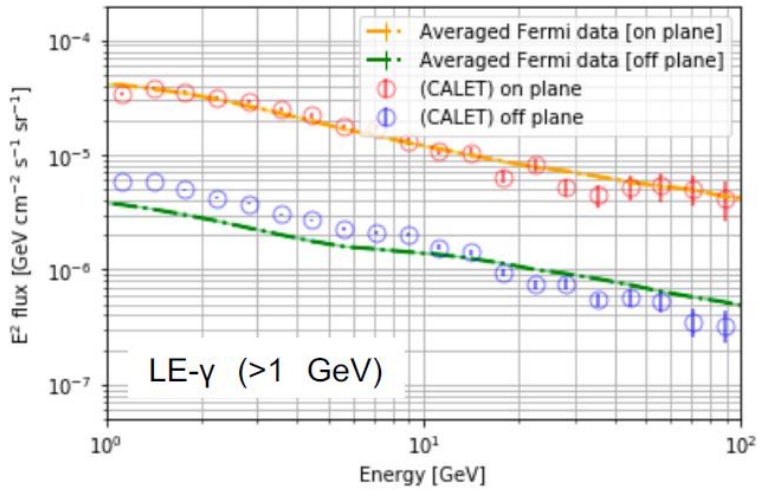
Gamma-ray sky map LE-γ trigger (E >1 GeV)

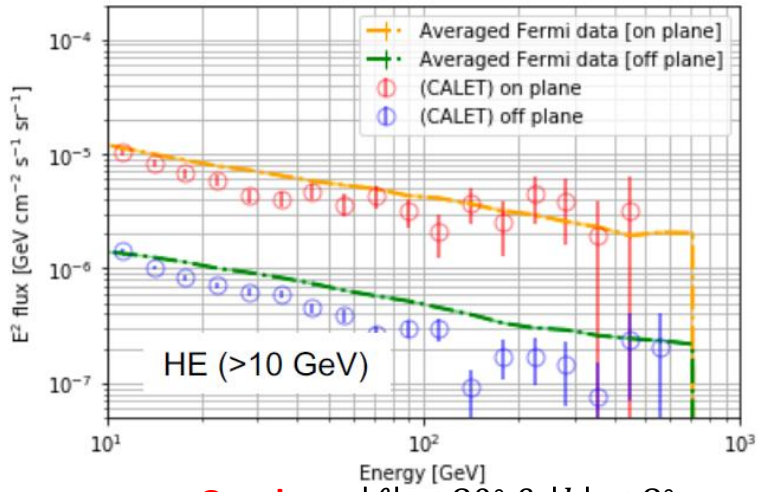


Identified bright point-sources (E >1 GeV)



Average galactic spectra





On-plane: $|\ell| < 80^\circ$ & $|b| < 8^\circ$

Off-plane: $|b| > 10^\circ$

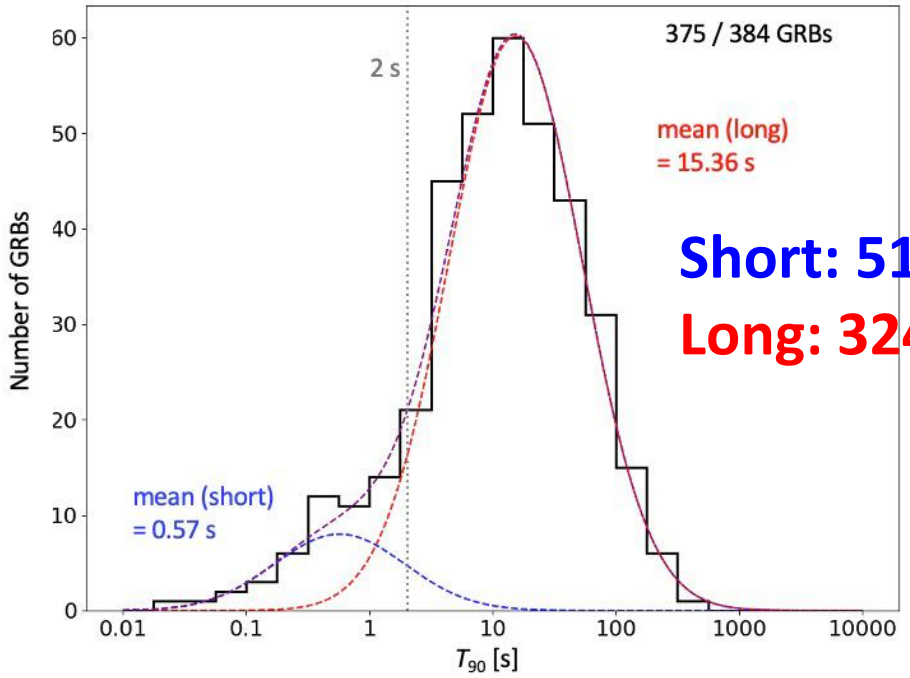
Measurements of energy spectra for point sources and diffuse structures are found to be consistent with those by Fermi-LAT.

CALET Gamma-ray Burst Monitor

ICRC2025

GRB search

CGBM has performed GRB observations on ISS for more than 9 years.
In Oct. 5th, 2015 – Apr. 30th, 2025, we have detected 365 GRBs.

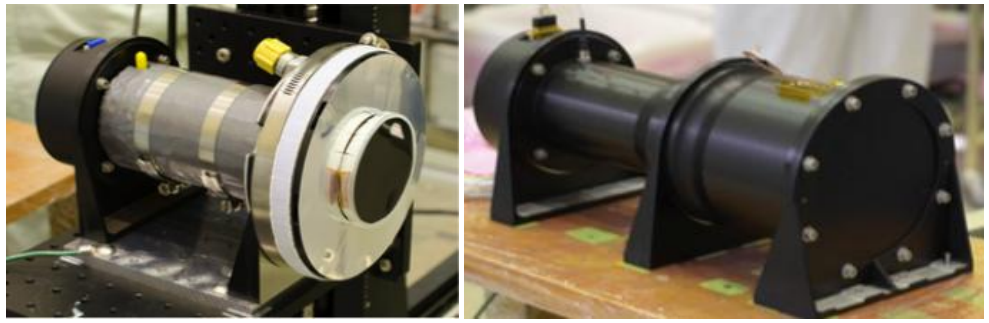


Short: 51 (< 2.0 s)
Long: 324 (>= 2.0 s)

CGBM detector

Hard X-ray Monitor
7 – 1000 keV

Soft Gamma-ray Monitor
40 keV – 20 MeV



Searched for electromagnetic counterparts of GW events in O4.

	Detection (SNR>=7)	No detection	HV off	Outside of FOB
O4a	0	44	37	4
O4b	1*	51	47	7
O4c	0	8	7	2
O4 total	**1**	**103**	**91**	**13**

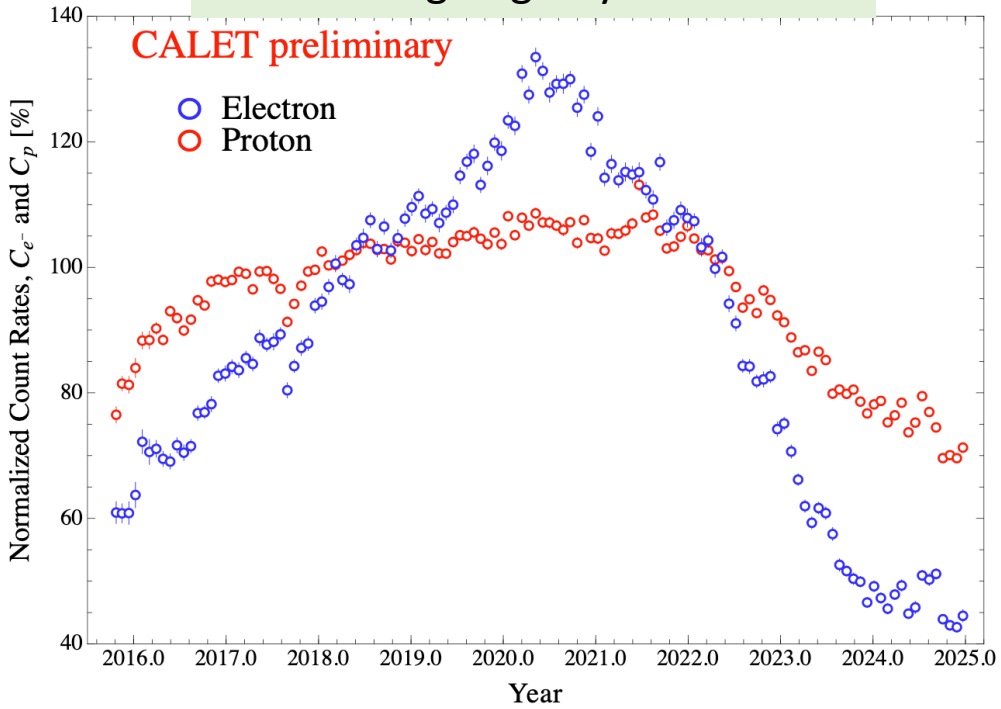
As of the end of April 2025, no GW candidates.

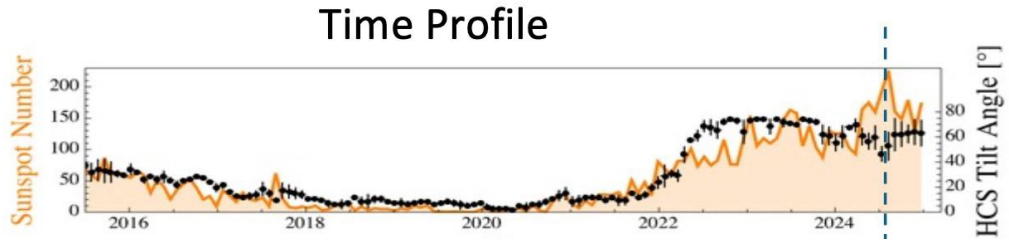
* solar event coincided with S241122a

Charge-sign Dependent Solar Modulation

PRL 130, 211001 (2023)
ICRC 2025 Update

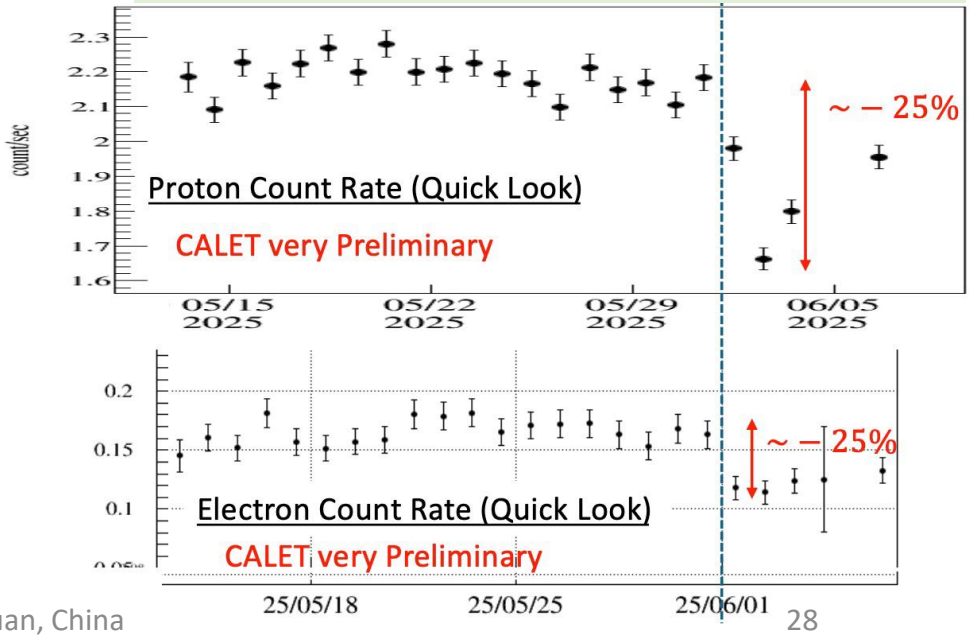
electron and proton count rates at an average rigidity of 3.8 GV





- CALET have been recorded the count rates of proton/electron >1GeV in the past 10 years including the solar minimum and the solar maximum.
- We have observed a clear charge-sign dependence of the solar modulation of galactic cosmic-rays and have succeeded in reproducing variations with a numerical drift model.

Forbush decrease observed in Jun. 2025



Summary

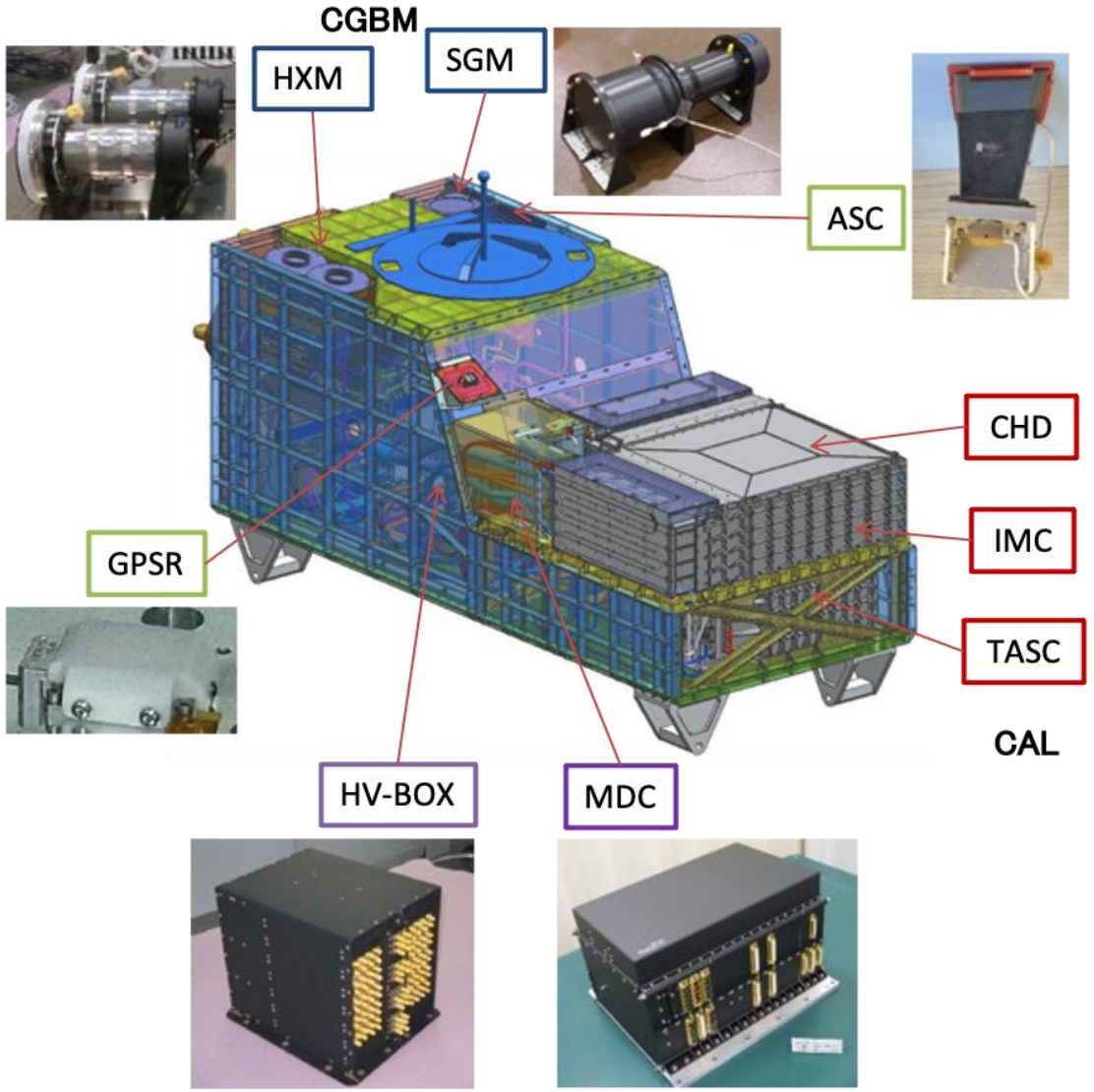
- CALET has been running stably for 10 years after the launch in Aug. 2015.
- HE trigger operation for >3368days with >86% live time.
- Total number of >GeV triggers ~5billion.
- We have achieved the following observations:
  - Cosmic-ray spectra: electron/proton/He/B/C/O/Fe/Ni/more
  - Solar modulation/diffuse and point source gamma-ray/GRB/GW follow up.
- New results:
  - Ti/Cr/Fe (PRL 135, 021002 (2025))
  - UH (14<=Z<=44) (APJ 988:148 (2025)
- Extended operations has been approved by JAXA/NASA/ASI through 2030.

We greatly appreciate JAXA staff for great support of the CALET operations at the TKSC of JAXA!

Backup

Overview of CALET Payload

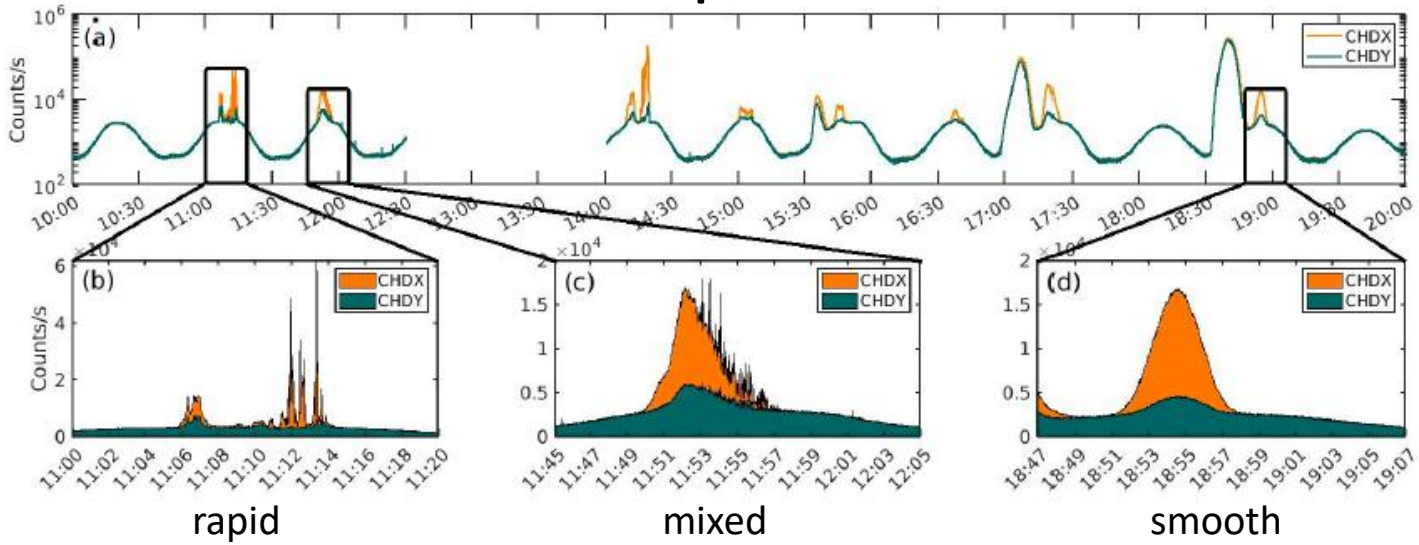
CAL
▪ Charge Detector (CHD) ▪ Imaging Calorimeter (IMC) ▪ Total Absorption Calorimeter (TASC)
CGBM
▪ Hard X-ray Monitor (HXM) x 2 $LaBr_3$: 7keV～1MeV ▪ Soft γ-ray Monitor (SGM) BGO ： 100keV～20MeV
Data Processing & Power Supply
▪ Mission Data Controller (MDC) CPU, telemetry, power, trigger etc. ▪ HV-BOX (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）



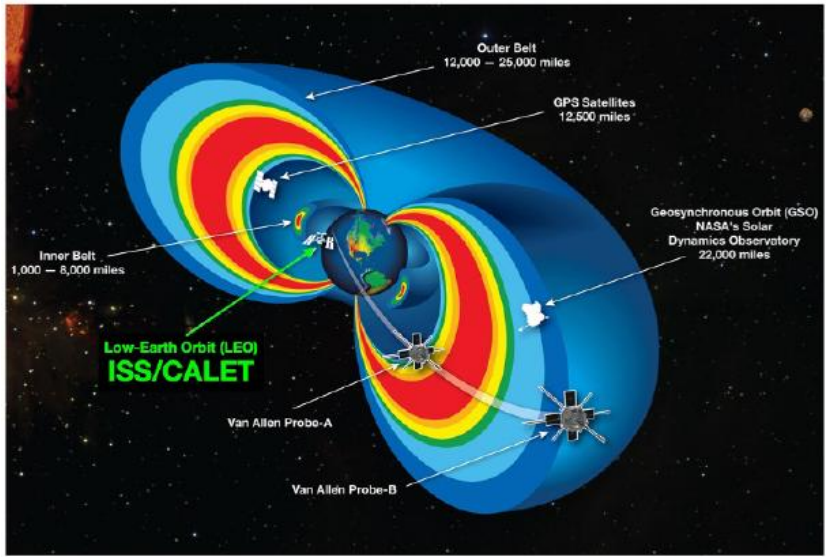
Space Weather Transients

- Objectives of CALET include continuous monitoring of space-weather phenomena in the LEO radiation environment, including relativistic electron precipitation (REP) from the outer Van Allen Belt
- REP drivers were investigated in magnetically conjugate observations by CALET and Van Allen Probes, showing the role of wave scattering and the contribution of EMIC-wave driven precipitation to radiation-belt losses (Bruno et al., 2021†; Blum et al., 2024‡)

Relativistic Electron Precipitation Events with CALET



CALET and Radiation Belt Science Probes (RBSP)



- An automated algorithm based on machine-learning techniques was implemented to identify and classify the REP events collected during >9 years of the mission (Vidal-Luengo et al, 2024a•)
- The large statistical sample allowed to investigate the contribution of REP to the radiation belt dropouts, and the correlations with solar-wind/geomagnetic drivers (Freund et al., 2024*)
- The occurrence of REP events was found to exhibit a semi-annual variation (peaking at equinoxes), in agreement with the temporal periodicity of outer-belt electron intensities (Vidal-Luengo et al, 2024b^)