CALETによる中・重元素のスペクトル観測

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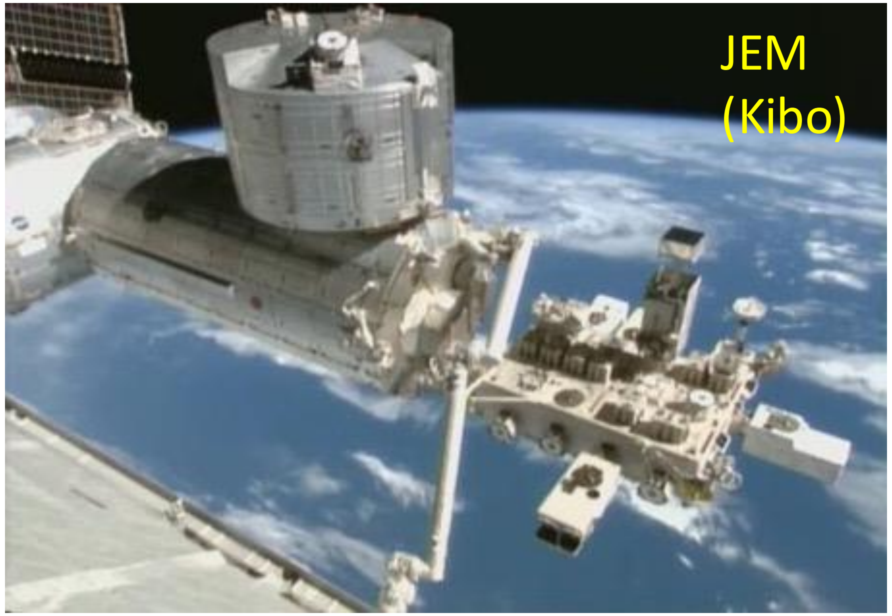
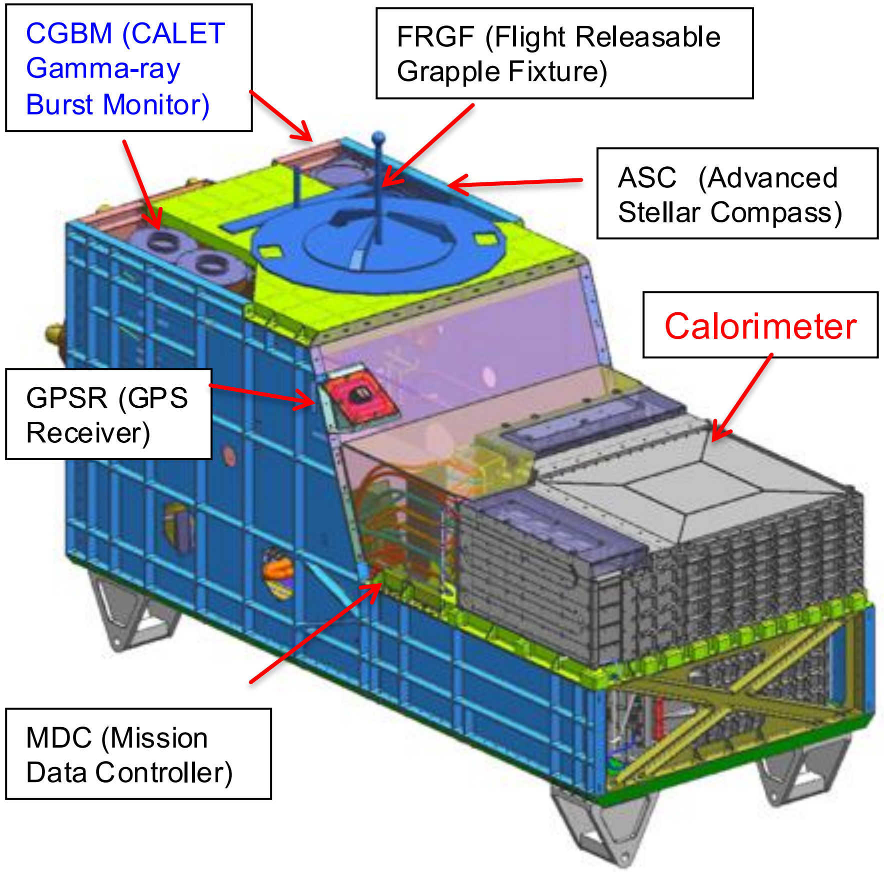
The CALET Payload

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

HTV(Kounotori)-5



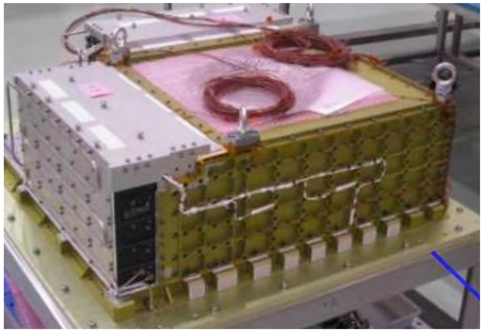
- Mass: 612.8 kg (JEM Standard Payload)
- Size: 1850mm(L) × 800mm(W) × 1000mm(H)
- Power: 507 W（max）
- Telemetry: Medium 600 kbps (6.5GB/day) / Low 50 kbps



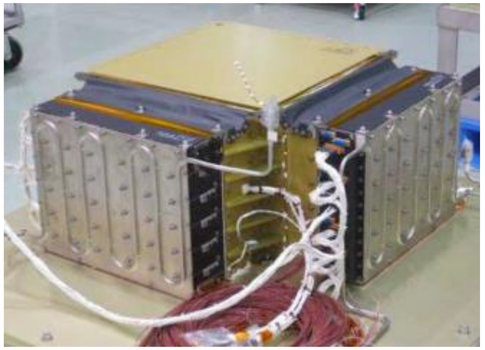
Overview of the CALET Calorimeter

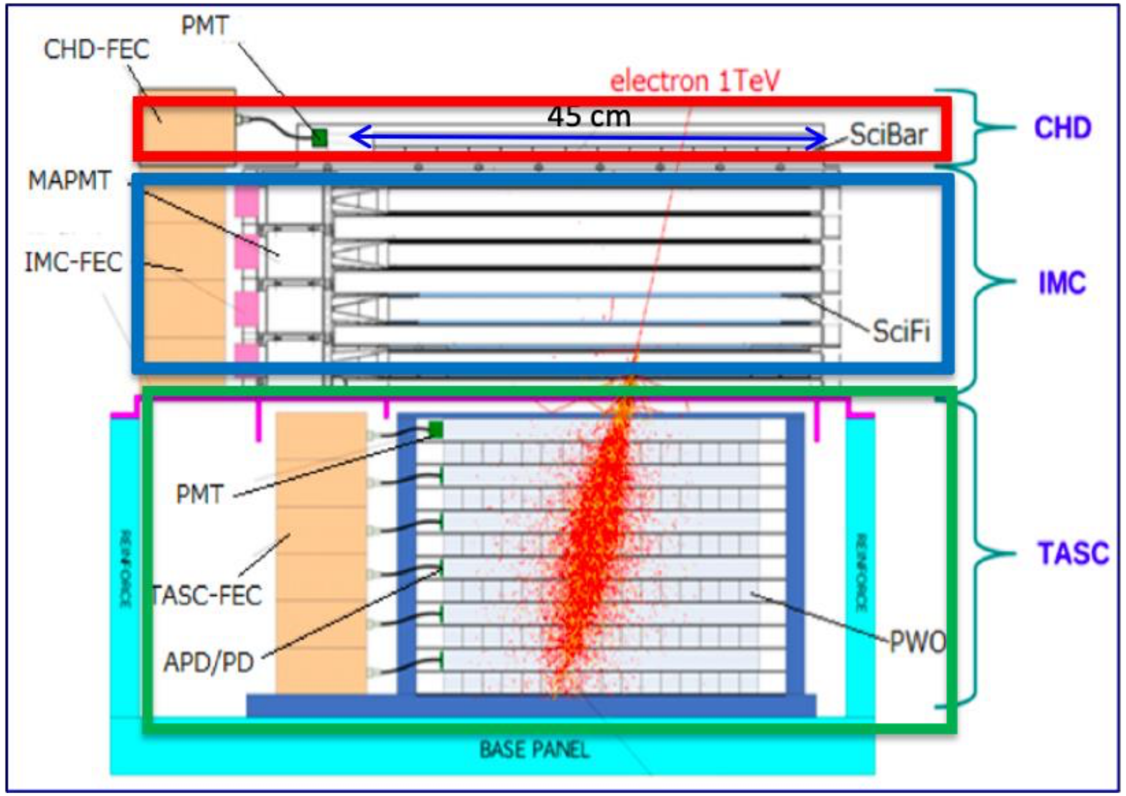
A 30-radiation length deep calorimeter designed to detect electrons and gamma-rays to 20 TeV and cosmic rays up to 1 PeV

CHD/IMC



TASC





CHD – Charge Detector

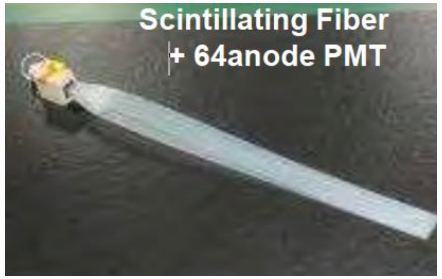
- 2 layers x 14 plastic scintillating paddles
- **single element charge ID** from p to Fe and above ($Z = 40$)
- charge resolution ~0.1-0.3 e

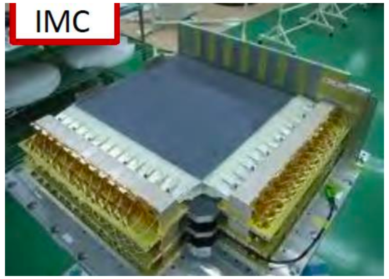
IMC – Imaging Calorimeter

- Scifi. + tungsten absorbers: **3 X_0**
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **tracking** (~0.1° angular resolution) + **Shower imaging**
- **angular resolution:** 0.2° for gamma-rays > ~50 GeV

TASC – Total Absorption Calorimeter

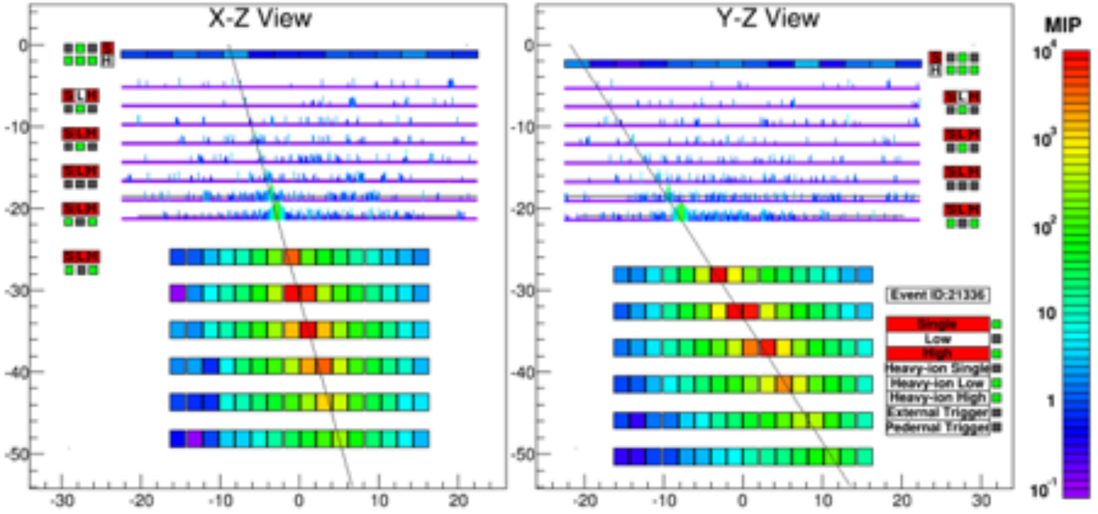
- 6 x 2 x 16 lead tungstate ($PbWO_4$) logs: **27 X_0, 1.2 λ_I**
- **energy resolution:** ~2 % (>10GeV) for e , γ
  ~30-35% for p, nuclei
- **e/p separation:** ~10^{-5}



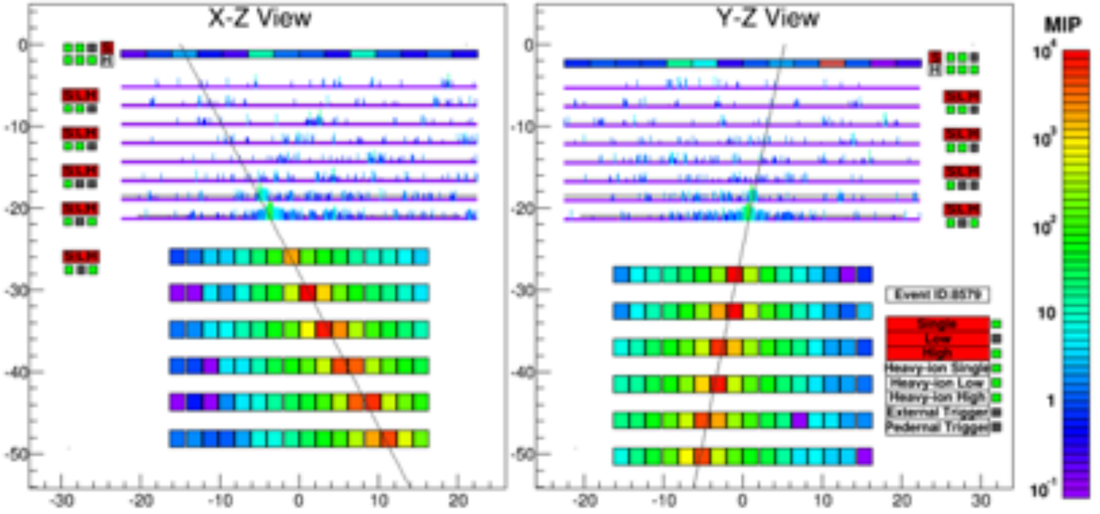


Examples of Event Candidates

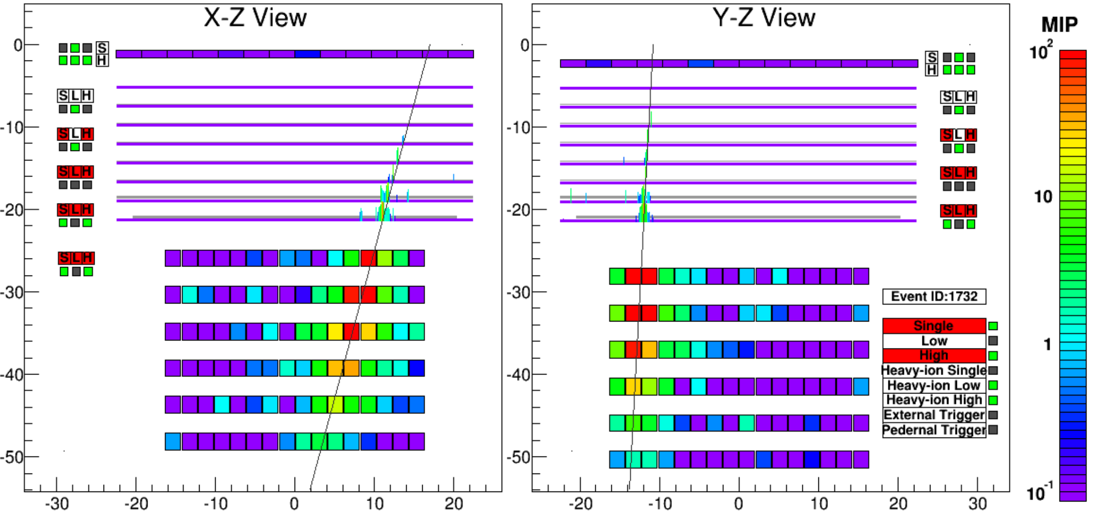
Electron, E=3.05 TeV



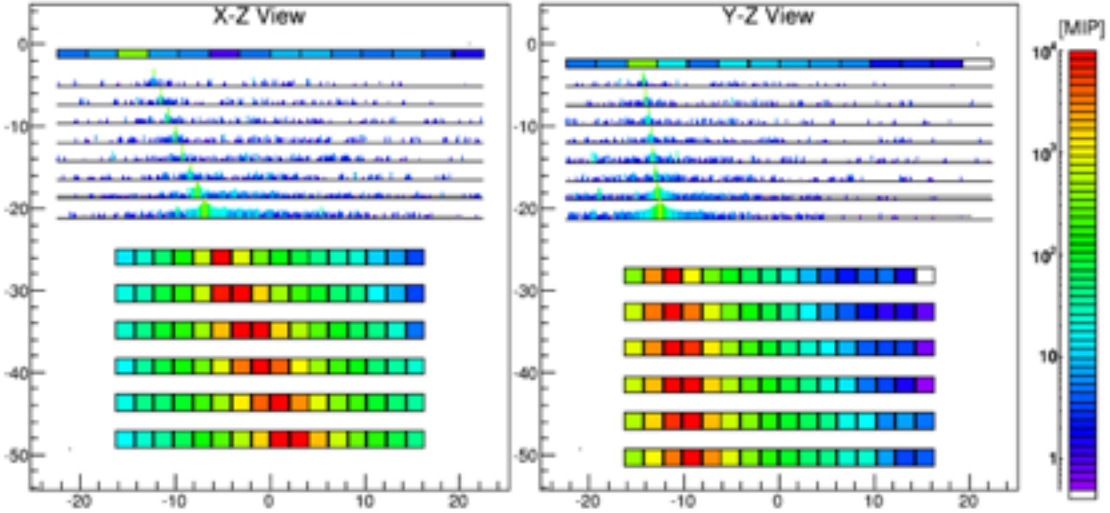
Proton, E_{TASC}=2.89 TeV



Gamma-ray, E=44.3 GeV

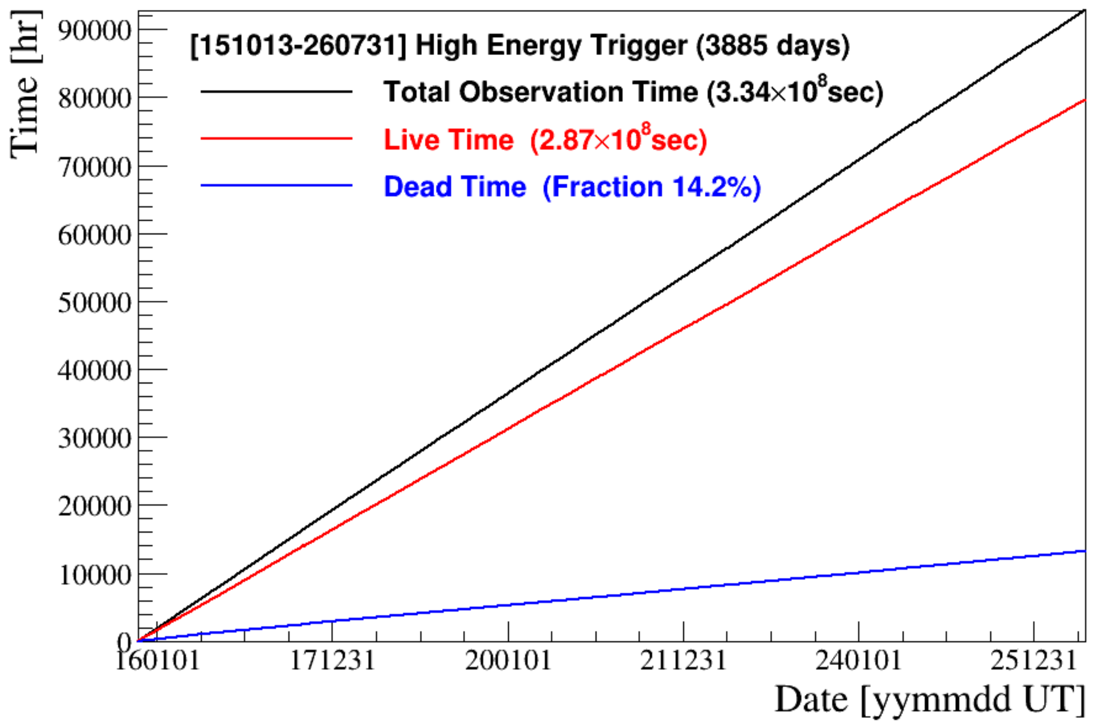


Iron, E_{TASC} =9.3 TeV

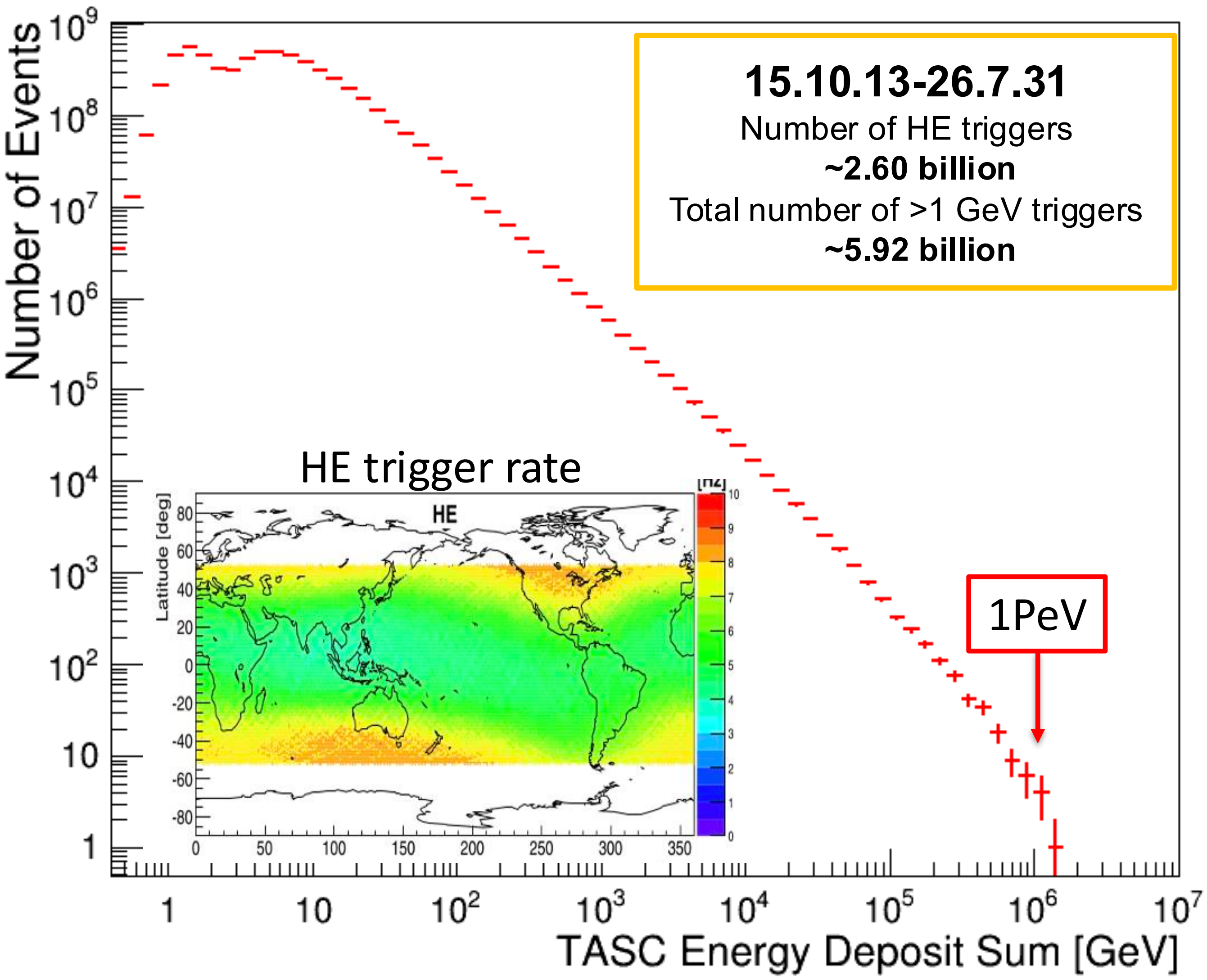


Orbital Operation for the first 11 years

High-energy trigger (> 10 GeV) statistics:
- Orbital operations : **3945 days** as of July 31, 2026
- Observation time : **3.34×10^8 sec**
- Live time fraction: **～86%**
- Total number of triggers: **~5.92×10^9**



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



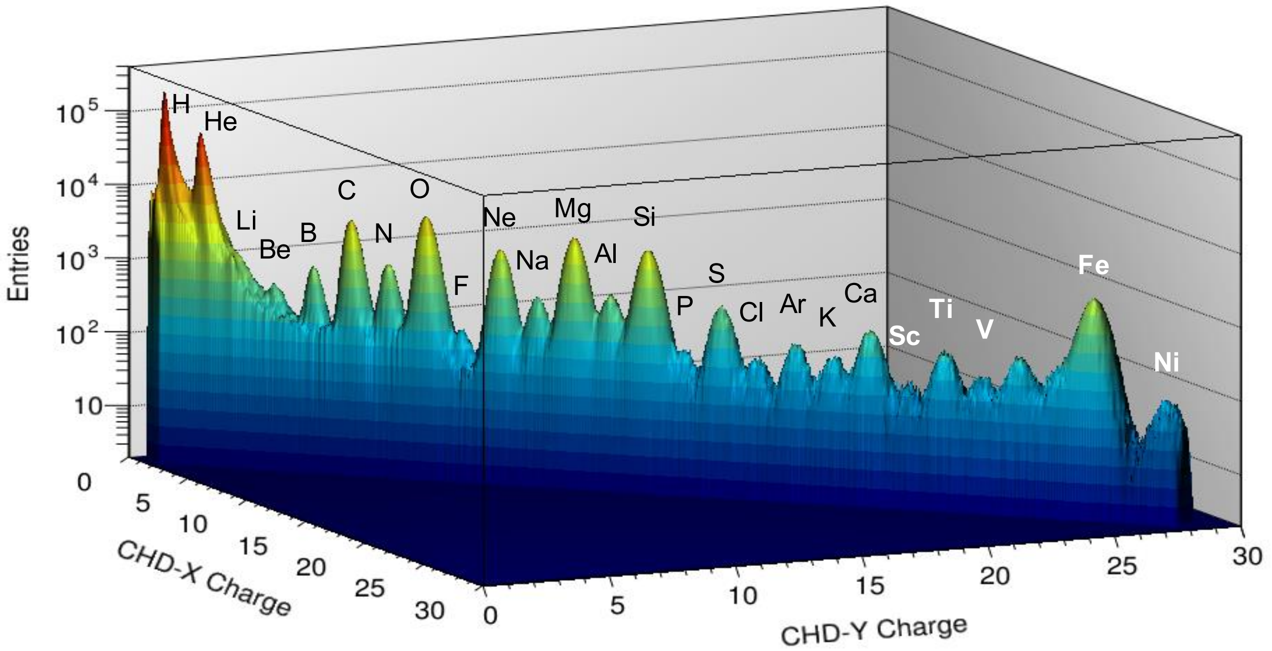
Capabilities of nuclei measurements

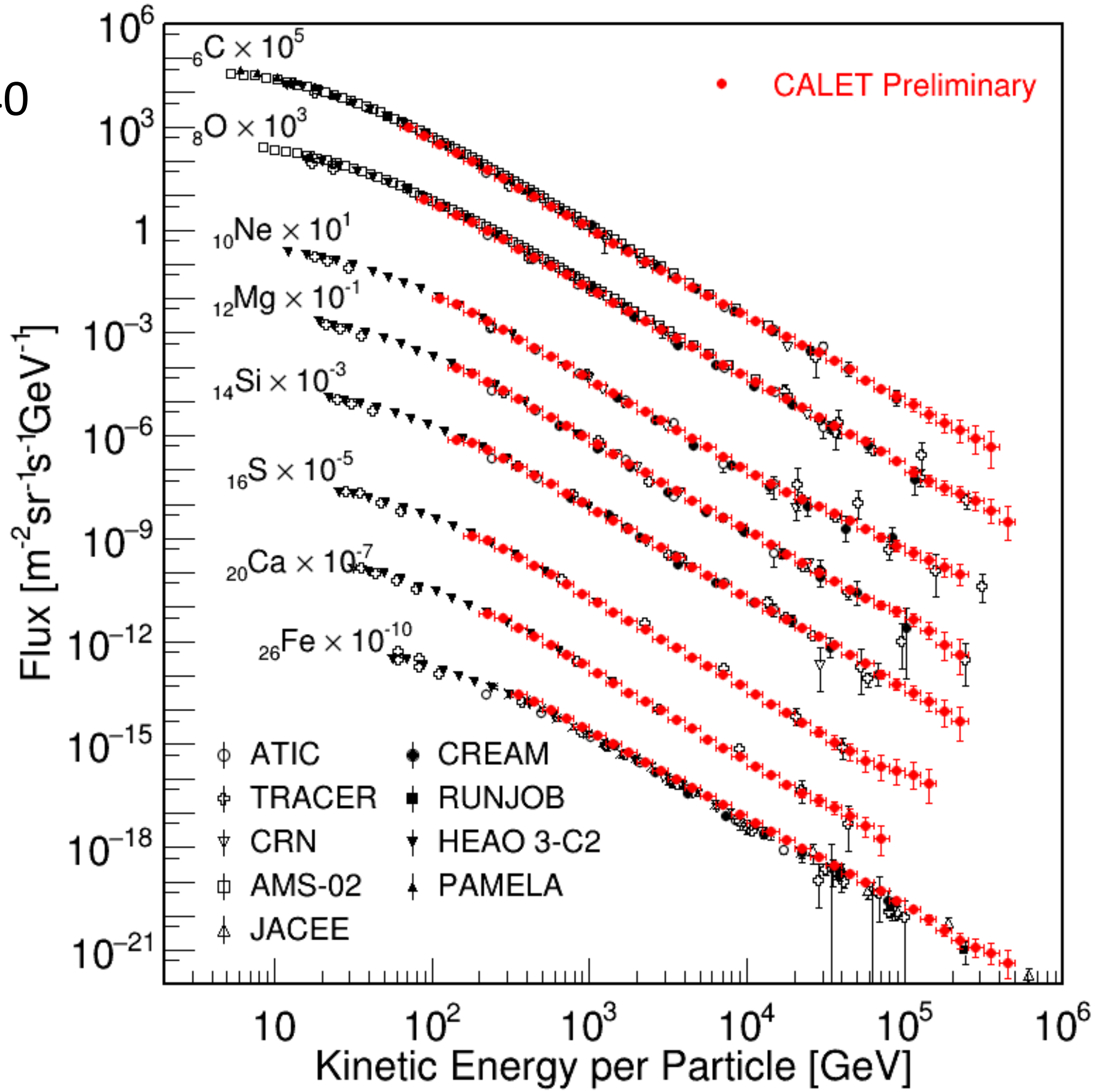
Charge measurement

- CHD enables individual charge identification from Z=1 – 40
- Charge resolution ranges from 0.15*e* to 0.3*e* in p - Fe

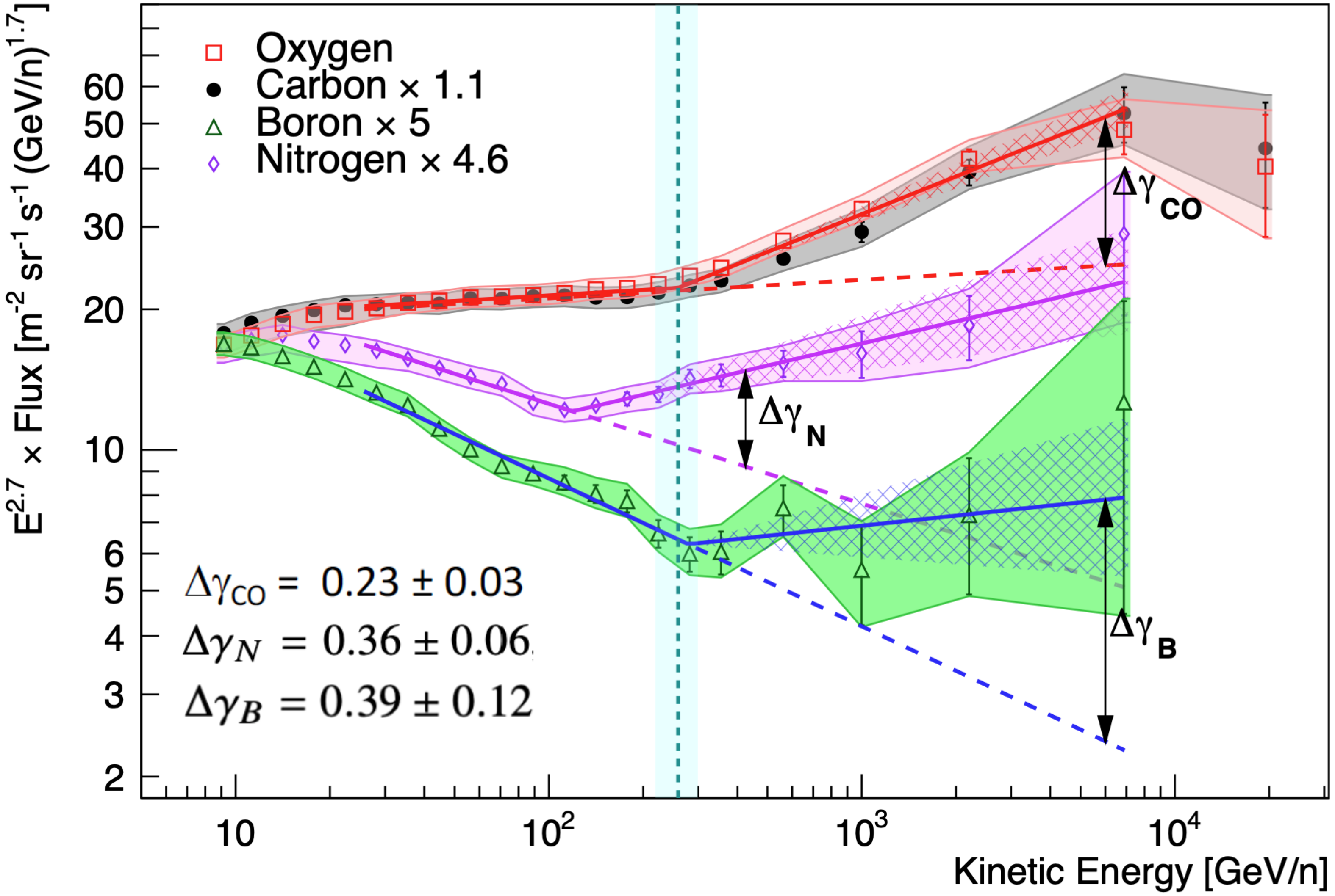
Energy measurement

- High dynamic range read out from 1 GeV to 1 PeV
- Energy resolution for nuclei: 30 – 35%



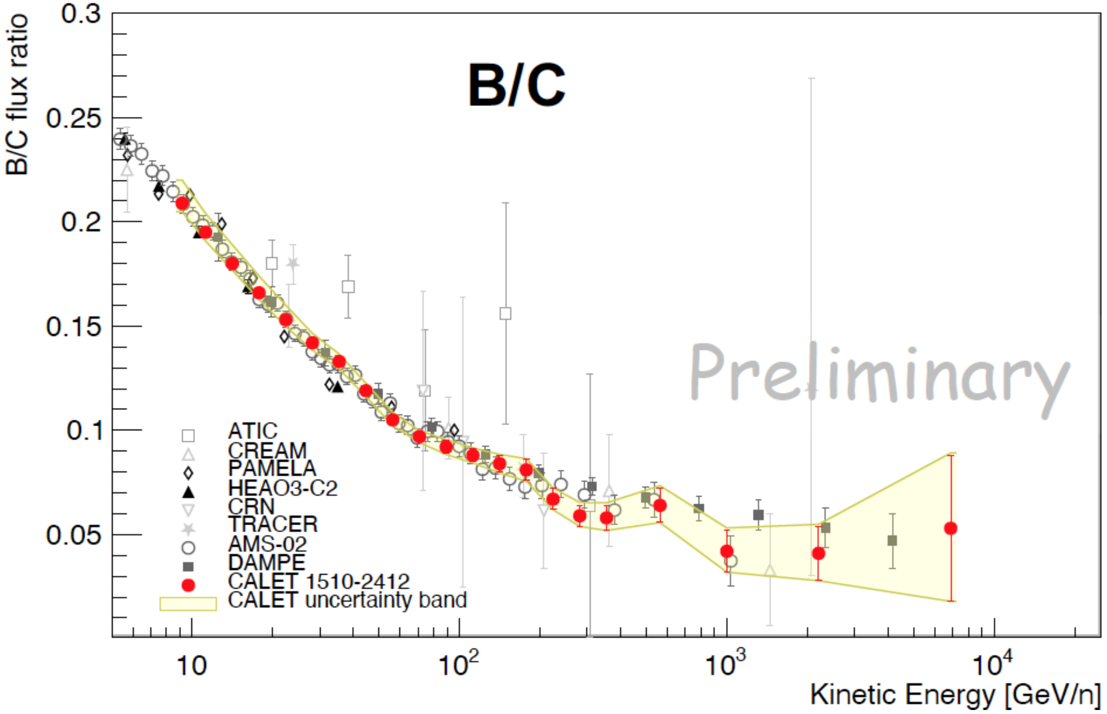


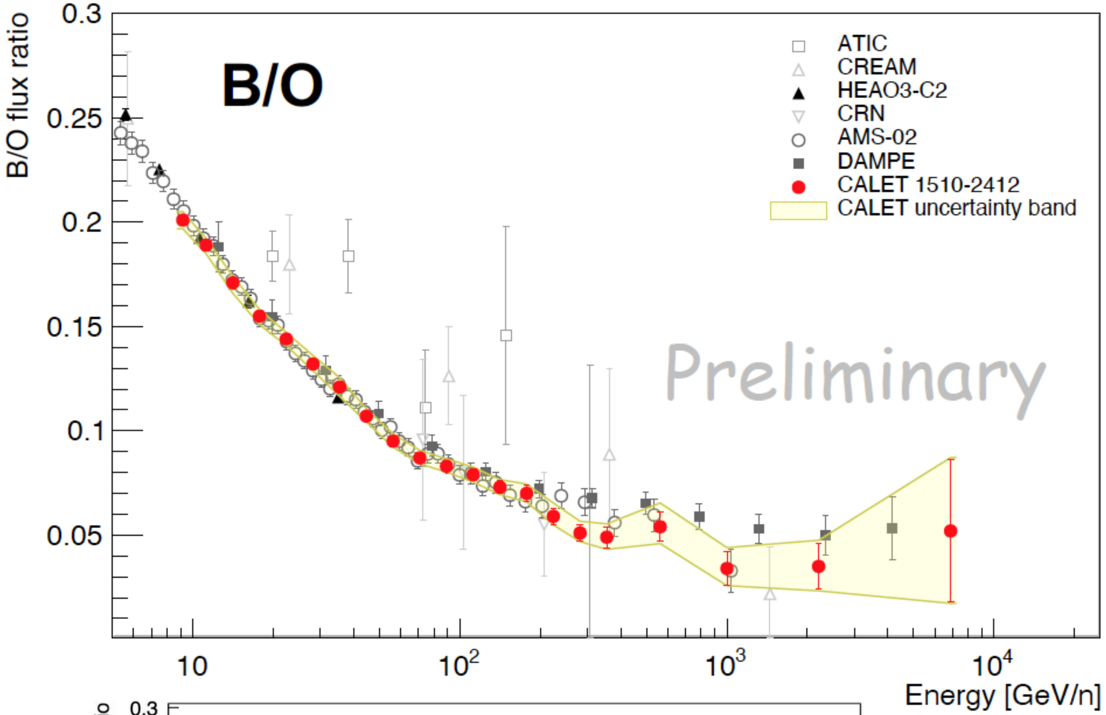
Spectral analysis for BCNO



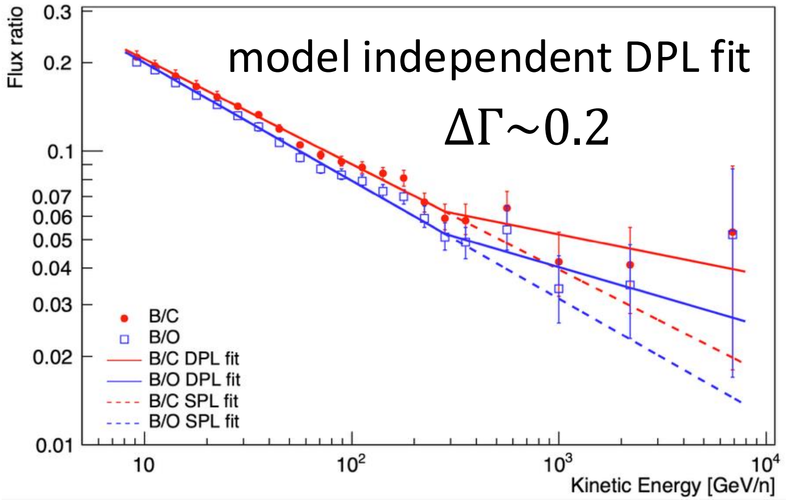
- C and O fluxes harden similarly above 200 GeV/n (significance 7σ)
- B hardens ~twice as much as C, O (significance 2.5σ) as expected from propagation of a purely secondary element.
- N consistent with a mixed composition of primary and secondary: hardens more than C, O but less than B, (significance 5σ) with hardening starting at lower energy than for C, O and B.

Boron flux ratios

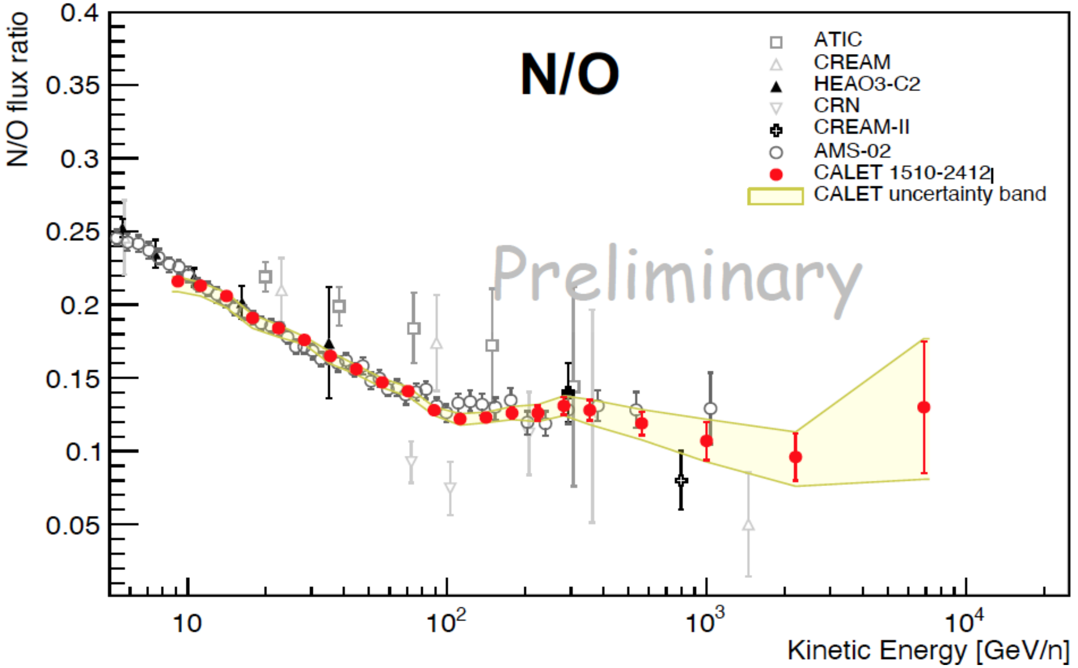


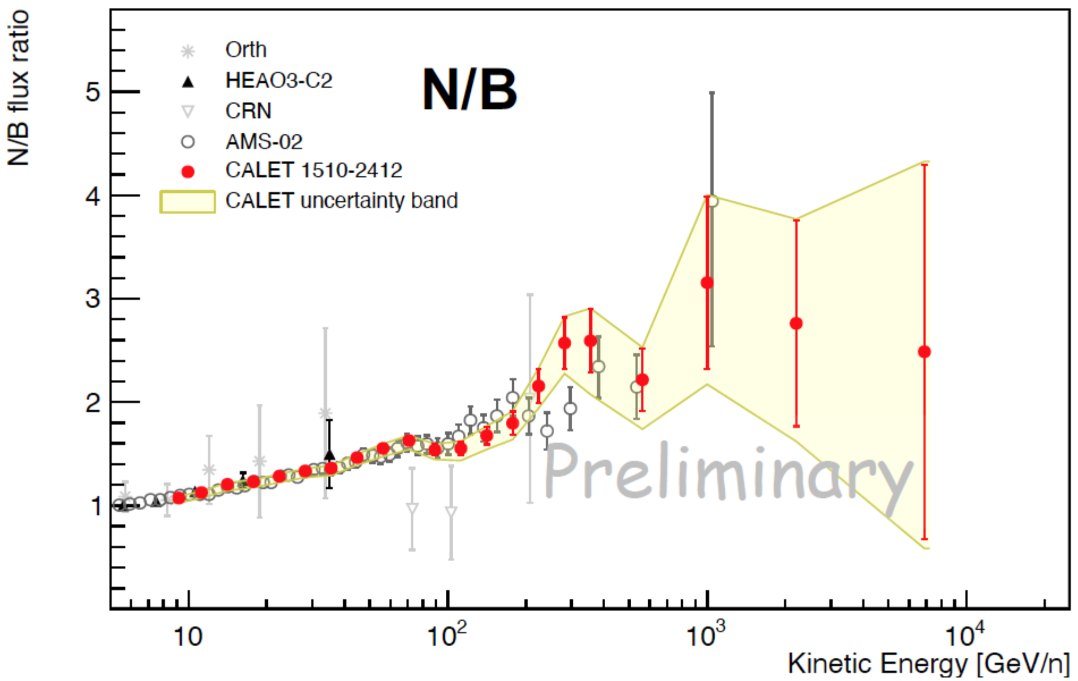


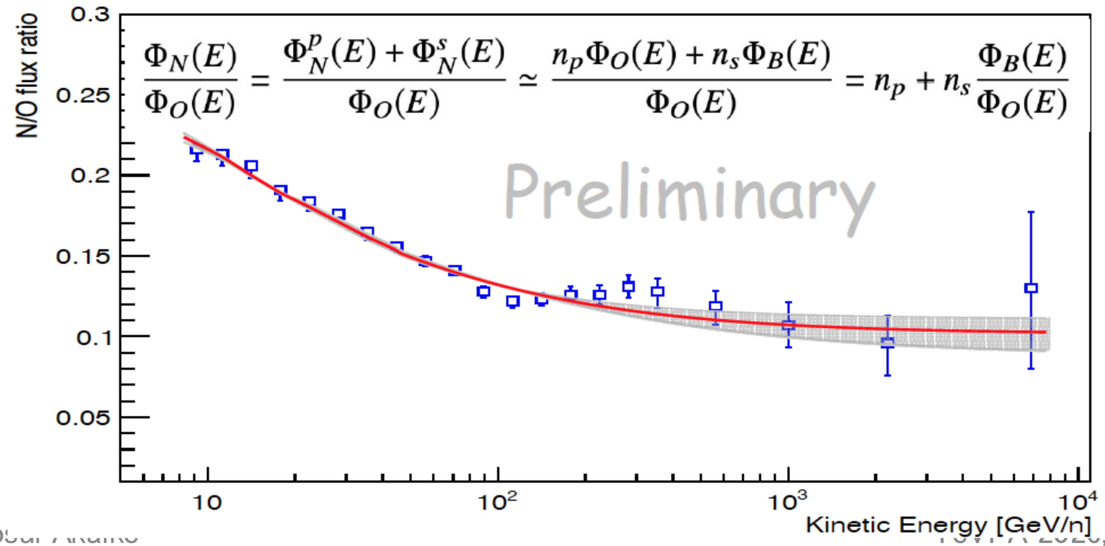
- Observe of a flattening of B/C and B/O with energy
- The observed flattening at TeV/n might be due to a change in the spectral index of δ of the diffusion coefficient or the presence of source grammage (~1.3 g/cm^2)



Nitrogen flux ratios



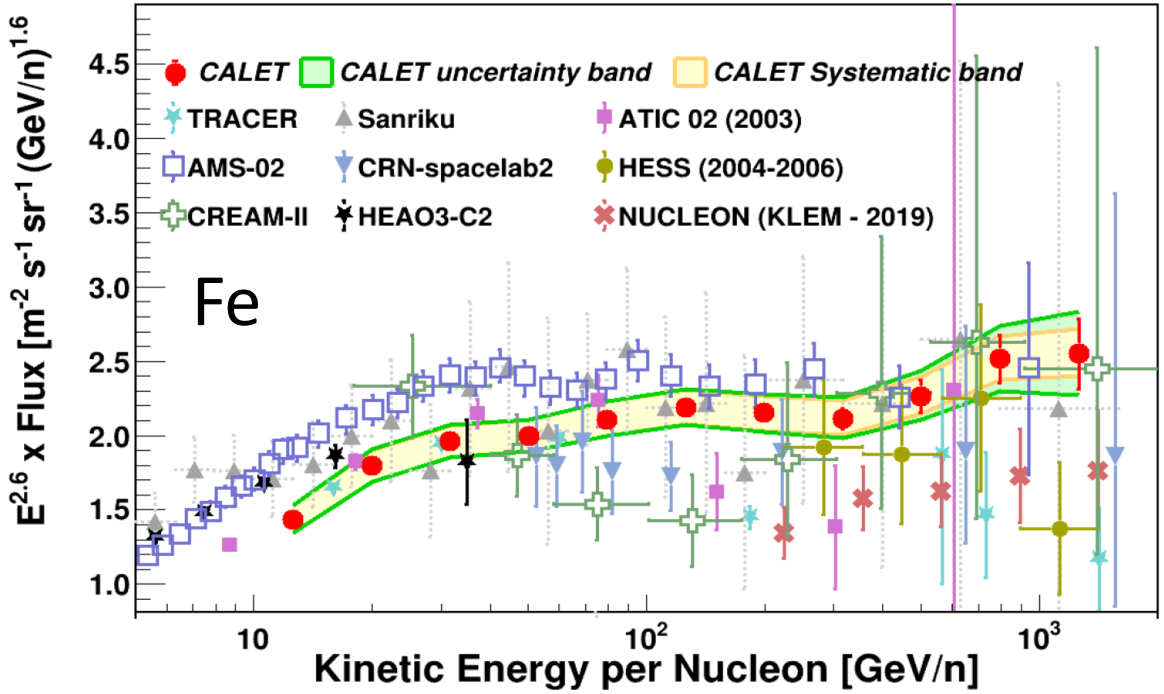


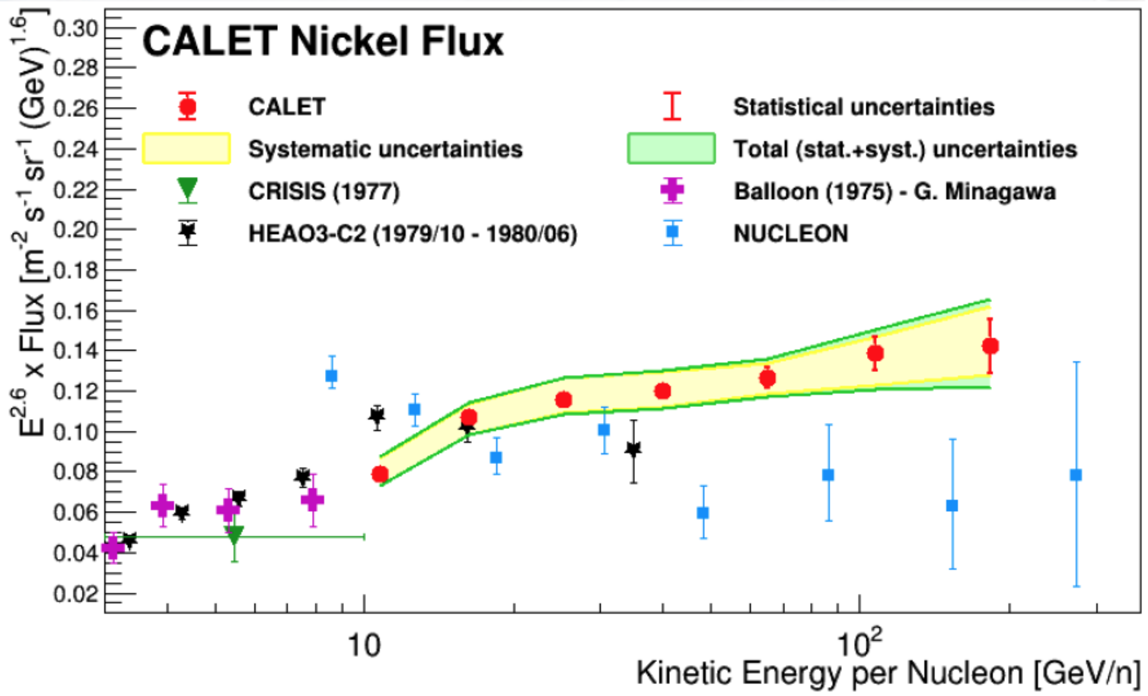


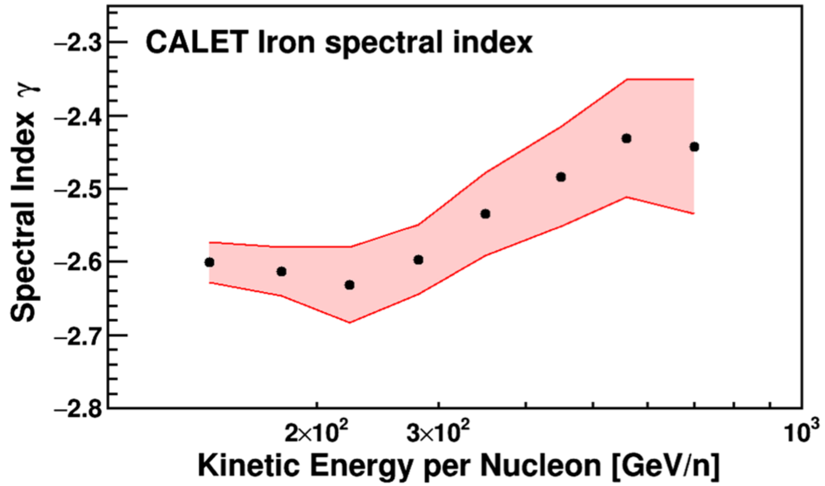
- N/O ratio decreases with E and flattens above 100 GeV/n, while N/B continues to rise
  - ⇨ N components: primary $\Phi_N^P = n_P \Phi_O$
  - \+ secondary $\Phi_N^S = n_S \Phi_B$

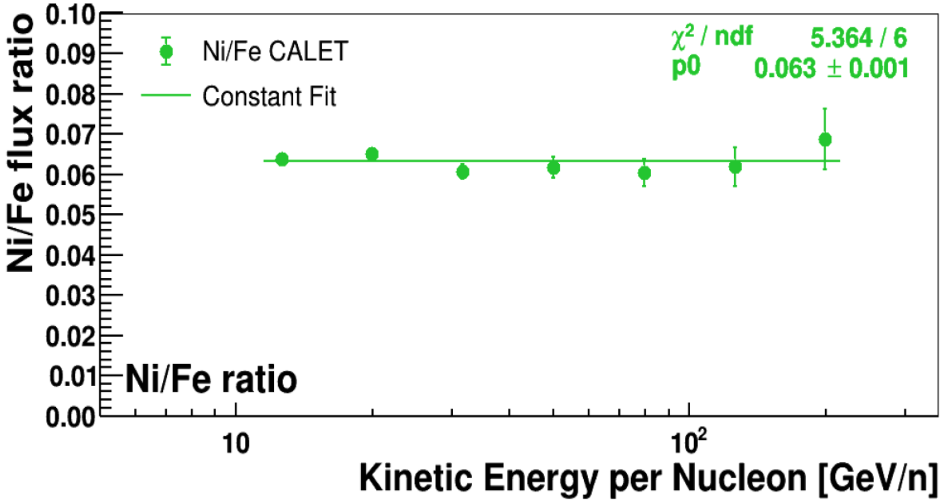
$$\rightarrow n_P = 0.074 \pm 0.003\,(\text{stat}) \pm 0.02\,(\text{sys})$$
$$n_S = 0.74 \pm 0.02\,(\text{stat}) \pm 0.05\,(\text{sys})$$

Energy spectra of Fe and Ni

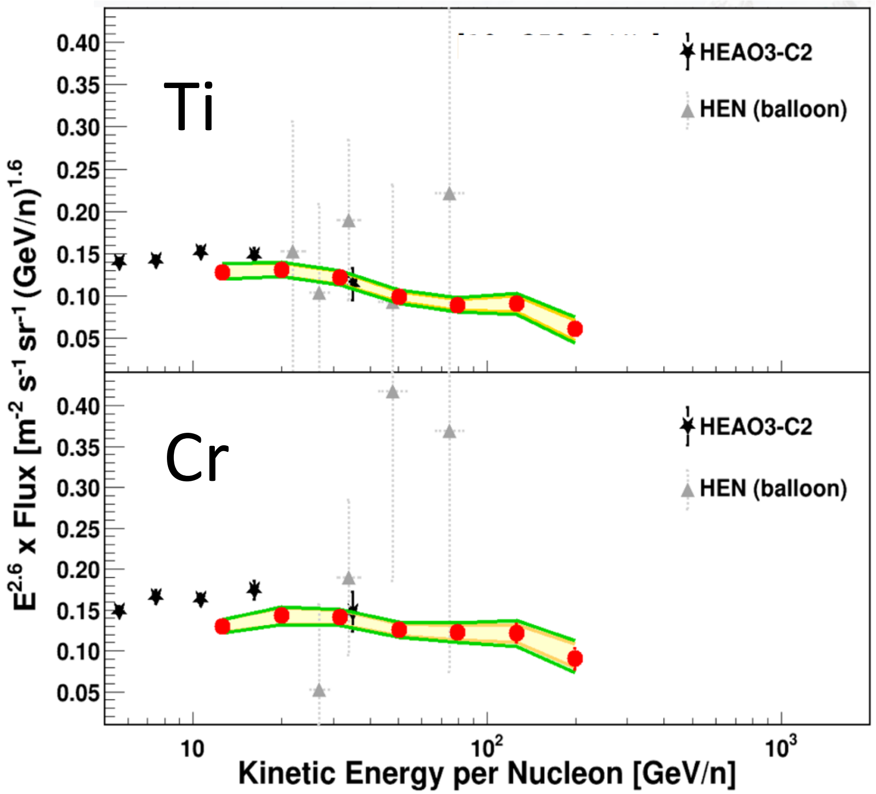


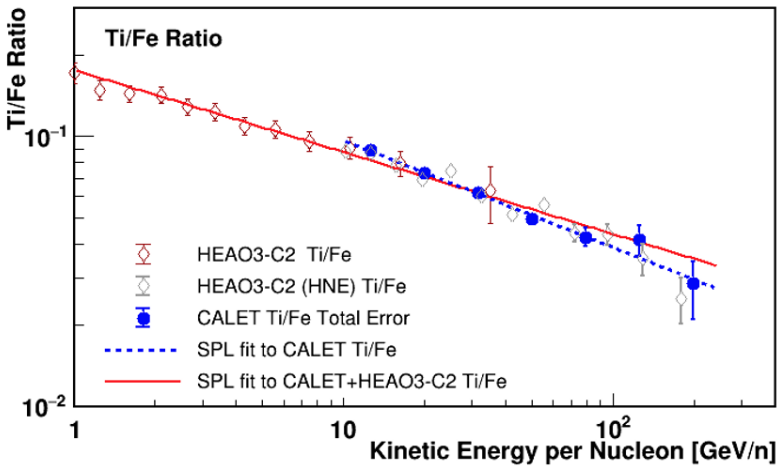


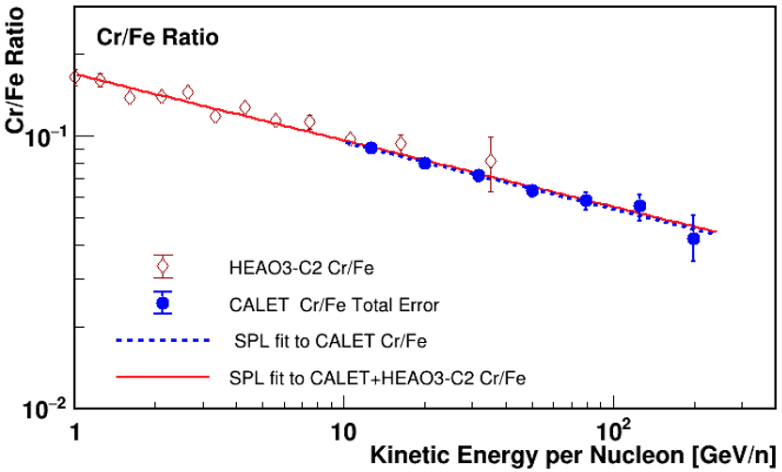




Energy spectra of Ti and Cr, and their ratios to Fe







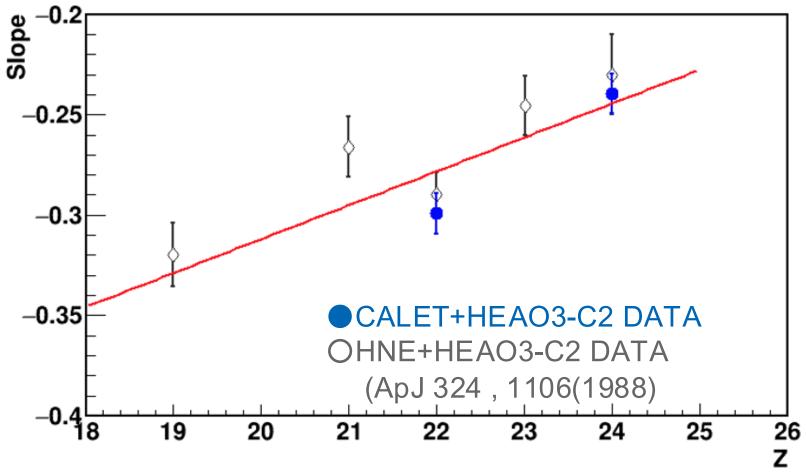
SPL fit for CALET data

$$\gamma_{\mathrm{Ti/Fe}} = -0.39 \pm 0.03, \chi^2/\mathrm{ndf} = 1.9/5$$
$$\gamma_{\mathrm{Cr/Fe}} = -0.24 \pm 0.03, \chi^2/\mathrm{ndf} = 0.8/5$$

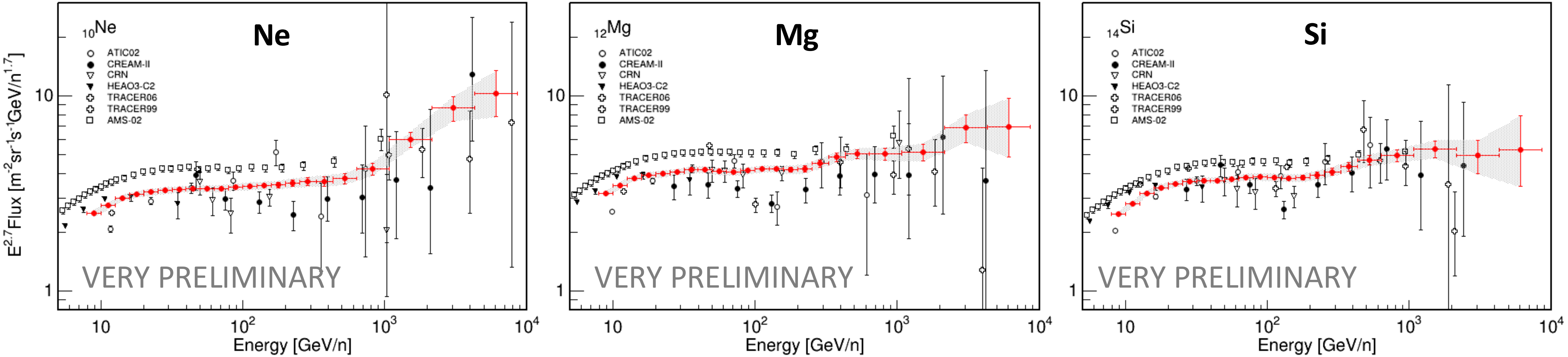
SPL fit for CALET + HEAO3-C2

$$\gamma_{\mathrm{Ti/Fe}} = -0.30 \pm 0.01, \chi^2/\mathrm{ndf} = 15/17$$
$$\gamma_{\mathrm{Cr/Fe}} = -0.24 \pm 0.01, \chi^2/\mathrm{ndf} = 17/17$$

Dependence of the spectral indices of flux ratios to iron vs atomic number Z



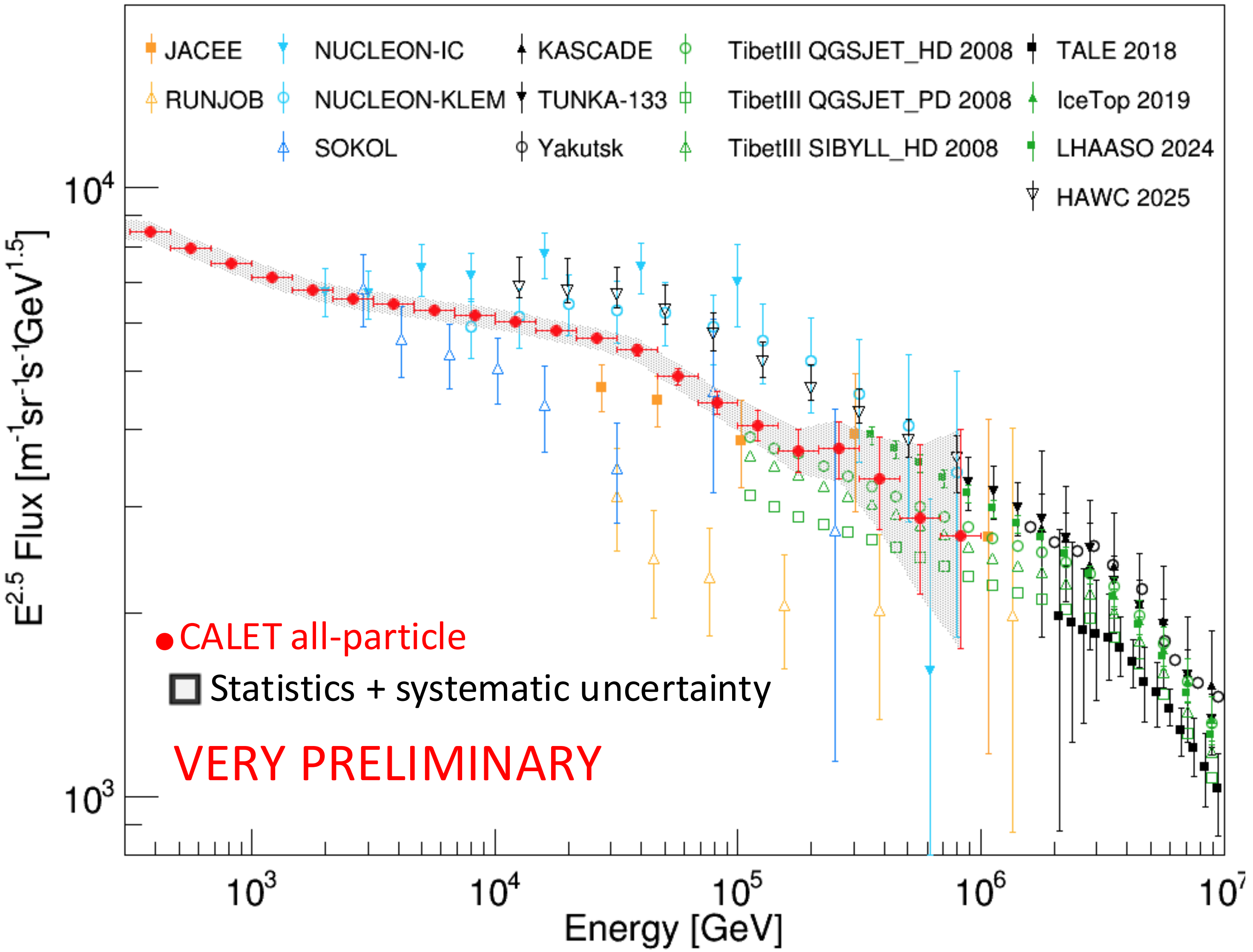
Ne, Mg, Si spectra



- The Ne, Mg, and Si spectra measured by CALET indicate spectral hardening above a few 100 GeV/n.
- The flux normalizations are lower than those measured by AMS-02, as also observed for other heavy nuclei.
- Pure ^{20}Ne, ^{24}Mg, and ^{28}Si compositions are assumed.
- The AMS-02 data are converted from rigidity to kinetic energy per nucleon assuming pure ^{20}Ne, ^{24}Mg, and ^{28}Si compositions

All-particle spectrum

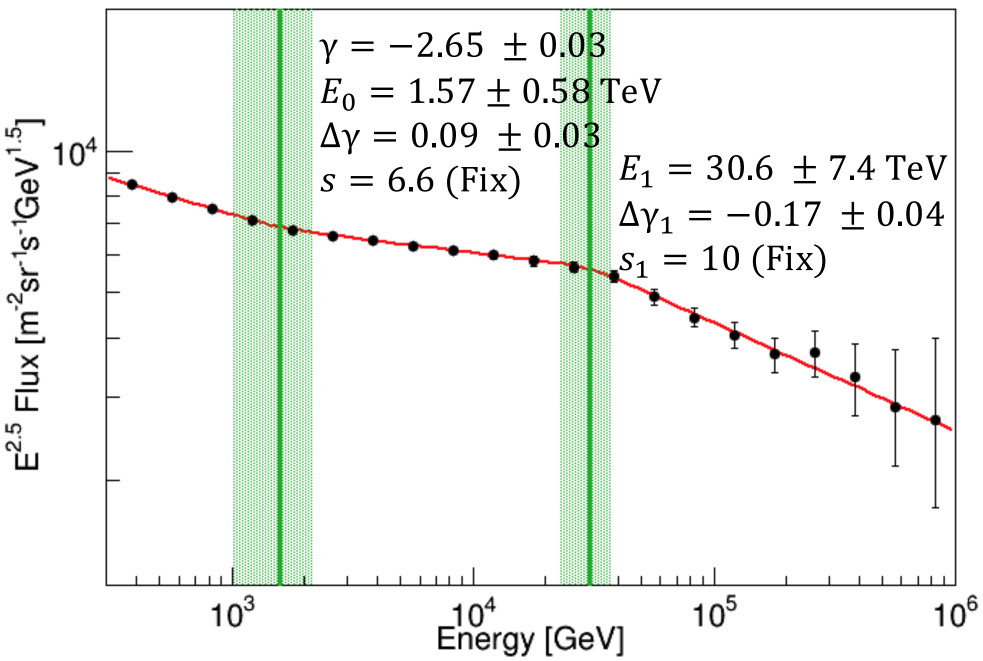
CALET closes the gap with indirect measurements from ground experiments



MC events are weighted to reproduce the fit results of each energy spectrum by CALET. The response matrix from MC is based on a weighted mixture of nuclei from Z = 1 to 28

Smoothly broken-power law fit:

$$\Phi(E) = C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left[1+\left(\frac{E}{E_0}\right)^{S}\right]^{\frac{\Delta\gamma}{S}}\left[1+\left(\frac{E}{E_1}\right)^{S_1}\right]^{\frac{\Delta\gamma_1}{S_1}}$$



Summary

- CALET has been operating stably since October 2015 for 11 years.
  - High dynamic range from MIPs to the PeV scale
  - Direct, high-precision measurements of cosmic-ray nuclei from proton to nickel
- CALET has precisely measured the energy spectra of individual cosmic-ray nuclei, extending the measurements beyond 100 TeV
  - In addition, to B, C, N, O, sub-Fe, and Fe, analysis of Ne, Mg, and Si are currently in progress
- A preliminary all-particle spectrum in the range of 316 GeV – 1 PeV has been derived by combining events over a wide charge range.
- Further refinement of systematic uncertainties is ongoing.
- Extended operations have been approved by JAXA, NASA, and ASI through the end of 2030.