CALETによる宇宙線原子核のエネルギースペクトルの観測

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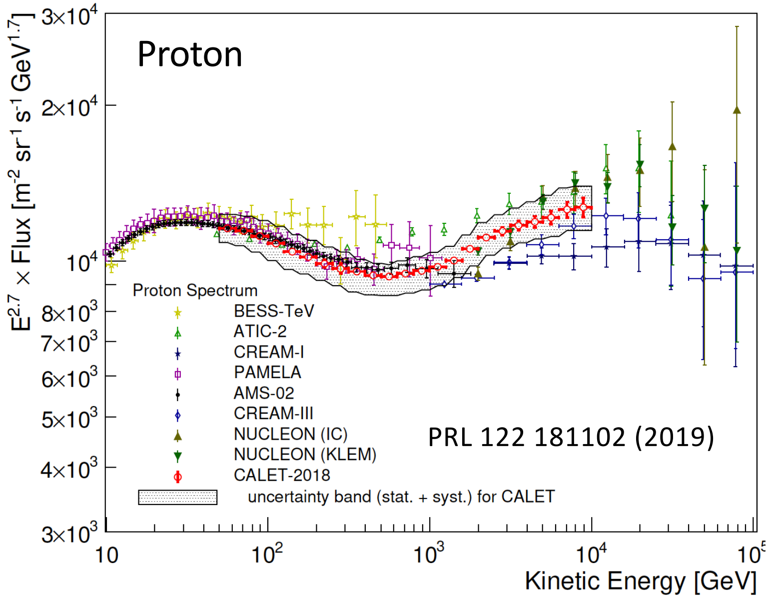
Energy Spectra of Galactic Cosmic Rays

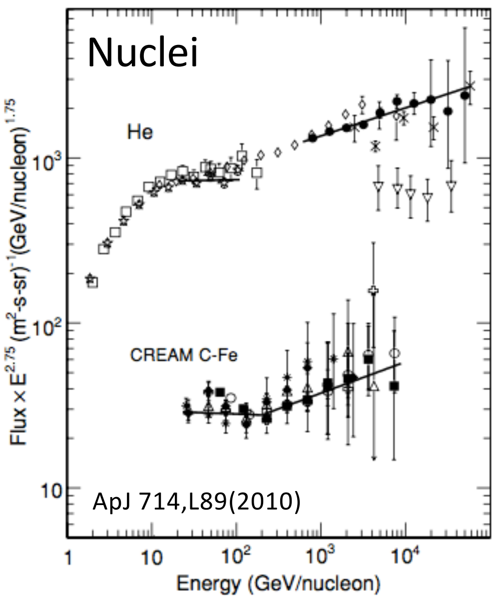
”Standard” model of galactic cosmic rays

- Diffusive shock acceleration via supernovae remnant
- Diffusion propagation in our Galaxy
  - Same power law spectra for all primary cosmic rays ($dN/dE \propto E^{-\gamma-\delta}$)
  - Acceleration limit proportional to the charge (Ec 〜 60 Z TeV), etc.

Unexpected observation results

- Spectra of proton and nuclei break at R~300GV





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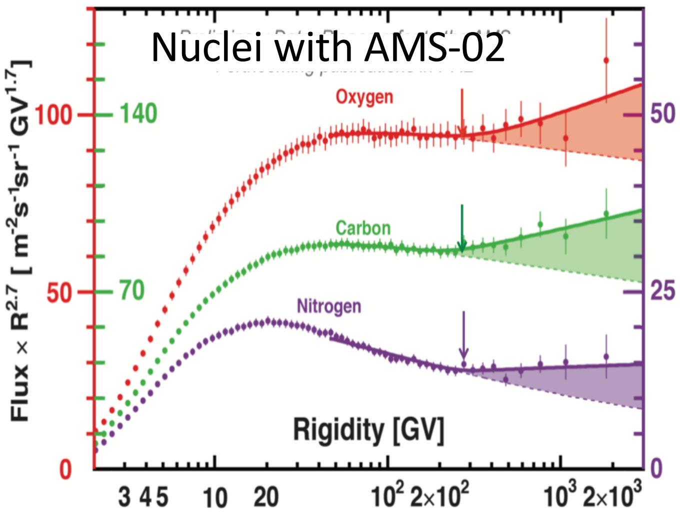
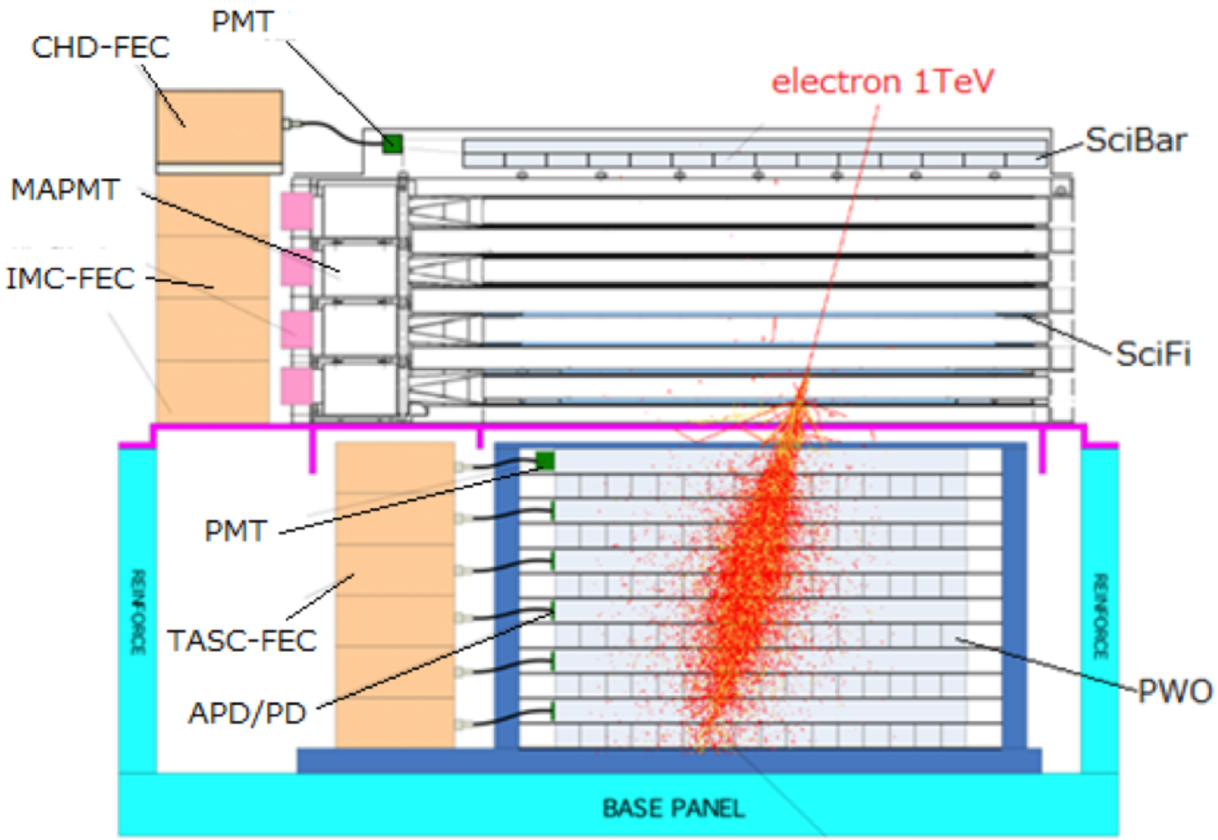


Instrument of CALET

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



<u>CHD: Charge Detector</u>

Charge measurements (Z=1-40)

- Plastic scintillator paddles 14 x (X, Y)
  Unit size: 32mm x 10 mm x 450 mm
  ΔZ/Z = 0.15 for C, 0.30 for Fe

<u>IMC: Imaging Calorimeter</u>

Arrival direction, Particle ID

- Scintillating fiber belts 448 x 16 layers
  Unit size: 1 mm^2 x 448 mm
- Tungsten plates 7 layers
  3 X_0 (=0.2 X_0 x 5 + 1.0 X_0 x 2)
  ΔX at CHD = 200μm, ΔZ/Z = 0.20 for C

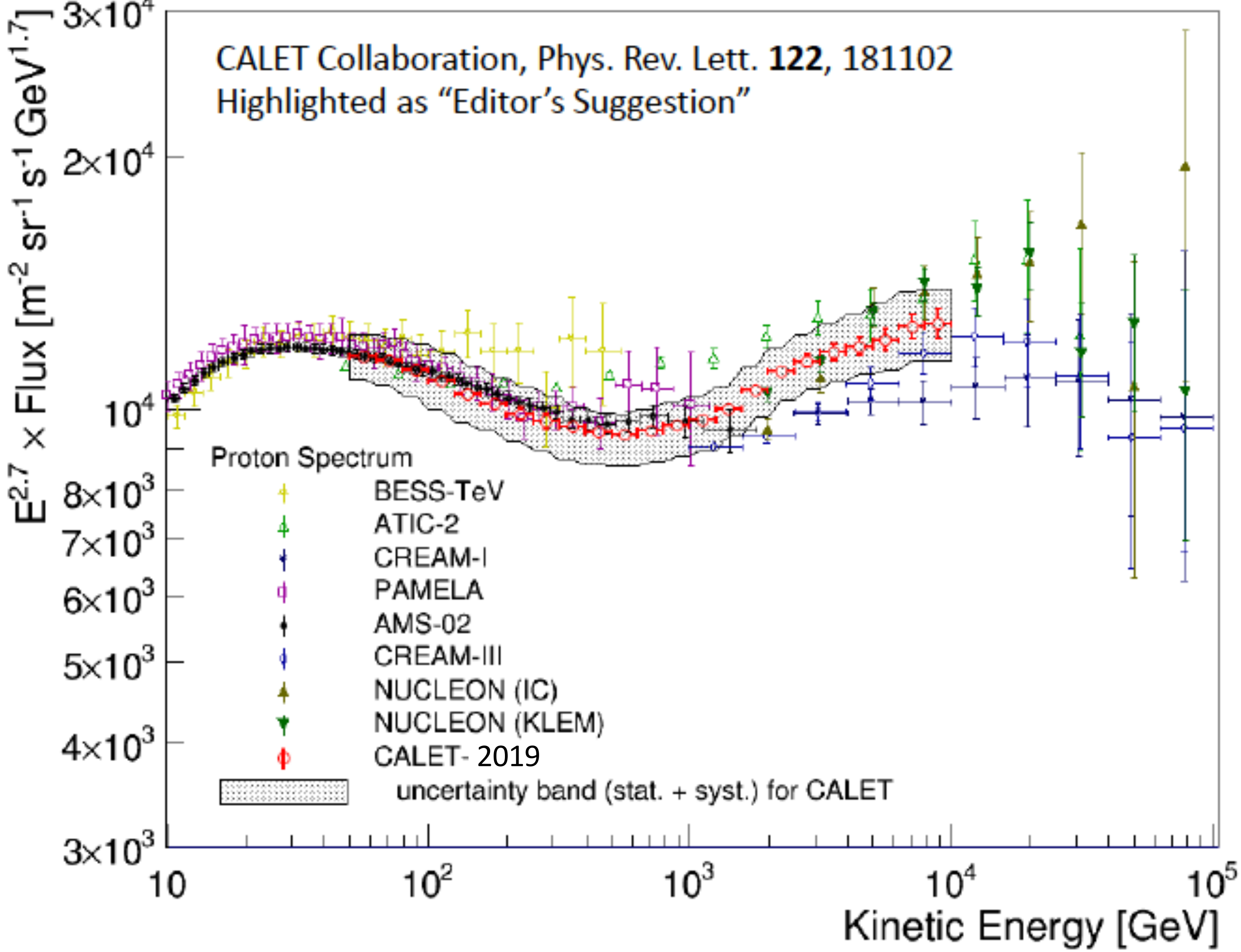
<u>TASC: Total Absorption Calorimeter</u>

Energy measurement, Particle ID

- PWO logs 16 x 12 layers
  Unit size: 19 mm x 20 mm x 326 mm
  27 X_0 for electrons
  1.2 interaction length for protons
  Dynamic range ; 1 – 10^6 MIP (1GeV – 1PeV)

Proton Spectrum

CALET Observations: Oct.13,2015- Aug.31,2018 (for 1,056 days)



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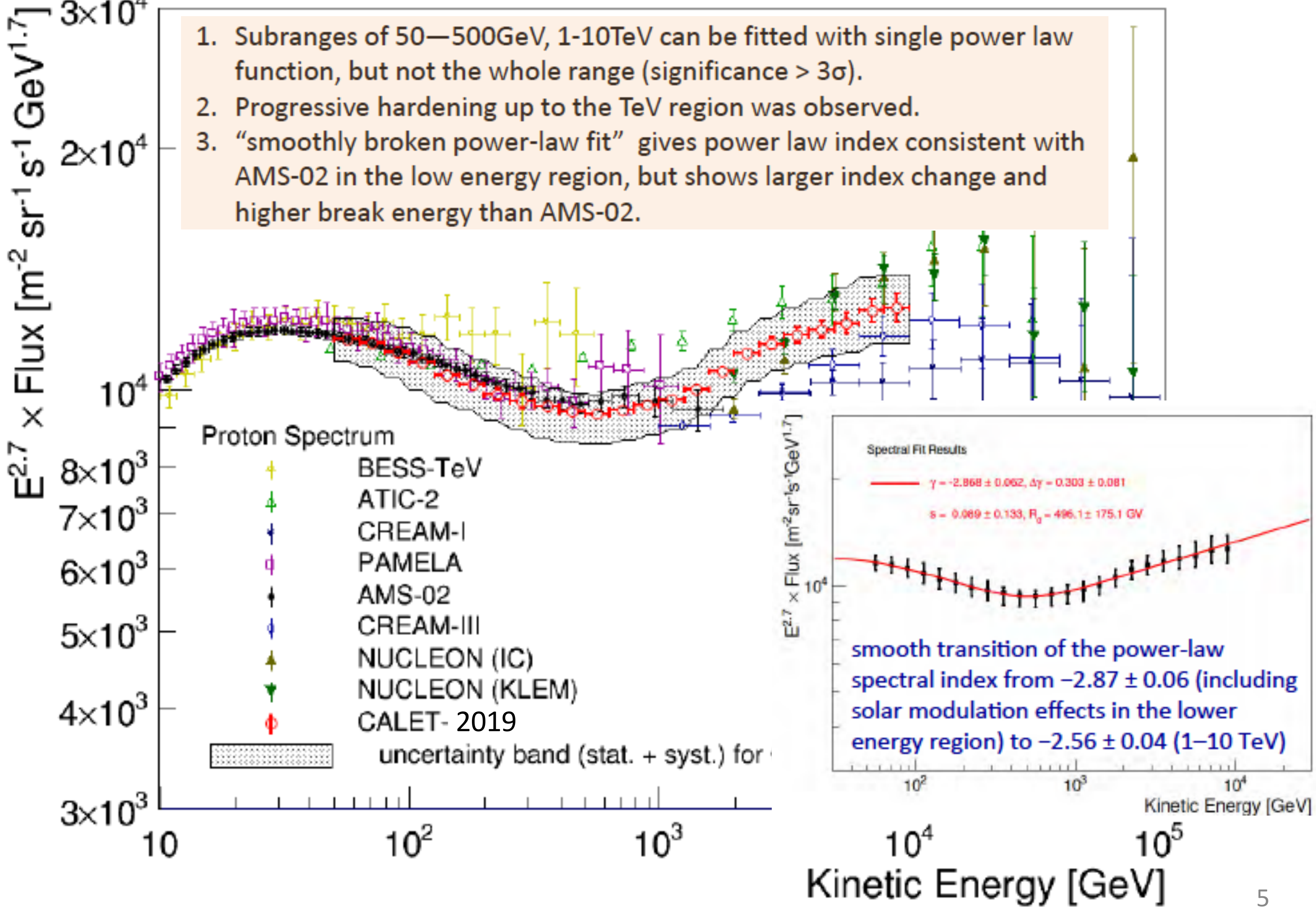
Proton Spectrum

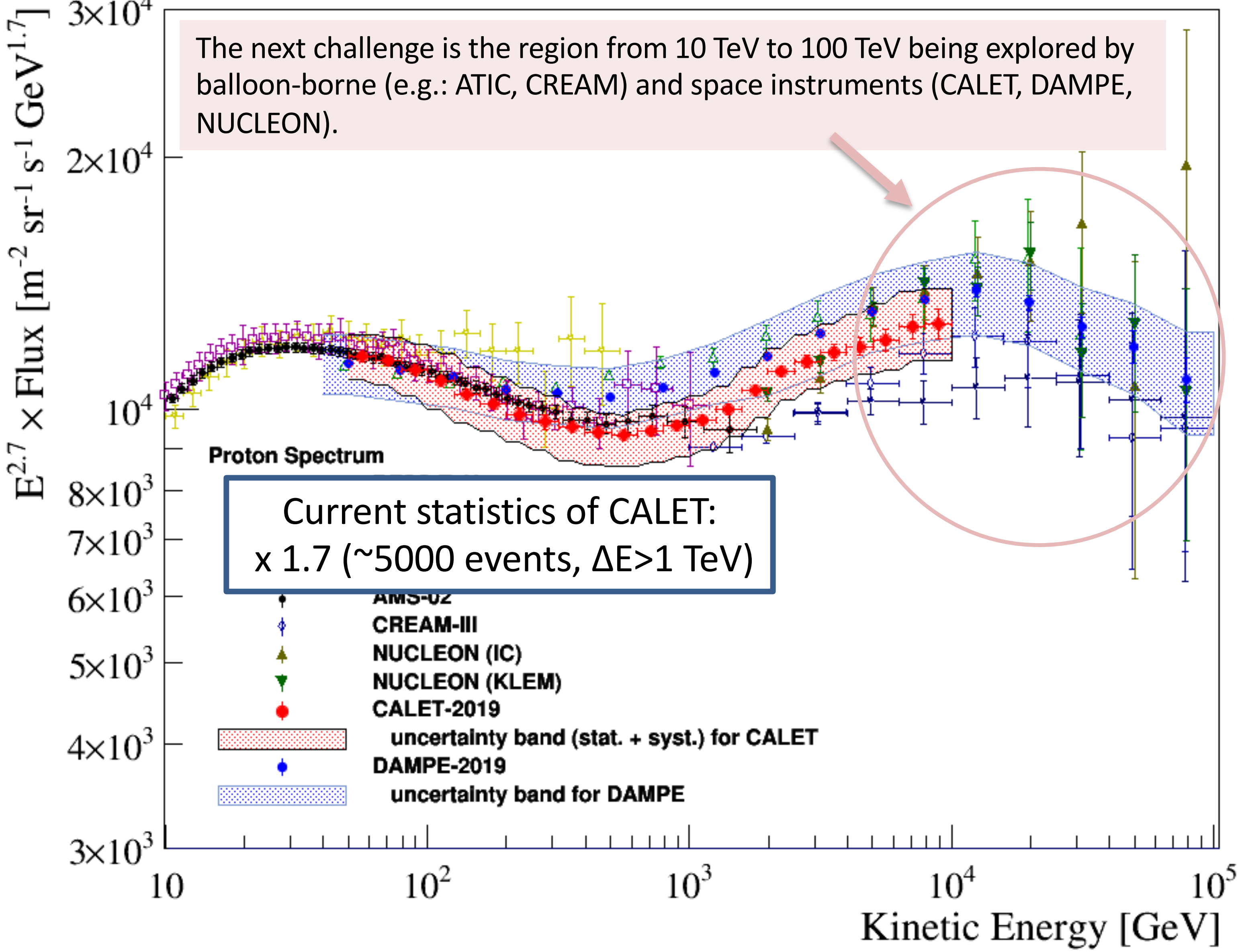
CALET Observations: Oct.13,2015- Aug.31,2018 (for 1,056 days)

1. Subranges of 50—500GeV, 1-10TeV can be fitted with single power law function, but not the whole range (significance > 3σ).
2. Progressive hardening up to the TeV region was observed.
3. "smoothly broken power-law fit" gives power law index consistent with AMS-02 in the low energy region, but shows larger index change and higher break energy than AMS-02.



Proton Spectrum

CALET Observations: Oct.13,2015- Aug.31,2018 (for 1,056 days)



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Selection for C, O candidate events

Analyzed Flight Data

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

T_{live}=3.00 x 10^4 hours

Analysis procedure

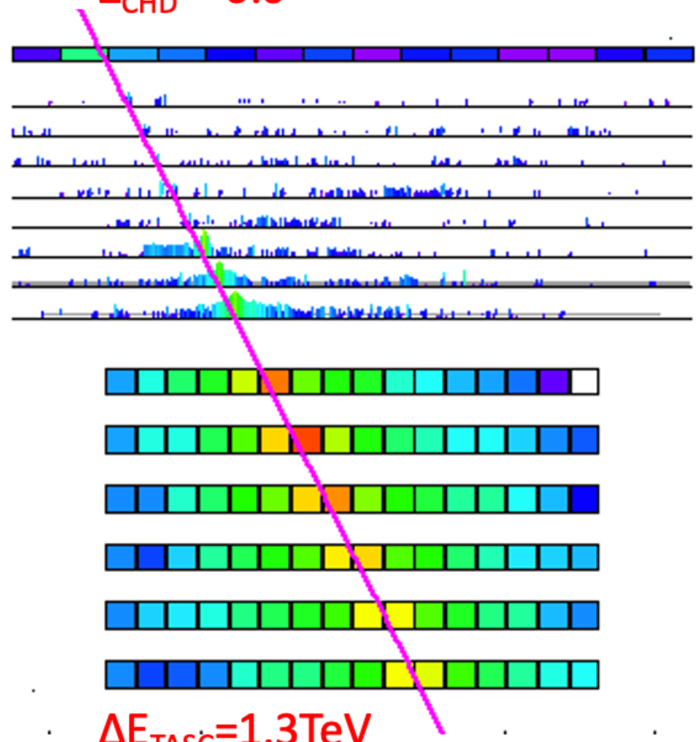
- HE + offline shower trigger
  50MIP in IMC-X/Y78, 100MIP in TASC-X1
- Tracking with IMC
- Acceptance cut
  CHD, TASC top (2cm from edge) and bottom layers
- Charge identification with CHD and IMC
- Background estimation
- Energy measurement and unfolding
- Flux calculation

MC data

- EPICS v9.22, Cosmos8.02, DPMJET-III
- H – Ni in 1 GeV – 1 PeV

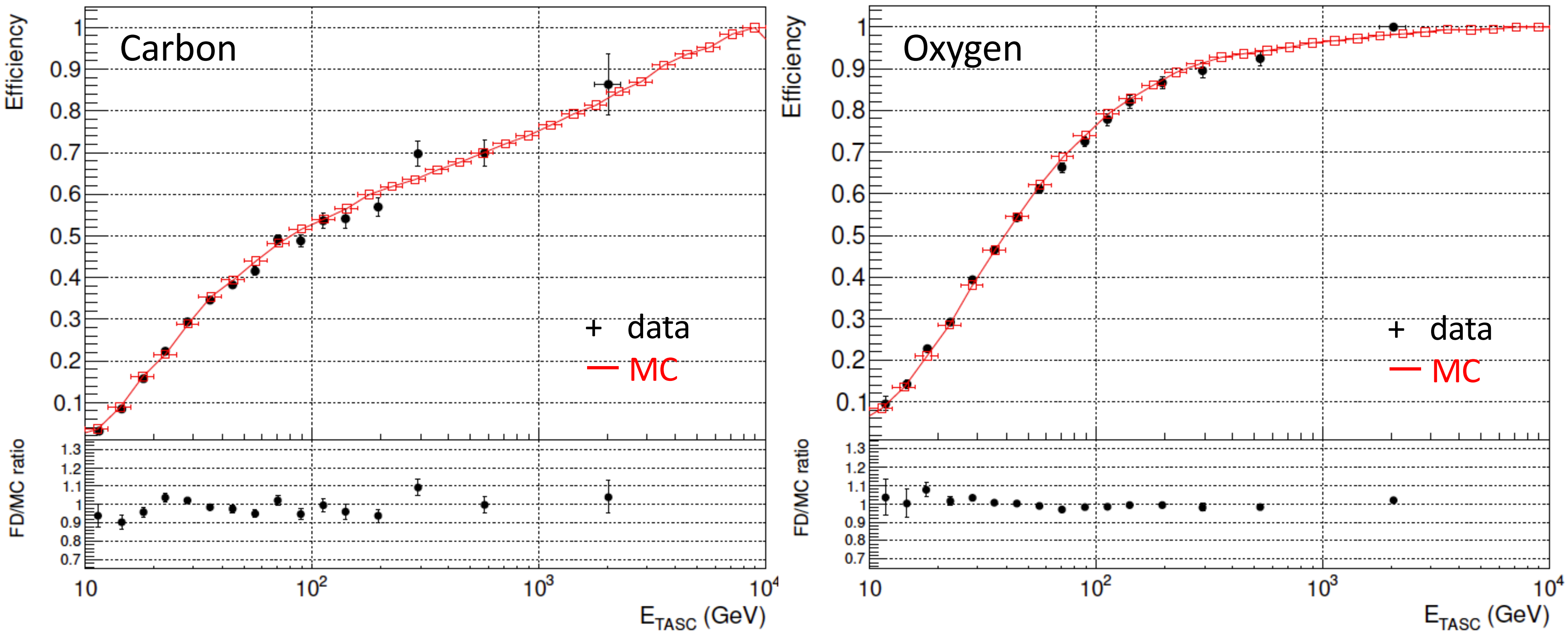
Digitization of signals in simulation are modelled and tuned by beam test results and flight data; quenching, noise and saturation.

An example of Carbon event from Flight data

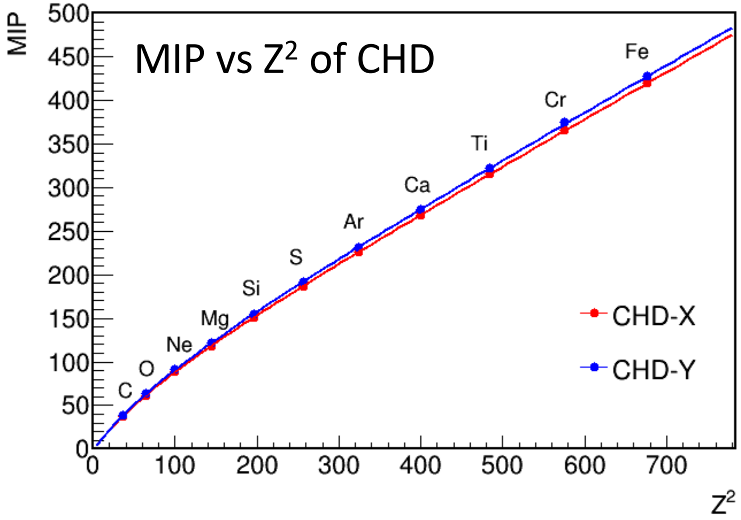


Study of trigger efficiency

- High-Energy Trigger (HET) is the primary CALET mission trigger, which is based on the coincidence of signals in last two IMC layers and top TASC layer
- HET efficiency for nuclei is measured using subset of data taken with the same trigger logic but lower threshold (allonging to trigger also penetrating particles)
- HET is modelled in simulation: good agreement between MC and flight data

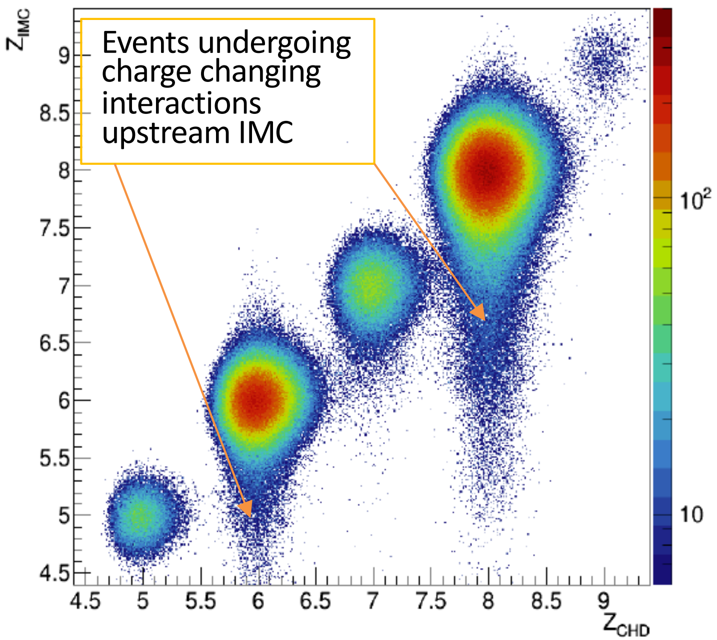


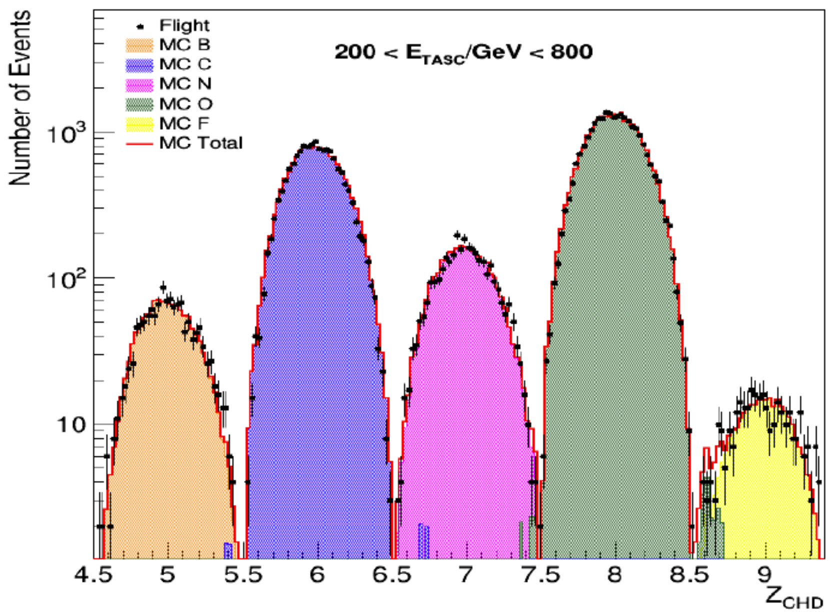
Charge identification



- Redundant charge measurements by combined CHD and multiple dE/dx in IMC fibers in the fast 4 X,Y layers
- Non-linear response to Z^2 due to light saturation in the scintillators is corrected from flight data
- Charge resolution;
  - CHD σ_Z ~ 0.15*e* in BCNO
  - IMC σ_Z ~ 0.20*e* in BCNO

→ Events with Z±0.4*e* are selected for flux calculation





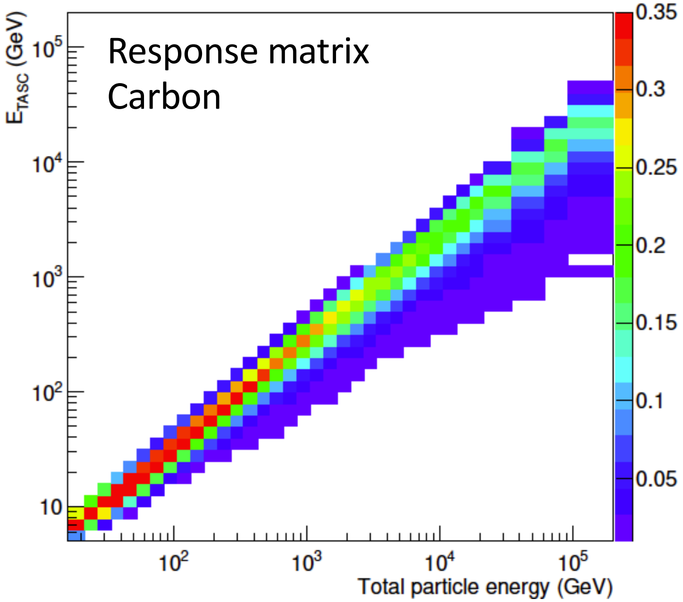
Energy unfolding

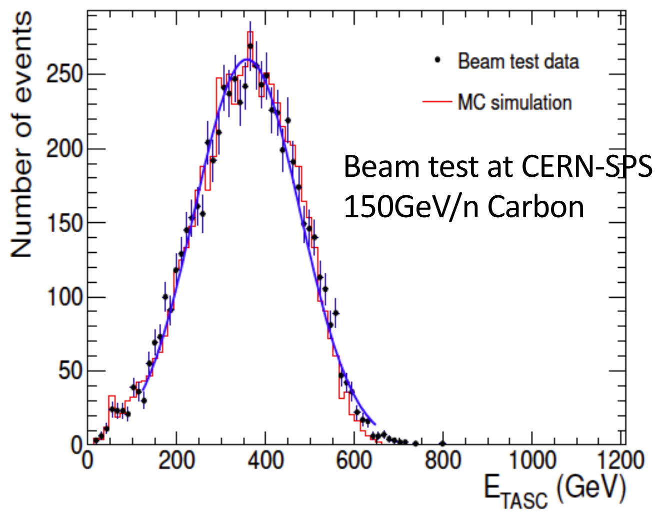
Characteristics of nuclei measurements with CALET calorimeter:
- thickness: 30 X_0 for electron, 1.3λ for proton
- σ(E)/E : 2% for electron, 30% for nuclei

➡ Need energy unfolding for nuclei to obtain primary energy spectrum

<u>Iterative Bayesian unfolding</u>

- Initial assuming spectra: f(E)=A x $E^{-2.60}$
  A is normalized by charge distribution in CHD
- Response function:
  E_{TASC} [GeV] (deposit energy in calorimeter) vs E_0 [GeV] (primary energy)





Correction factors of MC are 6.7% for E_{TASC}<45GeV and 3.5% for E_{TASC} >350GeV, respectively, while a simple linear interpolation Is used to determine the correction factor for intermediate energies

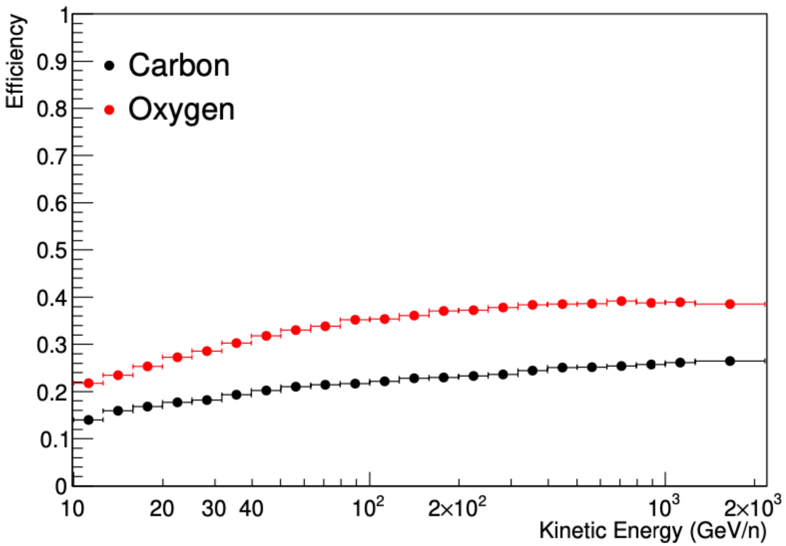
Energy spectra of C and O and the ratio

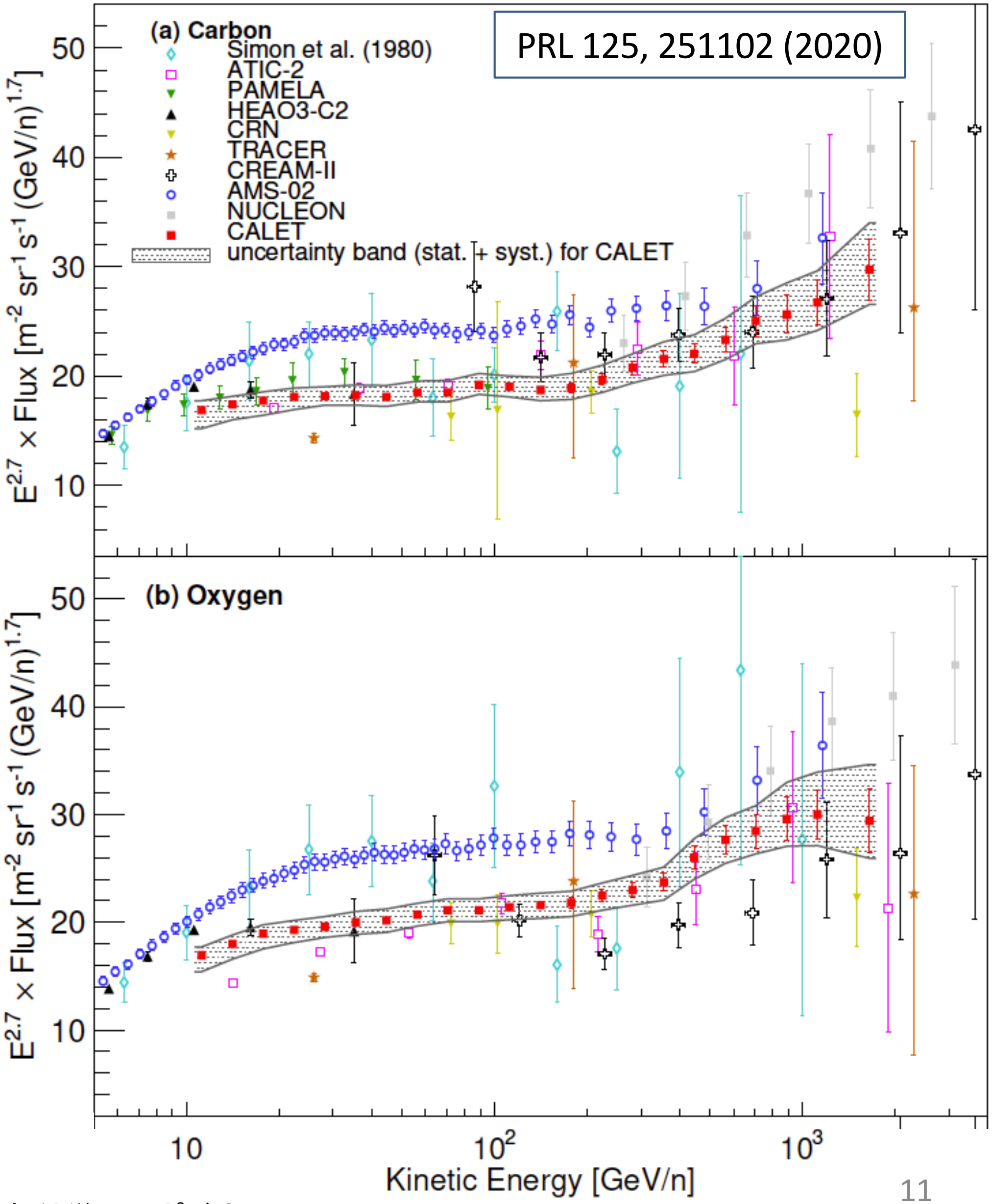
$$\Phi(E) = \frac{N(E)}{\Delta E \; \varepsilon(E) \; S\Omega \; T}$$

$$N(E) = U\left[N_{obs}(E_{\mathrm{TASC}}) - N_{bg}(E_{\mathrm{TASC}})\right]$$

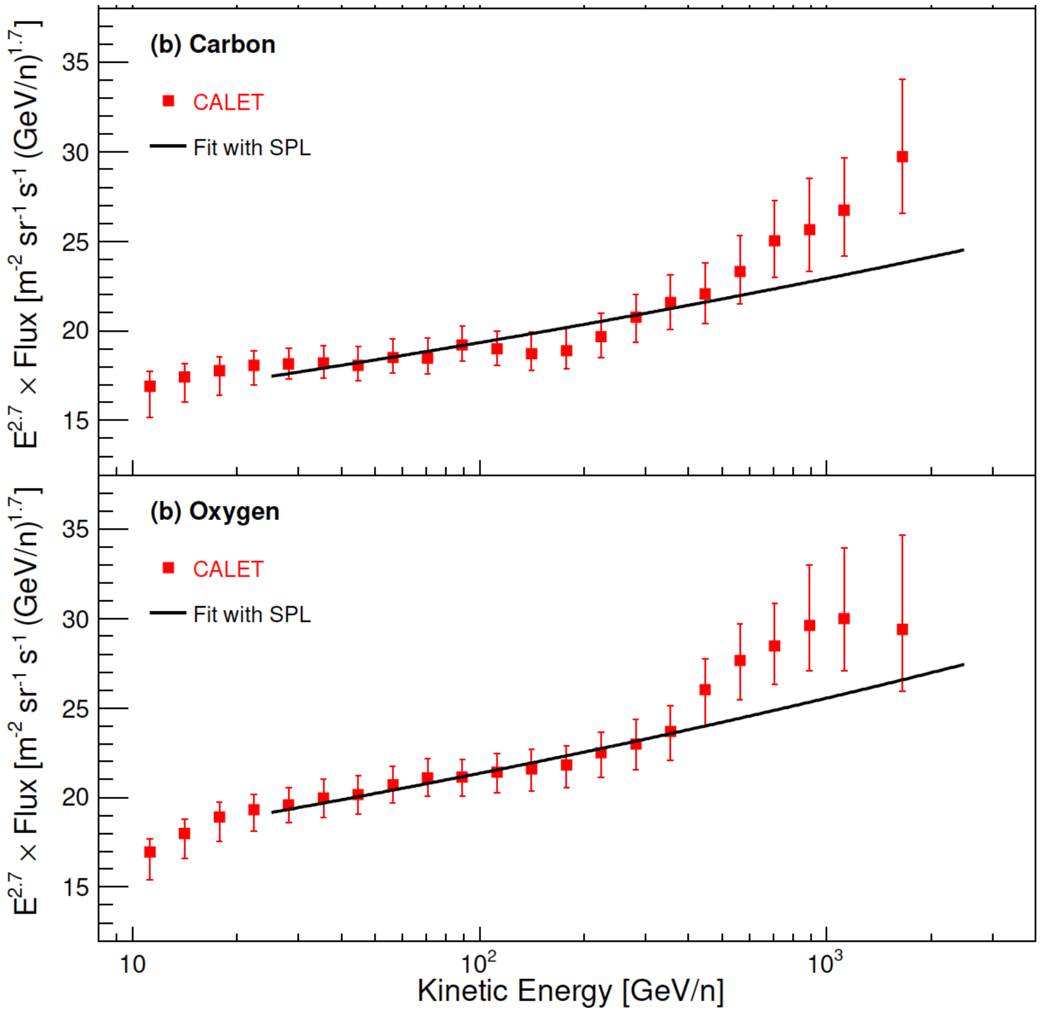
$N(E)$: Events in unfolded energy bin
ΔE : Energy bin width
$\varepsilon(E)$: Efficiency
$S\Omega$: Geometrical acceptance (510cm^{2}sr)
T : Live Time (3.00 x 10^9 hours)

Total efficiencies including HE trigger





Fitting with single power law function



$$\Phi(E) = C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}$$

Fitting results of Carbon

$$\gamma = -2.626 \pm 0.010$$

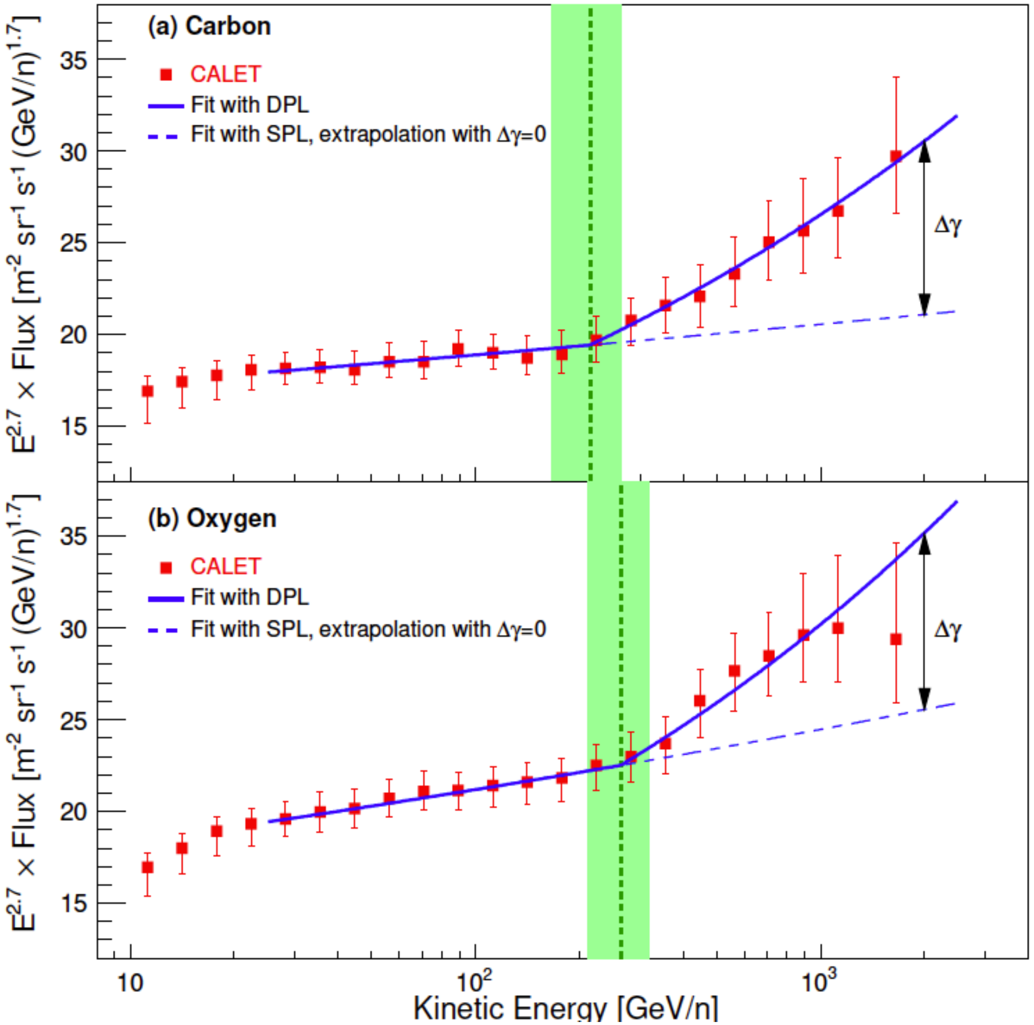
$$\text{with } \chi^2/\text{d.o.f.} = 27.5/10$$

Fitting results of Oxygen

$$\gamma = -2.622 \pm 0.008$$

$$\text{with } \chi^2/\text{d.o.f.} = 15.9/10$$

Fitting with double power law function



$$\Phi(E) = \begin{cases} C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma} & E \le E_0 \\ C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left(\frac{E}{E_0}\right)^{\Delta\gamma} & E > E_0 \end{cases}$$

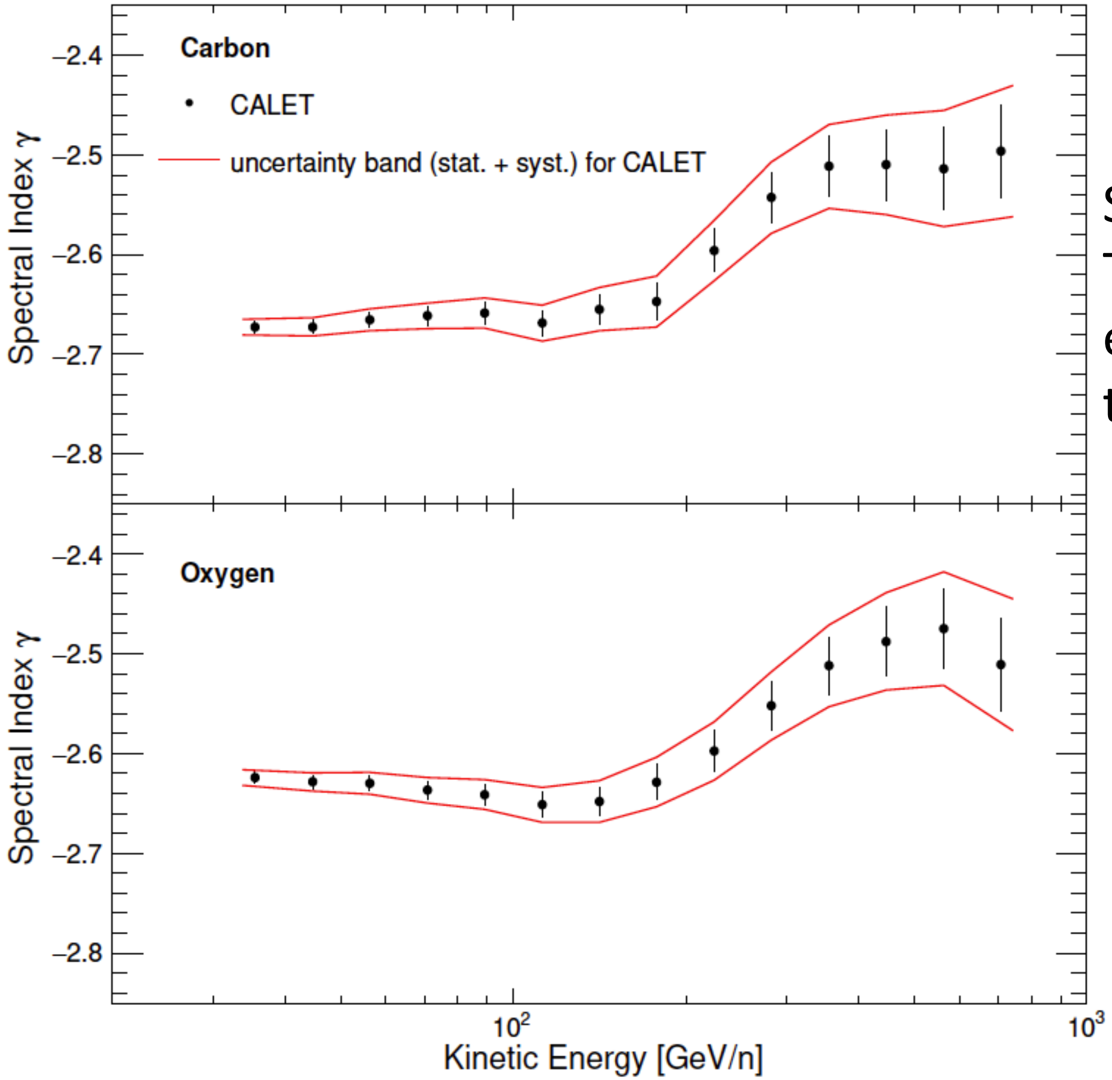
Fitting results of Carbon

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

Fitting results of Oxygen

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

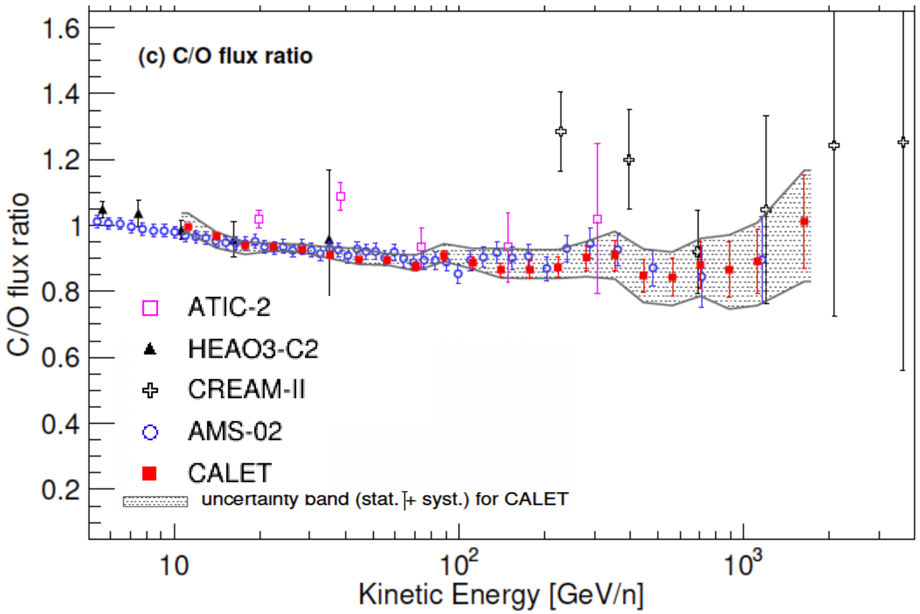
Spectral indies of C, O spectra

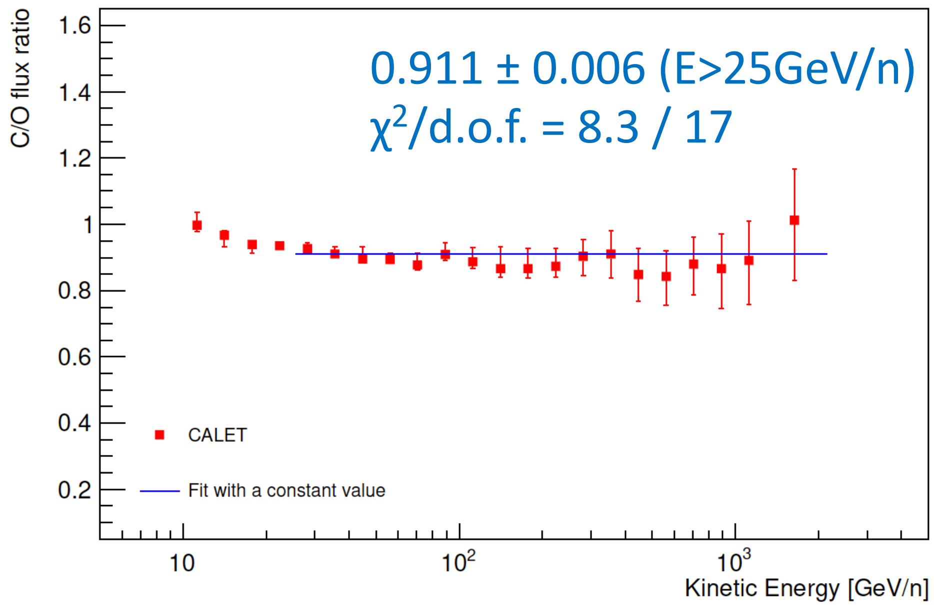


Sliding energy window method
The spectral index is computed for each bin by a fit to data including the neighbor ± 3 bins

Clear Hardening of the spectra above a few hundred GeV

C/O flux ratio





The carbon to oxygen flux ratio is well fitted to a constant value above 25 GeV/n, indicating that the two fluxes have the same energy dependence

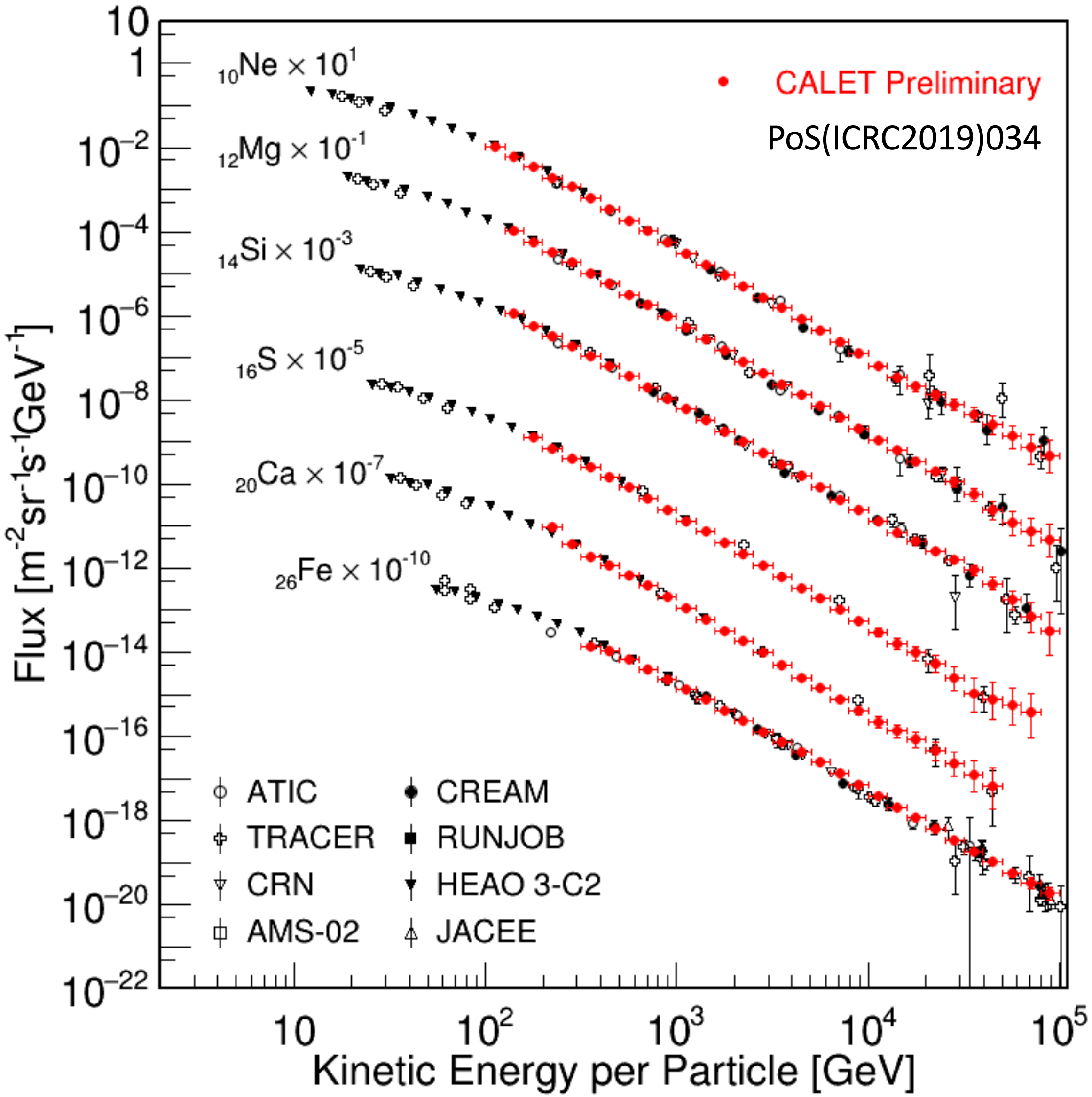
Energy spectra of heavy components

Flux measurements:

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

$N(E)$: Events in unfolded energy bin
$S\Omega$: Geometrical acceptance
$\varepsilon(E)$: Efficiency
T : Live Time
ΔE : Energy bin width

Observation period:
Oct.13 2015 – Dec.31 2018
(1,176 days)



Summary and prospects

- As of Sep.30, 2020, CALET has successfully carried out 1815-day observations with live time fraction to total time close to 85%. Neary 2.5 billion events corrected with low (>1GeV) + high energy (>10 GeV) triggers.
- Preliminary measurements of the primary cosmic ray elements have been carried out up to 100 TeV using 5 years of data.
- Direct measurement of proton spectrum in 50 GeV – 10 TeV with 1,054 days of operation. Our observation allow to exclude a single power law spectrum for proton by more than 3σ.
- Direct measurement of carbon and oxygen spectra in 10 GeV/n – 2.2 TeV /n with 1,480 days of operation. Our observations allow to exclude a single power law spectrum for C and O by more than 3σ; they show a spectral index increase and the same energy dependence above 25GeV/n
- The spectral hardening of carbon and oxygen is consistent with that measured by AMS-02, but the absolute normalization of the flux is about 27% lower, though in agreement with observations from previous experiments including PAMELA and CREAM.
- CALET mission is planed by March 2021 over 5.7 years after launch and is expected by 2024 with the approval by reviewing of the project status.