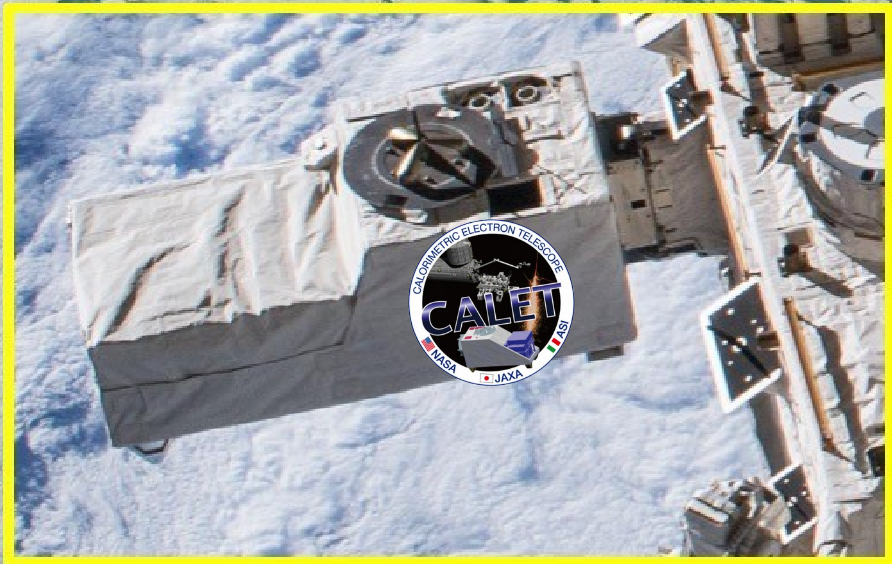
Latest results on observations with the CALorimetric Electron Telescope (CALET) on the International Space Station

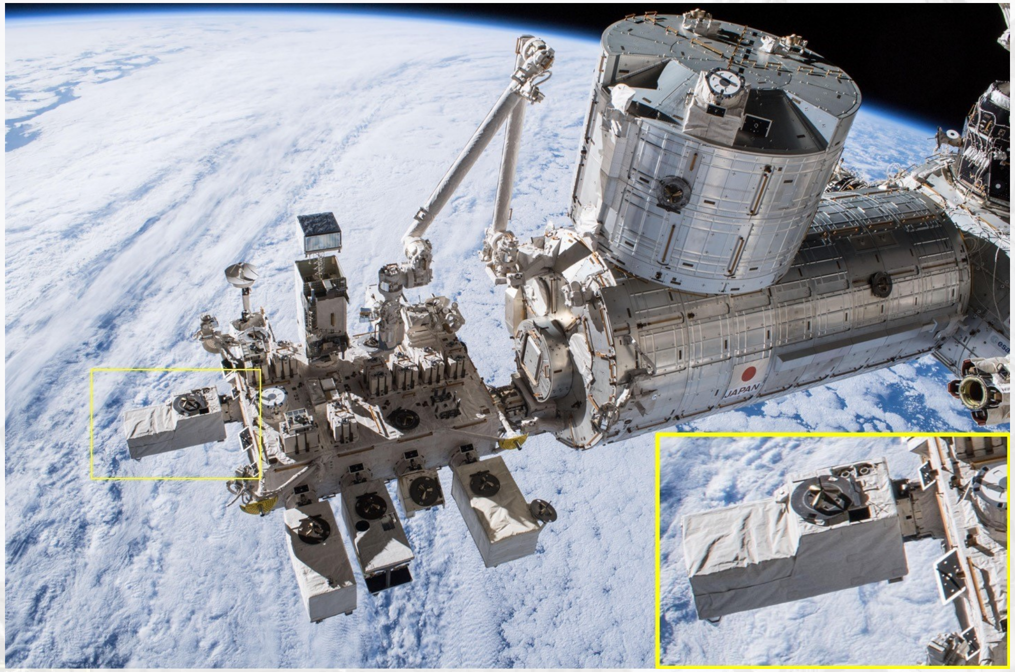


Francesco Stolzi
University of Siena & INFN-Pi
On behalf of the CALET collaboration

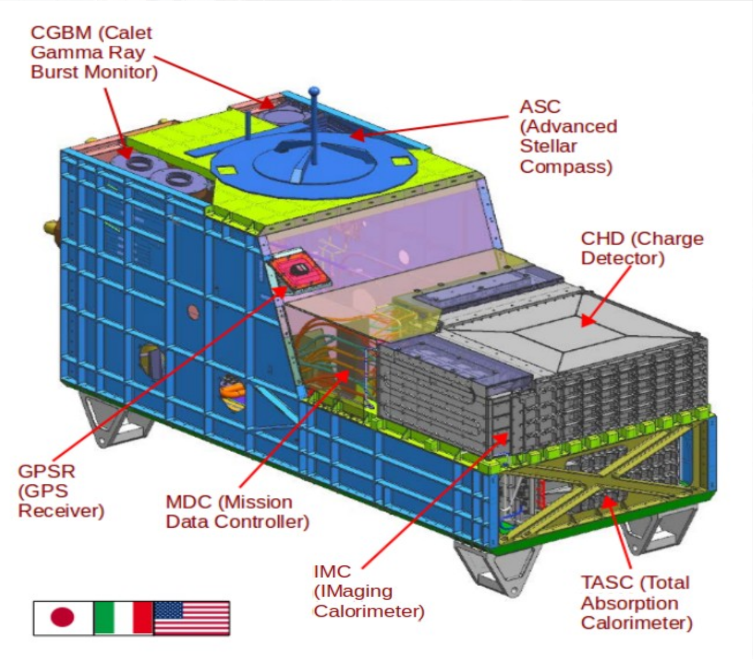
TeVPA 2023
Napoli, Italy

CALET PAYLOAD

CALET launch on Aug. 19th, 2015 on Japanese H2-B rocket



CALET was emplaced on Japanese Experiment Module – Exposed Facility (JEM-EF) port#9 on Aug. 25th, 2015



JEM Standard Payload
Mass: 612.8 kg
Size: 1850 mm (L) x 800 mm (W) x 1000 mm (H)
Power Consumption: 507 W (max)

CALET started scientific observations on Oct. 13Th, 2015. More than 4 billion events collected so far.

Overview of CALET payload

The main detector of the CALET payload is a calorimeter (CAL) to observe <u>high-energy cosmic rays and gamma rays from 1 GeV to 10 TeV</u>. In addition, the Gamma-ray Burst Monitor (CGBM) covers the <u>gamma-ray energy range from 7 keV to 20 MeV</u>

CAL

- Charge Detector (CHD)
- Imaging Calorimeter (IMC)
- Total Absorption Calorimeter (TASC)

CGBM (CALET Gamma Ray Burst Monitor)

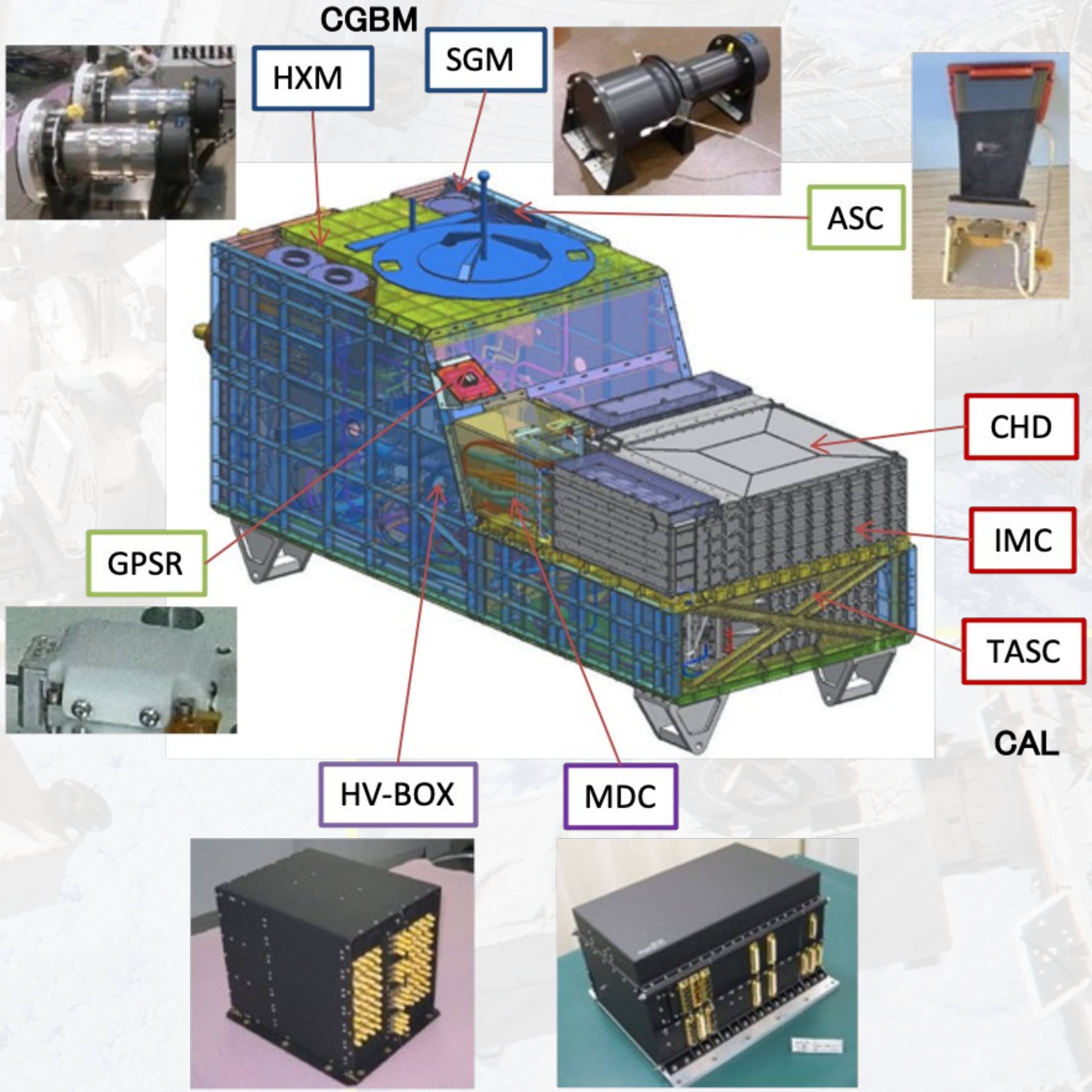
- Hard X-ray Monitor (HXM) x 2 (3 sr)
  Scintillators $LaBr_3$: 7keV ～ 1MeV
- Soft γ-ray Monitor (SGM) (8 sr)
  Scintillators BGO ： 40keV ～ 20MeV

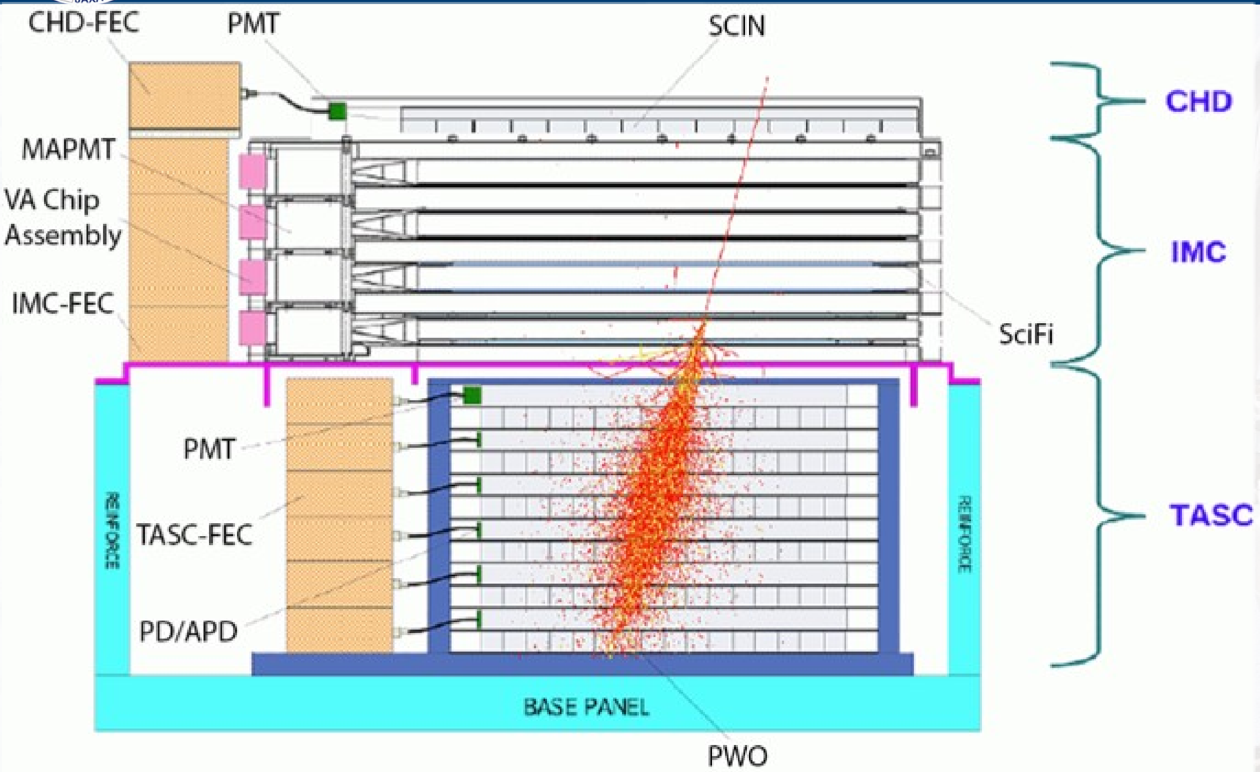
Data Processing & Power Supply

- 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）





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

	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimiter)
Measure	Charge $(1 \leq Z \leq 40)$ $\Delta Z/Z = 0.15$ for C, 0.35 for Fe	*Particle ID*, Tracking ΔX at CHD = 300 μm	Energy, *Dynamic range: 1 –10⁶ MIP (1 GeV –1 PeV)*
Geometry/ Material	Plastic Scintillator 14 paddles x 2 layers (X,Y) Paddle size: 32 mm x 10 mm x 450 mm	Scintillating fibers 448 x 16 (X,Y) 7 W layers, total thickness: $3\ X_0$ Scifi Size: 1 mm^2 x 448 mm	16 PWO *logs* x 12 layers (X,Y) Total thickness: $27\ X_0$, $1.2\ \lambda_I$ Log size: 19 mm x 20 mm x 326 mm
Readout	PMT + CSA	64-anode MAPMT + ASIC	APD/PD + CSA PMT + CSA (for trigger)

CALET OBJECTIVES

Science Objectives	Observation Targets	Energy Range
Nearby CR Sources	Electron Spectrum	100 GeV – 20 TeV
Dark Matter	Signatures in γ/e spectra	100 GeV – 20 TeV
CR Origin and Acceleration	Electron Spectrum p-Fe individual spectra Ultra Heavy Ions (26<Z≤40)	1 GeV – 20 TeV 10 GeV -10^3 GeV Few GeV/n
Galactic CR Propgation	B/C subFe/Fe ratio	Up to some TeV/n
Solar Physics	Electron Flux	<10 GeV
Transient Phenomena (GRB, e.m. counterpart of GW)	Gamma and x-rays	7 KeV -20 MeV

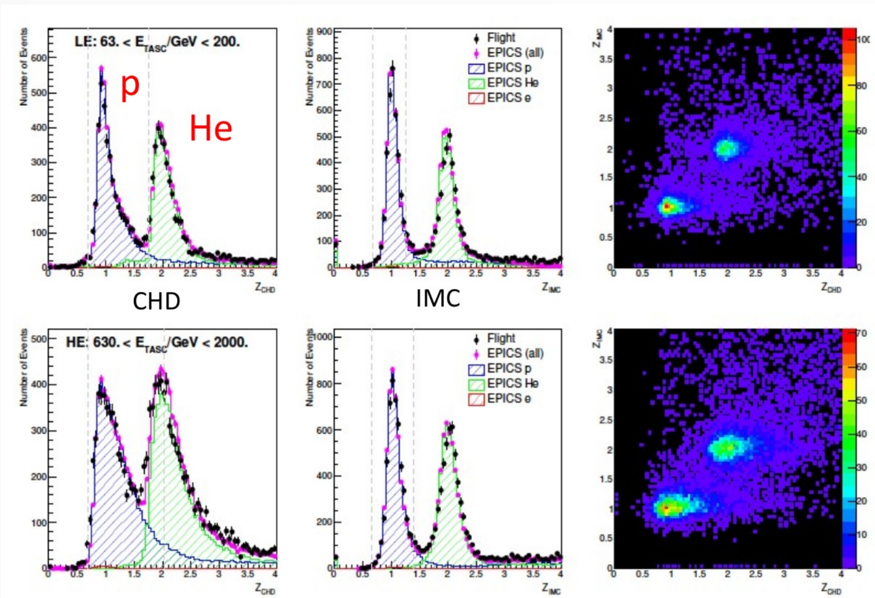
- Wide dynamic range (1-10^6 MIP)
- Large thickness (30 X_0, 1.3 λ)
- Excellent charge ID (0.2e)

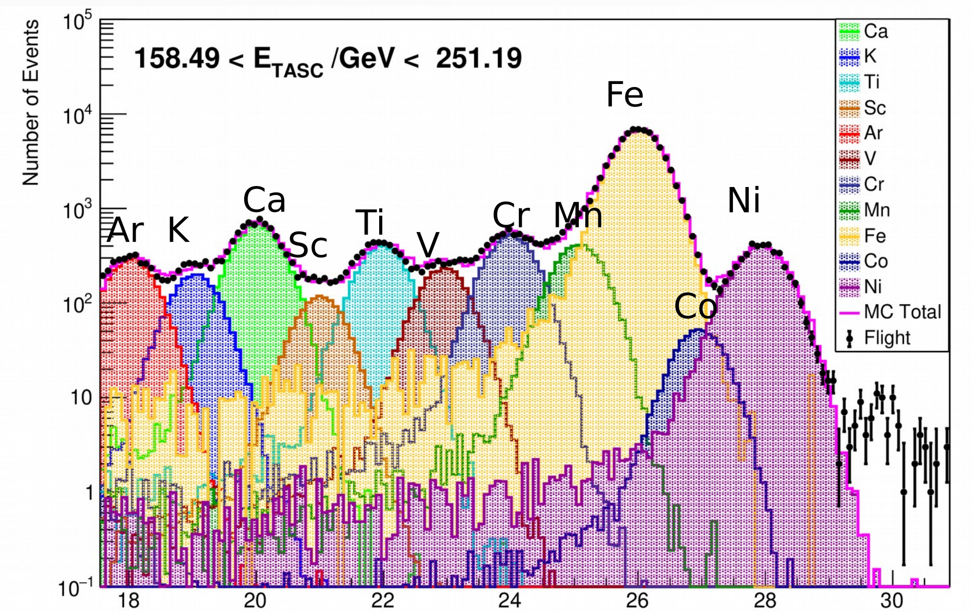
⇒

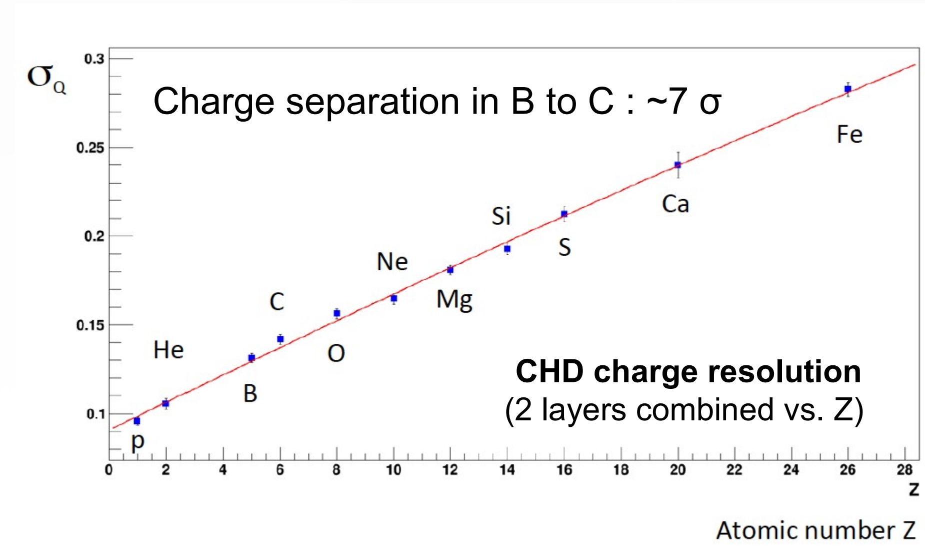
CALET can cover the whole energy range previously investigated in separate subranges by magnetic spectrometers and calorimeters

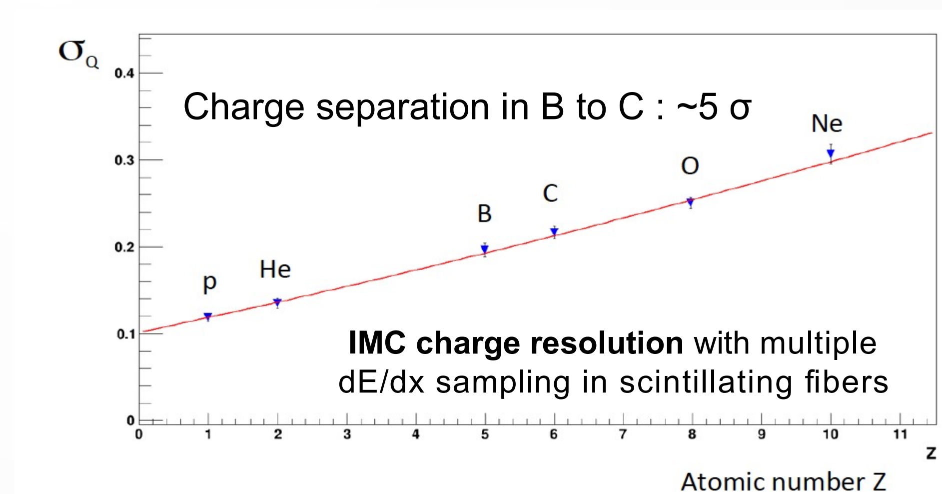
Charge identification with CHD and IMC

- Charge identification for p, He and light nuclei is achieved by CHD+IMC;
- Charge identification for heavy nuclei is achieved by CHD: saturation of signals occurring in the IMC layers.



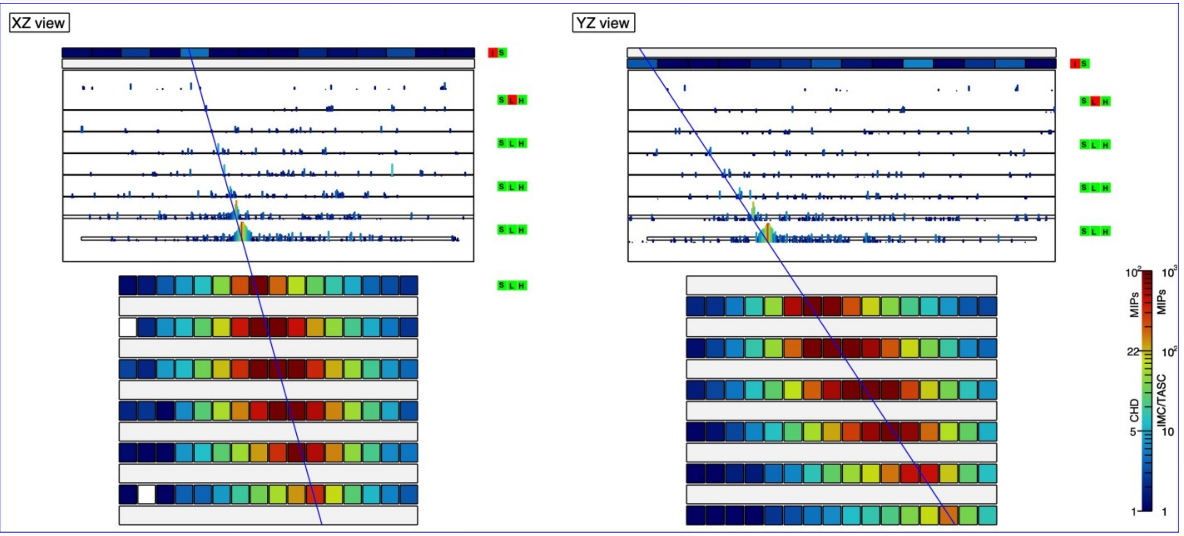




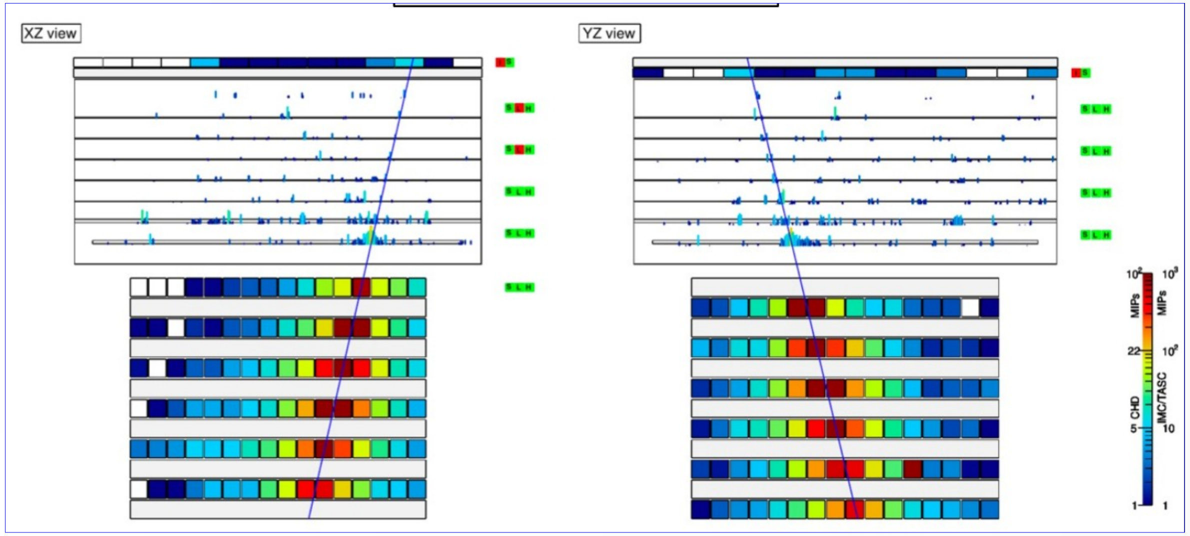


CALET EVENT CANDIDATES

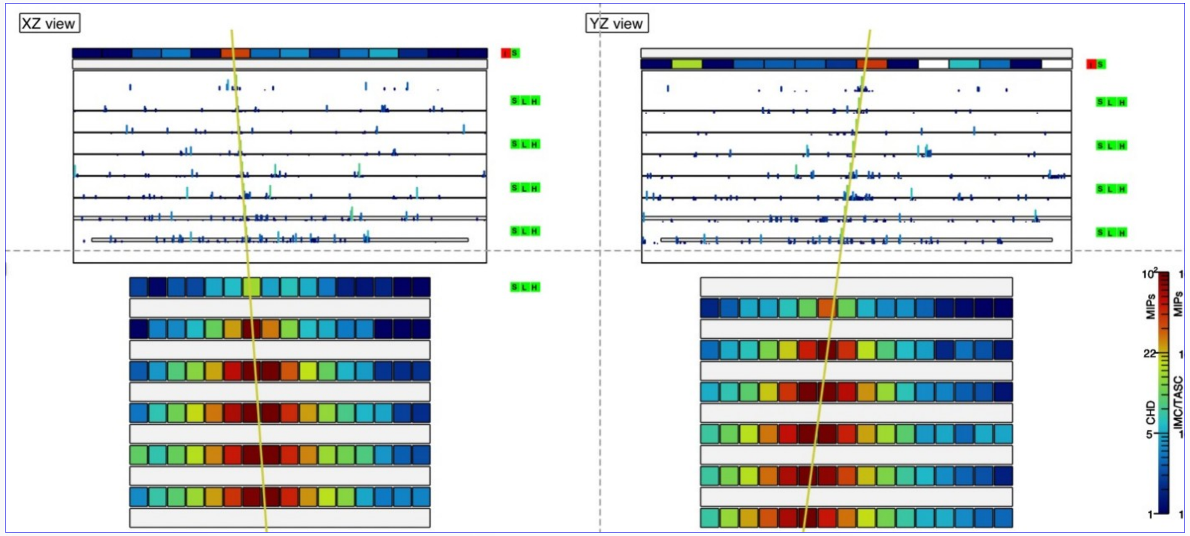
Electron 3 TeV



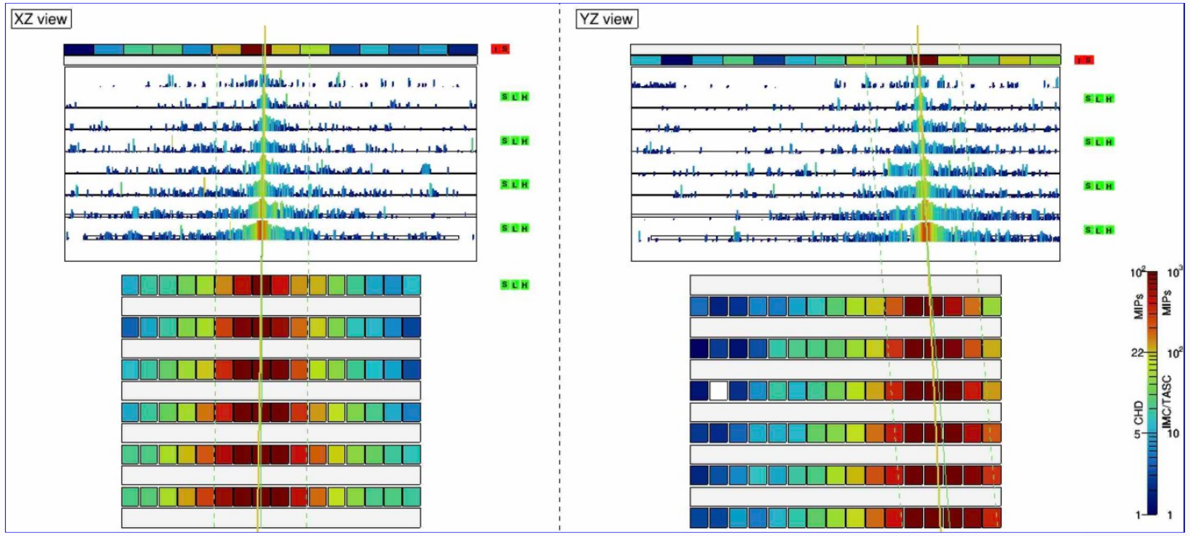
Helium 700 GeV

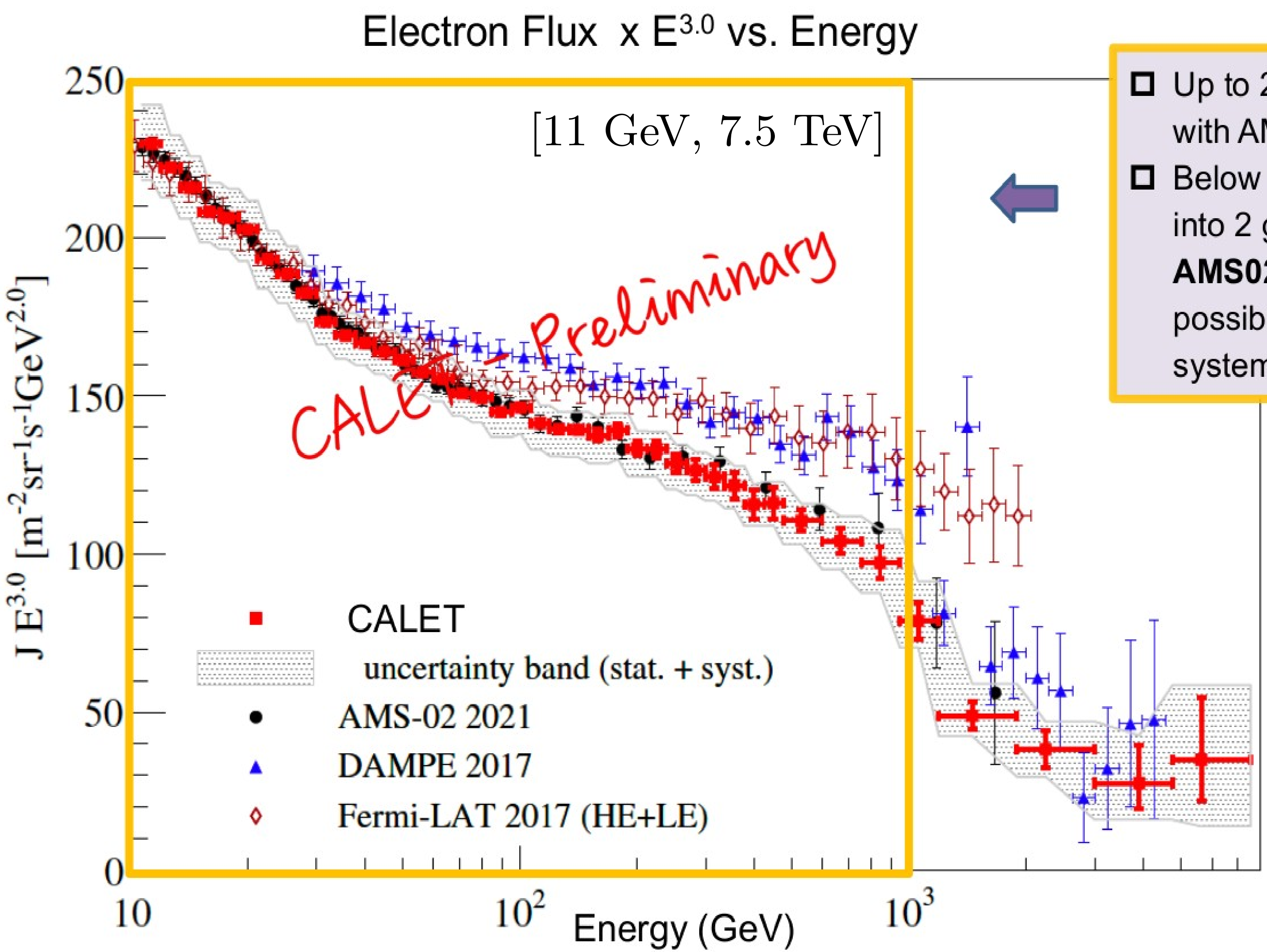


Carbon 2 TeV



Iron 3.9 TeV

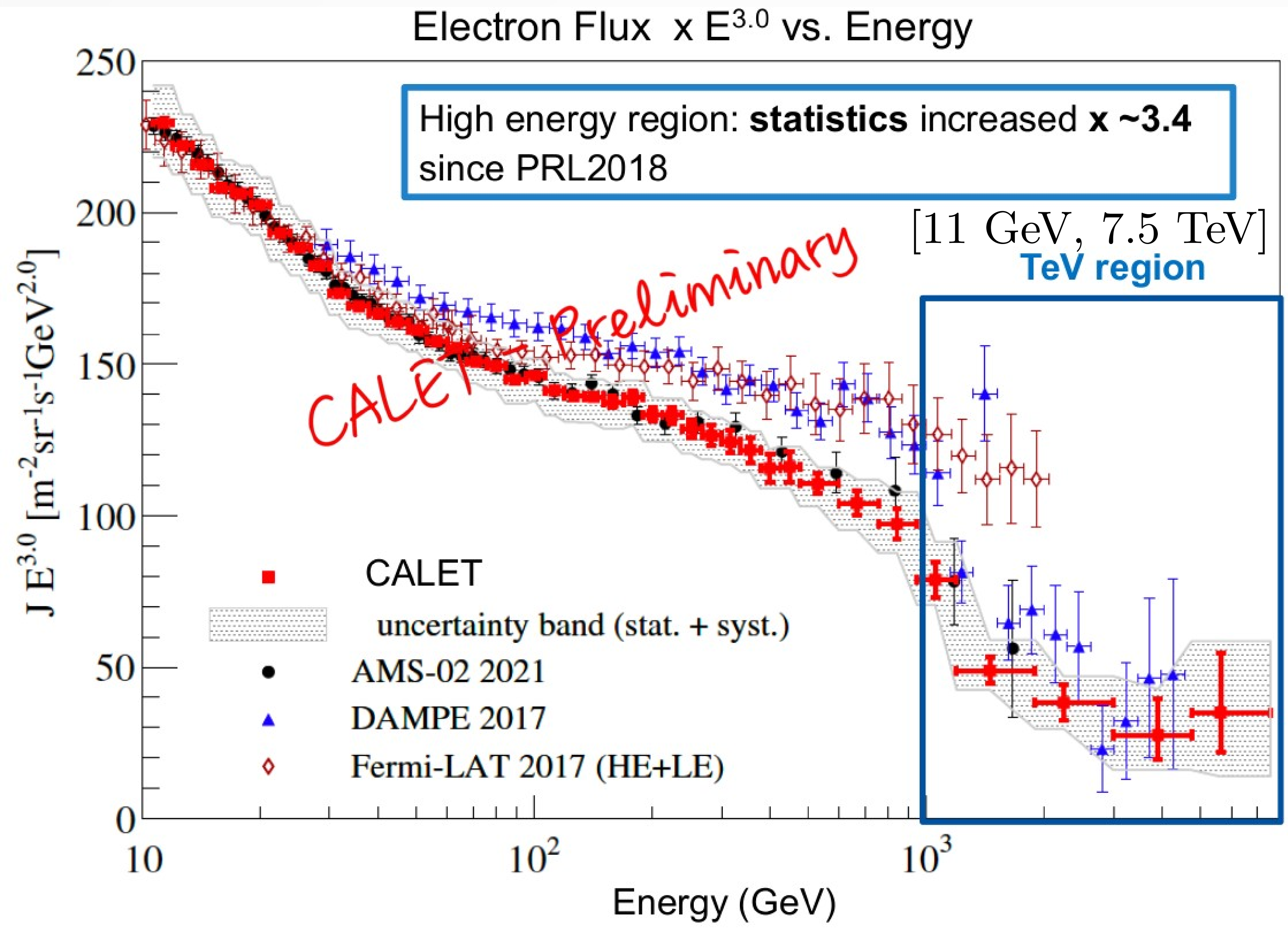




- Up to 2 TeV : CALET spectrum is consistent with AMS-02
- Below 1 TeV : Present measurements cluster into 2 groups: **AMS02 + CALET** and **FERMI + DAMPE** possibly indicating the presence of unkown systematics

Preliminary spectrum is **updated** using 2637 days of CALET observations:
Oct.13, 2015 – Dec. 31, 2022
7.02 million events > 10 GeV

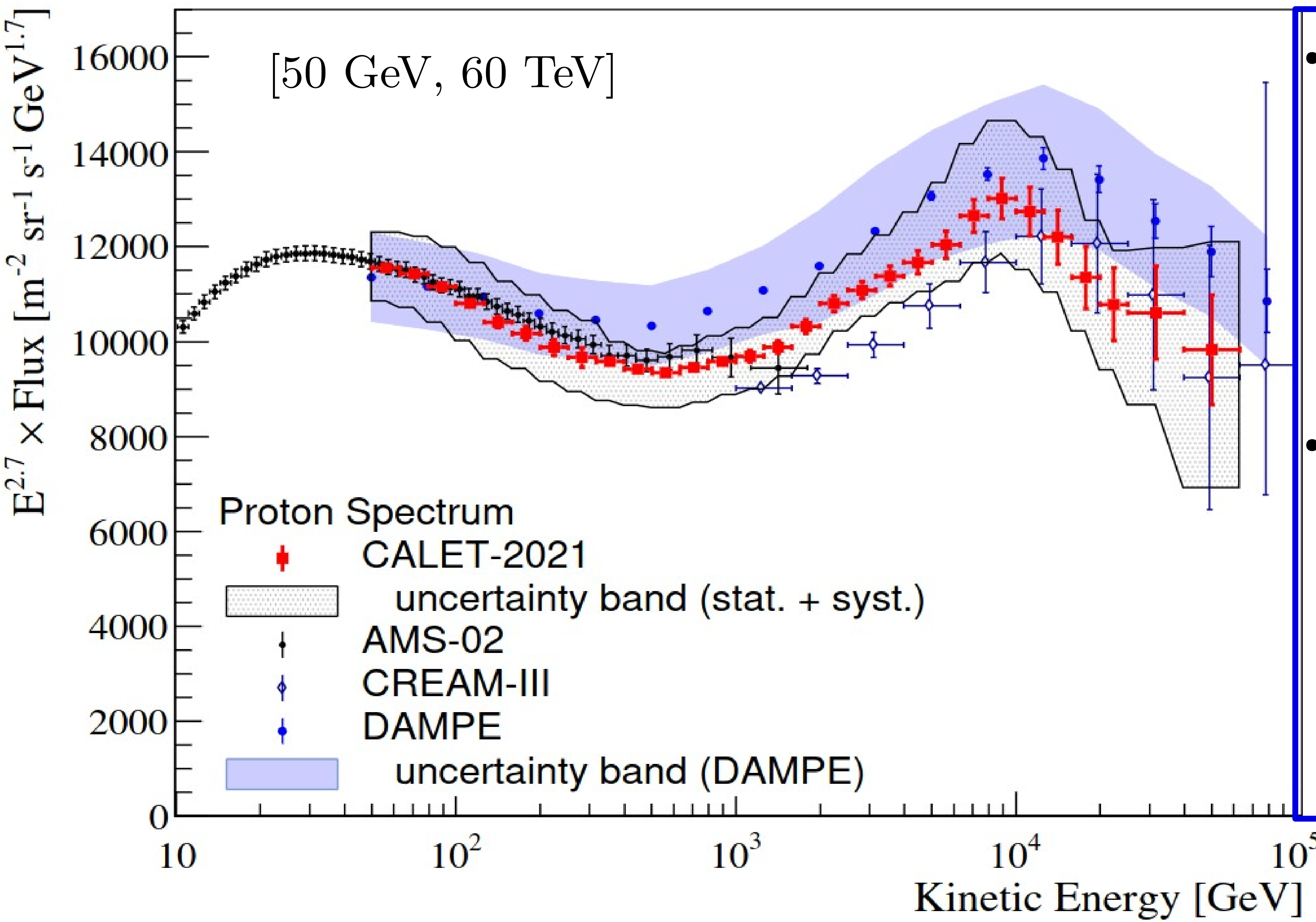
All-Electron Spectrum



CALET observes a flux suppression above 1 TeV with a **significance > 6 σ**, a considerable improvement with respect to the result published in PRL2018 (~4 σ).

Advanced analysis is going on for electron identification above 5 TeV.

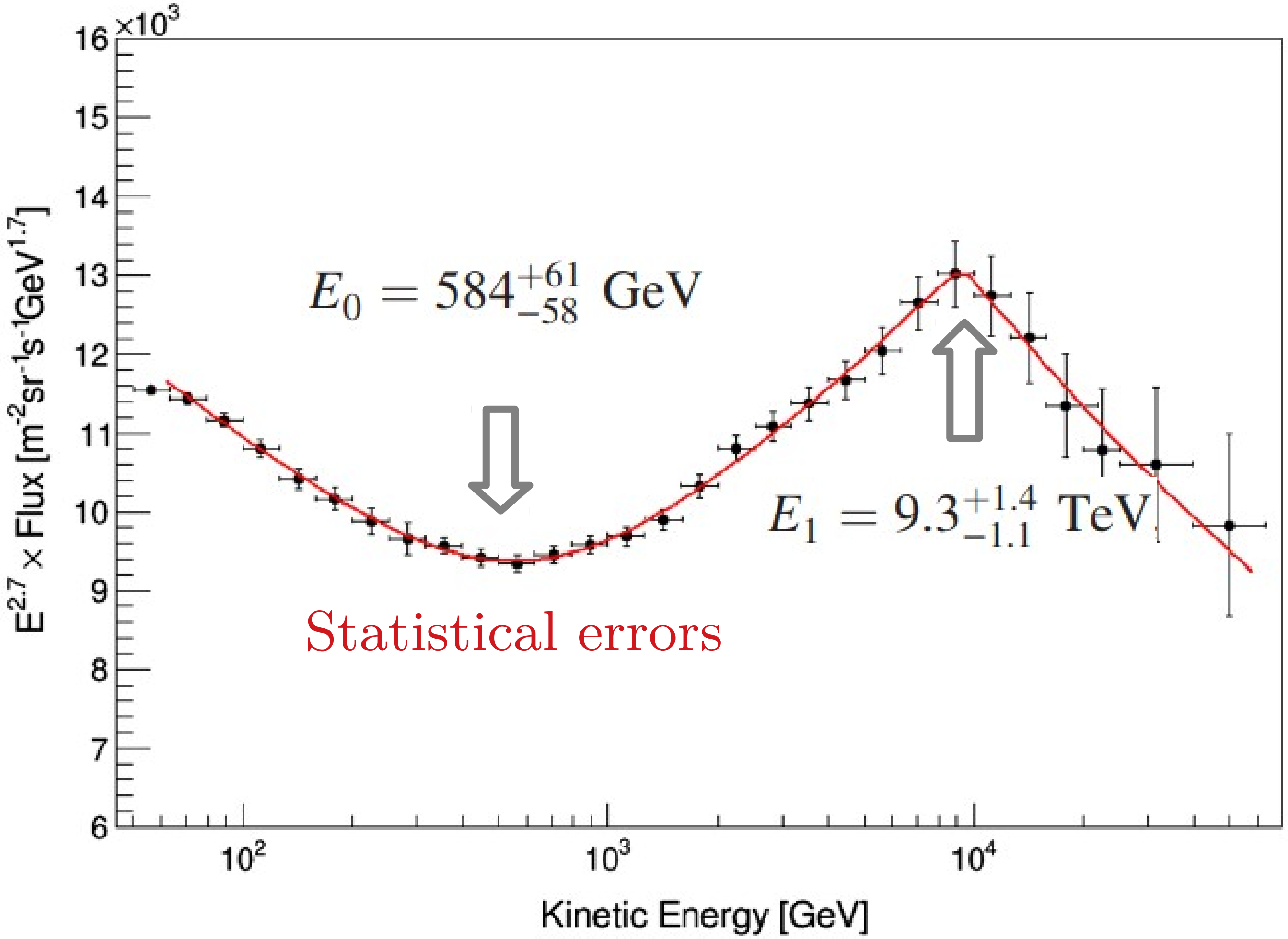
Phys. Rev. Lett. **129** (2022)



- CALET confirms proton spectral hardening above a few hundred GeV with a higher significance of more than 20 sigma;
- CALET observes a spectral softening starting around 10 TeV consistent, within the errors, with the measurement reported by DAMPE.

Proton Spectrum

Fit from 80 GeV to 60 TeV with Double-Broken Power Law (DBPL)



The fit gives a **spectral index hardening** $\Delta\gamma = 0.28^{+0.04}_{-0.02}$ from $\gamma = -2.83$ and a **spectral index softening** $\Delta\gamma_1 = -0.34^{+0.06}_{-0.06}$ with $\chi^2/\mathrm{d.o.f.} = 4.4$.

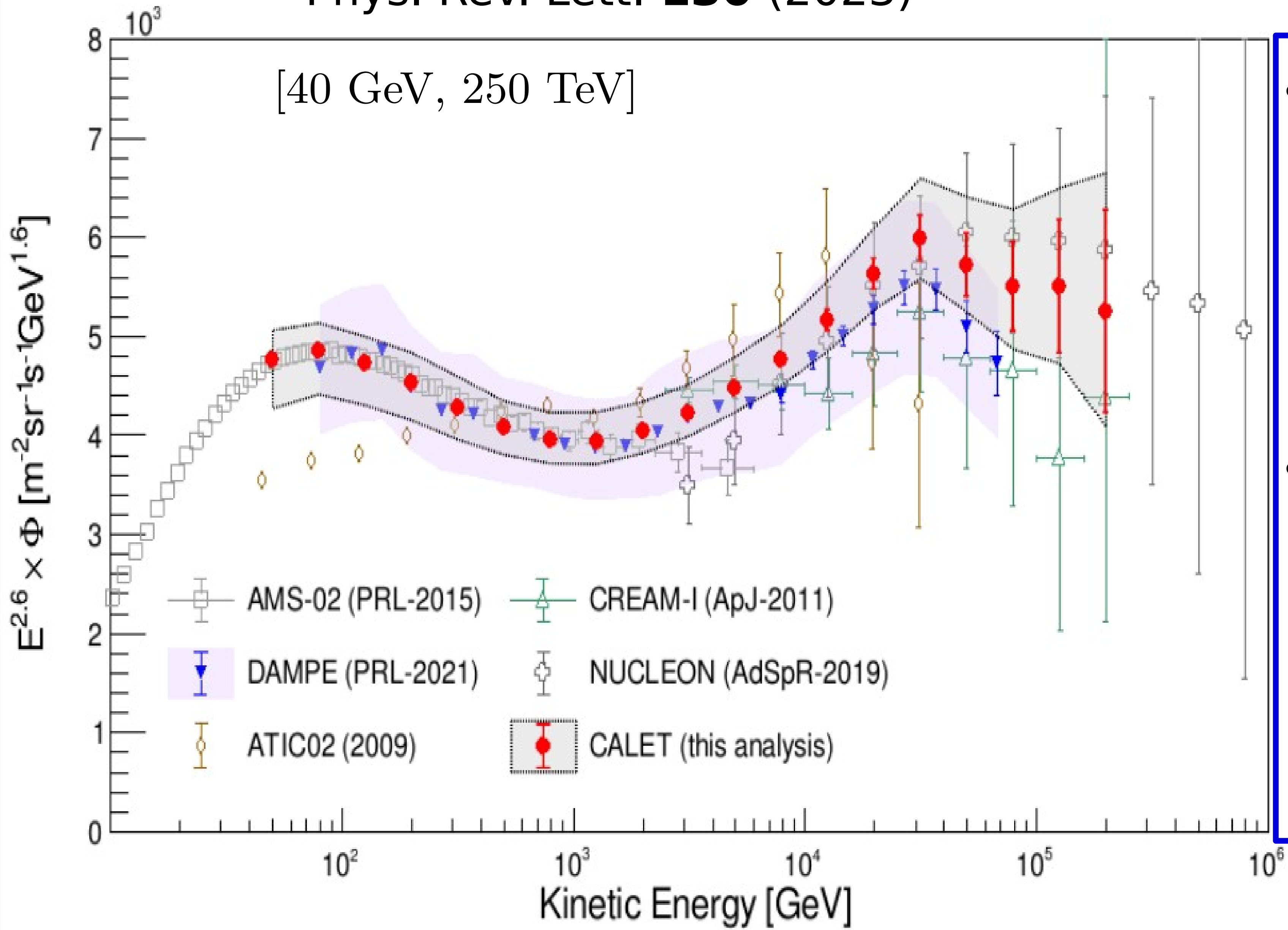
$$\Phi'(E) = E^{2.7} \times C \times \left(\frac{E}{1\ \mathrm{GeV}}\right)^{\gamma} \times \phi(E)$$

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

Spectral hardening — *Spectral softening*

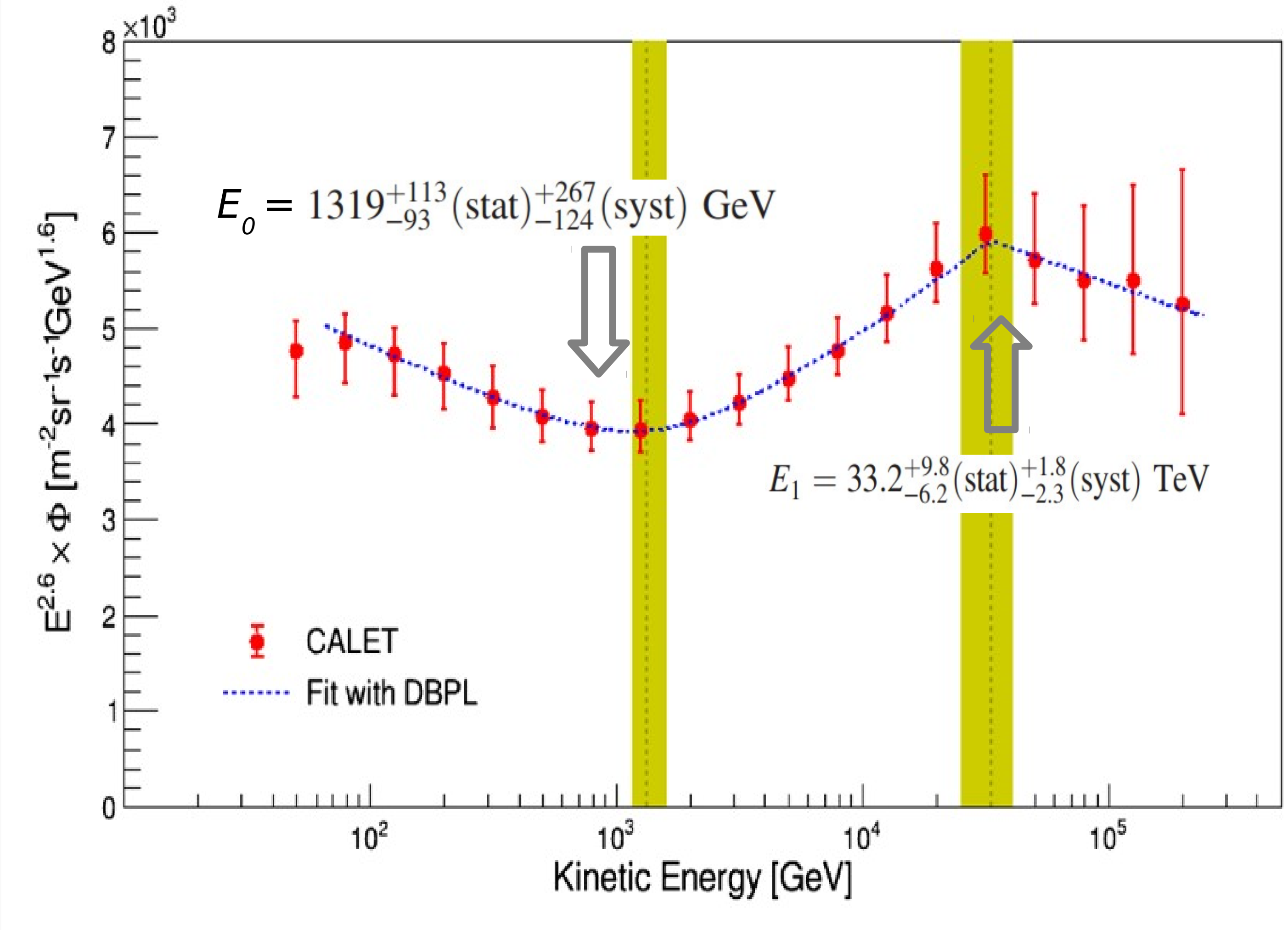
Helium Spectrum

Phys. Rev. Lett. **130** (2023)



- CALET observes spectral hardening from a few hundred GeV to a few tens TeV with a significance of 8 sigma;
- CALET observes a spectral softening starting above few tens of TeV consistent, within the errors, with the measurement reported by DAMPE.

Fit from 60 GeV to 250 TeV with Double-Broken Power Law (DBPL)



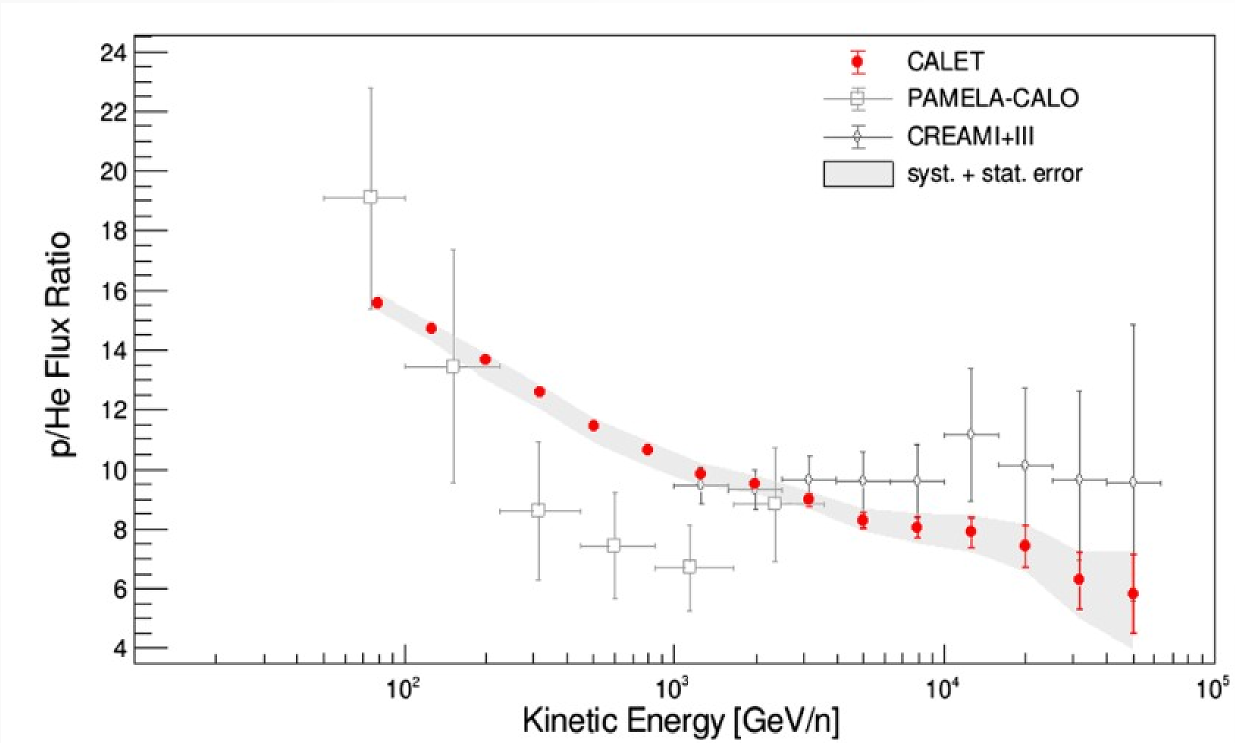
The fit gives a **spectral index hardening** $\Delta\gamma = 0.25^{+0.02}_{-0.01}(\text{stat})^{+0.02}_{-0.03}(\text{syst})$ from $\gamma = -2.703^{+0.005}_{-0.006}(\text{stat})^{+0.032}_{-0.009}(\text{syst})$, and a **spectral index softening** $\Delta\gamma_1 = -0.22^{+0.07}_{-0.10}(\text{stat})^{+0.03}_{-0.04}(\text{syst})$

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

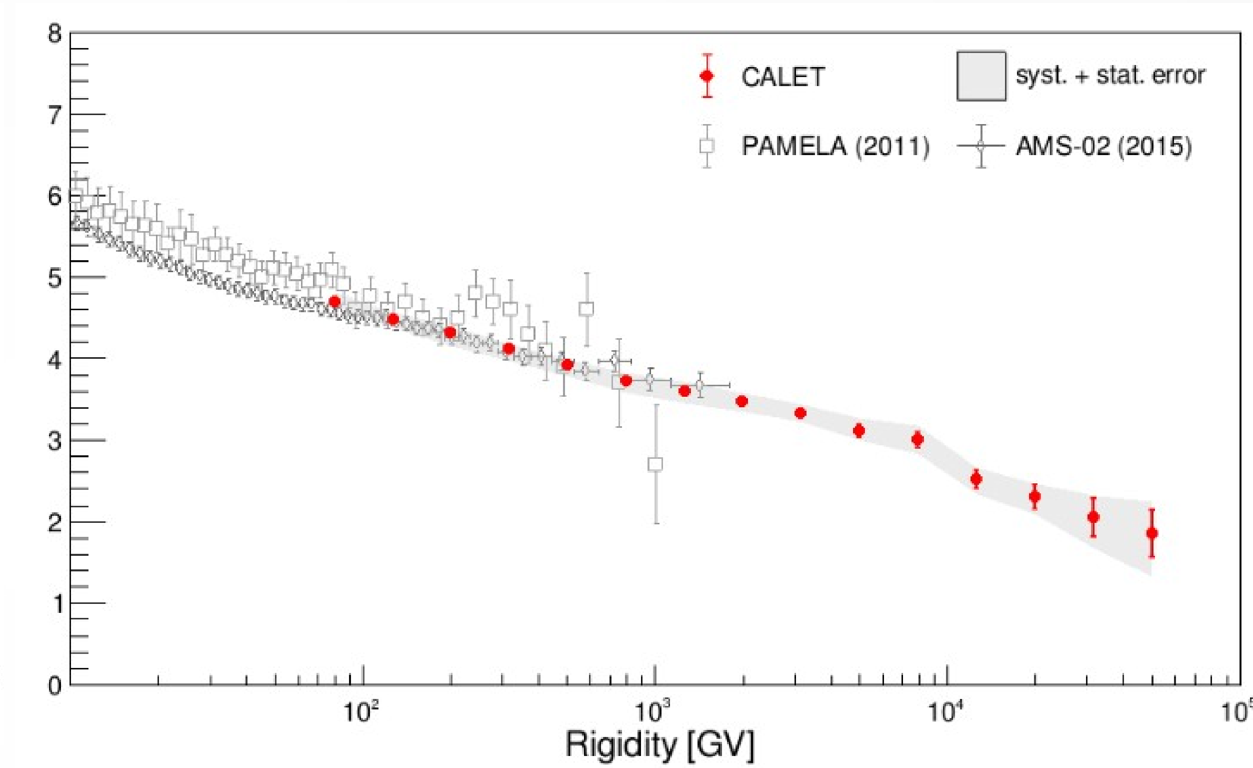
Spectral hardening *Spectral softening*

Proton to Helium ratio

p/He ratio as a function of kinetic energy



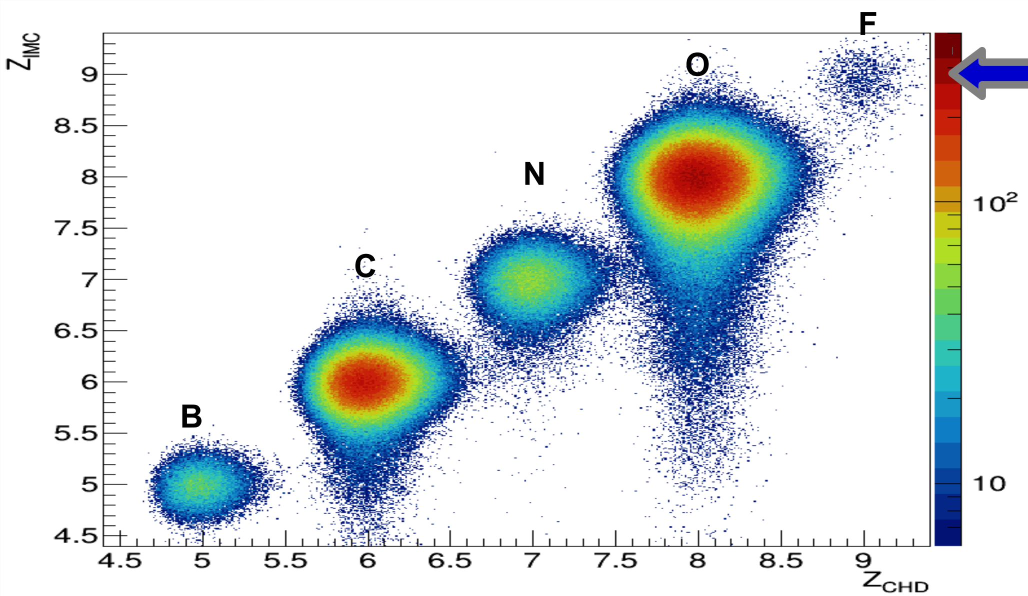
p/He ratio as a function of rigidity



- Good agreement with previous measurements from magnetic spectrometers up to their maximum detectable rigidity
- The spectral index of helium is harder than that of proton (by ~0.1) in the whole rigidity range.
- Possible change of the spectral index of p/He ratio seen above 10 TV will be carefully checked by analyzing higher statistics data in future.

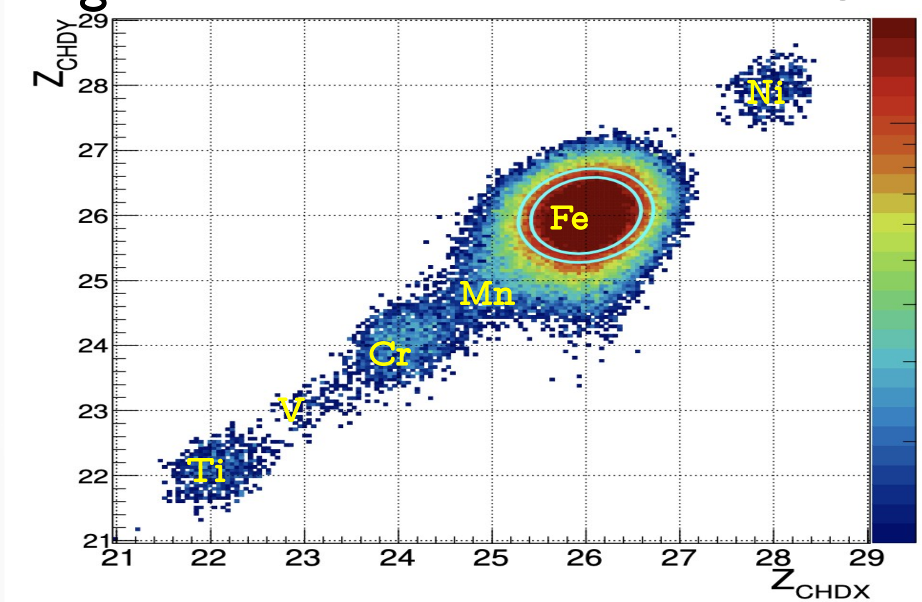
Spectra of Cosmic Ray nuclei from C to Fe

Charge measurement with CHD and IMC

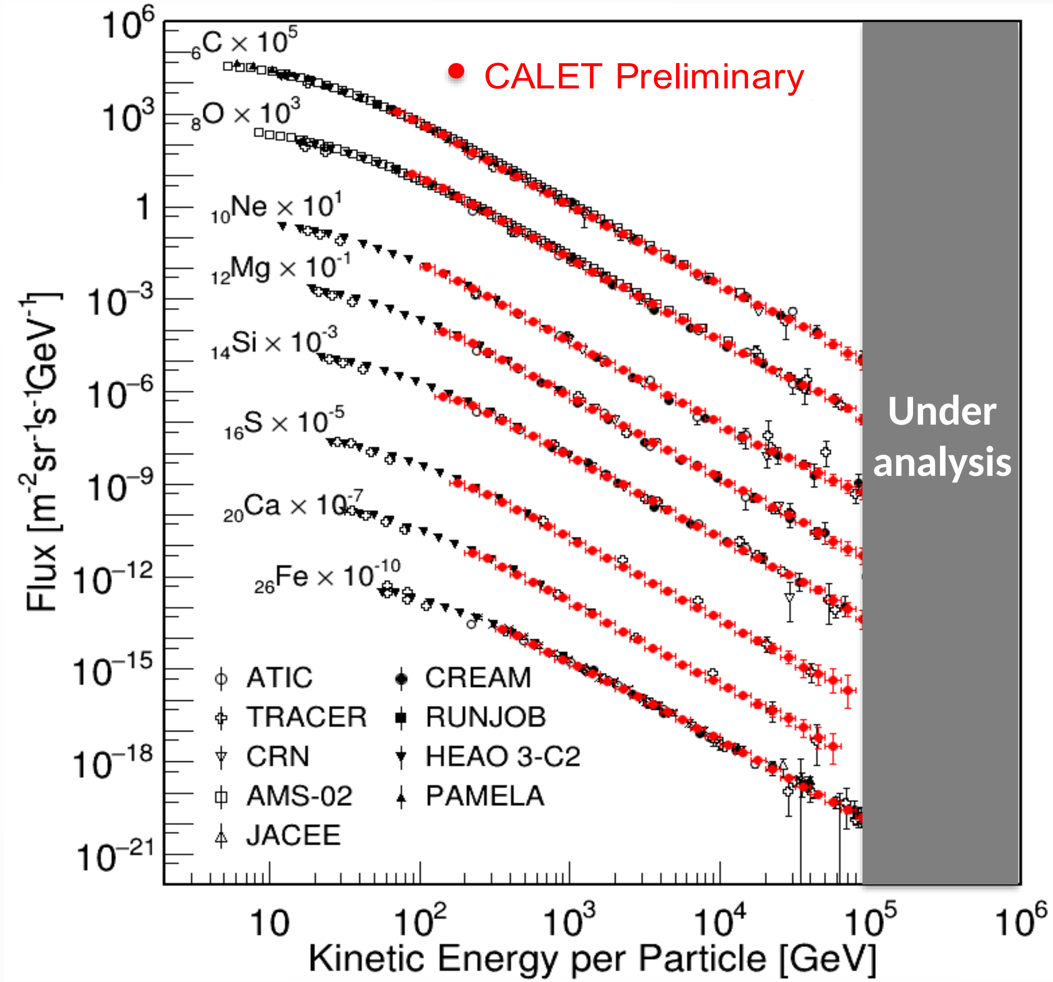


With excellent charge-ID of individual elements CALET is exploring the Table of Elements in the multi-TeV domain

Charge measurement with the two CHD layers

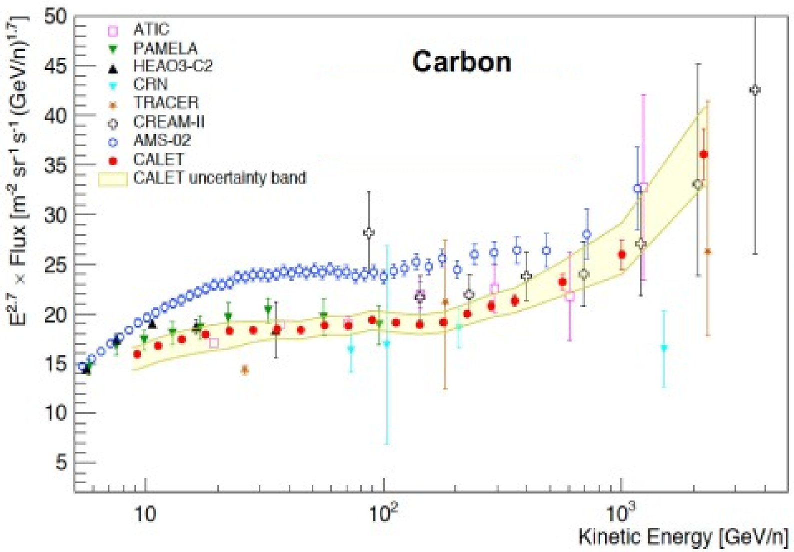


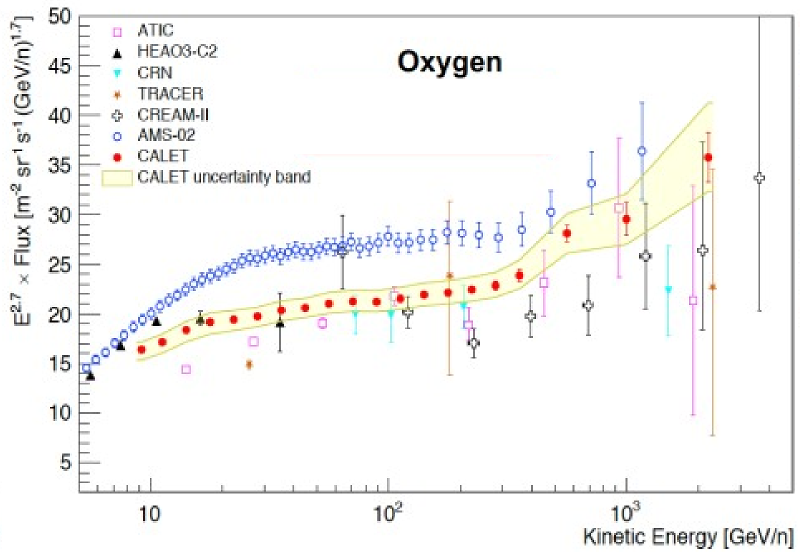
Preliminary Spectra of Carbon – Iron

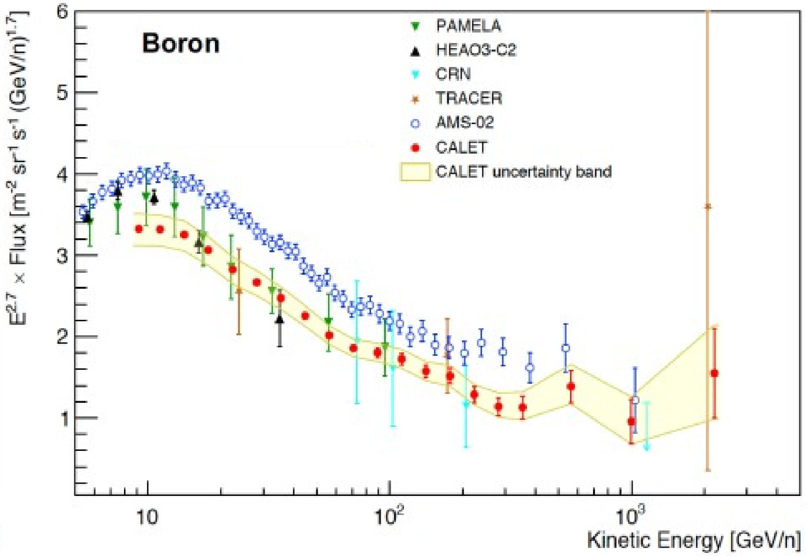


Carbon, Oxygen and Boron Energy Spectra

Flux x $E^{2.7}$ vs kinetic energy per nucleon [8.4 GeV- 3.8 TeV]







Fitting with double power law function

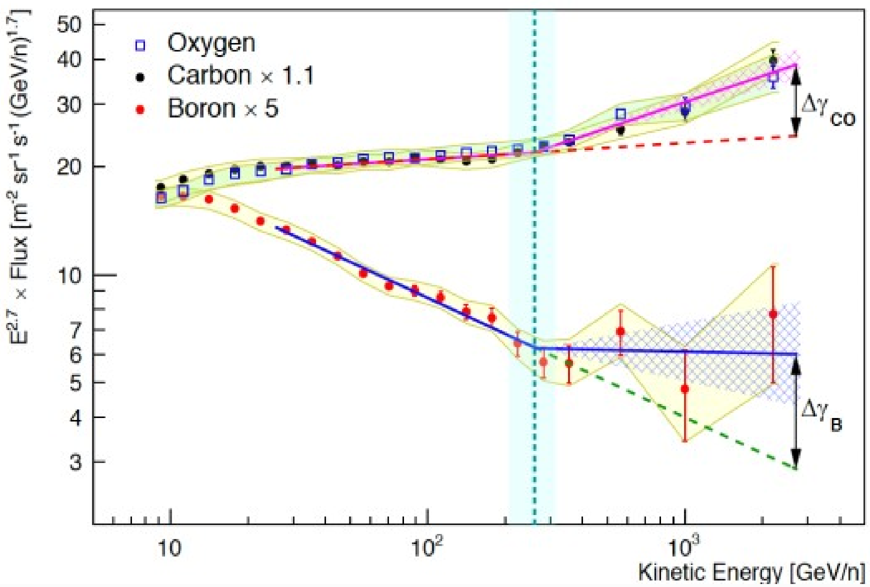
$$\Phi(E) = \begin{cases} c\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma} & E \le E_0 \\ c\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left(\frac{E}{E_0}\right)^{\Delta\gamma} & E > E_0 \end{cases}$$

C-O fit

$\gamma = -2.66 \pm 0.02$
$E_0 = (260 \pm 50)$ GeV/n
$\Delta\gamma = 0.19 \pm 0.04$
$\chi^2/\mathrm{dof} = 23/25$

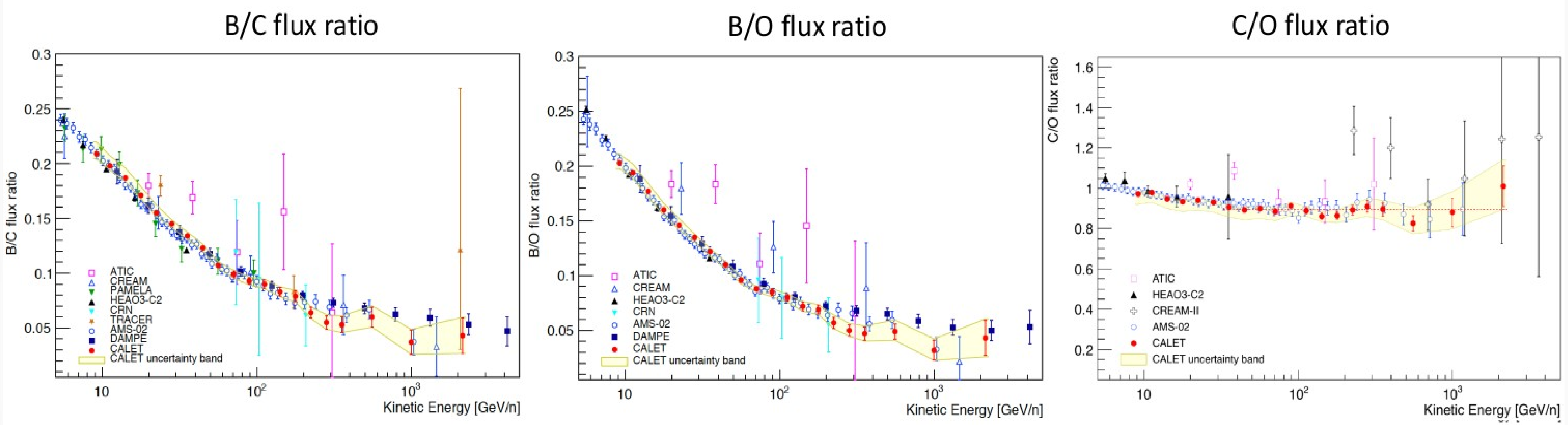
B fit

$\gamma = -3.03 \pm 0.03$
E_0 fixed from C-O
$\Delta\gamma = 0.32 \pm 0.14$
$\chi^2/\mathrm{dof} = 5.2/11$



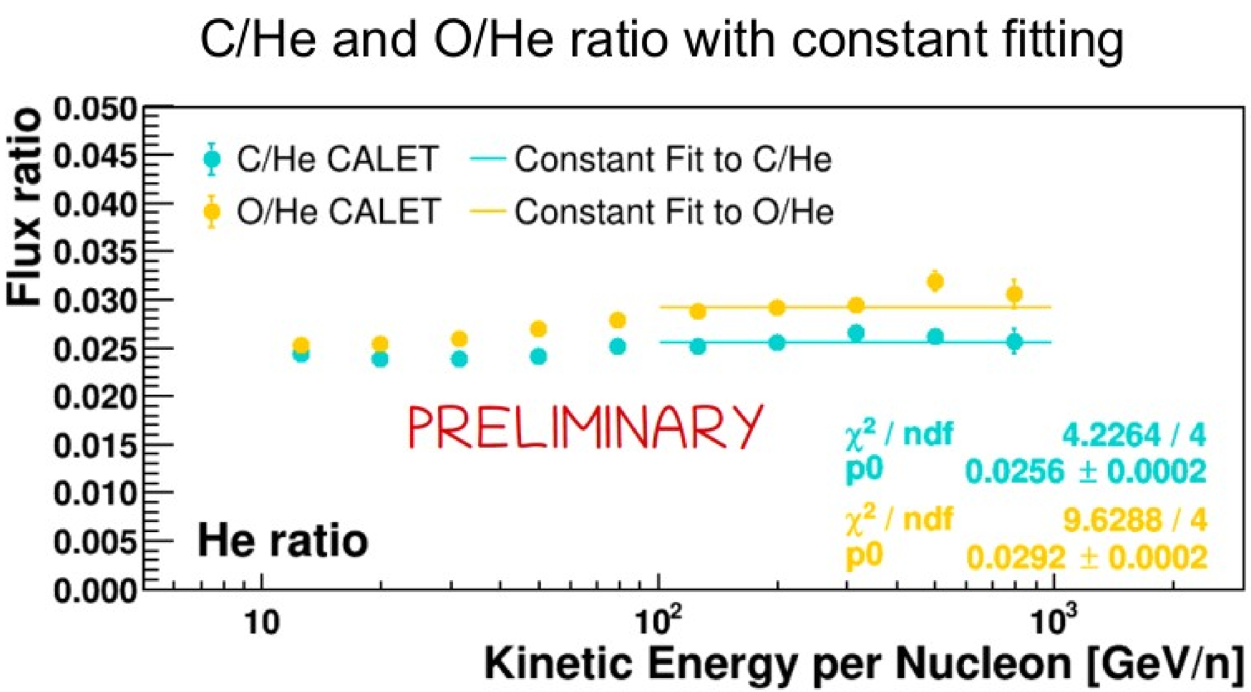
- C and O fluxes harden in a similar way above 200 GeV/n.
- B spectrum clearly different from C-O as expected for primary and secondary CR.
- The flux hardens more for B than for C and O above 200 GeV/n, albeit with low statistical significance.

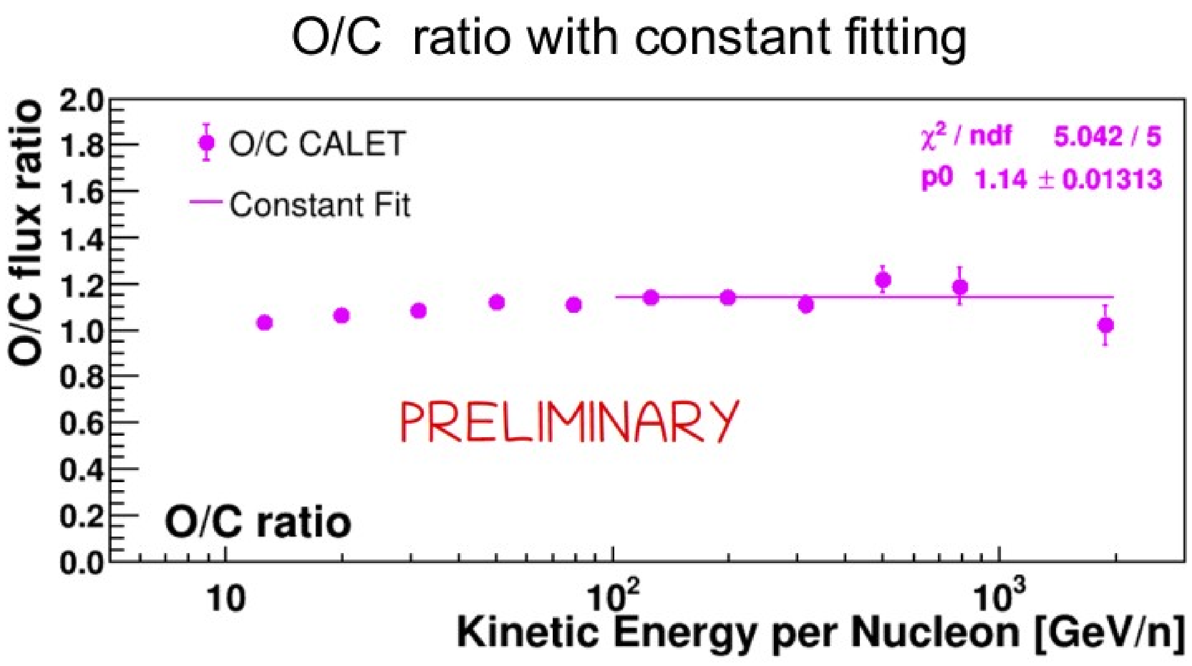
B/C, B/O and C/O Flux Ratio



- Flux ratios of B/C and B/O are in agreement with AMS02 and lower than DAMPE result above 300 GeV/n, although consistent within the error bars.
- C/O flux ratio as a function of energy is in good agreement with AMS-02.
- At E > 30 GeV/n the C/O ratio is well fitted to a constant value 0.90±0.03 with χ^2/dof = 8.1/13.
  ⇨ C and O fluxes have the same energy dependence.

Flux Ratio between Light Nuclei

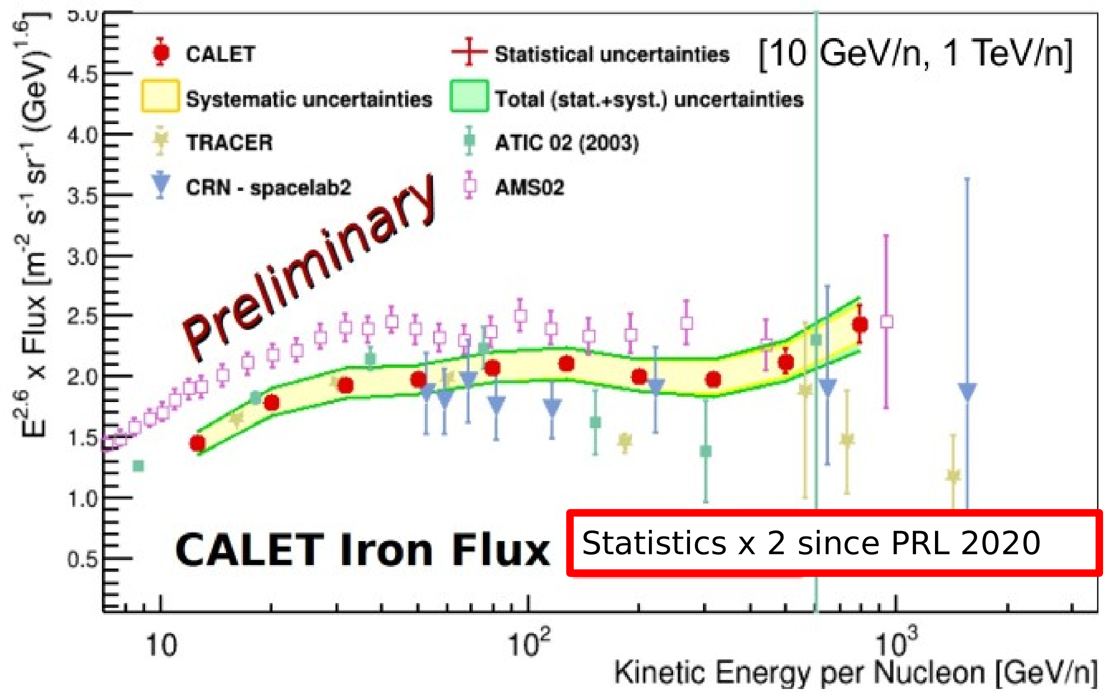




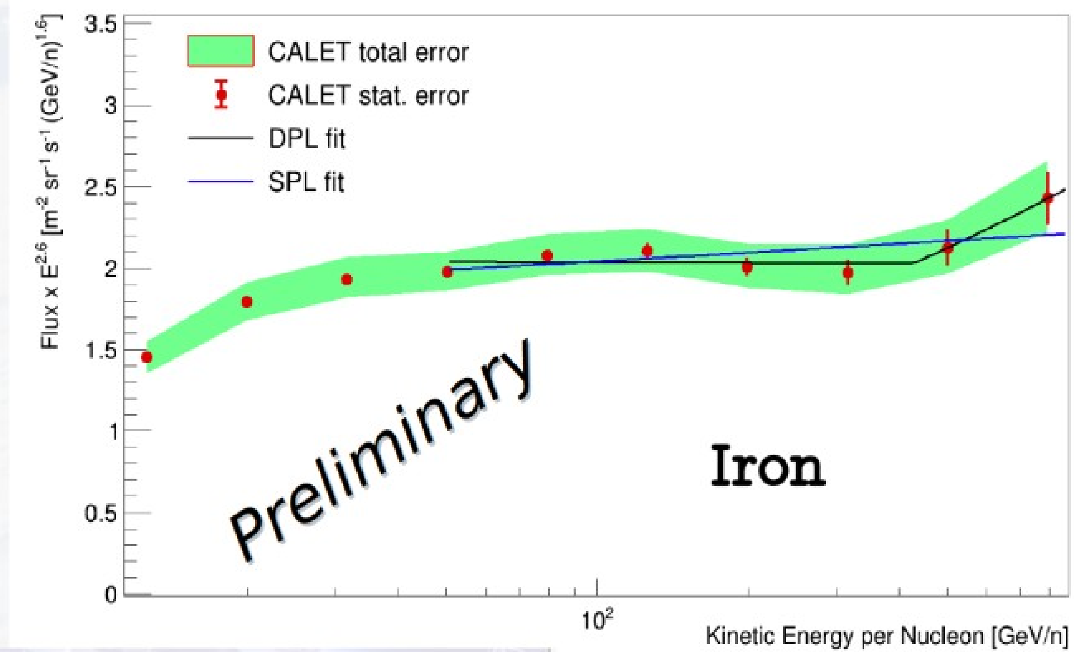
The flux ratio between light nuclei (He, C, O) is constant above 100 GeV/n.

Iron Energy Spectrum

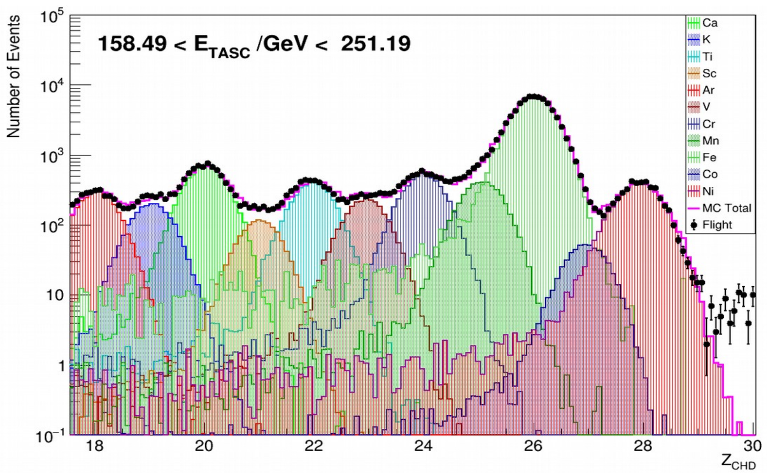
Flux x $E^{2.6}$ vs kinetic energy per nucleon (Nov.2016-Dec.2022)

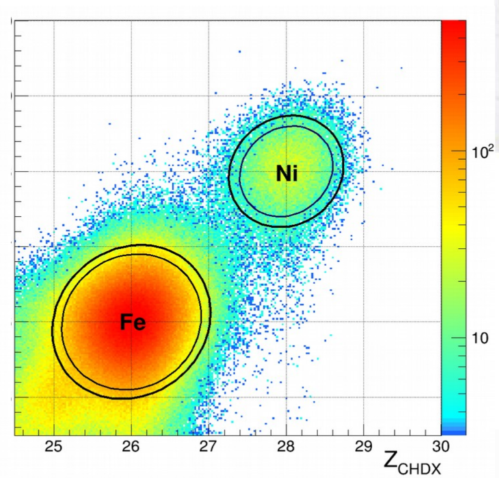


Fit from 50 to 800 GeV/n, with SPL & DPL



Charge separation between Fe and Ni





SPL Fit

$$\Phi(E) = C\left(\frac{E}{1\ \mathrm{GeV}}\right)^{\gamma}$$

- $\gamma = -2.56 \pm 0.01(\mathrm{stat}) \pm 0.03(\mathrm{sys})$
- $\chi^2/\mathrm{DOF} = 2.7/5$

The significance of the fit with the DPL in the studied energy range is not sufficient to exclude the possibility of a single power law

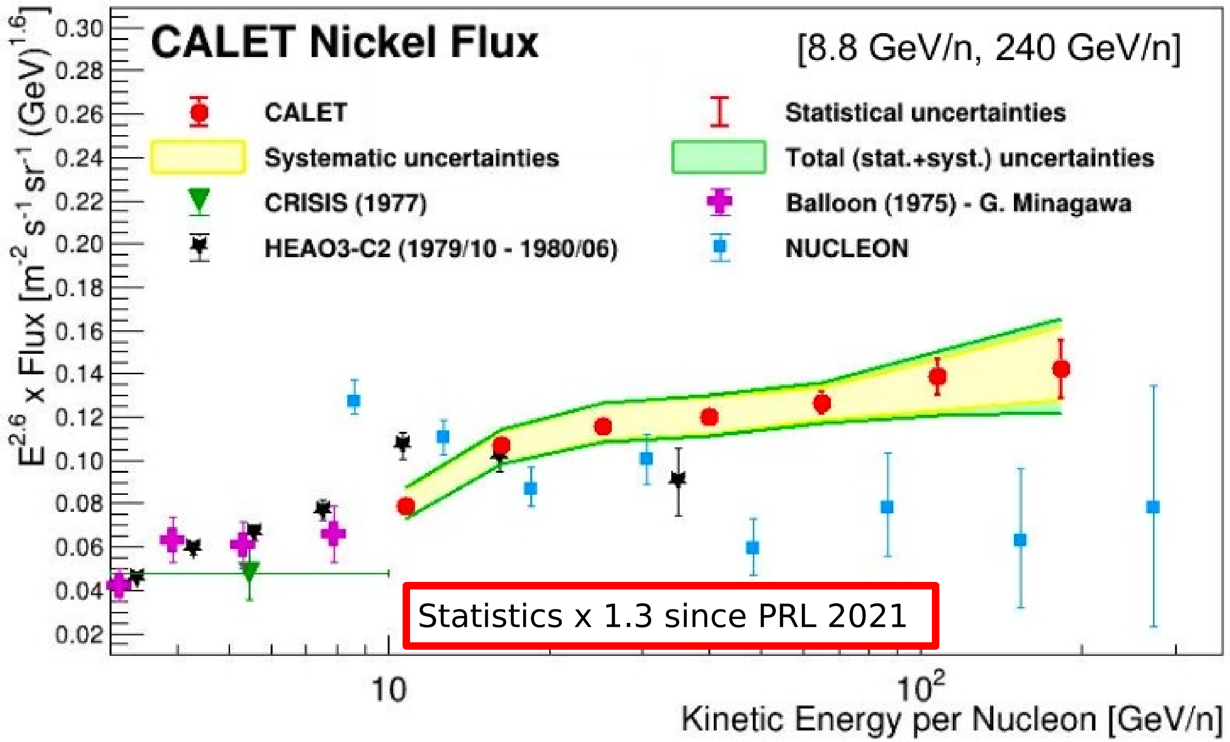
DPL Fit

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

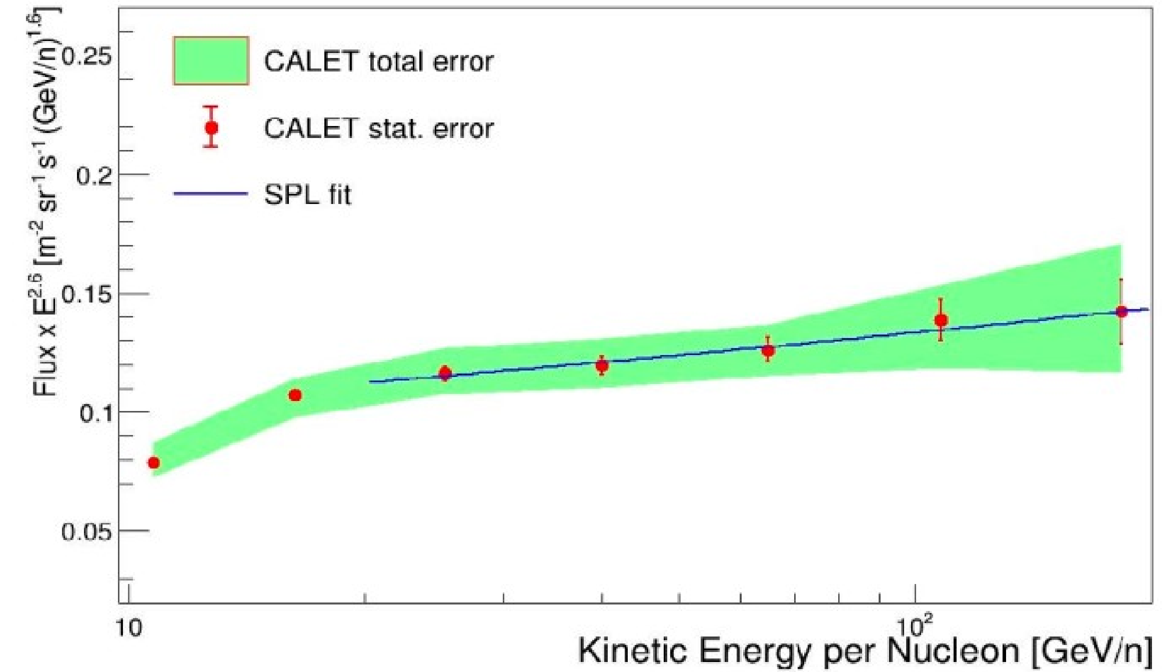
- $\gamma = -2.60 \pm 0.01(\mathrm{stat}) \pm 0.08(\mathrm{sys})$
- $\chi^2/\mathrm{DOF} = 0.8/3$
- $\Delta\gamma = 0.29 \pm 0.27$
- $E_0 = (428 \pm 314)$ Gev/n

Nickel Energy Spectrum

Flux x $E^{2.6}$ vs kinetic energy per nucleon



Fit from 20 to 240 GeV/n, with a SPL

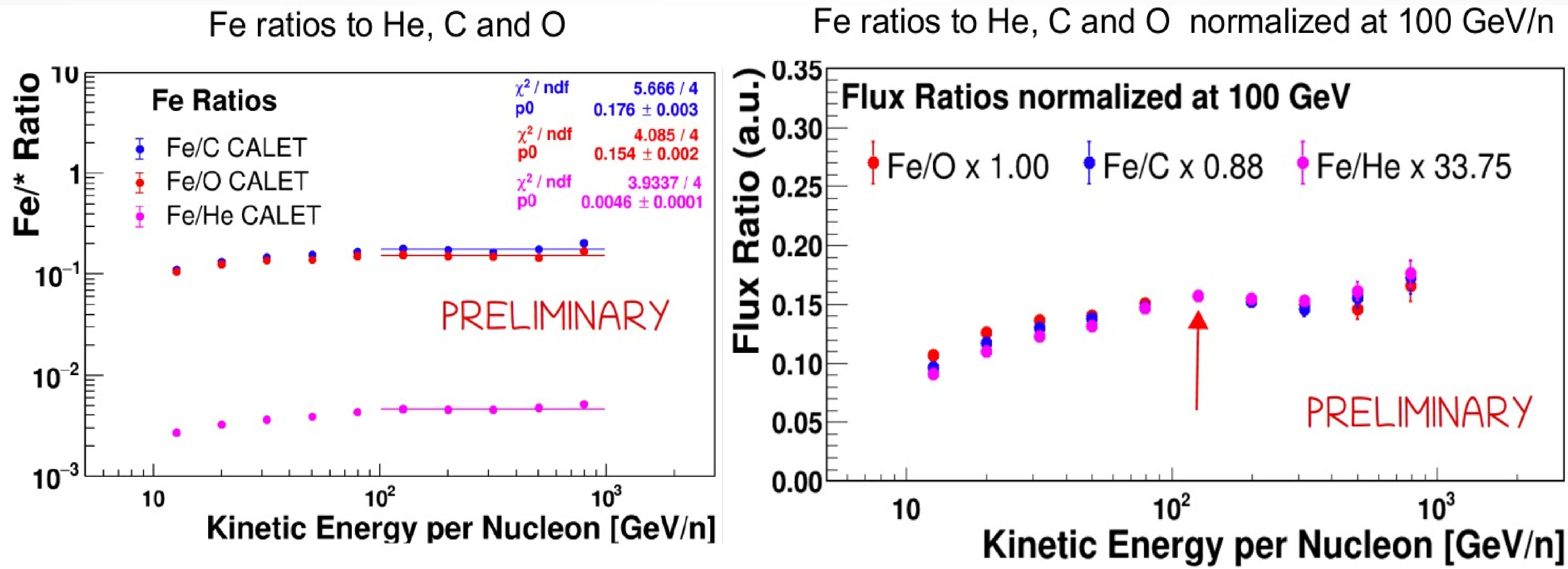


SPL Fit

$$\Phi(E) = C\left(\frac{E}{1\ \mathrm{GeV}}\right)^{\gamma}$$

- $\gamma = -2.49 \pm 0.03(\mathrm{stat}) \pm 0.07(\mathrm{sys})$
- $\chi^2/\mathrm{DOF} = 0.1/3$

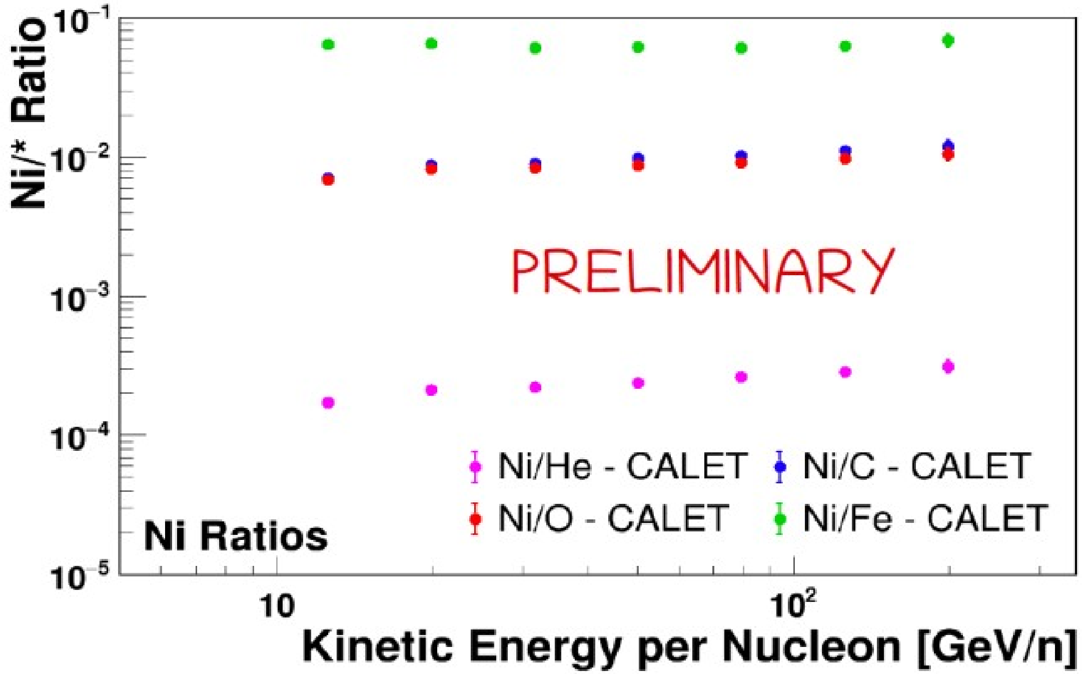
From 20 to 240 GeV/n the nickel flux is consistent with the hypothesis of an SPL Spectrum.



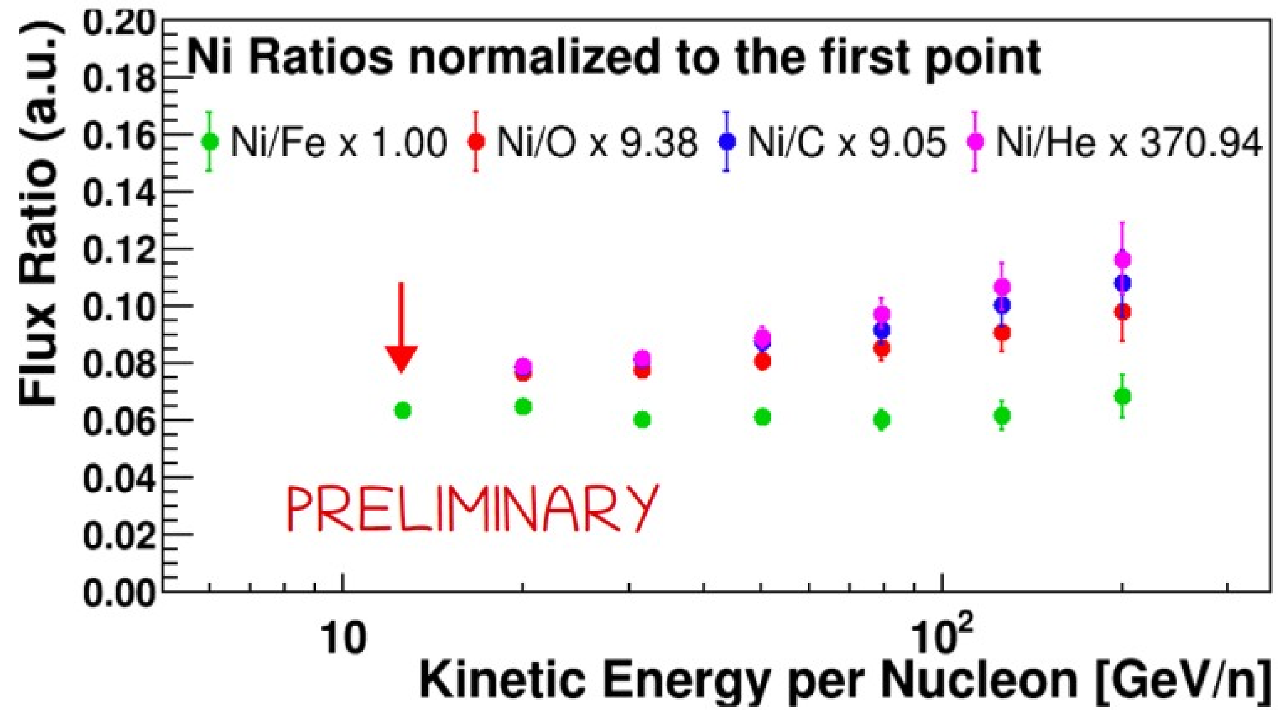
Fe/O, Fe/C and Fe/He are compatible with a constant above 100 GeV/n within errors.
⇨ Fe, O, C, He follow similar propagation

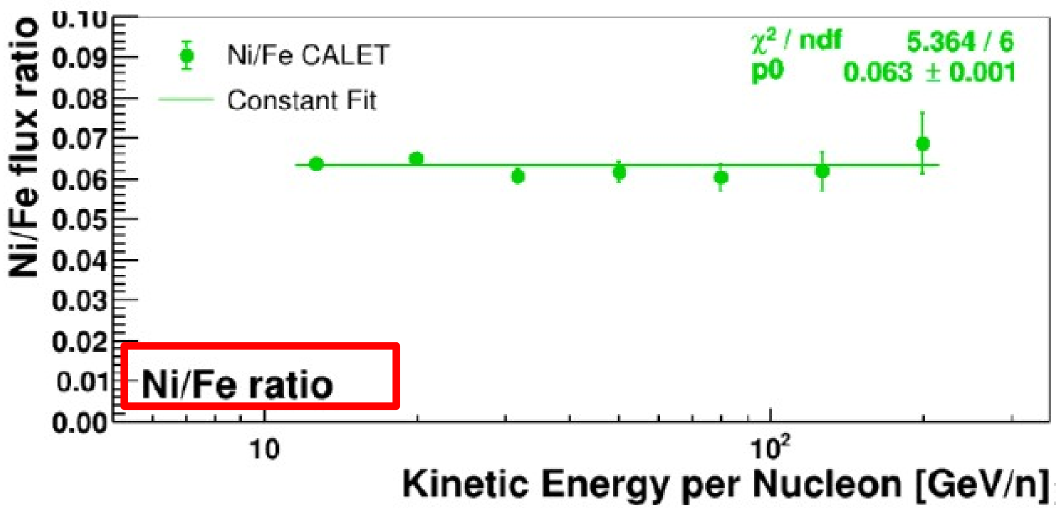
Nickel to Primary Elements Flux ratio

Ni ratios to He, C, O and Fe

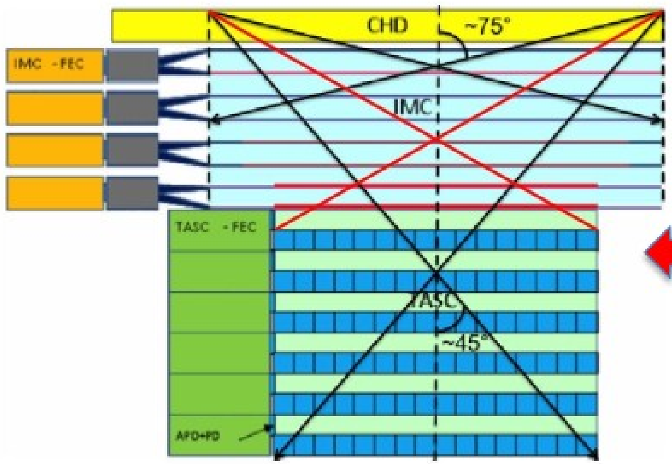


Ni ratios normalized at around 10 GeV/n

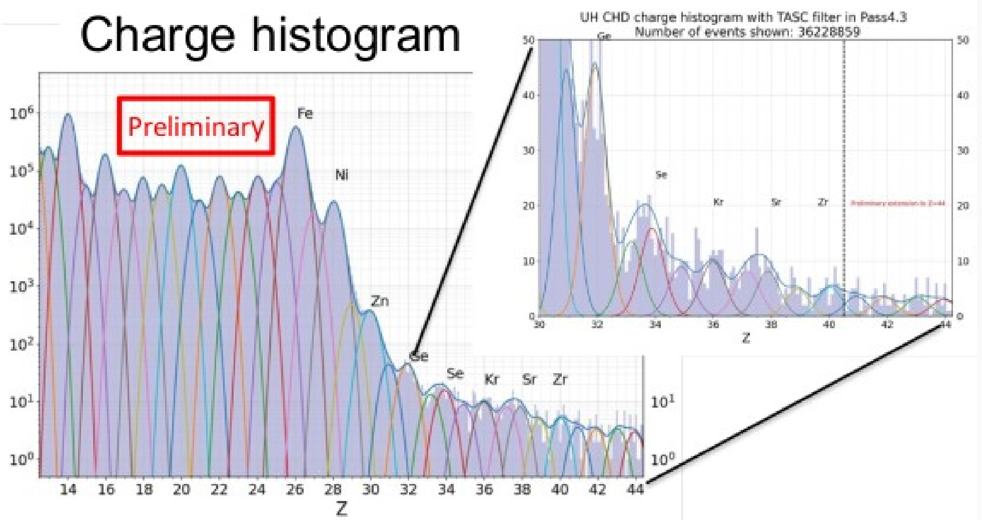




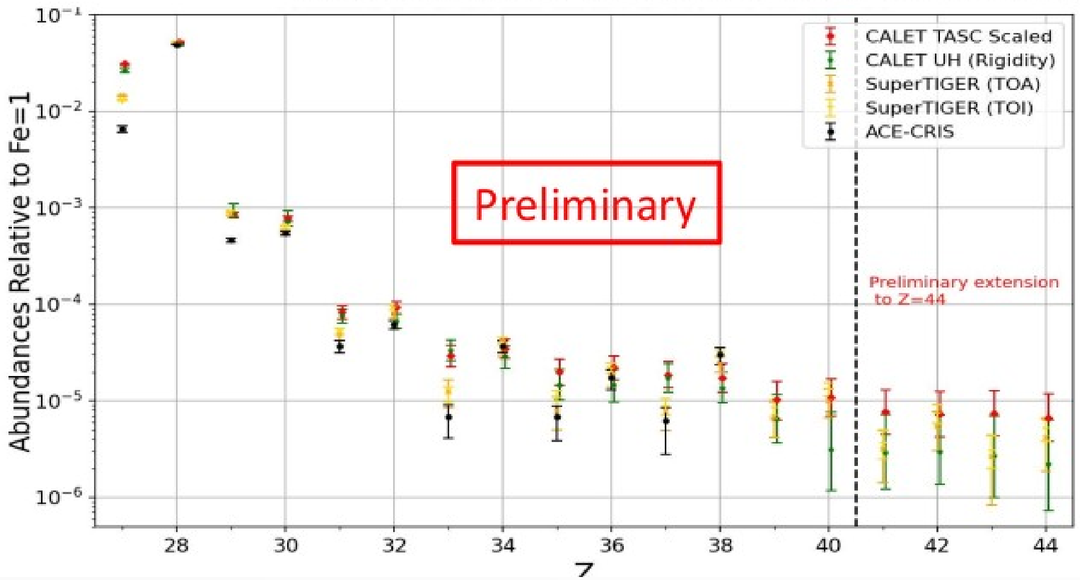
- The Ni/Fe flux ratio is constant in all the energy range thus Ni and Fe have very similar behavior.
- The present energy range of nickel flux does not allow to fit the Ni/* ratios with a constant above 100 GeV/n.
- At low energy the Ni/O, Ni/C, Ni/He flux ratio show an increasing trend also visible in Fe/* ratios.

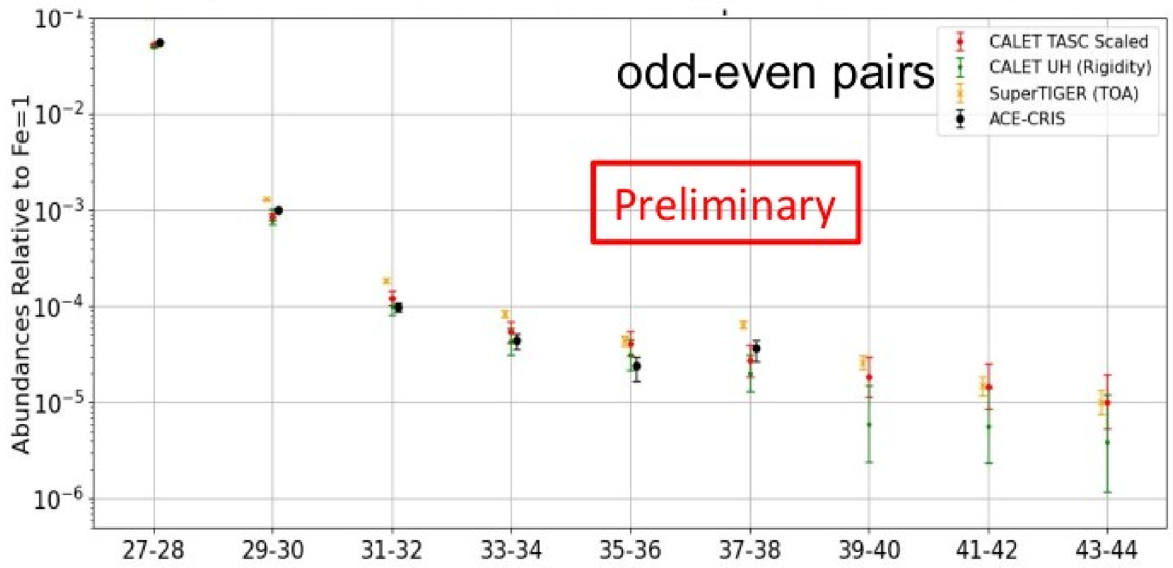


- A special UH CR trigger uses the CHD and the first 4 layers of the IMC to achieve an expanded x 4 geometric factor **GF ~ 4400 cm^2 sr** without energy information. (~260 million events)
- A subset of events pass through the top of the TASC (~65 million events) with energy information,



Mesurement of the relative abundances of the elements above Fe through $_{44}$Ru (Fe =1)





The CALET UH element ratios relative to Fe are consistent with Super-TIGER and ACE abundances.

CALET γ-ray Analysis Overview and GW Follow-up

- Observations with high-energy (HE) trigger are always active (E > ~10 GeV)
- Observations with low-energy gamma (LEG) trigger are active at low geomagnetic latitudes (E > ~1 GeV)
- Trigger of CGBM instrument prompts CALET to temporarily activate LEG mode to search for transient counterparts
- Transient analysis pipeline allows for quick follow-up of GRBs or LIGO/Virgo GW triggers

Observations corresponding to triggers in LIGO/Virgo O3-O4 run was analyzed .

No candidate of EM counterparts was found in CALET data. We obtained upper limits of high energy gamma-ray flux

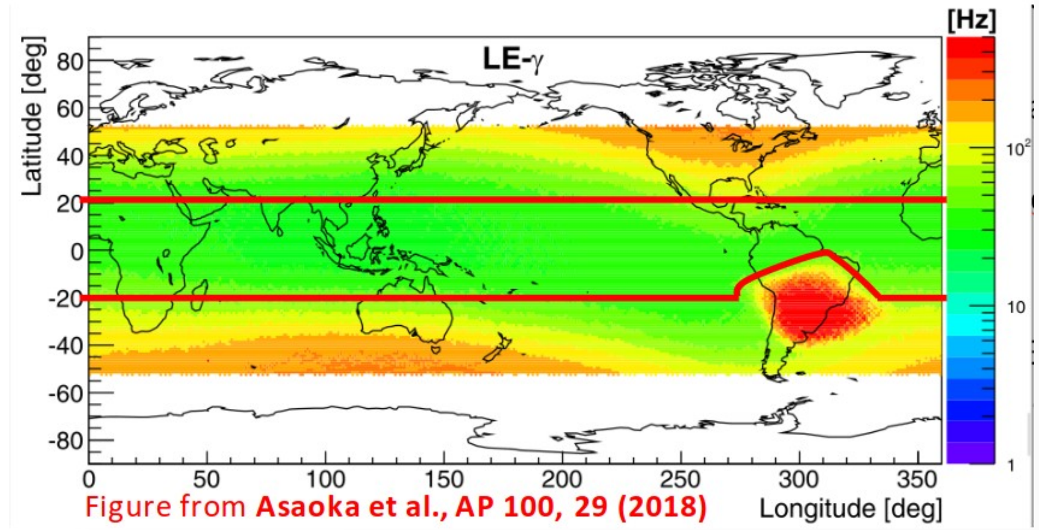
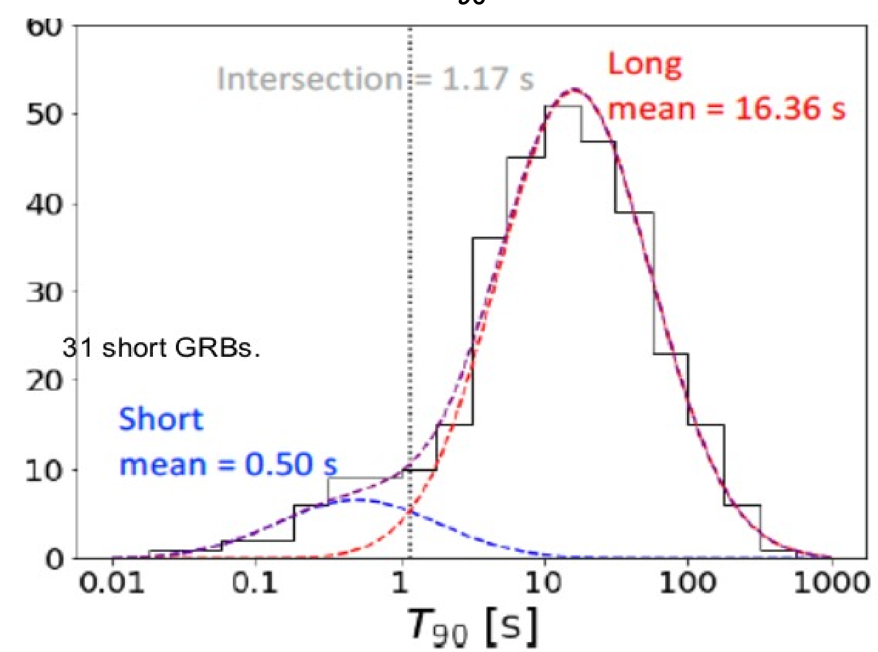


Figure from Asaoka et al., AP 100, 29 (2018)

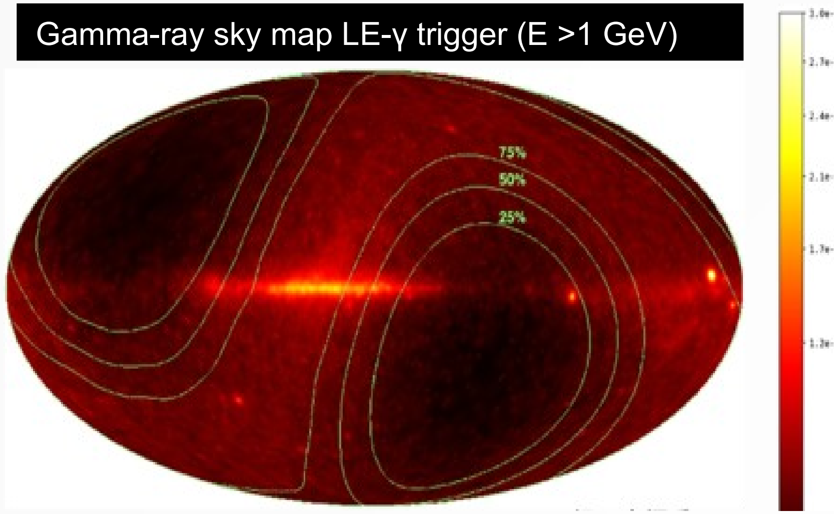
CGBM has detected 327 GRBs as of June 2023

Time distribution (T_{90}) of GRB durations

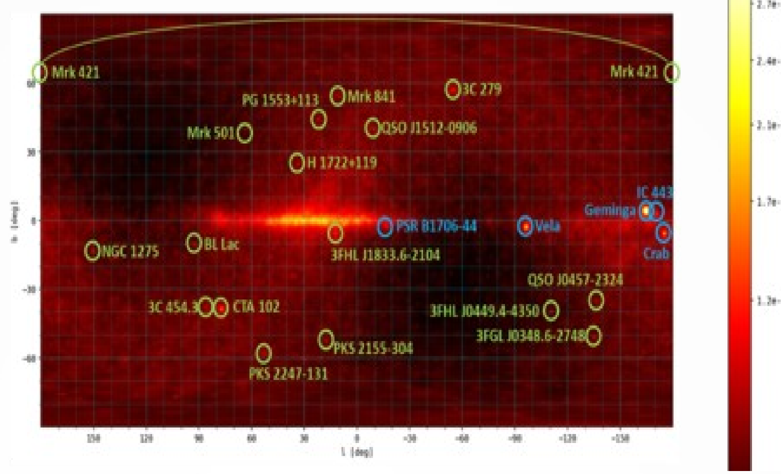


CALET γ-RAY SKY MAP AND ENERGY SPECTRA

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



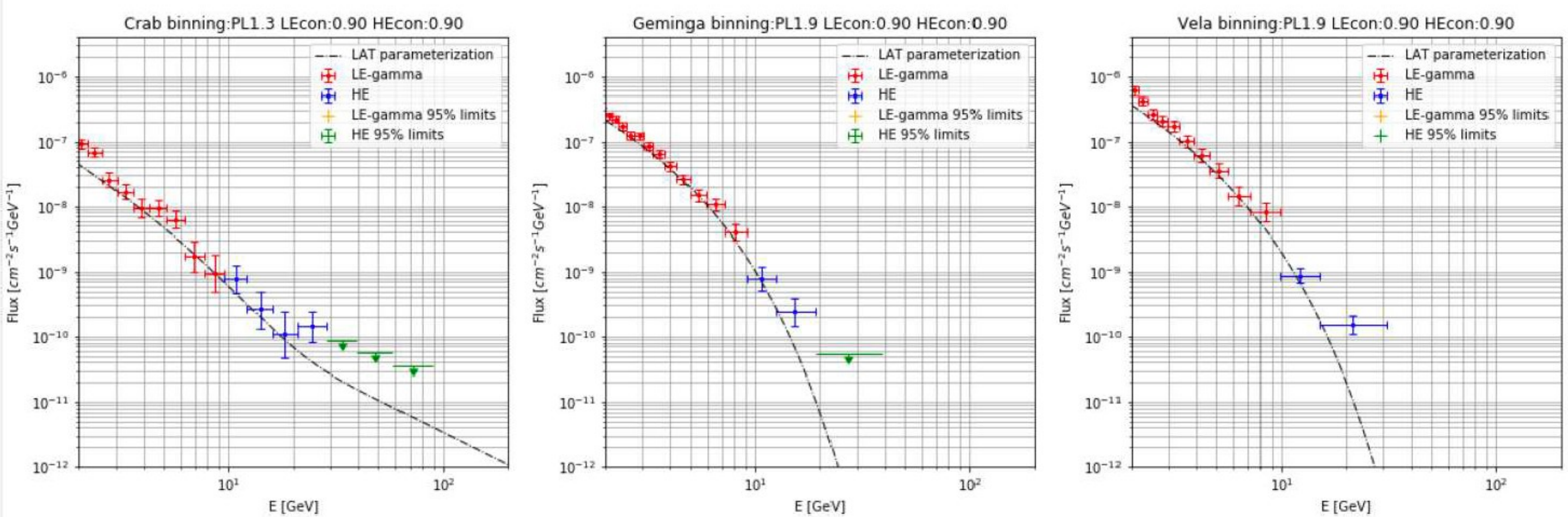
Identified bright point-sources (E >1 GeV)



- Effective area: ~400 cm^2 above 2 GeV
- Angular resolution:< 0.2° above 10 GeV
- Energy resolution: ~5% at 10 GeV

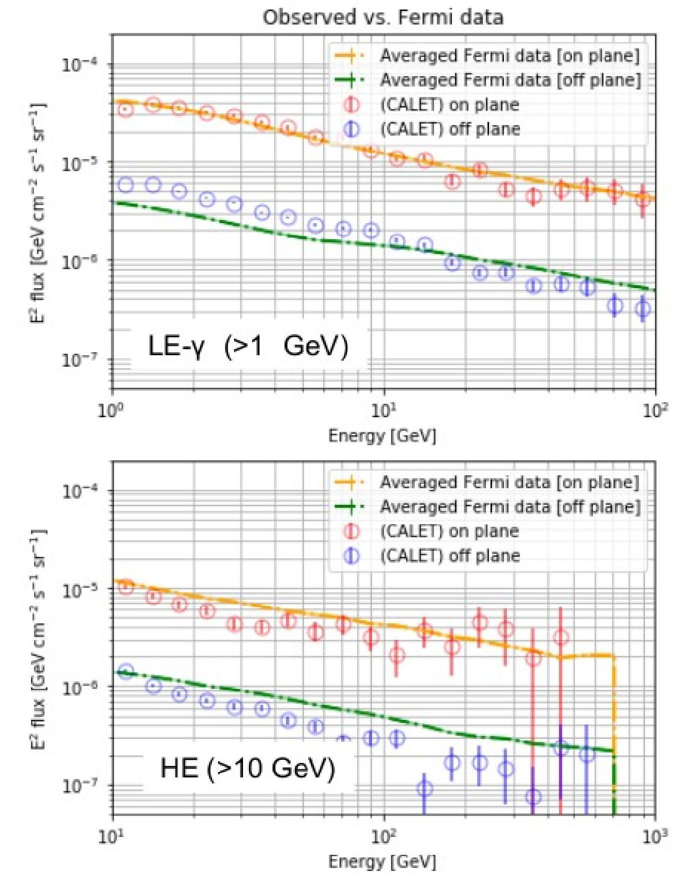
Energy spectra for bright point sources

Preliminary



Gamma-ray spectrum

Preliminary



"On-plane": $|l| < 80°$ & $|b| < 8°$, "Off-plane": $|b| > 10°$

The spectra for point sources and diffuse components are found to be consistent with those by Fermi-LAT

Summary and Future Prospects

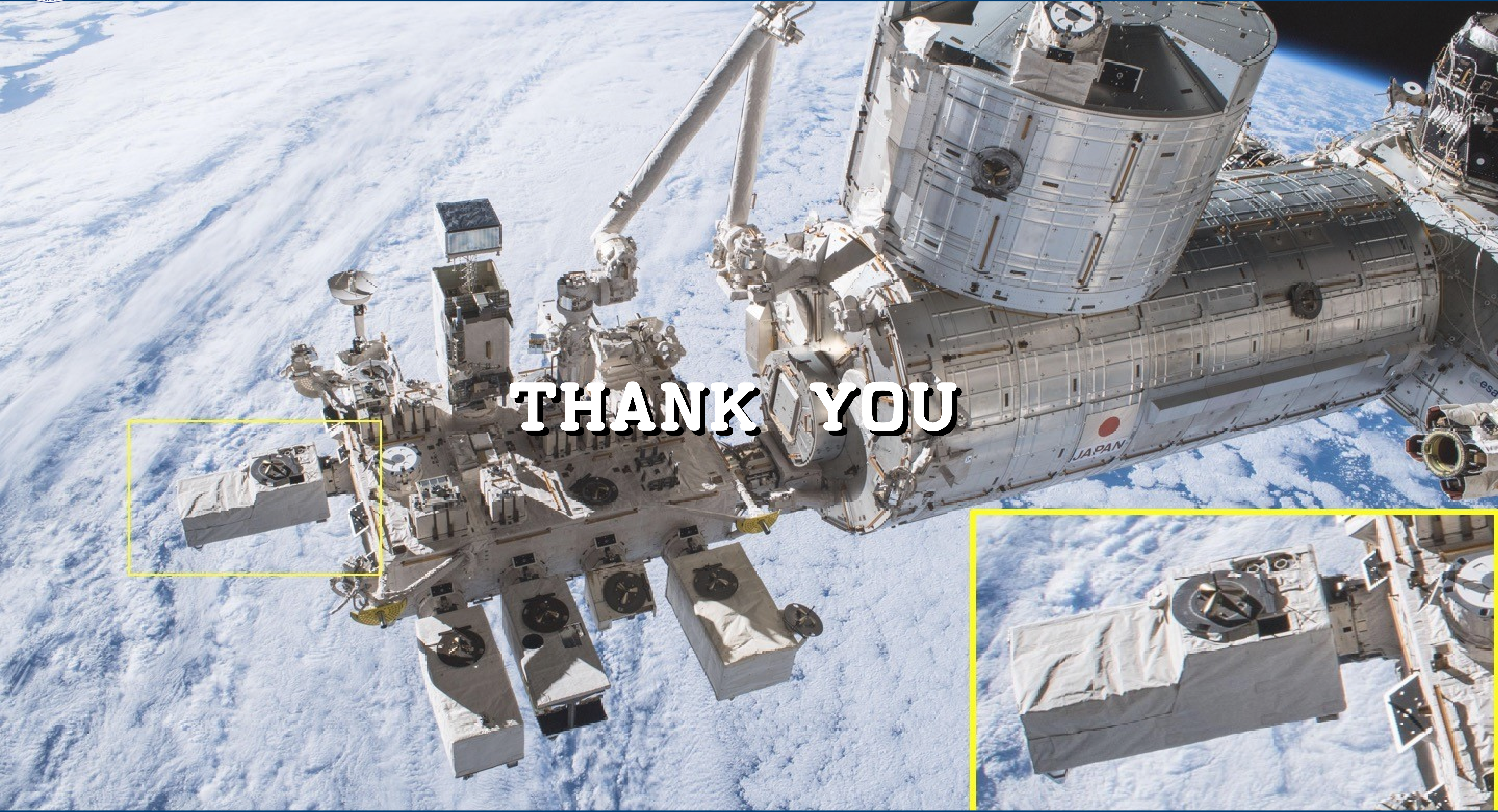
- CALET was successfully launched on Aug. 19th, 2015. The observation campaign started on Oct. 13th, 2015. Excellent performance and remarkable stability of the instrument were confirmed.

- CALET is able to obtain precise measurements of the fluxes of CR electrons up to the TeV region, the energy spectra of CR nuclei from proton to nickel up to hundreds of TeV and secondary-to-primary ratios of individual elements:

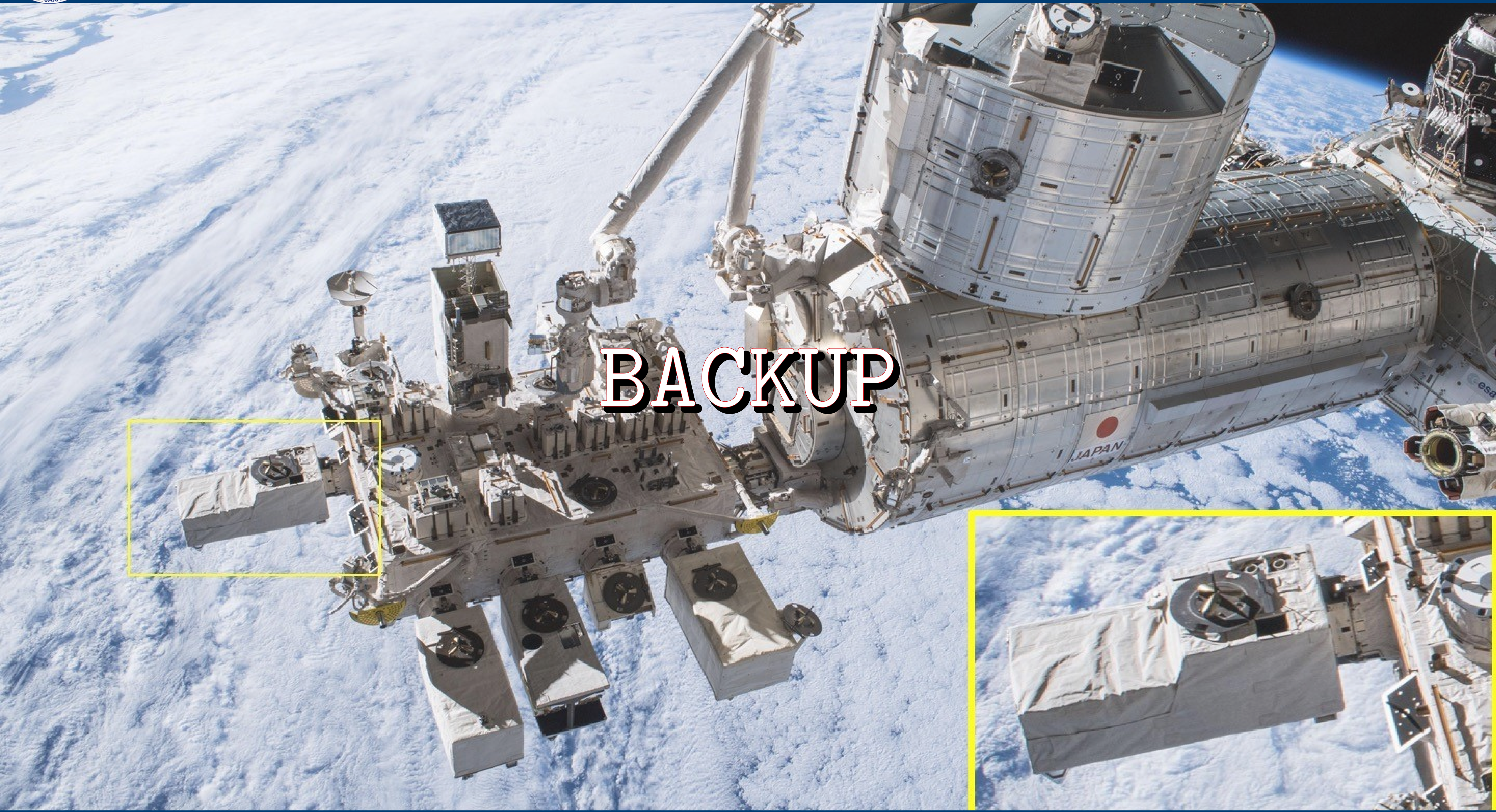
All-electron spectrum in the range 11 GeV – 4.8 TeV	PRL 120, 261102 (2018)	(2^{nd} update)
Proton spectrum in the range 50 GeV – 60 TeV	PRL 129, 101102 (2022)	(2^{nd} update)
Carbon and oxygen spectra in the range 10 GeV/n – 2.2 TeV/n	PRL 125, 251102 (2020)	1^{st} paper
Iron spectrum in the range 50 GeV/n – 2 TeV/n	PRL 126, 241101 (2021)	1^{st} paper
Nickel spectrum in the range 8.8 GeV/n – 240 GeV/n	PRL 128, 131103 (2022)	1^{st} paper
Boron spectrum in the range 8.4 GeV/n – 3.8 TeV/n	PRL 129, 251103 (2022)	new
Helium spectrum in the range 40 GeV – 250 TeV	PRL 130, 171002 (2023)	new
Preliminary analysis of ultra-heavy cosmic-ray abundances	(ICRC2023)	preliminary

- Analysis of gamma-ray sources and transients continues:
  GW follow-up and GRB analysis with CGBM & CAL : ApJL 829:L20 (2016)
  Counterpart search in LIGO/Virgo O3 with CGBM & CAL: ApJ 933:85 (2022)

Extended operations approved by JAXA/NASA/ASI in March 2021 through the end of 2024 (at least)


THANK YOU
JAPAN
esa

BACKUP

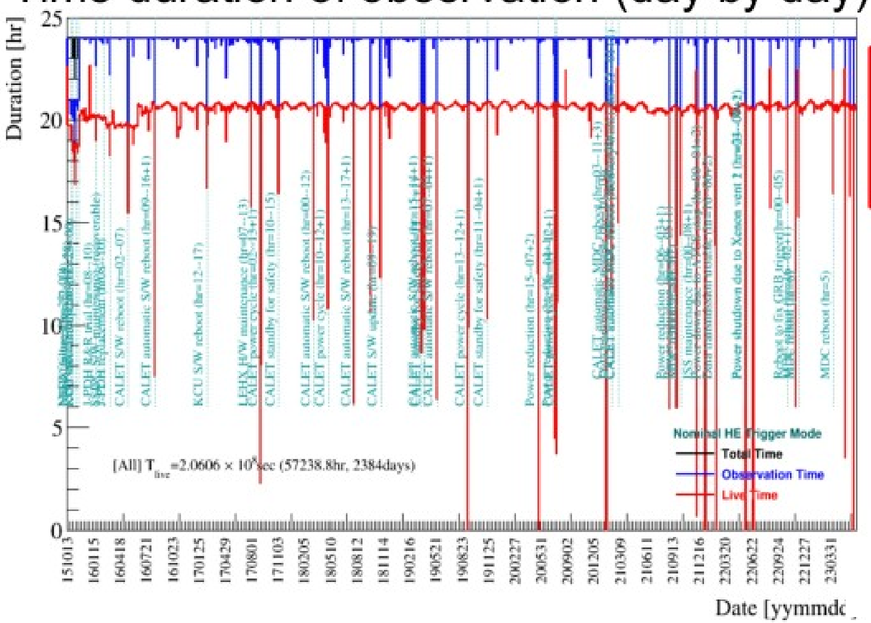


CALET Orbital Operations (first 7.5 years)

Geometrical Factor:
- 1040 cm^2 sr for electrons, light nuclei
- 1000 cm^2 sr for gamma-rays
- 4000 cm^2sr for ultra-heavy nuclei

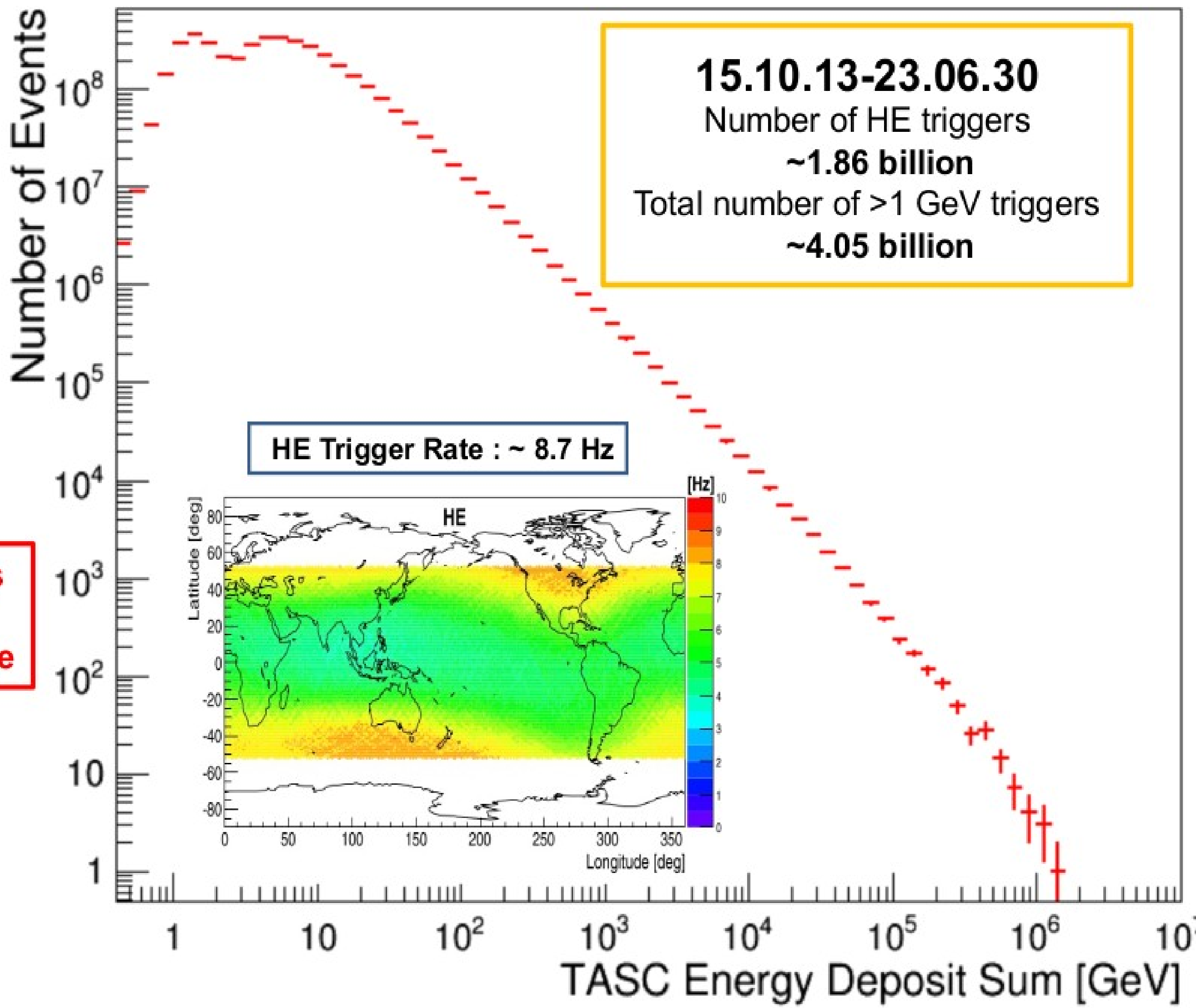
High-energy trigger (> 10 GeV) statistics:
- Orbital operations : **2818 days (>7.5 years)** as of June 30, 2023
- Observation time : 2.39×10^8 sec
- Live time fraction: **~ 86%**
- Exposure of HE trigger : **~250 m^2 sr day**

Time duration of observation (day by day)



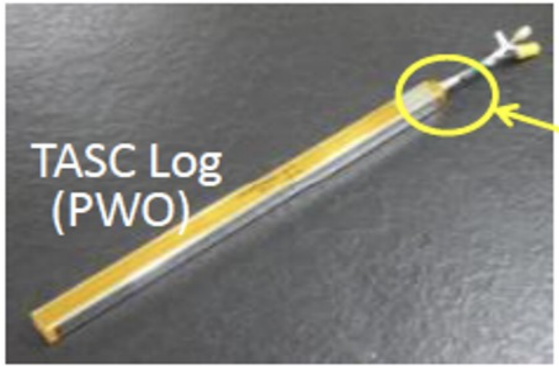
20.6 hours per day on average

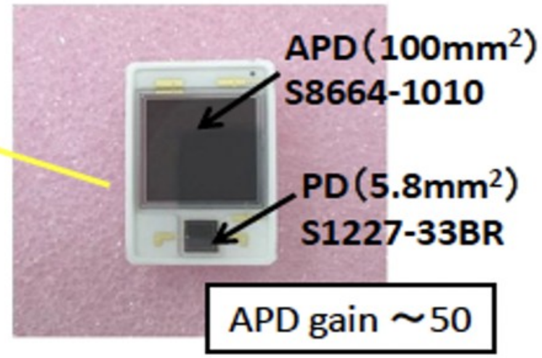
Energy deposit (in TASC) spectrum: 1 GeV-1 PeV



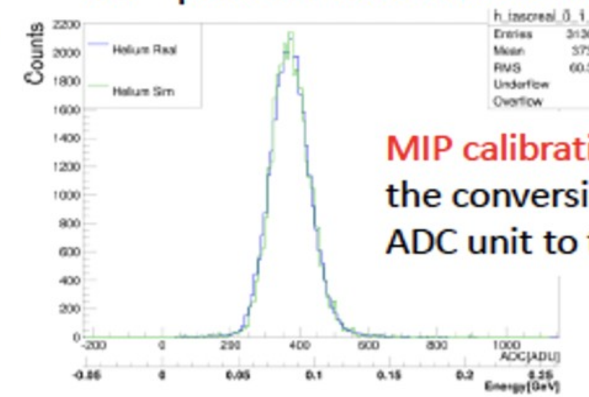
LK

Energy measurements: wide dynamic range 1-10^6 MIPs

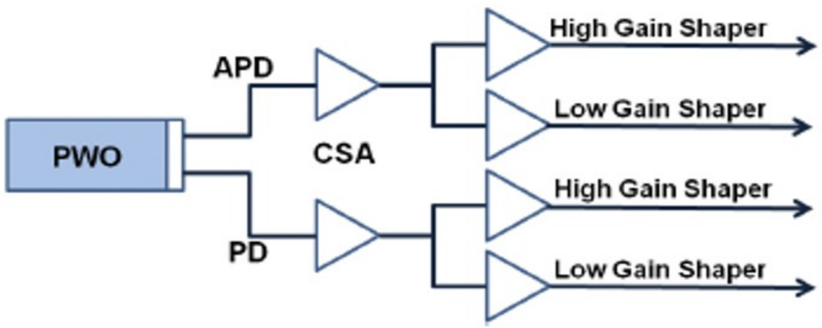




"MIP" peak in PWO: Obs. vs. MC



MIP calibration determines the conversion factor from ADC unit to the energy

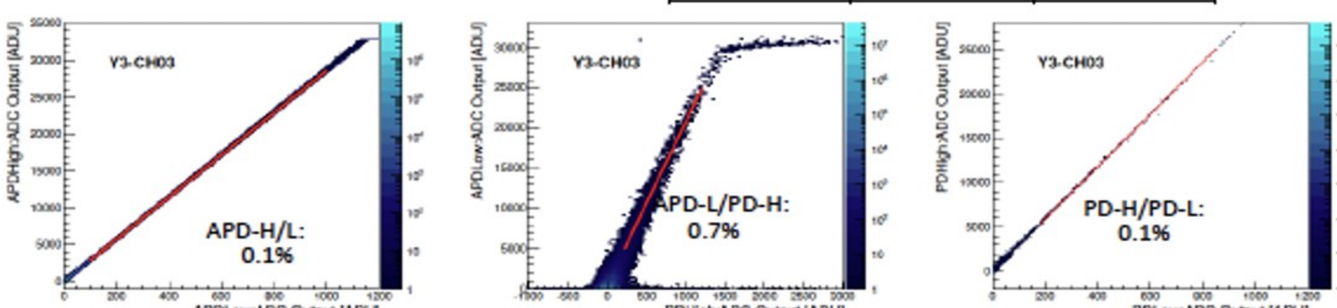


The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

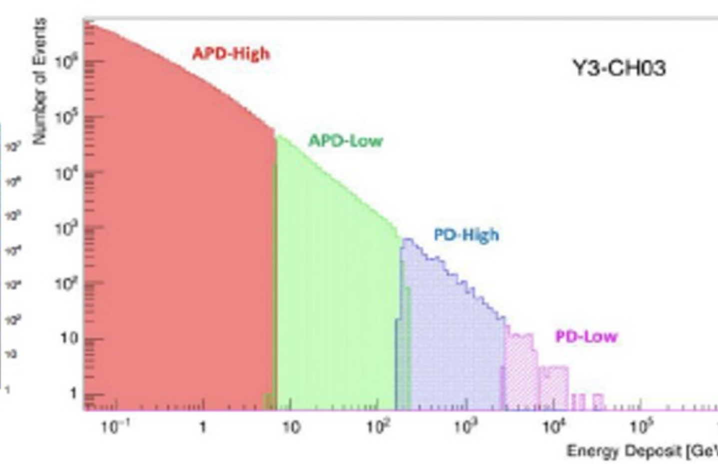
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

The correlation between adjacent gain ranges is calibrated by using in-flight data in each channel.

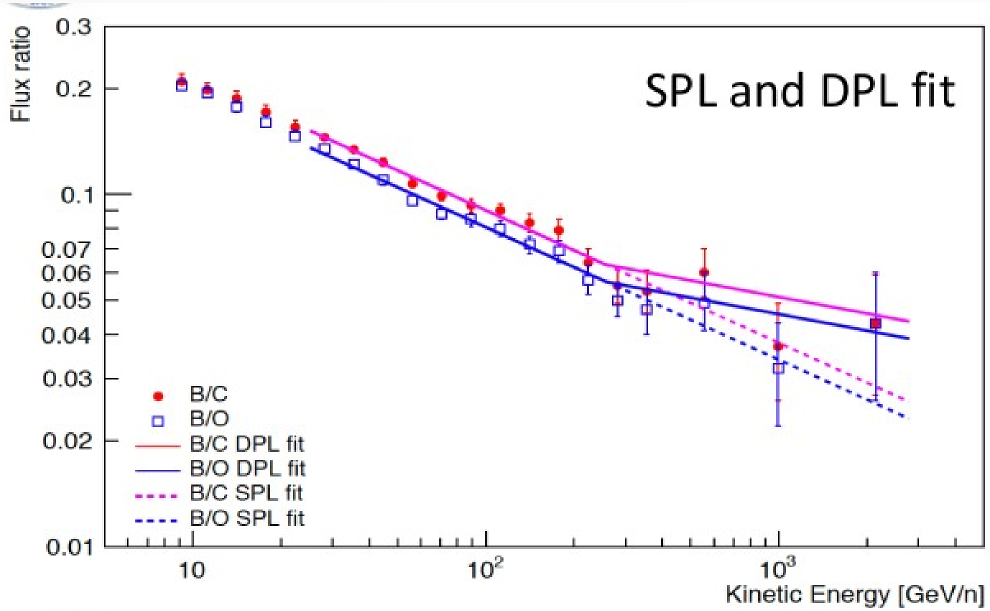
APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%

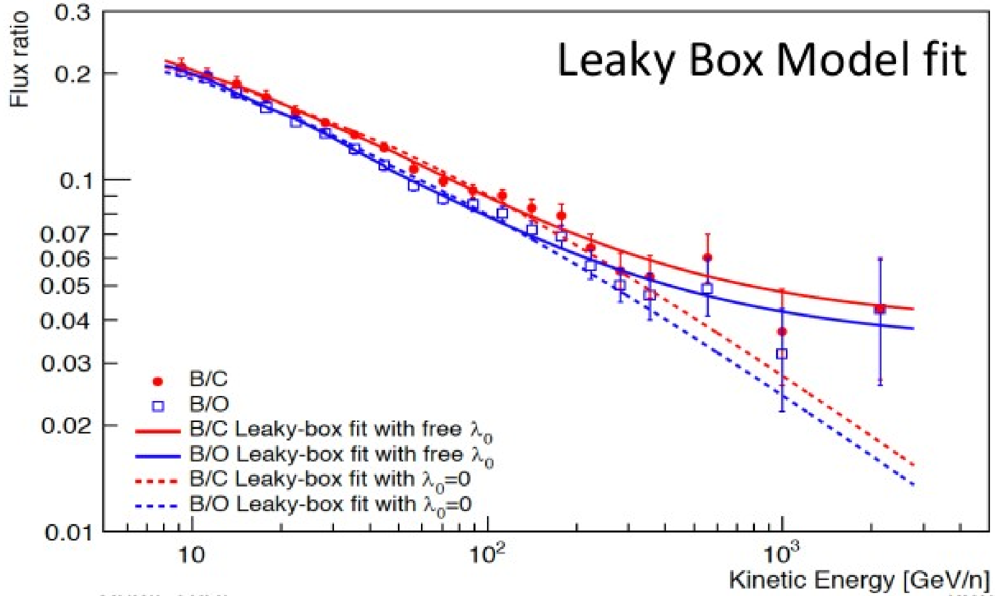


Example of energy distribution in one PWO log



B/C, B/O and C/O Flux Ratio





Simultaneous fit to B/C and B/O (E>25 GeV/n) with same parameters except normalization

SPL fit	$\Gamma = -0.376 \pm 0.014$	(χ^2/dof = 19/27)
DPL fit	$\Delta\Gamma = 0.22 \pm 0.10$	(χ^2/dof = 15/26)

Leaky-box model fit [ApJ **752** 69 (2012)]

$$\frac{\Phi_B(E)}{\Phi_C(E)} = \frac{\lambda(E)\lambda_B}{\lambda(E)+\lambda_B}\left[\frac{1}{\lambda_{C\to B}} + \frac{\Phi_O(E)}{\Phi_C(E)}\frac{1}{\lambda_{O\to B}}\right] \quad \frac{\Phi_B(E)}{\Phi_O(E)} = \frac{\lambda(E)\lambda_B}{\lambda(E)+\lambda_B}\left[\frac{1}{\lambda_{O\to B}} + \frac{\Phi_C(E)}{\Phi_O(E)}\frac{1}{\lambda_{C\to B}}\right]$$

$\lambda(E)$: mean escape path length

$\lambda(E) = kE^{-\delta} + \lambda_0$

λ_0 : residual path length

δ : diffusion coefficient spectral index

Fit parameters	λ_0=0 fixed	λ_0 free
k (g/cm^2)	13.1 ± 0.2	13.0 ± 0.3
δ	0.61 ± 0.01	0.81 ± 0.04
λ_0 (g/cm^2)	0	1.17 ± 0.16
χ^2/dof	58.3/38	17.9/37

Significance of $\lambda_0 \neq 0$ > 5σ
⇨ Residual path length could explain the flattening of B/C, B/O ratios at high energies.

Beam Test Calibration

The energy response of the TASC derived from the MC simulations was tuned using the results of a beam test carried out at the CERN-SPS in 2015 with beams of accelerated ion fragments of 150 GeV/c/n.

- **Correction factors are:**
  - → 6.7% for $E_{TASC} < 45$ GeV;
  - → 3.5% for $E_{TASC} \geq 350$ GeV;
  - → linear interpolation for $45 \leq E_{TASC} < 350$ GeV.

- **Good linearity up to maximum available beam energy (~6 TeV) between the observed TASC energy and the primary energy.**
- **Fraction of particle energy released in TASC is ~20%.**

- **Energy resolution around 30%.**