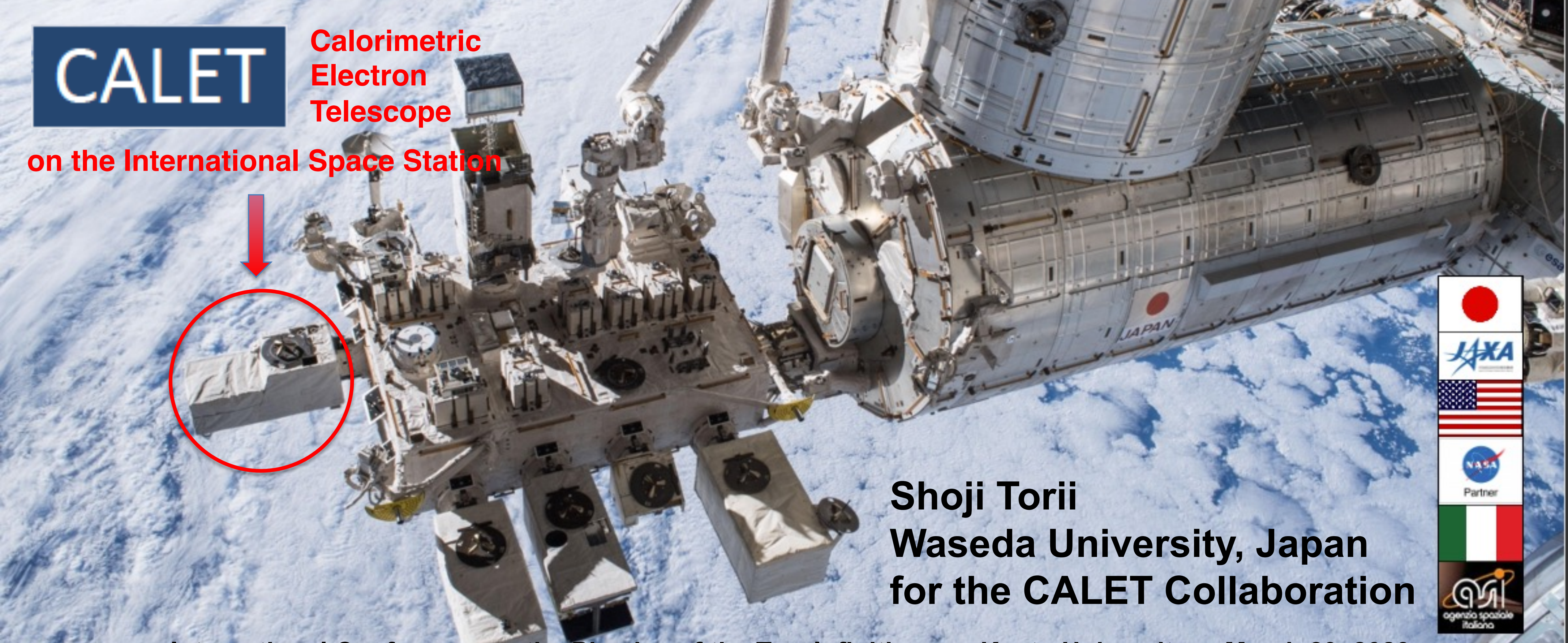
The Latest Results of CALorimetric Electron Telescope (CALET) on the International Space Station



Shoji Torii
Waseda University, Japan
for the CALET Collaboration

International Conference on the Physics of the Two Infinities   Kyoto University   March 29, 2023

The CALET collaboration member

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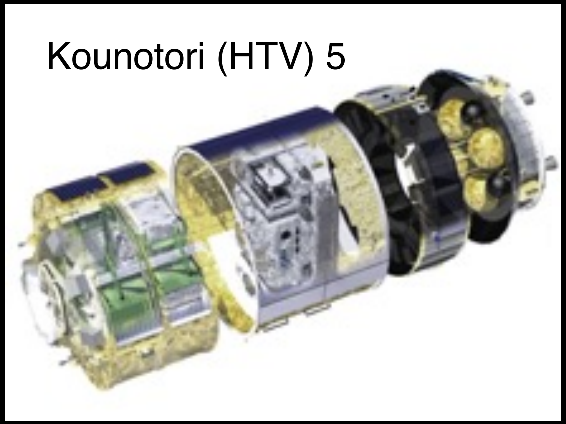
Co-PI : Italy
Co-PI : USA

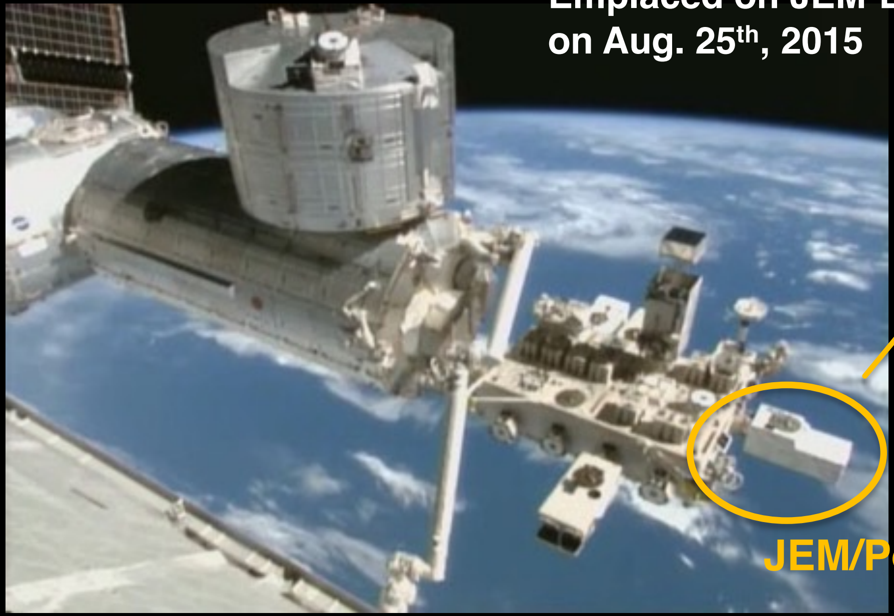
Guest Investigator: Lauren W. Blum (University of Colorado Boulder, USA), M. Teramoto (Kyushu Institute of Technology, Japan)

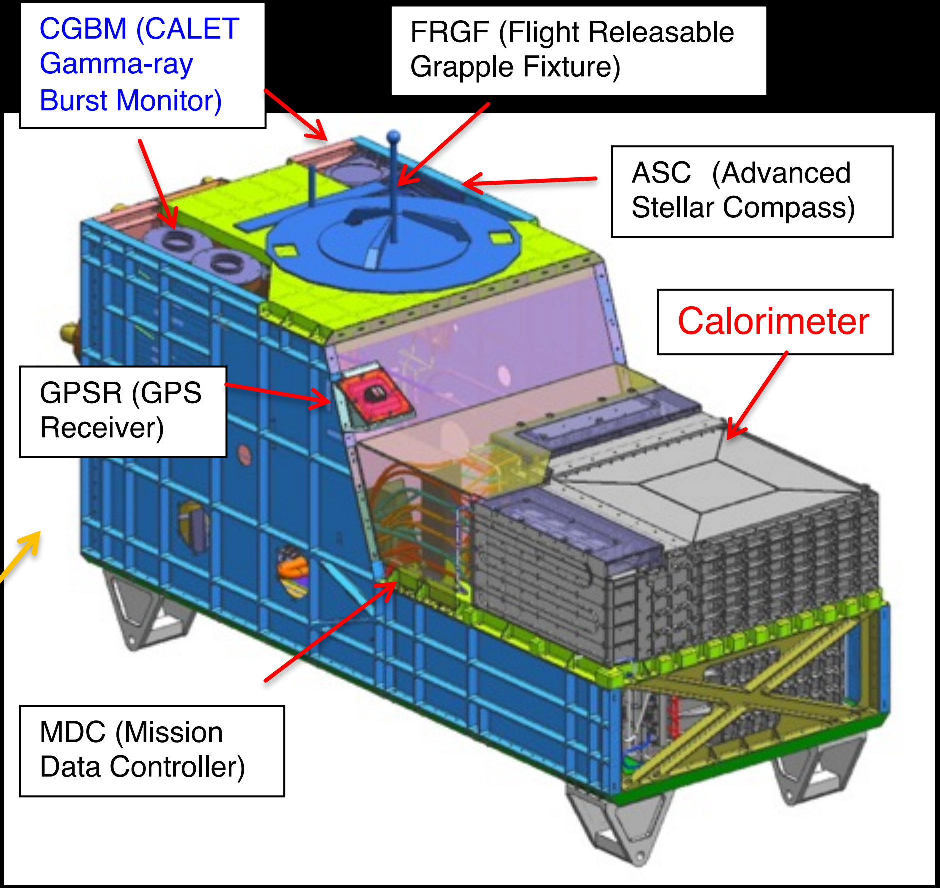
CALET Payload



Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

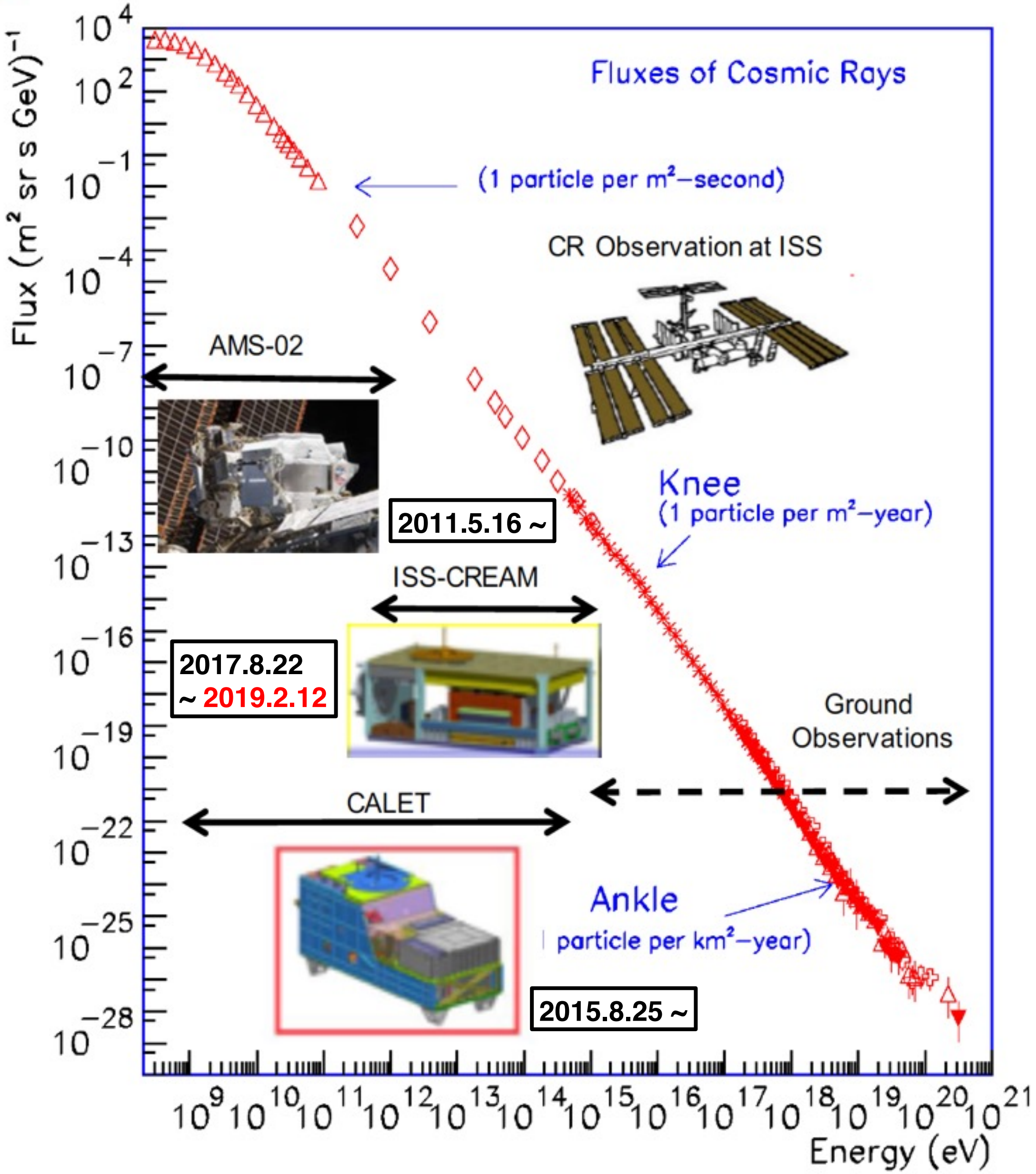
Emplaced on JEM-EF port #9 on Aug. 25th, 2015





- **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**

Cosmic ray observation with CALET on the ISS



Overview of CALET Observations

- Direct cosmic ray observations in space at highest energy region
- Cosmic ray observation at world-record level using a large-scale detector at the ISS over a long-term more than 5 years.
- Electron observation in 1 GeV - 20 TeV is achieved with high energy resolution due to optimization for electron detection

⇨ Search for Dark Matter and Nearby Sources

- Observation of cosmic-ray nuclei will be performed in energy region from 10 GeV to 1 PeV

⇨ Unravelling the CR acceleration and propagation mechanism

- Detection of transient phenomena in space by stable observations

⇨ Gamma-ray burst, Solar flare, EM radiation from GW sources etc.

CALET Instruments

CAL

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

CGBM

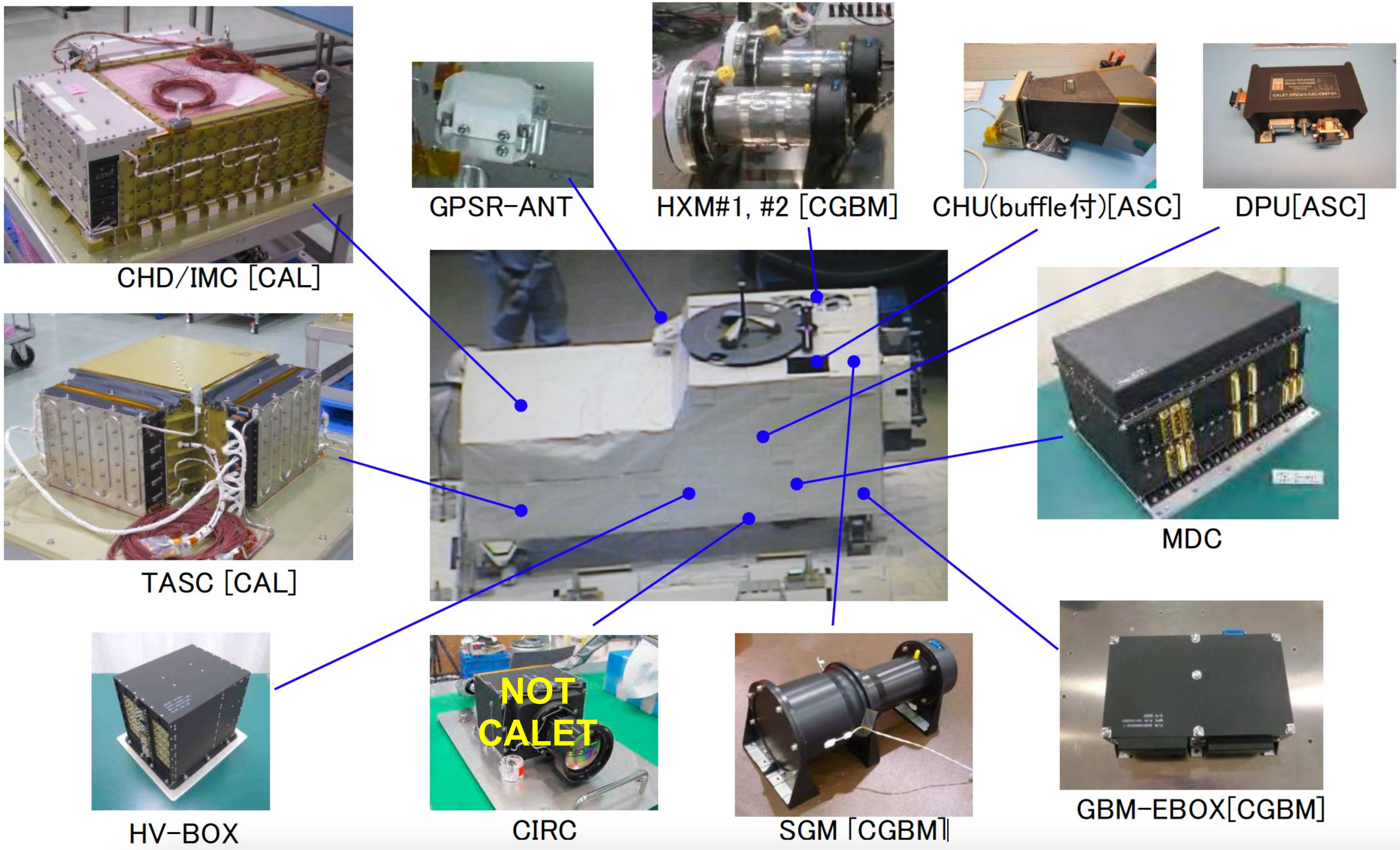
- Hard X-ray Monitor (HXM) x 2
  $LaBr_3$: 7keV～1MeV
- Soft γ-ray Monitor (SGM)
  BGO : 100keV～20MeV

Data Processing & Power Supply

- Mission Data Controller (MDC)
  CPU, telemetry, power, trigger etc.
- HV-BOX (Italian contribution)
  HV supply（PMT:68ch, APD:22ch）

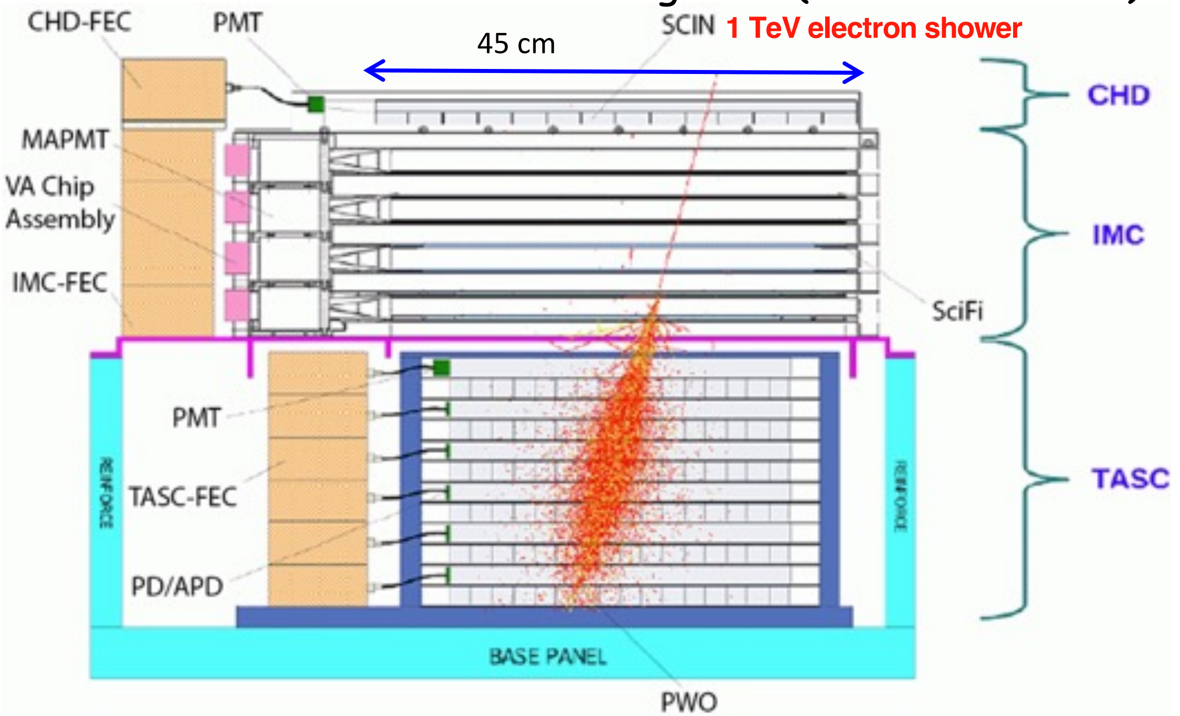
Support Sensors

- Advanced Stellar Compass (ASC)
  Directional measurement
- GPS Receiver (GPSR)
  Time stamp of triggered event (<1ms)



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

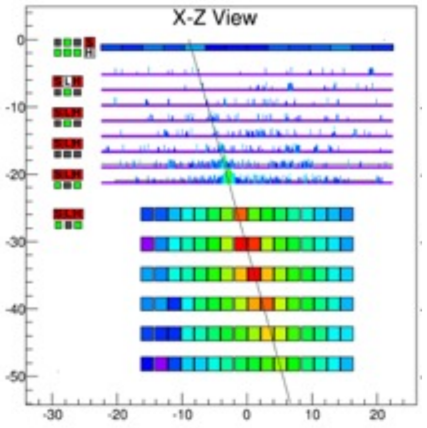
IMC – Imaging Calorimeter

- 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**

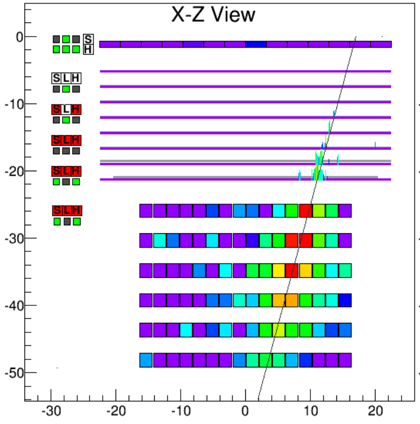
TASC – Total Absorption Calorimeter $27\ X_0,\ 1.2\ \lambda_I$

- 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}

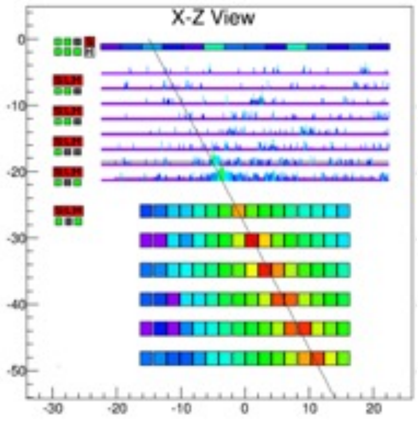
Electron, *E*=3.05 TeV



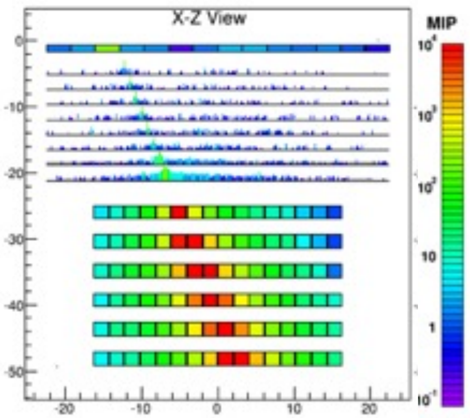
Gamma-ray, *E*=44.3 GeV



Proton, E_{TASC}=2.89 TeV

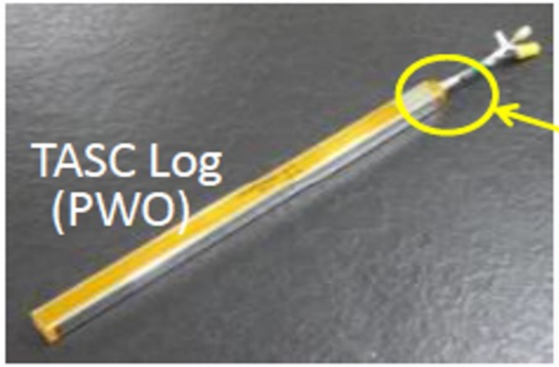


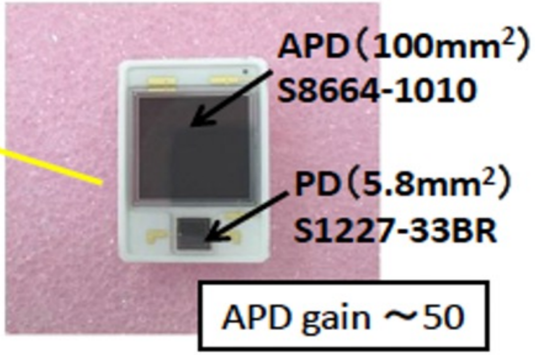
Iron, E_{TASC} =9.3 TeV



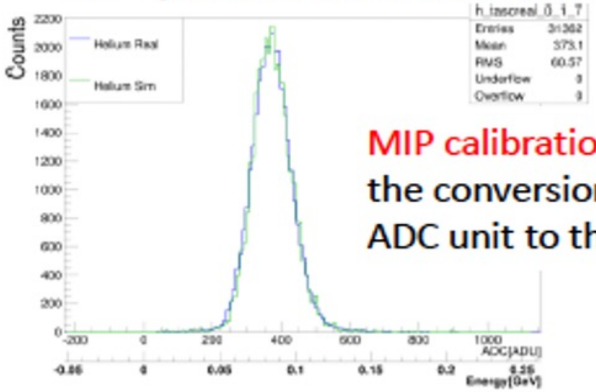
Event Display: Electron Candidate (>100 GeV)

Energy Measurement: a wide dynamic range 1-10^6 MIPs

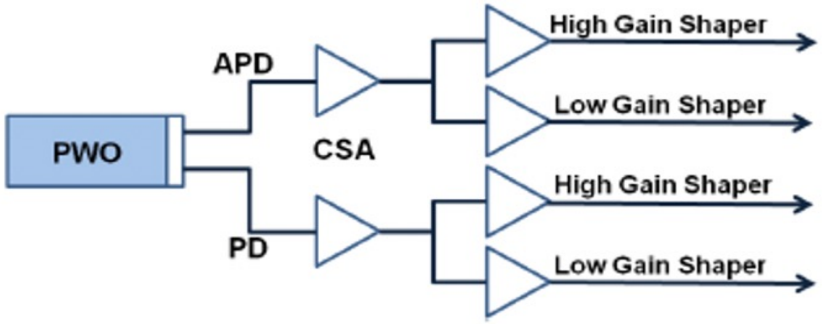




"MIP" peak in PWO: Obs. vs. MC



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

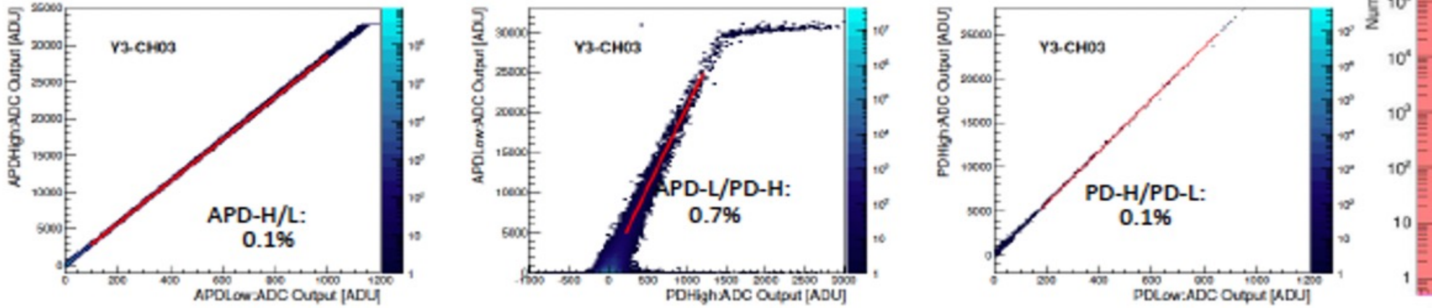


The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

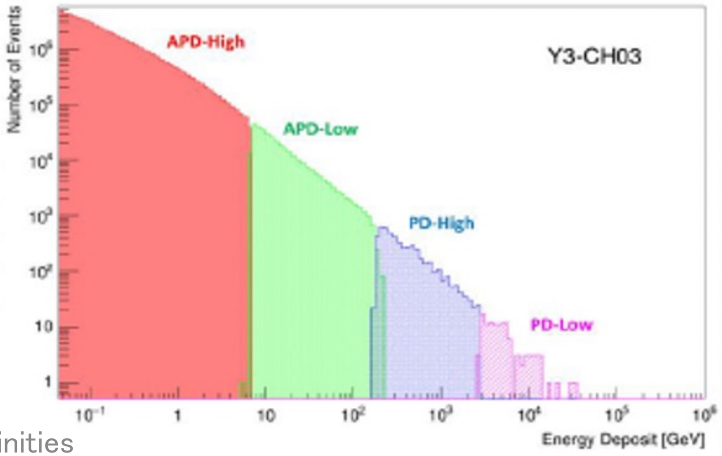
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

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%

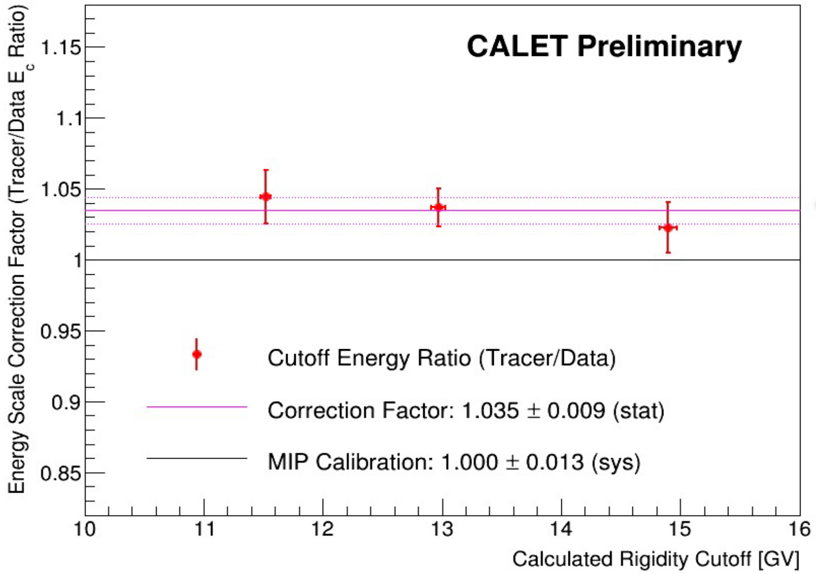


Example of energy distribution in one PWO log



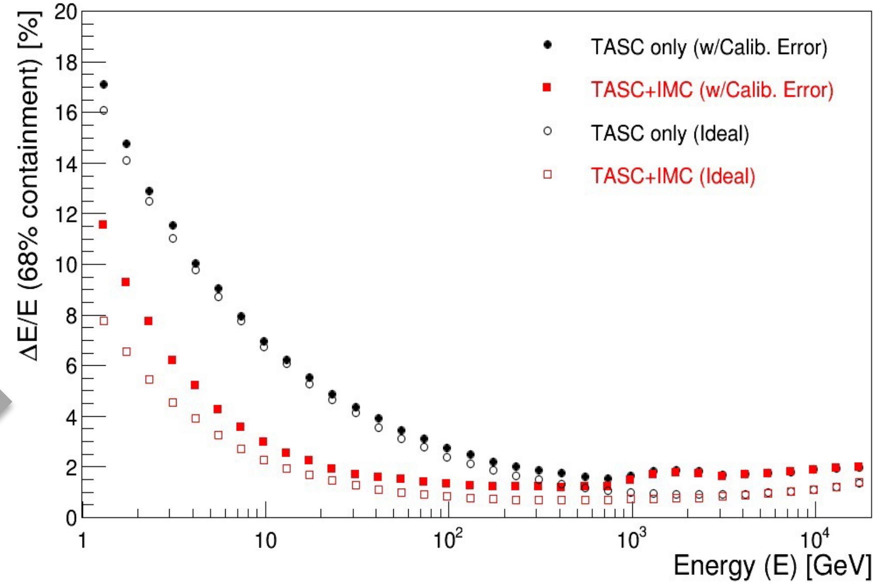
Energy Measurement: energy scale and resolution

ELECTRONS

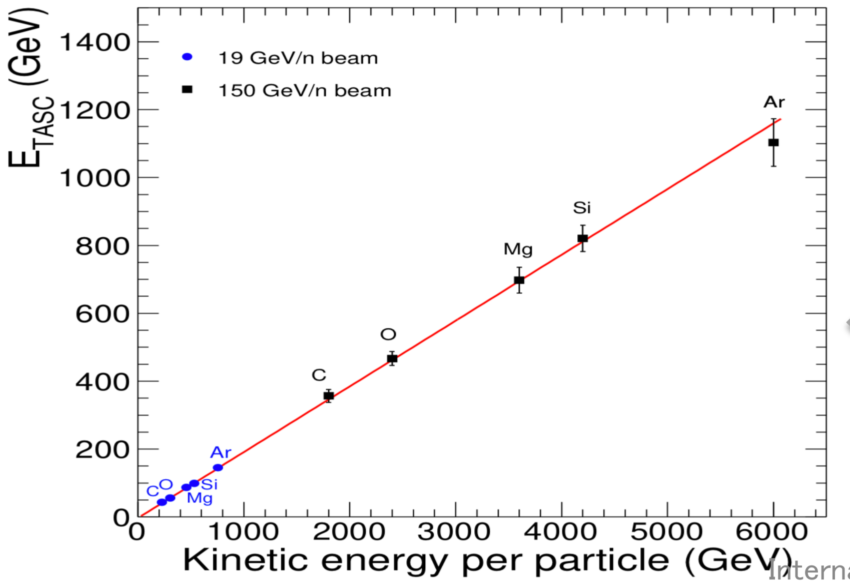


Absolute energy scale calibration for electrons using rigidity cutoff
+ Beam calibration at CERN-SPS

Simulated energy dependence of electron energy resolution:
< 2% above 20 GeV
Using both TASC and IMC
Including the calibration errors



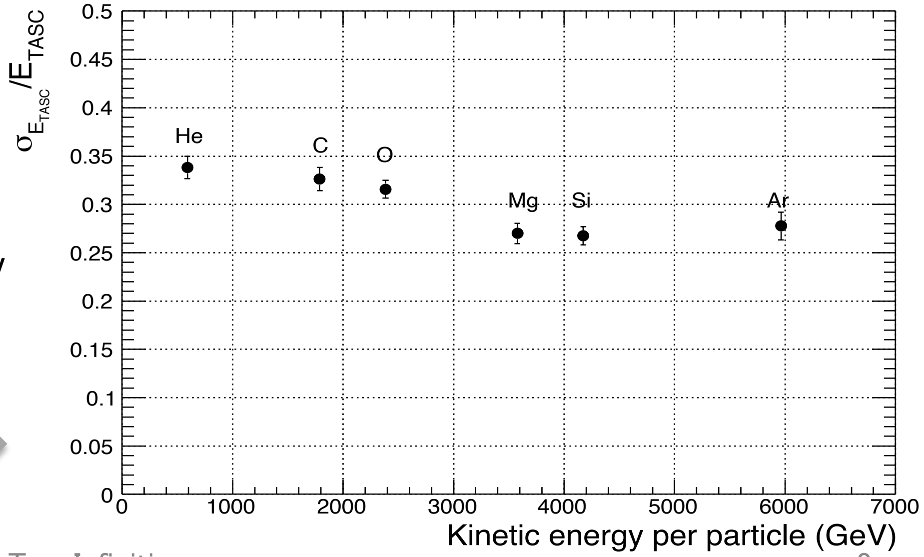
HADRONS



Beam calibration at CERN-SPS with Ion fragments at 13, 19 150 GeV/n

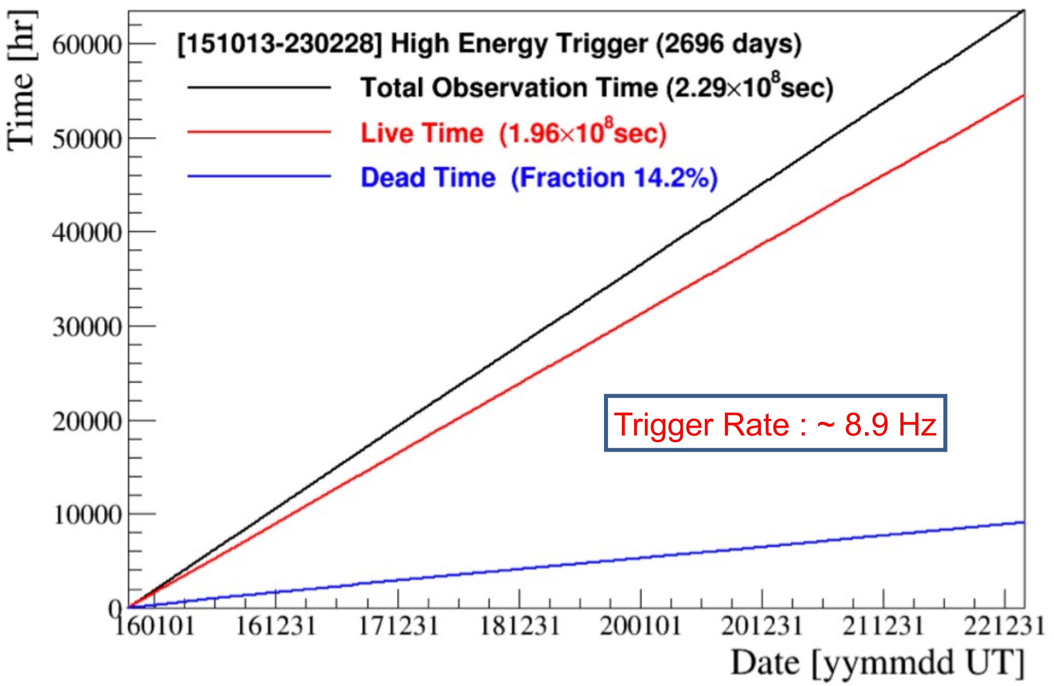
Linearity assessed up to ~6 TeV with primary beam of 40Ar at 150 GeV/n

Energy resolution ~30%



CALET performance of observations on orbit

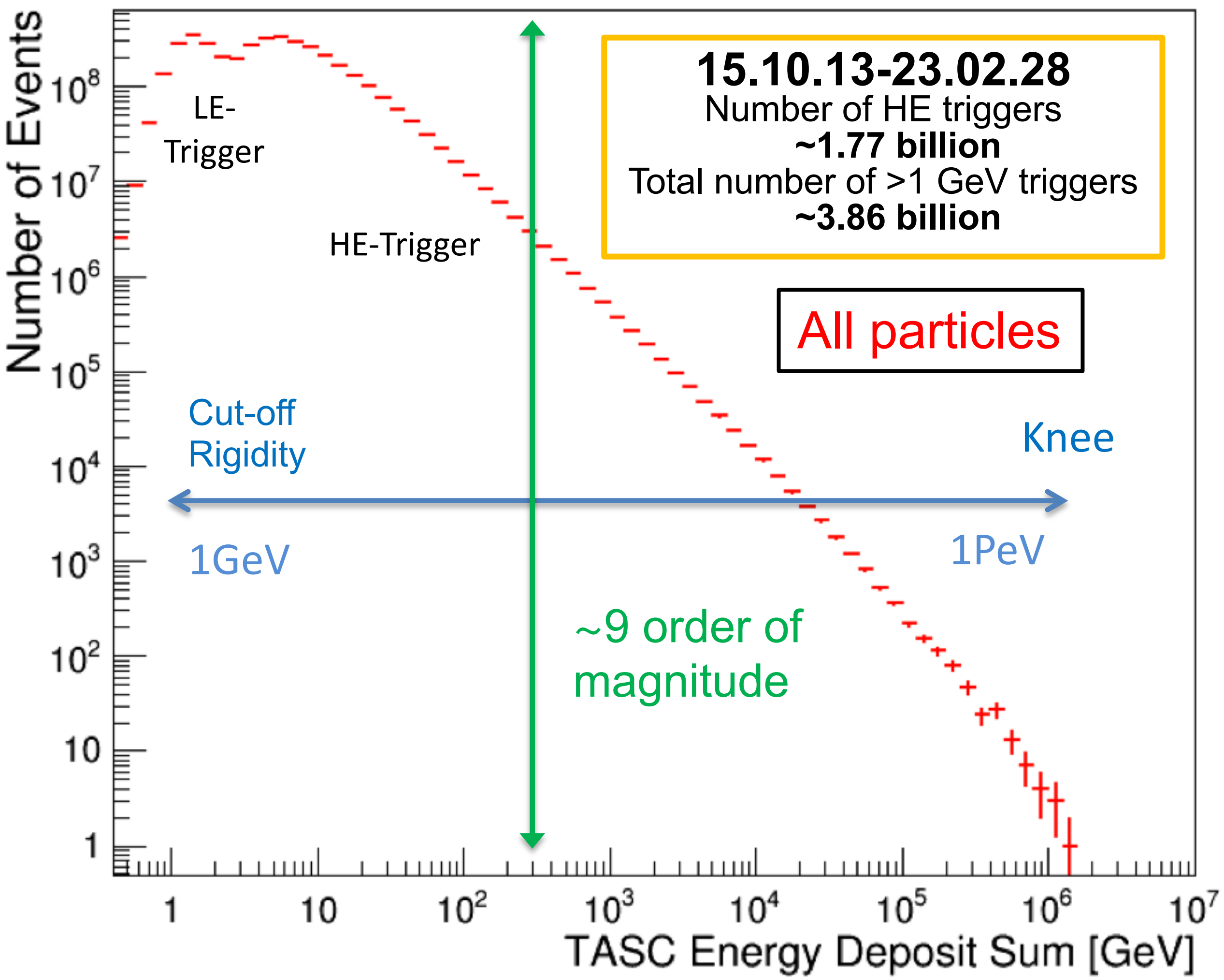
Accumulated observation time (live, dead)



High-energy trigger (> 10 GeV) statistics:

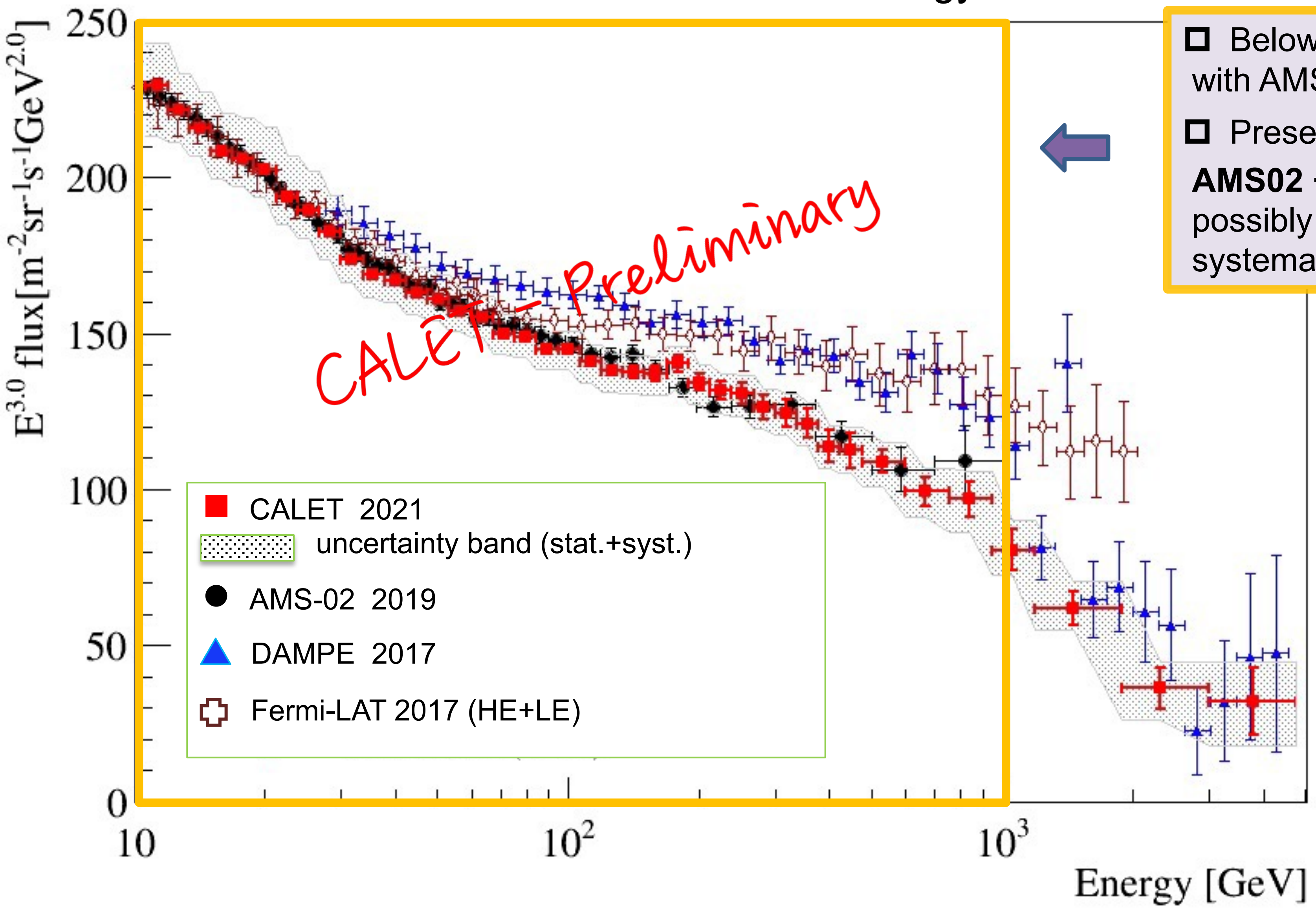
- Operational time **2696 days (> 7 years)**(*)
  (*) as of Feb. 28, 2023
- Live time fraction **~ 86%**
- Exposure of HE trigger
  ~235 m^2 sr day
- HE-gamma point source exposure
  ~4.2 m^2 day (for Crab, Geminga)

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



Cosmic-ray all-electron spectrum (update: as of May 30, 2021)

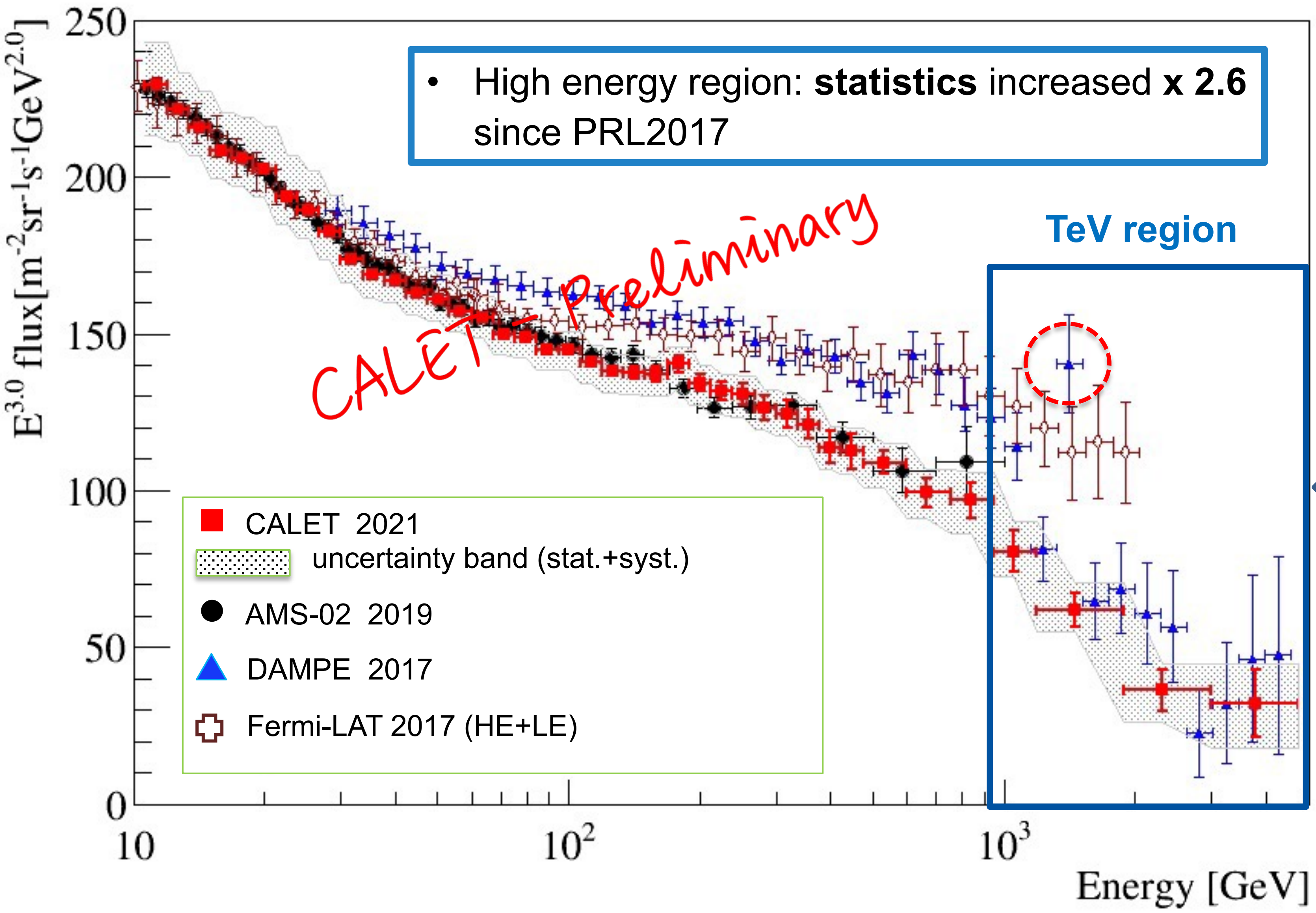
Electron Flux x $E^{3.0}$ vs. Energy



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

Preliminary spectrum is **updated** using 2057 days of CALET observations: Oct.13, 2015 – May 30, 2021

Cosmic-ray all-electron spectrum (update: as of May 30, 2021)



Energy loss due to Synchrotron and Inverse Compton : d*E*/d*t* = -b*E*²
⇨ **Observable sources of the electrons in the TeV region** should be located at **a distance < ~1 kpc** and produced at **a year < ~10^5 yr.**
⇨ **Softening of the spectrum is expected above 1 TeV** since only a few SNRs are observed to keep this condition.

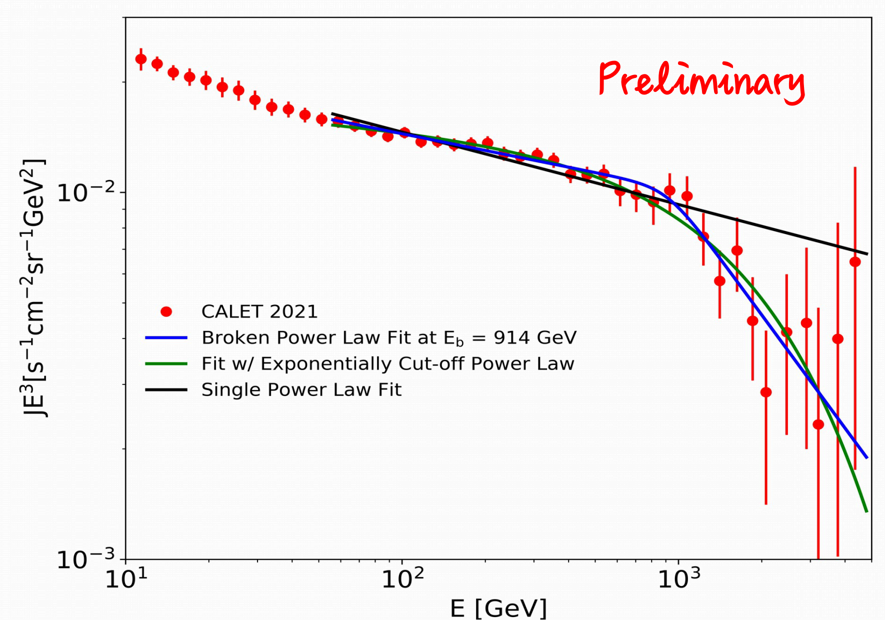
- ☐ CALET observes a flux suppression above 1 TeV with a **significance > 6.5 σ**, a considerable improvement with respect to the result published in PRL2018 (~4 σ).
- ☐ No peak-like structure at 1.4 TeV in CALET measurement irrespective of binning.

Statistics x 3.4 as of Dec. 2022
=> Updated results coming soon...

Towards an interpretation of the CALET all-electron spectrum

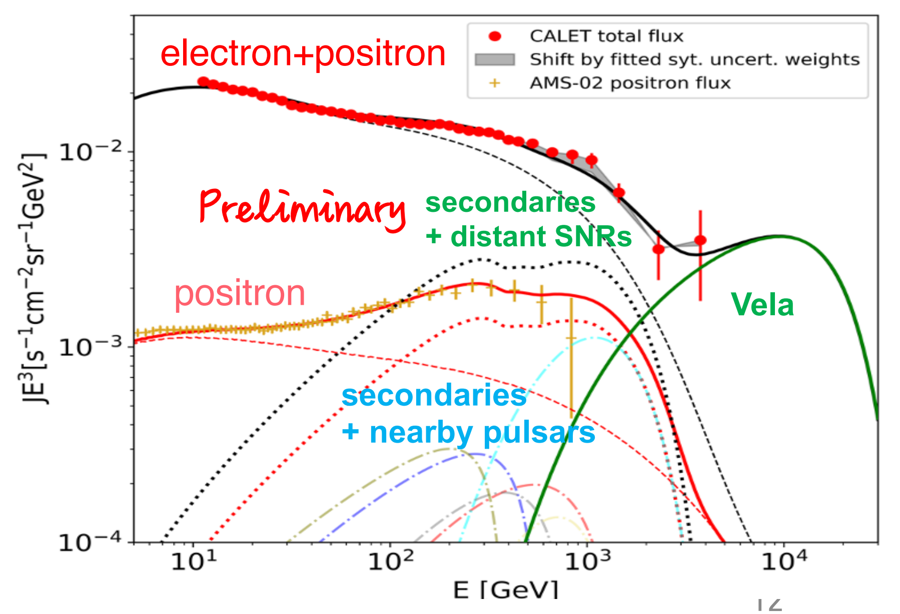
- Fits of the CALET all-electron spectrum in 55 GeV - 4.8 TeV, using the same energy binning as DAMPE [Nature, 2017]
  - Broken power law used in DAMPE
    $\gamma = -3.151 \Rightarrow -4.024$ (χ^2 /NDF=11.64/29)
  - Exponential cut-off power law [PRL, 2018]
    $\gamma = -3.054$ with $E_c = 2.17$ TeV (χ^2 /NDF=11.25/29)
  - Single power law
    $\gamma = -3.197$ (χ^2 /NDF=54.50/30)

The significance of both fits of softening spectrum is considerably improved: 4 σ (PRL2018) => nearly 6.5 σ,



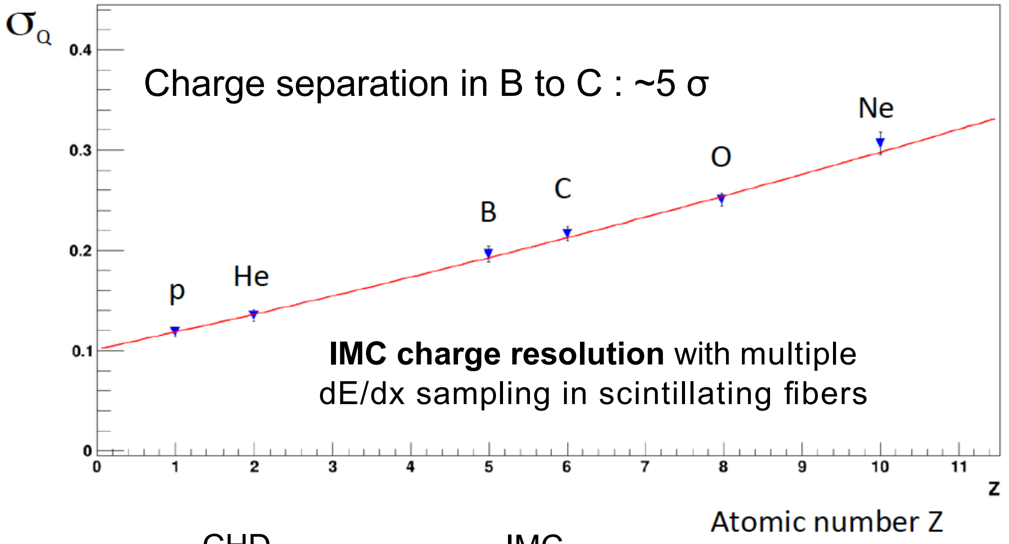
- Tentative spectral fit in 11 GeV-4.8 TeV including pulsars and a possible Vela SNR contribution.
  - Positron flux(AMS): secondaries+ nearby pulsars
  - Electron flux (CALET-AMS):
    Secondaries + Distant SNRs (black dashed line)
    + Vela SNR (green line).

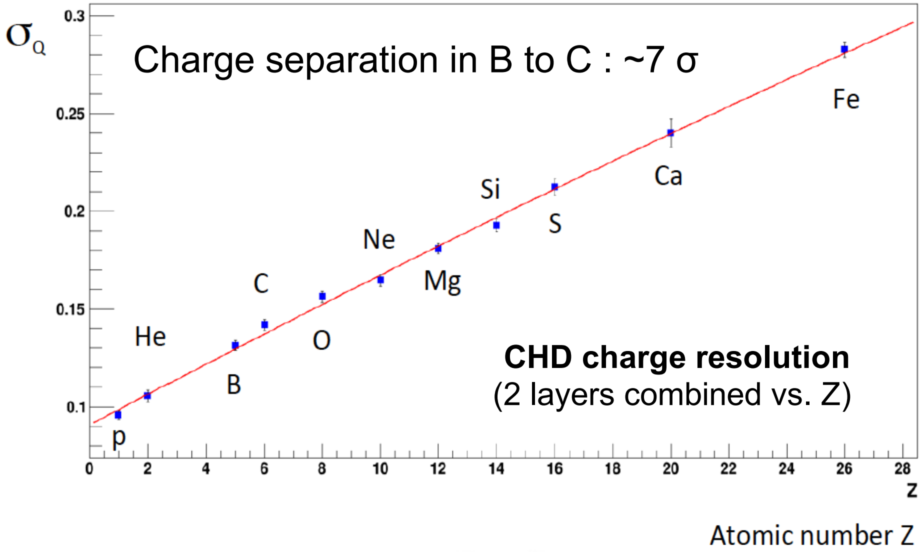
A possible contribution from the Vela SNR:
Energy output of 2.08×10^{48} erg in electron CR above 1 GeV.



Nuclei Measurement: Charge Identification with CHD and IMC

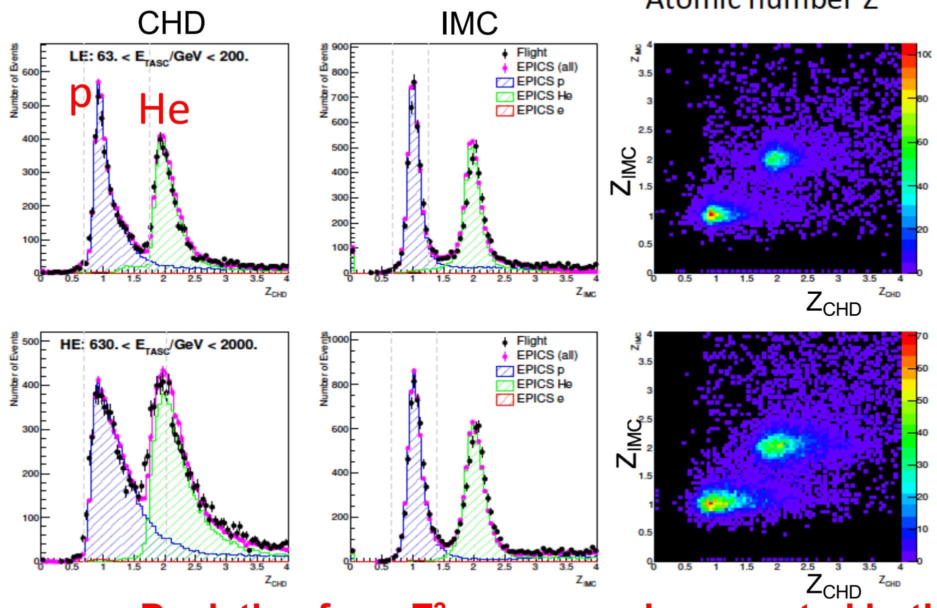
Single element identification for p, He and light nuclei is achieved by CHD+IMC charge analysis.

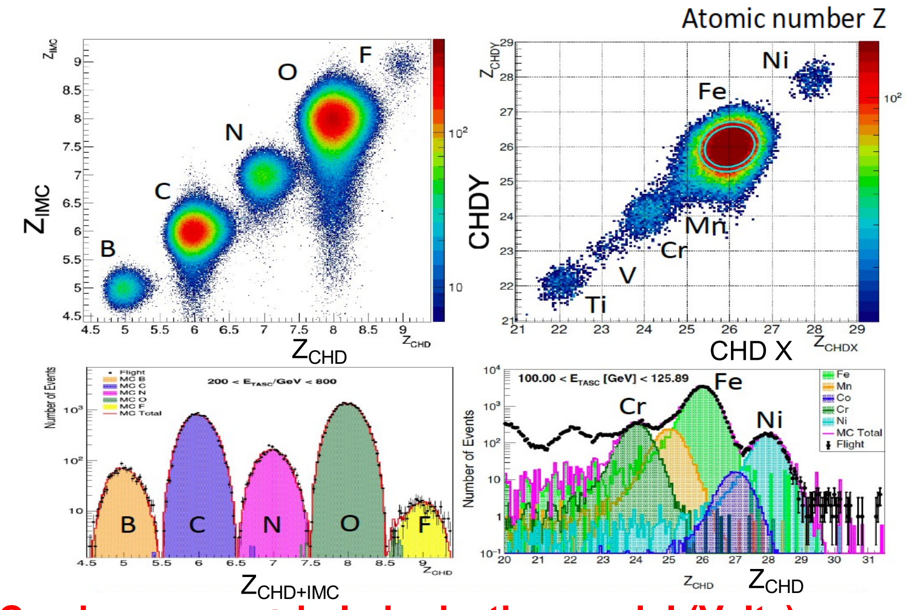




Low Energy

High Energy



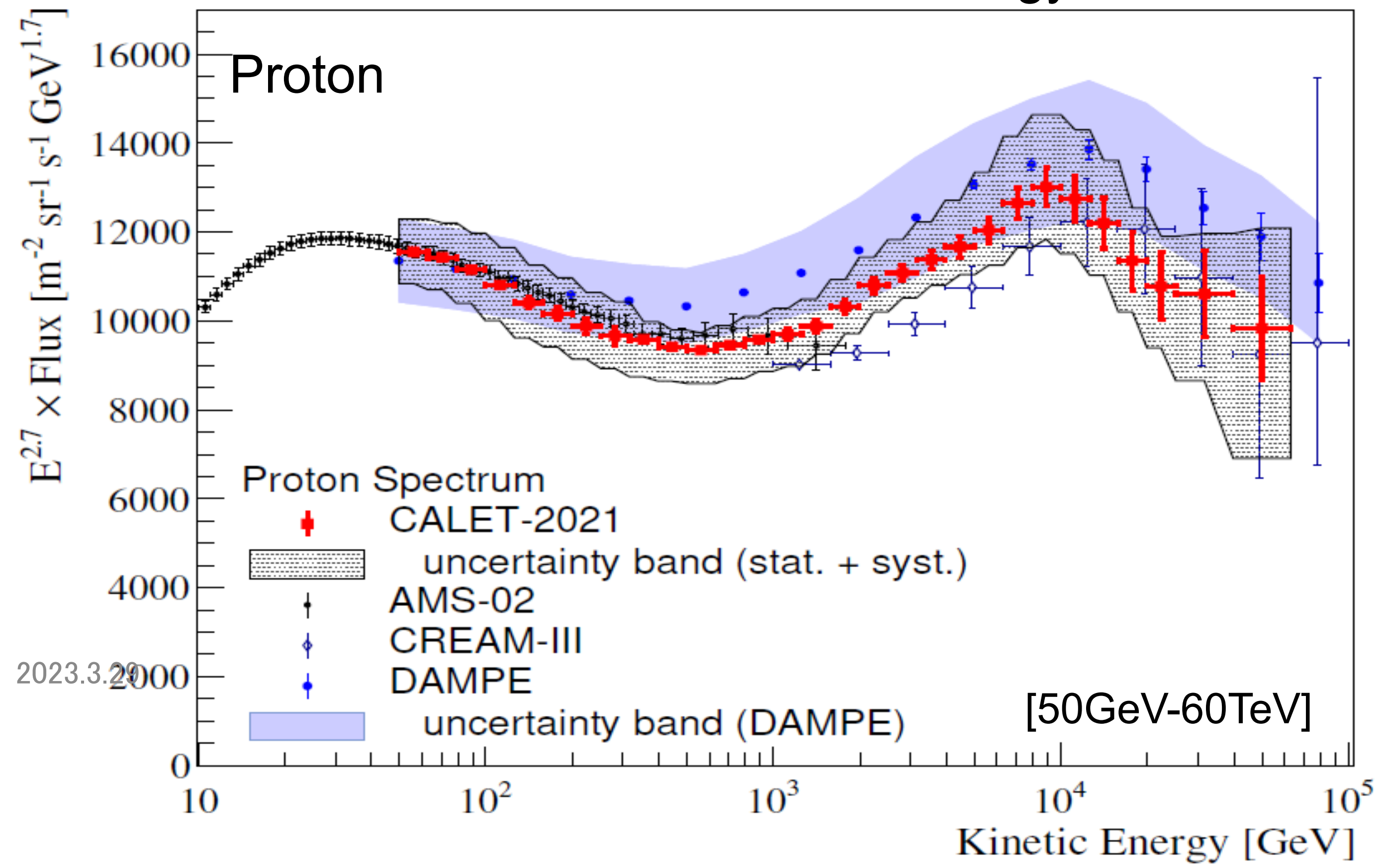


Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

Cosmic-ray Proton spectrum

PRL **129**, 101102 (2022)

Flux x $E^{2.7}$ vs. Kinetic energy



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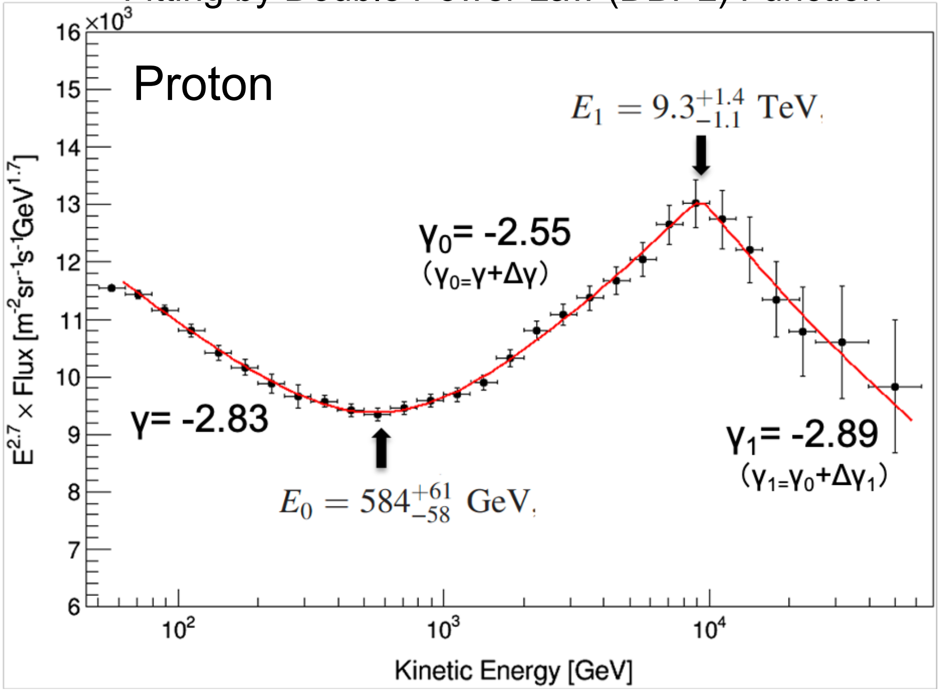
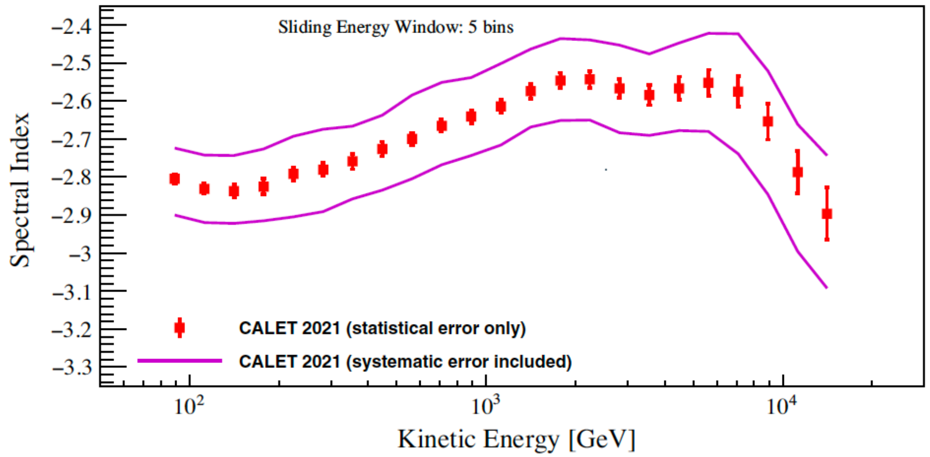
Fitting by Double Power Law (DBPL) Function



Energy dependence of power index

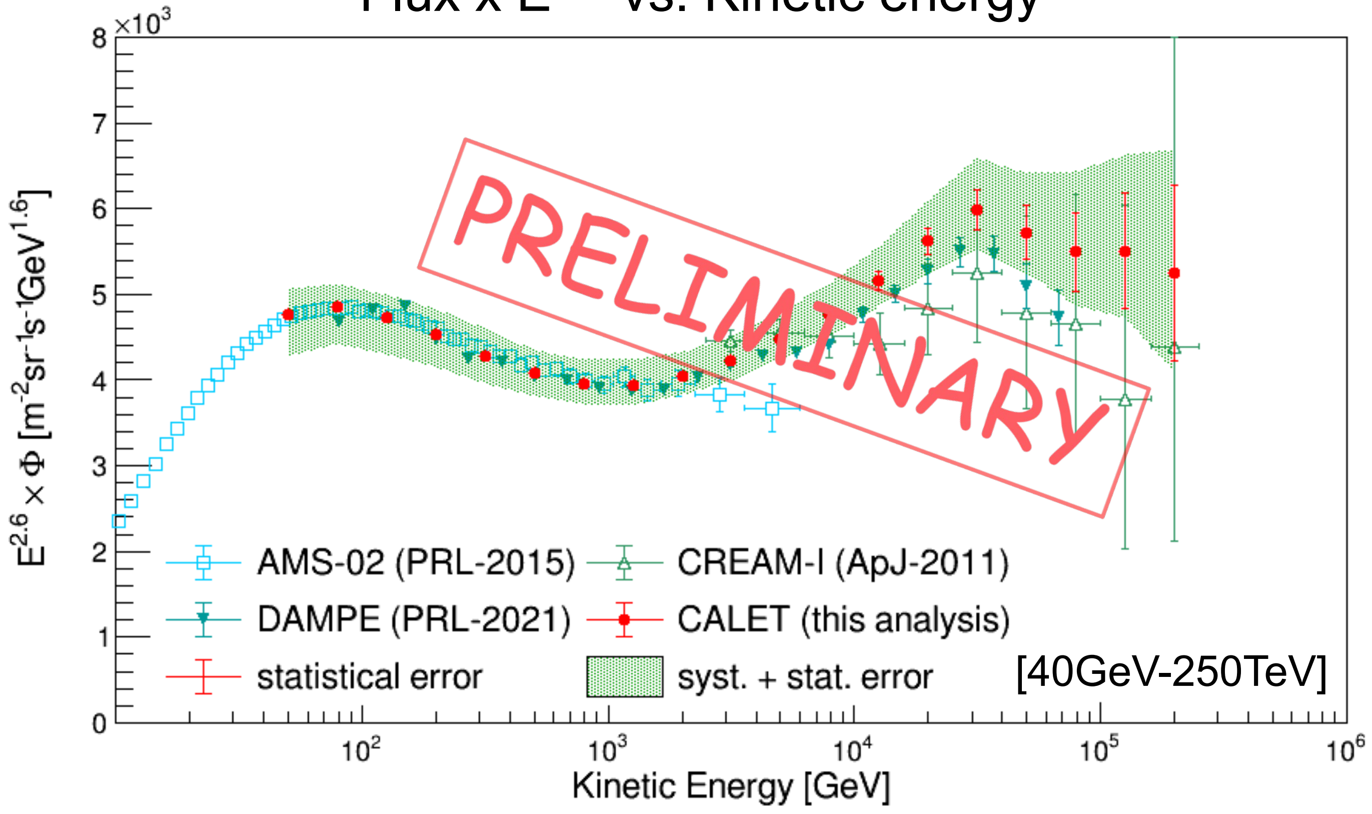


Double Power Law Function: HARDENING SOFTENING

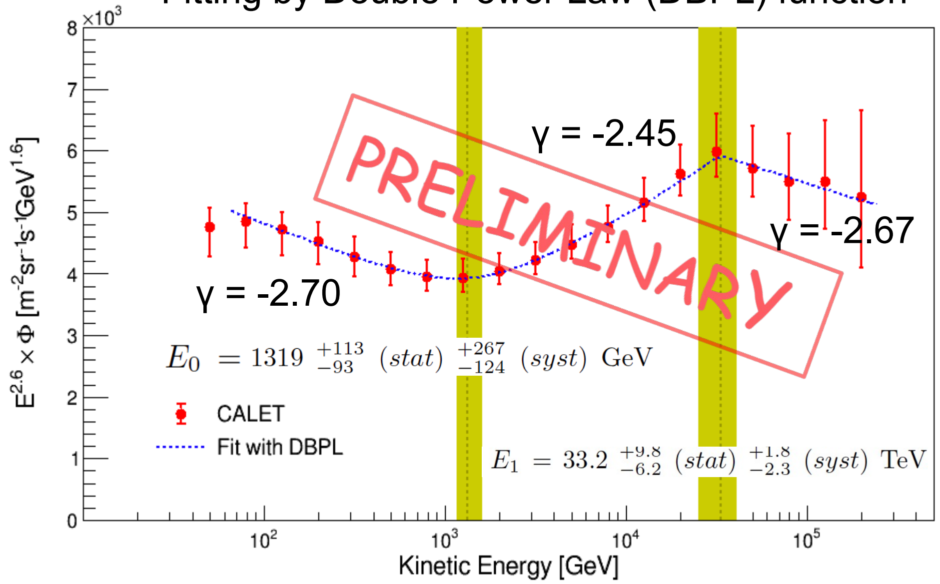
$$\Phi(E) = C \times \left(\frac{E}{1\ \mathrm{GeV}}\right)^{\gamma} \times \left[1 + \left(\frac{E}{E_0}\right)^{s}\right]^{\frac{\Delta\gamma}{s}} \times \left[1 + \left(\frac{E}{E_1}\right)^{s_1}\right]^{\frac{\Delta\gamma_1}{s_1}}$$

Cosmic-ray Helium spectrum (*Preliminary*)

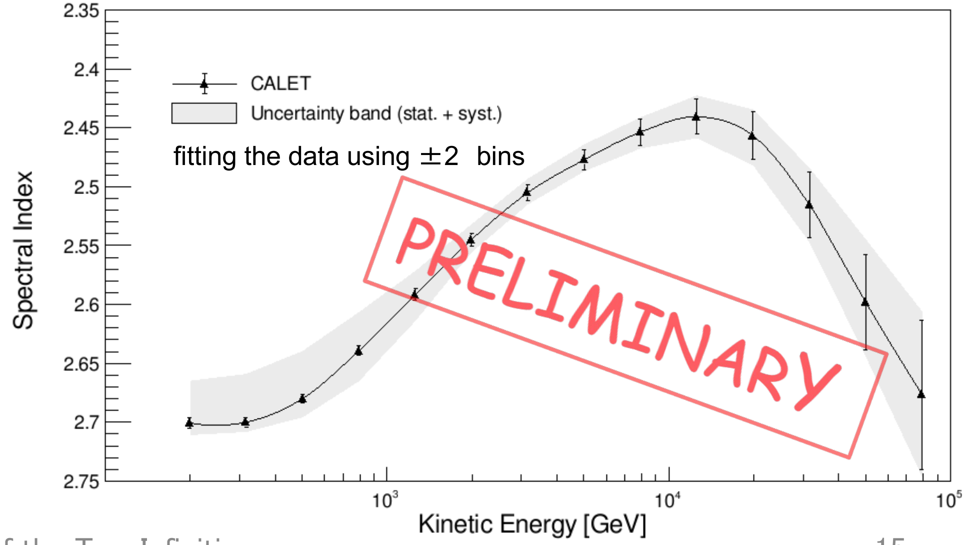
Flux x $E^{2.6}$ vs. Kinetic energy



Fitting by Double Power Law (DBPL) function



Energy dependence of power index



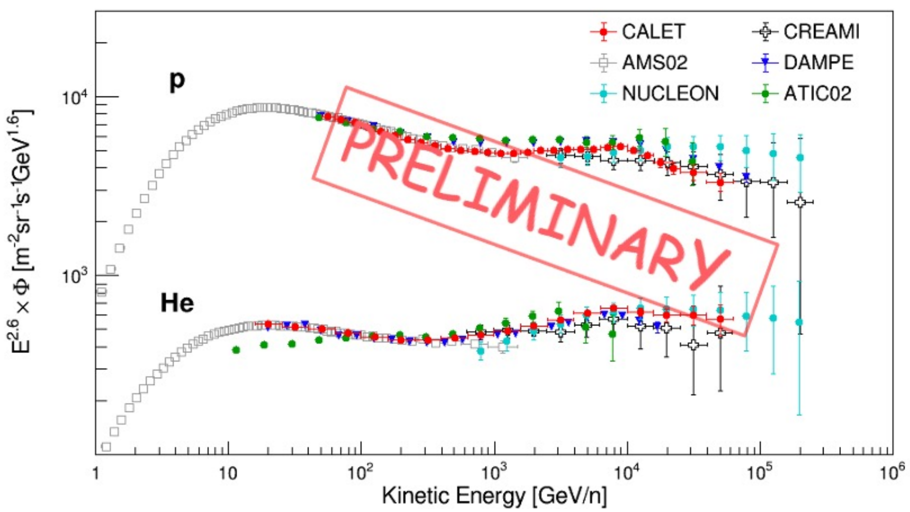
Double Power Law Function: HARDENING SOFTENING

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

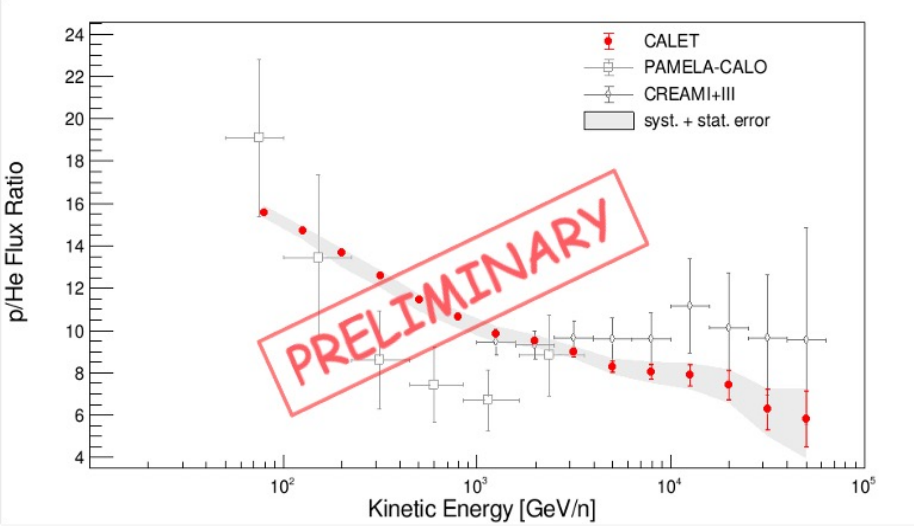
Comparison of Proton and Helium spectrum (*Preliminary*)

- **Both of proton and helium spectrum have a similar structure of hardening and softening around same region of rigidities.**
- **However, the spectral index of helium is harder than that of proton (by ~0.1) in the whole rigidity range.**
- **The softening of p & He spectrum around 10-20 TV is coincident with expectation from shock wave acceleration in SNR.**

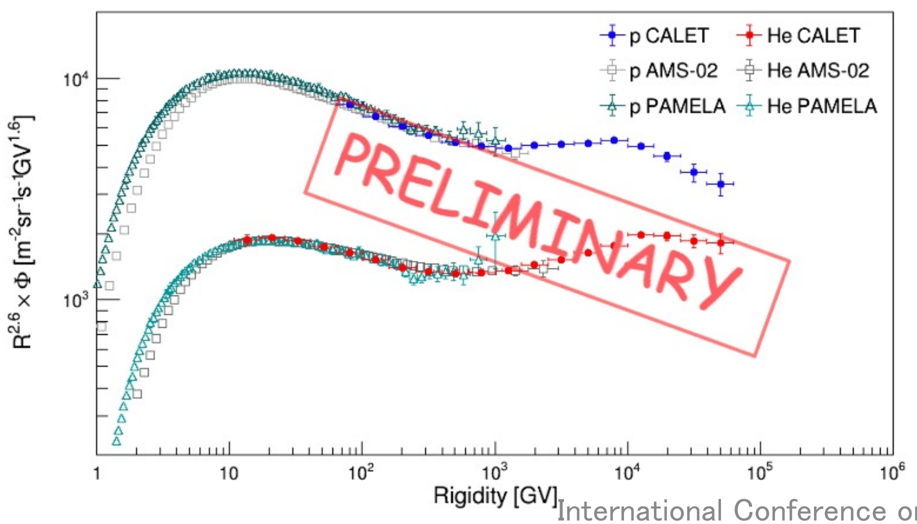
Proton & Helium spectrum vs. energy/ nucleon



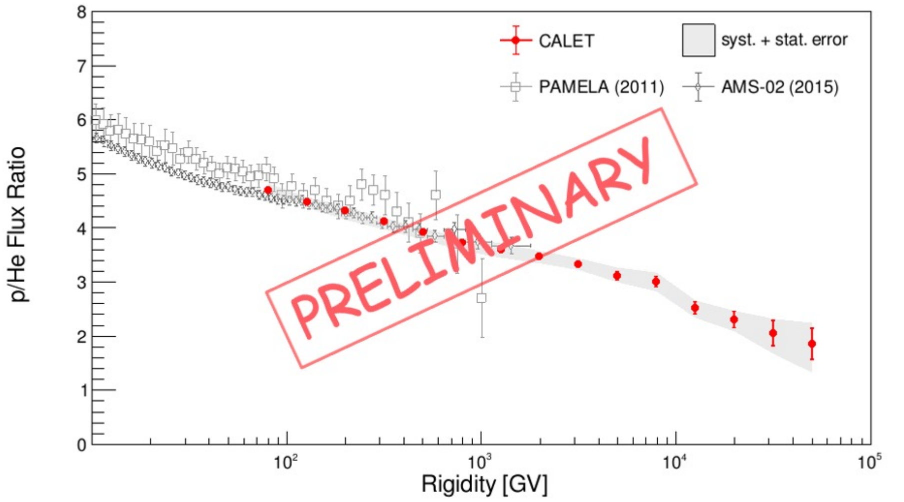
Proton/Helium ratio vs. energy/ nucleon



Proton & Helium spectrum vs. rigidiy

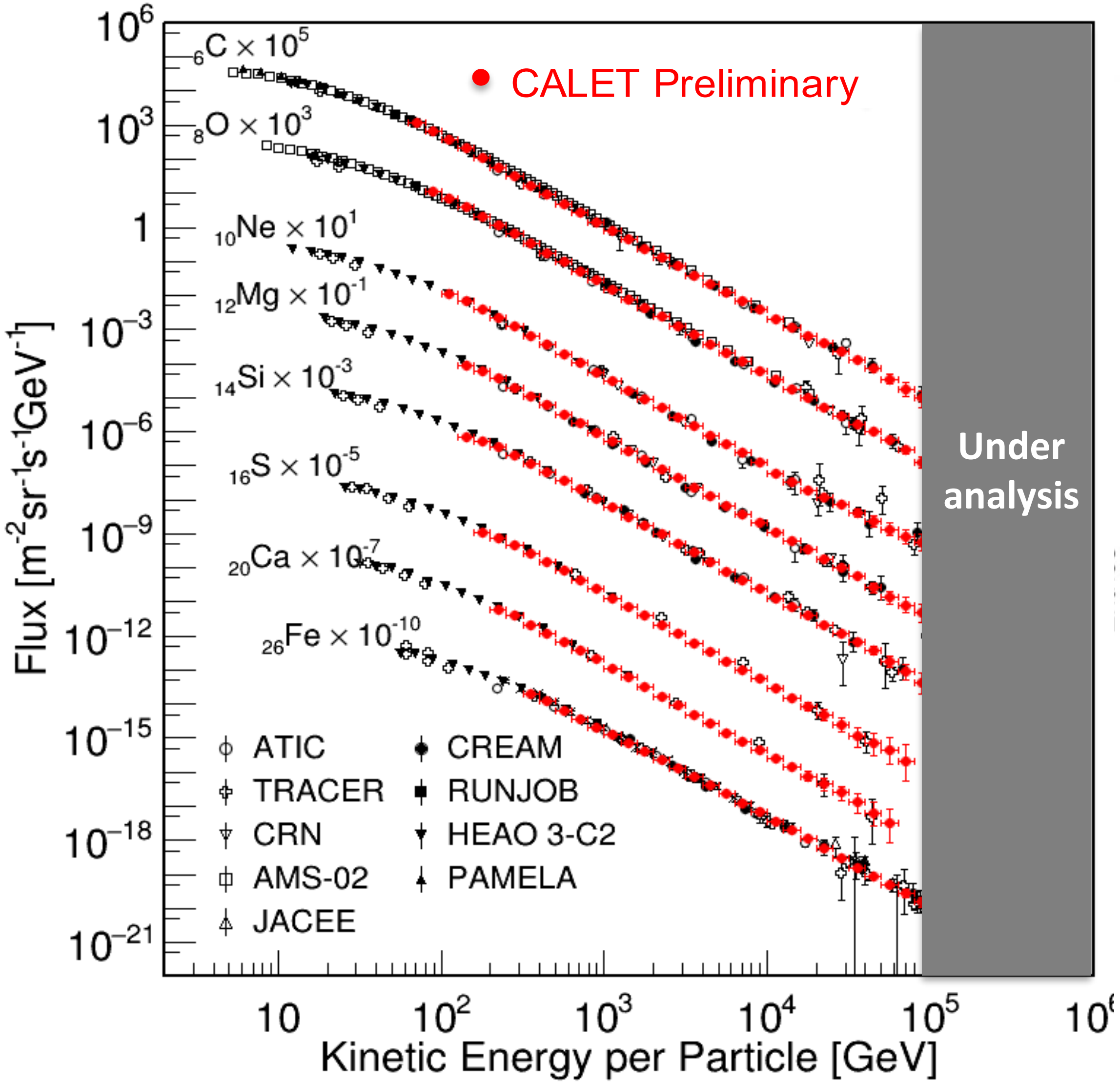


Proton/Helium ratio vs. rigidity



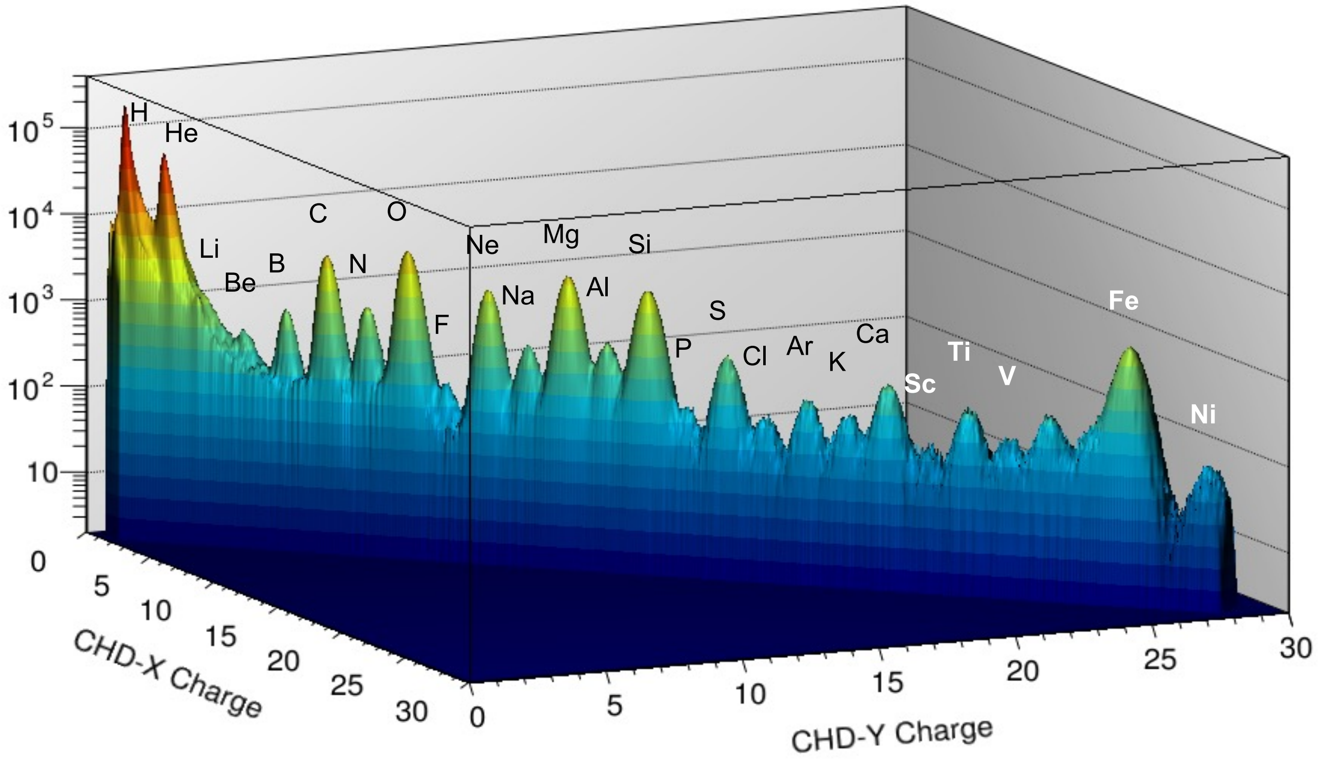
Observations of cosmic-ray nuclei from C to Fe

Preliminary spectra of Carbon – Iron



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

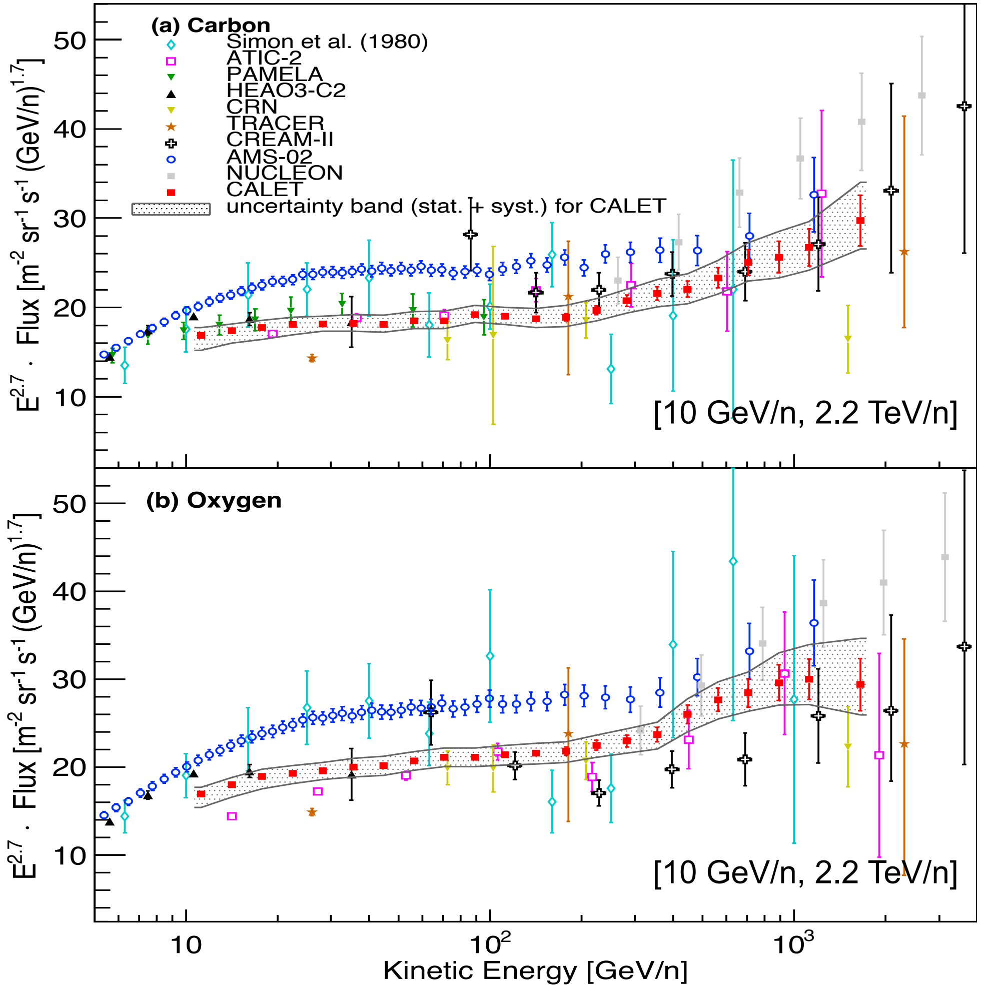
Charge distribution from Proton to Nickel (periodic table of elements by CALET)



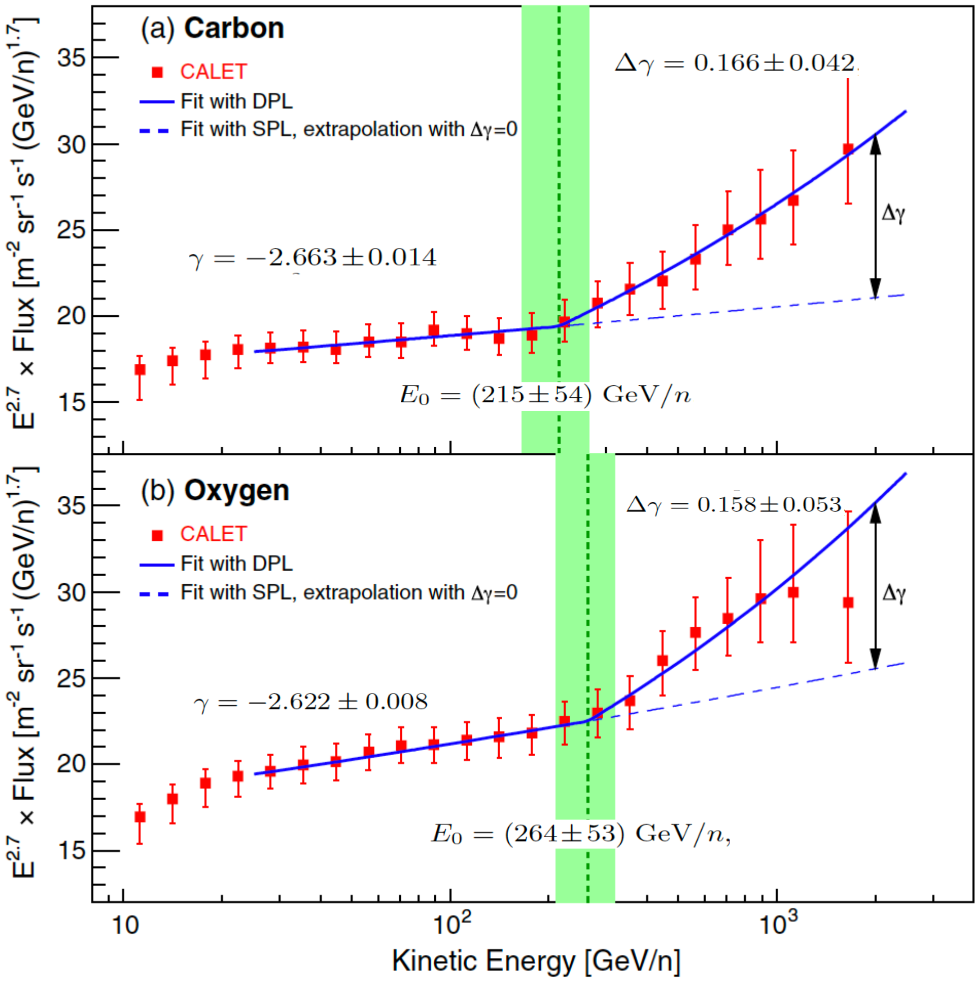
Carbon and Oxygen energy spectra

PRL 125, 251102 (2020)

Flux x $E^{2.7}$ vs kinetic energy per nucleon



Fitting with double power law function

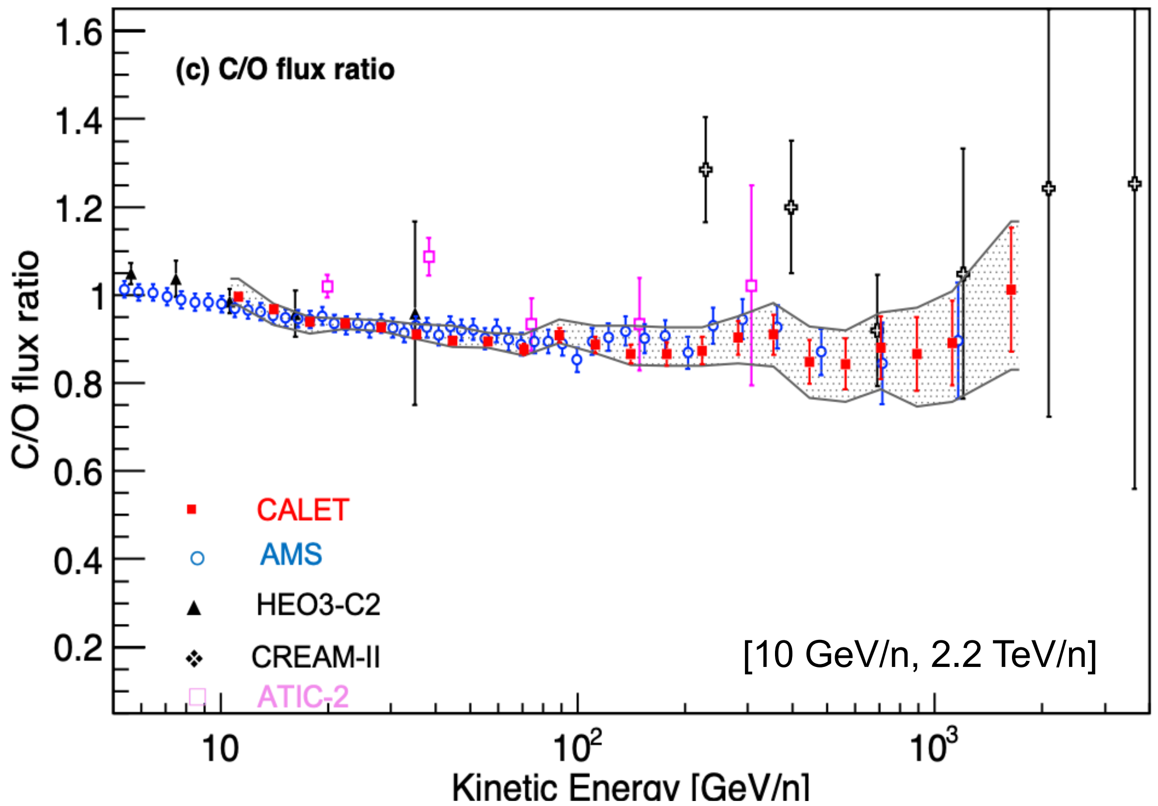


Single power law hypothesis excluded at 3.9 σ level for C and 3.2 σ for O

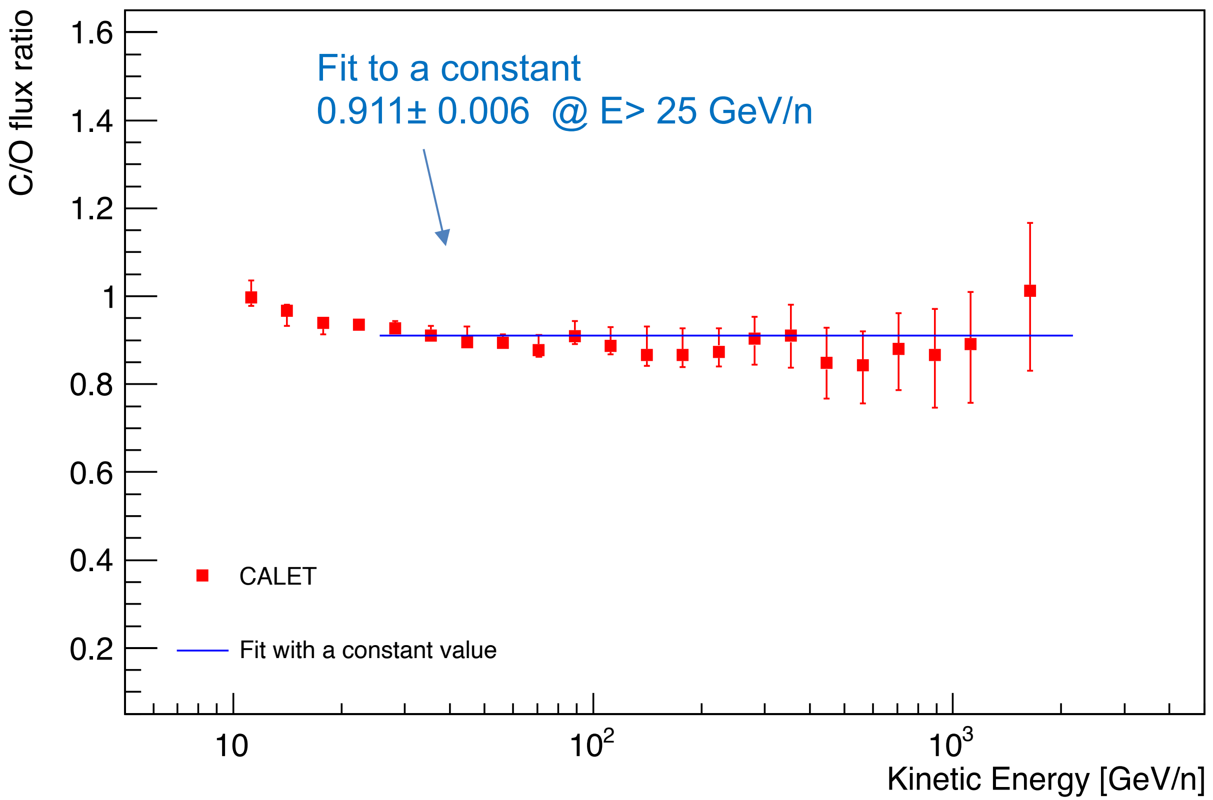
The hardening of the C and O spectra is consistent with that observed in p and He within errors, in the energy region (per charge) of 400-600 GeV/Z.

Carbon/Oxygen flux ratio

C/O flux ratio



Fitting of C/O flux ratio



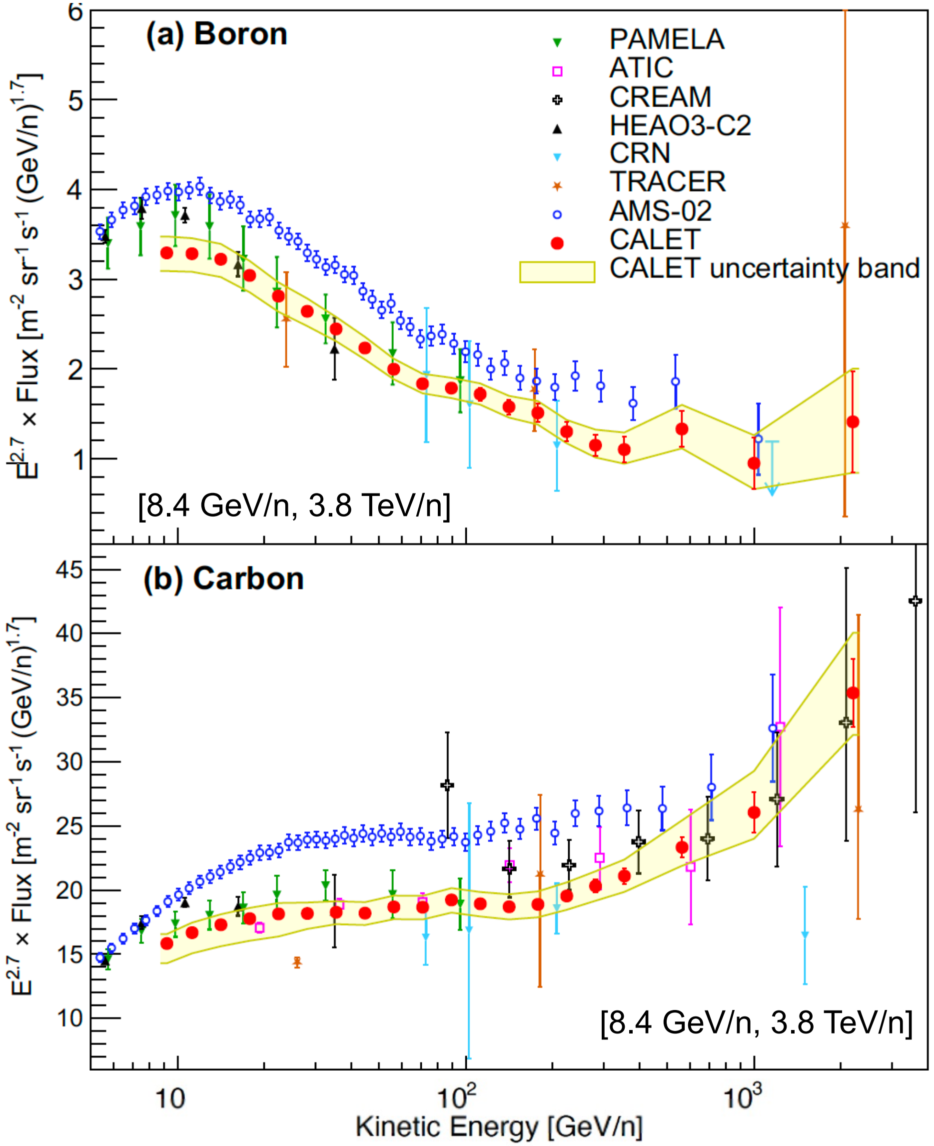
- The C/O flux ratio as a function of energy is in good agreement with the one reported by AMS-02.
- Above 25 GeV/n **the C/O ratio is well fitted to a constant value of 0.911 ± 0.006** with χ^2/dof = 8.3/17.

⇨ C and O fluxes have the same energy dependence.

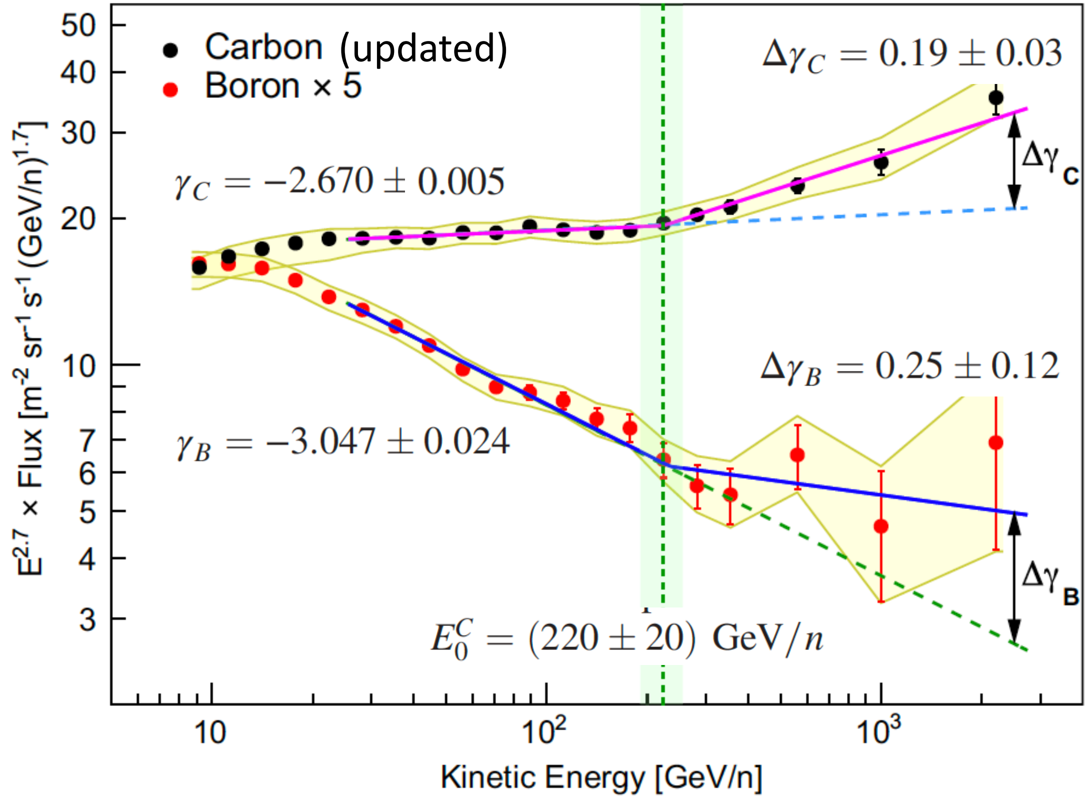
Boron and Carbon energy spectra

PRL 129, 251103 (2022)

Flux x $E^{2.7}$ vs. kinetic energy per nucleon



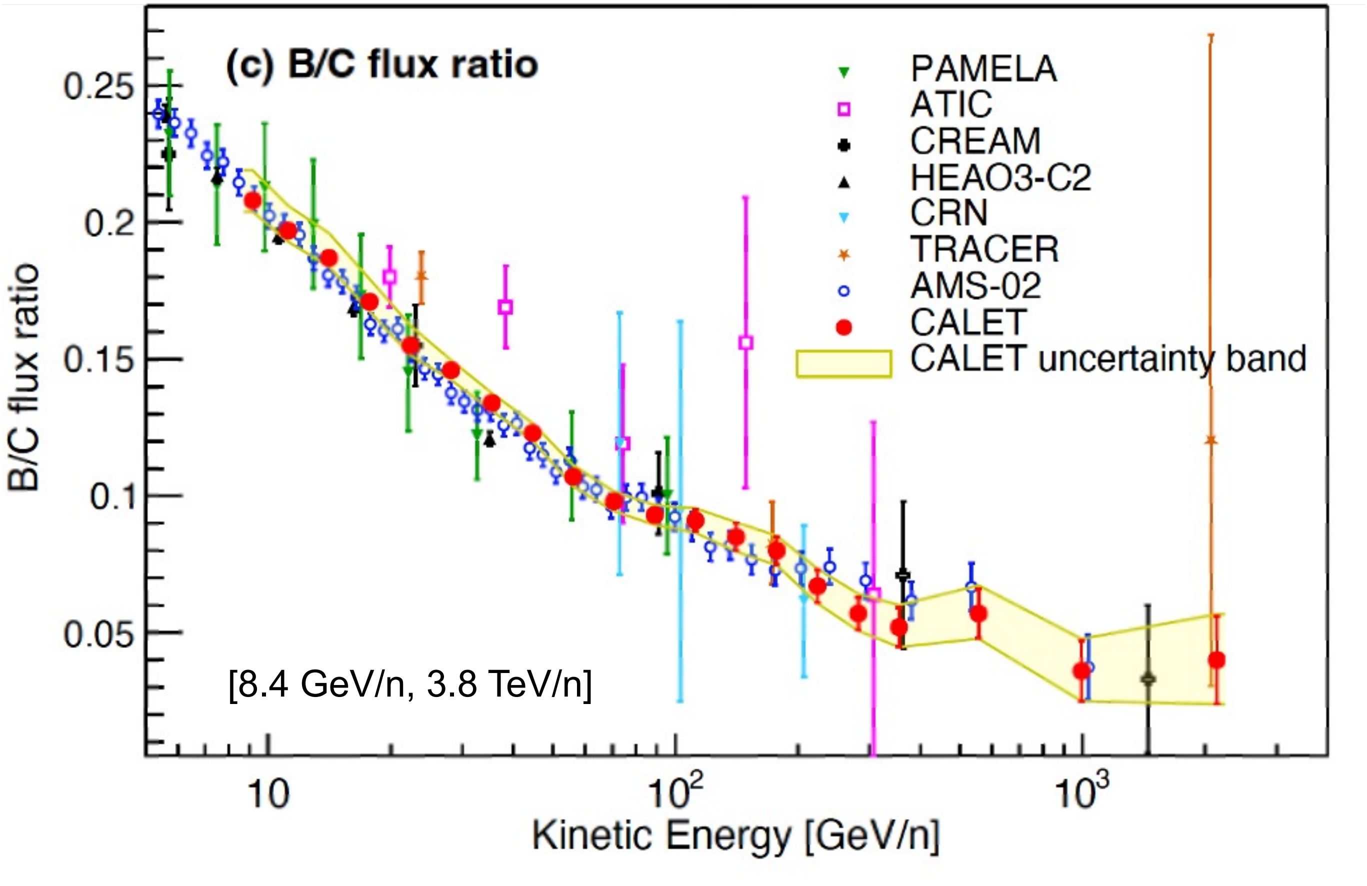
Comparison of energy spectra of Boron and Carbon



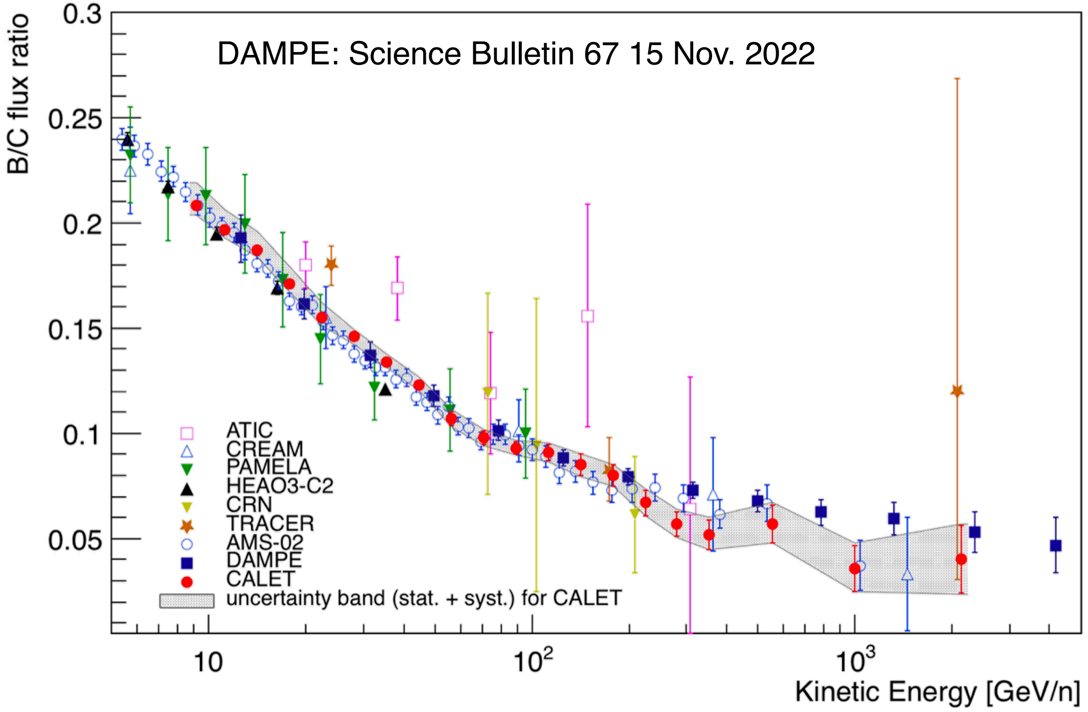
Boron and Carbon energy spectra are fitted by Double Power Law functions. Δγ is the change of spectral index above the transition energy of Carbon, E_0^C.

Flux ratio of Boron to Carbon

B/C ratio vs. kinetic energy per nucleon



DAPME published a similar result at same timing.



Precise measurements of B/C ratio up to the TeV region.

DAMPE has no reports on the individual spectrum of Boron or Carbon.

An interpretation of B/C ratio by Leaky Box Model

Single / Double power law fit:

$\Gamma = -0.366 \pm 0.018$ (χ^2/d.o.f. = 9.4/13) in 25 – 3800 GeV/n

$\Delta\Gamma = 0.09 \pm 0.05$ (χ^2/d.o.f. = 8.7/12) at 220 GeV/n

➡ consistent with that of AMS-02 and supports the hypothesis that secondary B exhibits a stronger hardening than primary C, although no definitive conclusion can be drawn due to the large uncertainty

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

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

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

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

λ_0 : residual path length

δ : diffusion coefficient spectral index

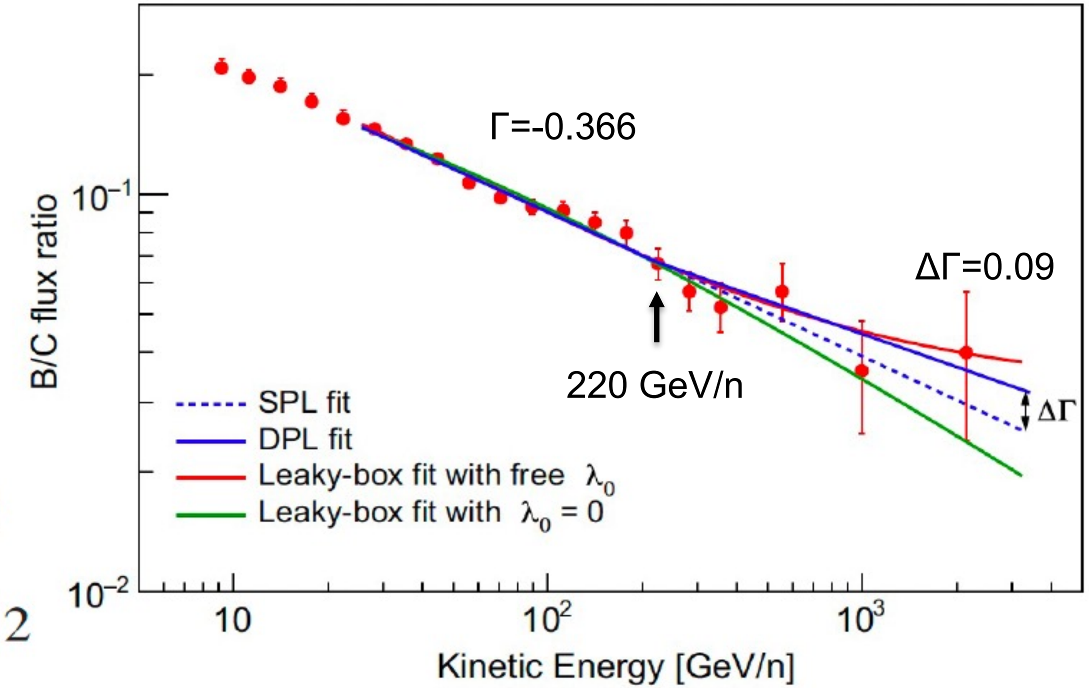
$\lambda_0 = 0$

$\delta = 0.52 \pm 0.02$ χ^2/d.o.f. = 13.6/13

λ_0 : free

$\delta = 0.71 \pm 0.11$ χ^2/d.o.f. = 9.6/12

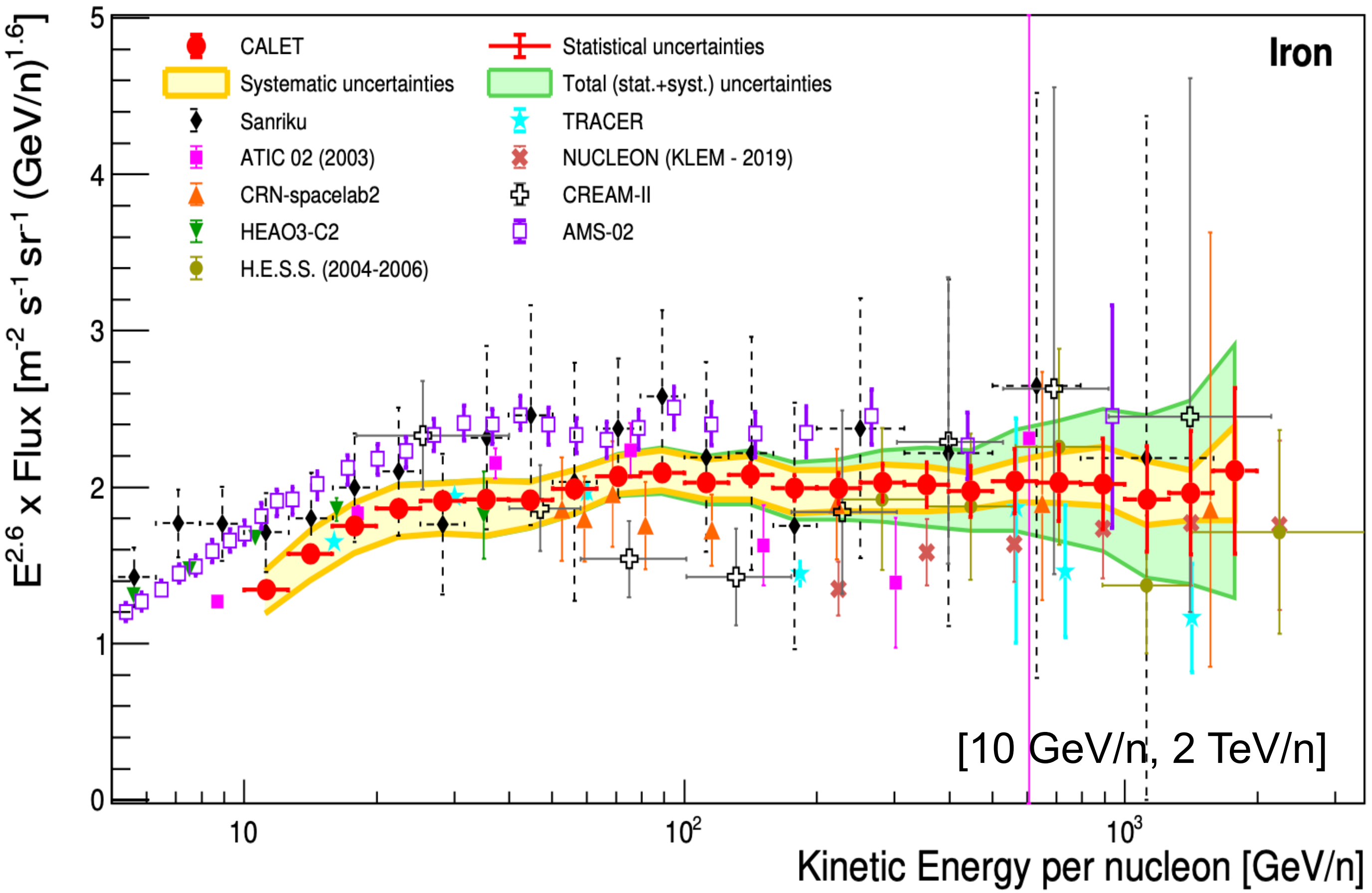
$\lambda_0 = 0.95 \pm 0.35$ g/cm^2



Iron energy spectrum

PRL 126, 241101 (2021)

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

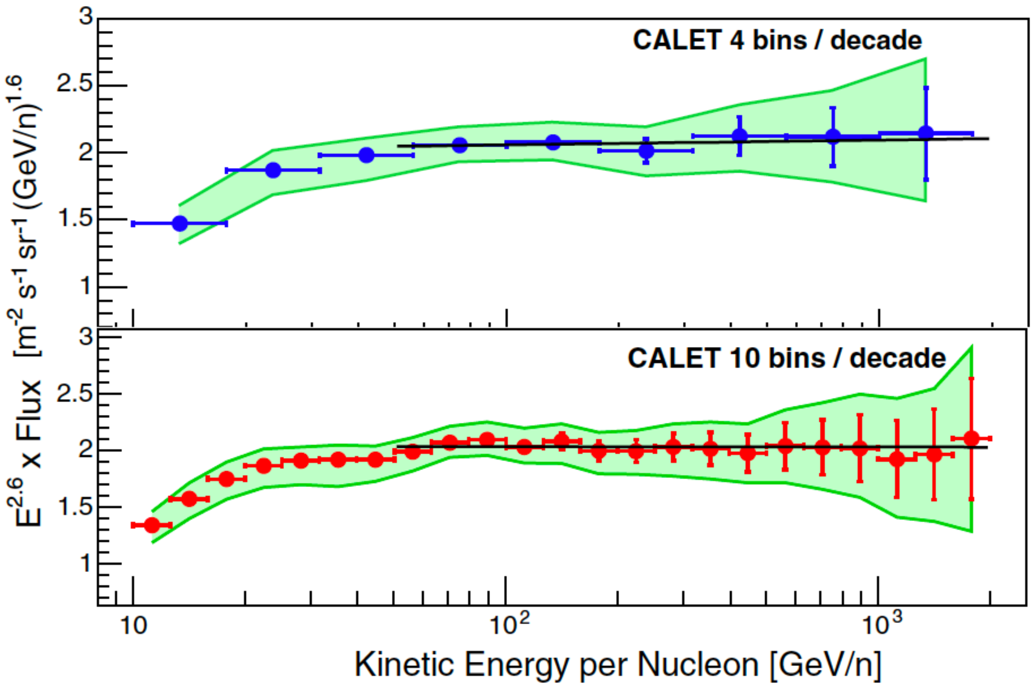


Iron Single Power Law fit:

50 GeV/n, 2.0 TeV/n

$\gamma = -2.60 \pm 0.02(\mathrm{stat}) \pm 0.02(\mathrm{sys})$

with $\chi^2/\mathrm{d.o.f.} = 4.2/14$



Flux normalization:

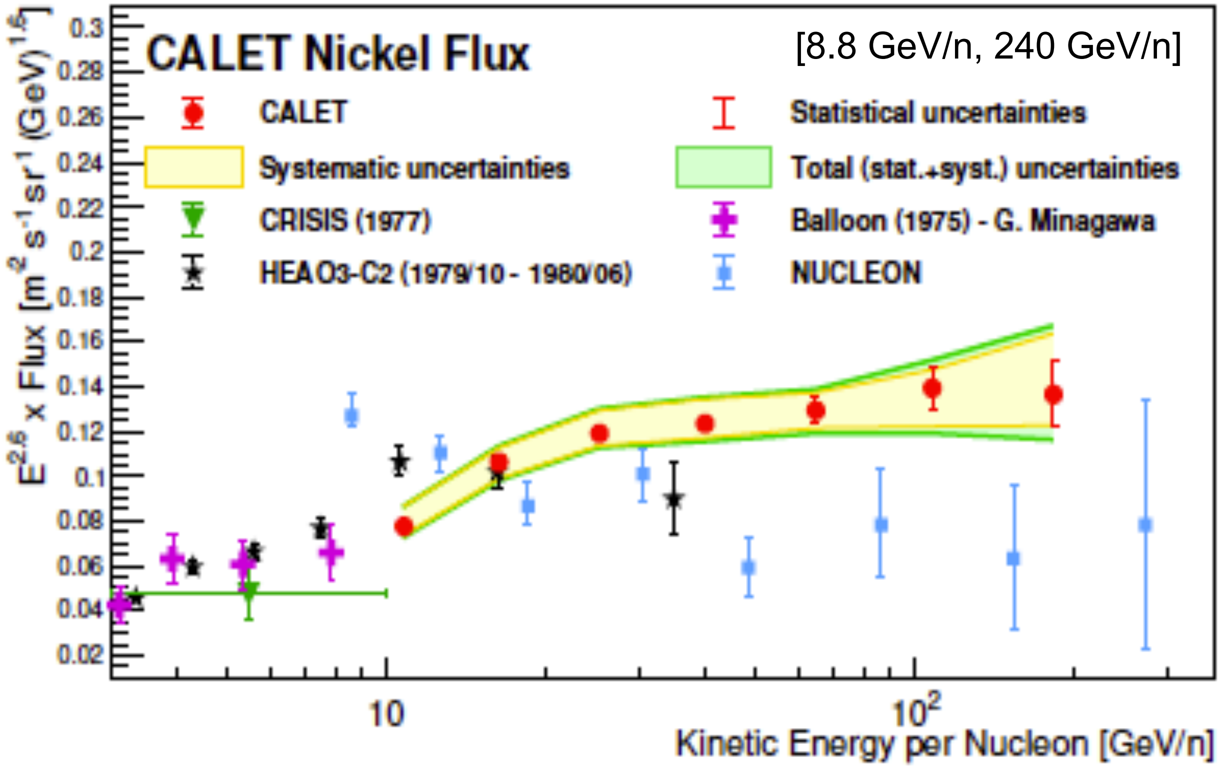
Consistent with ATIC-02 and TRACER at low energy and with CNR and HESS at high energy in tension with AMS-02 and SANRIKU (balloon)

The hardening seen in light nuclei is NOT observed in Iron spectrum up to 2 TeV/n.

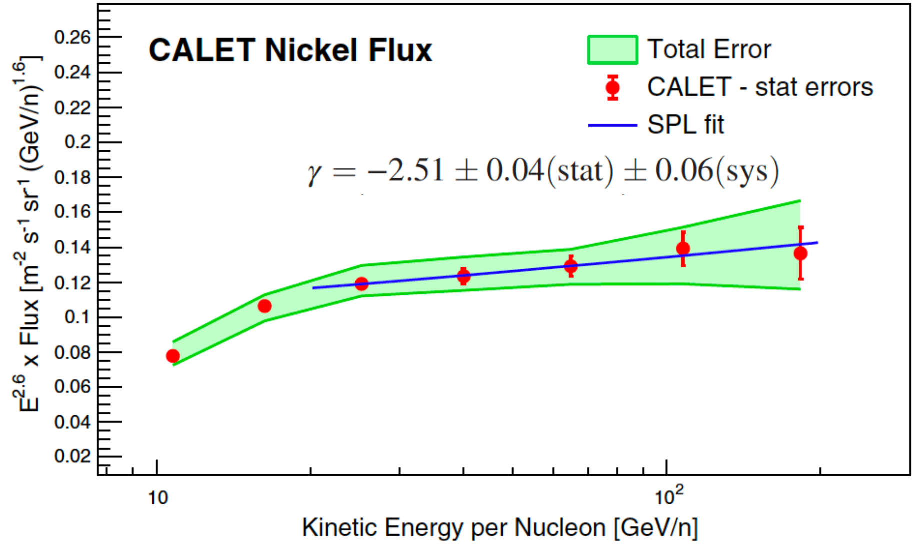
Nickel energy spectrum

PRL 126,131103 (2022)

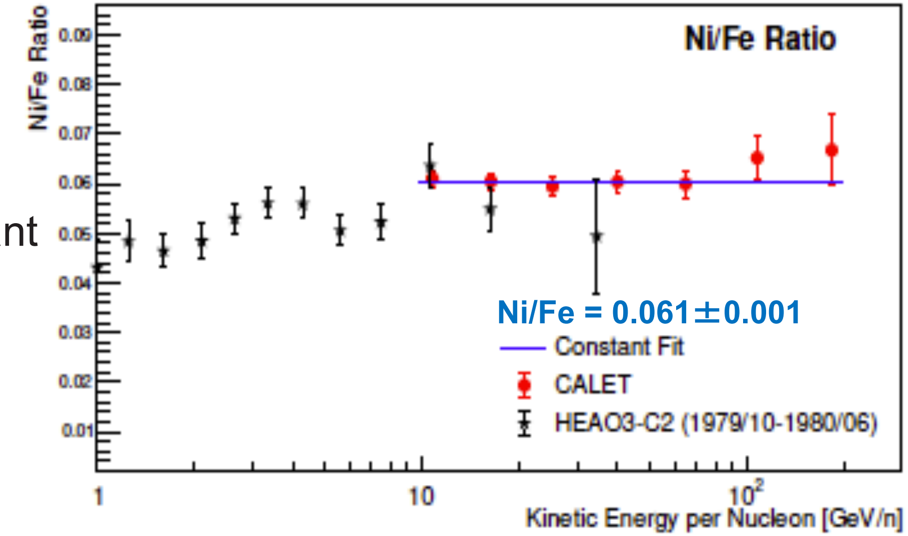
Flux x $E^{2.6}$ vs kinetic energy per nucleon



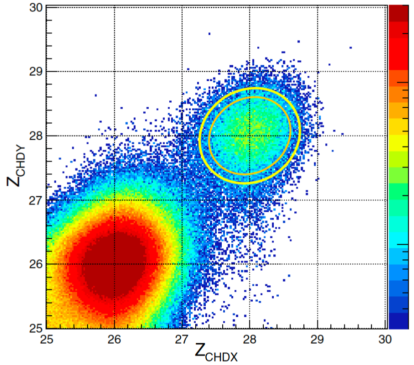
Fitting with single power law function

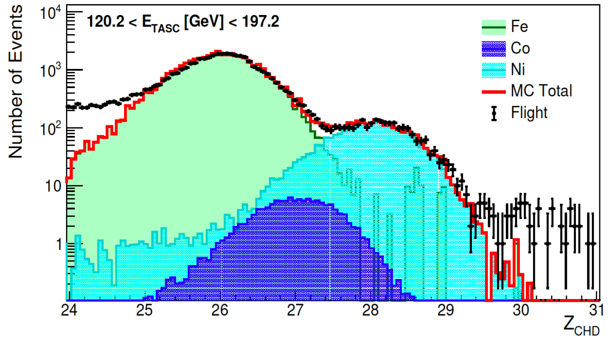


Ni/Fe flux ratio fitted with a constant function.

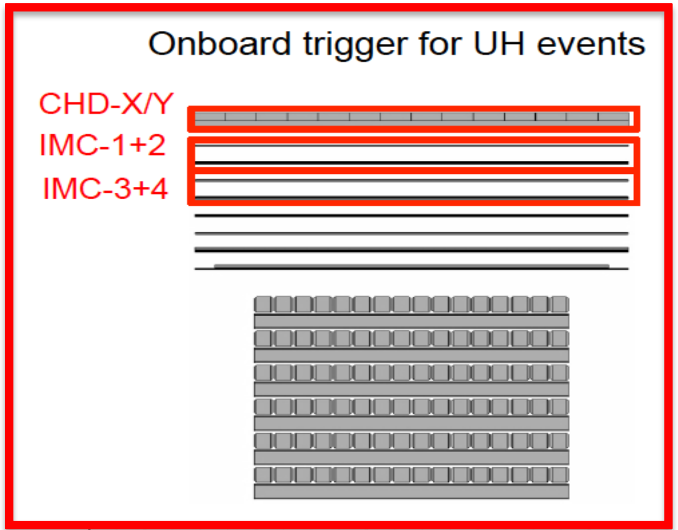


Charge separation between Fe and Ni

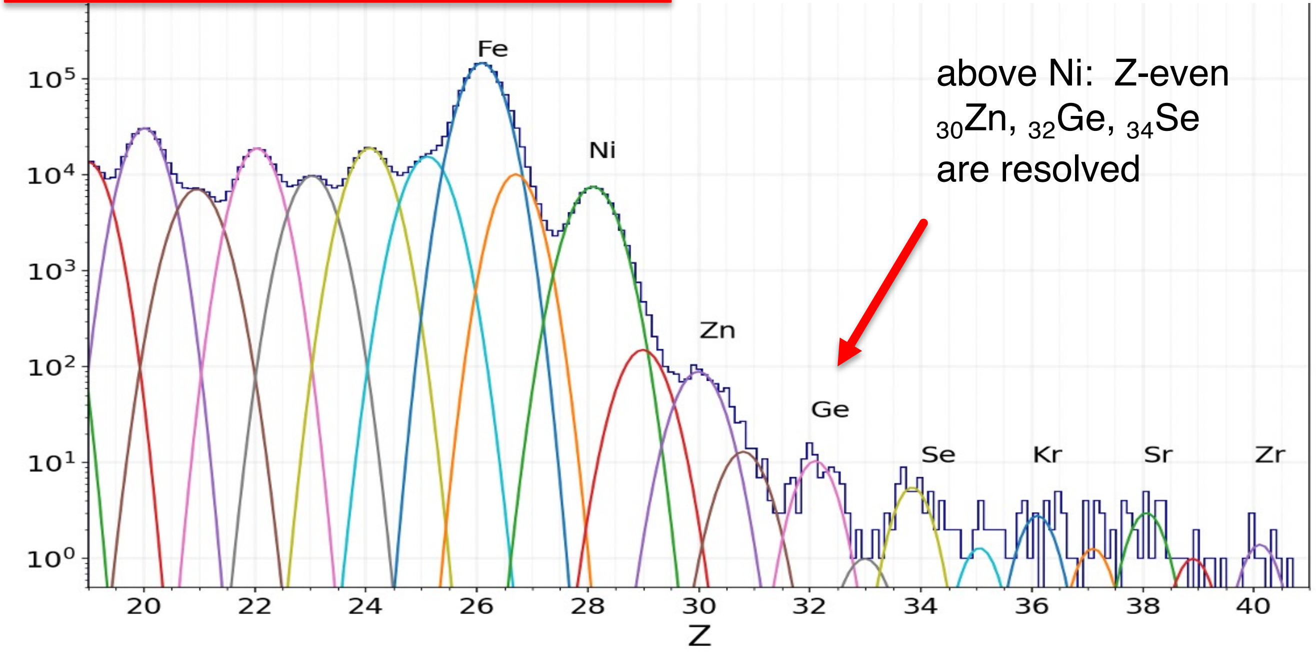




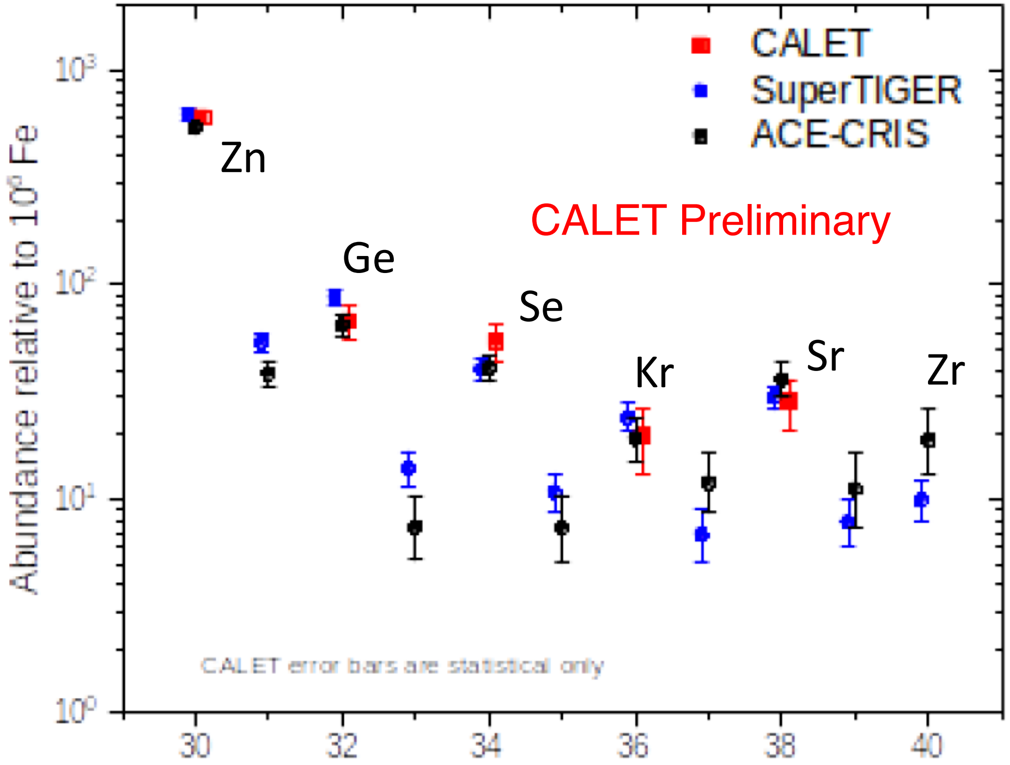
Ultra-heavy cosmic-ray nuclei (26 < Z ≤ 40)



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 cm² sr



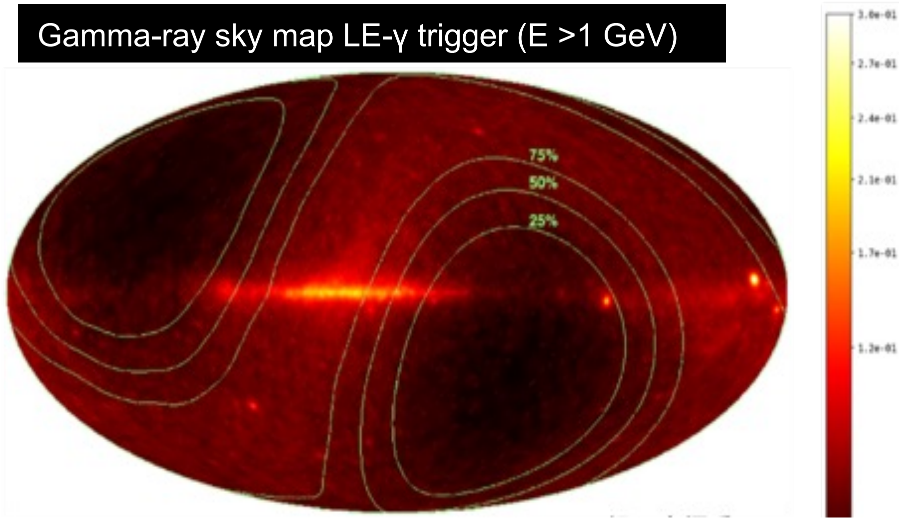
Measurement of the relative abundances of the elements above Fe through $_{40}$Zr (normalized to 10^6 Fe)



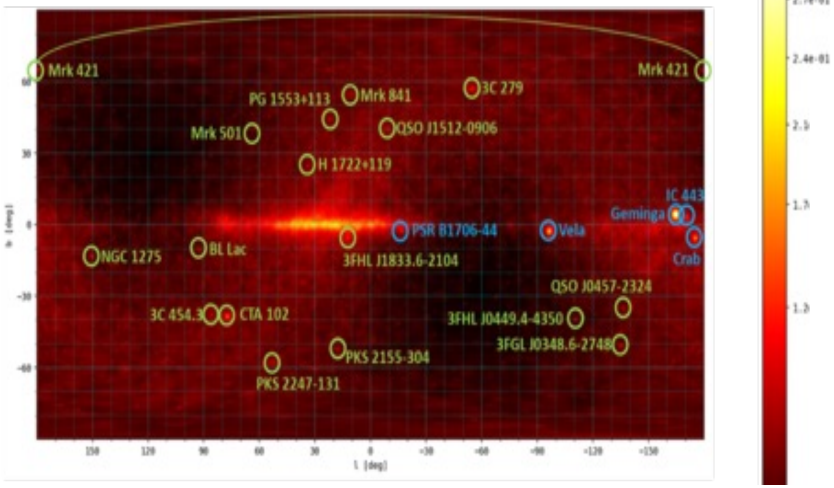
The CALET UH element ratios relative to Fe are consistent with Super-TIGER and ACE abundances.

CALET γ–ray Sky Map (>1GeV) and Energy Spectra

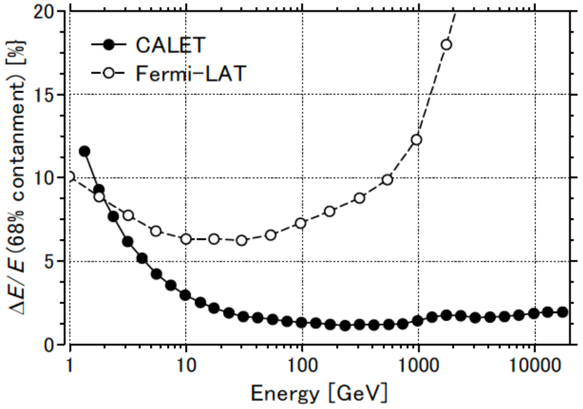
Gamma-ray sky map LE-γ trigger (E >1 GeV)



Identified bright point-sources (E >1 GeV)

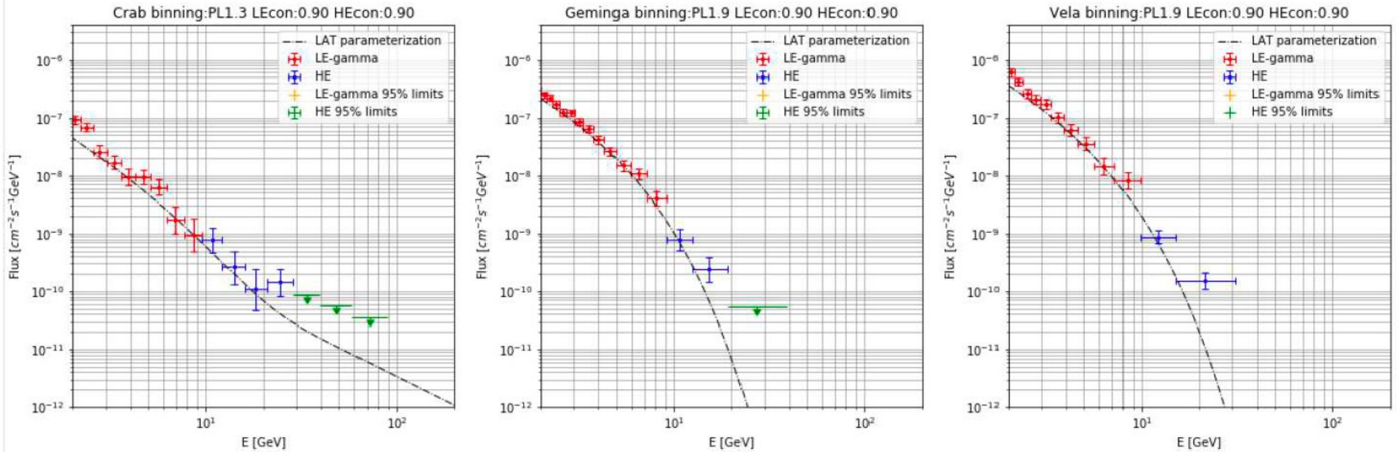


- Effective area: ~400 cm^2 (>2 GeV)
- Angular resolution: < 0.2° (> 10 GeV)
- Energy resolution: ~2% (> 10 GeV)



Energy spectra for bright point sources

Preliminary



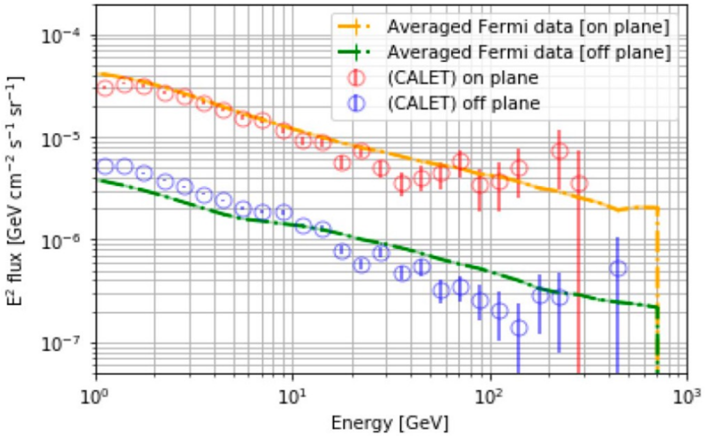
Diffuse Gamm-ray Spectrum Compared with Fermi-LAT

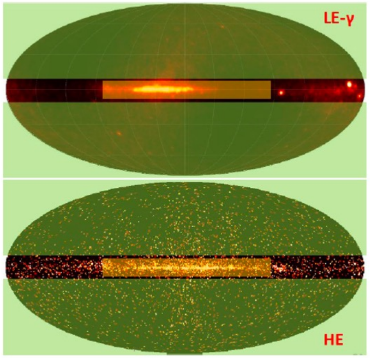
Preliminary

LE-γ + HE

November 2015 – February 2022

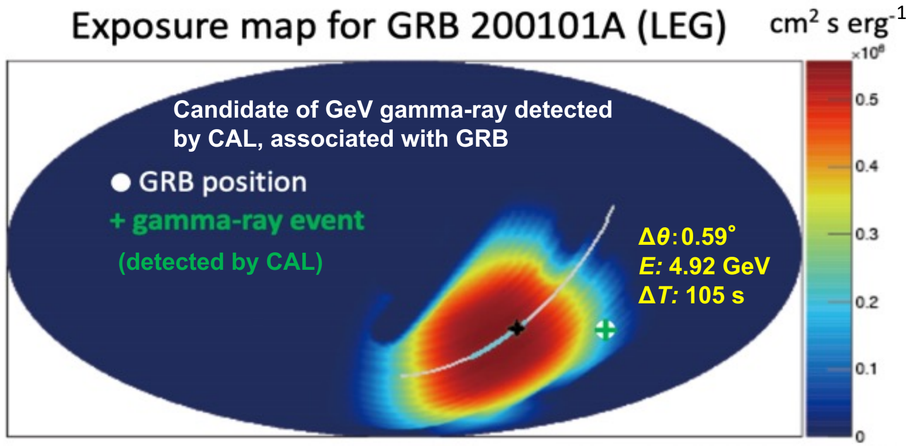
(Fermi data: analyzed from public data





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

Gamma-ray Bursts and GW Follow-up



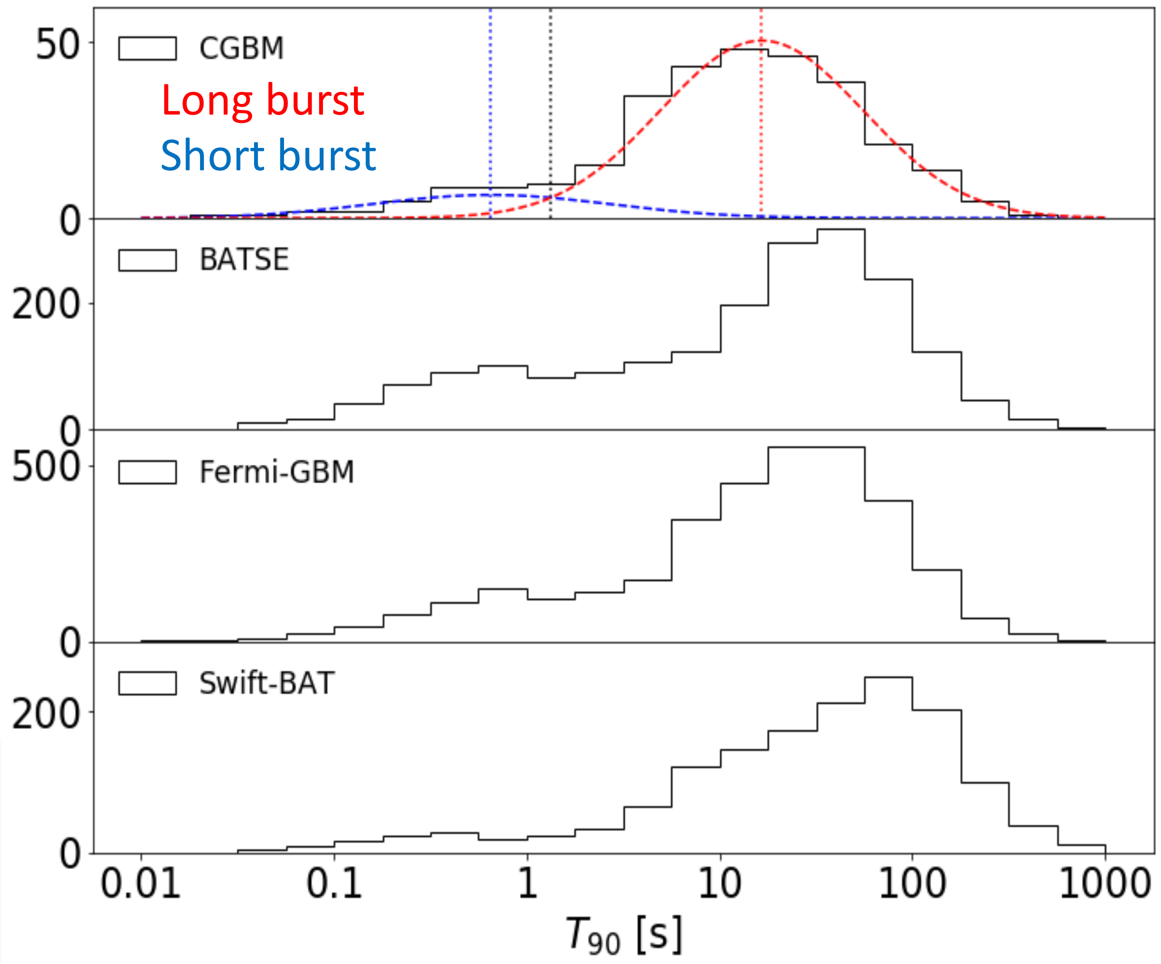
CGBM: dedicated Gammay-Ray Burst Monitor with energy range 7 keV-20 MeV

from 2015-10-05 to 2022-1-31

314 GRBs (~44 GRBs / year)

247 Long (89%) **33 Short (11%)**

Time distribution (T_{90}) of GRB durations



- **Follow-up** of LIGO/Virgo **GW** observations during O3
- X-ray and gamma-ray bands
- high-energy gamma-ray in the calorimeter

***published in Astrophysical Journal* 933:85 (2022)**

CALET: Summary and Future Prospects

- CALET was launched on Aug. 19th, 2015. The observation campaign started on Oct. 13th, 2015. Excellent performance and remarkable stability of the instrument have been confirmed.
- As of Feb. 28, 2023, total observation time is 2969 days (> 7 years) with live time fraction close to 86%. Nearly 3.86 billion events collected with low energy trigger (> 1 GeV) and 1.77 billion events with high energy trigger (> 10 GeV).
- Accurate calibrations have been performed in the energy measurements established in 1 GeV-1PeV.
- Following results of the cosmic-ray spectra have been obtained by now.
  - Measurement of electron + positron spectrum in 11 GeV- 4.8 TeV.
  - Direct measurement of proton and Helium in 50 GeV ~ 60 or 50 TeV energy range, and of Carbon and Oxygen spectra in 10 GeV/n -2.2 TeV/n: Spectral hardening was consistently observed around a few hundred GeV/n. B/C flux is precisely measured up to 3.8 TeV/n.
  - Iron and Nickel spectra were measured to energies beyond those covered by previous experiments..
- Continuous observations of GRBs, Solar Modulation and REP events have being carried out.
- CALET observation has successfully been carried out over 7 years, and is approved to be extended for further 4 years (at least) until the end of 2024 (or more).

✓ We greatly appreciate JAXA staffs for perfect support of the CALET operation at the TKSC of JAXA !!
✓ **This work is partially supported by JSPS KAKENHI Kiban (S) Grant Number 19H05608 (2019-2023FY).**