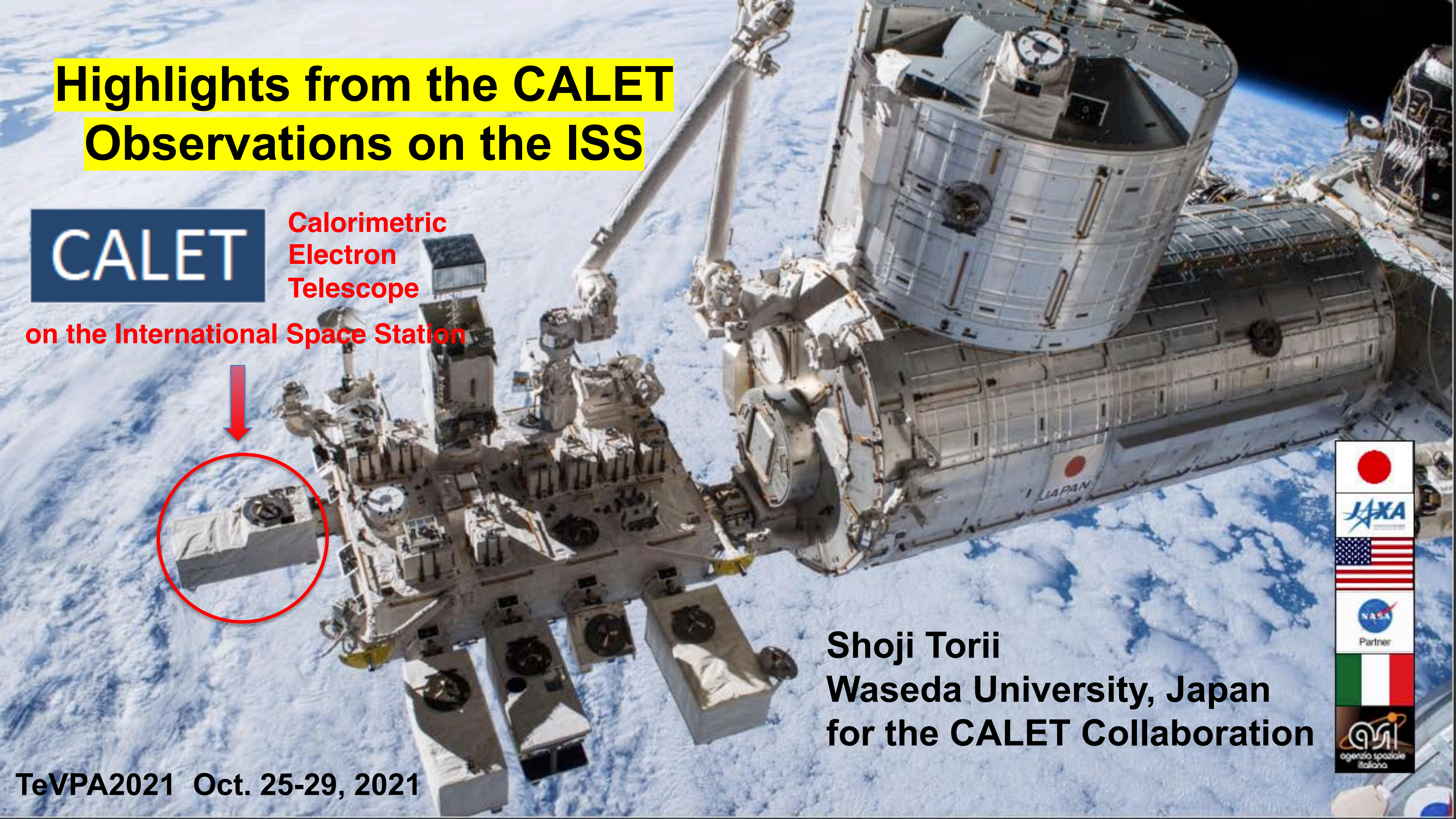
Highlights from the CALET Observations on the ISS



CALET

Calorimetric
Electron
Telescope

on the International Space Station

Shoji Torii
Waseda University, Japan
for the CALET Collaboration

TeVPA2021 Oct. 25-29, 2021

The CALET Collaboration Member

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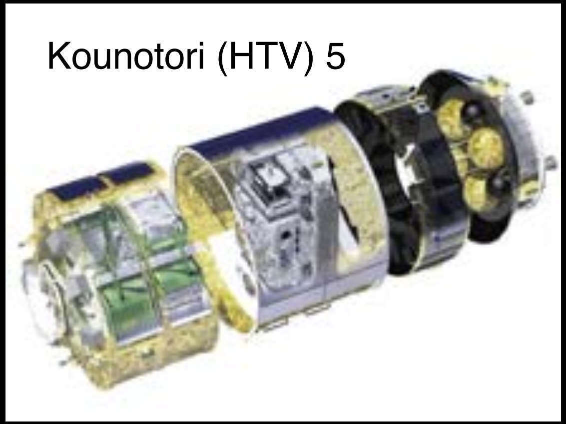
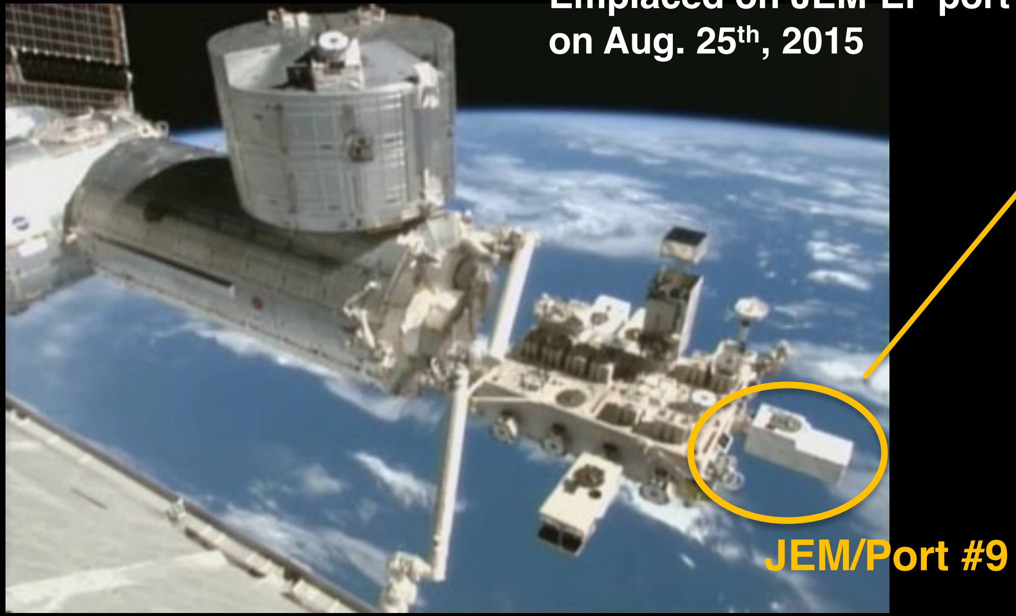
Co-PI : Italy
Co-PI : USA

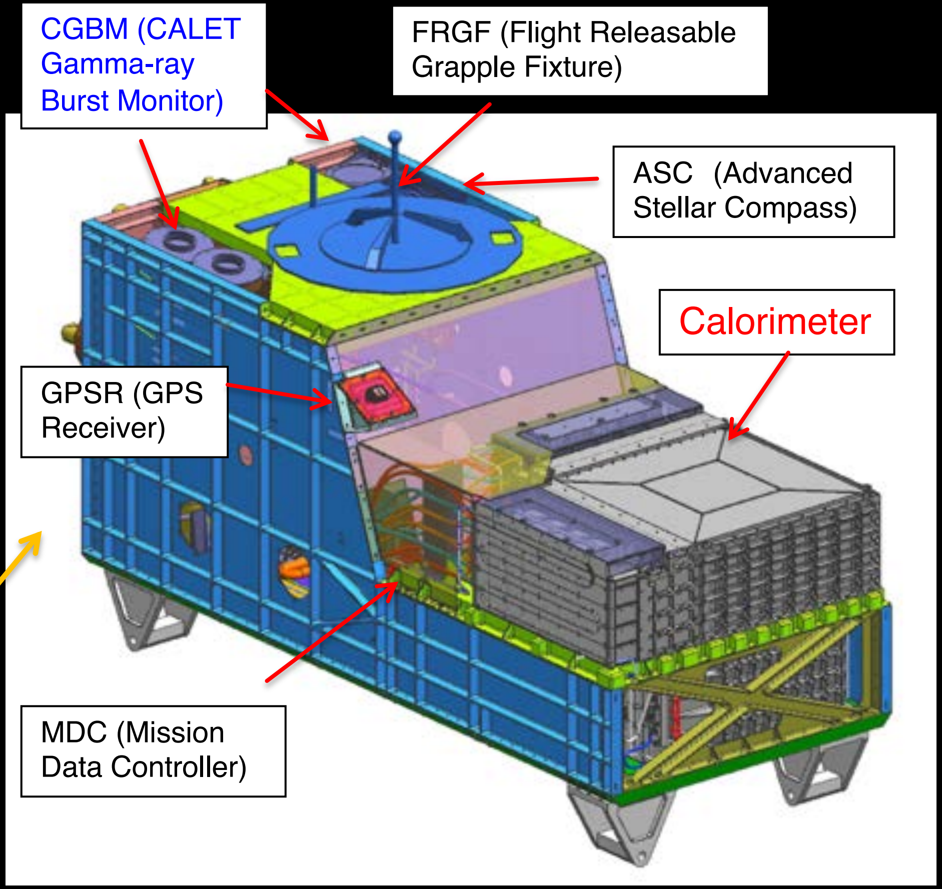
CALET Payload



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

Overview of CALET Payload

CAL

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

CGBM

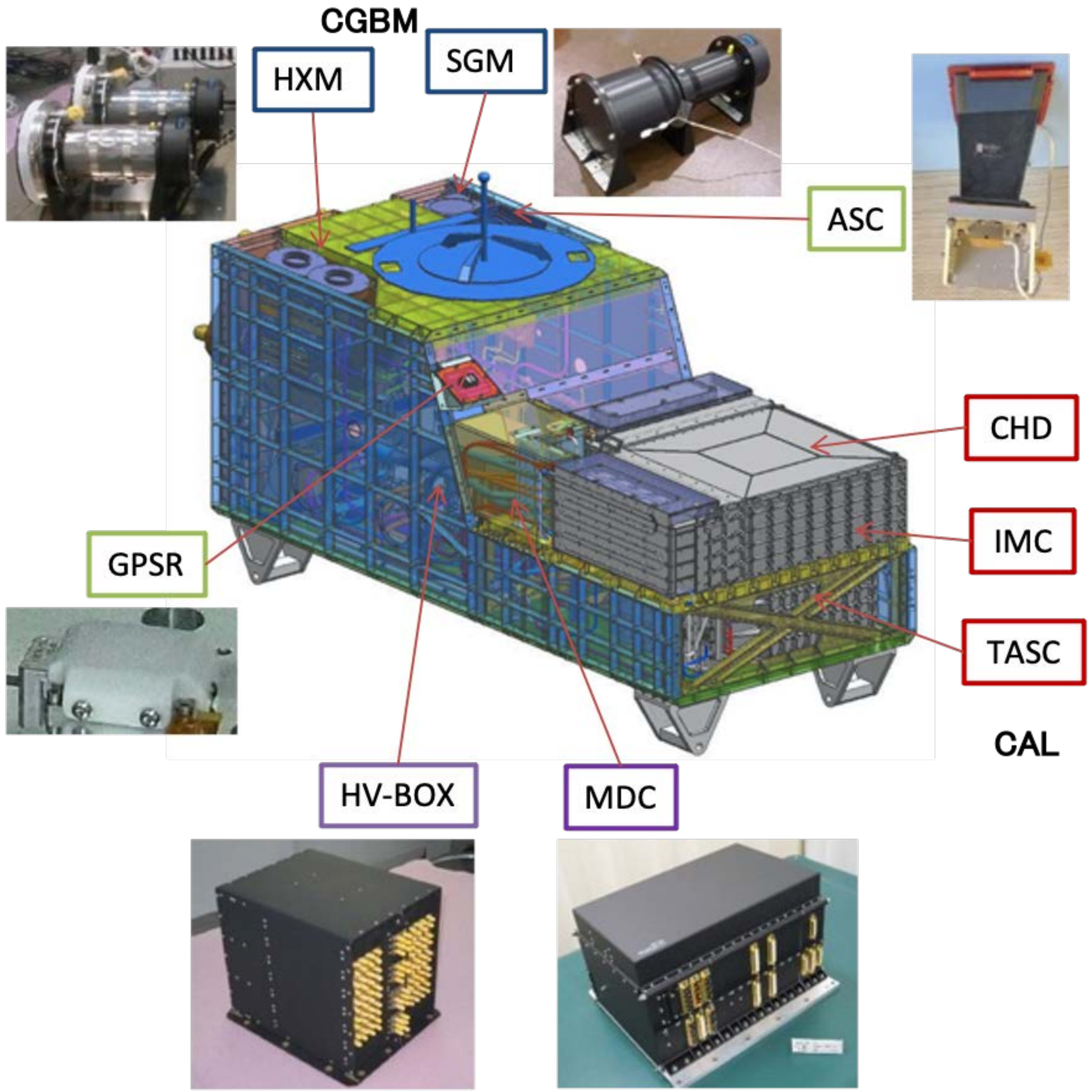
- Hard X-ray Monitor (HXM) x 2
  $LaBr_3$: 7keV～1MeV
- Soft γ-ray Monitor (SGM)
  BGO : 100keV～20MeV

Data Processing & Power Supply

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

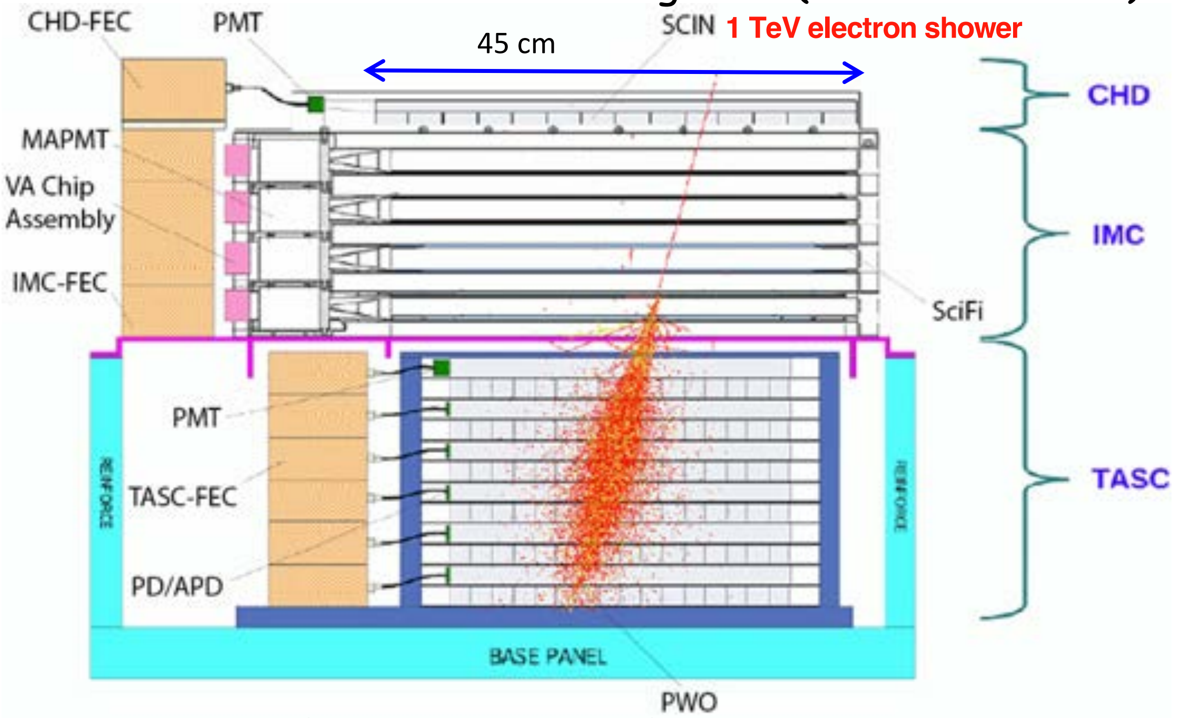
Support Sensors

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



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

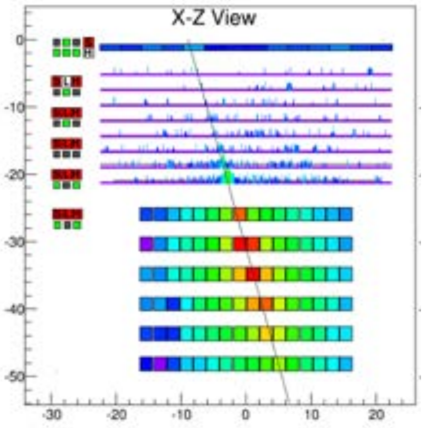
IMC – Imaging Calorimeter

- 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**

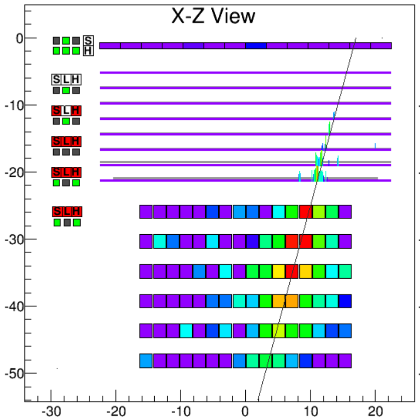
TASC – Total Absorption Calorimeter 27 X_0, 1.2 λ_I

- 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}

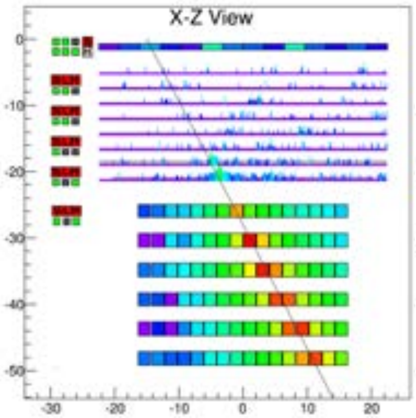
Electron, E=3.05 TeV



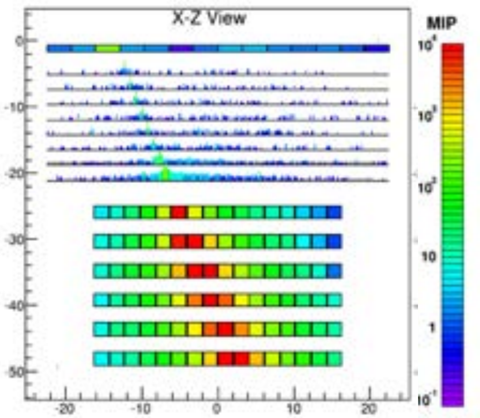
Gamma-ray, E=44.3 GeV



Proton, E_{TASC}=2.89 TeV

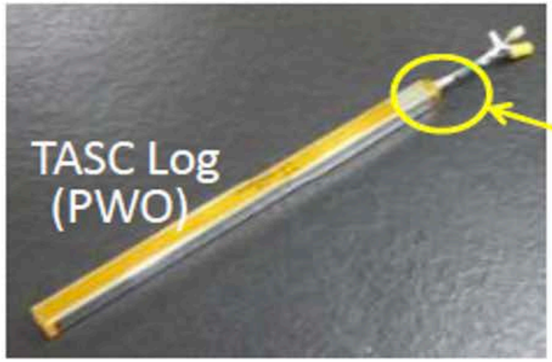


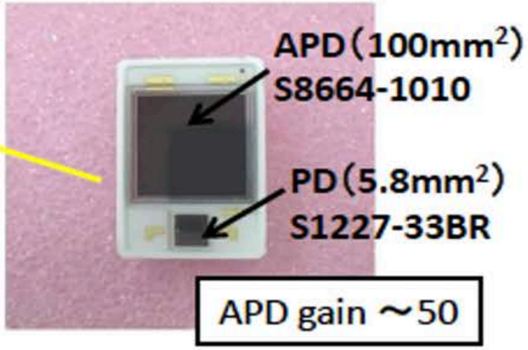
Iron, E_{TASC} =9.3 TeV



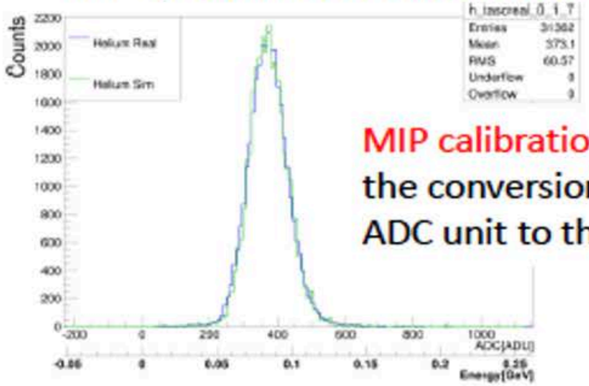
Event Display: Electron Candidate (>100 GeV)

Energy Measurement in a Wide Dynamic Range 1-10^6 MIPs

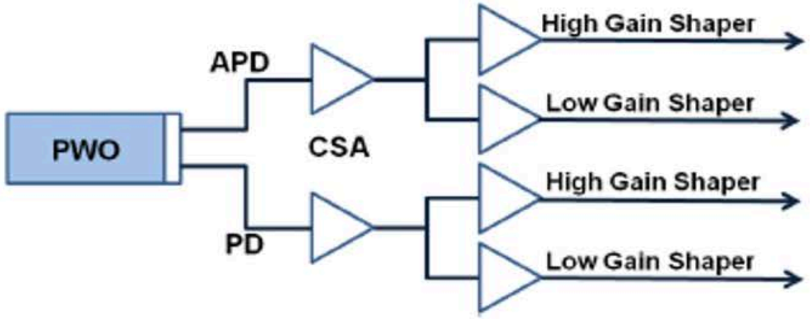




"MIP" peak in PWO: Obs. vs. MC



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

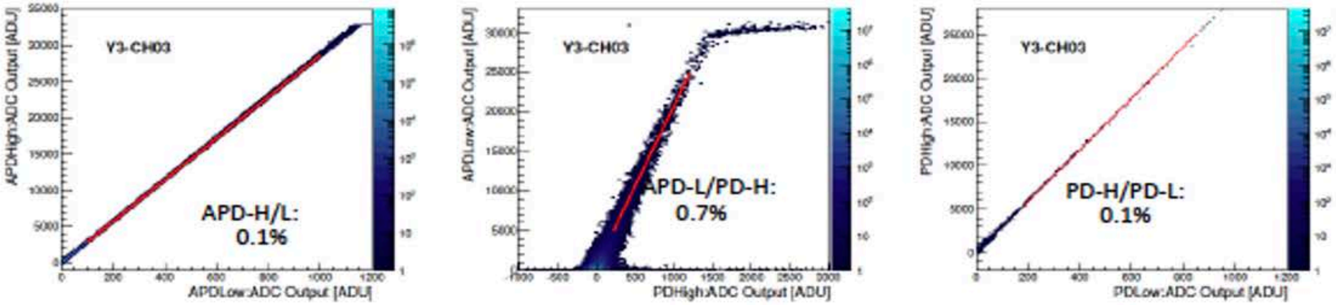


The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

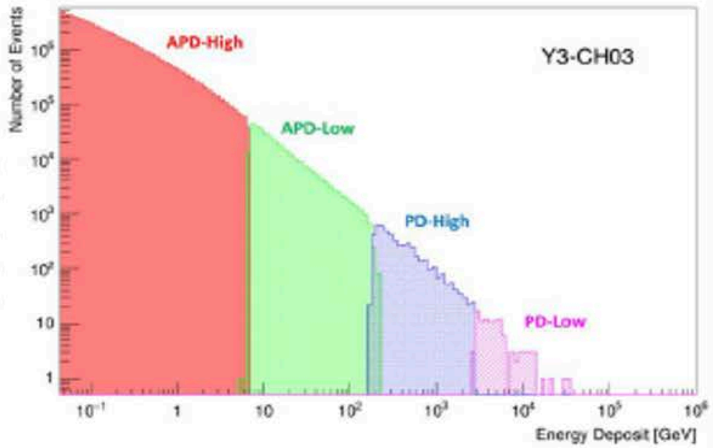
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

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%

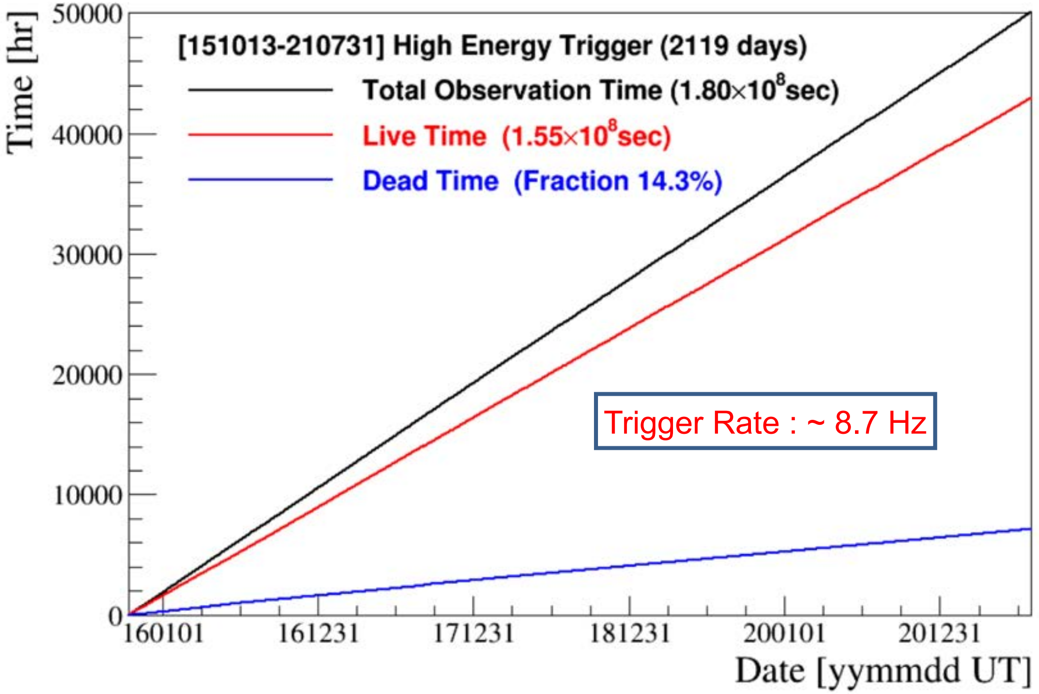


Example of energy distribution in one PWO log



CALET Observations on the ISS

Accumulated observation time (live, dead)



High-energy trigger (> 10 GeV) statistics:

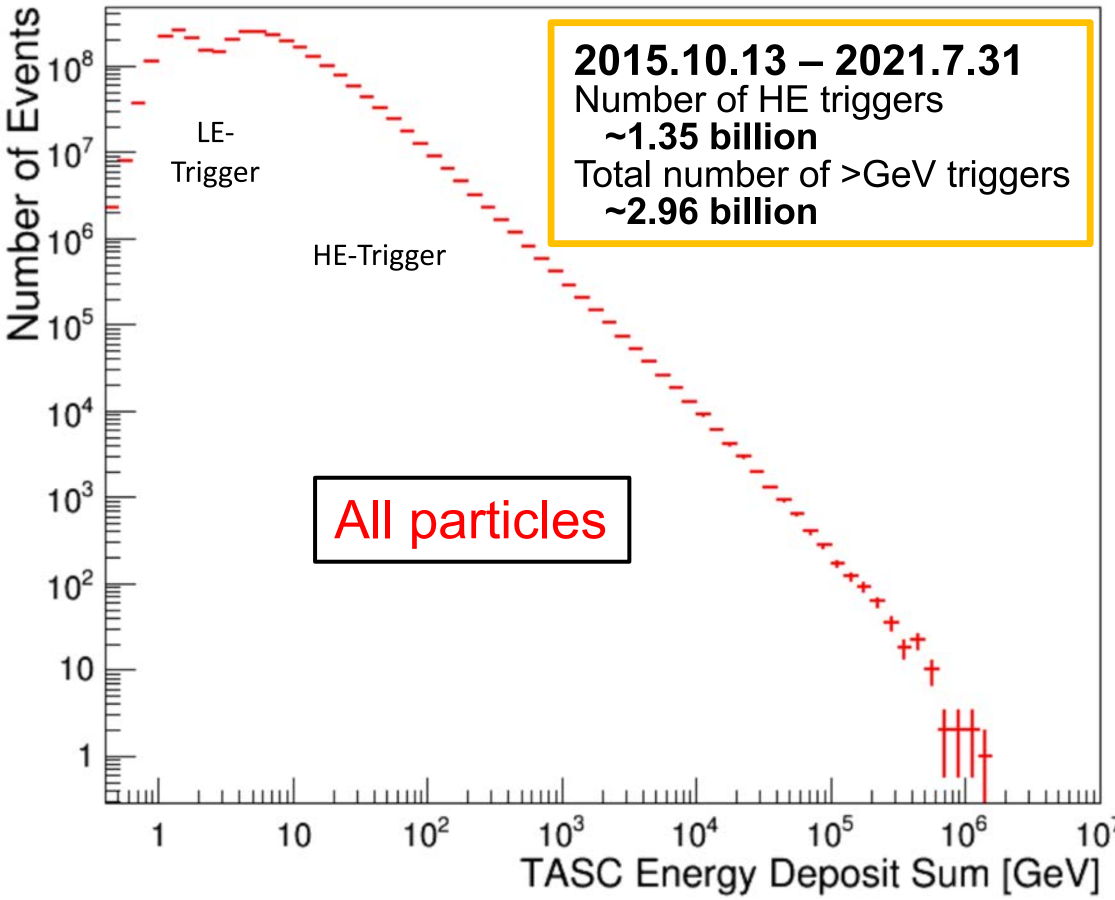
- Operational time > **2119 days**(*)

  (*) as of July 31, 2021
- Live time fraction **> 85%**
- Exposure of HE trigger
  ~186 m^2 sr day
- HE-gamma point source exposure
  ~3.6 m^2 day (for Crab, Geminga)

Geometrical Factor:

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

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



Electron Measurement with CALET: Accurate Measurements Constrain Systematics

1. Acceptance - Geometrical factor	➡	well defined SΩ because of reliable tracking
2. Detection efficiency - Losses in the detector	➡	ε ~ 70 % (after electron selection, E>30 GeV) keeps mostly constant up to 5 TeV
3. Energy determination - Energy resolution - Calibration	➡	ΔE/E < 2% (E>20 GeV) Absolute energy scale calibrated by beam tests and rigidity cutoff
4. Particle Identification - Proton contamination	➡	P_{BG} < 5 % (E<1 TeV) P_{BG} ~ 10-20 % (1 TeV<E< 5 TeV)

➡ Minimize the effects of unforeseen systematics,
combined with detailed systematic studies (see PRLs and SM)

Electron Identification

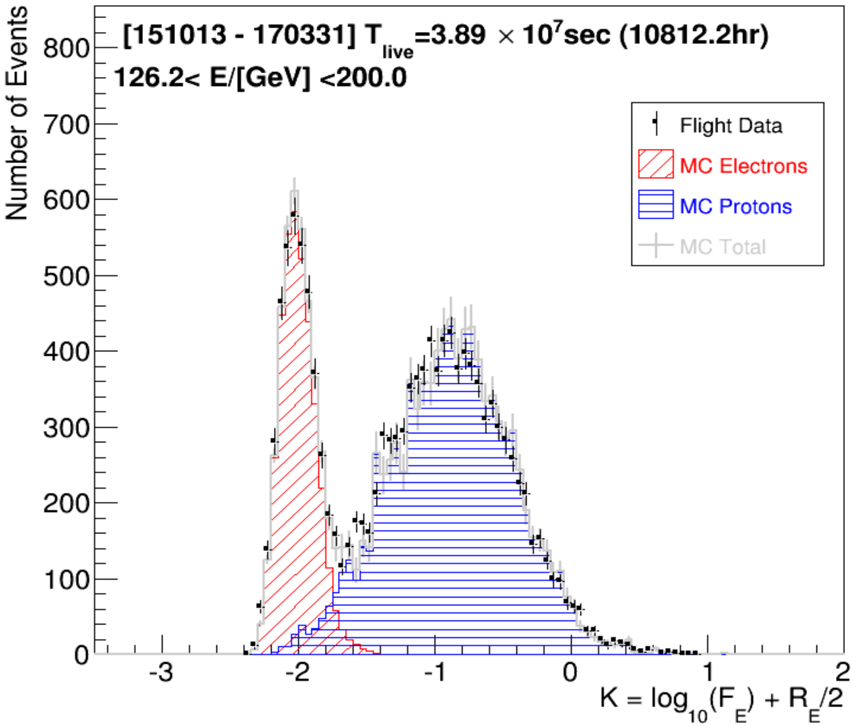
Simple Two Parameter Cut

F_E: Energy fraction of the bottom layer sum to the whole energy deposit sum in TASC

R_E: Lateral spread of energy deposit in TASC-X1

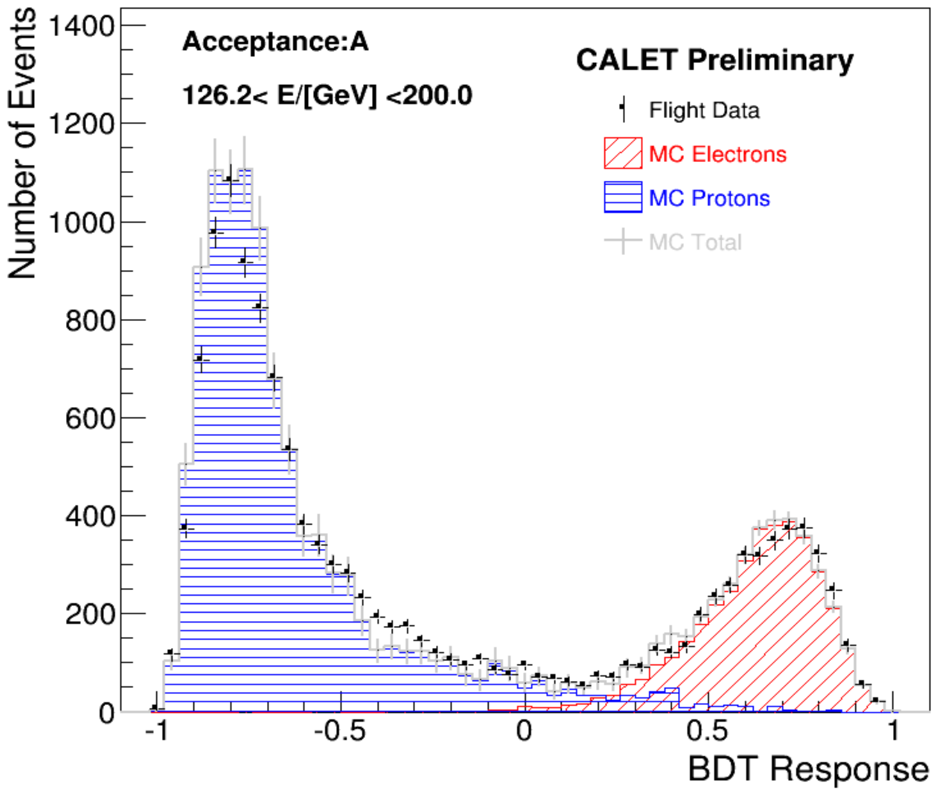
Cut Parameter K is defined as follows:

$K = \log_{10}(F_E) + 0.5\ R_E$ (/cm)



Boosted Decision Trees (BDT)

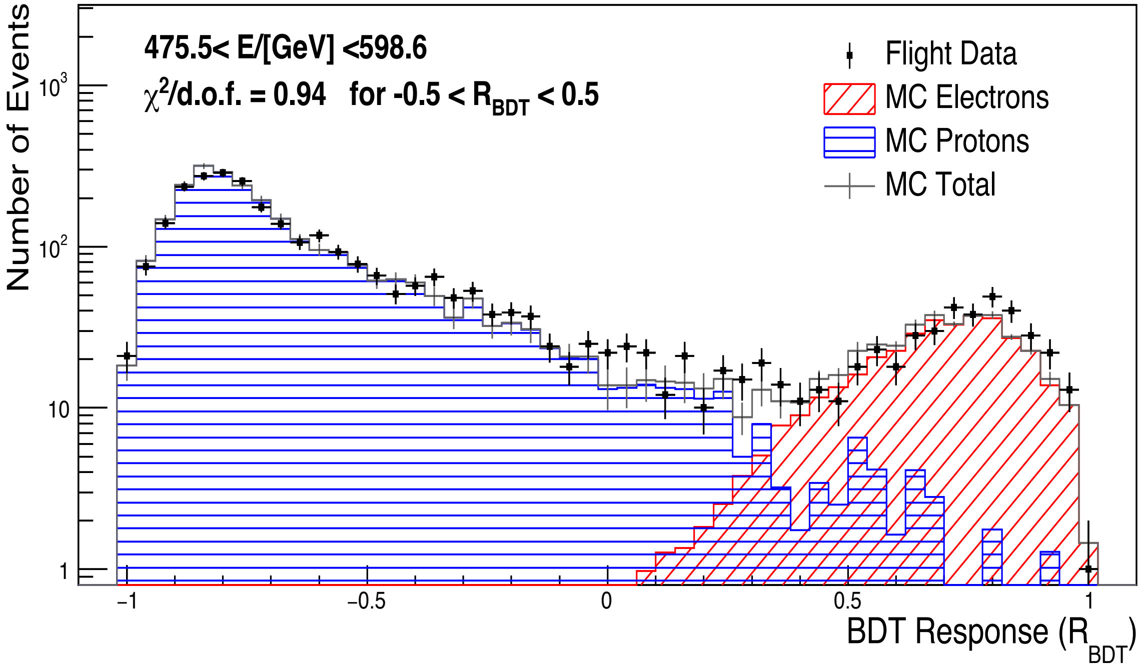
In addition to the two parameters in the left, TASC and IMC shower profile fits are used as discriminating variables.



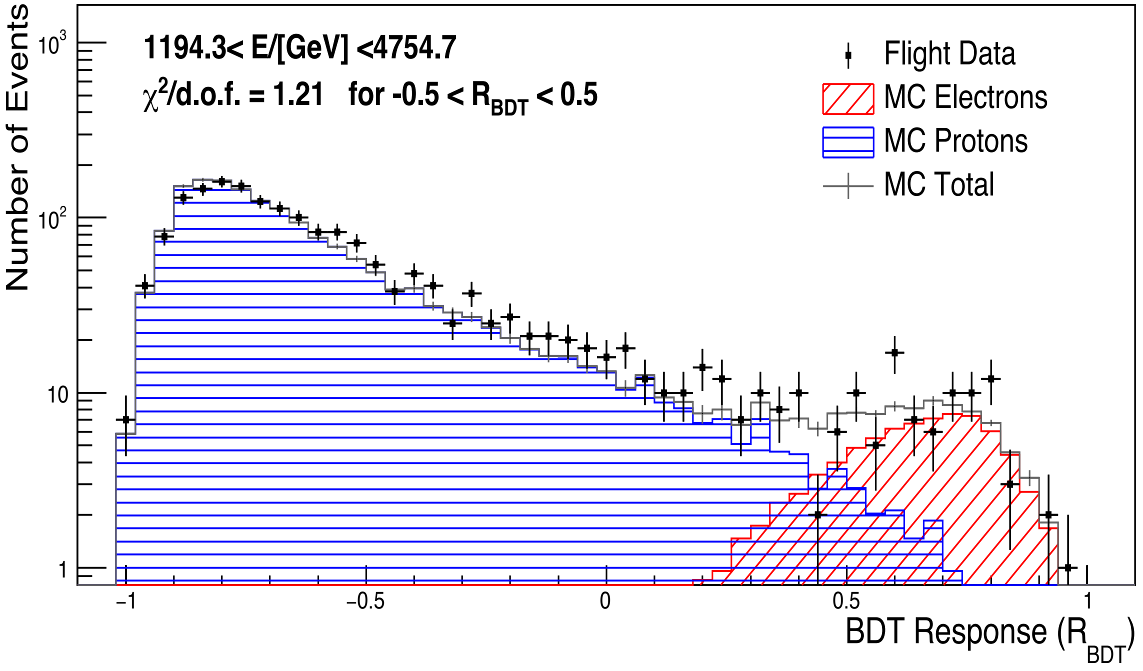
BDT Response Distribution at Higher Energies

In the final electron sample, the resultant contamination ratios of protons are:
< 5 % up to 1 TeV ; 5 % - 20 % in the 1 – 5 TeV region
, while keeping a constant high efficiency of 80 % for electrons.

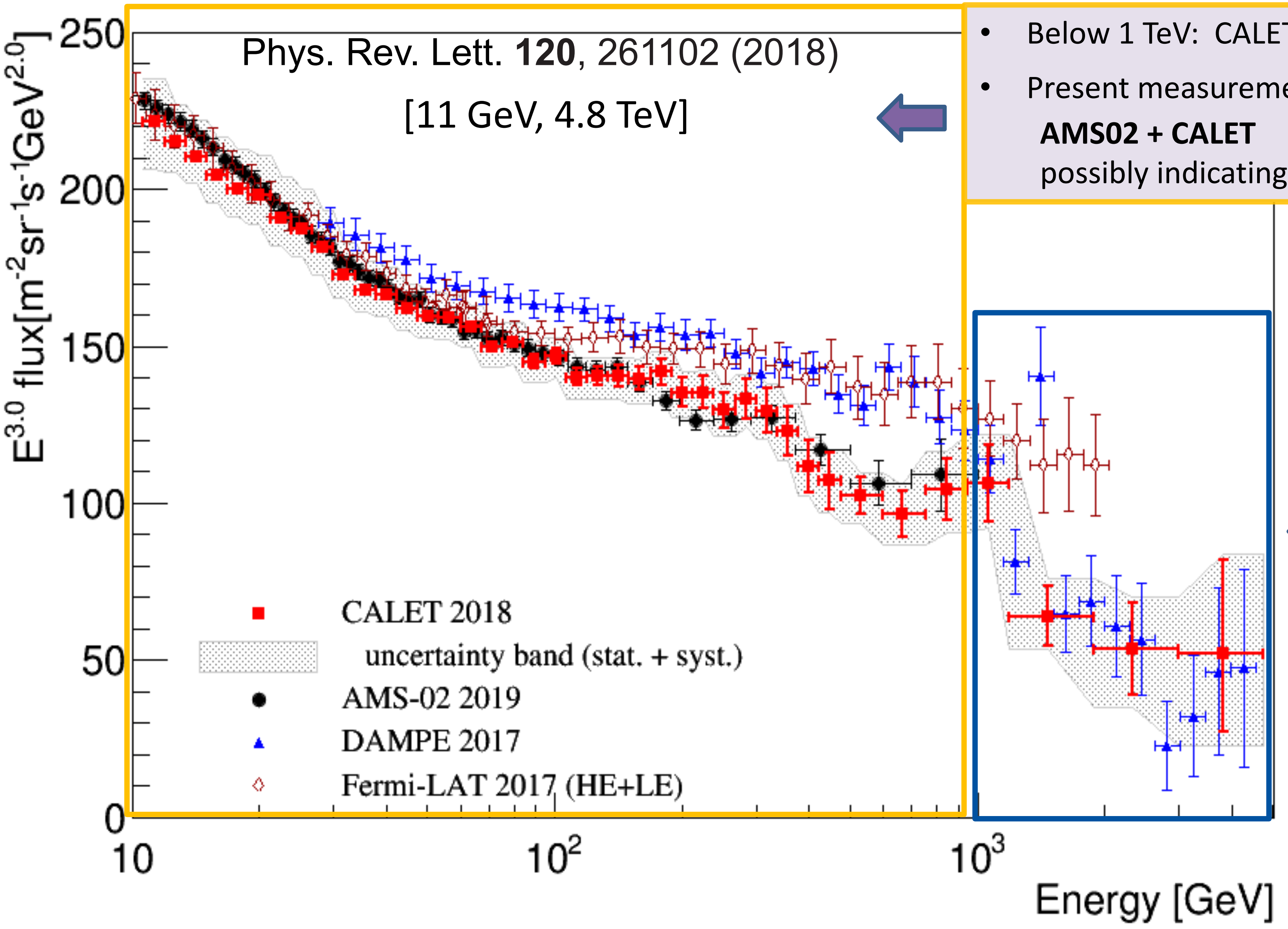
476 < E < 599 GeV



1196 < E < 4755 GeV (highest energy bin)



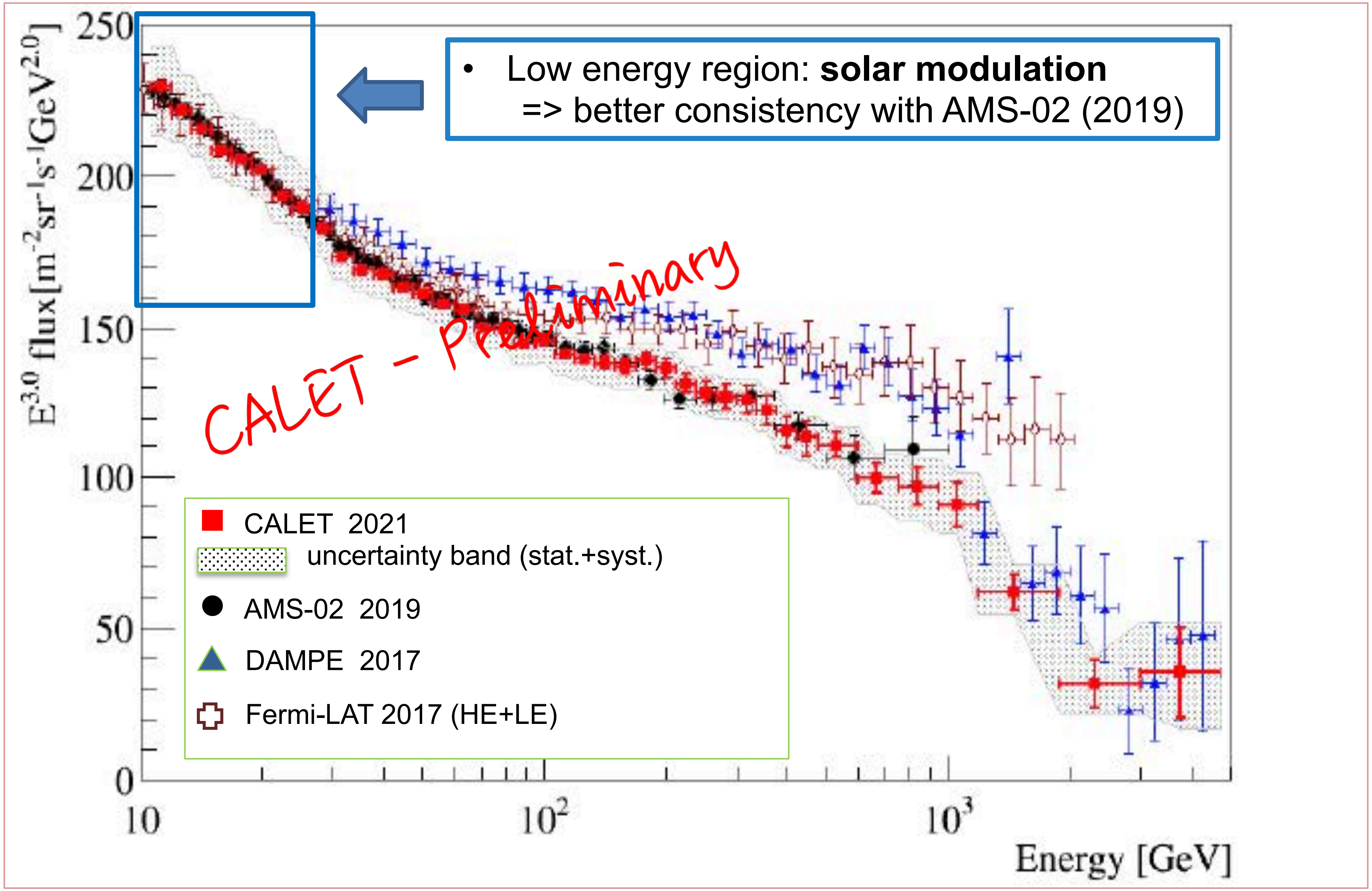
Cosmic-ray All-electron Spectrum



- 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 unknown systematics

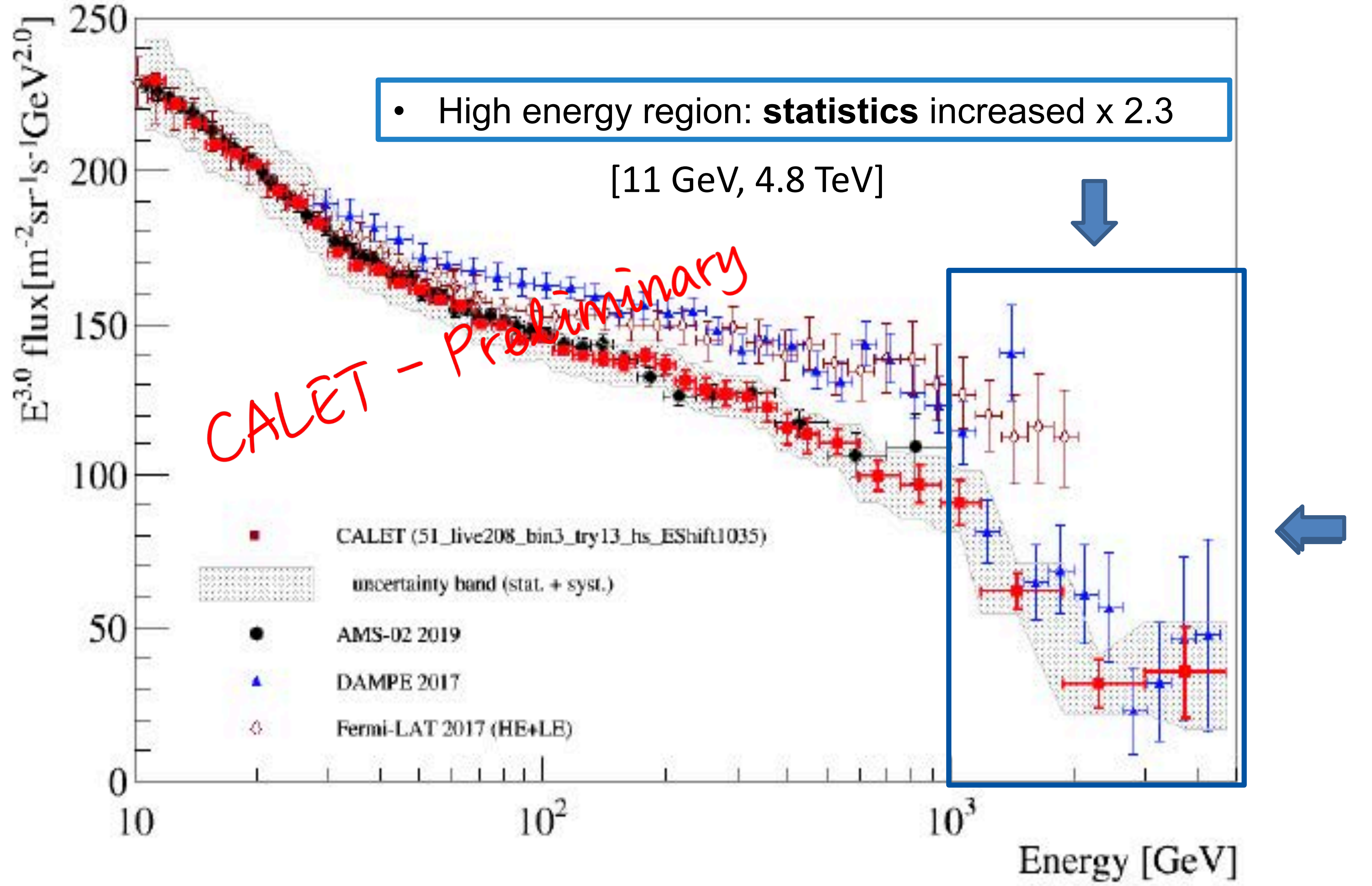
- Above 1 TeV CALET observes a suppression of the flux consistent with DAMPE within errors
- No peak-like structure at 1.4 TeV in CALET measurement irrespective of binning

Cosmic-ray all-electron spectrum (update: as of Sep. 30, 2020)



Preliminary spectrum is **updated** after 1815 days of CALET observations: Oct.13, 2015 - Sep.30, 2020

Cosmic-ray all-electron spectrum (update: as of Sep. 30, 2020)



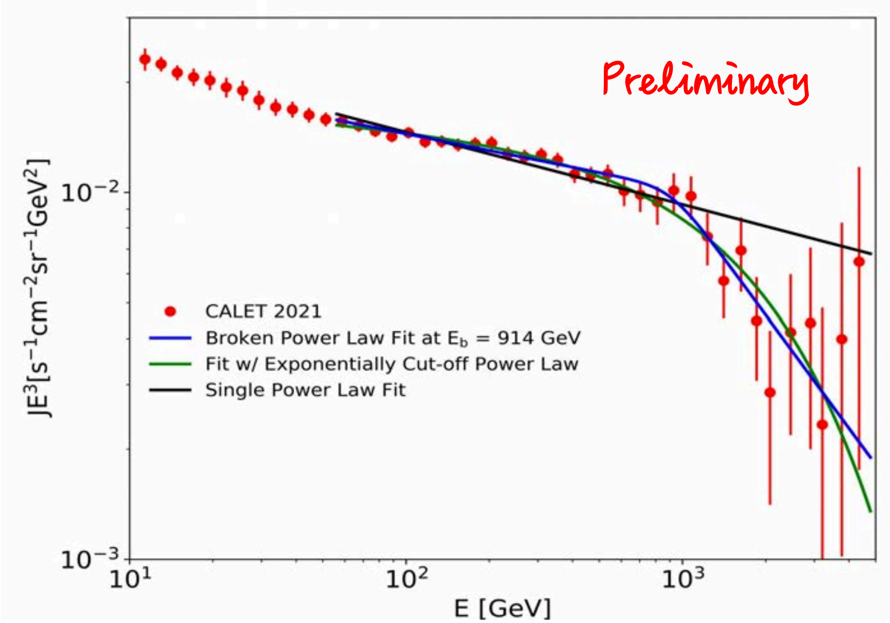
- High energy region: **statistics** increased x 2.3

[11 GeV, 4.8 TeV]

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)

Towards an interpretation of the CALET all-electron spectrum

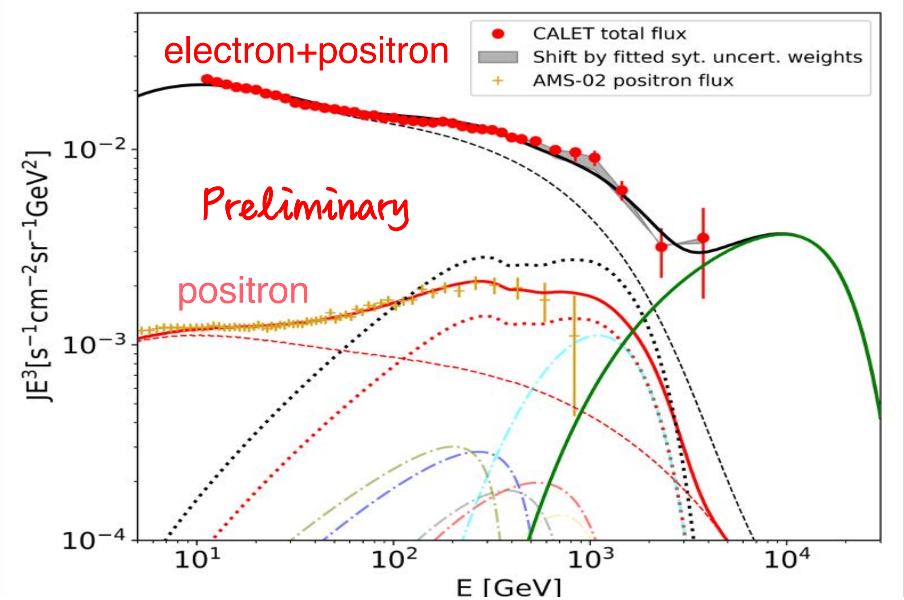
- Fits of the CALET all-electron spectrum in 55 GeV - 4.8 TeV, using the same energy binning as DAMPE [Nature, 2017]



- Broken power law used in DAMPE
  γ= - 3.151 ⇨ - 4.024 (χ^2 /NDF=11.64/29)
- Exponential cut-off power law [PRL, 2018]
  γ= - 3.054 with E_c= 2.17 TeV (χ^2 /NDF=11.25/29)
- Single power law
  γ=-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.

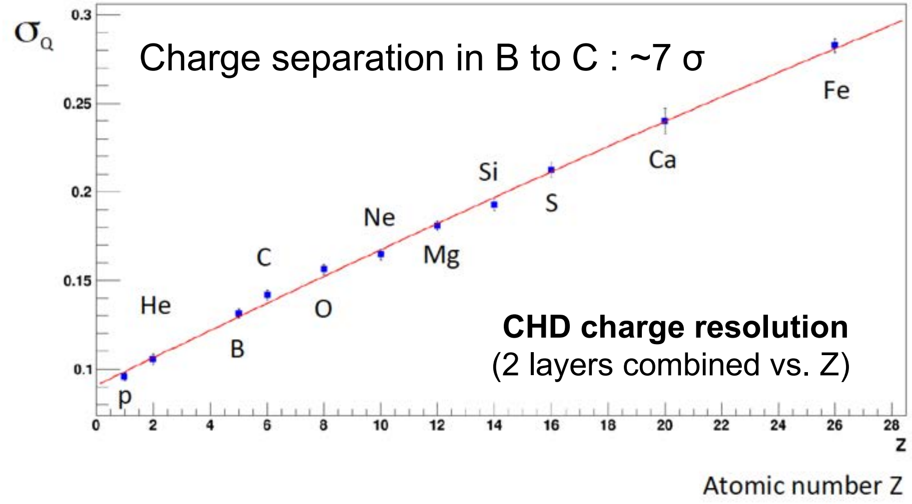


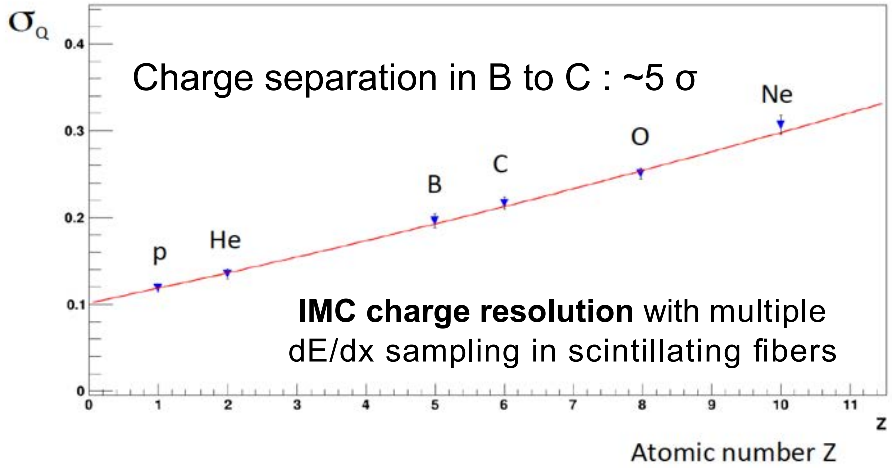
- Positron flux(AMS): secondaries+ nearby pulsars
- Electron flux (CALET-AMS):
  Secondaries + Distant SNRs (black dashed line)
  + Vela SNR (green line).

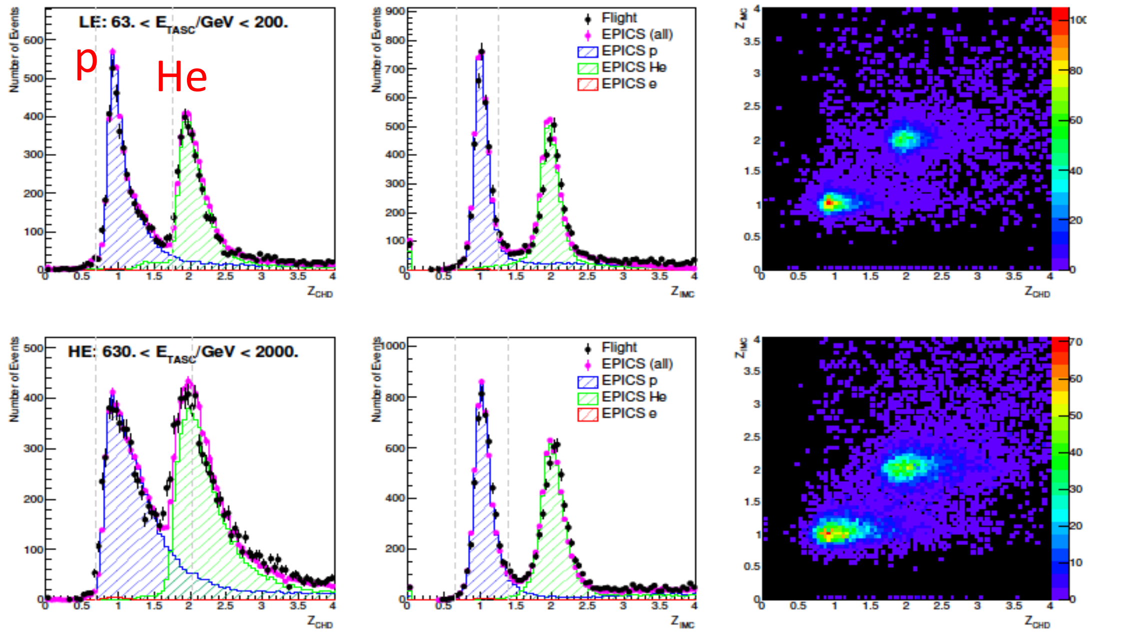
A possible contribution from the Vela SNR:
Energy output of 2.08 x 10^{48} erg in electron CR above 1 GeV.

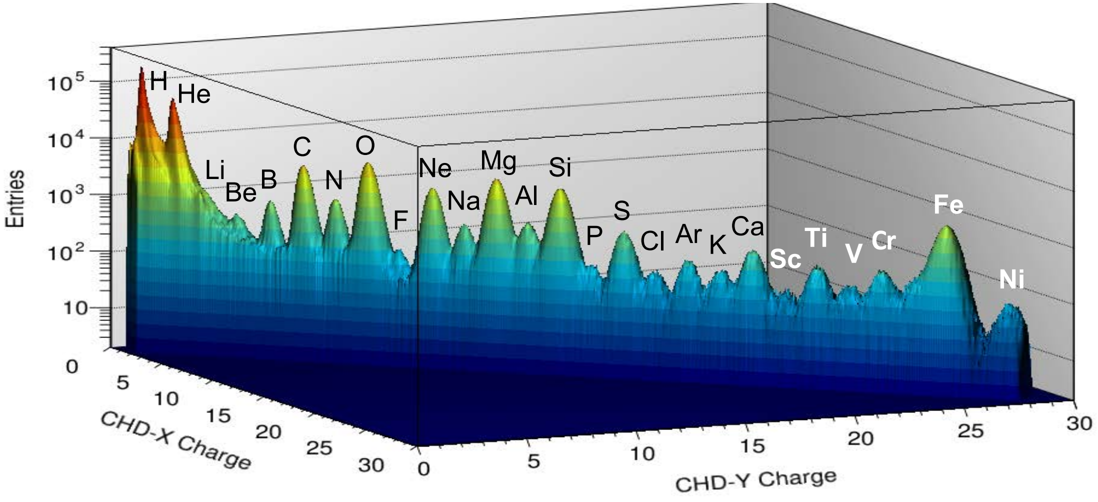
Charge Identification with CHD and IMC

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









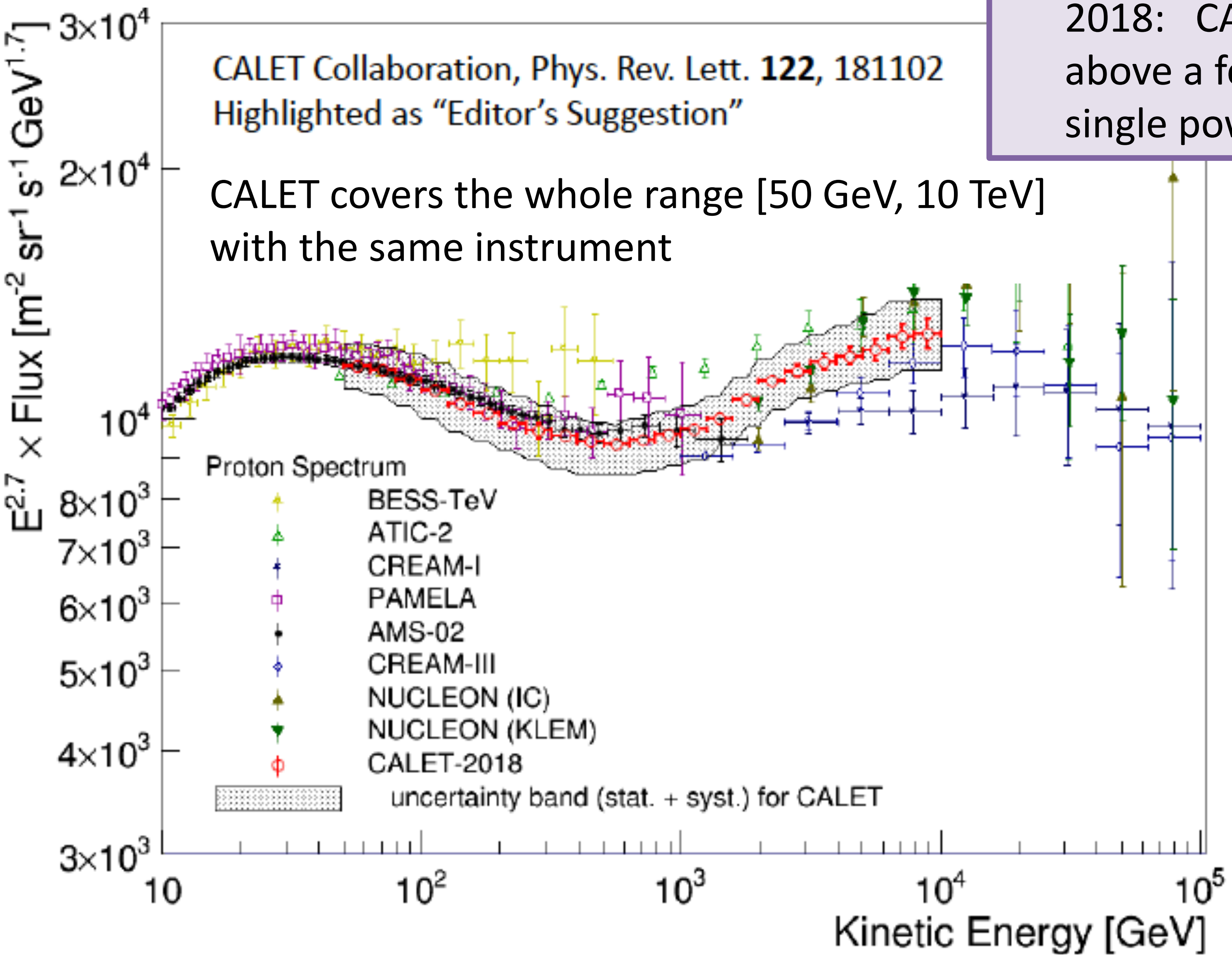
Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

Cosmic-ray proton spectrum

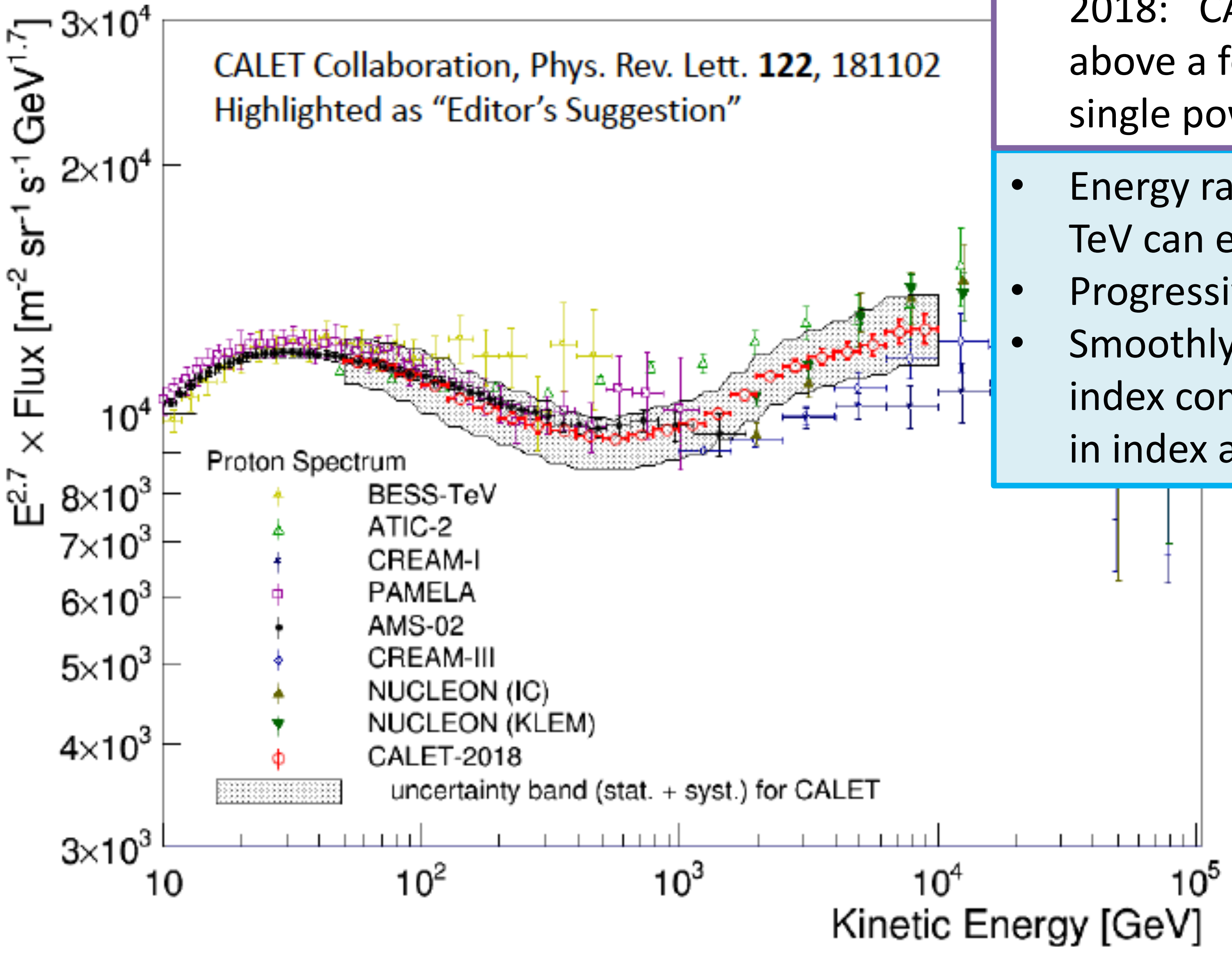
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

CALET Collaboration, Phys. Rev. Lett. **122**, 181102
Highlighted as "Editor's Suggestion"

CALET covers the whole range [50 GeV, 10 TeV] with the same instrument

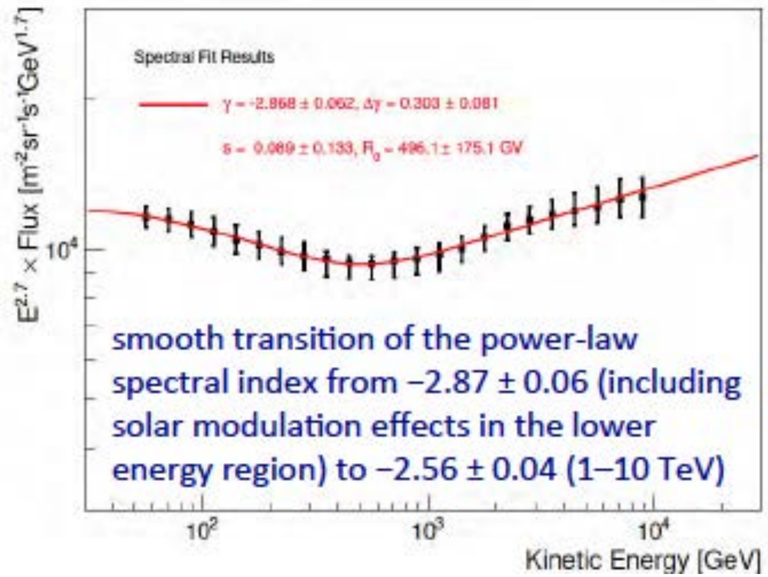


Cosmic-ray proton spectrum

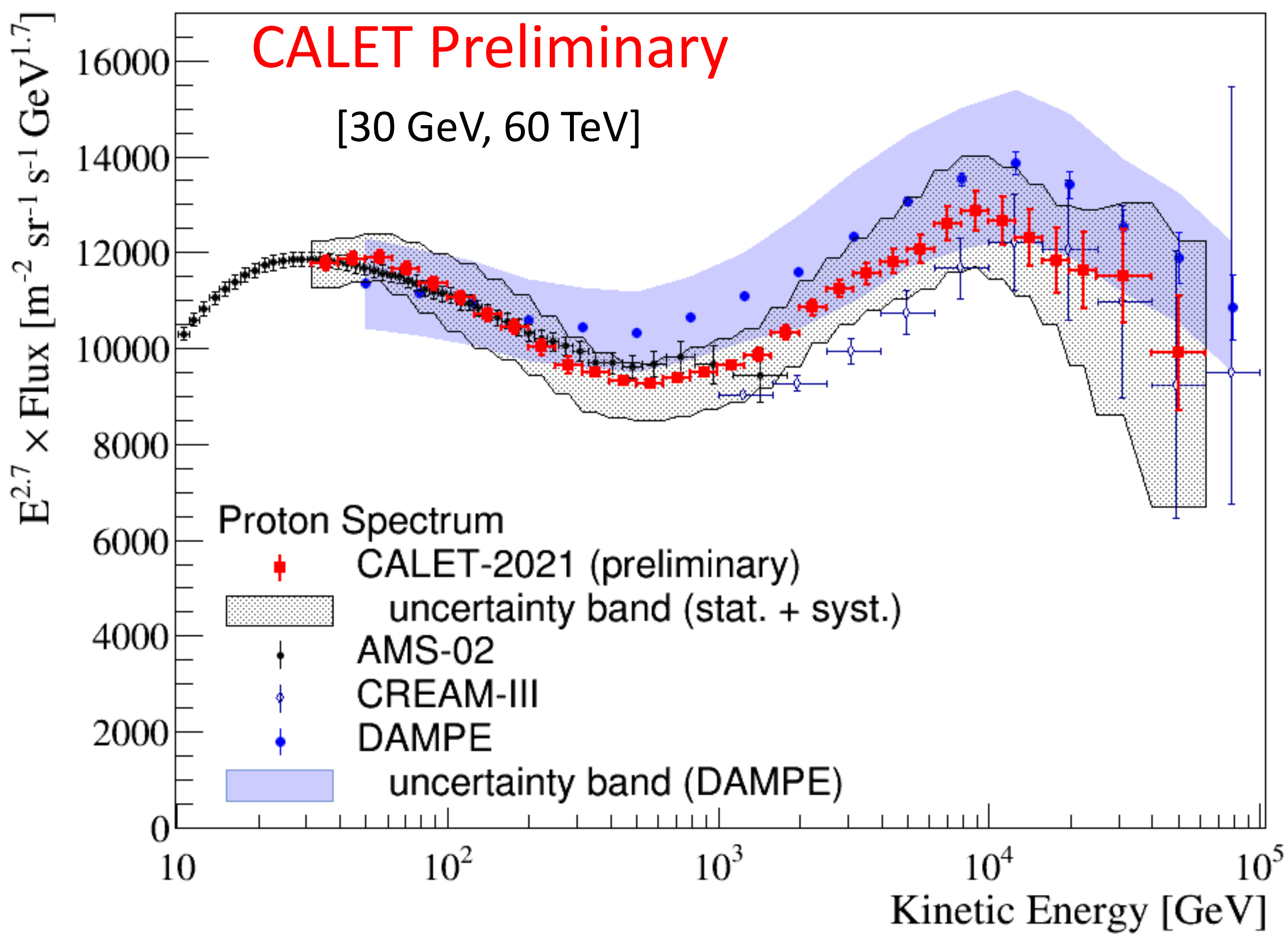


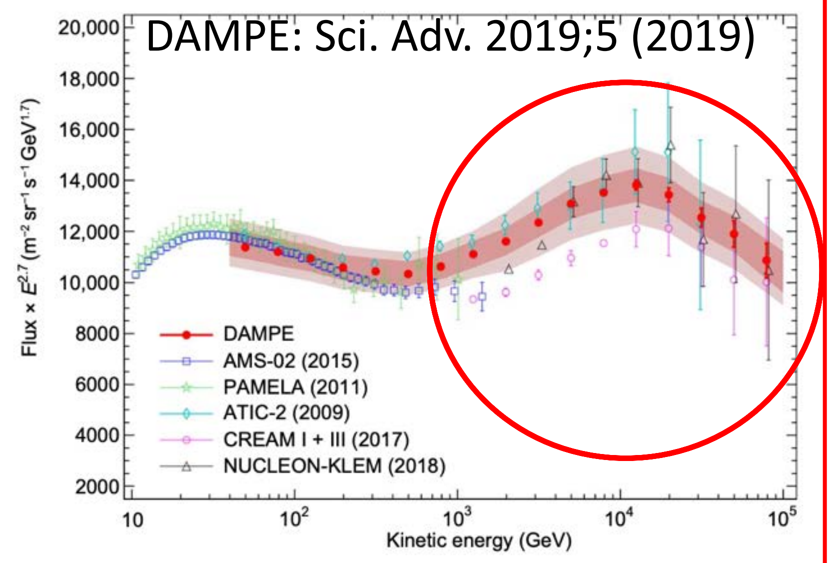
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

- Energy ranges 50 GeV – 500 GeV and 1 TeV – 10 TeV can each be fitted with single power laws
- Progressive hardening up to TeV energies
- Smoothly-broken power law fit gives low energy index consistent with AMS-02, but larger change in index and higher break energy



Cosmic-ray proton spectrum (update: as of Sep.30, 2020)

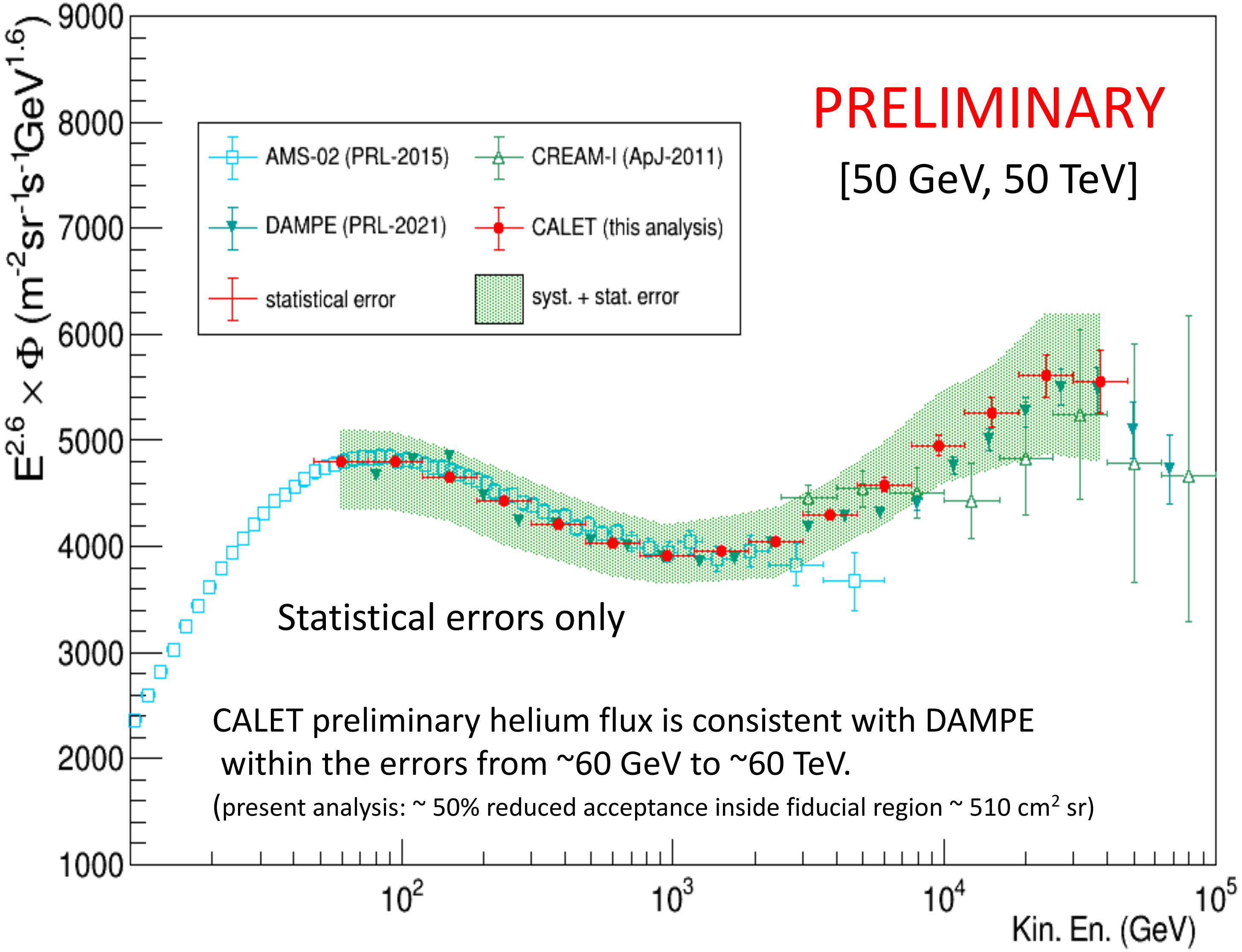


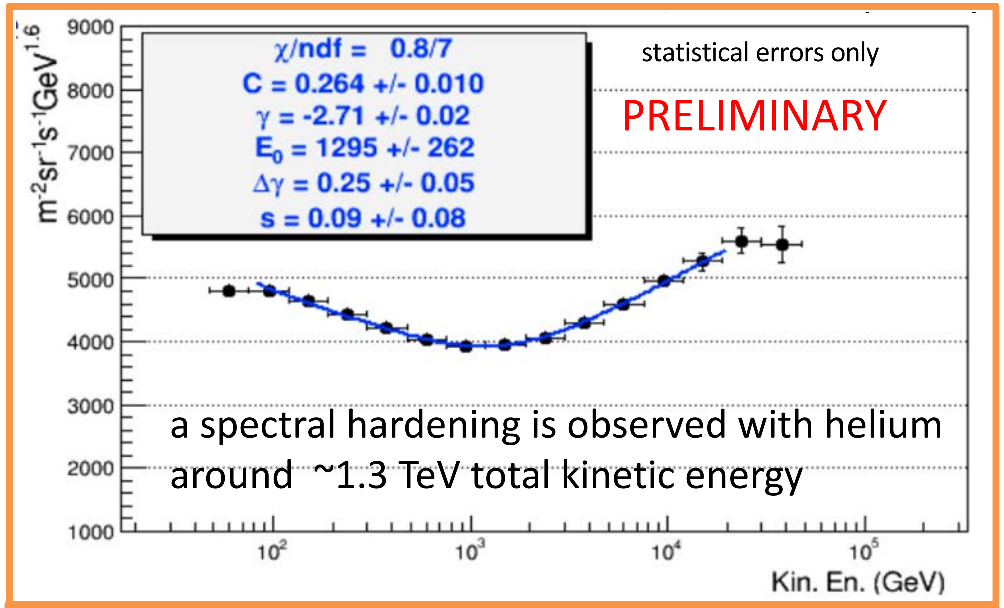


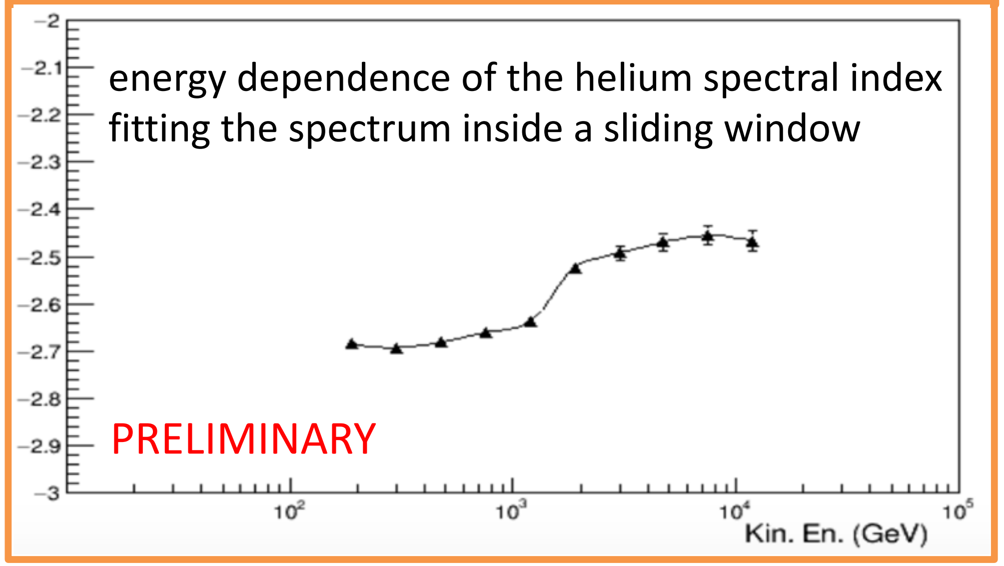
- DAMPE reported a spectral index softening $\Delta\gamma = -0.25 \pm 0.07$ from ~-2.60 to ~-2.85. above 10 TeV at E_{break} = $13.6^{+4.1}_{-4.8}$ TeV with ~30% error.

- DAMPE flux is consistent with AMS-02 and CALET up to 200 GeV. Above, the flux is higher (close to the limit of the systematic error band).

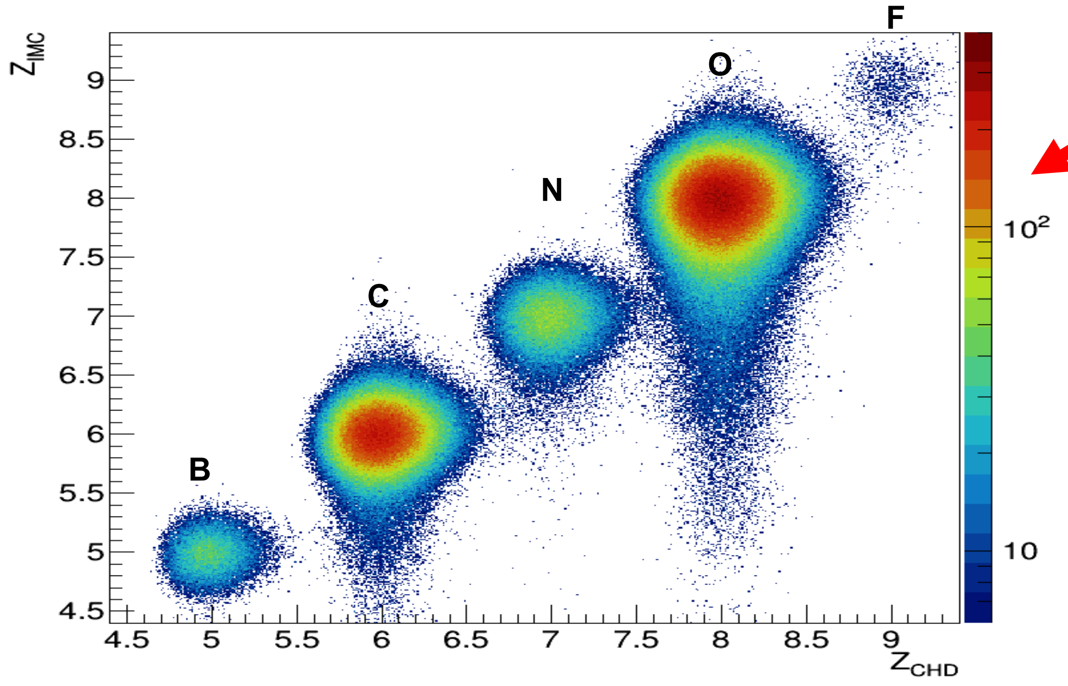
Cosmic-ray helium spectrum (preliminary)



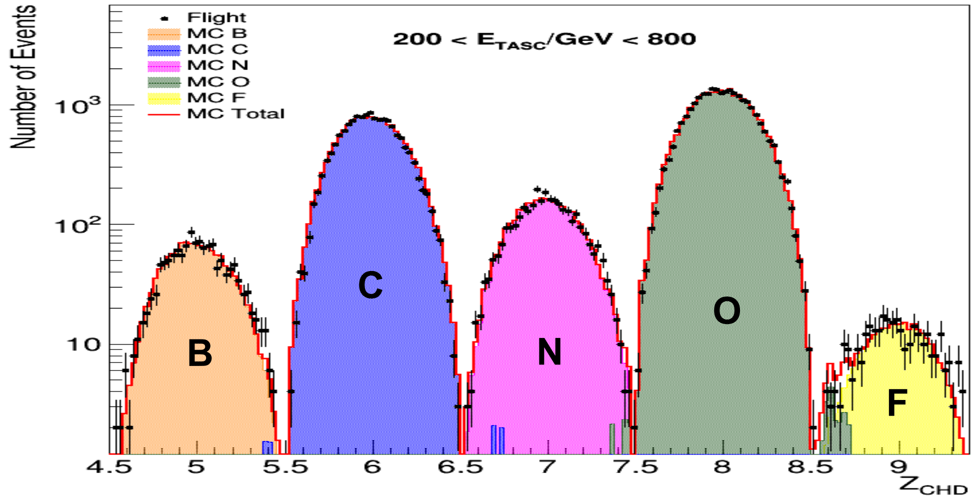


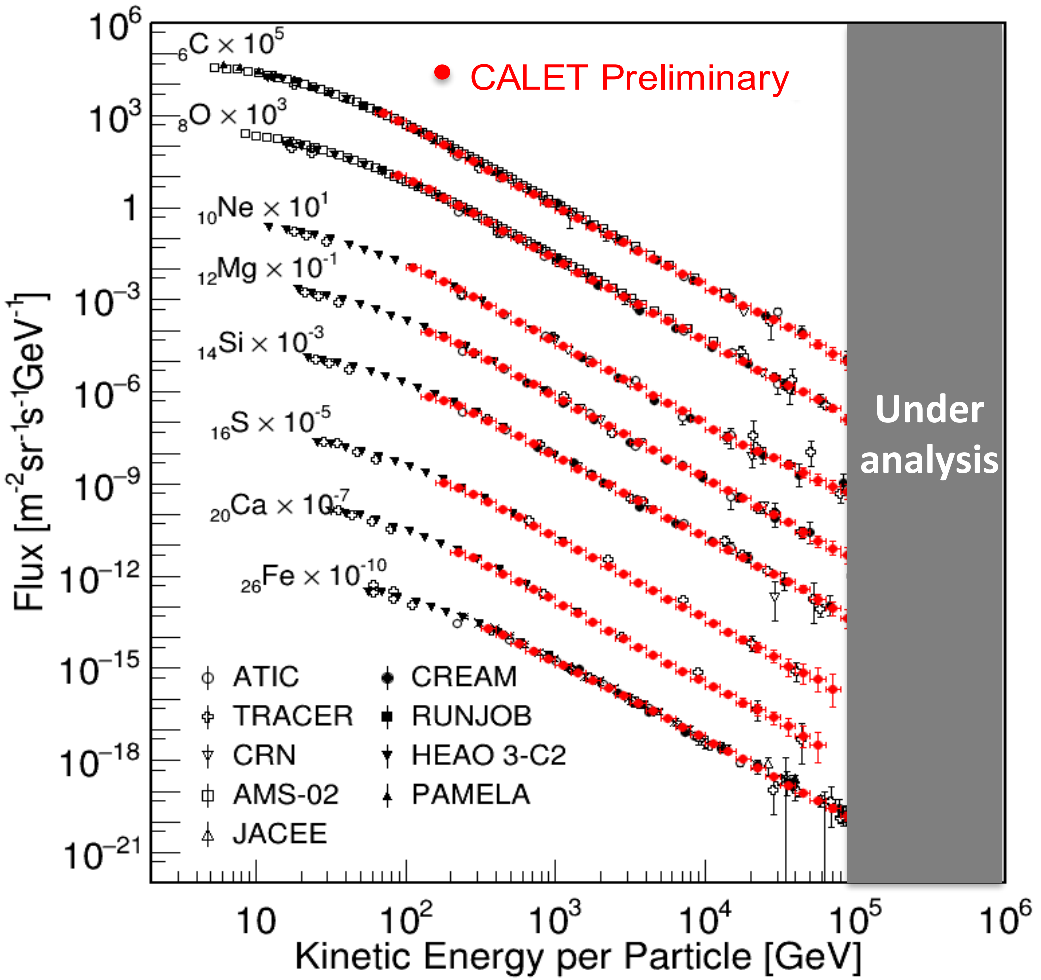


Spectra of Cosmic-ray Nuclei from C to Fe

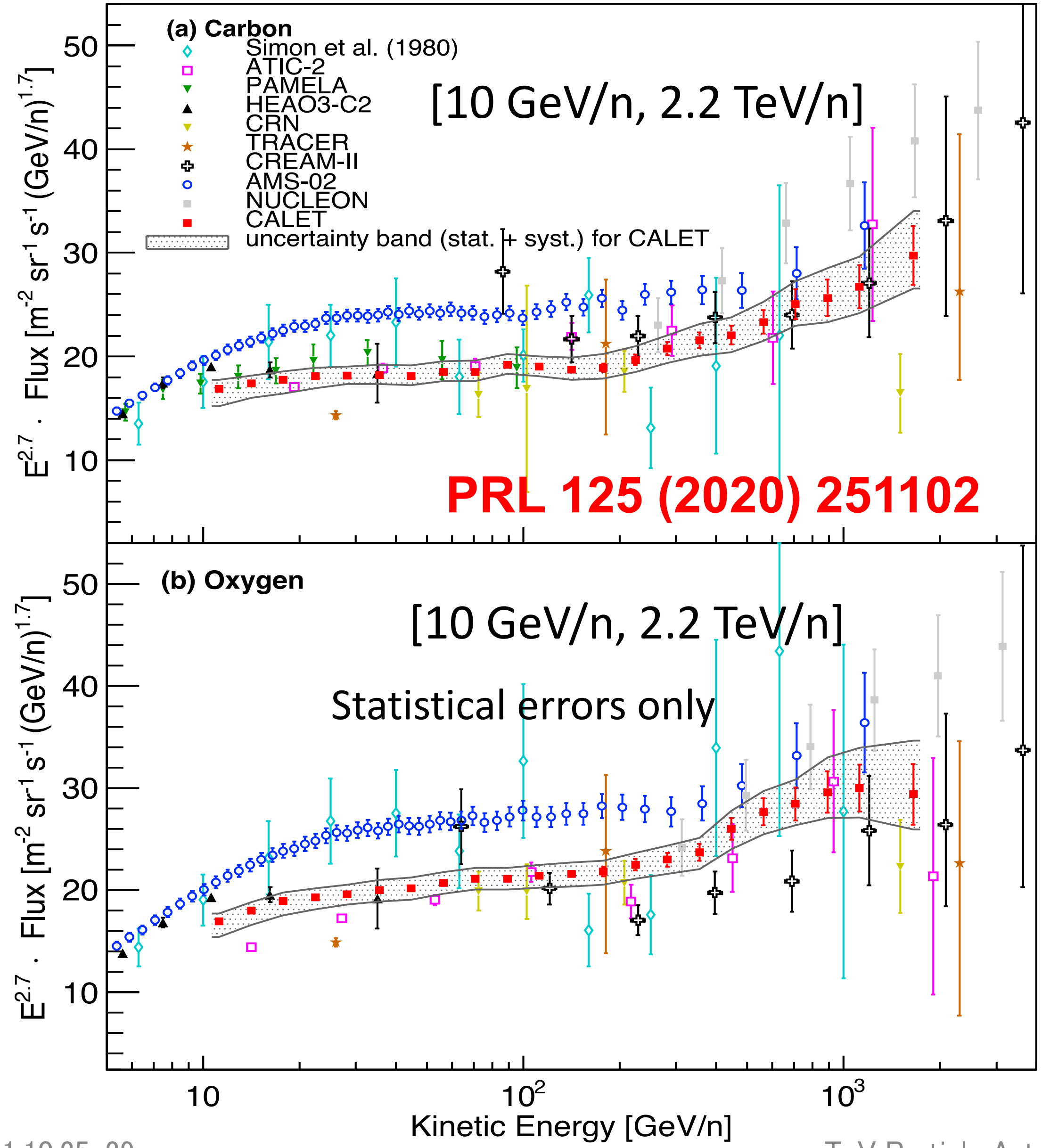


With excellent charge-ID of individual elements CALET is exploring the Table of Elements in the multi-TeV domain





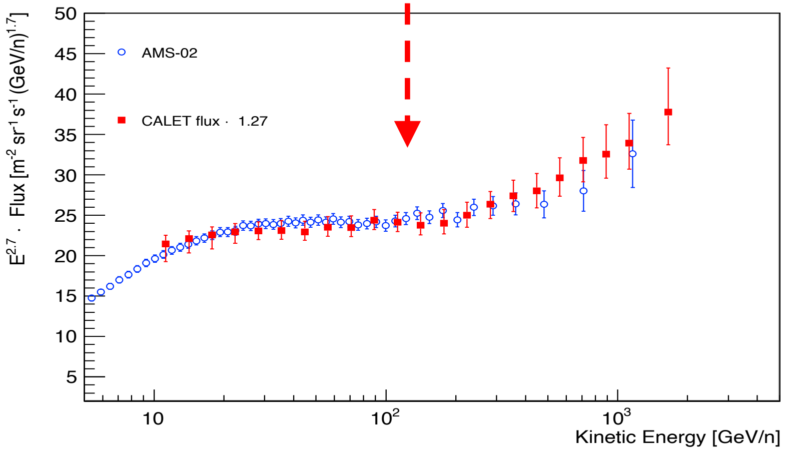
Carbon and Oxygen Energy Spectra

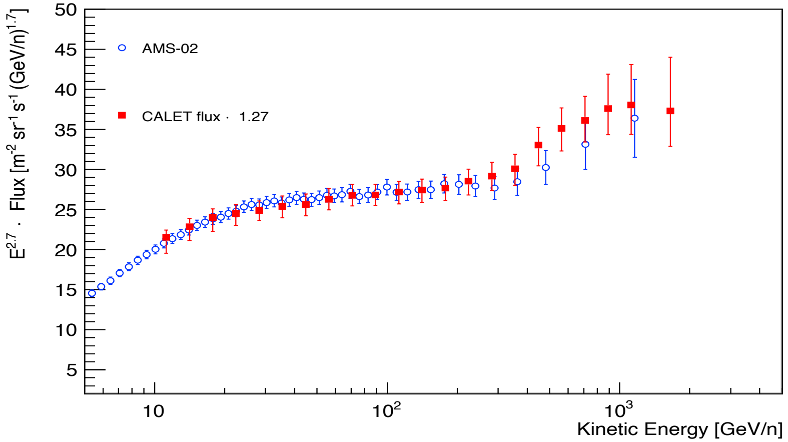


CALET C is consistent with PAMELA and most of the previous experiments. PAMELA did not publish oxygen.

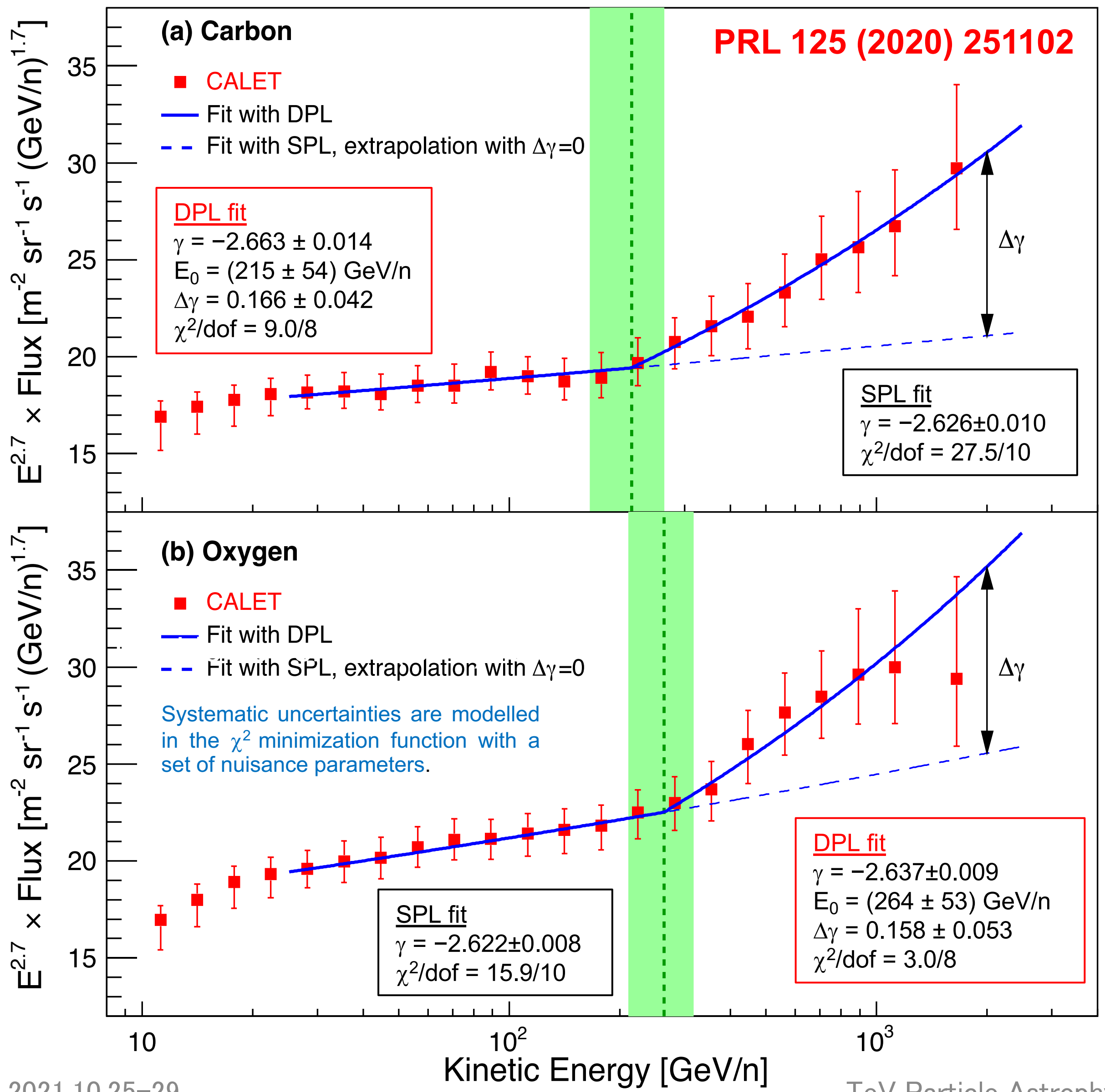
The spectra show a clear hardening around 200 GeV/n.

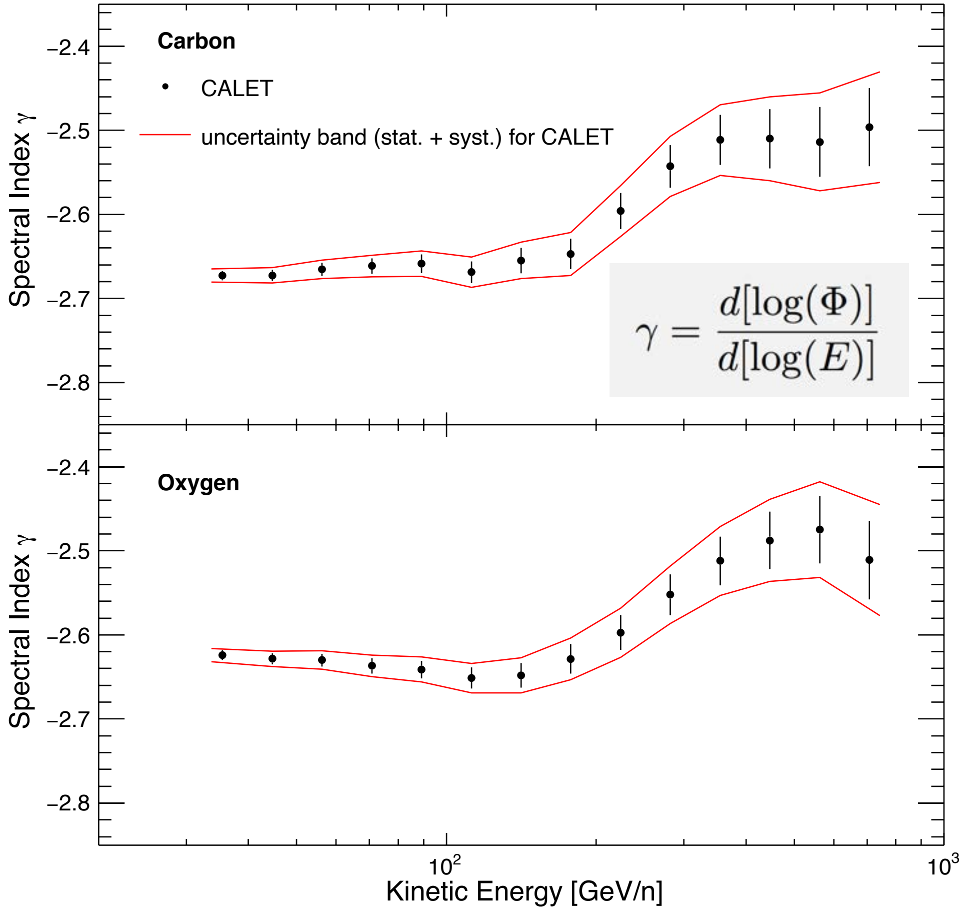
They have shapes similar to AMS-02 but the absolute normalization is significantly lower (~ 27%)





Carbon and Oxygen: Spectral Analysis



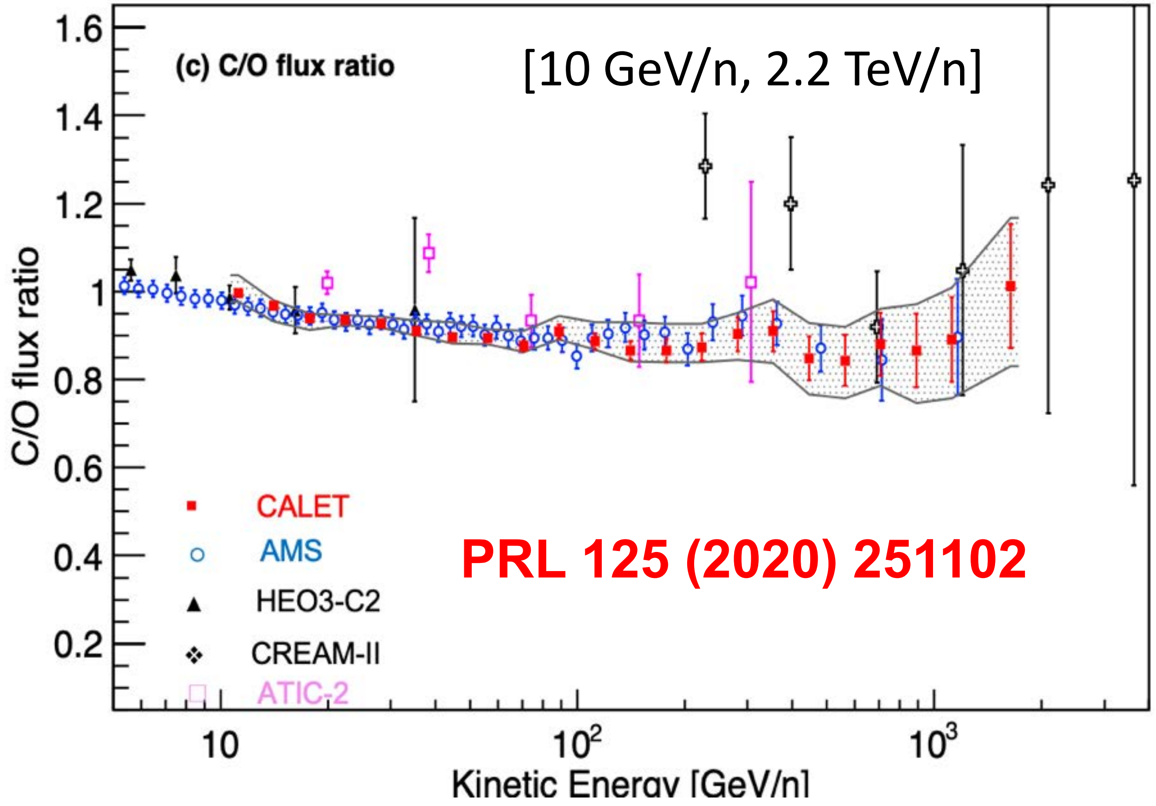


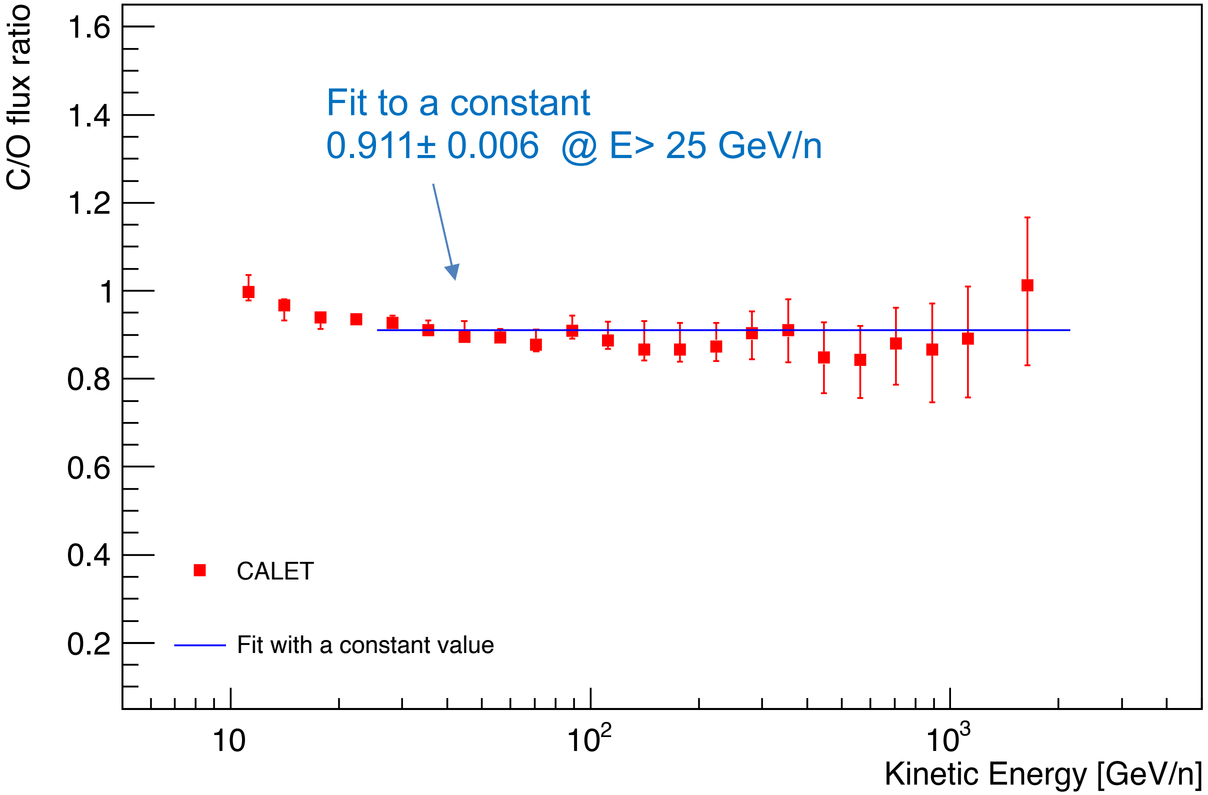
Double power-law (DPL) fit

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

Single Power Law hypothesis excluded at 3.9σ level for C and 3.2σ for O

C/O flux ratio





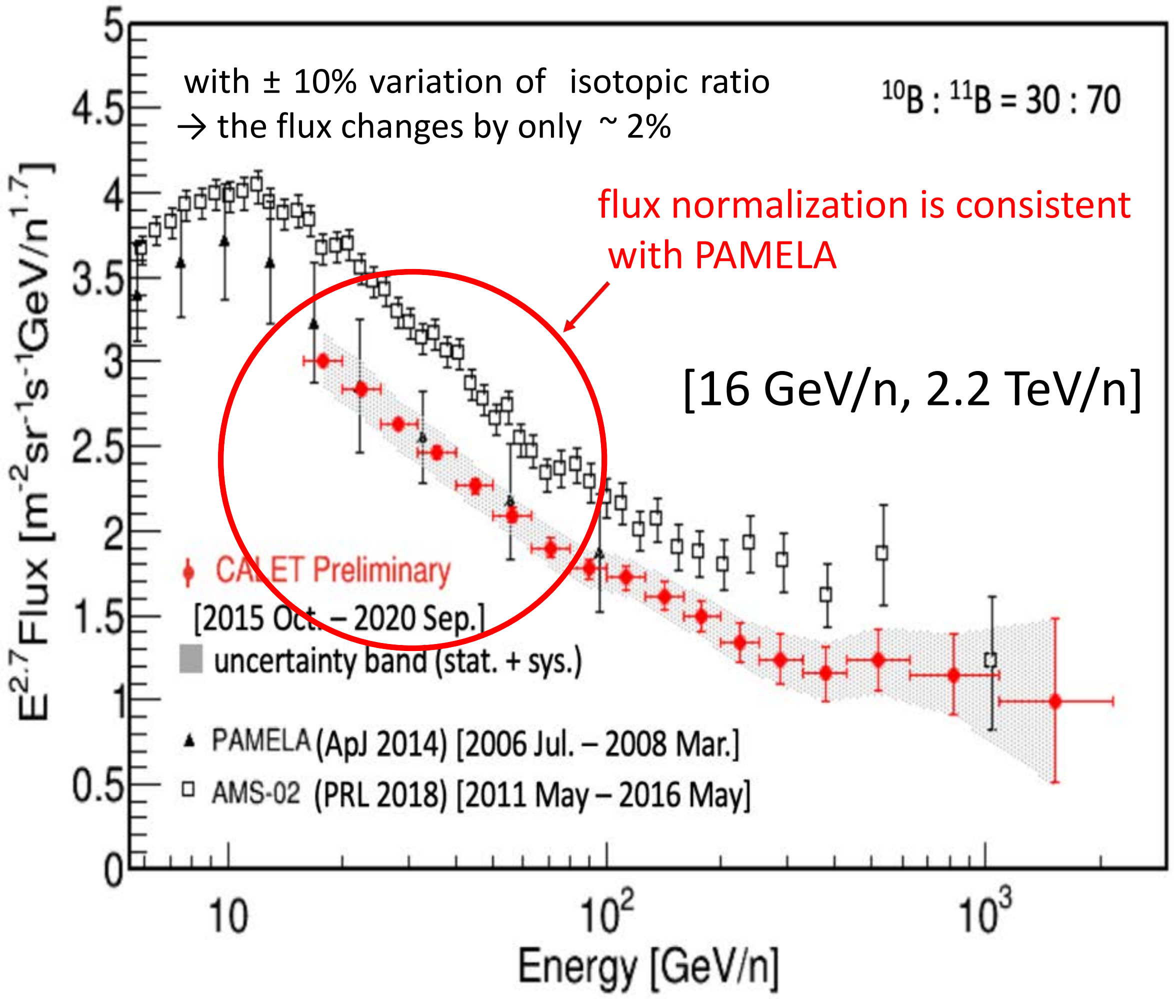
The C/O flux ratio as a function of energy is in good agreement with the one reported by AMS

Above 25 GeV/n the C/O ratio is well fitted to a constant value of 0.911 ± 0.006 with c^2/dof = 8.3/17

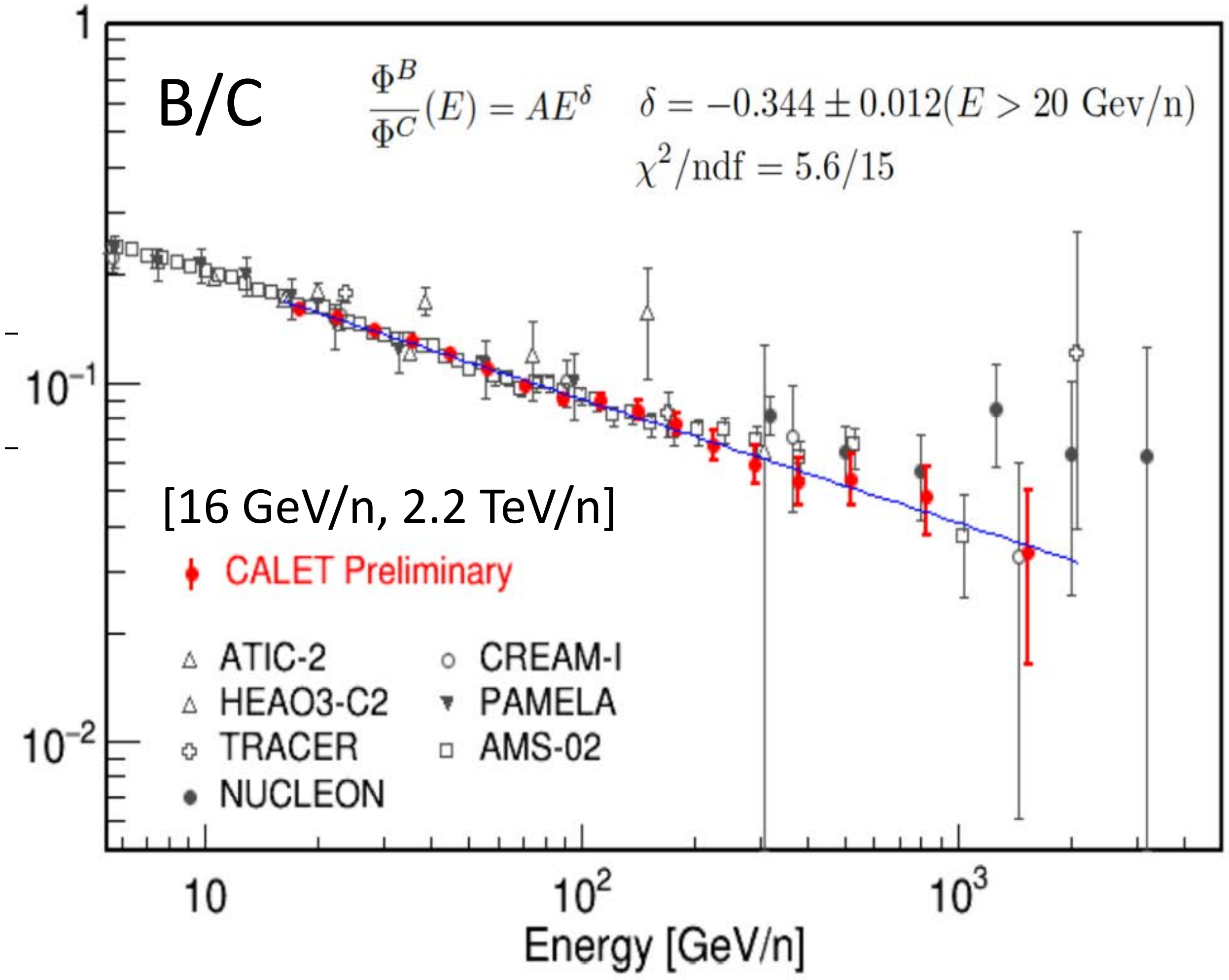
→ C and O fluxes have the same energy dependence.

Boron Spectrum and B/C Ratio (preliminary)

Boron energy spectrum

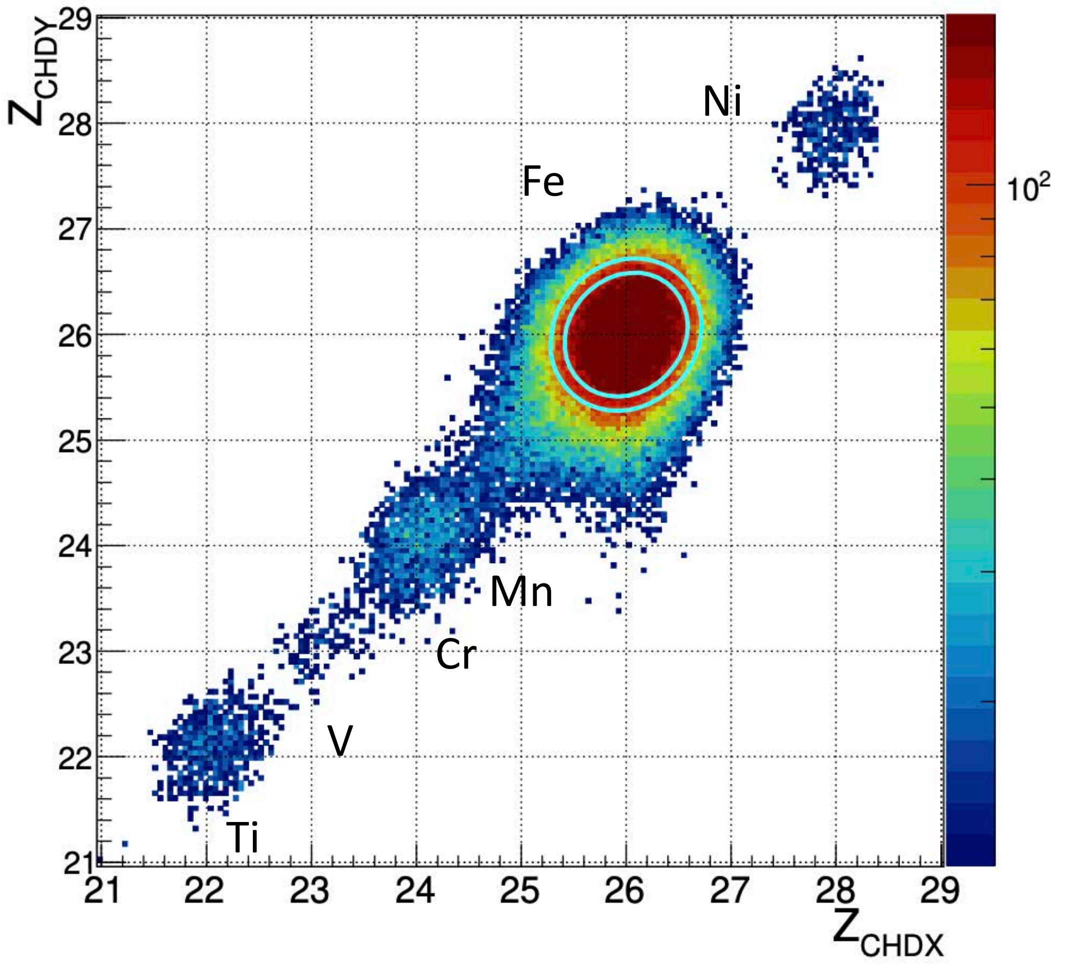


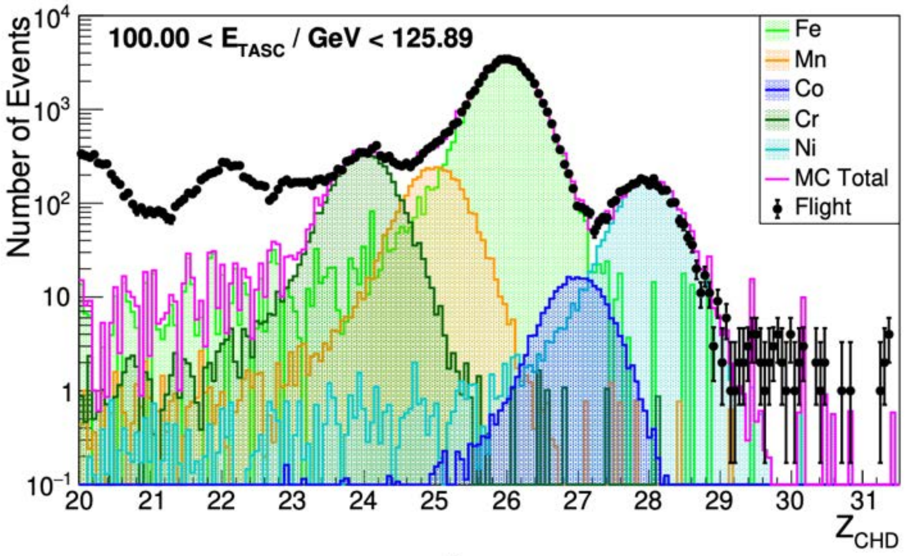
B/C ratio



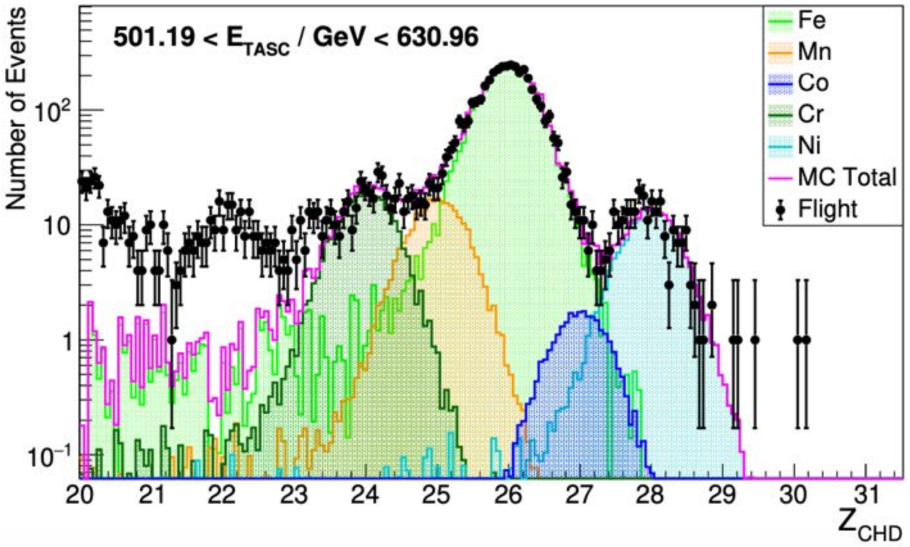
Iron – Analysis (Charge Selection)

Charge measurement with the two CHD layers





(a)

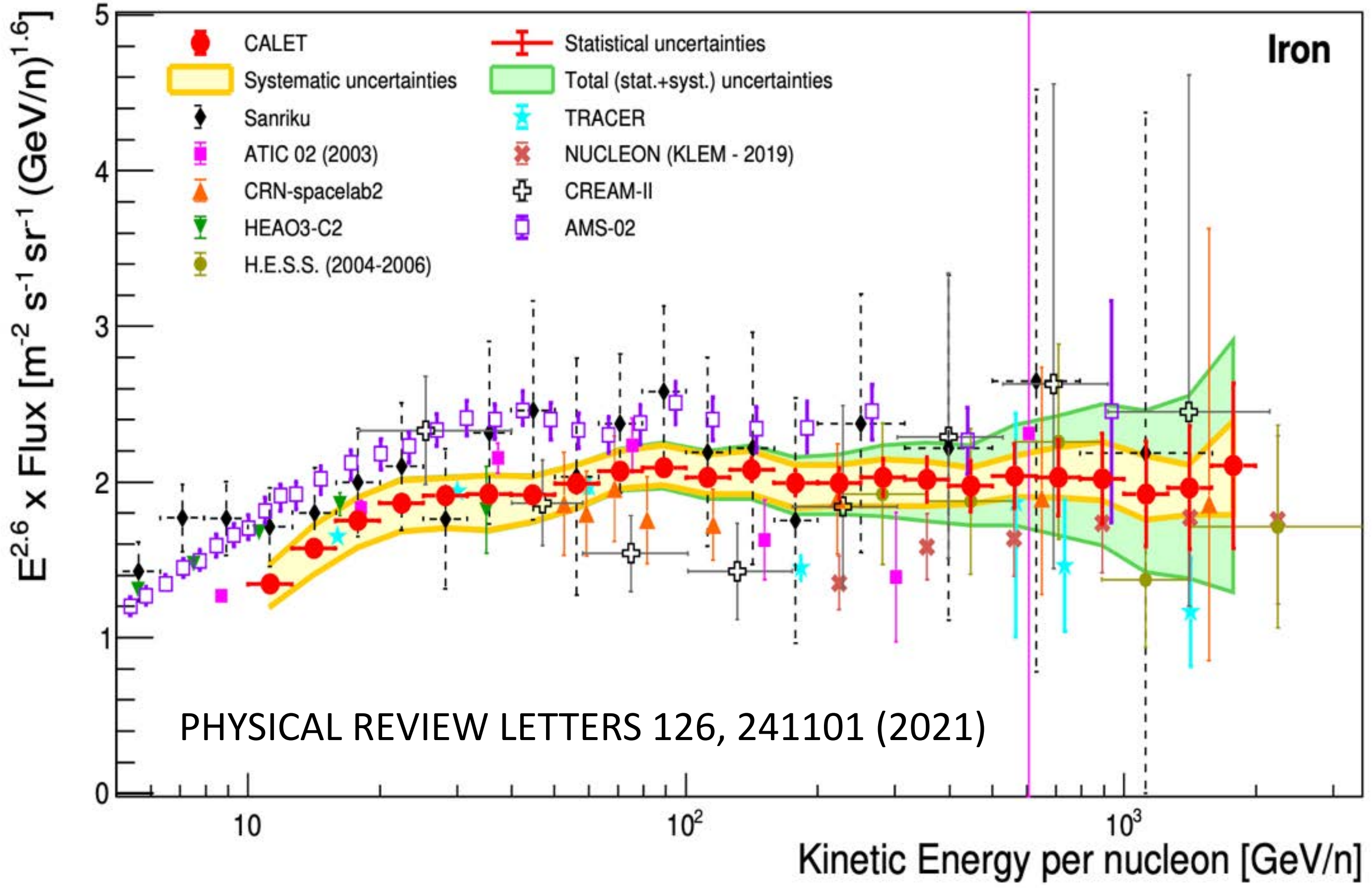


(b)

Iron Spectrum

Flux x $E^{2.6}$ vs kinetic energy per nucleon [10 GeV/n, 2 TeV/n]

analyzed data: Jan, 2016 – May 2020

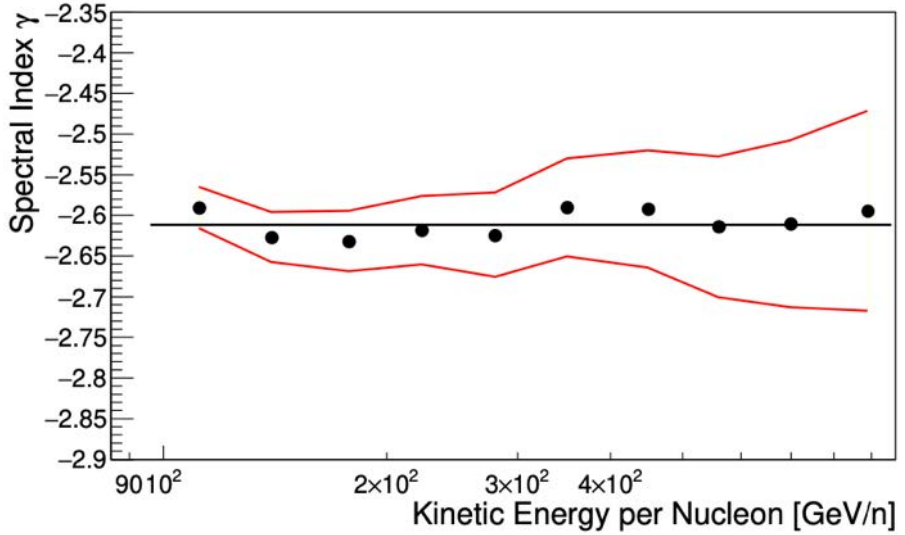


Iron Single Power Law fit:

50 GeV/n, 2.0 TeV/n

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

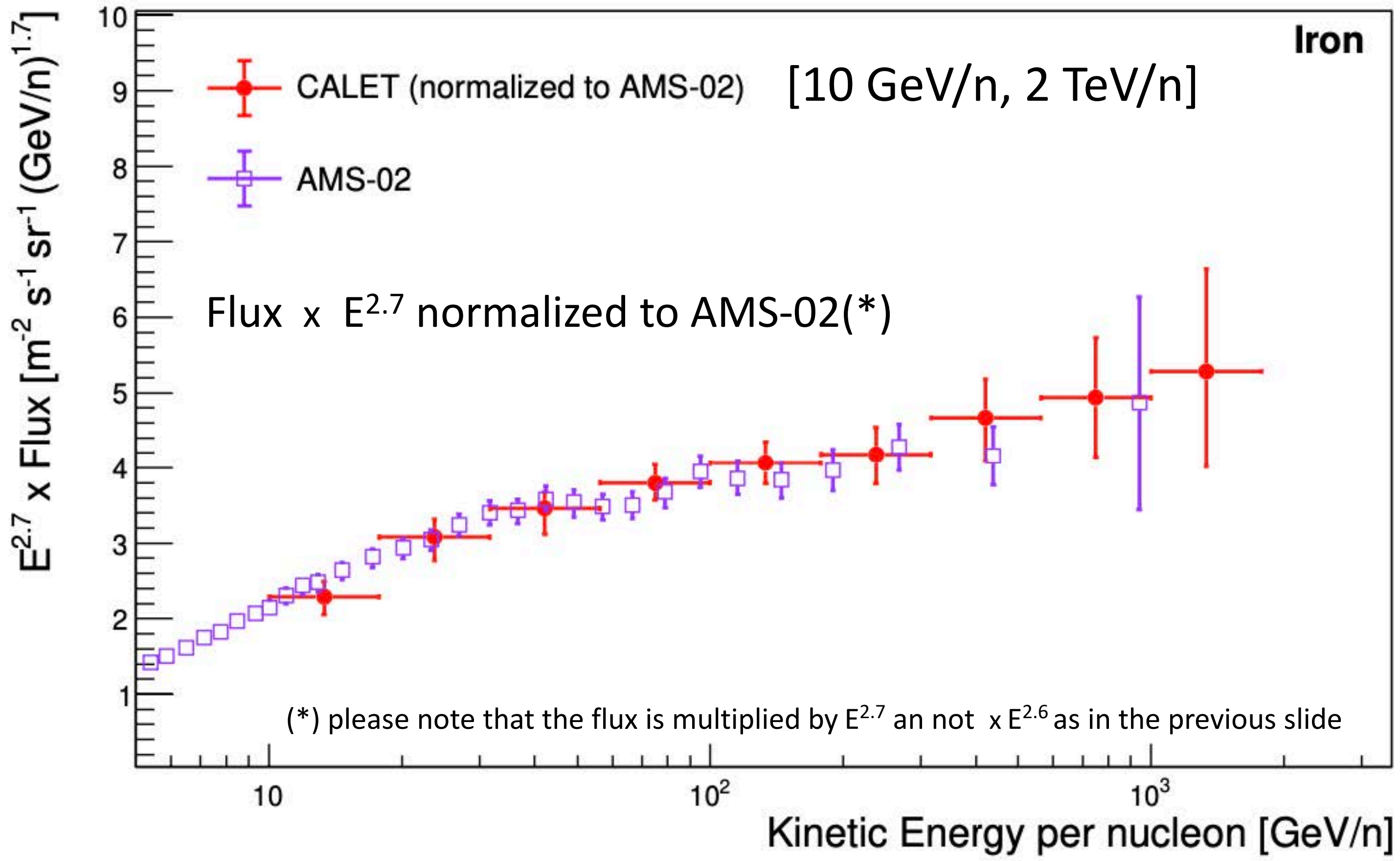
with χ^2/d.o.f. = 4.2/14



Iron Spectral Shape and Normalization

AMS-02 Phys. Rev. Lett. **126**, 041104 (2021)

CALET Phys. Rev. Lett. **126**, 241101 (2021)



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)

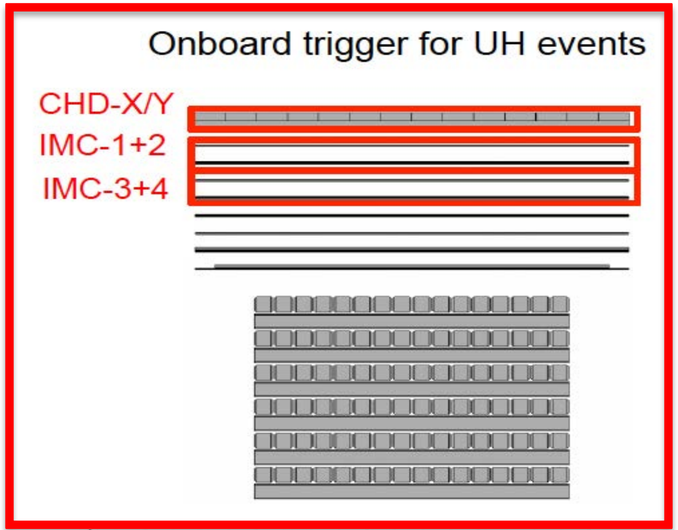
Spectral shape:

- CALET $E^{2.7}$ x Flux vs kinetic energy/n normalized to AMS-02:
  - similar spectral shape
  - comparable errors above 200 GeV/n

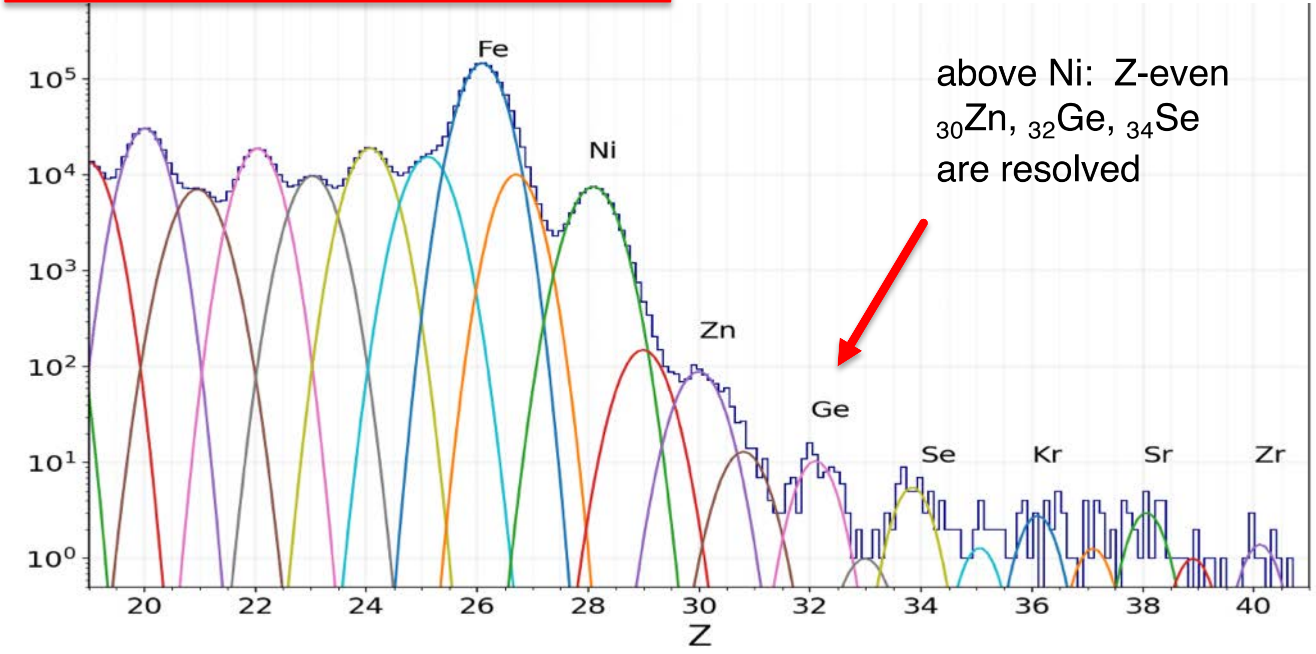
Spectral hardening:

- CALET iron data are consistent with an SPL spectrum up to 2 TeV/n.
- Beyond this limit, the present statistics and large systematics do not allow to draw a significant conclusion on a possible deviation from a single power law.

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

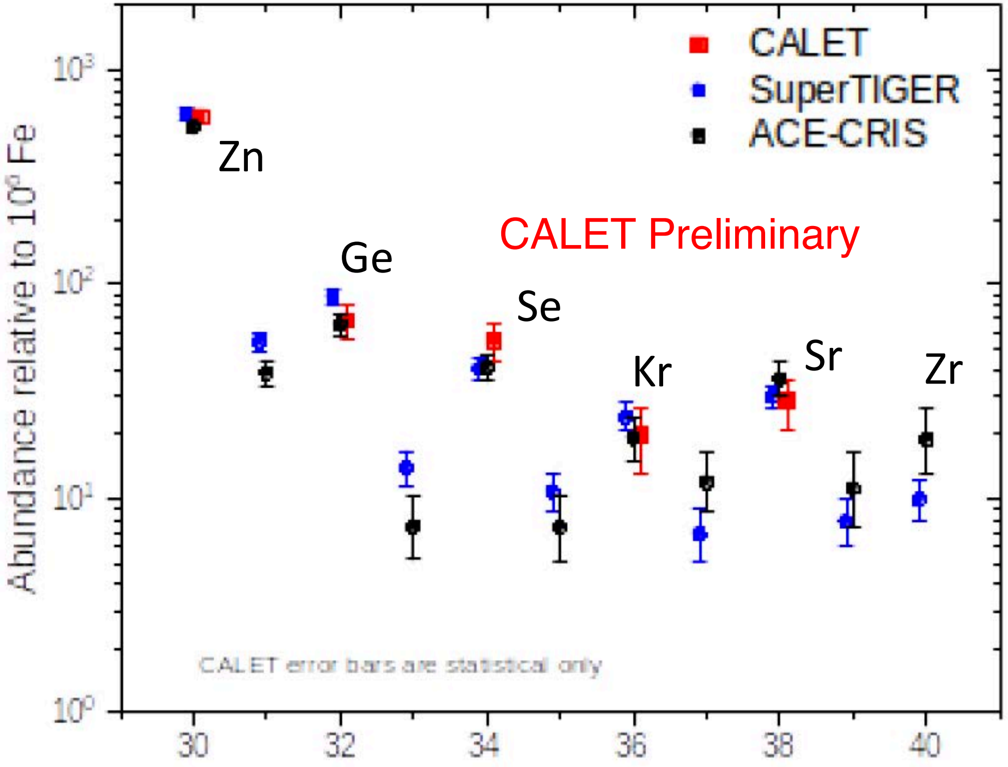


A special UH CR trigger uses the CHD and the first 4 layers of the IMC to achieve an expanded x 4 geometric factor
GF ~ 4400 cm² sr



above Ni: Z-even $_{30}$Zn, $_{32}$Ge, $_{34}$Se are resolved

Measurement of the relative abundances elements above Fe through $_{40}$Zr

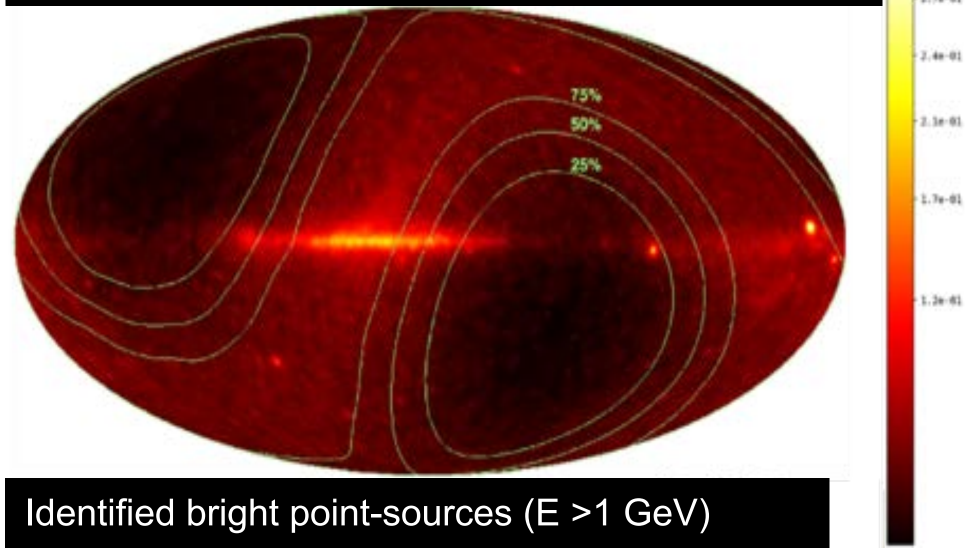


The CALET UH element ratios relative to Fe are consistent with Super-TIGER and ACE abundances.

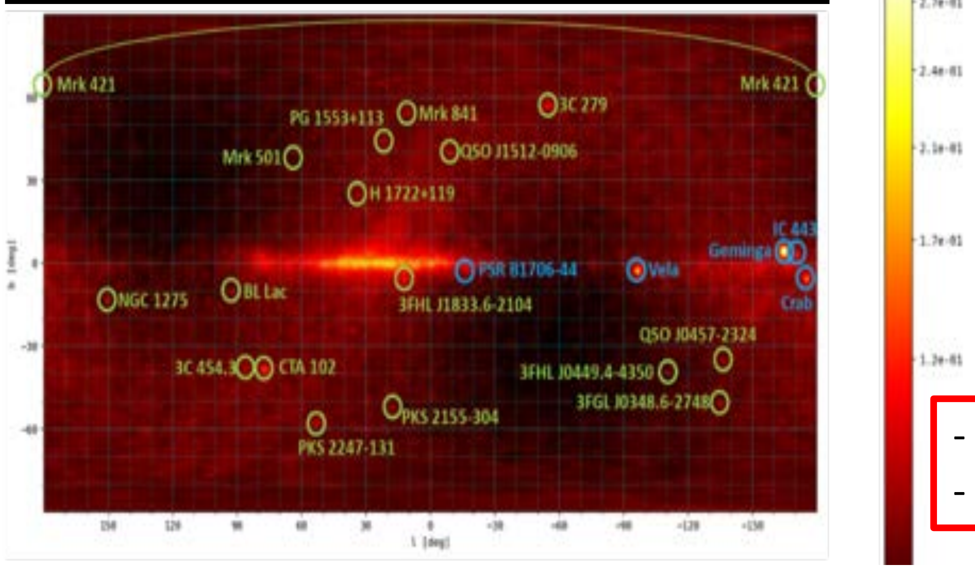
CALET γ–ray Sky (>1GeV) ,GRBs, GW follow-up, DM limits

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

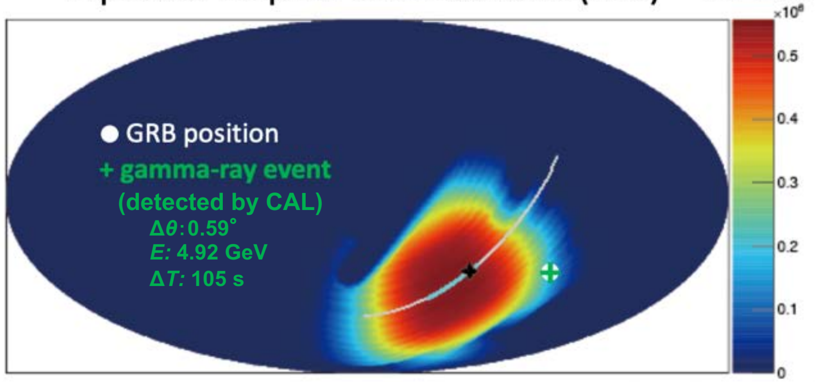
Gamma-ray sky map LE-γ trigger (E >1 GeV)



Identified bright point-sources (E >1 GeV)



Exposure map for GRB 200101A (LEG)



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

from 2015-10-05 to 2021-07-23

259 GRBs (44.9 GRBs / year)

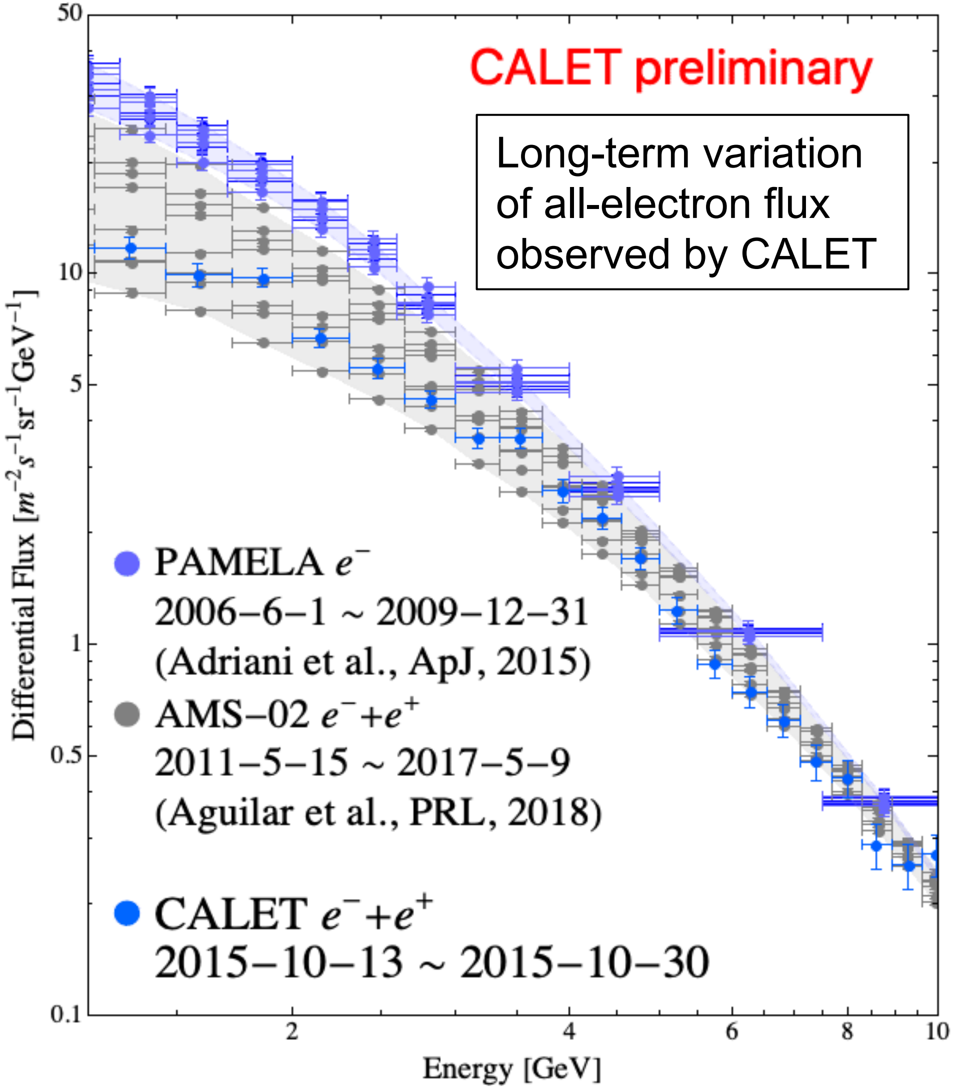
228 Long (88%) **31 Short (12%)**

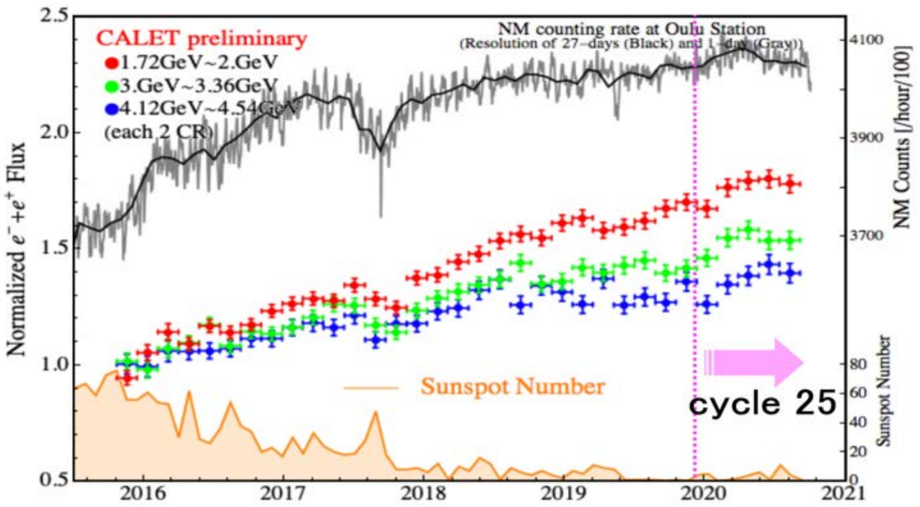
- **Follow-up** of LIGO/Virgo **GW** observations
  - X-ray and γ-ray bands
  - high-energy γ-in calorimeter

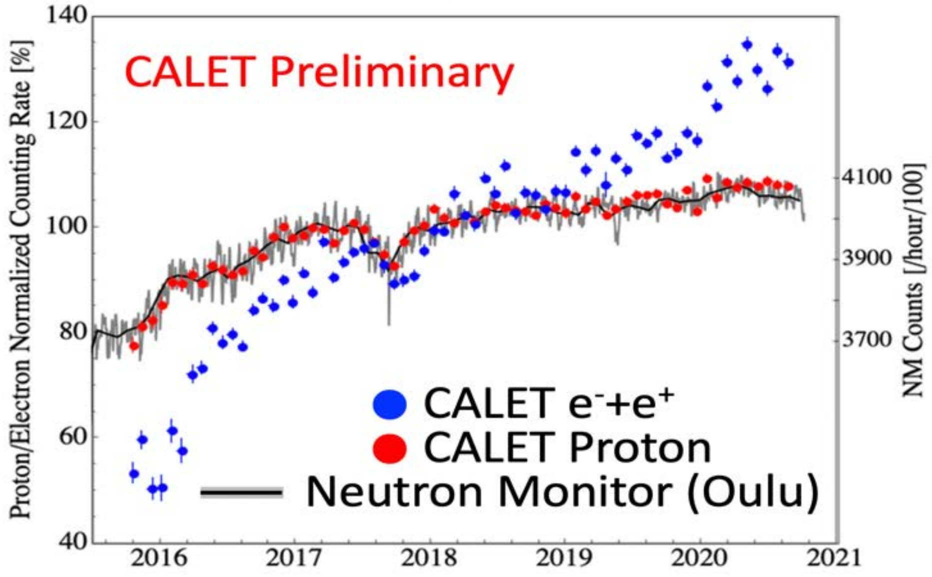
- **Limits on DM** annihilation into γγ: $\langle\sigma v\rangle < 10^{-28}$-$10^{-25} cm^{-3}s^{-1}$
- Limits on DM decay $\chi \to \gamma\nu$ etc.: $\tau_{DM} > 10^{30}$s (m_{DM}>100 GeV)

Solar modulation

- **Since the start of observations in 2015/10, a steady increase in the 1-10 GeV all-electron flux has been observed.**
- **In the past two years, the flux has reached the maximum flux observed with PAMELA during the previous solar minimum.**



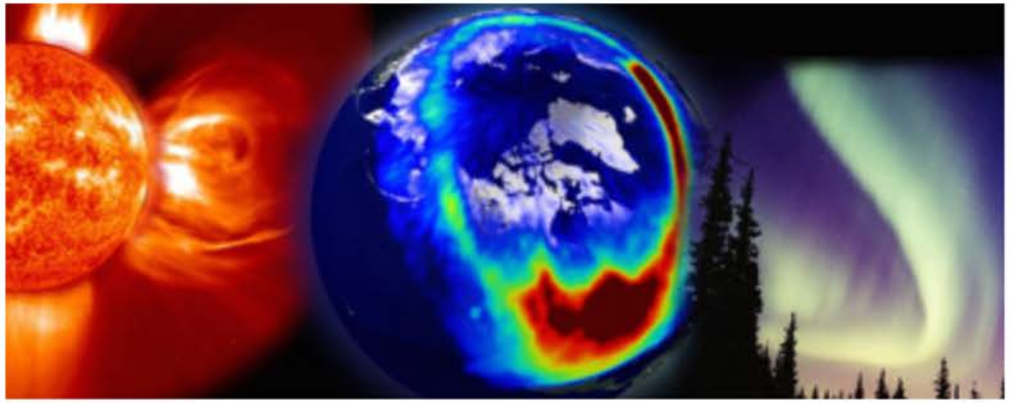


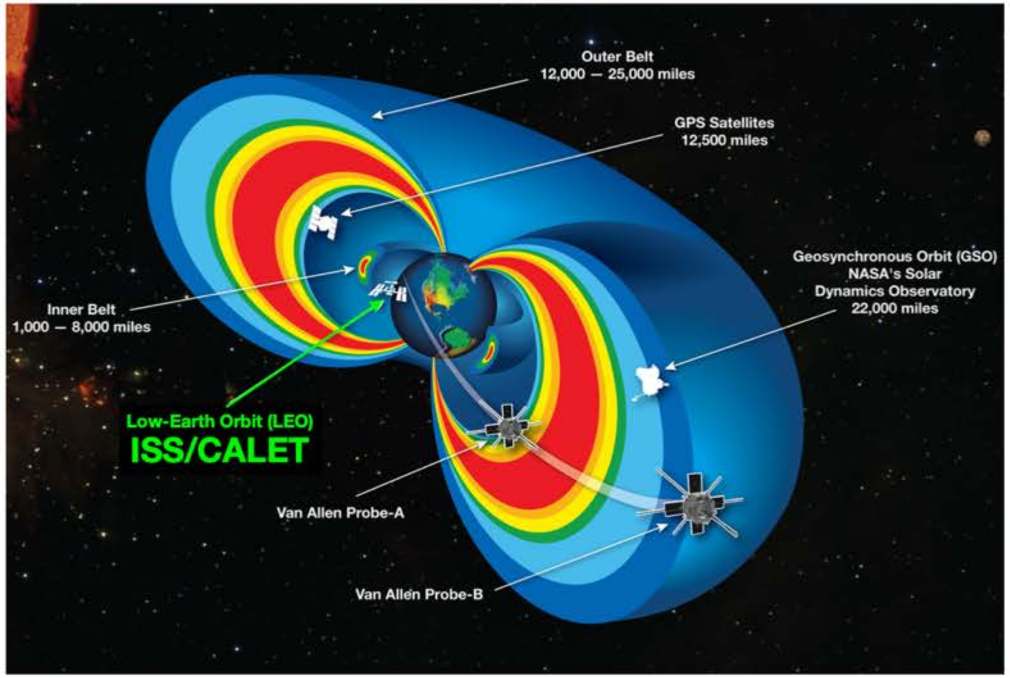


Good correlation of NM counting rate at Oulu station (black points) with the CR e^- + e^+ flux increase in the 1-10 GeV until ~half a year after the beginning the new solar cycle 25.
The flux has now started decreasing.

The count rate increase of CR e^- + e^+ is found to be larger than that of CR protons. Consistent with the expected CHARGE SIGN dependence of the solar modulation.

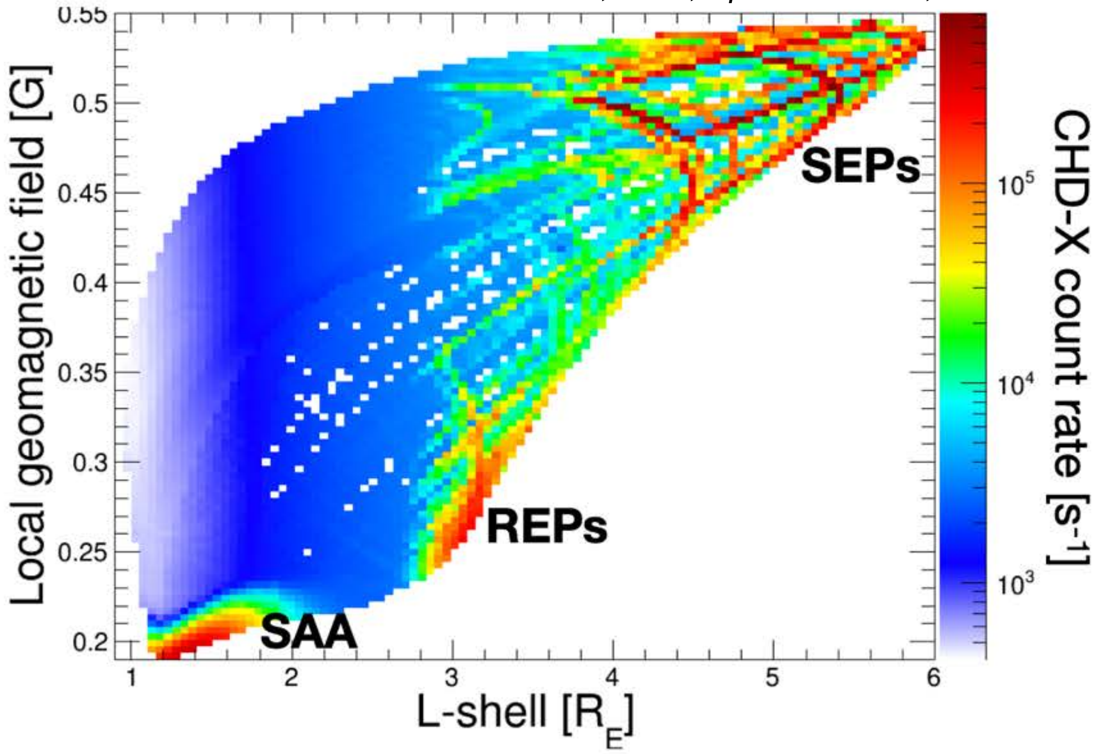
Space Weather Phenomena with CALET





- In addition to the aforementioned astrophysics goals, CALET is able to provide a **continuous monitoring of space weather phenomena affecting the near-Earth environment**, including
  - ☑ solar energetic particles (SEPs) at high geomagnetic latitudes
  - ☑ inner-belt protons in the South-Atlantic anomaly (SAA) region
  - ☑ relativistic electron precipitation (REP) events in the inner boundary of the outer radiation belt

Kataoka et al., 2016, *Geophys Res Letter, 43, 4119*
Ueno et al., 2020, Space Weather, 18



Main Science Goals and Status of the Analysis

Scientific Objectives	Observables	Energy Reach	Reported	Reference	Present
Cosmic-ray origin and acceleration	**Electron spectrum**	1 GeV – 20 TeV	to 4.8 TeV	PRL 120, 261102 (2018)	**11 GeV – 4.8 TeV**
	Proton spectrum	10 GeV – 1 PeV	to 10 TeV	PRL 122, 181102 (2019)	**30 GeV – 60 TeV**
	Helium spectrum	10 GeV – 1 PeV	preliminary	preliminary	**50 GeV – 50 TeV**
	Carbon and oxygen spectra	10 GeV – 1 PeV	to 2.2 TeV/n	PRL 125, 251102 (2020)	**10 GeV/n – 2.2 TeV/n**
	Iron spectrum	10 GeV – 1 PeV	to 2 TeV/n	PRL 125,241101 (2021)	**50 GeV/n – 2 TeV/n**
	Elemental spectra of primaries	10 GeV – 1 PeV	to 100 TeV	ICRC 2019, 034	10 GeV – 100 TeV
	Ultra-heavy abundances	> 600 MeV/n	> 600 MeV/n	ICRC 2019, 130	> 600 MeV/n
CR propagation	**B/C and secondary-to-primary ratios**	Up to some TeV/n	to 200 GeV/n	ICRC 2019, 034	**16 GeV/n – 2.2 TeV/n**
Nearby electron sources	**Electron spectral shape**	100 GeV – 20 TeV	to 4.8 TeV	ICRC 2019, 142	to 4.8 TeV
Dark matter	**Signatures in e/γ spectra**	100 GeV–20TeV (e) 10 GeV-10TeV (γ)	to 4.8 TeV (e) to 600 GeV (γ)	ICRC2019 , 533	to 4.8 TeV
Gamma rays	**Diffuse & point sources**	1 GeV – 10 TeV	1 GeV – 1 TeV	ApJS 238:5 (2018)	1 GeV – 1 TeV
Heliospheric physics	**Solar modulation**	1 GeV – 10 GeV	1 – 10 GeV	ICRC 2019, 1126	**1 – 10 GeV**
Gamma-ray transients	**GW follow-up and GRB analysis**	7 keV–20MeV (CGBM) 1 GeV-1TeV (ECAL)	7 KeV-20MeV	ApJL 829:L20 (2016)	7 keV–20MeV (CGBM) > 1 GeV (ECAL)
Space weather	**Relativistic electron precipitation**	> 1.5 MeV	> 1.5 MeV	Geophys.Res.Lett,43 (2016)	> 1.5 MeV

CALET: Summary and Future Prospects

- ☐ CALET was successfully launched in August 2015 and installed on the Japanese Experiment Module – Exposure Facility on the ISS.
- ☐ More than 6 years of excellent performance and remarkable stability of the instrument since the start of data taking on Oct. 23, 2015.
- ☐ Linearity in the energy measurements established up to 10^6 MIP
  ⇨ [Astropart. Phys. 91, 1 – 10 (2017)]
- ☐ Continuous on-orbit calibration updates
- ☐ HE trigger operational for > 2100 days with > 85% live time fraction
- ☐ Total number of > GeV triggers ~3.0 billion

Extended operations are approved by JAXA/NASA/ASI in March 2021 through the end of 2024.

＊) We greatly appreciate JAXA staffs for perfect support of the CALET operation at the Tsukuba Space Center of JAXA !!