CALET on the ISS
the first 5 years

16th Marcel Grossmann Meeting July 5-10, 2021

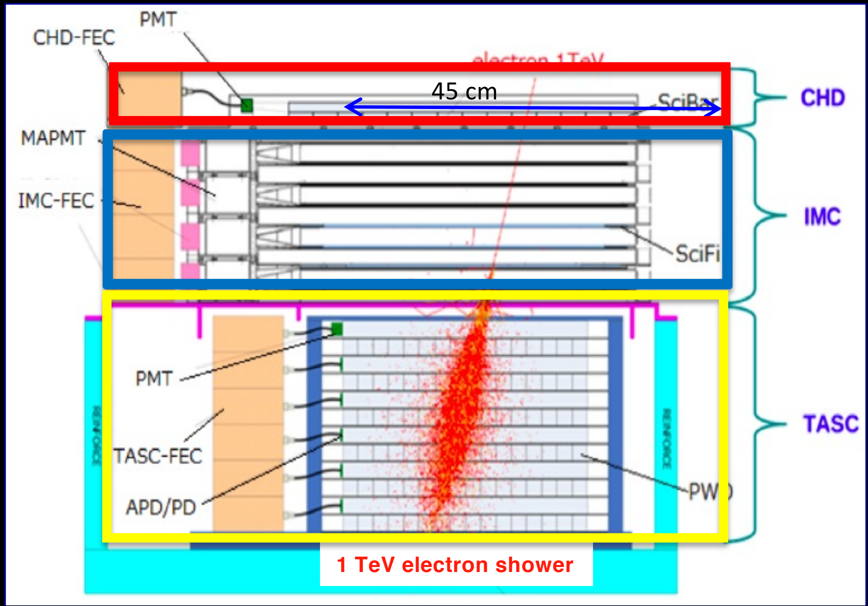
CALET

Calorimetric
Electron
Telescope

Pier Simone Marrocchesi
University of Siena and INFN Pisa
for the CALET Collaboration

CALET instrument in a nutshell

Field of view: ~ 45 degrees (from the zenith)   Geometrical Factor: ~ 1,040 $cm^2 sr$ (for electrons)   Thickness: 30 X_0, **1.2** λ_I



CHD – Charge Detector

- 2 x 14 plastic scintillating paddles
- single element charge ID from p to Fe and above (Z = 40)
- charge resolution ~0.15-0.3 e

IMC – Imaging Calorimeter

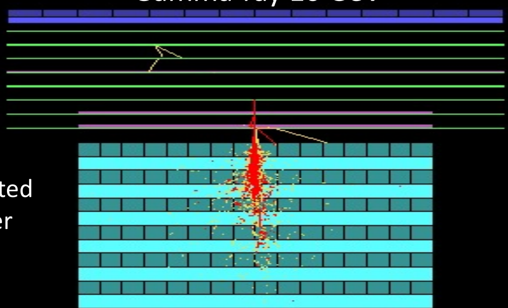
- Scifi + Tungsten absorbers: 3 X_0 at normal incidence
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **Tracking** (~0.1° angular resolution) + **Shower imaging**

TASC – Total Absorption Calorimeter 27 X_0, 1.2 λ_I

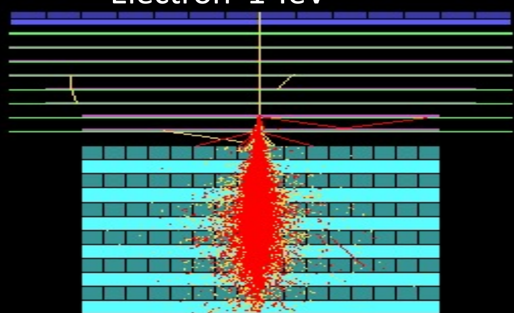
- 6 x 2 x 16 lead tungstate ($PbWO_4$) logs
- **Energy resolution:** ~2 % (>10GeV) for e , γ   ~30-35% for p, nuclei
- **e/p separation:** ~10^{-5}

Simulated Shower Profile

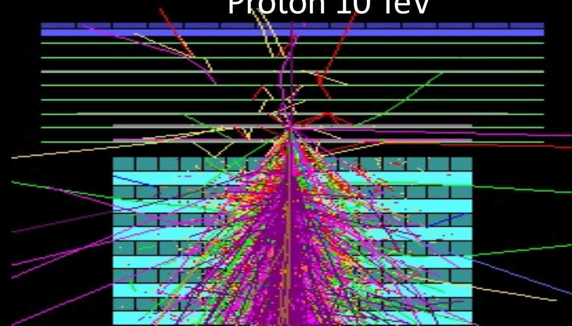
Gamma-ray 10 GeV



Electron 1 TeV

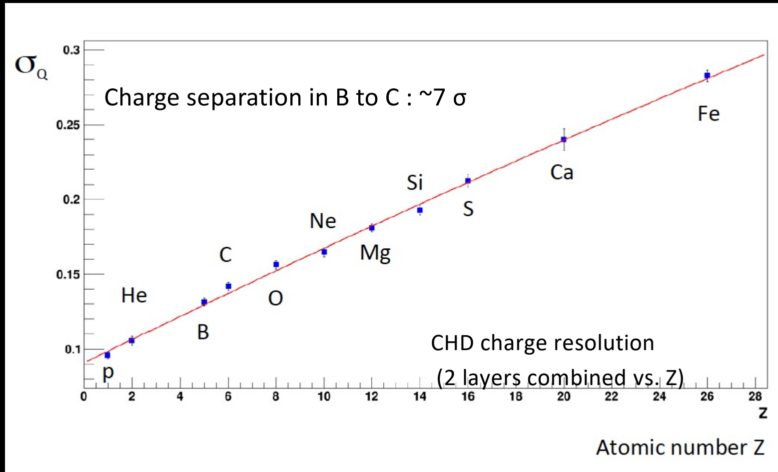


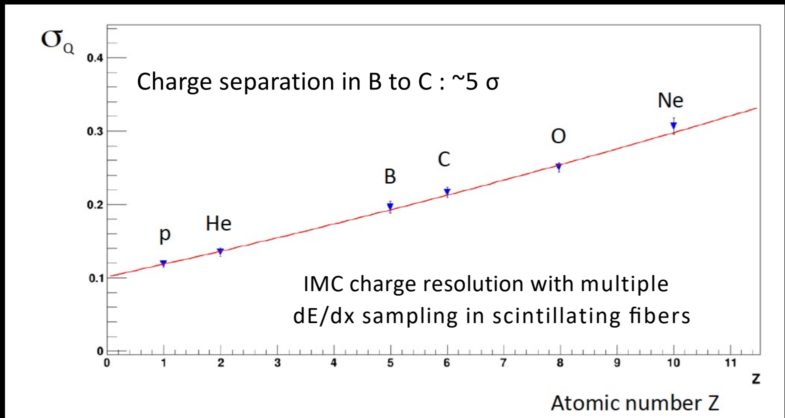
Proton 10 TeV

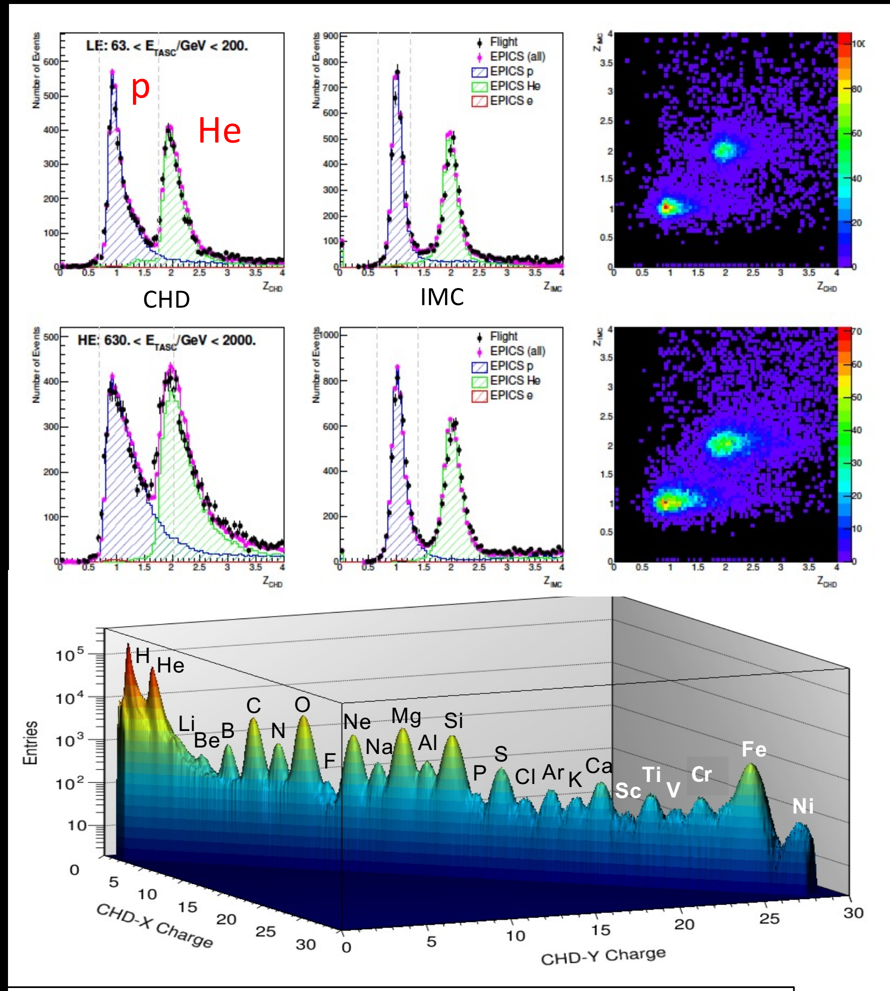


Charge Identification with CHD and IMC

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



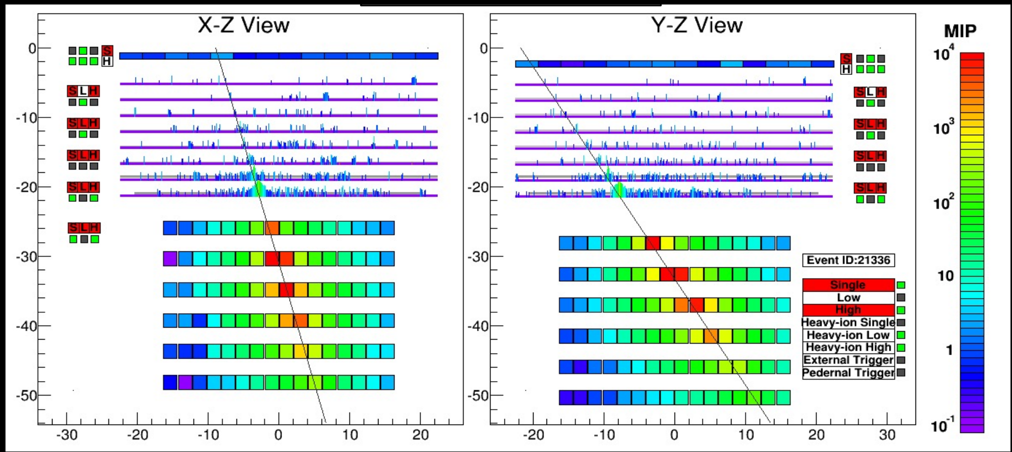




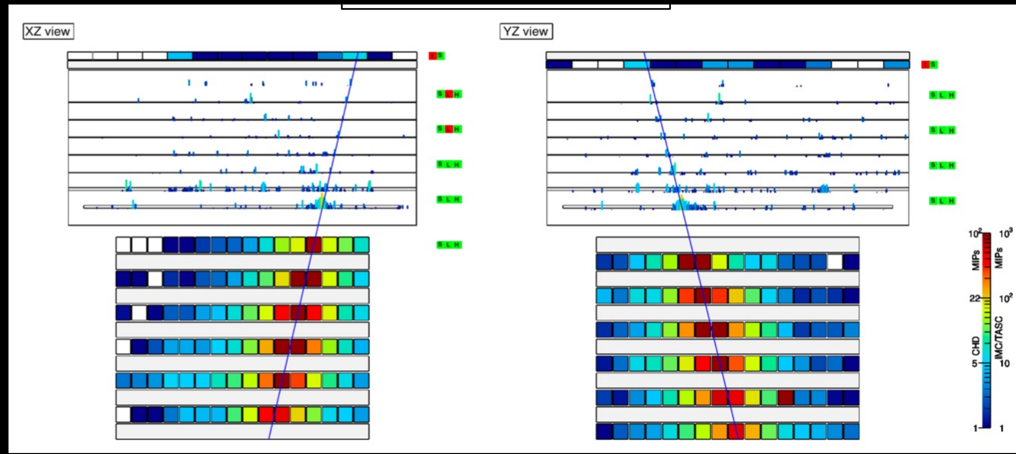
Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

Examples of CALET event candidates

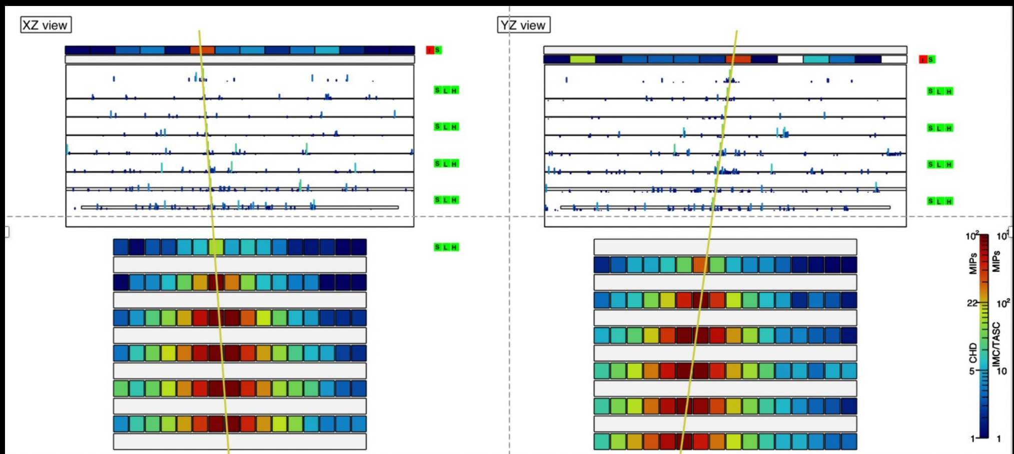
electron ~3 TeV



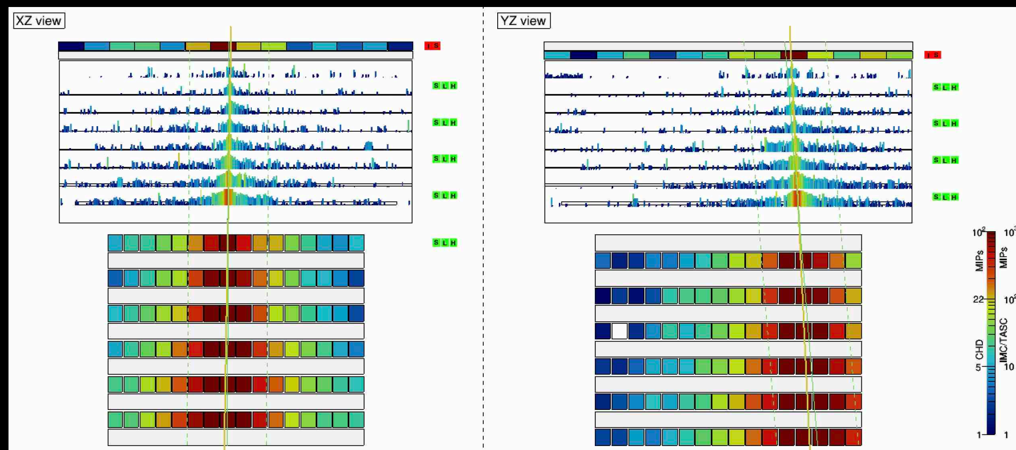
helium ~700 GeV



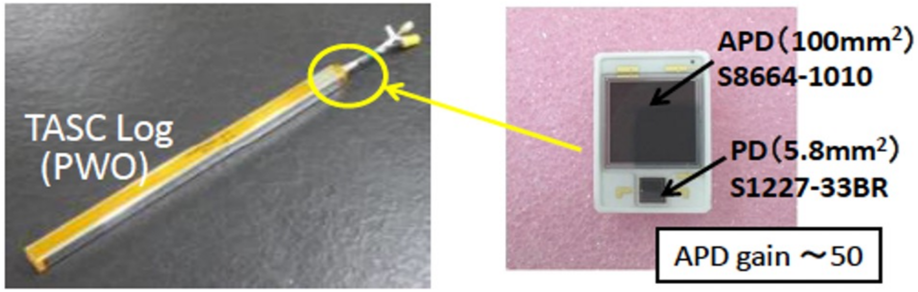
carbon ~2.0 TeV



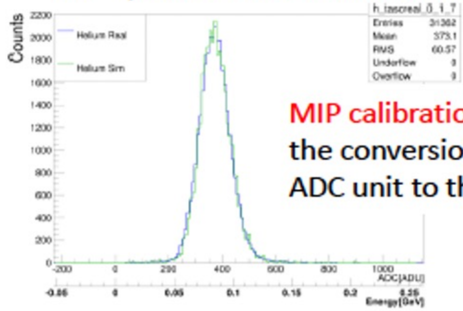
iron ~3.9 TeV



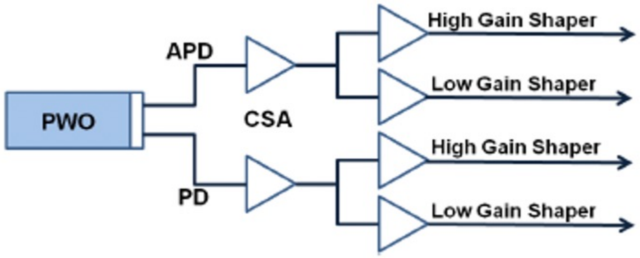
Energy Measurement in a wide dynamic range 1-10^6 MIPs



“MIP” peak in PWO: Obs. vs. MC



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

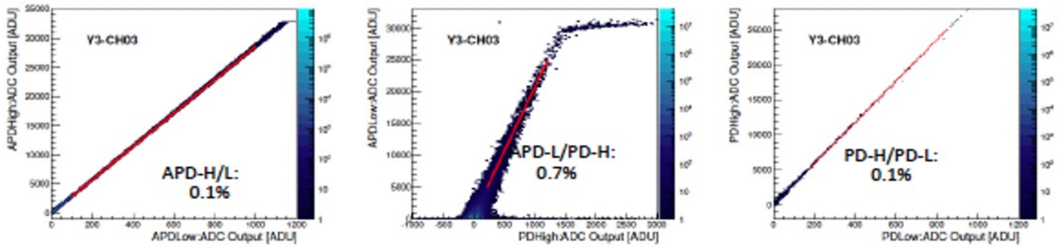


The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

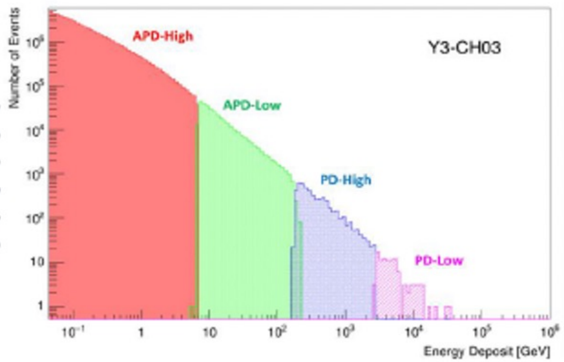
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

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

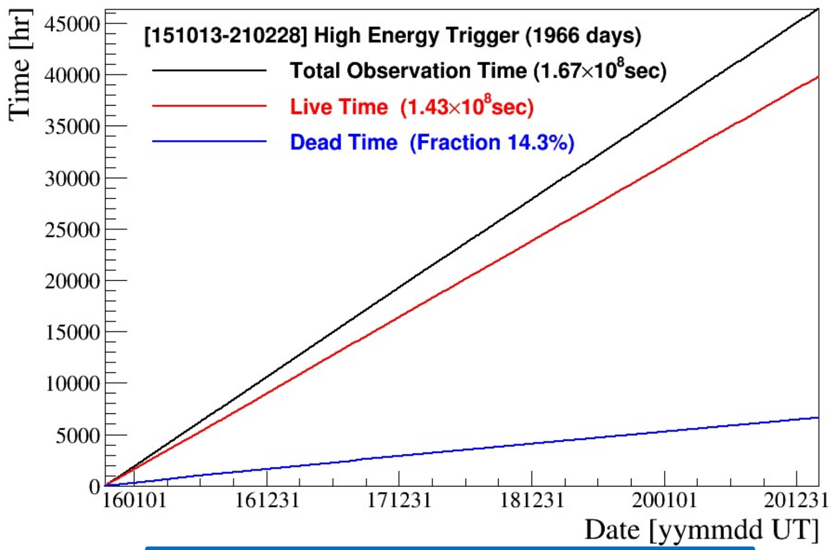
APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%



Example of energy distribution in one PWO log



The first five years of CALET observations on the ISS

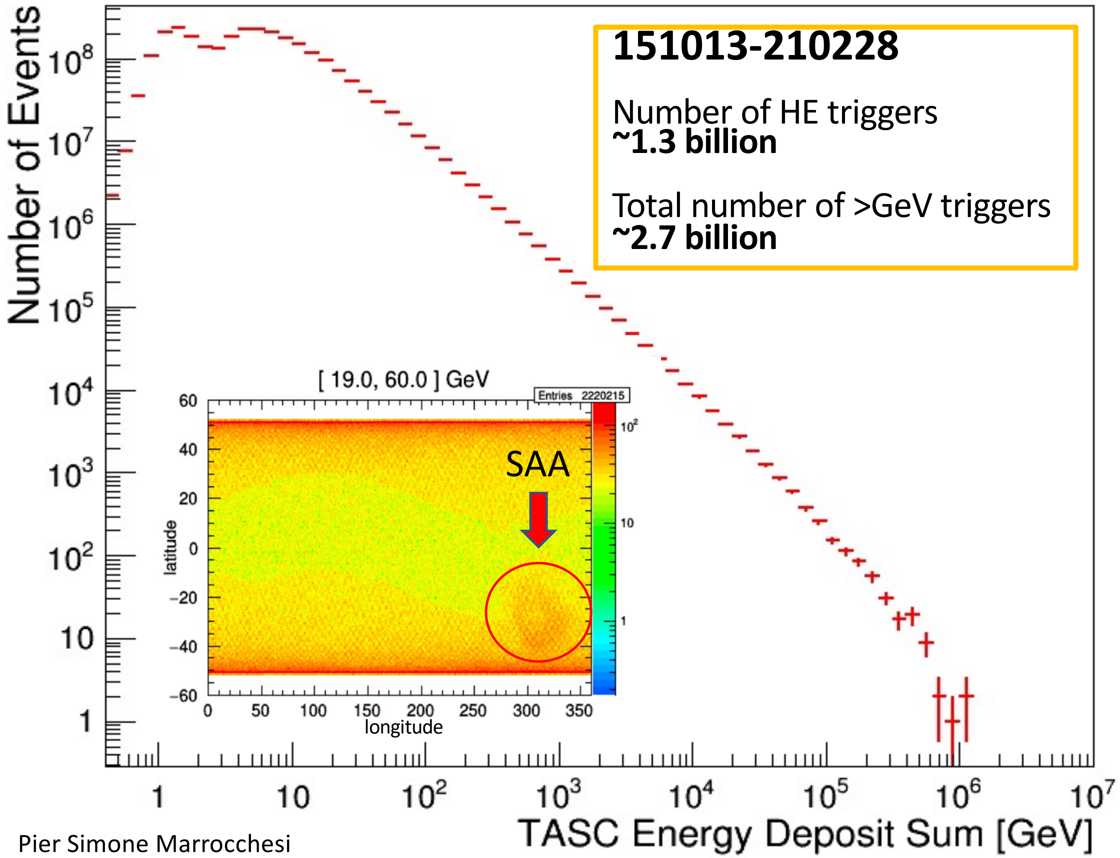


Geometrical Factor:

- 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 statistics:

- Operational time > **2027 days**(*)
  (*) as of April 30, 2021
- Live time fraction **> 85%**
- Exposure of HE trigger
  ~178 m^2 sr day
- HE-gamma point source exposure
  ~3.5 m^2 day (for Crab, Geminga)

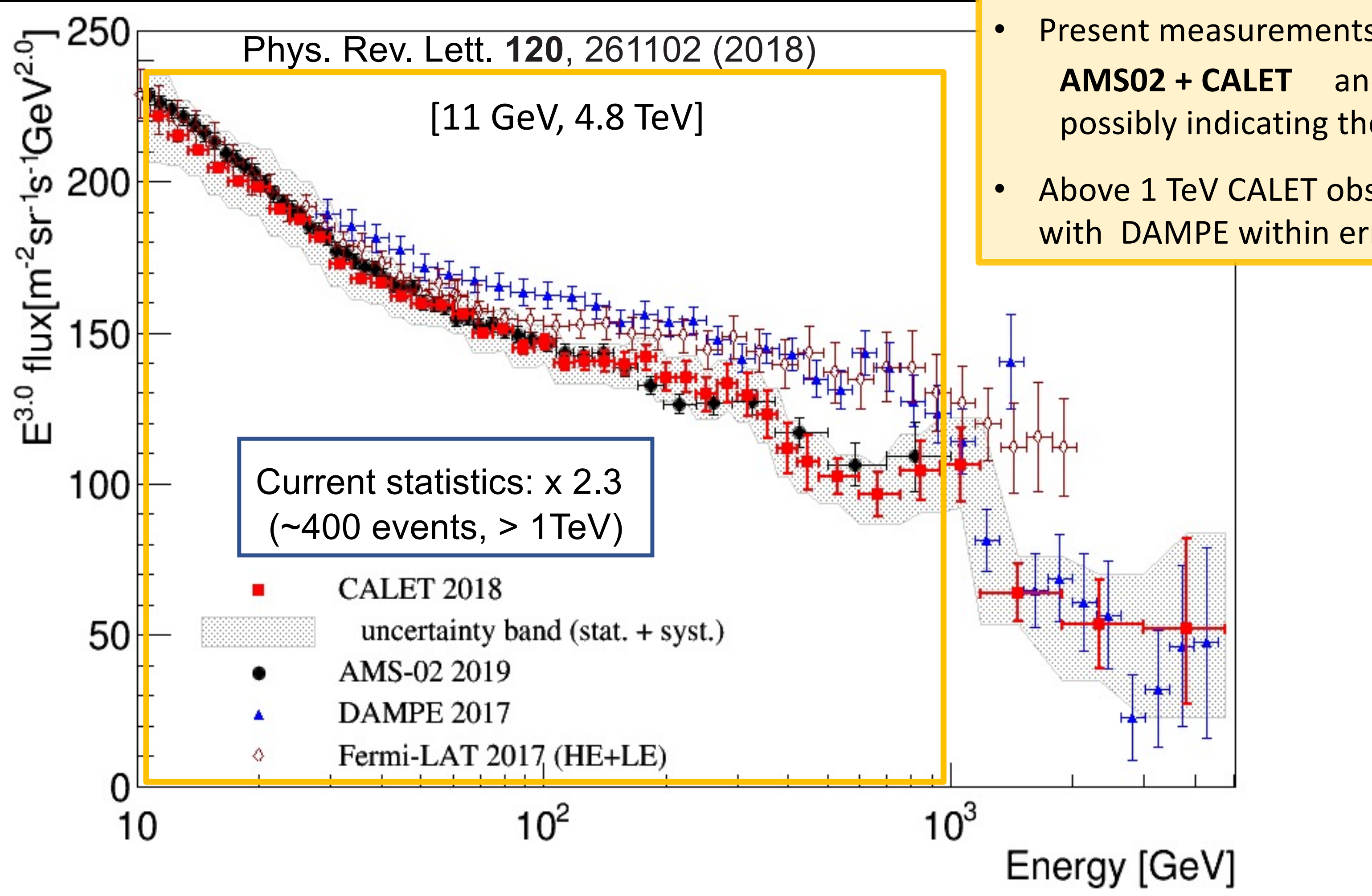


151013-210228

Number of HE triggers
~1.3 billion

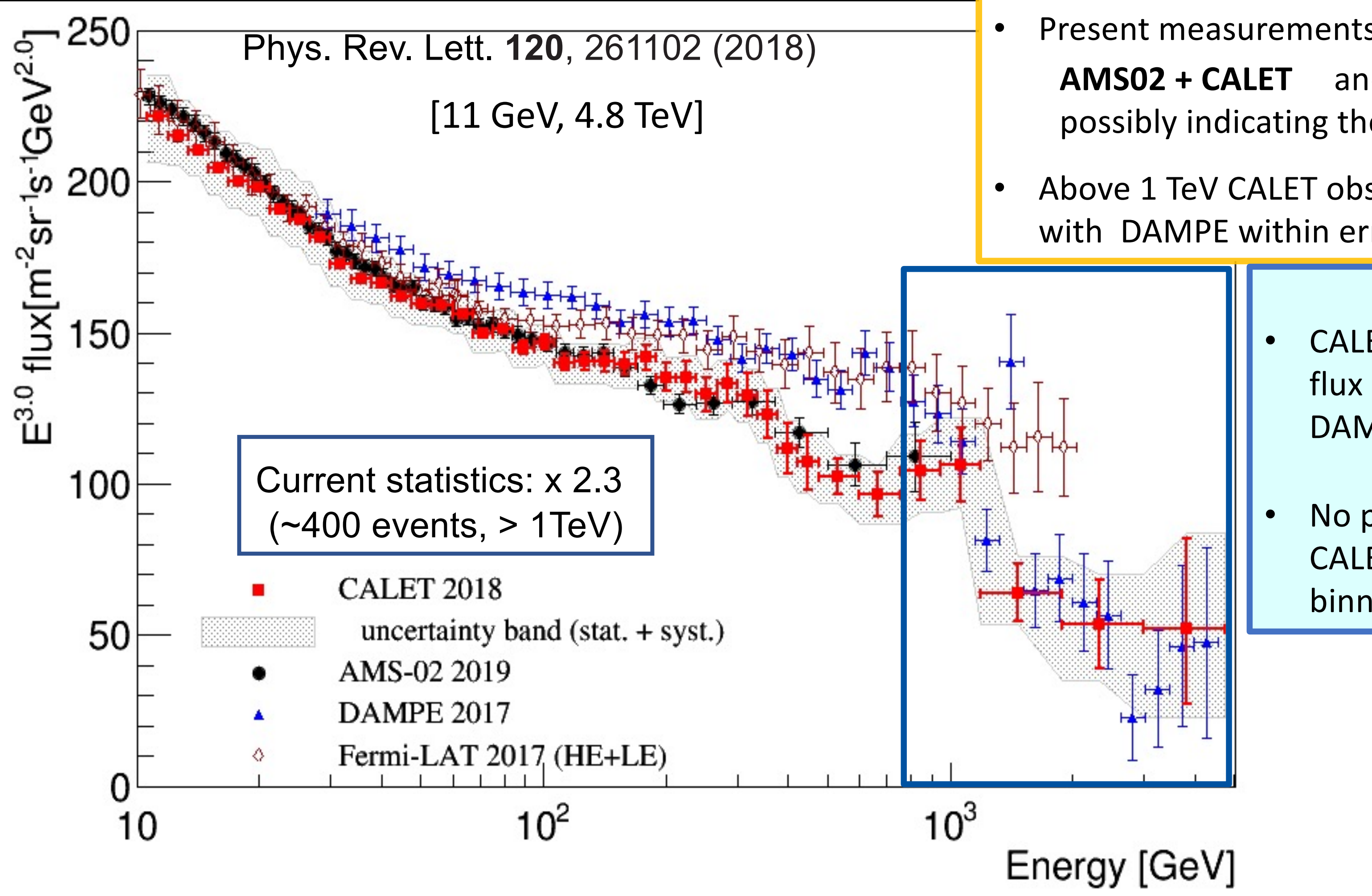
Total number of >GeV triggers
~2.7 billion

Cosmic-ray all-electron spectrum



- 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
- Above 1 TeV CALET observes a **flux reduction** consistent with DAMPE within errors.

Cosmic-ray all-electron spectrum



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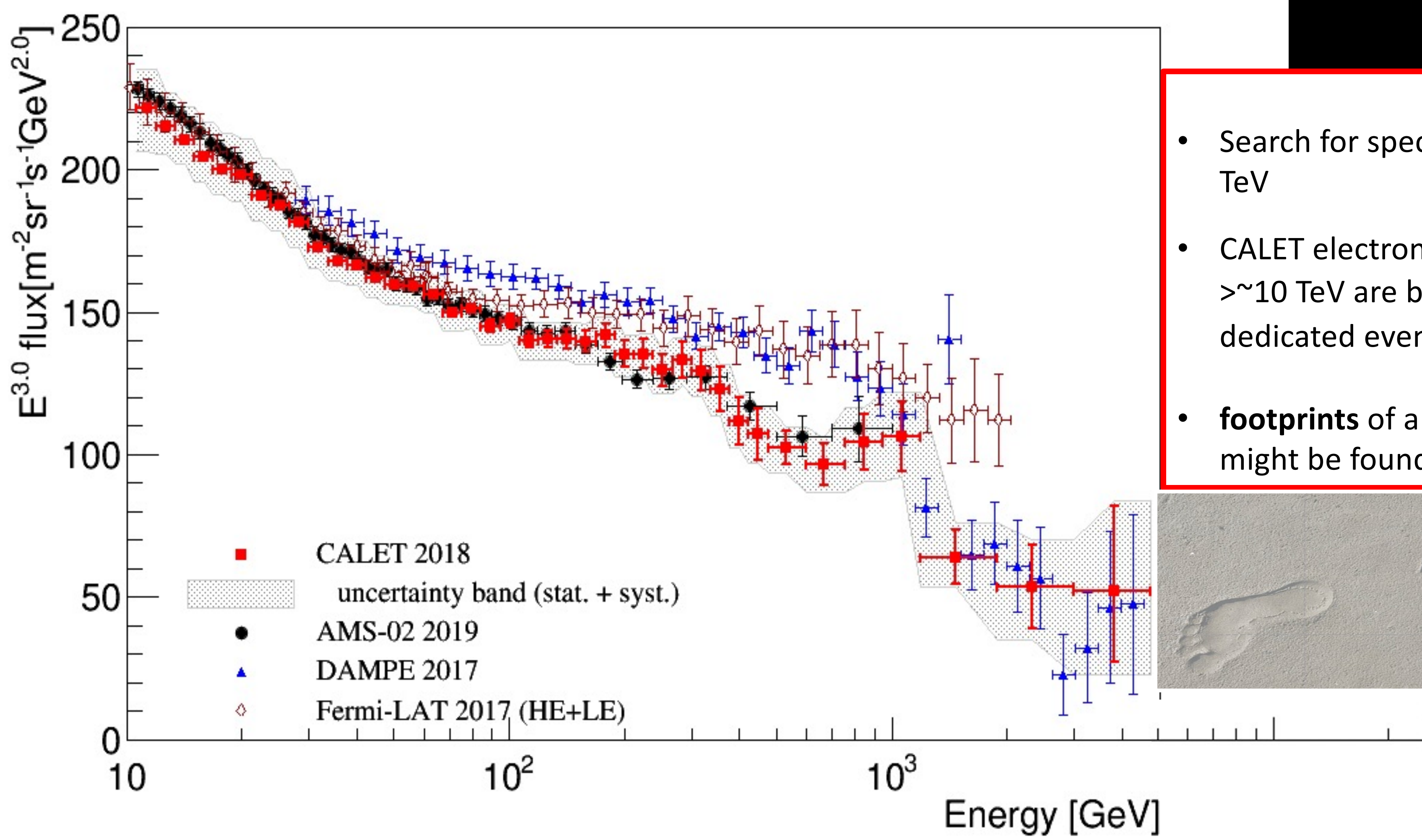
- CALET observes a suppression of the flux above 1 TeV consistent with DAMPE within errors
- No peak-like structure at 1.4 TeV in CALET measurement irrespective of binning

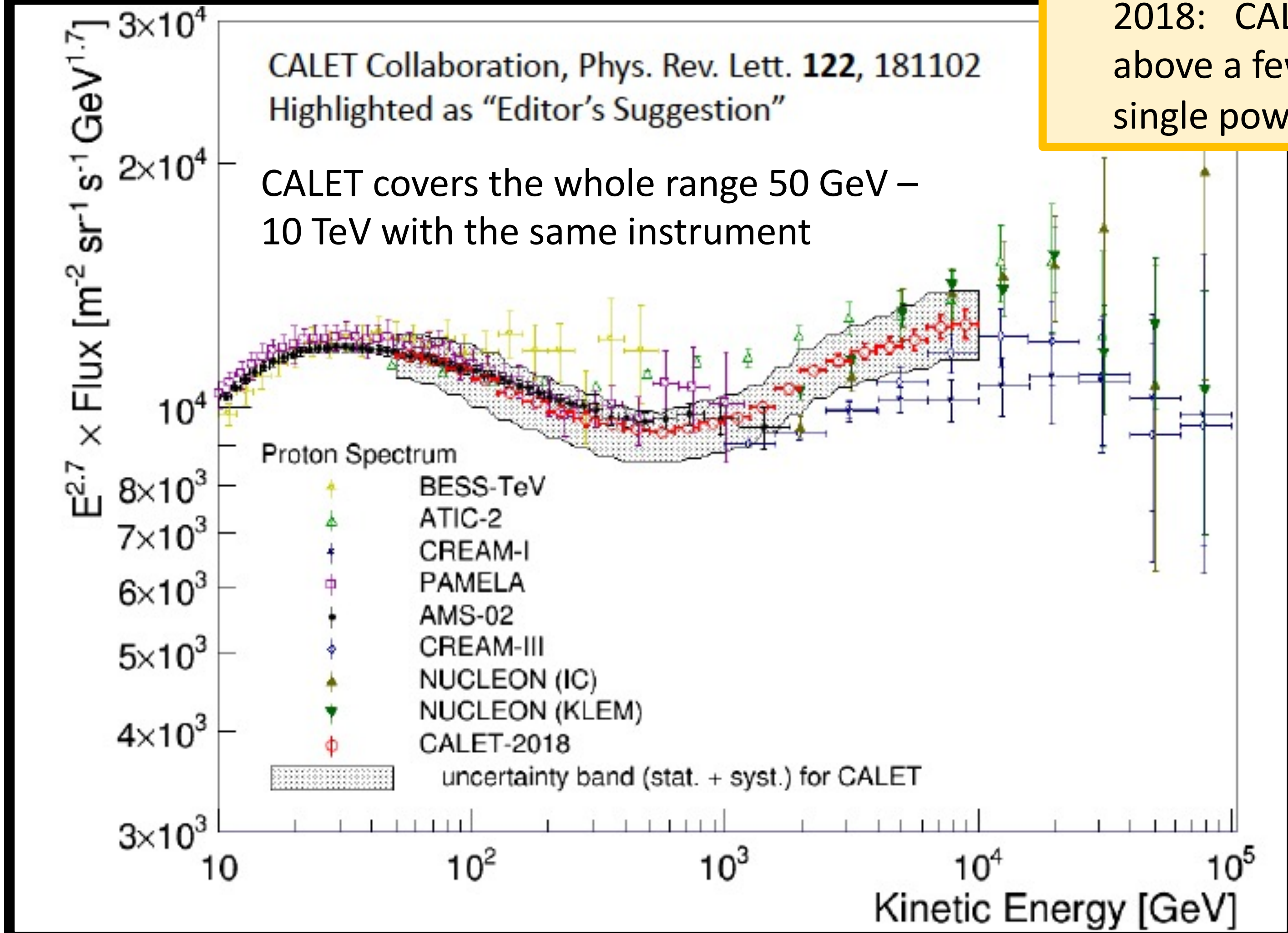
Cosmic-ray all-electron spectrum



- Search for spectral features above a few TeV
- CALET electron candidate events with E >~10 TeV are being studied with dedicated event-by-event analysis
- **footprints** of a possible **nearby source** might be found in this region

Cosmic-ray proton spectrum

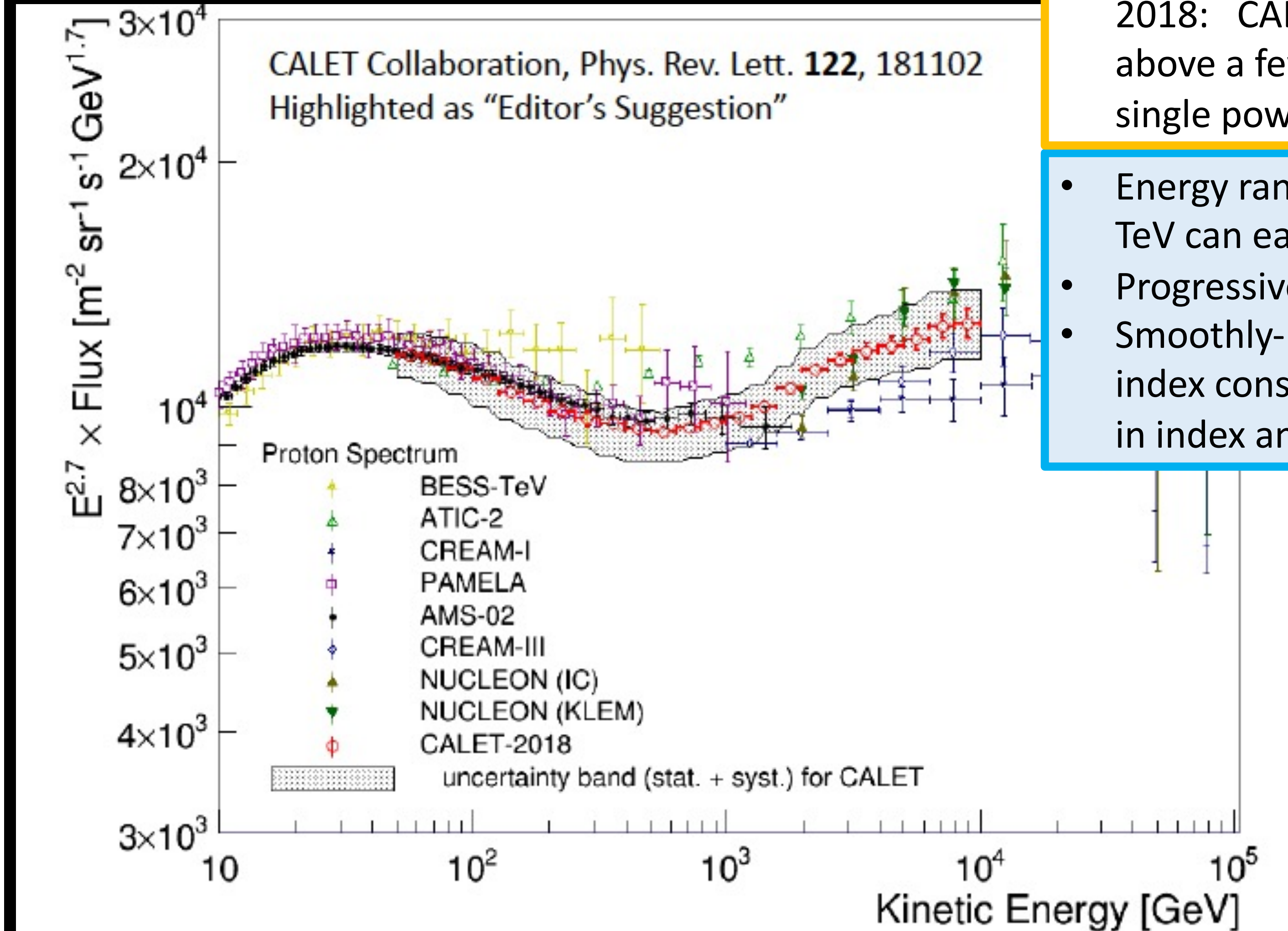
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

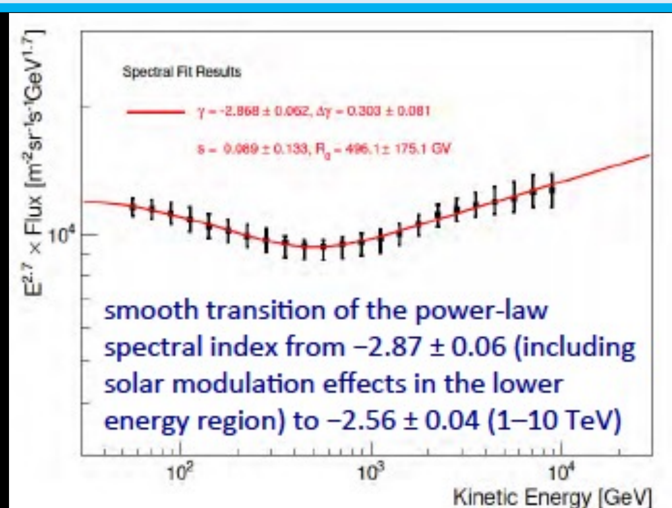


Cosmic-ray proton spectrum

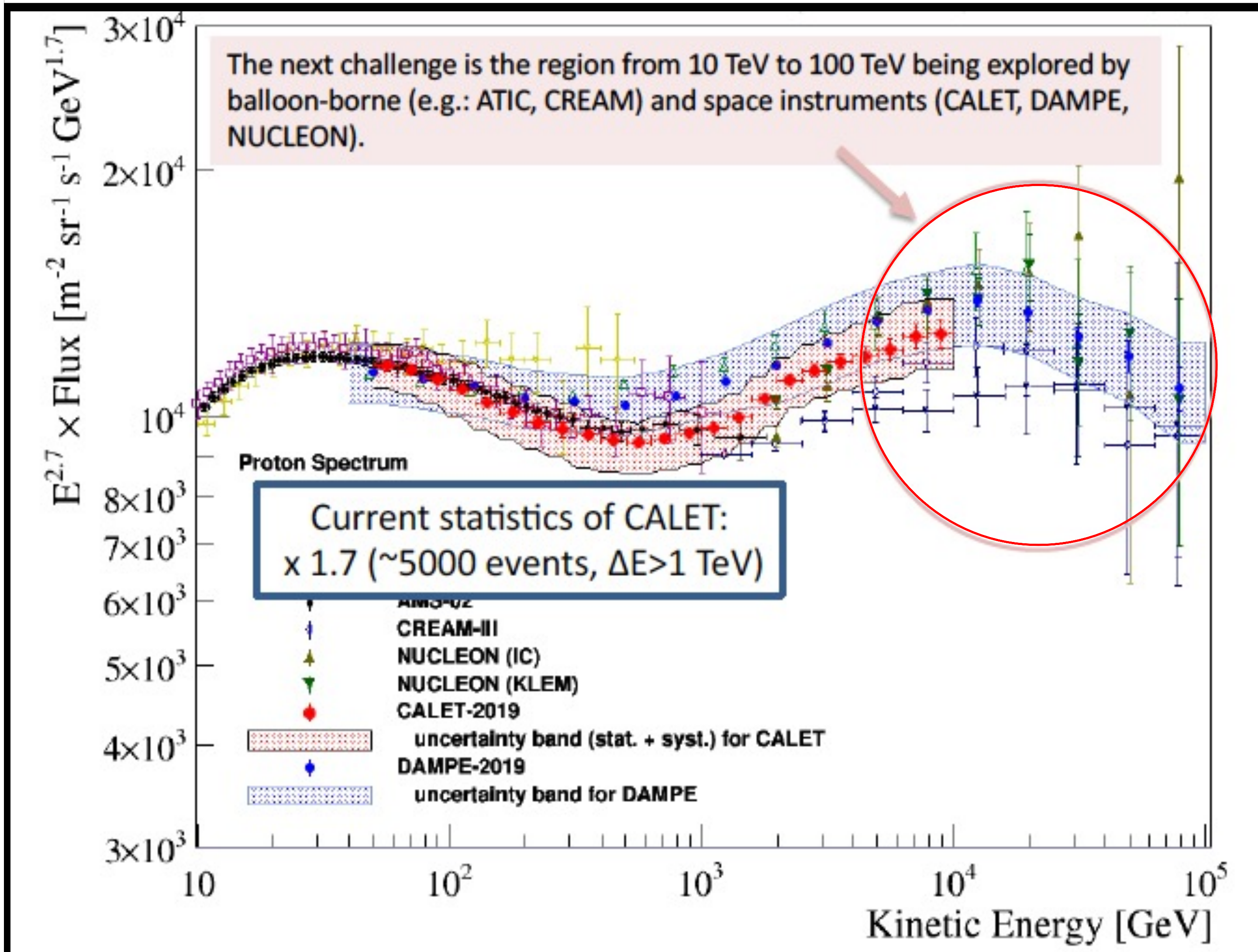
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

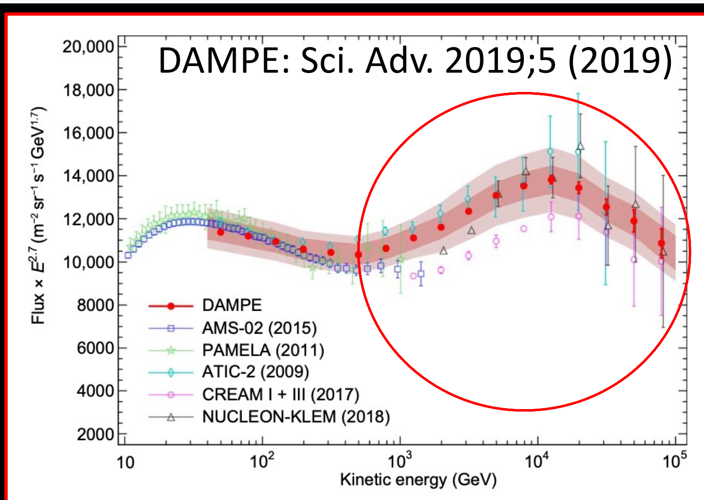
- Energy ranges 50 GeV – 500 GeV and 1 TeV – 10 TeV can each be fitted with single power laws
- Progressive hardening up to TeV energies
- Smoothly-broken power law fit gives low energy index consistent with AMS-02, but larger change in index and higher break energyß





Cosmic-ray proton spectrum





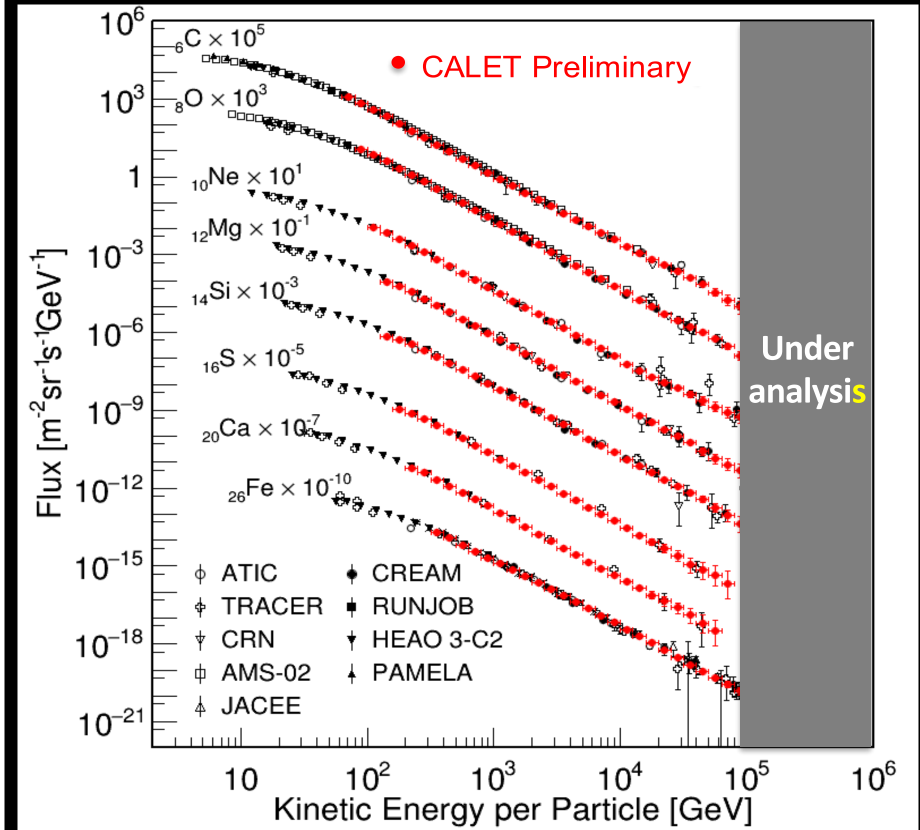
- DAMPE reported a spectral index softening $\Delta\gamma = -0.25 \pm 0.07$ from ~-2.60 to ~-2.85. above 10 TeV at E_{break} = $13.6^{+4.1}_{-4.8}$ TeV with ~30% error.
- DAMPE flux is consistent with AMS-02 and CALET up to 200 GeV. Above, the flux is higher (close to the limit of the systematic error band).

STAY TUNED FOR CALET UPDATES AT ICRC 2021 !

Spectra of cosmic-ray nuclei from C to Fe

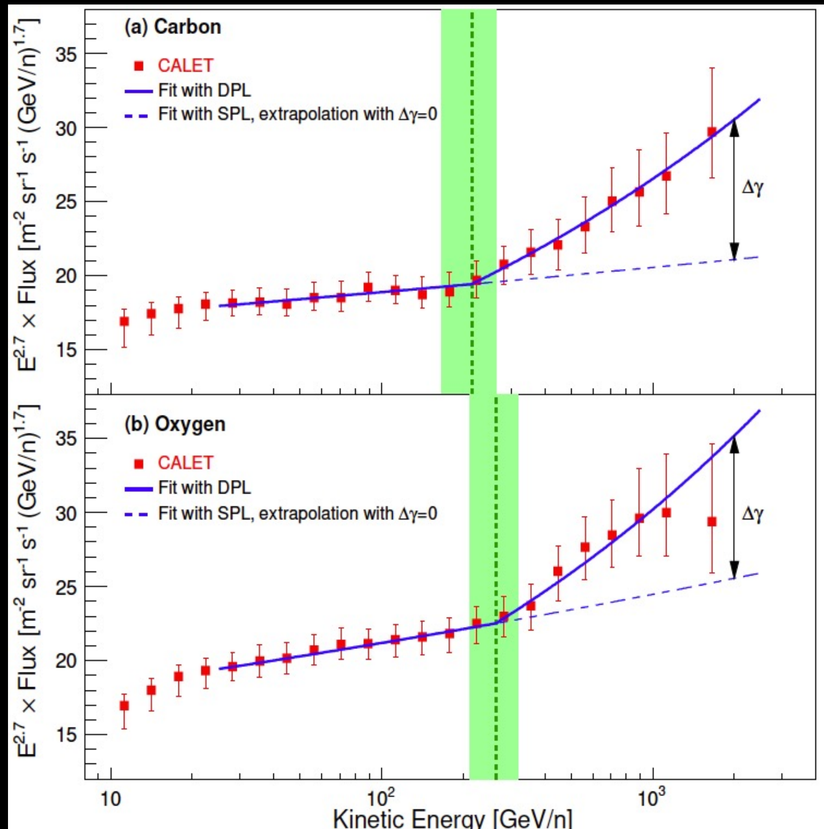
Spectra of Carbon – Iron

Oct.13, 2015 – Sep.30, 2020 (for 1818 days)



Spectral hardening of Carbon and Oxygen

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



Carbon

$\gamma = -2.663 \pm 0.014$

$E_0 = 215 \pm 54\,\mathrm{GeV/n}$

$\Delta\gamma = 0.166 \pm 0.042\ \ (4.0\,\sigma)$

with $\chi^2/\mathrm{d.o.f.} = 9.0/8$

Phys. Rev. Lett. **125**, 251102 (2020)

Oxygen

$\gamma = -2.637 \pm 0.009$

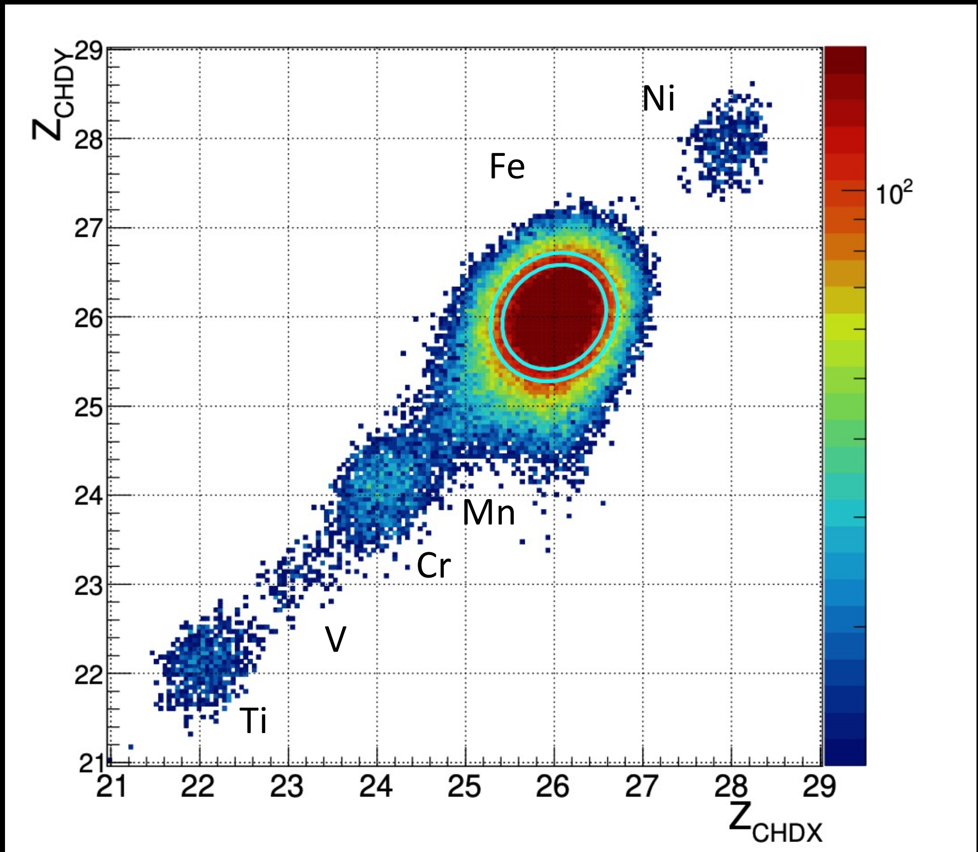
$E_0 = 264 \pm 53\,\mathrm{GeV/n}$

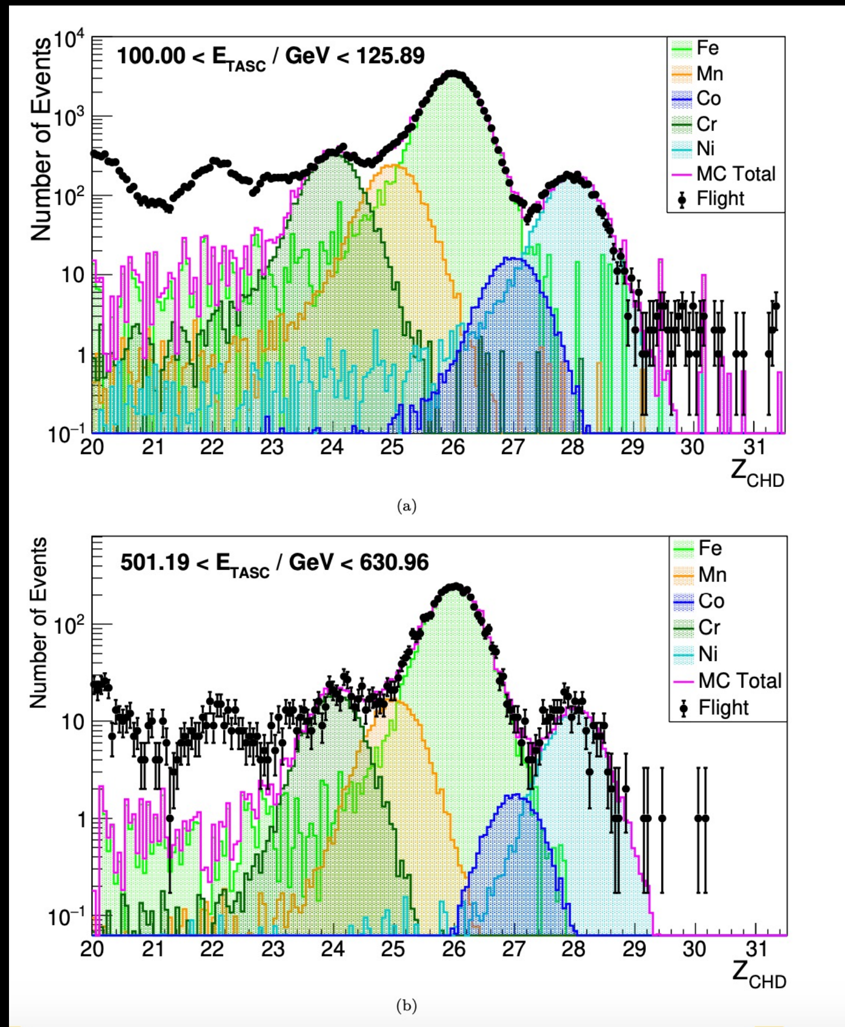
$\Delta\gamma = 0.158 \pm 0.053\ \ (3.0\,\sigma)$

with $\chi^2/\mathrm{d.o.f.} = 3.0/8$

Iron – analysis (charge selection)

Charge measurement from the two CHD layers

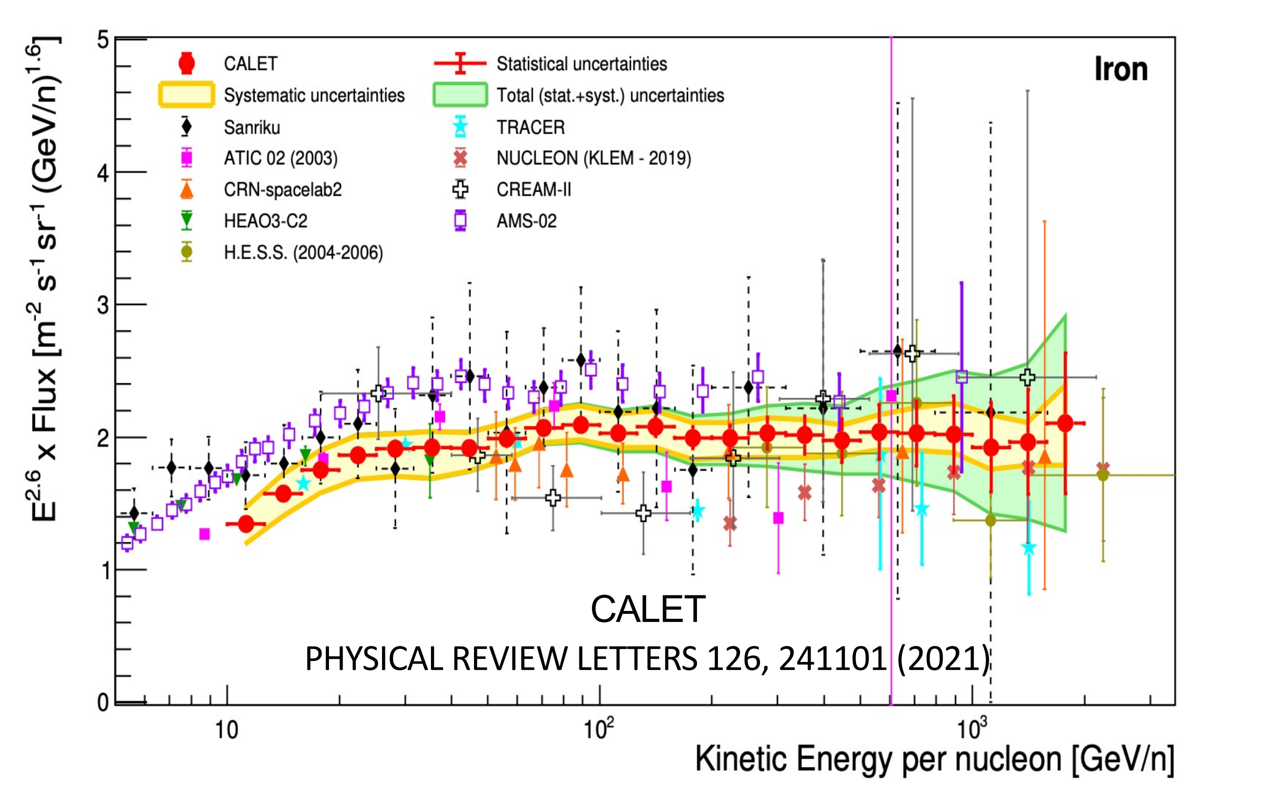




Iron spectrum

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

Jan 1, 2016 – May 2020

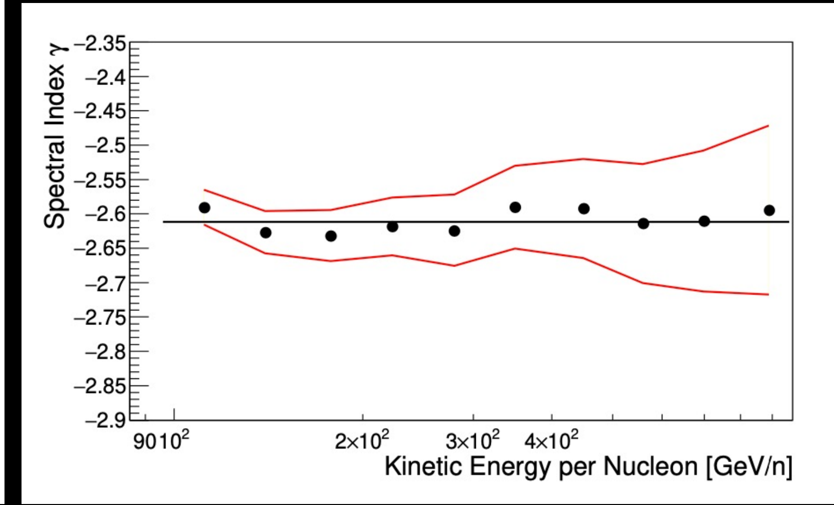


Iron Single Power Law fit:

50 GeV/n, 2.0 TeV/n

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

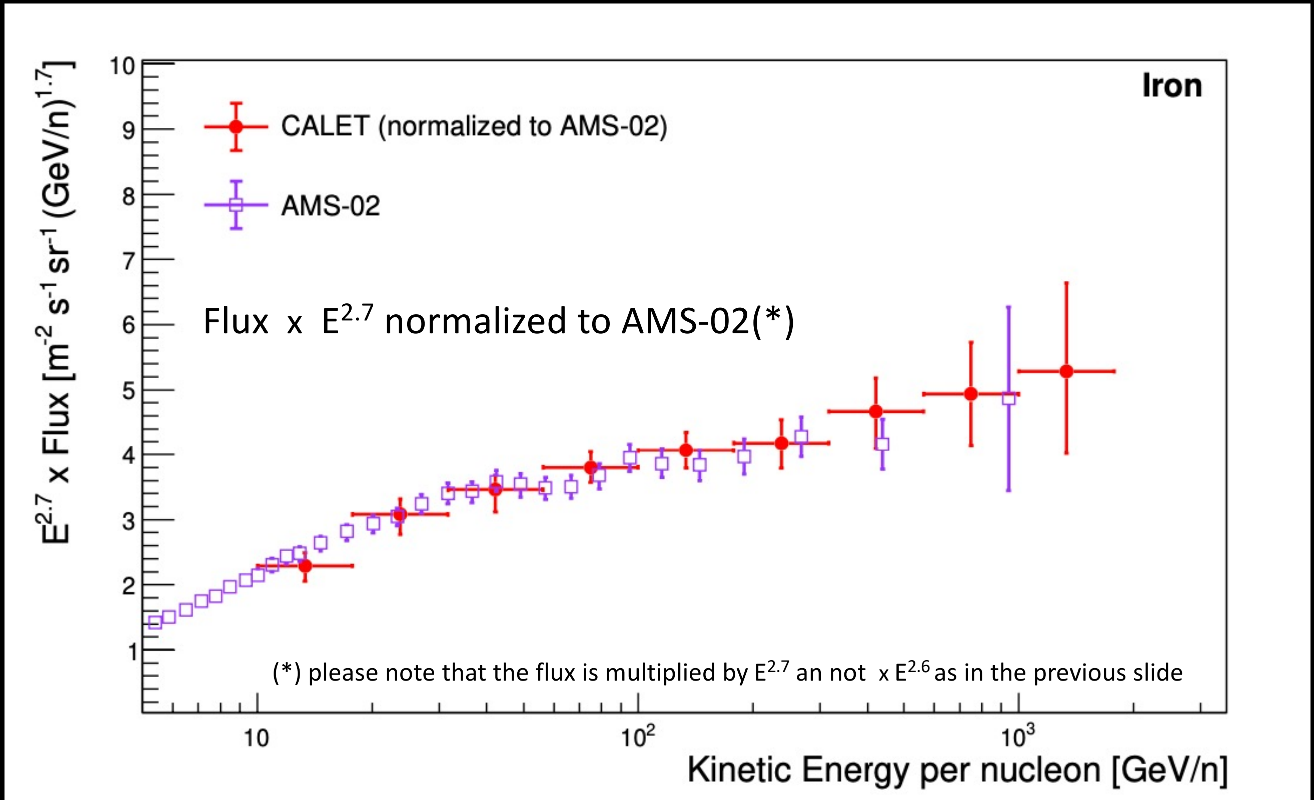
with $\chi^2/\text{d.o.f.} = 4.2/14$



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:

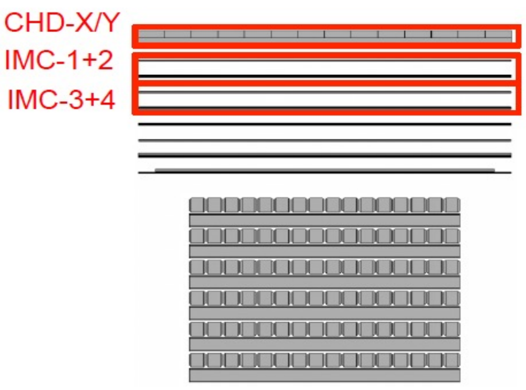
- CALET $E^{2.7}$ x Flux vs kinetic energy/n normalized to AMS-02:
  - similar spectral shape
  - comparable errors above 200 GeV/n

Spectral hardening:

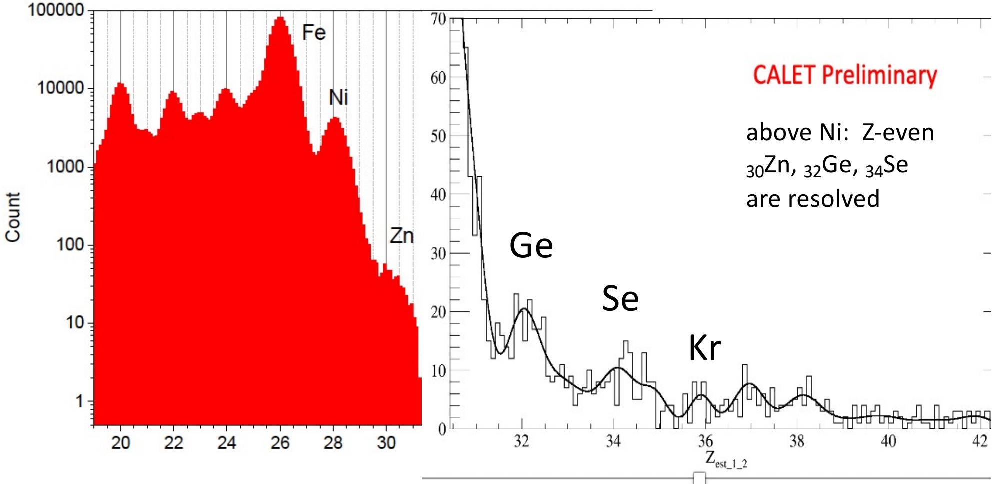
- CALET iron data are consistent with an SPL spectrum up to 2 TeV/n. Beyond this limit, the present statistics and large systematics do not allow to draw a significant conclusion on a possible deviation from a single power law

Ultra-heavy cosmic-ray nuclei (26 < Z $\leq$ 40)

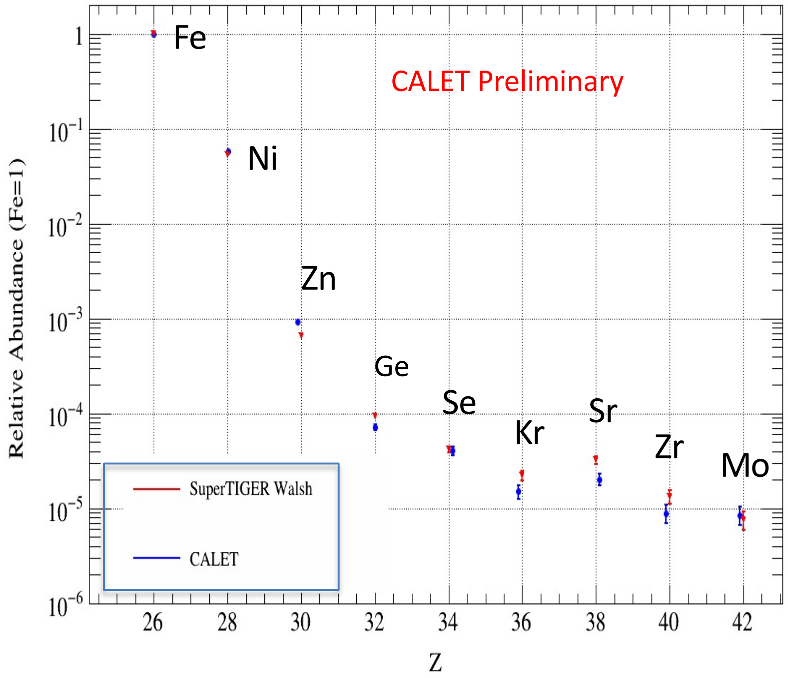
Onboard trigger for UH events



A special UH CR trigger uses the CHD and first 4 layers of the IMC to achieve an expanded x 4 geometric factor GF ~ 4400 cm^2 sr



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

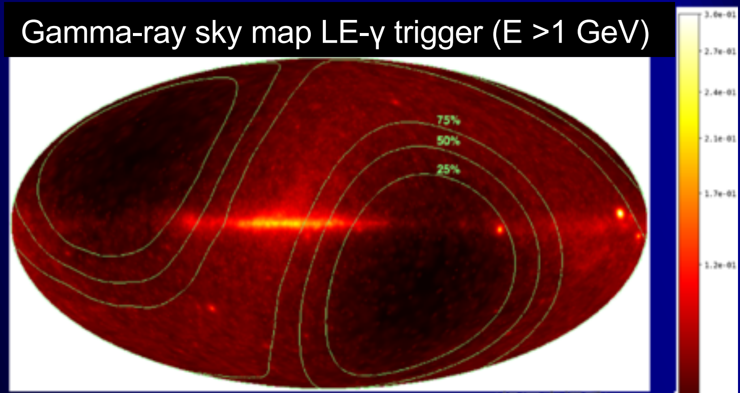


The CALET UH element ratios relative to $_{26}$Fe are consistent with SuperTIGER and ACE abundances.

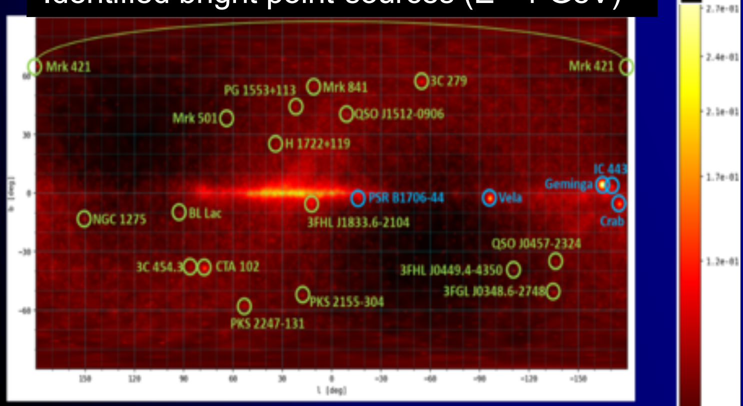
CALET γ–ray Sky (>1GeV) and GRBs

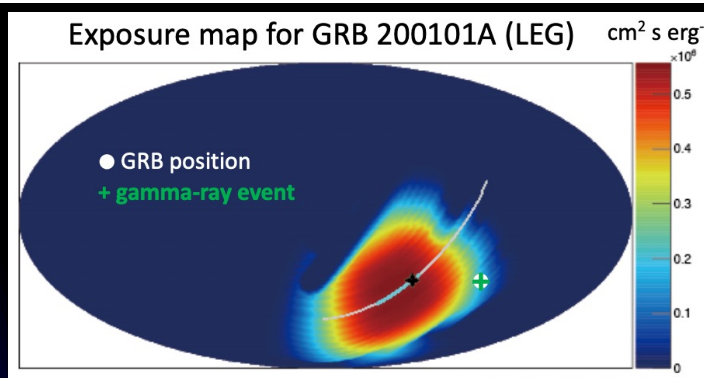
- Effective area ~400 cm^2 above 2 GeV
- Angular resolution < 0.2° above 10 GeV)
- Energy resolution ~5% at 10 GeV

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



Identified bright point-sources (E >1 GeV)



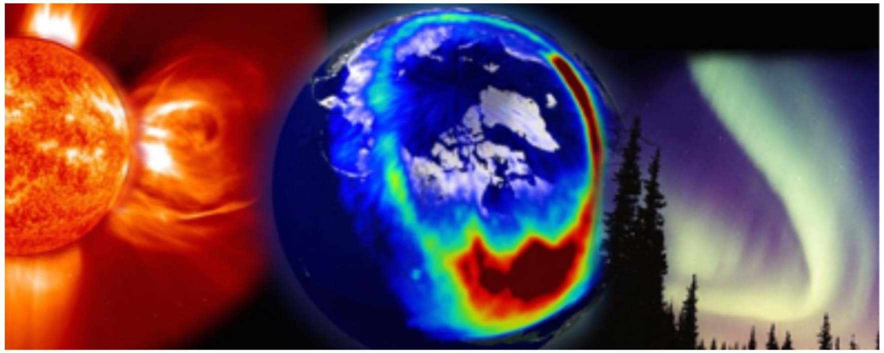


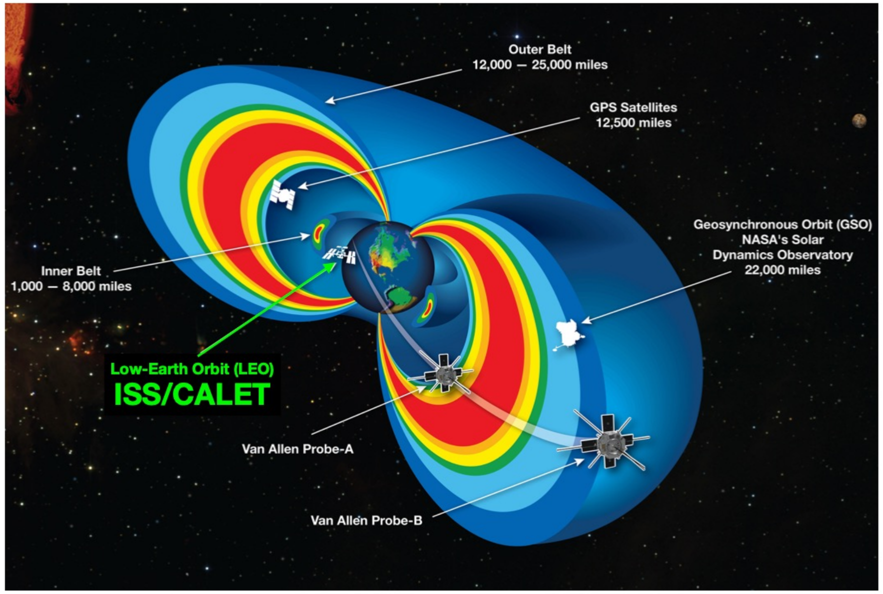
- Follow-up observations of GW events in X-ray and gamma-ray bands
- MOU with LIGO/Virgo

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

from 2015/10/05 to 2021/04/08
246 GRBs (44.6 GRBs / year)
216 Long (88%) **30 Short (12%)**

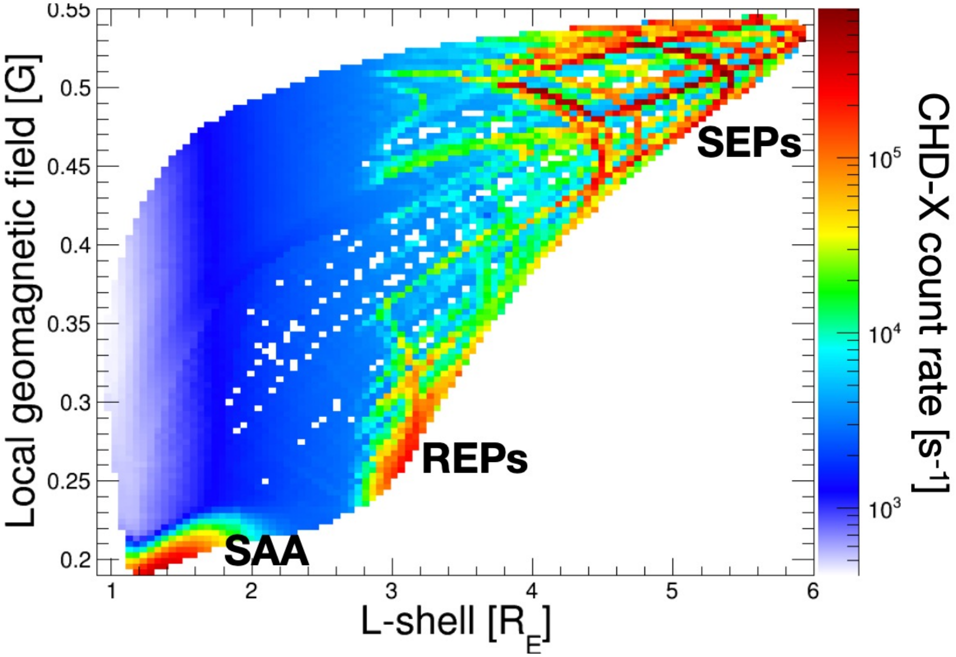
Space Weather Phenomena with CALET





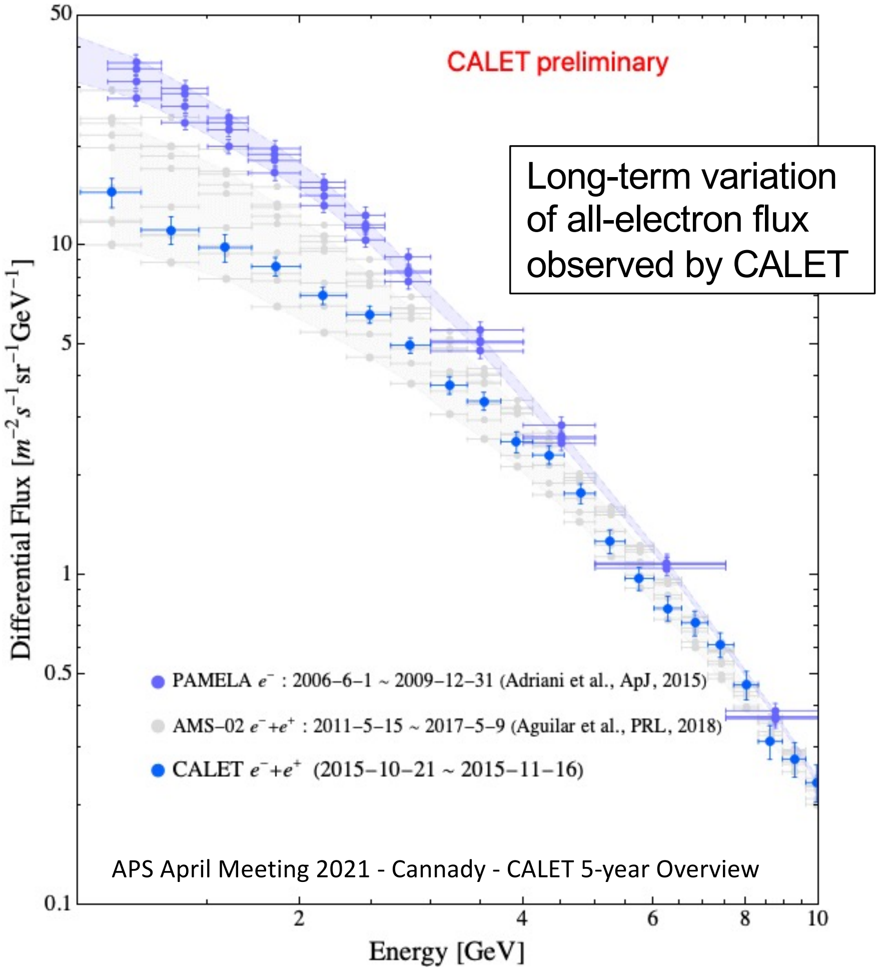
◆ In addition to the aforementioned astrophysics goals, CALET is able to provide a **continuous monitoring of space weather phenomena affecting the near-Earth environment**, including

- ☑ 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

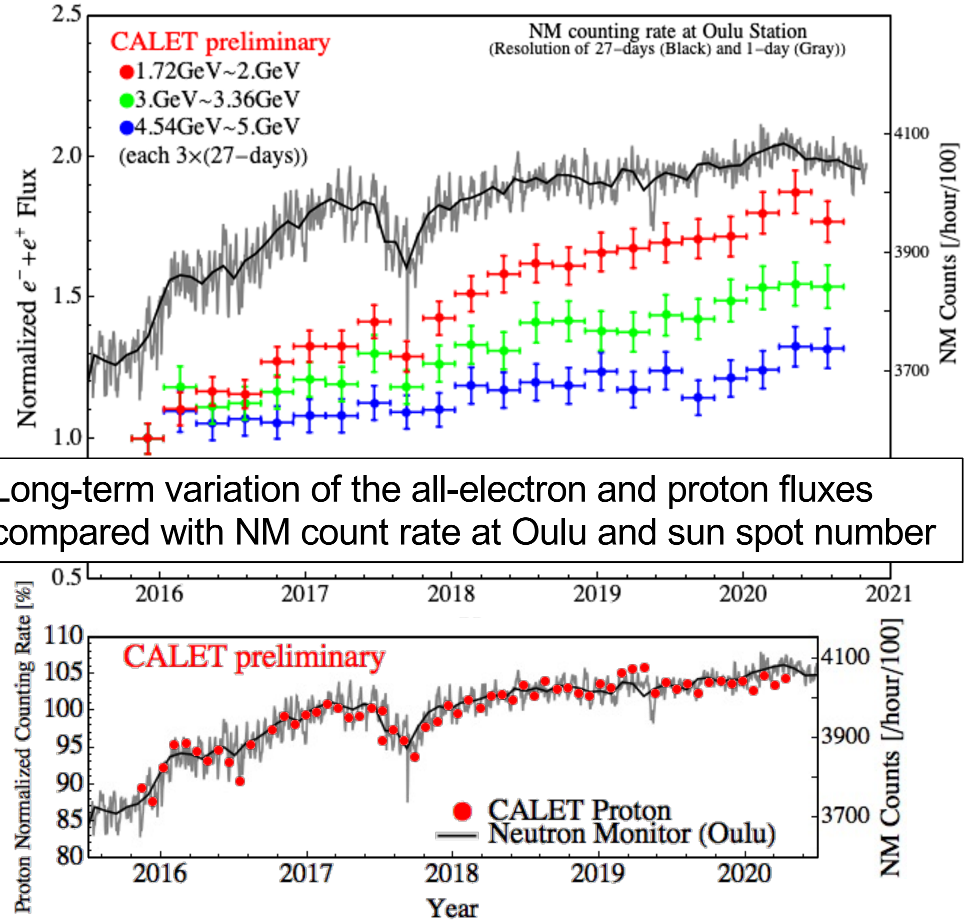


Solar modulation

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



Long-term variation of all-electron flux observed by CALET



Long-term variation of the all-electron and proton fluxes compared with NM count rate at Oulu and sun spot number

Main science goals and status of the analysis

- **Unravel CR acceleration and propagation**
- **Search for nearby sources and dark matter**

Scientific Objectives	Observables	Energy Reach	Reported Rsnge	Reference
Cosmic-ray origin and acceleration	**Electron spectrum**	1 GeV – 20 TeV	11 GeV – 4.8 TeV	published in **PRL 120, 261102 (2018)**
	Proton spectrum	10 GeV – 1 PeV	50 GeV – 10 TeV	published in **PRL 122, 181102 (2019)**
	Carbon and oxygen spectra	10 GeV – 1 PeV	10 GeV/n – 2.2 TeV/n	published in **PRL 125, 251102 (2020)**
	Iron spectrum	10 GeV – 1 PeV	50 GeV/n – 2 TeV/n	published in **PRL 126, 241101 (2021)**
	Elemental spectra of primaries	10 GeV – 1 PeV	10 GeV – 100 TeV	preliminary (see ICRC 2019, 034)
	Ultra-heavy abundances	> 600 MeV/n	> 600 MeV/n	preliminary (see APS 2020 L10.00006)
Galactic CR propagation	B/C and sub-Fe/Fe ratios	some TeV/n	to 200 GeV/n	preliminary (see ICRC 2019)
Nearby CR sources	Electron spectrum	100 GeV – 20 TeV	to 5 TeV	preliminary (see ICRC 2019)
Dark matter	Signatures in electron/gamma spectra	100 GeV – 20 TeV	to 5 TeV	**ApJL 829:L20 (2016)**
Gamma rays	Diffuse & point sources	1 GeV – 1 TeV	1 GeV – 1 TeV	**ApJS 238:5 (2018)**
Heliospheric physics	Solar modulation (low energy electrons)	1 GeV – 10 GeV	1 GeV – 10 GeV	see, e.g., ICRC 2019, 112
Gamma-ray transients	GW follow-up and GRB analysis	7 keV – 20 MeV	100 GeV (ECAL)	**ApJL 829:L20 (2016)**
Space weather	Relativistic electron precipitation	> 1.5 MeV	> 1.5 MeV	**Geophys. Res. Lett., 43, 4119 (2016)**

Summary and Future Prospects

- CALET was successfully launched on Aug. 19th, 2015
- **More than 5.5 years** of excellent performance and remarkable stability of the instrument
- 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 > 2000 days with > 85% live time fraction
- Total number of > GeV triggers **~2.7 billion**

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

STAY TUNED for the analysis updates at ICRC 2021 !