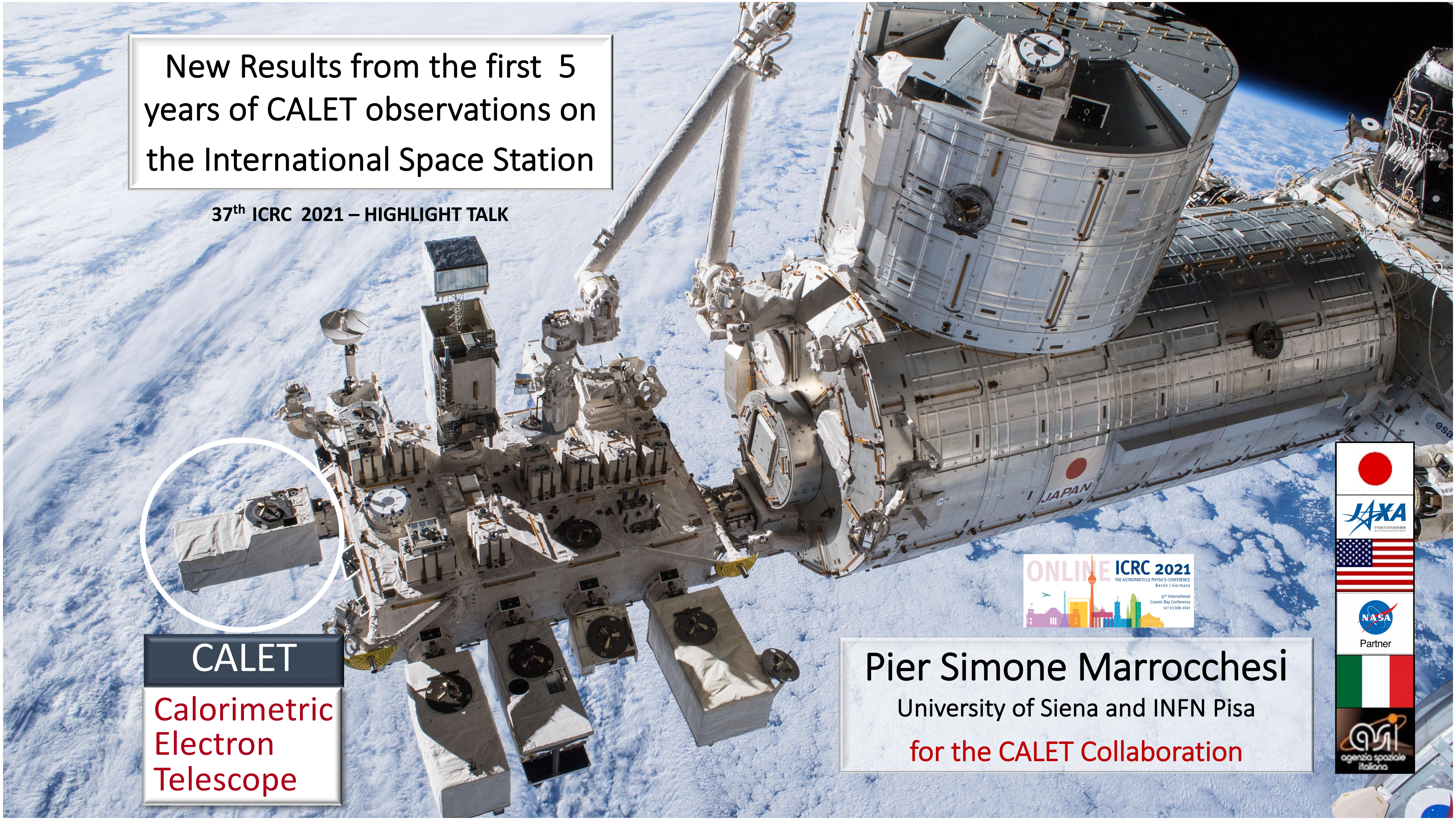
New Results from the first 5 years of CALET observations on the International Space Station

37th ICRC 2021 – HIGHLIGHT TALK



CALET

Calorimetric Electron Telescope

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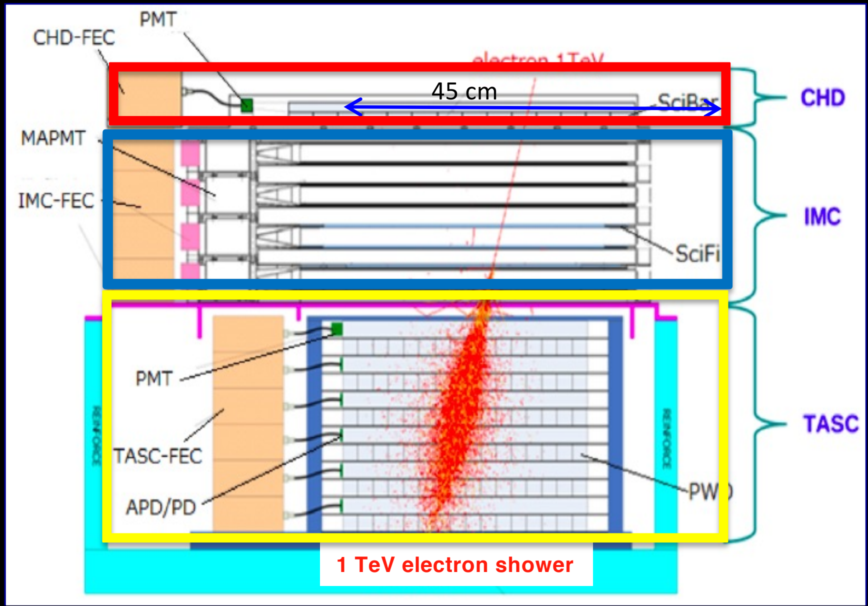
for the CALET Collaboration

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**

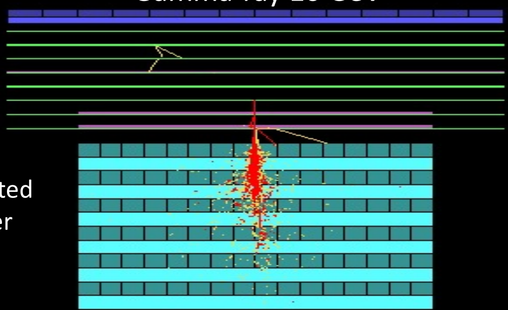


CHD – Charge Detector
- 2 x 14 plastic scintillating paddles
- single element charge ID from p to Fe and above (Z = 40)
- charge resolution ~0.15-0.3 e

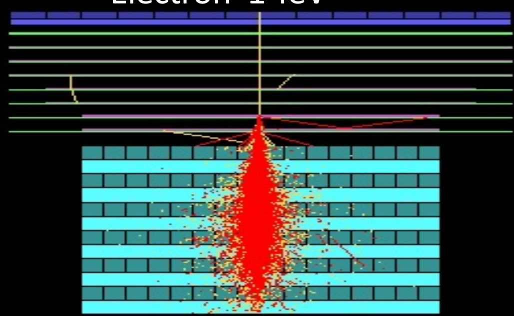
IMC – Imaging Calorimeter
- Scifi + Tungsten absorbers: 3 X_0 at normal incidence
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **Tracking** (~0.1° angular resolution) + **Shower imaging**

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}

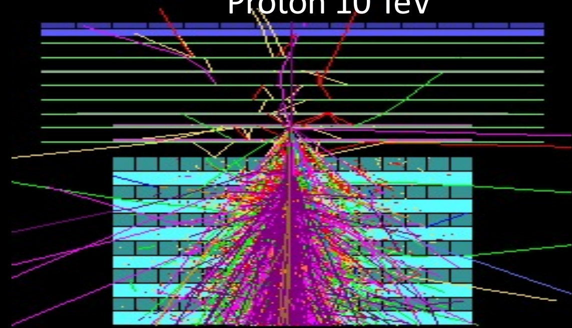
Gamma-ray 10 GeV



Electron 1 TeV



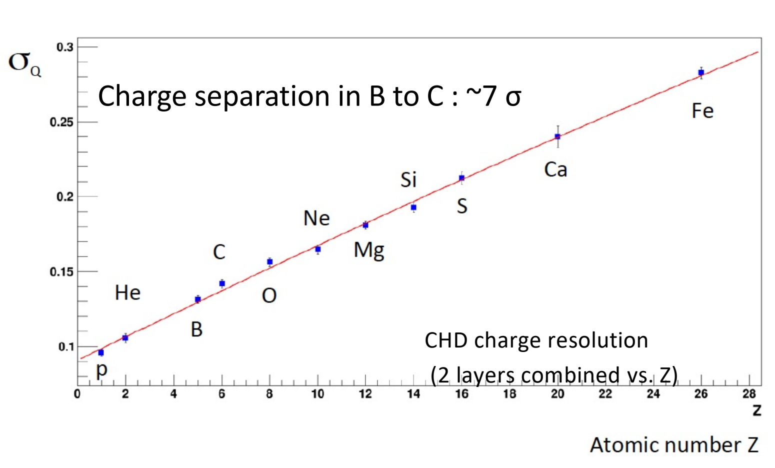
Proton 10 TeV

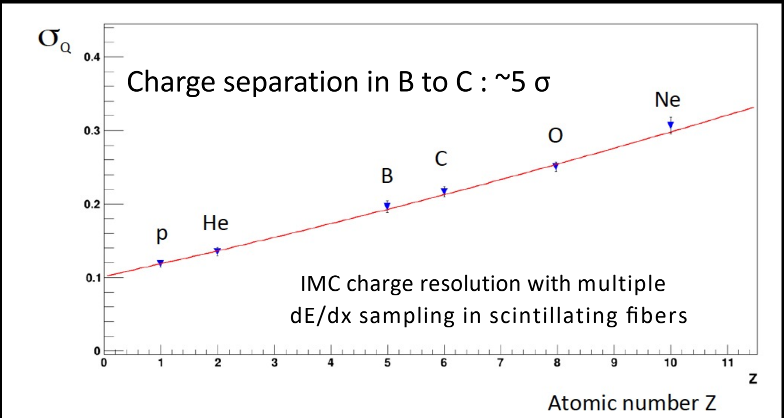


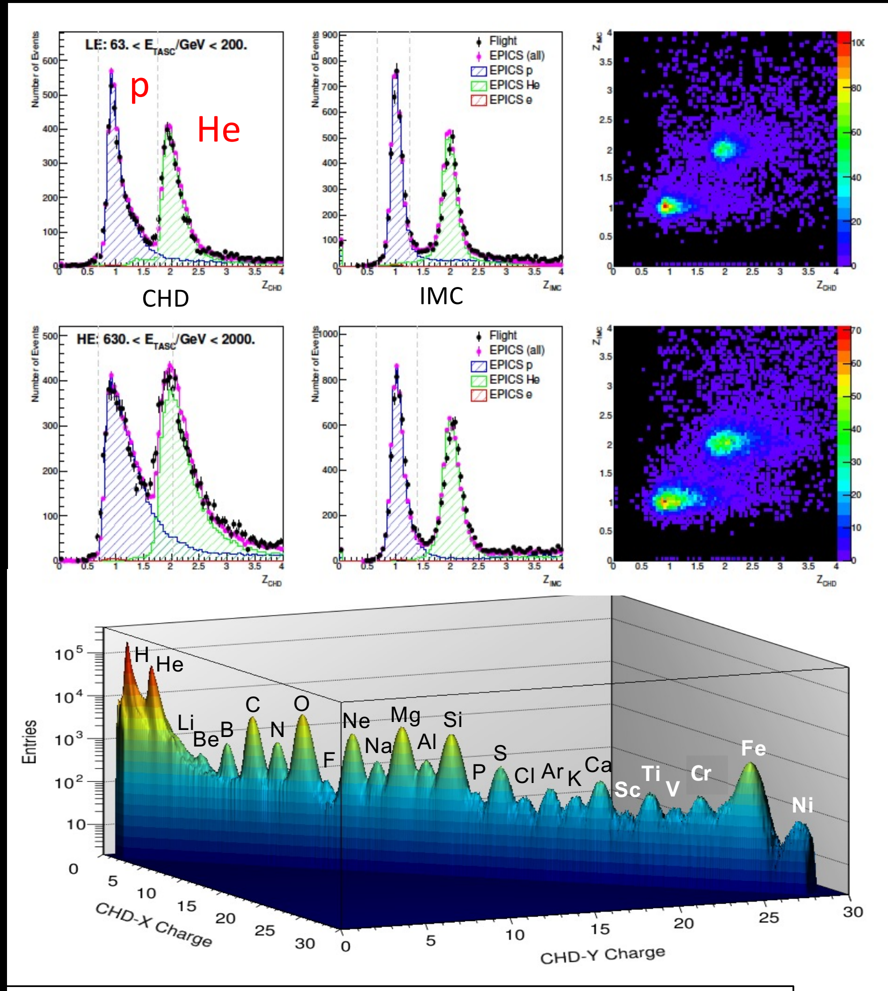
Simulated Shower Profile

Charge Identification with CHD and IMC

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



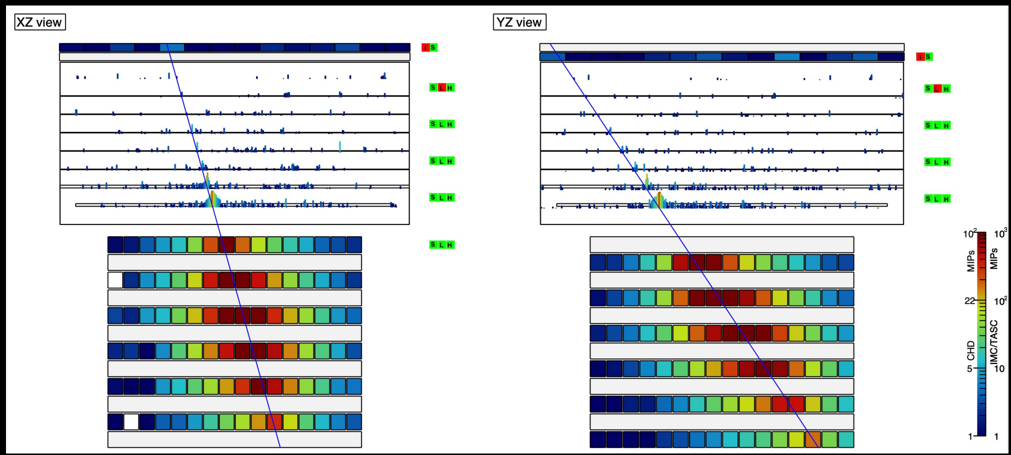




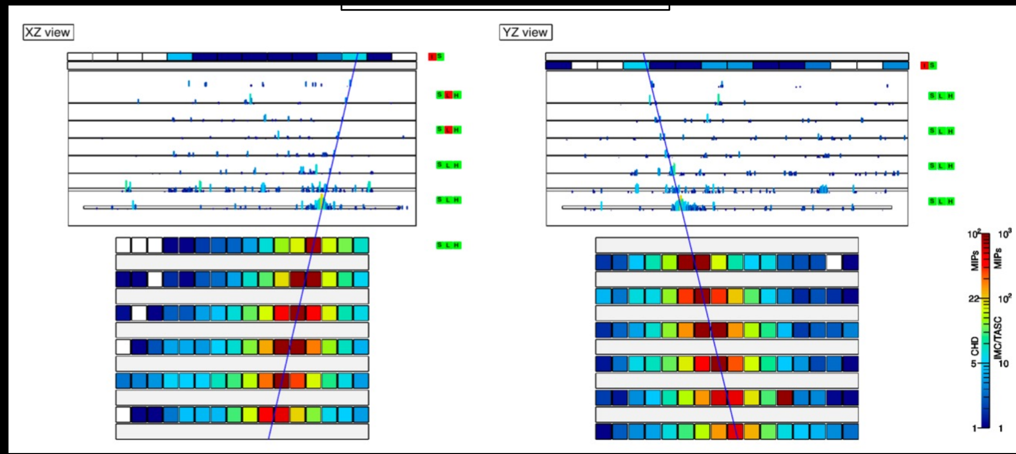
Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

Examples of CALET event candidates

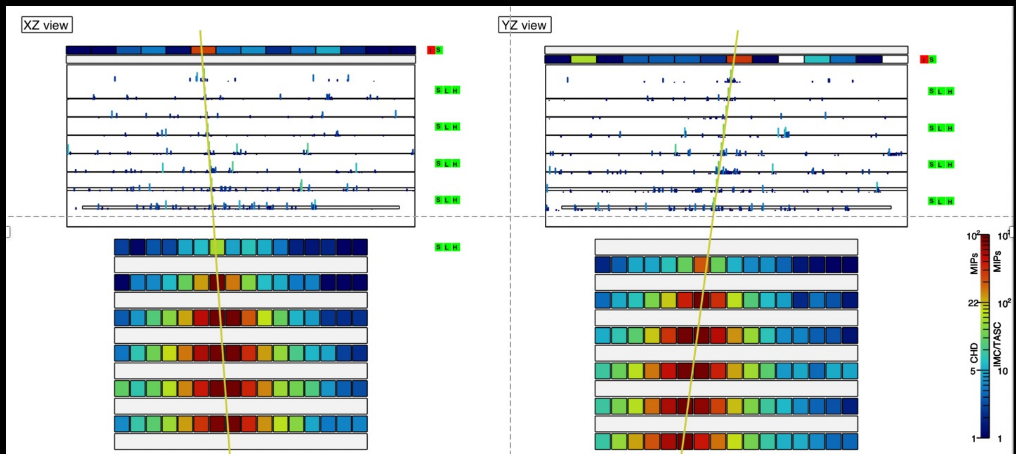
electron ~3 TeV



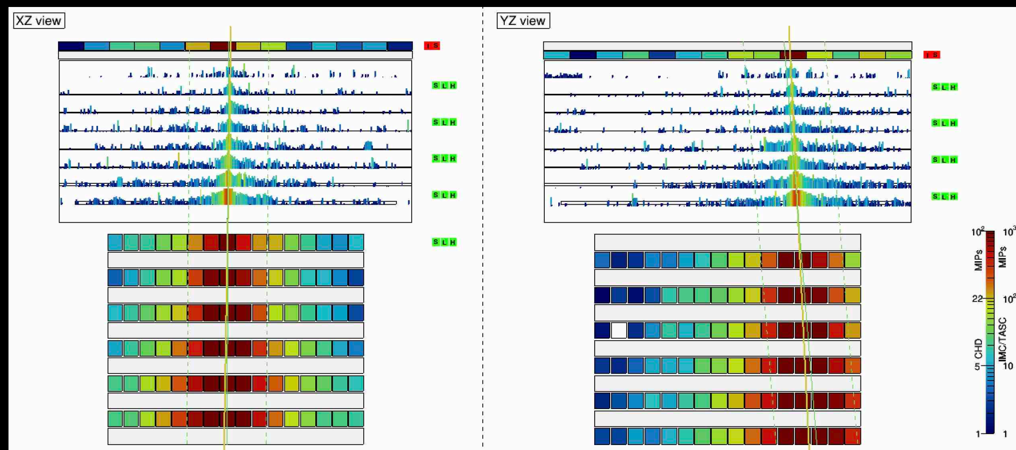
helium ~700 GeV



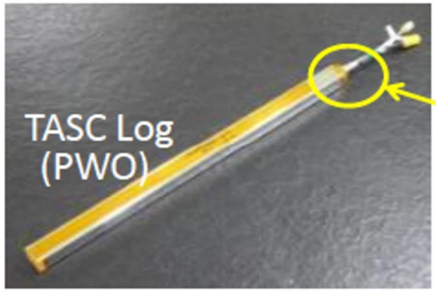
carbon ~2.0 TeV

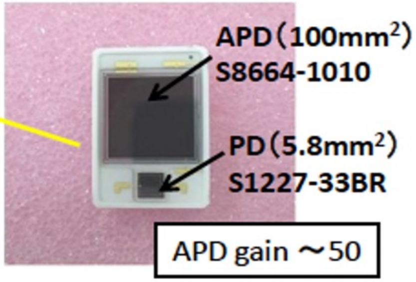


iron ~3.9 TeV

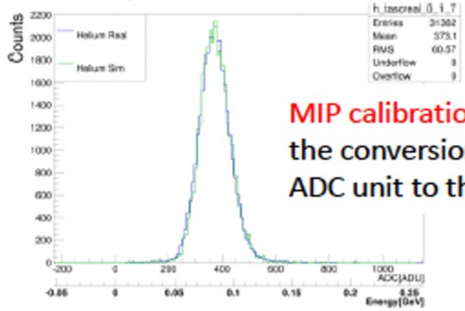


Energy Measurement in a wide dynamic range 1-10^6 MIPs

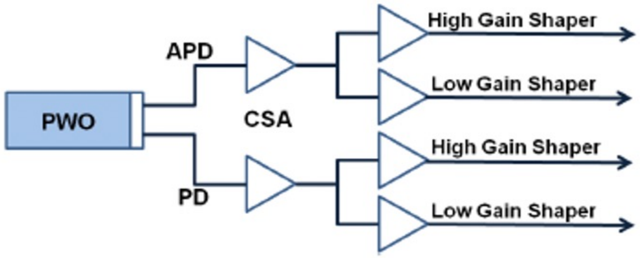




"MIP" peak in PWO: Obs. vs. MC



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

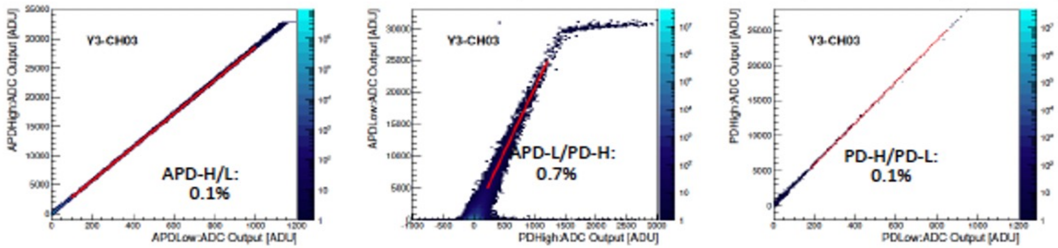


The whole dynamic range was calibrated by UV laser irradiation on ground :
1) The linearity of each gain range is confirmed in the range of 1.4-2.5 %.
2) Each channel covers from 1 MIP to 10^6 MIPs.

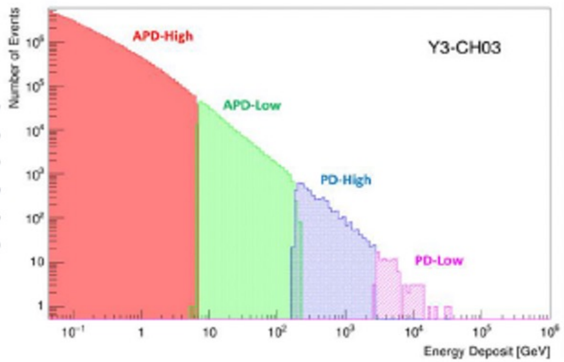
APD-H	APD-L	PD-H	PD-L
1.4%	1.5%	2.5%	2.2%

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

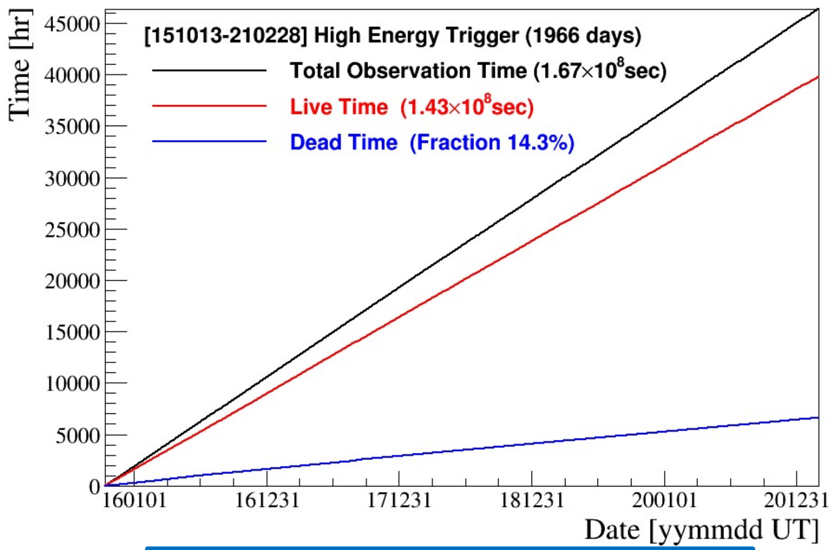
APD-H APD-L	APD-L PD-H	PD-H PD-L
0.1%	0.7%	0.1%



Example of energy distribution in one PWO log



The first five years of CALET observations on the ISS

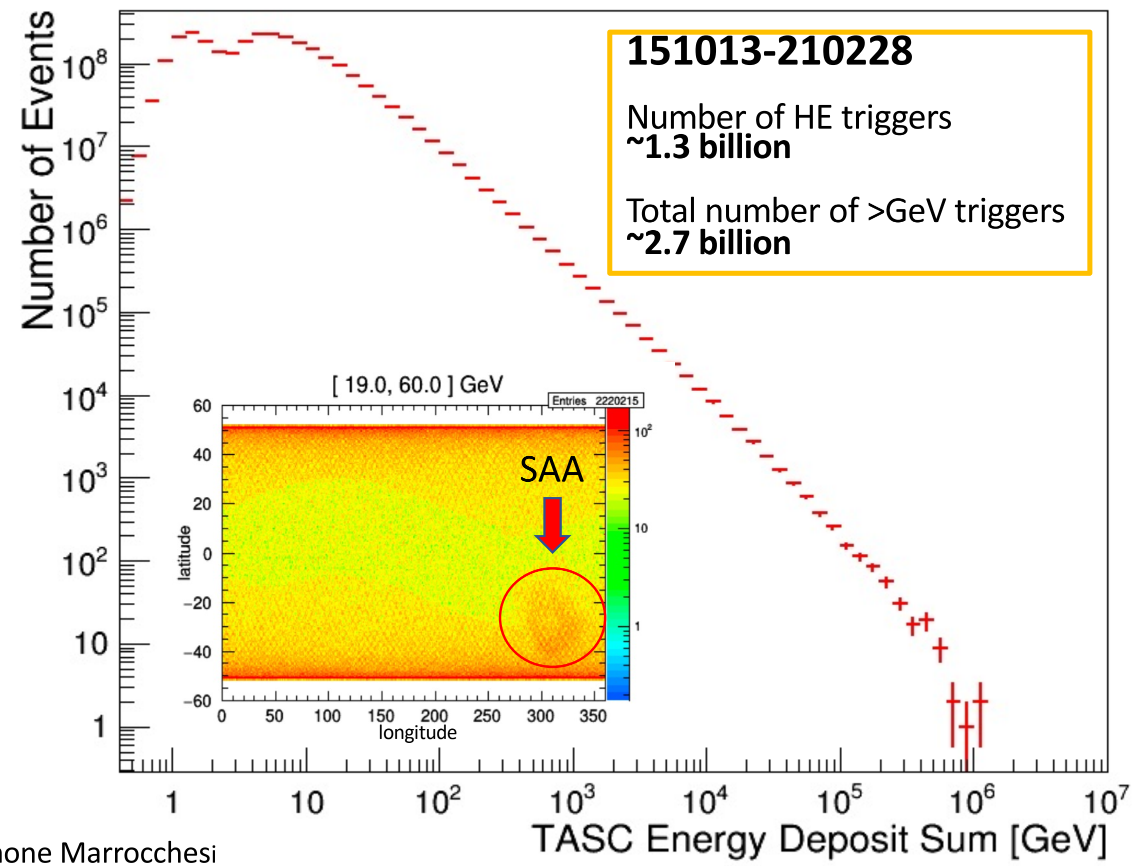


Geometrical Factor:

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

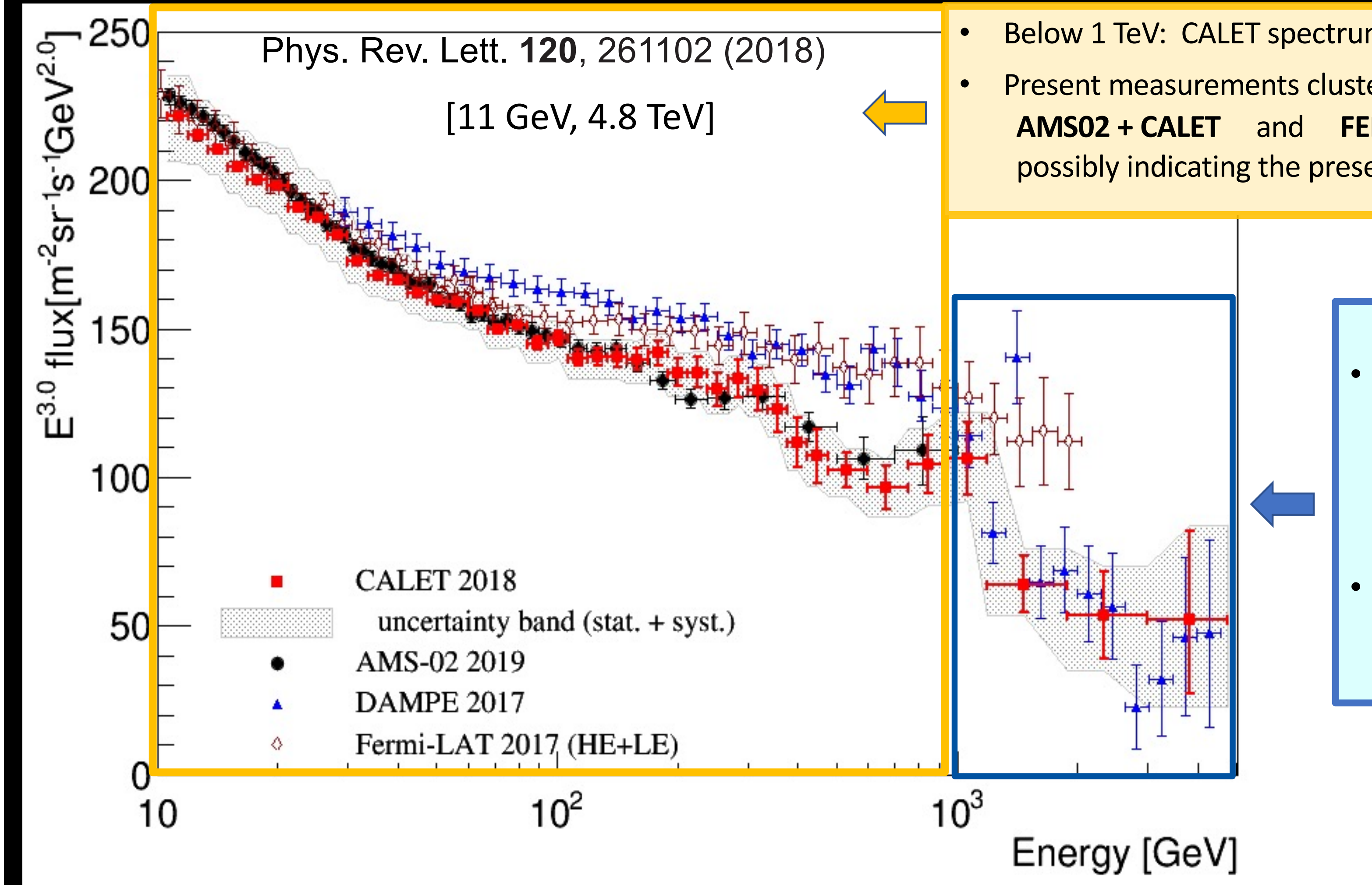
High-energy trigger statistics:

- 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)



Cosmic-ray all-electron spectrum

talk: CRD 737
poster: 628, 492

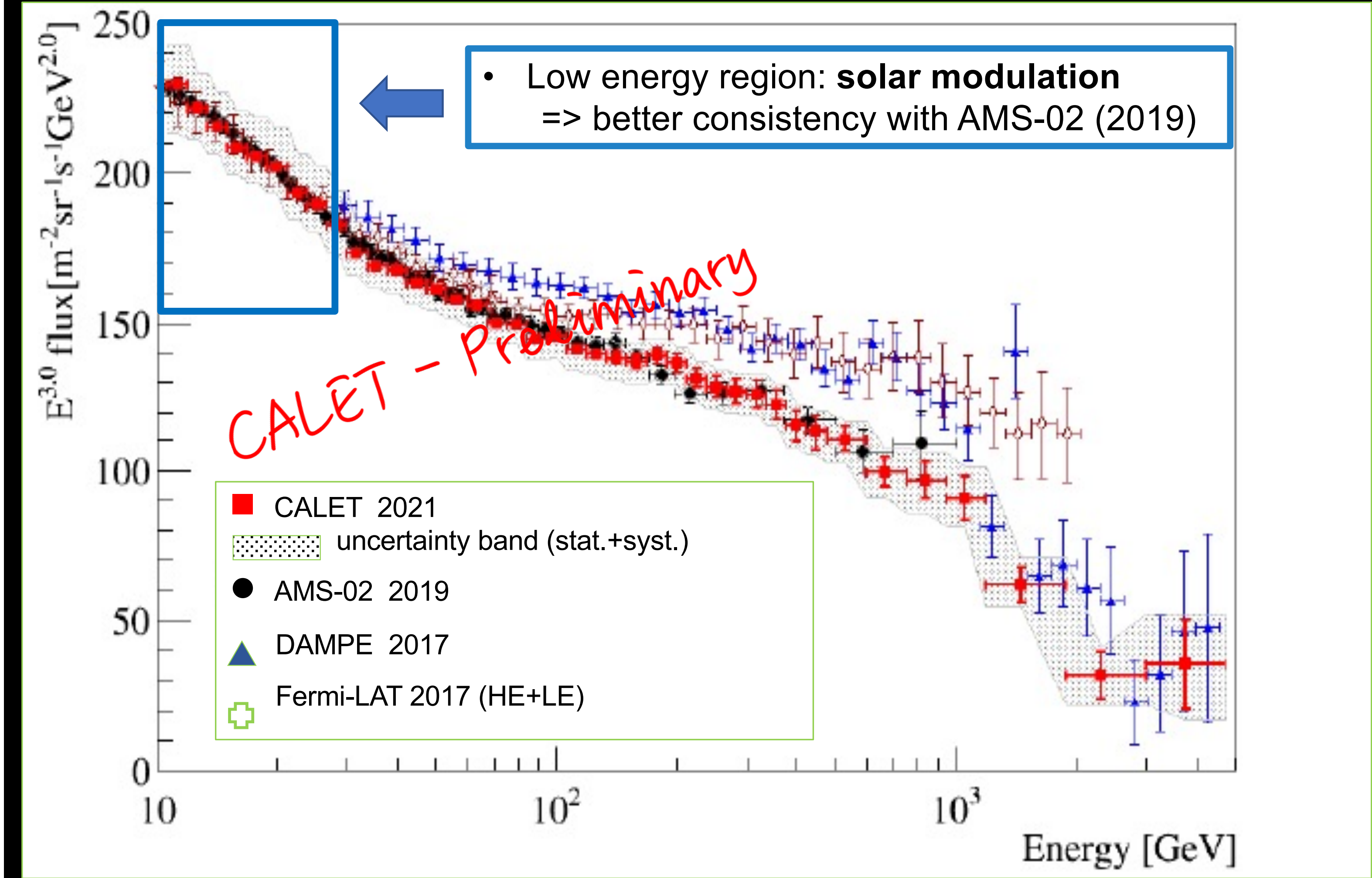


- Below 1 TeV: CALET spectrum is consistent with AMS-02
- Present measurements cluster into 2 groups:
  AMS02 + CALET and **FERMI + DAMPE**
  possibly indicating the presence of unkown systematics

- 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 (ICRC2021 update)

⇨ talk: CRD 737
poster: 628, 492



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

Cosmic-ray all-electron spectrum (ICRC2021 update)

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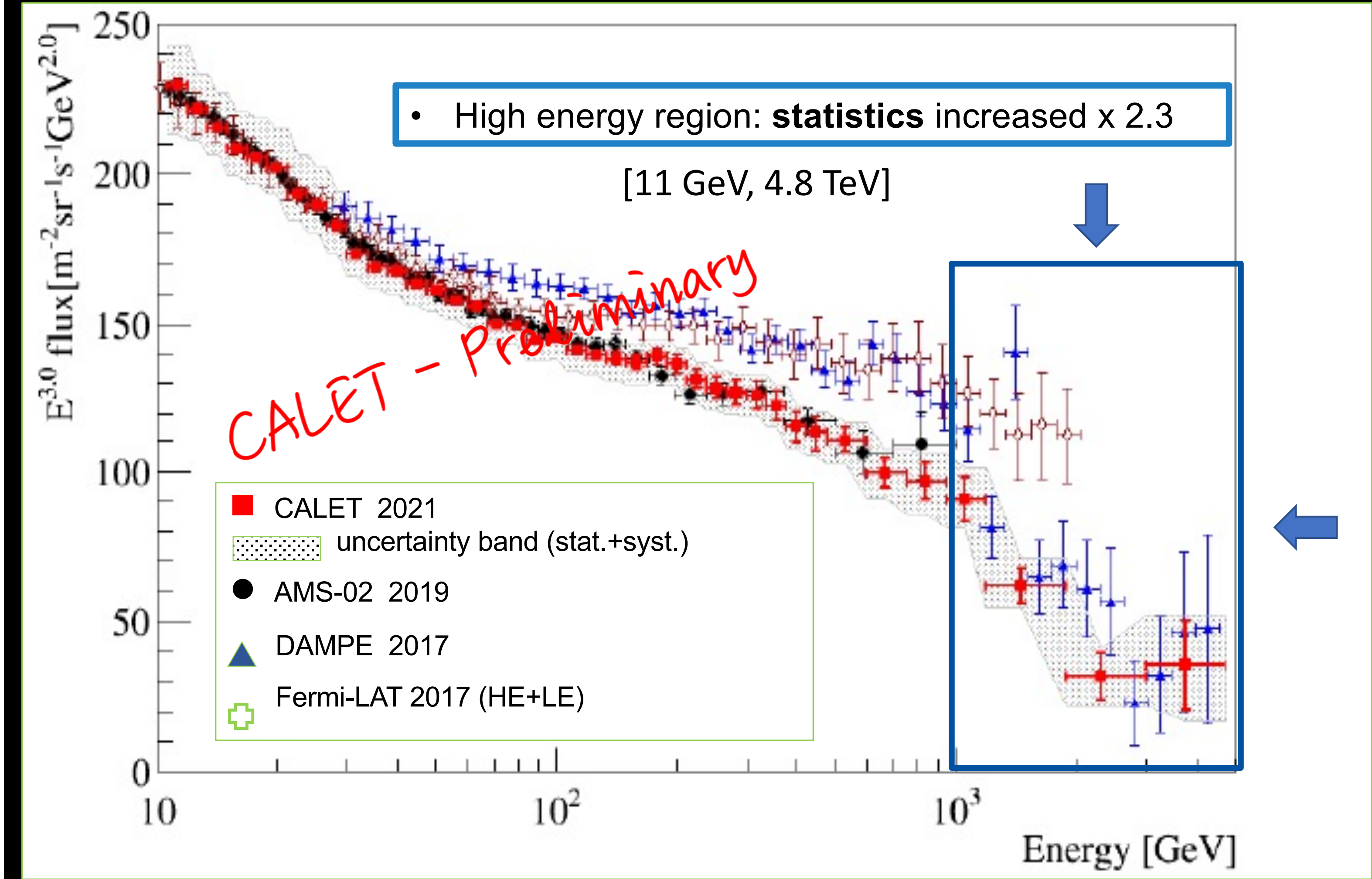
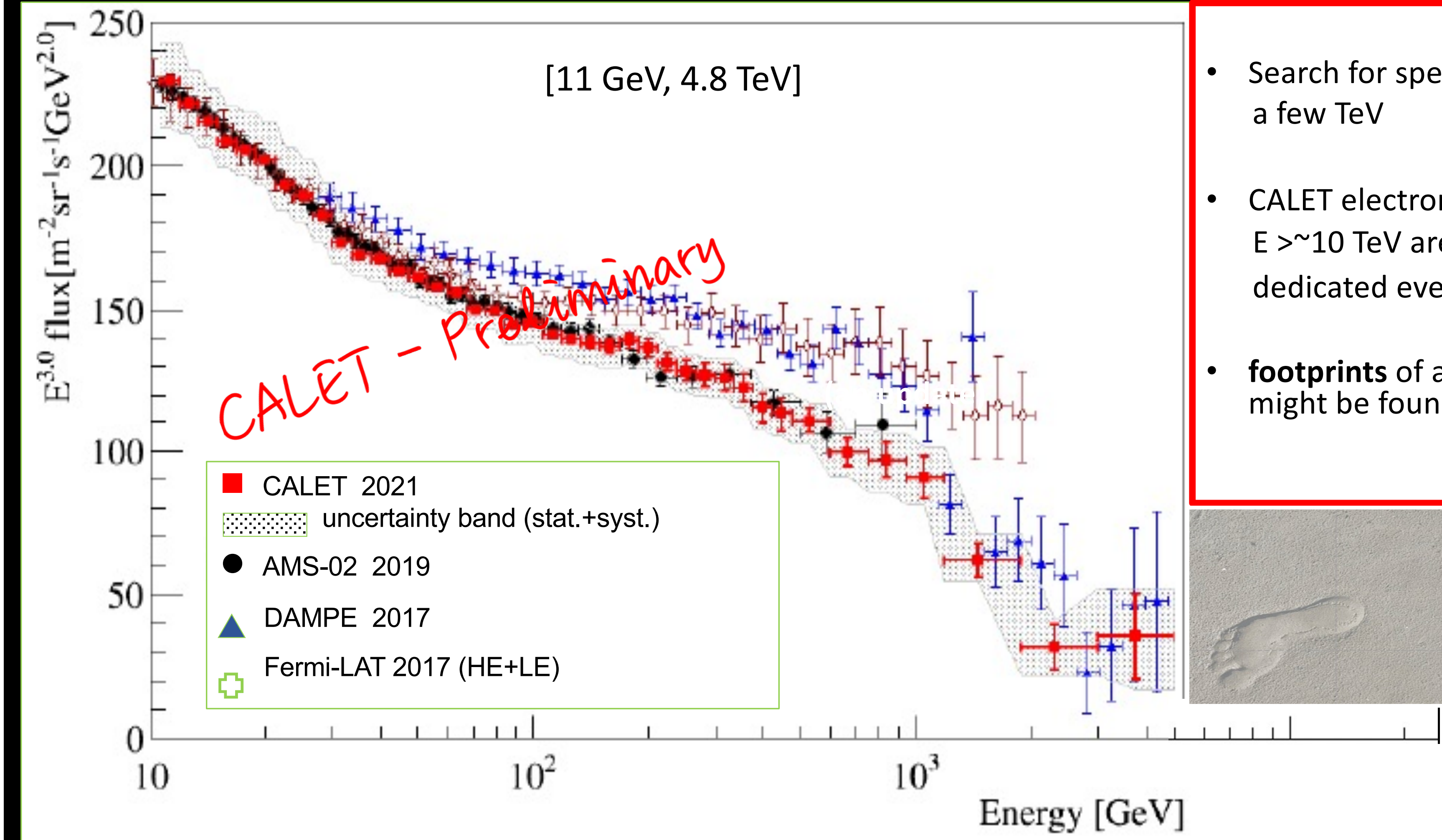


Preliminary spectrum is **updated** after 1815 days of CALET observations: Oct.13, 2015 - Sep.30, 2020

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)

Cosmic-ray all-electron spectrum (ICRC2021 update)

talk: CRD 737
poster: 628, 492

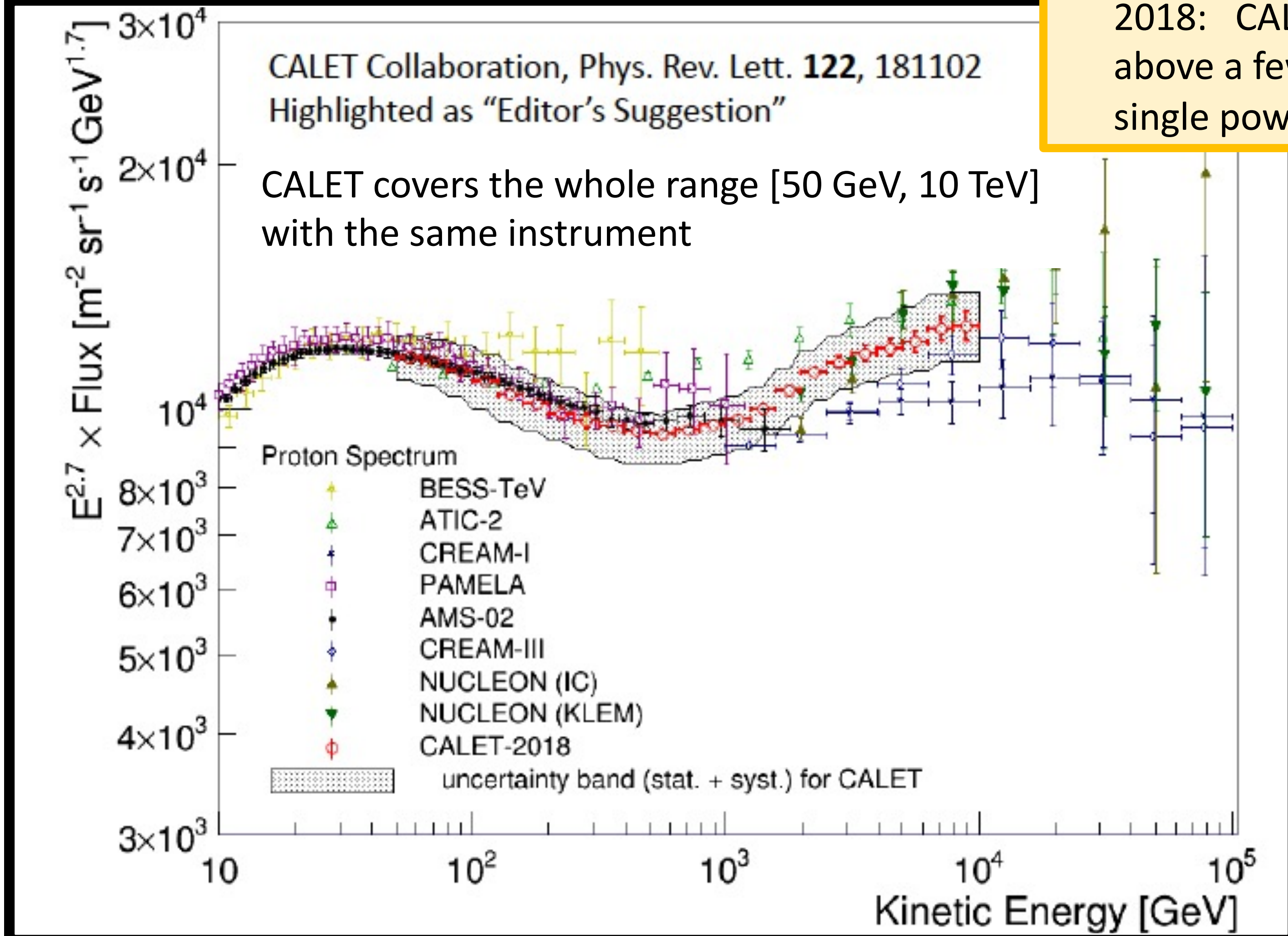


- Search for spectral features above a few TeV
- CALET electron candidate events with E >~10 TeV are being studied with a dedicated event-by-event analysis
- **footprints** of a possible **nearby source** might be found in this region

Cosmic-ray proton spectrum

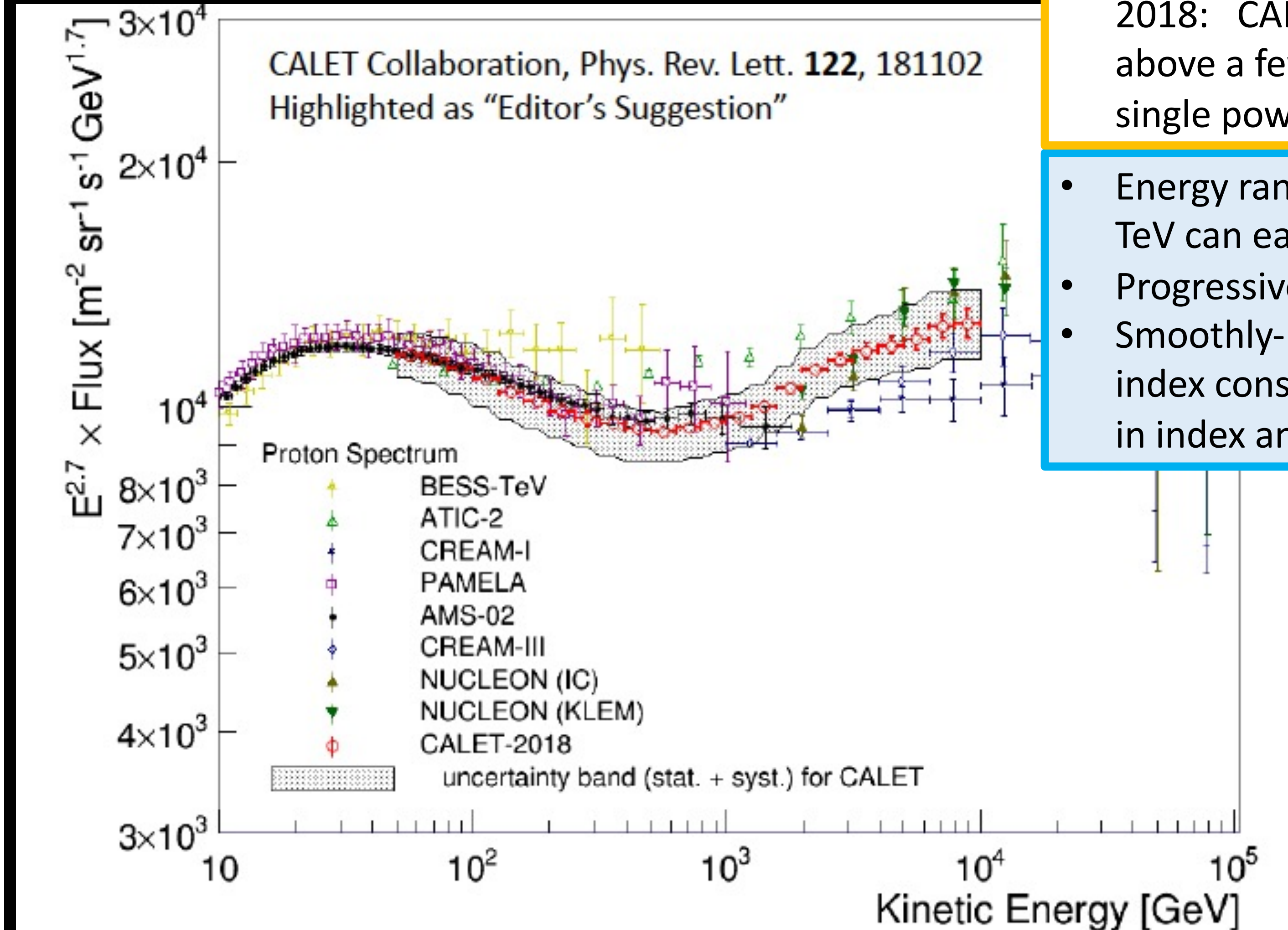
talk: CRD 390

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



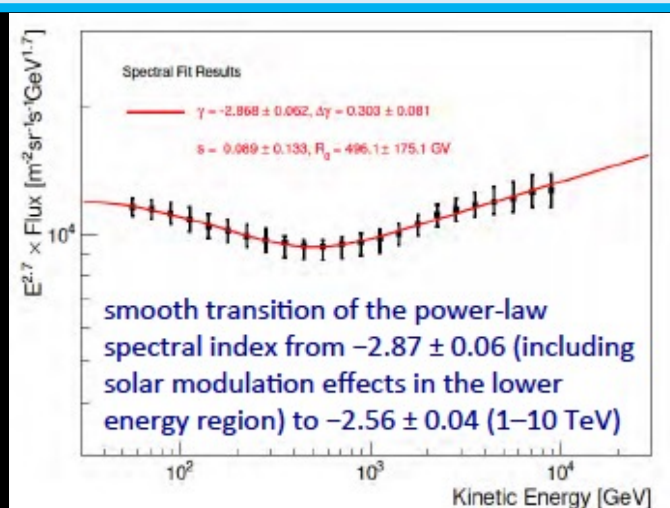
Cosmic-ray proton spectrum

⇨ talk: CRD 390



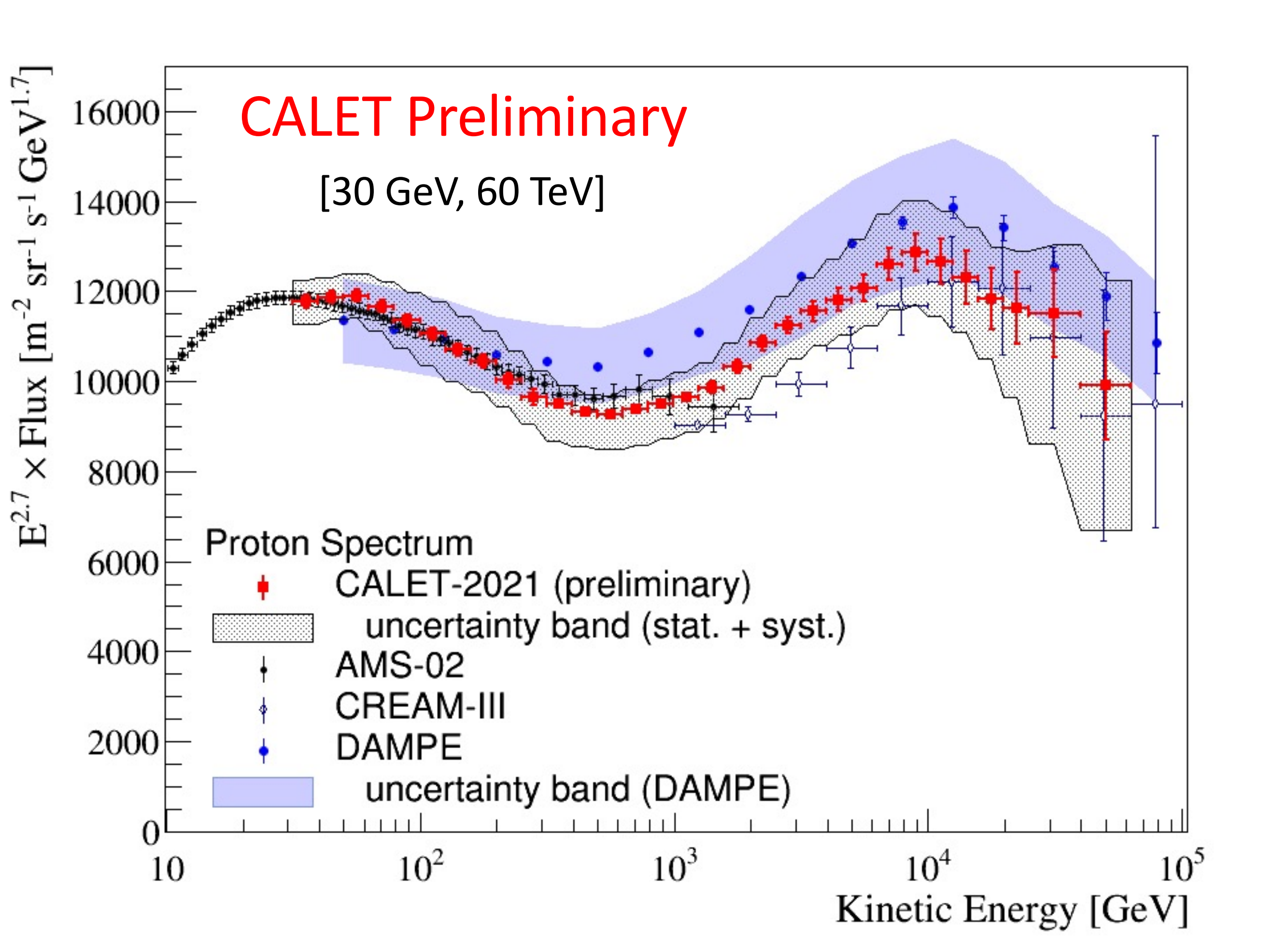
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

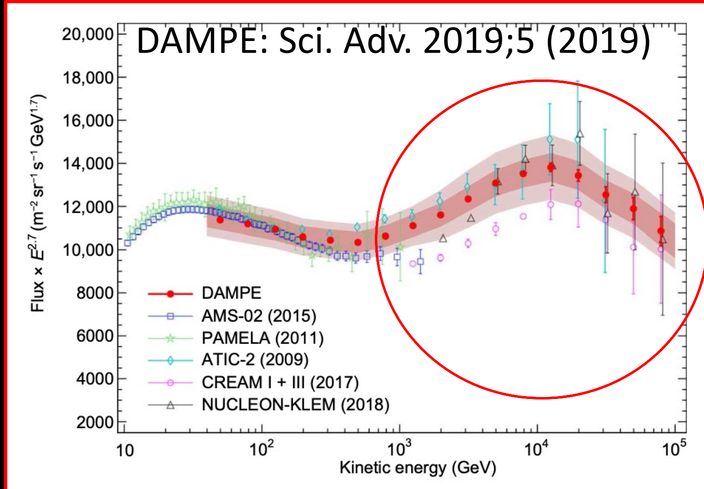
- Energy ranges 50 GeV – 500 GeV and 1 TeV – 10 TeV can each be fitted with single power laws
- Progressive hardening up to TeV energies
- Smoothly-broken power law fit gives low energy index consistent with AMS-02, but larger change in index and higher break energy



Cosmic-ray proton spectrum (ICRC2021 update)

⇨ talk: CRD 390

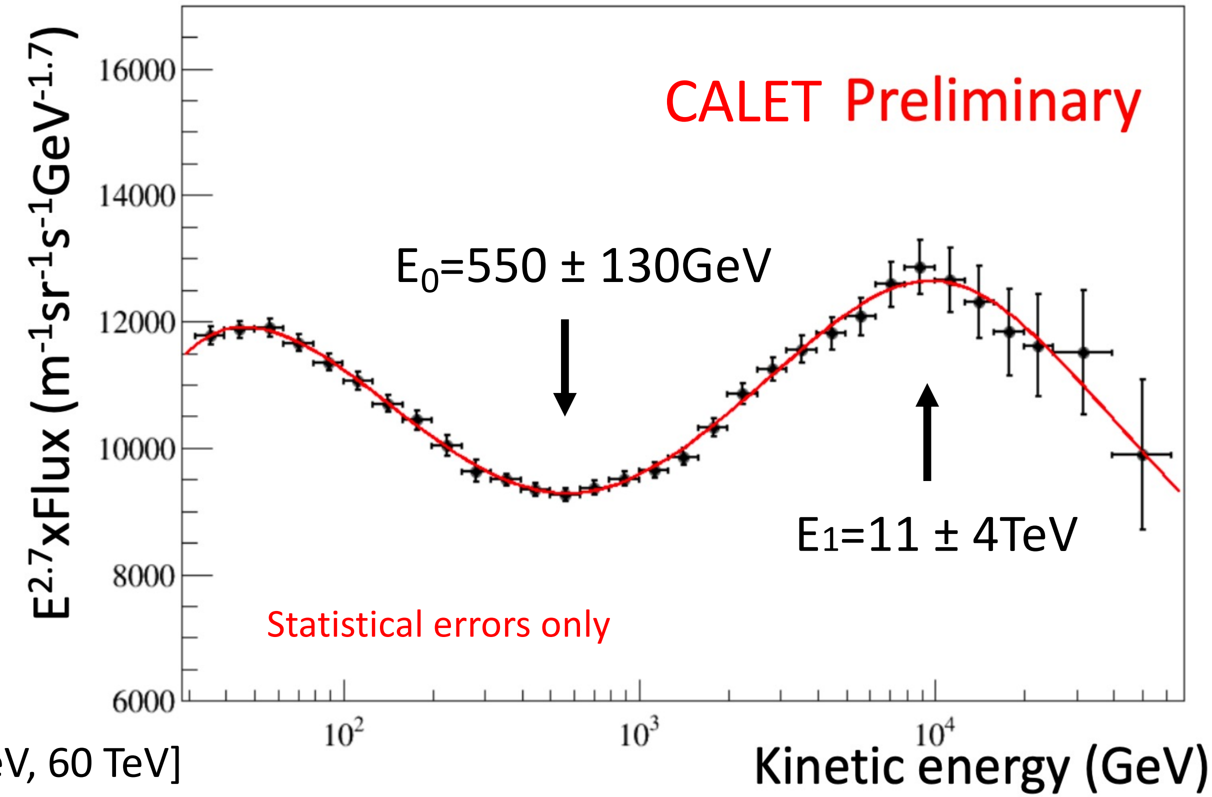




- DAMPE reported a spectral index softening $\Delta\gamma = -0.25 \pm 0.07$ from ~-2.60 to ~-2.85. above 10 TeV at E_{break} = $13.6^{+4.1}_{-4.8}$ TeV with ~30% error.
- DAMPE flux is consistent with AMS-02 and CALET up to 200 GeV. Above, the flux is higher (close to the limit of the systematic error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

Cosmic-ray proton spectrum (ICRC2021 update

talk: CRD 390



(*) free S parameter in DBPL fit

$\chi^2 = 2.9/22$

C	$(5.1\pm2.1)\times10^{-1}$
p_0	9.1 ± 26
P_1	-6.6 ± 470
γ	-2.9 ± 0.3
S (*)	2.1 ± 2.0
Δγ	$(4.4\pm3.8)\times10^{-1}$
E_0	$(5.5\pm1.3)\times10^{2}$
$\Delta\gamma_1$	$(-4.4\pm3.0)\times10^{-1}$
E_1	$(1.1\pm0.4)\times10^{4}$

[30 GeV, 60 TeV]

Fitting a Double-Broken Power Law (DBPL):

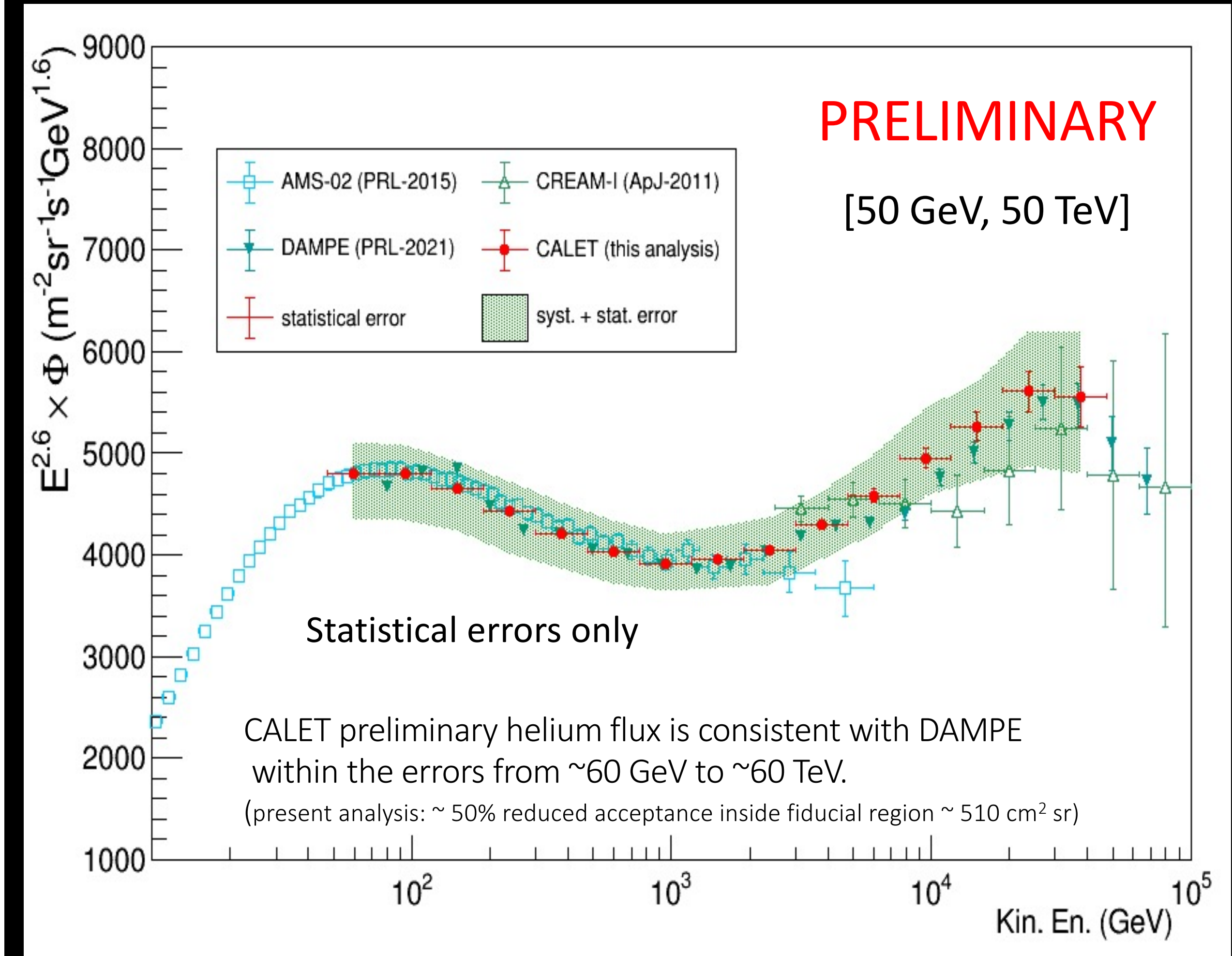
$$\Phi = E^{2.7} \times C \left(1 - \frac{p_1}{E} - \frac{p_2}{E^2}\right)\left(\frac{E}{45\ \mathrm{GeV}}\right)^{\gamma}\left[1 + \left(\frac{E}{E_0}\right)^{\frac{\Delta\gamma}{s}}\right]^{s}\left[1 + \left(\frac{E}{E_1}\right)^{\frac{\Delta\gamma_1}{s}}\right]^{s}$$

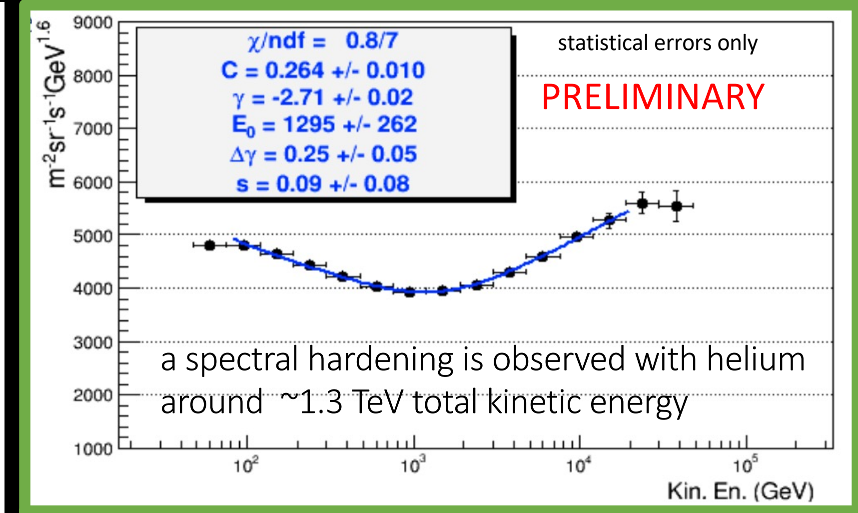
spectral hardening

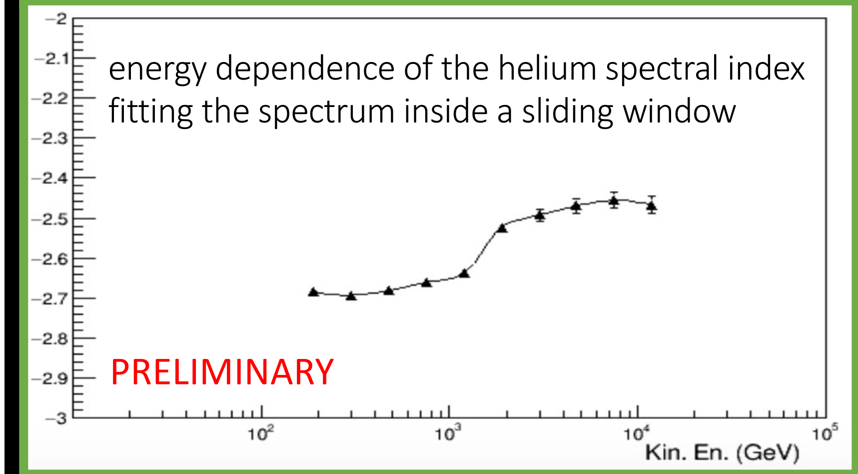
spectral softening

Cosmic-ray helium spectrum (preliminary)

talk: CRD 512

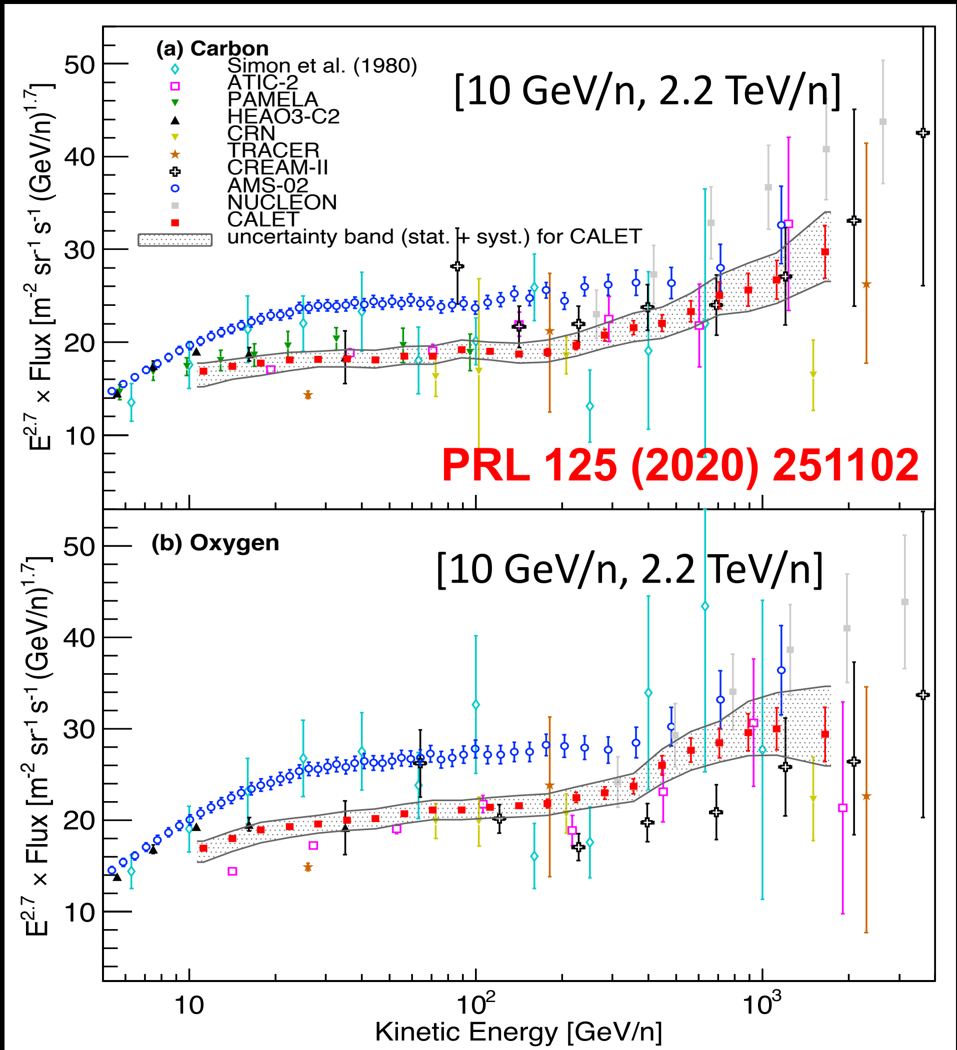






Carbon and oxygen energy spectra

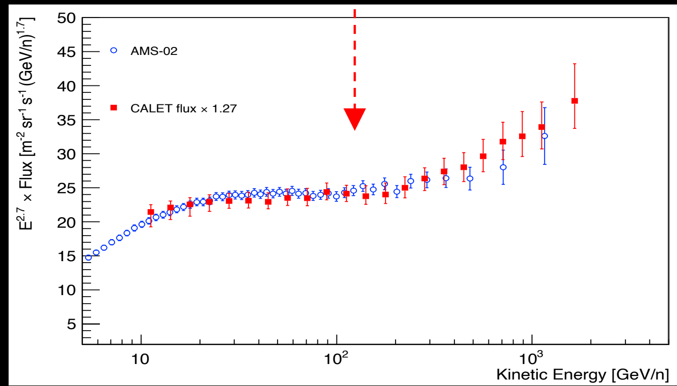
⇨ talk CRD 260

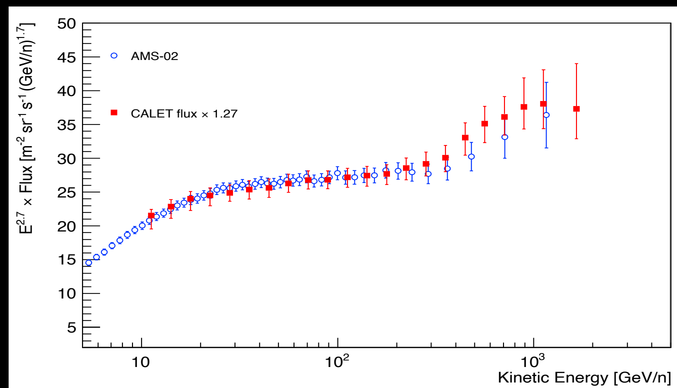


CALET C is consistent with PAMELA and most of the previous experiments. PAMELA did not publish oxygen.

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

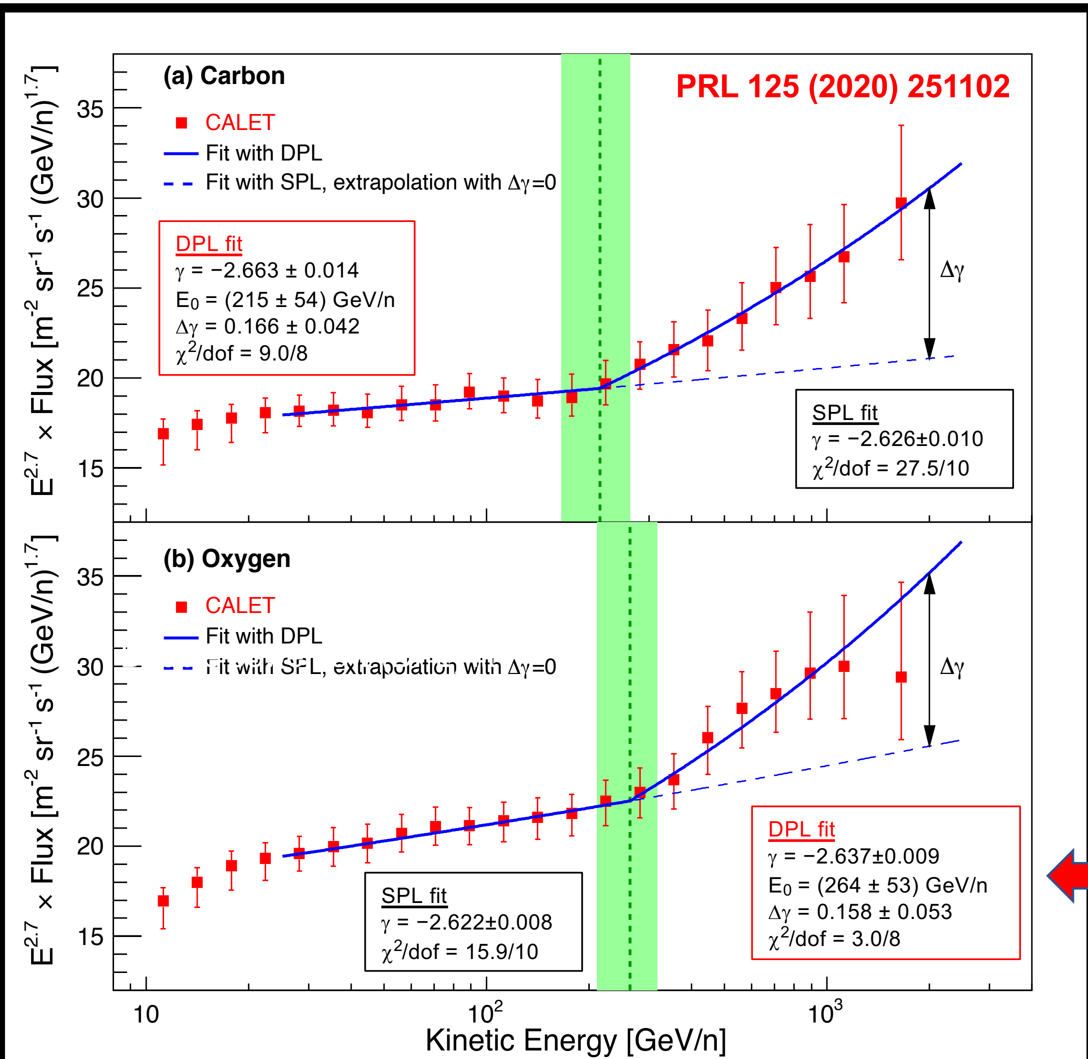
They have shapes similar to AMS-02 but the absolute normalization is significantly lower (~ 27%)

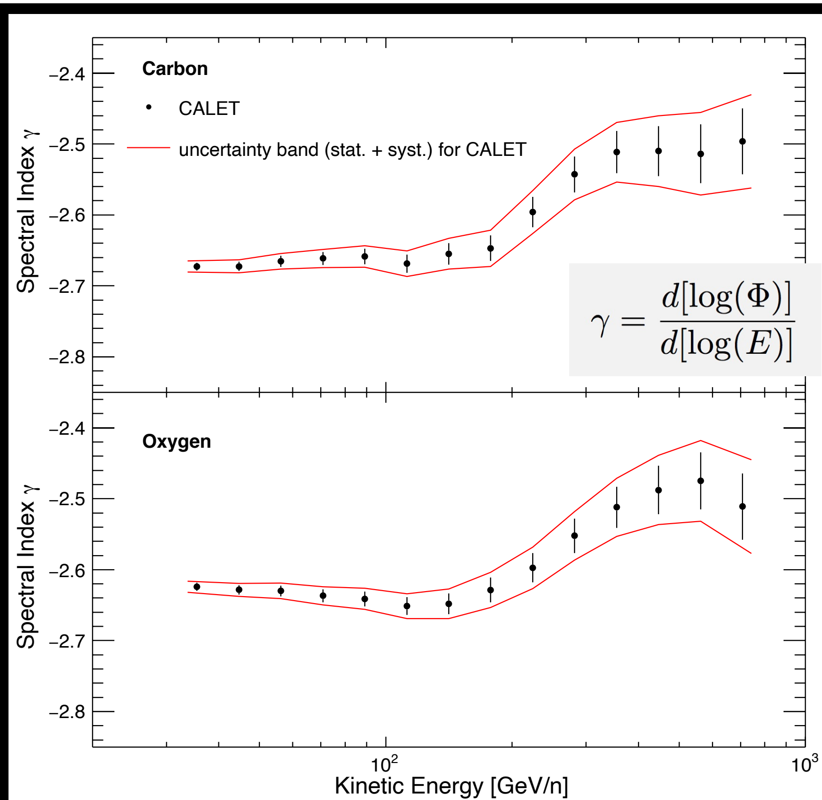




Carbon and oxygen: spectral analysis

⇨ talk: CRD 260





$$\gamma = \frac{d[\log(\Phi)]}{d[\log(E)]}$$

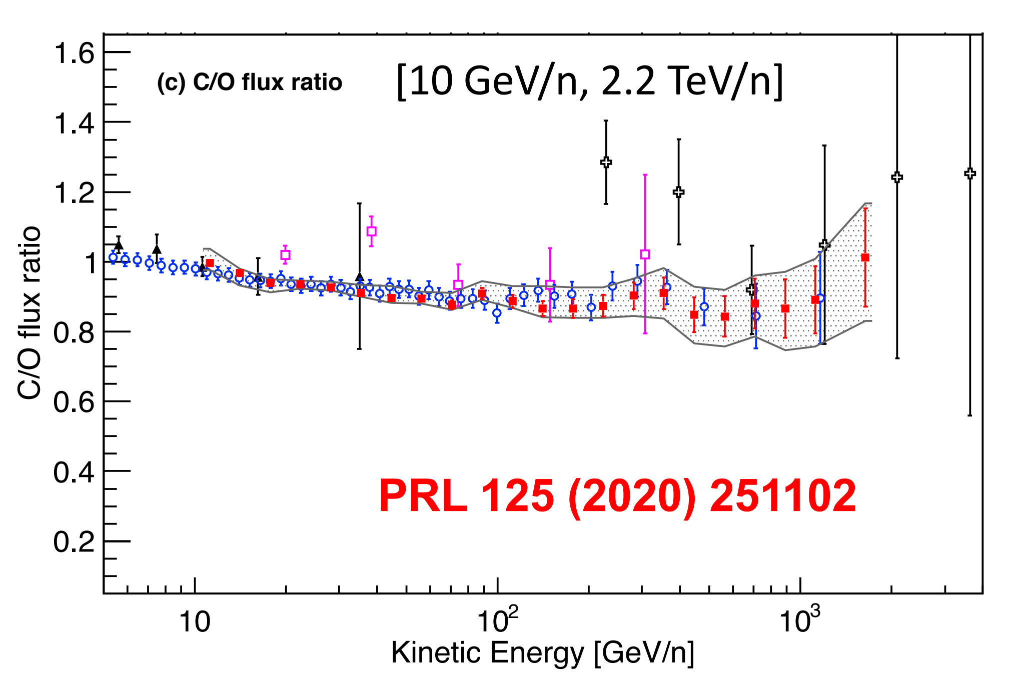
Double power-law (DPL) fit

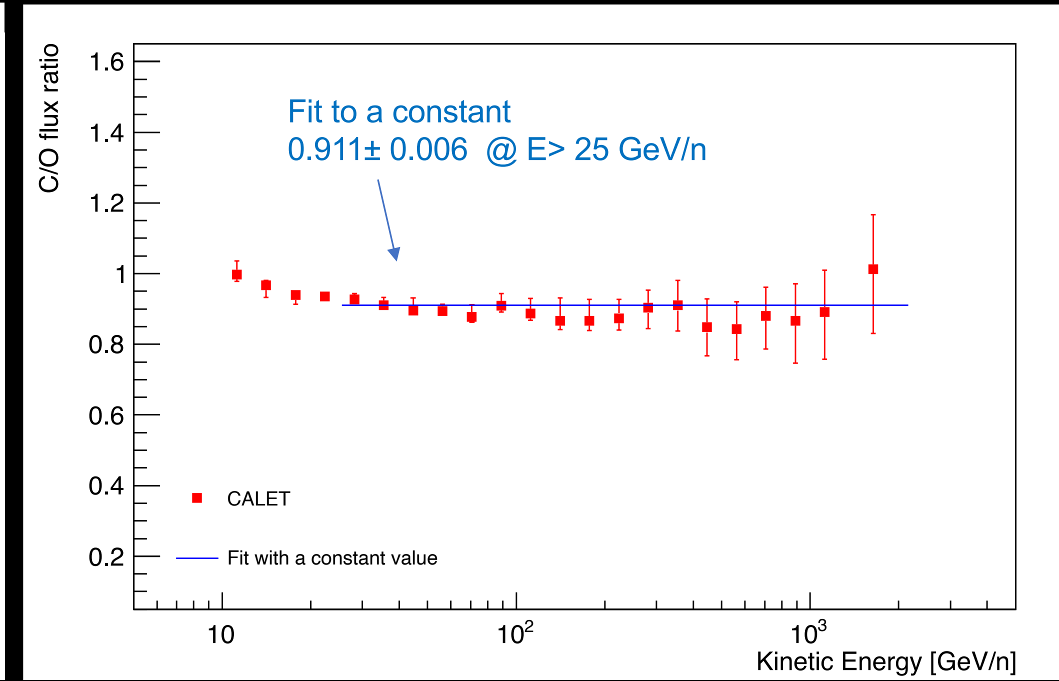
$$\Phi(E) = \begin{cases} C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma} & E \le E_0 \\ C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left(\frac{E}{E_0}\right)^{\Delta\gamma} & E > E_0 \end{cases}$$

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

C/O flux ratio

→ talk: CRD 260





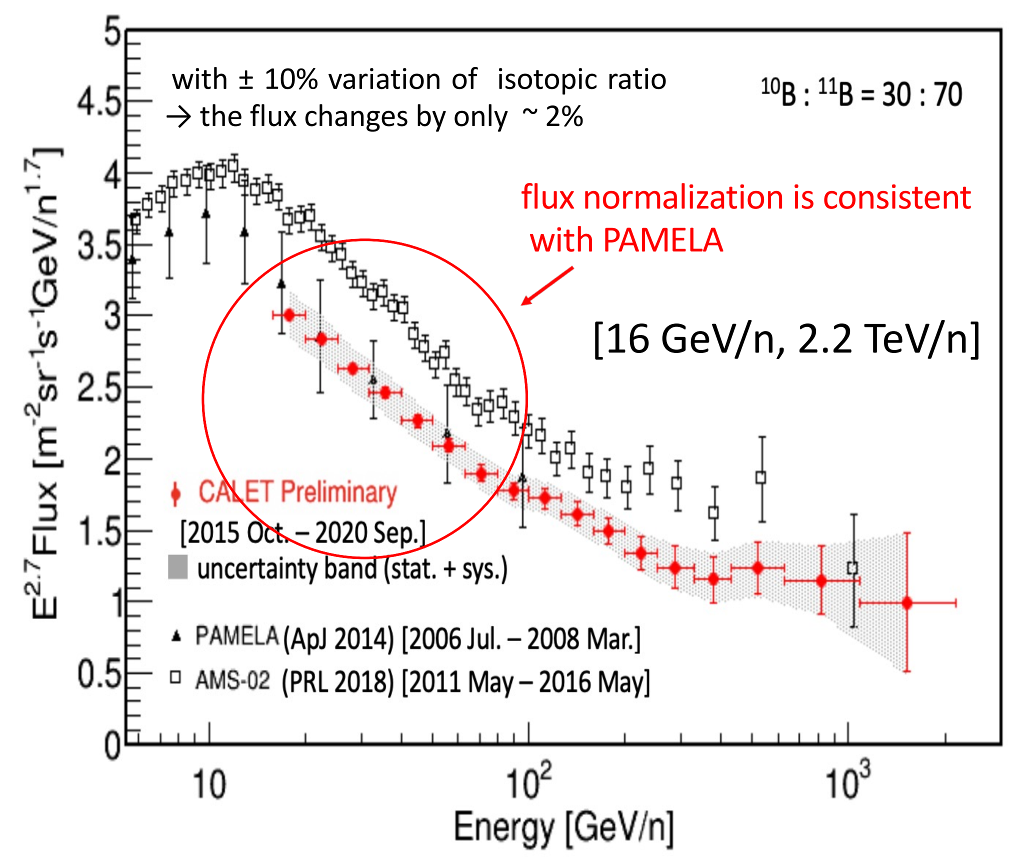
The C/O flux ratio as a function of energy is in good agreement with the one reported by AMS

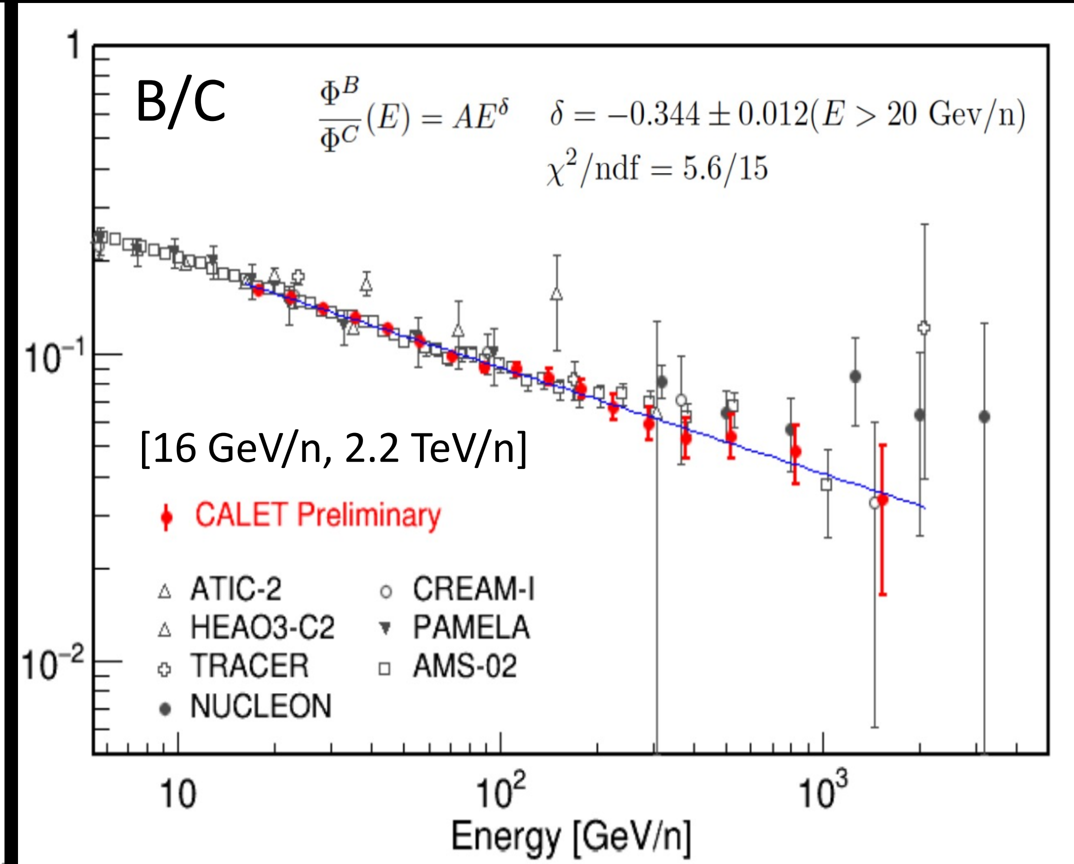
Above 25 GeV/n the C/O ratio is well fitted to a constant value of 0.911 ± 0.006 with χ^2/dof = 8.3/17

→ C and O fluxes have the same energy dependence.

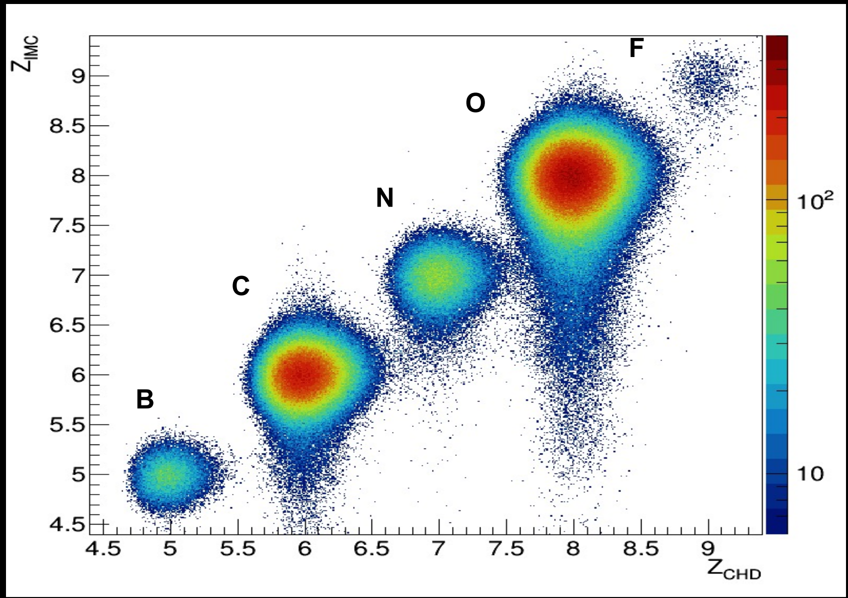
Boron spectrum and B/C ratio

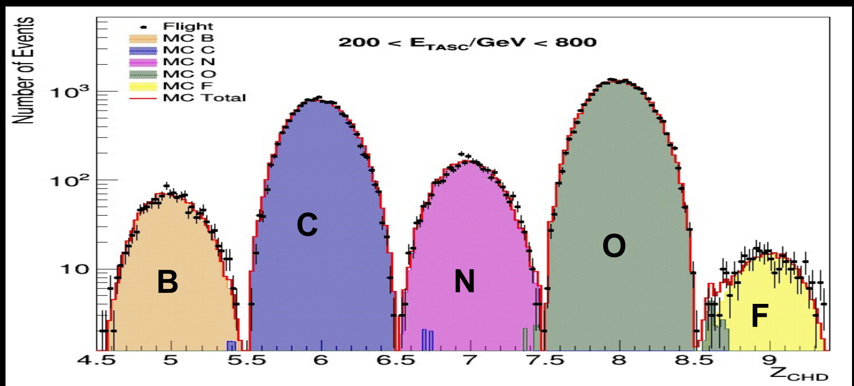
talk: CRD 842





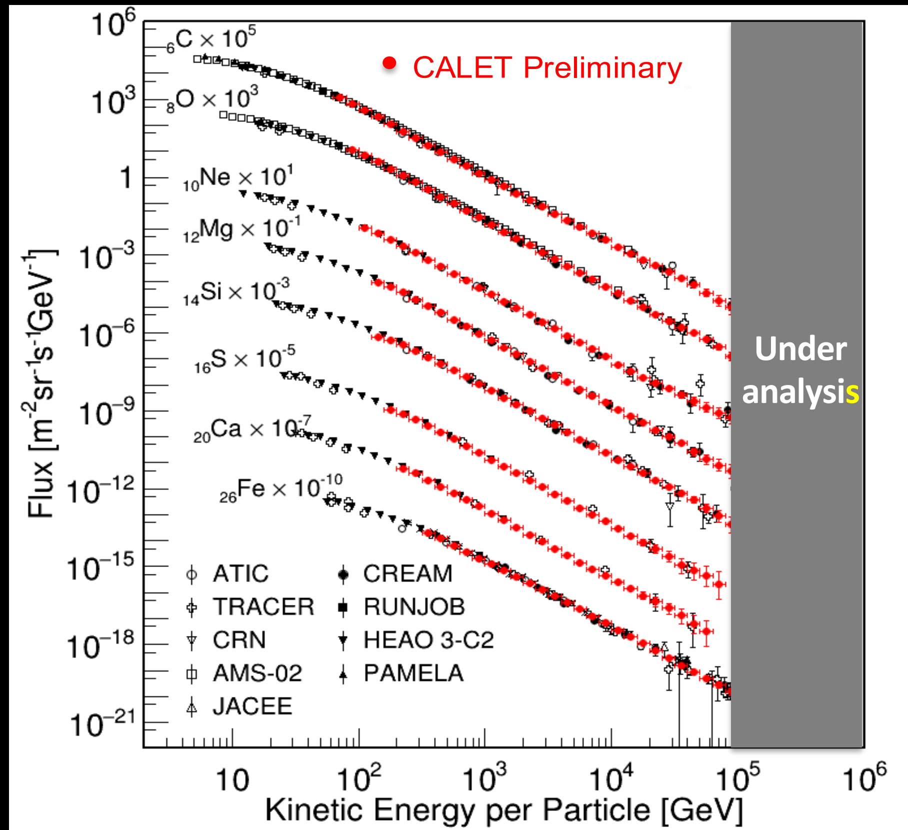
Spectra of cosmic-ray nuclei from C to Fe





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

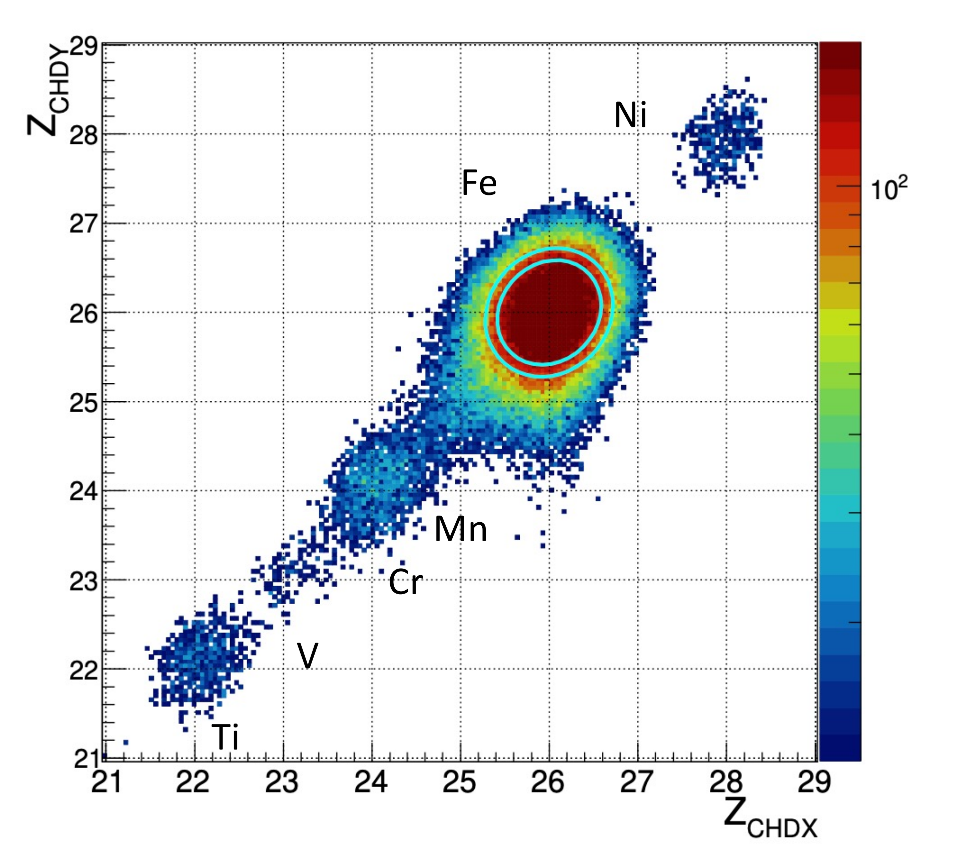
Preliminary Spectra of Carbon – Iron

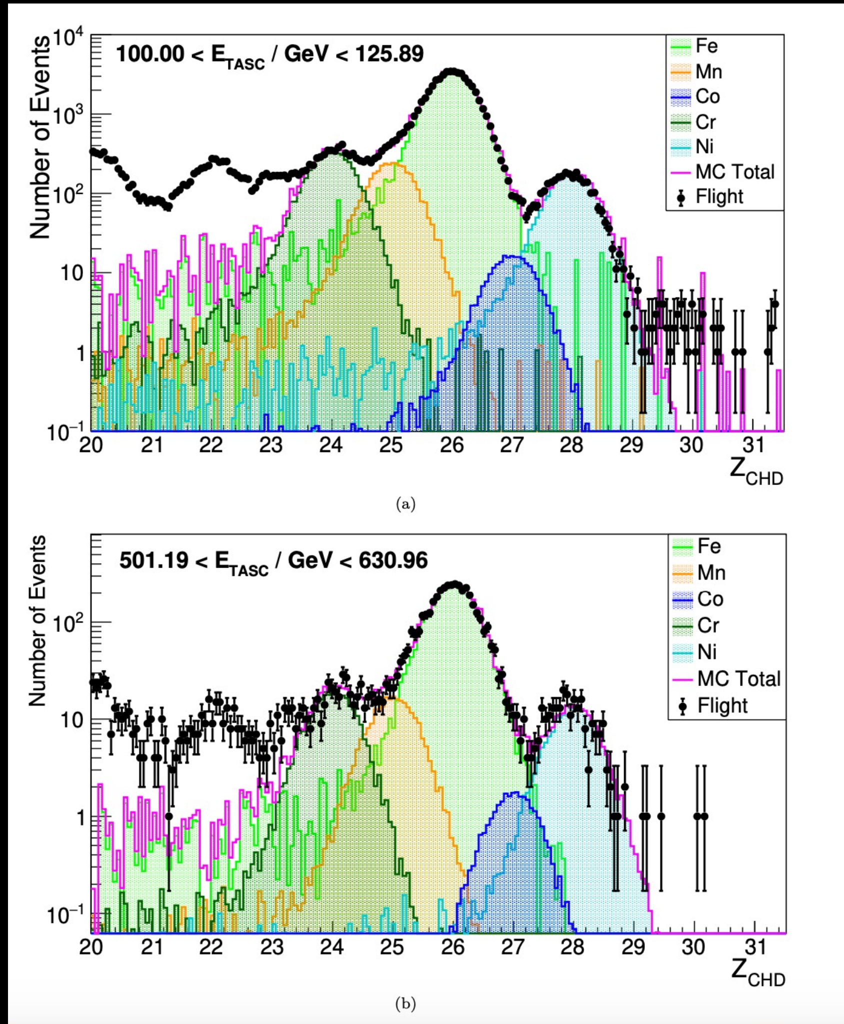


Iron – analysis (charge selection)

talk: CRD 797

Charge measurement with the two CHD layers

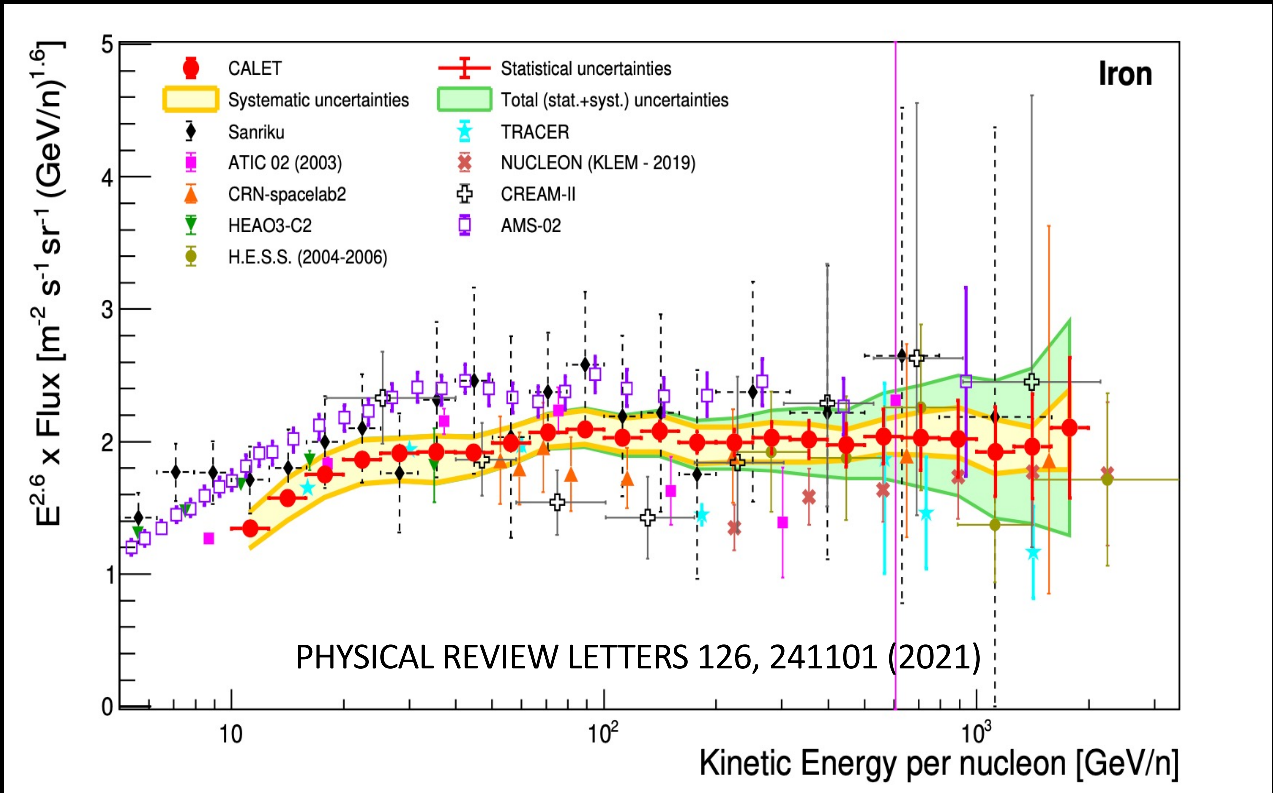




Iron spectrum

talk: CRD 797

Flux x $E^{2.6}$ vs kinetic energy per nucleon [10 GeV/n, 2 TeV/n] analyzed data: Jan 1, 2016 – May 2020

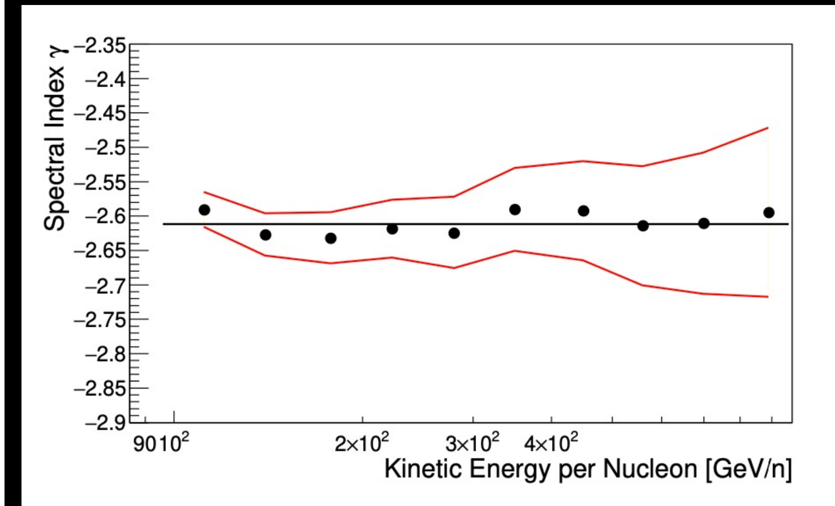


Iron Single Power Law fit:

50 GeV/n, 2.0 TeV/n

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

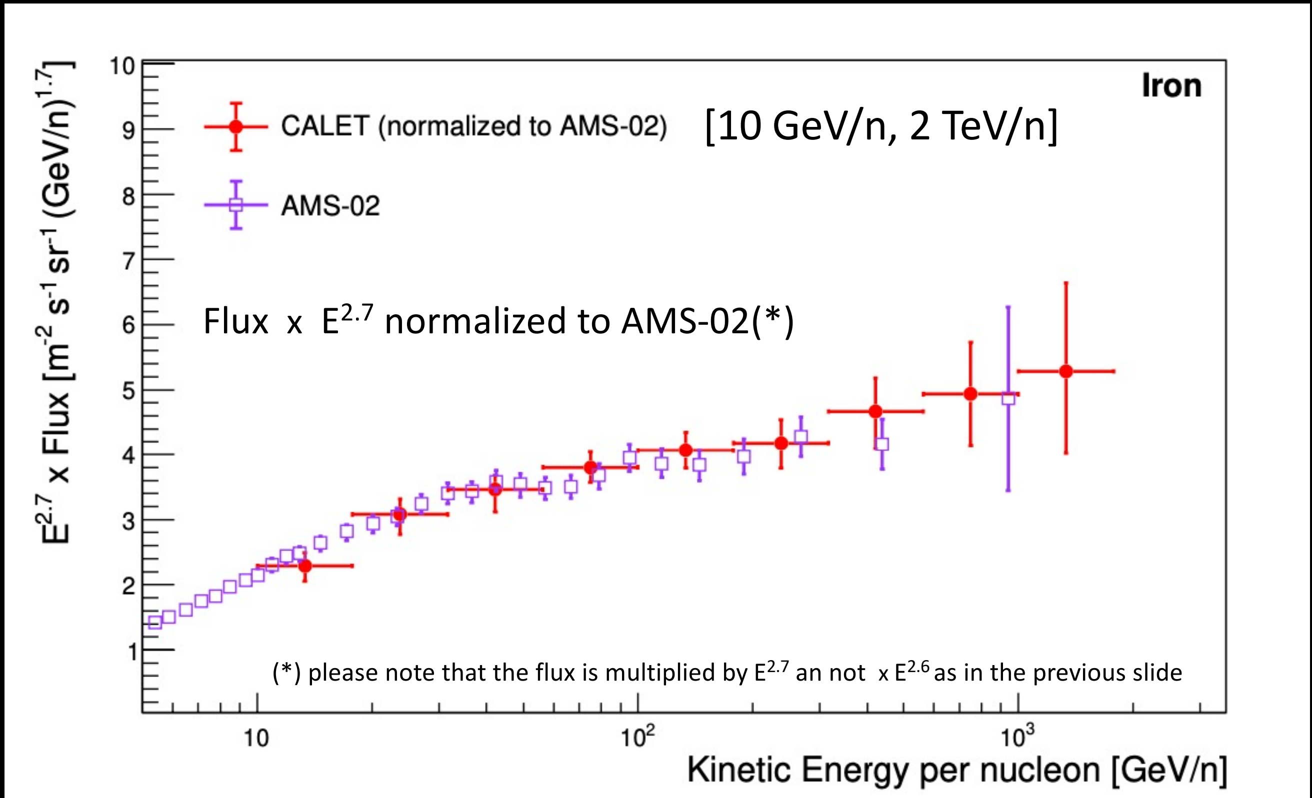
with χ^2/d.o.f. = 4.2/14



Iron spectral shape and normalization

talk: CRD 797

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:

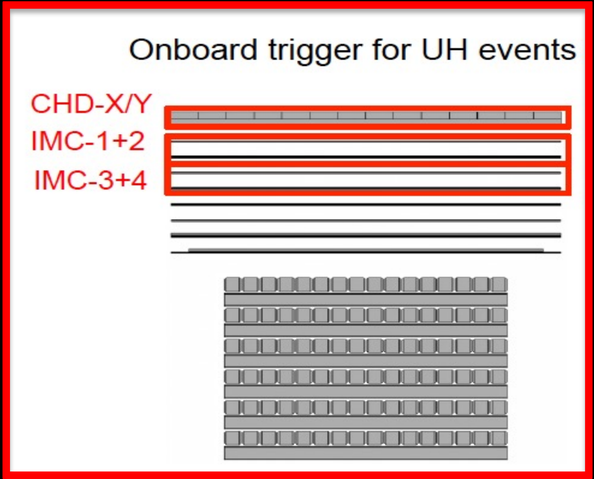
- CALET $E^{2.7}$ x Flux vs kinetic energy/n normalized to AMS-02:
  - similar spectral shape
  - comparable errors above 200 GeV/n

Spectral hardening:

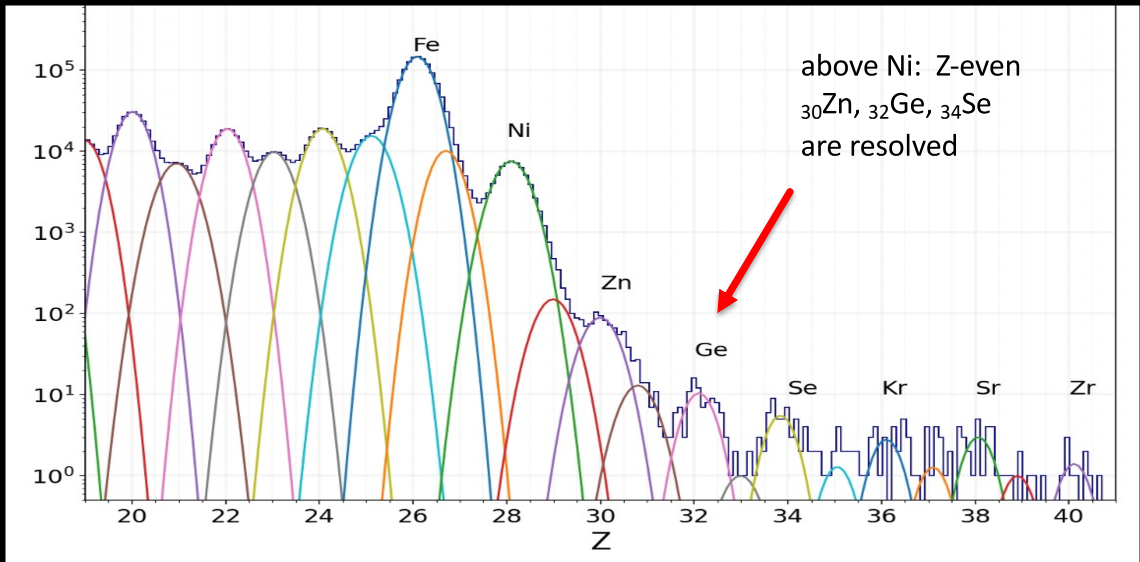
- CALET iron data are consistent with an SPL spectrum up to 2 TeV/n. Beyond this limit, the present statistics and large systematics do not allow to draw a significant conclusion on a possible deviation from a single power law

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

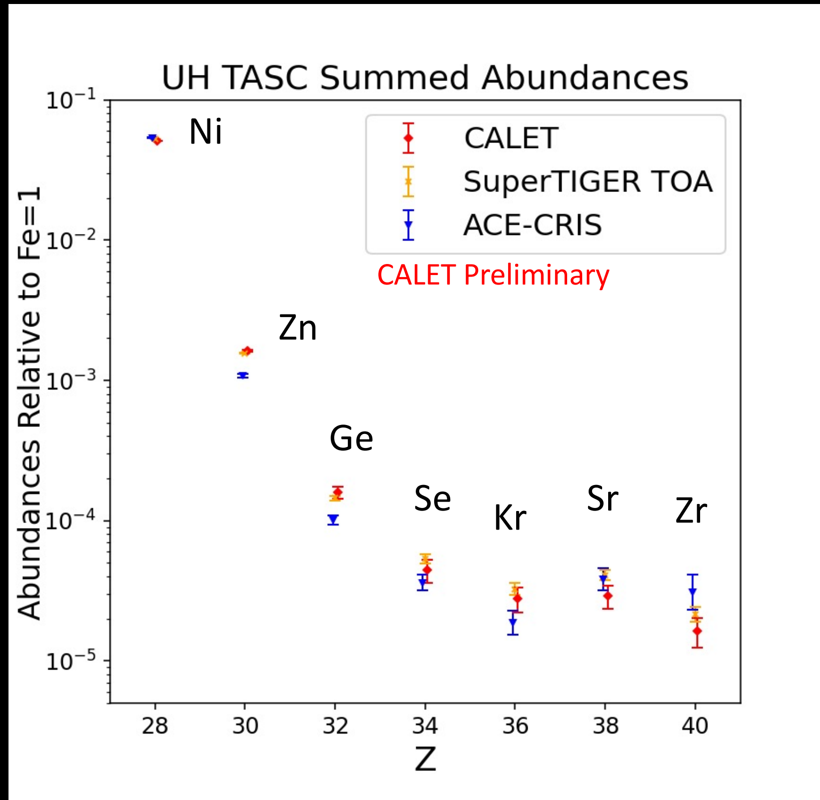
posters: CRD 1044, 657



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



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



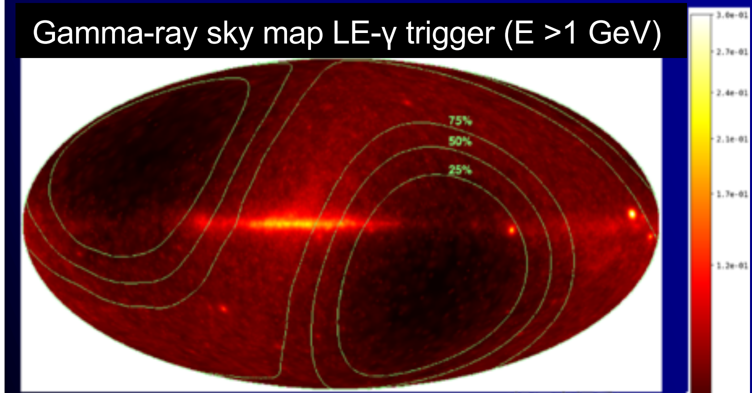
The CALET UH element ratios relative to Fe are consistent with Super-TIGER and ACE abundances.

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

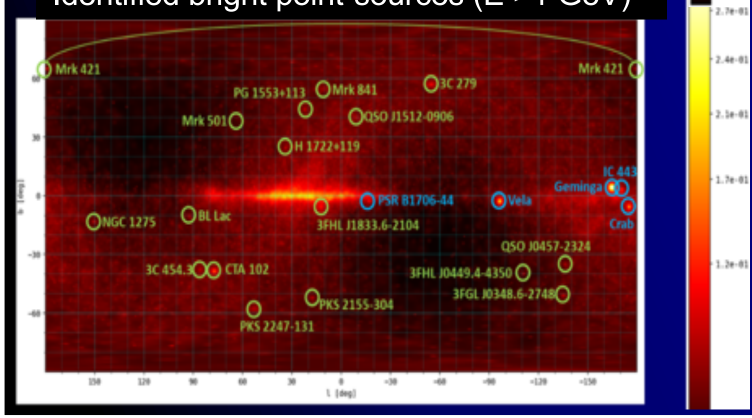
- Effective area ~400 cm^2 above 2 GeV
- Angular resolution < 0.2° above 10 GeV
- Energy resolution ~5% at 10 GeV

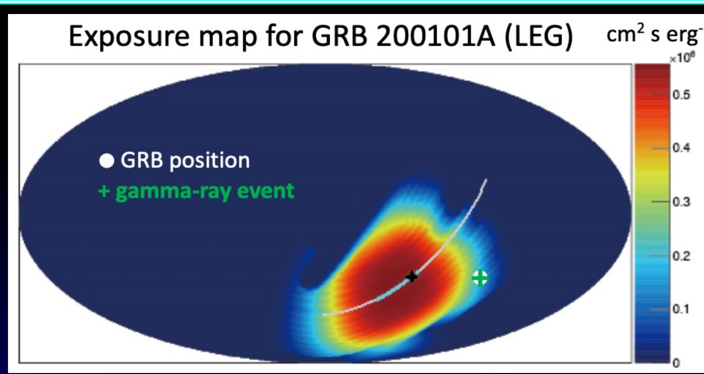
poster: GAD 322

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



Identified bright point-sources (E >1 GeV)





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

MM 817

from 2015-10-05 to 2021-04-08

246 GRBs (44.6 GRBs / year)

216 Long (88%) **30 Short (12%)**

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

poster: MM 817

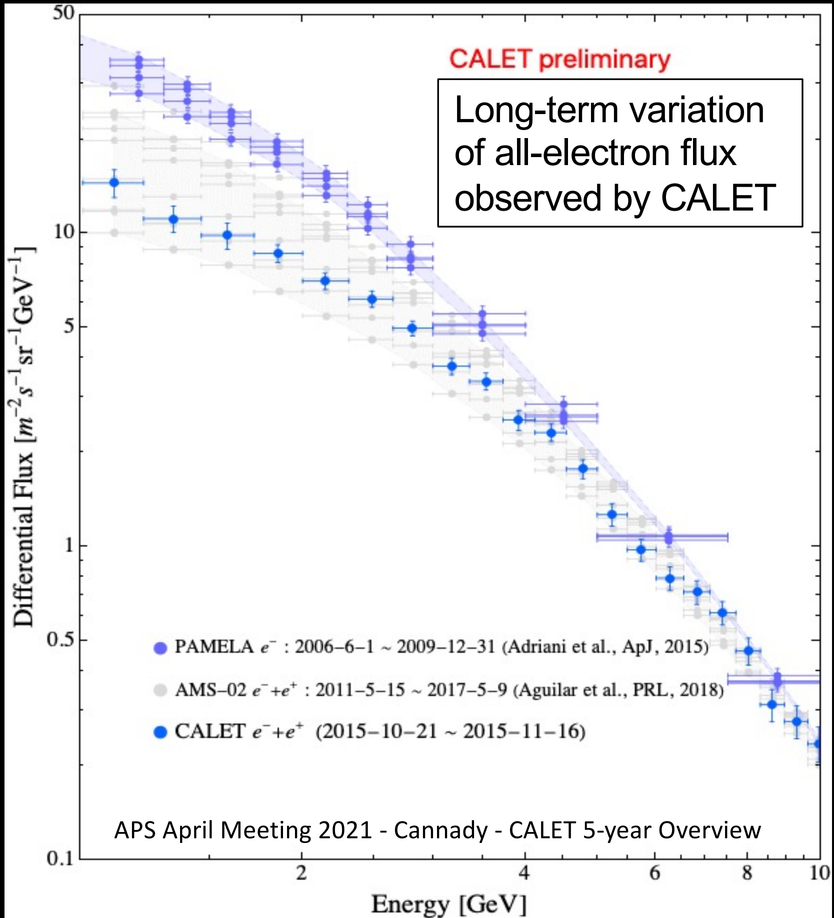
- **Limits on DM** annihilation into γγ
  $<\sigma v> < 10^{-28}$-$10^{-25} cm^{-3} s^{-1}$
- Limits on DM decay $\chi \to \gamma\nu$ etc.
  $\tau_{DM} > 10^{30}$s (m_{DM}>100 GeV)

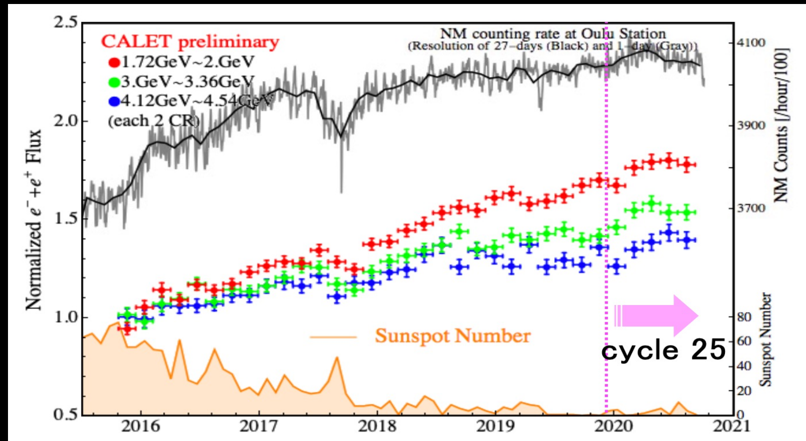
oral: GAD 517

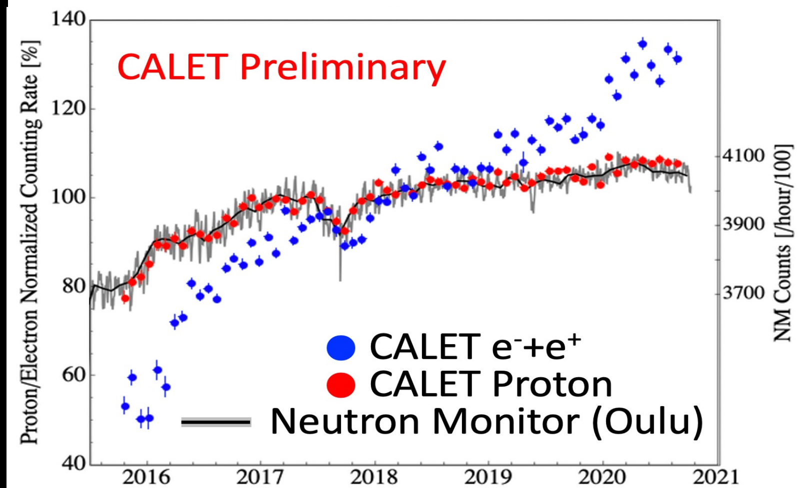
Solar modulation

talk: SH 332

- 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.





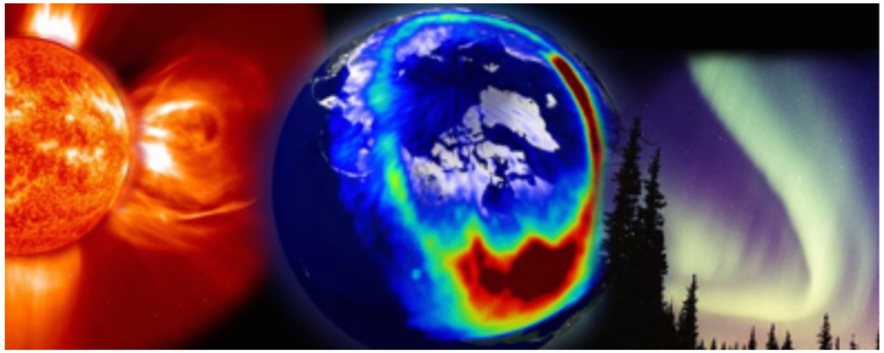


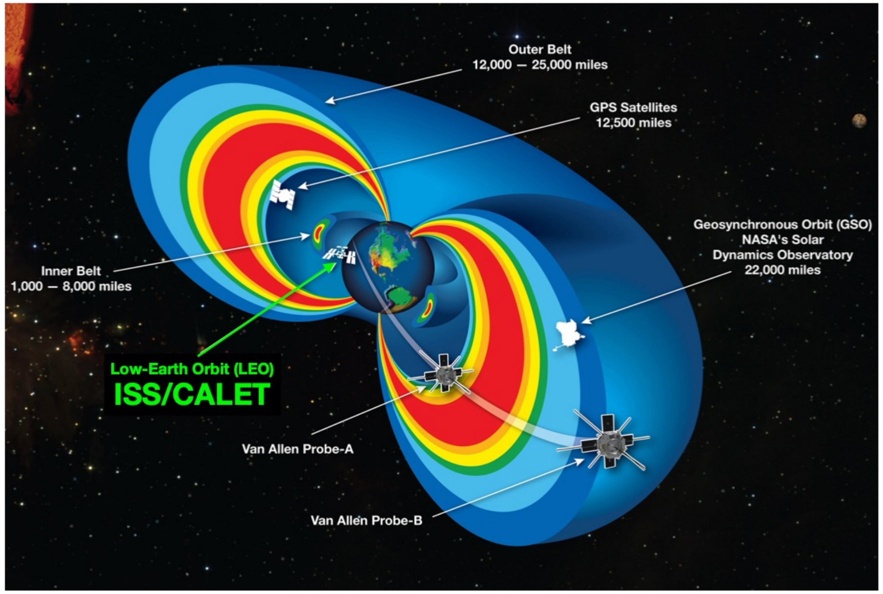
Good correlation of NM counting rate at Oulu station (black points) with the CR e^- + e^+ flux increase in the 1-10 GeV until ~half a year after the beginning the new solar cycle 25. The flux has now started decreasing.

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.

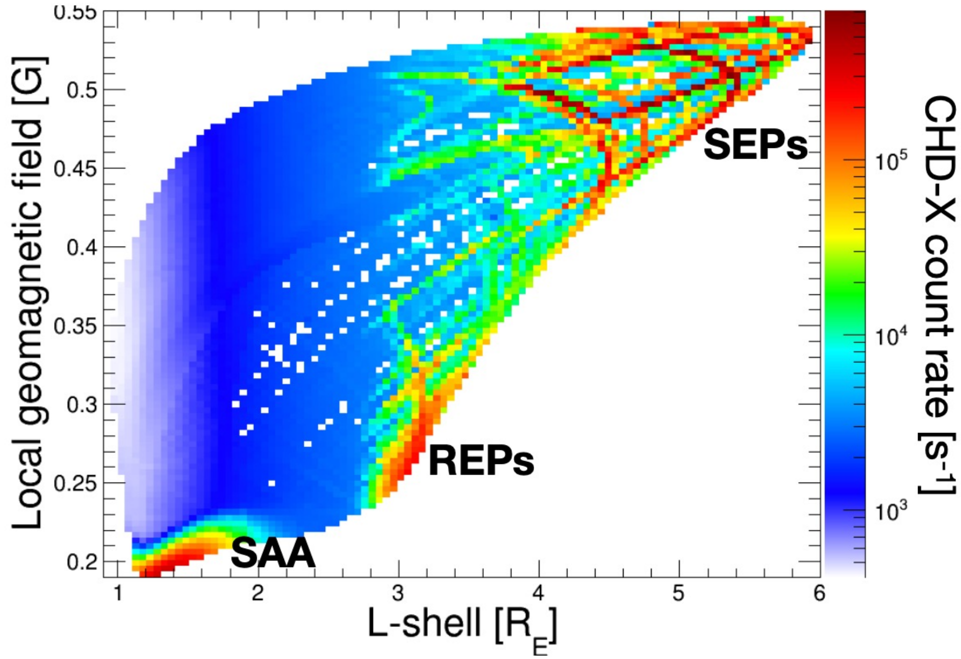
Space Weather Phenomena with CALET

⇨ poster: SH 959





- 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



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	Reference	ICRC2021	#
Cosmic-ray origin and acceleration	**Electron spectrum**	1 GeV – 20 TeV	to 4.8 TeV	PRL 120, 261102 (2018)	**11 GeV – 4.8 TeV**	**737, 628**
	Proton spectrum	10 GeV – 1 PeV	to 10 TeV	PRL 122, 181102 (2019)	**30 GeV – 60 TeV**	**390**
	Helium spectrum	10 GeV – 1 PeV	preliminary	preliminary	**50 GeV – 50 TeV**	**512**
	Carbon and oxygen spectra	10 GeV – 1 PeV	to 2.2 TeV/n	PRL 125, 251102 (2020)	**10 GeV/n – 2.2 TeV/n**	**260**
	Iron spectrum	10 GeV – 1 PeV	to 2 TeV/n	PRL 125,241101 (2021)	**50 GeV/n – 2 TeV/n**	**797**
	Elemental spectra of primaries	10 GeV – 1 PeV	to 100 TeV	ICRC 2019, 034	10 GeV – 100 TeV	**786**
	Ultra-heavy abundances	> 600 MeV/n	> 600 MeV/n	ICRC 2019, 130	> 600 MeV/n	**1044, 657**
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**	**842**
Nearby electron sources	**Electron spectral shape**	100 GeV – 20 TeV	to 4.8 TeV	ICRC 2019, 142	to 4.8 TeV	**737, 492**
Dark matter	**Signatures in e/γ spectra**	100 GeV – 20 TeV	to 4.8 TeV	ICRC2019 , 533	to 4.8 TeV	**517**
Gamma rays	**Diffuse & point sources**	1 GeV – 10 TeV	1 GeV – 1 TeV	ApJS 238:5 (2018)	1 GeV – 1 TeV	**322, 517**
Heliospheric physics	**Solar modulation**	1 GeV – 10 GeV	1 – 10 GeV	ICRC 2019, 1126	**1 – 10 GeV**	**332**
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)	**817**
Space weather	**Relativistic electron precipitation**	> 1.5 MeV	> 1.5 MeV	Geophys.Res.Lett,43 (2016)	> 1.5 MeV	**959**

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

Thank you for your attention

Thank you to ICRC2021 organizers