



CALET instrument in a nutshell

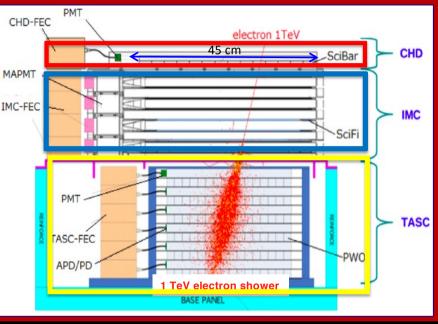
Field of view: \sim 45 degrees (from the zenith) Geometrical Factor: \sim 1,040 cm²sr (for electrons) Thickness: 30 X₀, 1.3 $\lambda_{\rm I}$



CHD/IMC



TASC



CHD - Charge Detector

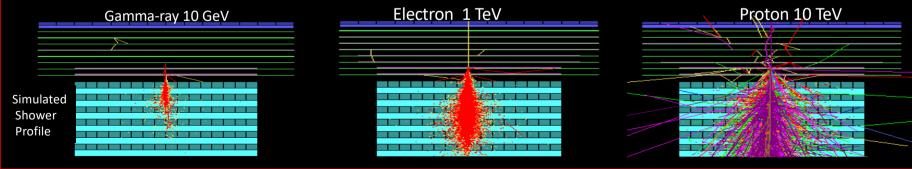
- 2 layers x 14 plastic scintillating paddles
- single element charge ID from p to Fe and above (Z = 40)
- charge resolution ~0.1-0.3 e

IMC - Imaging Calorimeter

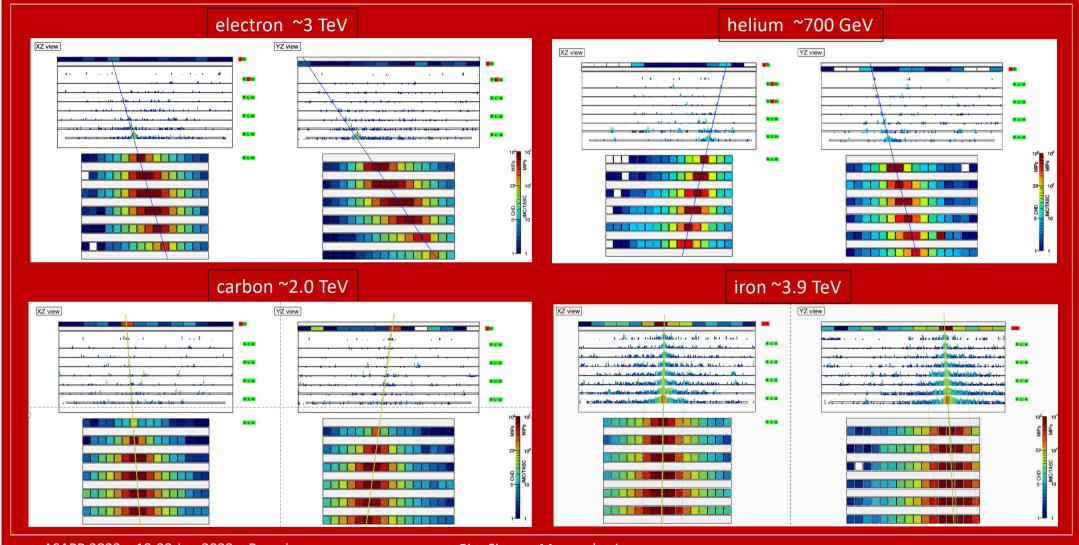
- Scifi + Tungsten absorbers: $3 X_0$ at normal incidence
- 8 x 2 x 448 plastic scintillating fibers (1mm) readout individually
- Tracking (~0.1° angular resolution) + Shower imaging

TASC – Total Absorption Calorimeter 27 $X_{0,}$ 1.2 λ_{I}

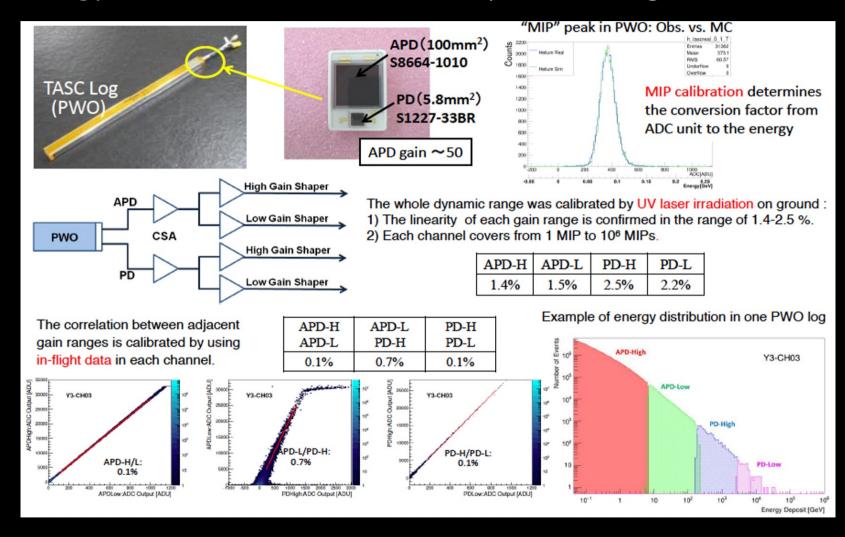
- 6 x 2 x 16 lead tungstate (PbWO₄) logs
- Energy resolution: ~2 % (>10GeV) for e , γ ~30-35% for p, nuclei
- e/p separation: ~10⁻⁵
- angular resolution: 0.2° for gamma-rays > ~50 GeV



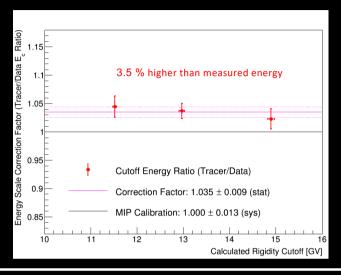
Examples of CALET event candidates



Energy Measurement in a wide dynamic range 1-10⁶ MIPs



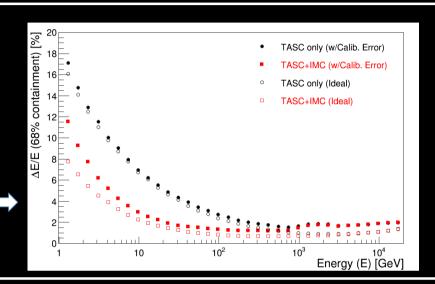
Energy Measurement: energy scale and resolution

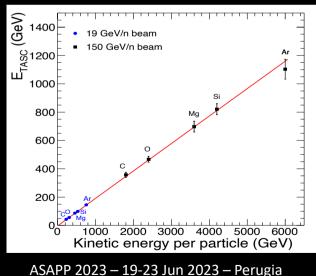


ELECTRONS

Absolute energy scale calibration for electrons using rigidity cutoff

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



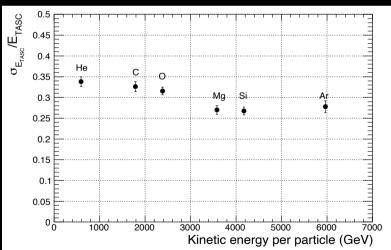


HADRONS

Beam calibrations 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%



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CALET orbital operations (during the first 7.5 years)

Geometrical Factor:

- 1040 cm² sr for electrons, light nuclei
- 1000 cm² sr for gamma-rays
- 4000 cm²sr for ultra-heavy nuclei

High-Energy (HE) trigger statistics:

Operational time >2700 days

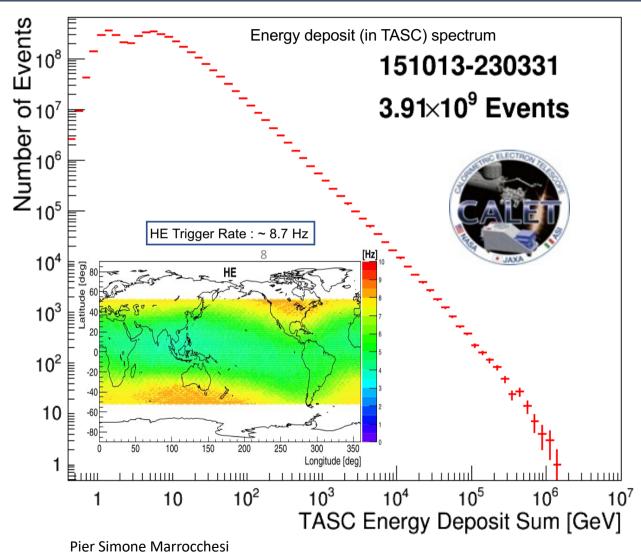
Live time fraction >85%

Exposure of HE trigger ~250 m² sr day

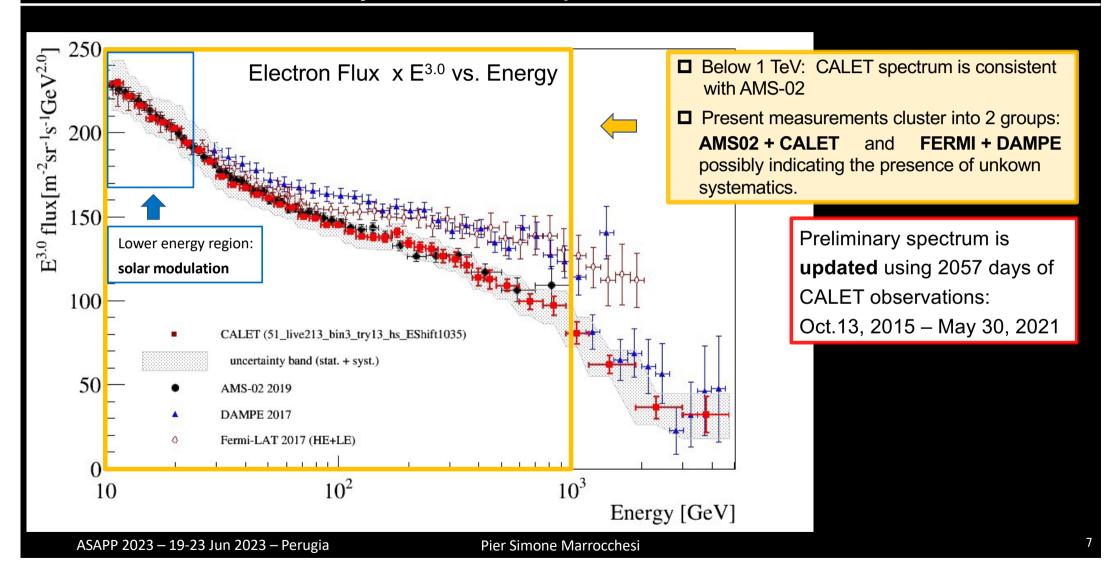
Number of HE events ~1.8 billion

Total number of >GeV triggers ~3.9 billion

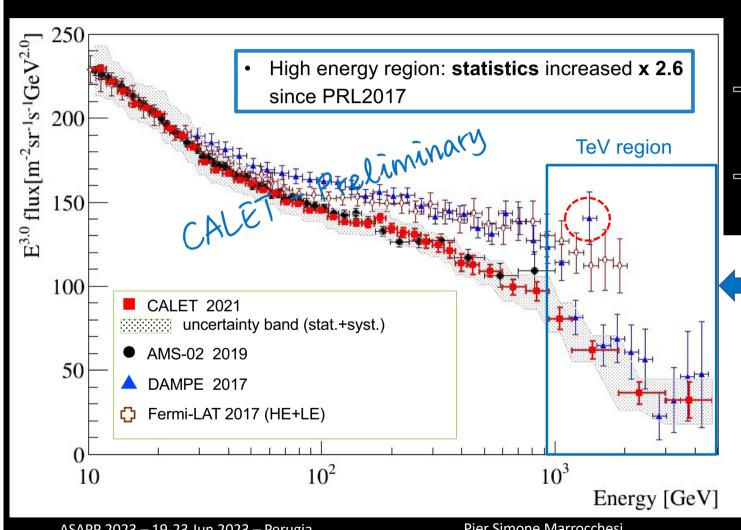
~4.8 m² day (for Crab, Geminga)



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



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



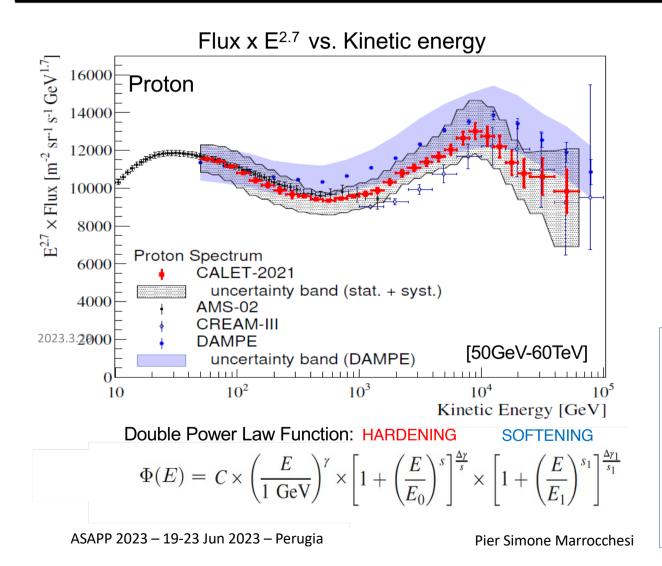
Energy loss due to Synchrotron and Inverse Compton: $dE/dt = -bE^2$

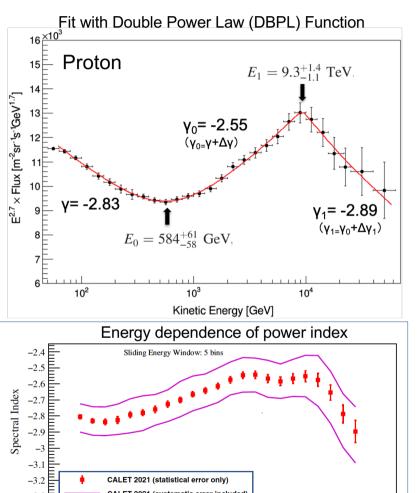
- ⇒ Observable electron sources in the TeV region should be located at a distance $< \sim 1$ kpc with age $< \sim 10^5$ yr.
- ⇒ Softening of the spectrum is expected above 1 TeV
 - ☐ Above 1 TeV CALET observes a flux suppression with a significance $> 6.5 \sigma$, a considerable improvement with respect to the result published in PRL2018 (\sim 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...

Cosmic-ray proton spectrum

PRL 129, 101102 (2022)



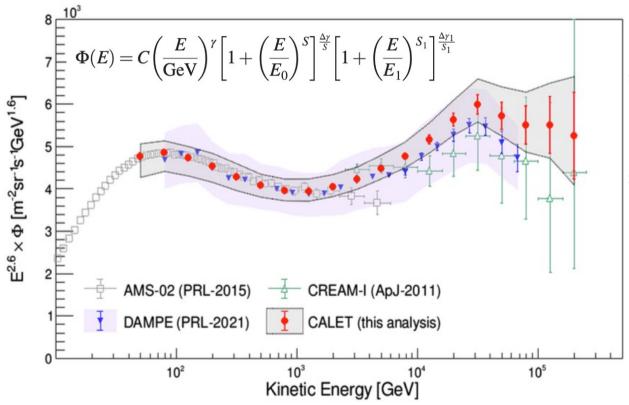


Kinetic Energy [GeV]

 10^{4}

Cosmic-ray helium spectrum

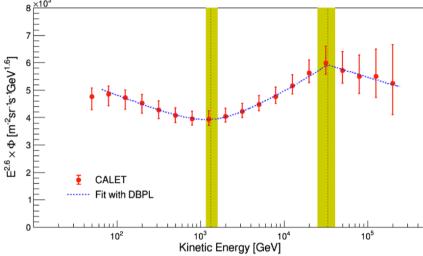
PRL 130, 171002 (2023)



CALET preliminary helium flux is consistent with DAMPE within the errors from ~70 GeV to ~50 TeV

(present analysis: $\sim 50\%$ reduced acceptance inside fiducial region ~ 510 cm² sr)

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Double Broken Power Law (DBPL) fit:

$$\gamma = -2.703^{+0.005}_{-0.006}(\text{stat})^{+0.032}_{-0.009}(\text{syst})$$

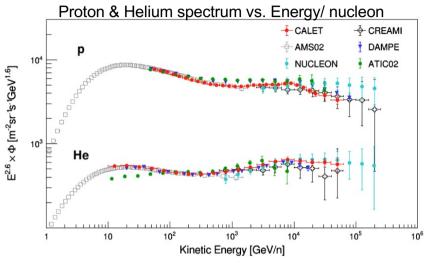
$$E_0 = 1319^{+113}_{-93}(\text{stat})^{+267}_{-124}(\text{syst}) \text{ GeV}$$

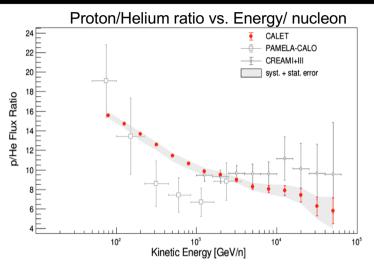
$$E_1 = 33.2^{+9.8}_{-6.2}(\text{stat})^{+1.8}_{-2.3}(\text{syst}) \text{ TeV}$$

$$\Delta \gamma = 0.25^{+0.02}_{-0.01}(\text{stat})^{+0.02}_{-0.03}(\text{syst})$$

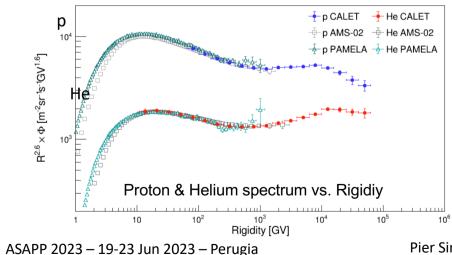
$$\Delta \gamma_1 = -0.22^{+0.07}_{-0.10}(\text{stat})^{+0.03}_{-0.04}(\text{syst})$$

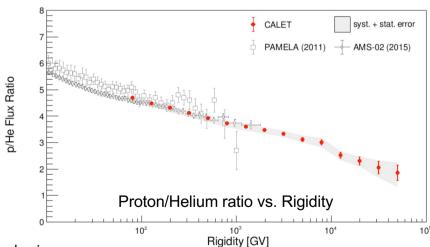
$$S = 2.7^{+0.6}_{-0.5} (\text{stat})^{+3.0}_{-0.9} (\text{syst})$$
 $S_1 = 30$





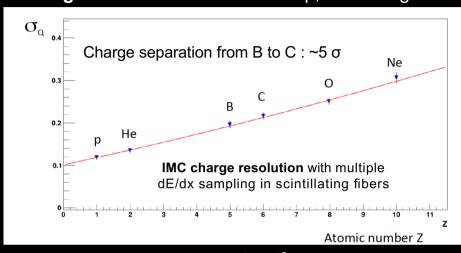
Both proton and helium have a similar spectral structure with hardening and softening breakpoints at similar rigidities. However, the spectral index of helium is harder than that of proton (by ~ 0.1).

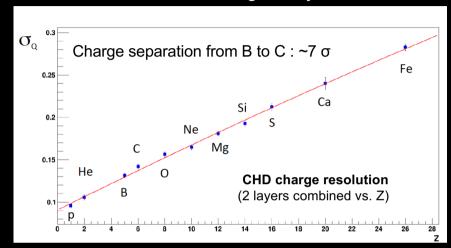




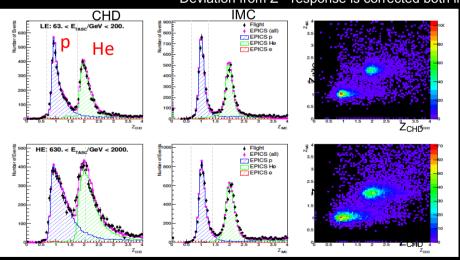
Charge Identification of CR nuclei with CHD and IMC

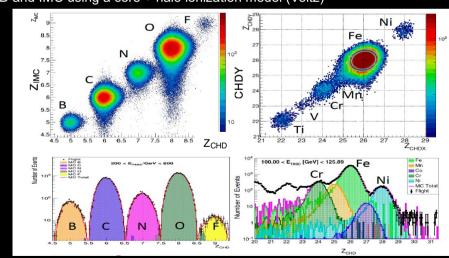
Single element identification for p, He and light nuclei is achieved with CHD+IMC charge analysis



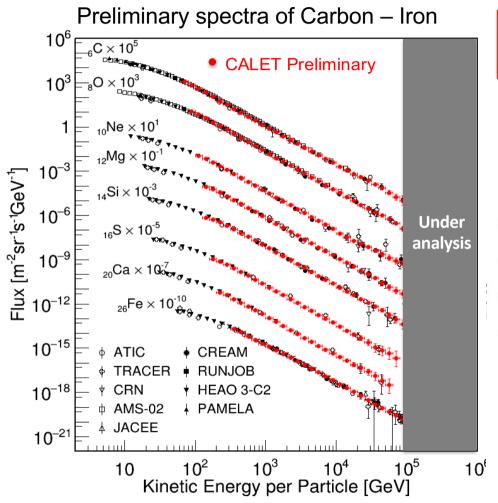


Deviation from Z² response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)



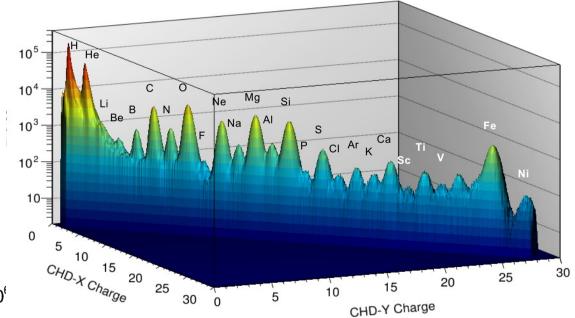


Observations of cosmic-ray nuclei from C to Fe



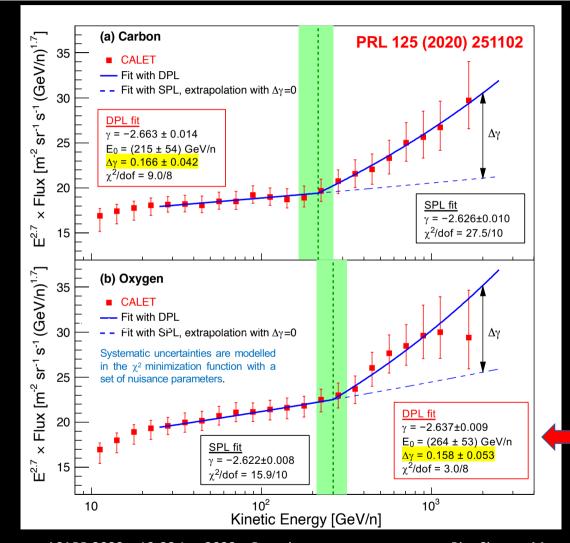
With excellent charge-ID of individual elements CALET is exploring the Table of Elements in the multi-TeV domain

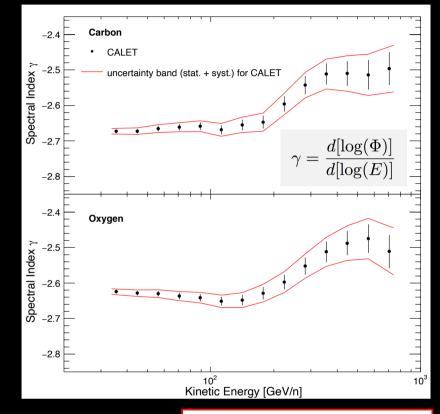
Charge distribution from Proton to Nickel



Carbon and oxygen: spectral analysis

PRL 125, 251102 (2020)

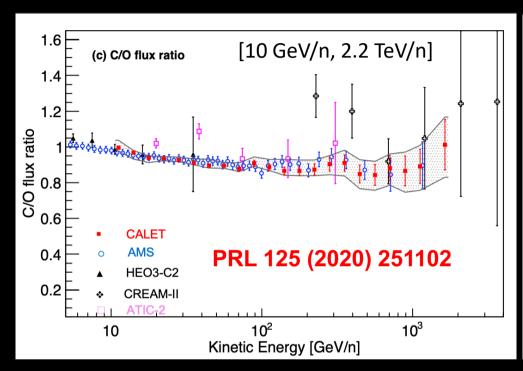


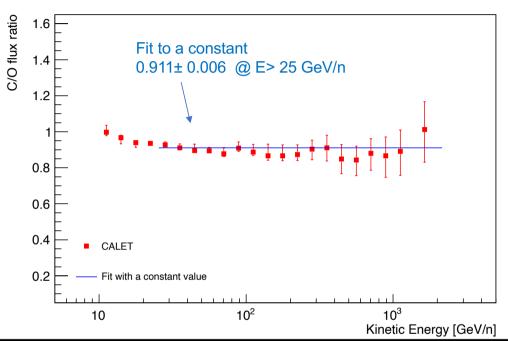


Double power-law (DPL) fit

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

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

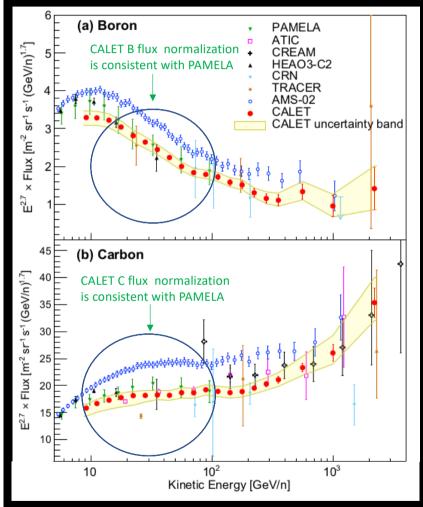




The C/O flux ratio as a function of energy is in good agreement with the measurement reported by AMS

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

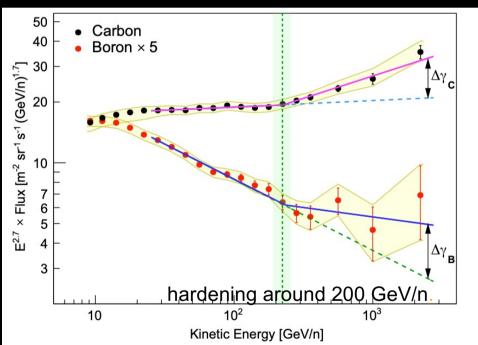
→ C and O fluxes have the same energy dependence.



CALET B, C fluxes are consistent with PAMELA and with most of the previous experiments. Shapes are similar to AMS-02 but the absolute normalization is significantly lower (\sim 27%)

Spectral fit with double power law:

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



$$\gamma_C = -2.670 \pm 0.005$$

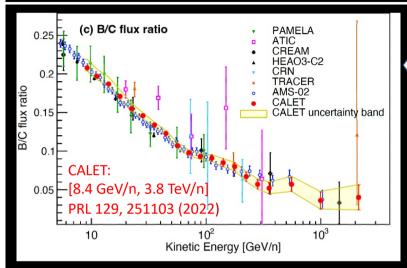
$$\Delta \gamma_C = 0.19 \pm 0.03$$

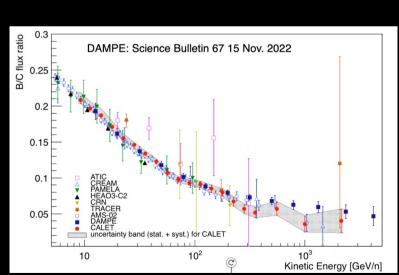
$$\gamma_R = -3.047 \pm 0.024$$

$$\Delta \gamma_B = 0.25 \pm 0.12$$

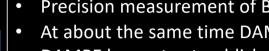
Direct measurement of the B/C flux ratio

PRL 129, 251103 (2022)





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- At about the same time DAMPE published their measurement of B/C
- DAMPE has not yet published their individual B, C spectra

Fit with a Leaky box model:

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

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

 λ_0 : residual path length

 $\cdot \delta$: diffusion coefficient spectral index



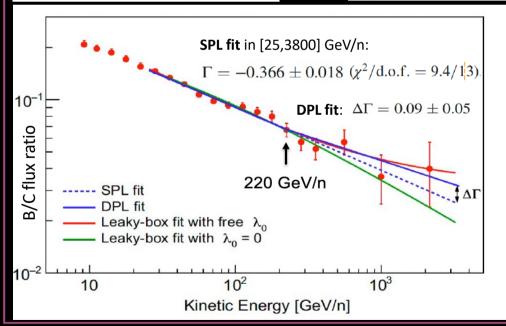
$$\lambda_0 = 0$$

 $\delta = 0.52 \pm 0.02$ $\chi^2/\text{d.o.f.} = 13.6/13$

 λ_0 : free

$$\delta = 0.71 \pm 0.11 \ \chi^2/\text{d.o.f.} = 9.6/12$$

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





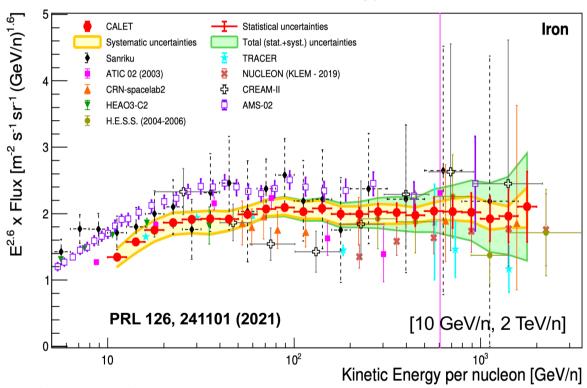
hint of a nonnull value of λ_0 ?

If so, it would be compatible with the hypothesis that a fraction of secondary B nuclei might be produced near the CR source.

Cosmic-ray iron spectrum

PRL 126, 241101 (2021)

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

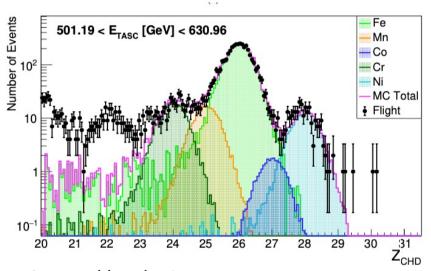


Flux normalization:

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

Iron Single Power Law (SPL) fit:

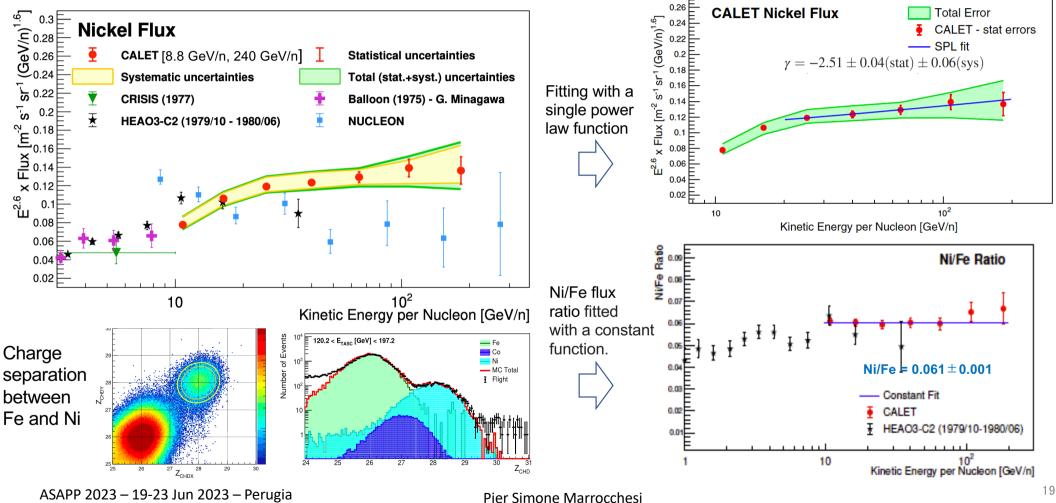
50 GeV/n, 2.0 TeV/n
$$\gamma = -2.60 \pm 0.02 (stat) \pm 0.02 (sys)$$
 with $\chi^2/d.o.f. = 4.2/14$

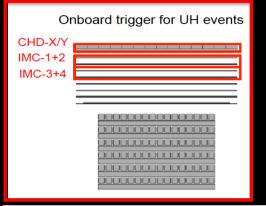


Spectral hardening:

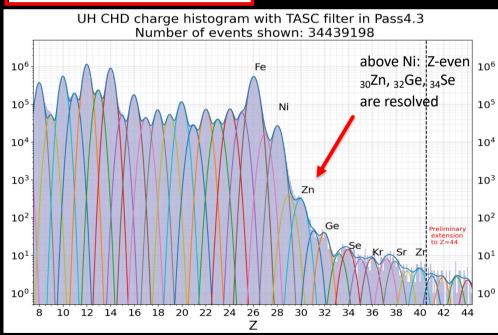
• CALET iron data are consistent with an SPL spectrum up to 2 TeV/n. Beyond this limit, the present statistics and large systematics do not allow to draw a significant conclusion on a possible deviation from a single power law.







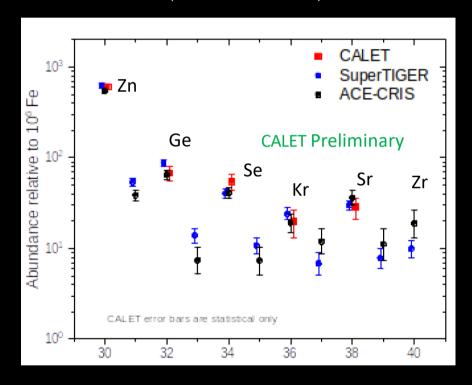
A special UH CR trigger uses the CHD and the first 4 layers of the IMC to achieve an expanded x 4 geometric factor **GF ~ 4400 cm² sr**



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Measurement of the relative abundances of elements above Fe through 40Zr

(normalized to 10⁶ Fe)

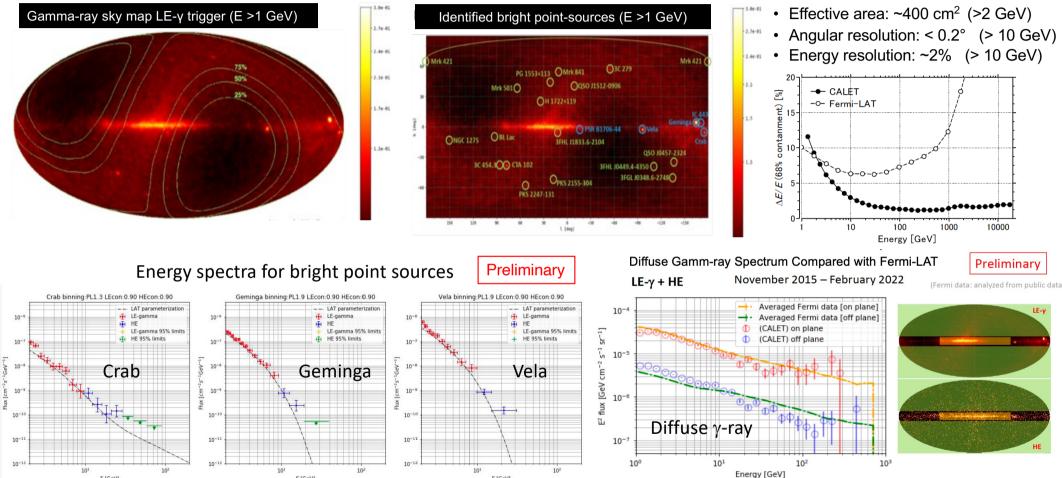


The CALET UH element ratios relative to Fe are consistent with Super-TIGER and ACE abundances.

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

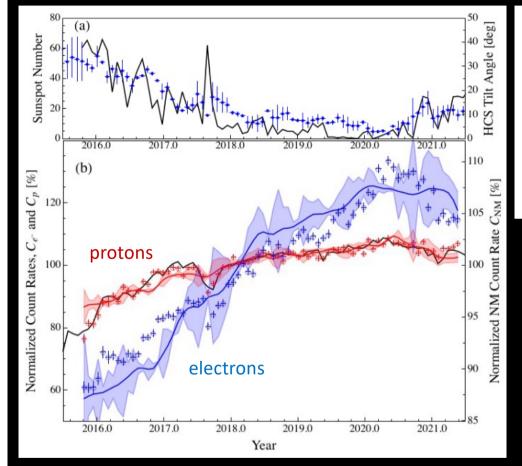


E [GeV]

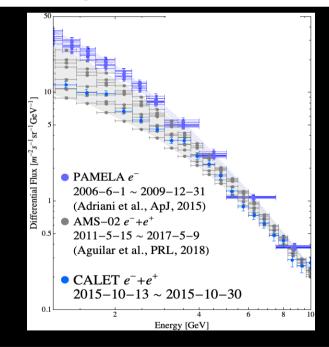
E [GeV]

"On-plane": $|l| < 80^{\circ} \& |b| < 8^{\circ}$, "Off-plane": $|b| > 10^{\circ}$

E [GeV]



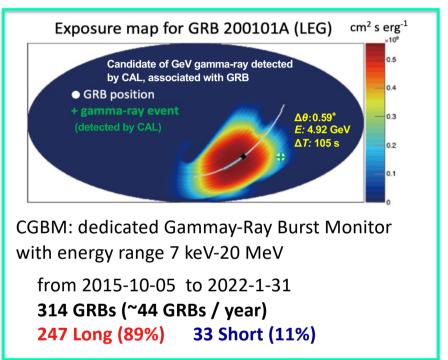
- CALET measurement of count rates of low-energy electrons and protons (E > 1 GeV) for the same rigidity selections. Observations from 2016 2020 with solar magnetic field polarity A > 0
- Modulation of electrons (i.e. qA < 0) count rates is stronger than modulation of protons (i.e. qA > 0) count rates
- Consistent with **drift model** prediction of a larger anti-correlation between Heliospheric Current Sheet (HCS) tilt angle and GCR intensity for qA < 0
- Results well consistent with numerical model of transport in the Heliosphere and modulation including drift effect



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

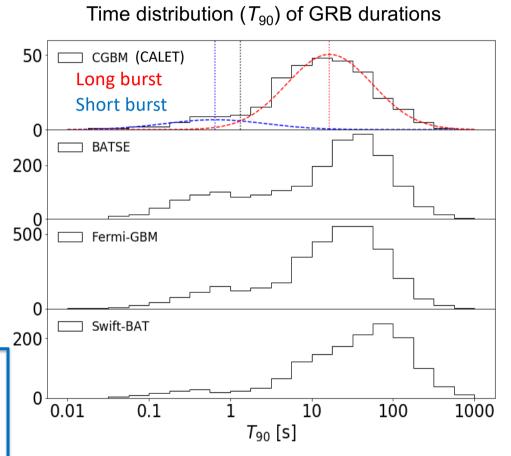


Gamma-ray Bursts and GW Follow-up



- 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)



Summary and Future Prospects

CALET was successfully launched in August 2015 and installed on the JEM-EF module on the ISS

Operational over 2700 days with 85% live time, total triggers approaching 4 billion

Continuous on-orbit updates from ground calibration
Stable operations over a range of observing modes continue

Astropart. Phys. 91, 1 – 10 (2017) Astropart. Phys. 100, 29 – 37 (2018)

Analysis of CR events continues, extending to higher energies and charges

All-electron spectrum in the range 11 GeV – 4.8 TeV	PRL 120, 261102 (2018)	(2 nd update)
Proton spectrum in the range 50 GeV – 60 TeV	PRL 129, 101102 (2022)	(2 nd update)
Carbon and oxygen spectra in the range 10 GeV/n – 2.2 TeV/n	PRL 125, 251102 (2020)	1 st paper
Iron spectrum in the range 50 GeV/n – 2 TeV/n	PRL 126, 241101 (2021)	1 st paper
Nickel spectrum in the range 8.8 GeV/n – 240 GeV/n	PRL 128, 131103 (2022)	1 st paper
Boron spectrum in the range 8.4 GeV/n – 3.8 TeV/n	PRL 129, 251103 (2022)	new
Helium spectrum in the range 40 GeV – 250 TeV	PRL 130, 171002 (2023)	new
Preliminary analysis of ultra-heavy cosmic-ray abundances	see W.Zober U13.00005 (APS 2023)	preliminary

Analysis of gamma-ray sources and transients continues

Calorimeter instrument response characterized GW follow-up and GRB analysis with CGBM & CAL Counterpart search in LIGO/Virgo O3 with CGBM & CAL

ApJS 238:5 (2018) ApJL 829:L20 (2016) ApJ 933:85 (2022)

Analysis of transient heliospheric and space weather phenomena underway

Charge-sign dependence of Solar modulation

PRL 130, 211001 (2023)

new

Solar energetic particle and relativistic electron precipitation events

see A.Bruno ICRC 2021, SH 959

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

Thank
you
for
your
attention

