CALET: results of the first 8 years of cosmic-ray direct measurements.

Lorenzo Pacini for the CALET collaboration,

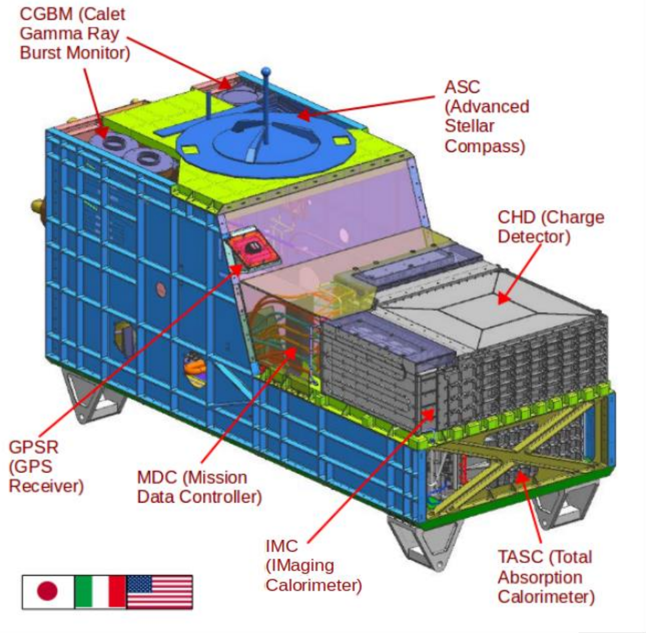
17/06/2024

The 13th CRIS-MAC in Trapani

The CALET mission is supported by the Italian Space Agency through the ASI - Univ. of Siena agreement n. 2013-018-R.4-2023.

The CALET mission

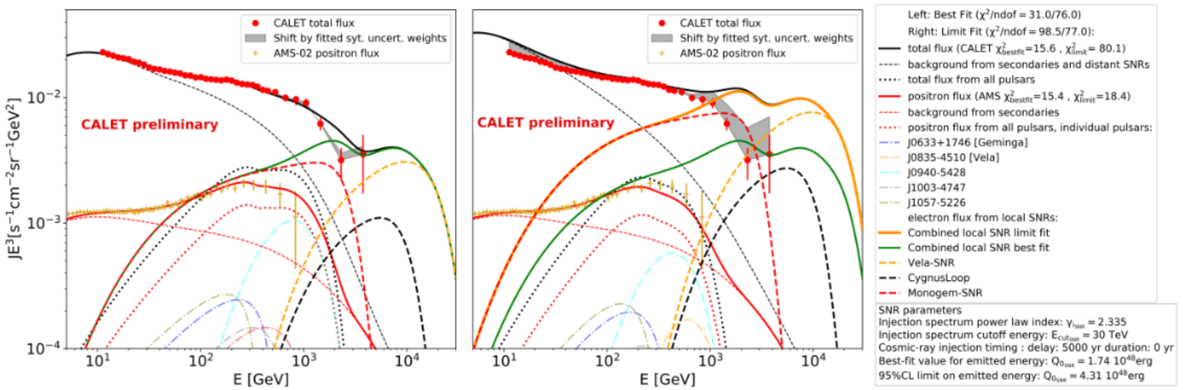
- Launch: Aug. 19th, 2015
- Emplaced on JEM-EF port 9 on Aug. 25th
- Scientific observations from Oct. 13th , 2015
- More than 4.5 billion events collected so far.
- Payload parameter:
  - Mass: : 612.8 kg
  - Size: 1850 (L) x 800 (W) x 1000 (H) mm^3
  - Power Consumption: 507 W (max)
  - Telemetry: 600 kbps (6.5 GB/day)
- Two main instruments:
  - CAL: calorimetric experiment (slide 4)
  - CGBM: Gamma-ray burst monitor

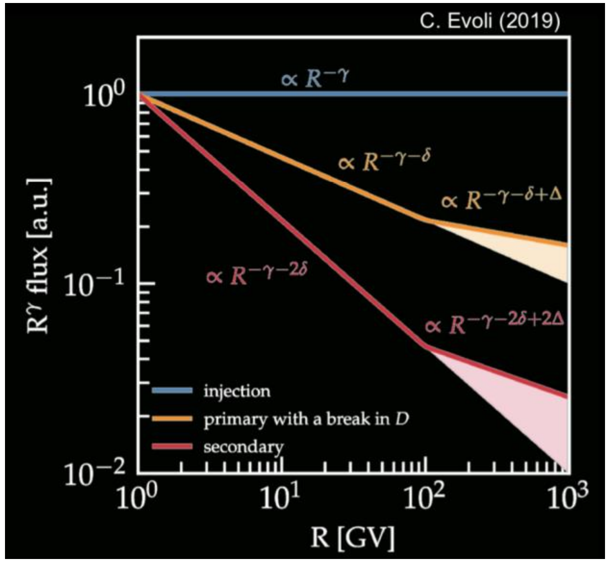


The CALET scientific goals

- Electron+positron (all electron) flux up to TeV region: nearby source and dark matter signatures.
- Proton and primary nuclei spectra up to 100 TeV/n: check acceleration and propagation galactic CR.
- Secondary over primary ratios up to few TeV: test diffusion models and understanding of spectral features.
- Gamma ray: check diffuse flux, source contribution and transient phenomena (low energy region, 7 keV to tens MeV)

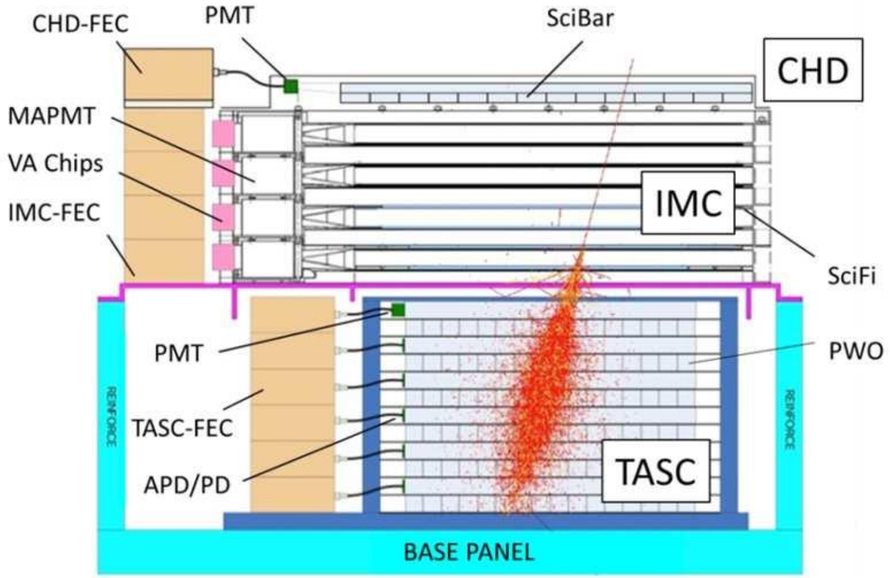
POS (ICRC2021) 100





The main (CAL) instrument

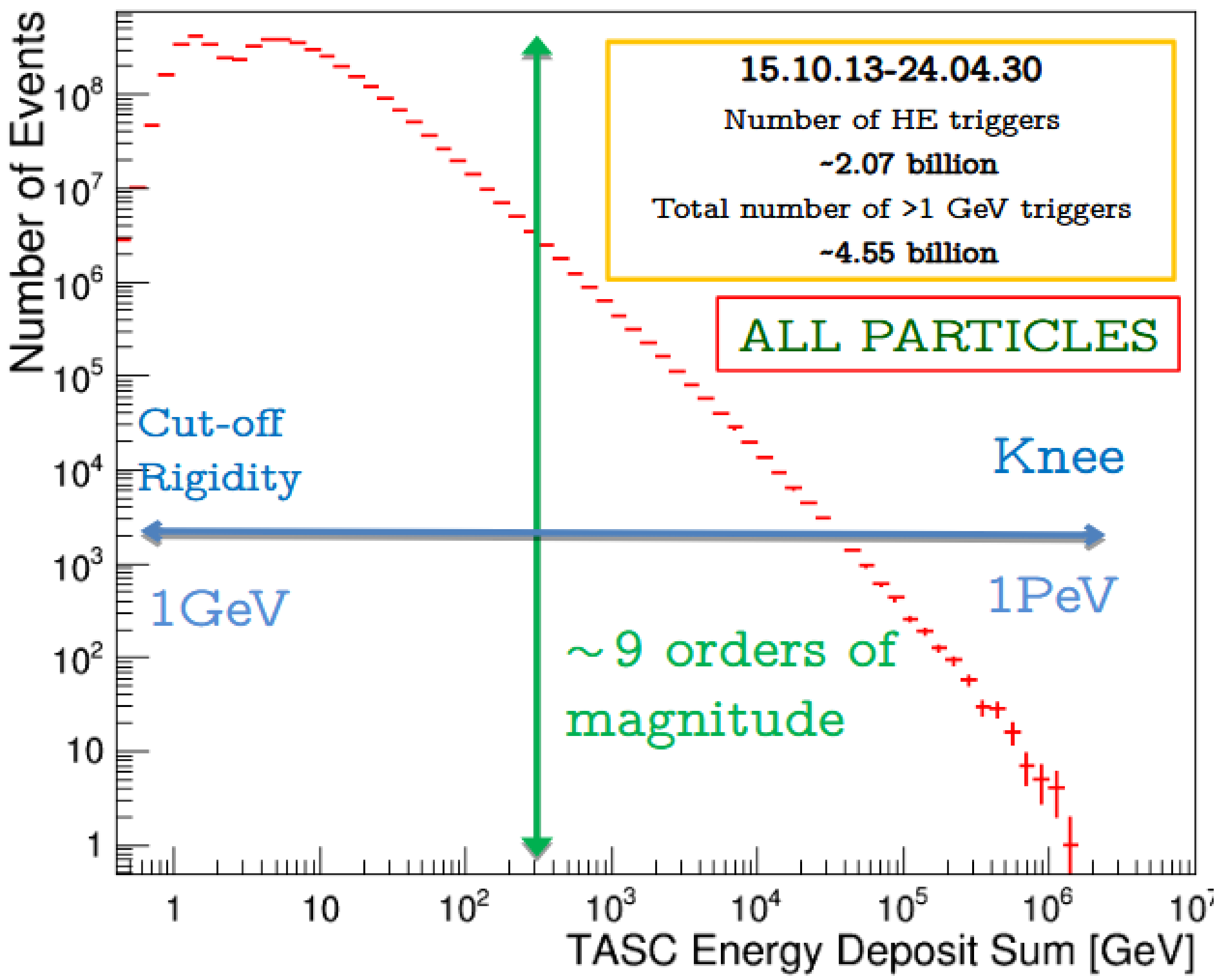
- Charge detector (CHD) with a high dynamic range, up to Iron and above,
- Imaging segmented calorimeter (IMC), used also to reconstruct tracks,
- Total absorption and homogeneous calorimeter (TASC).



	TASC	IMC	CHD
Depth	27 X_0	3 X_0	~0.1 X_0
Read-out	APD/PD	MaPMT	PMT
Material	PbWO logs	SciFis + W sheets	Plastic paddles
Segmentation	2 x 2 x 32 cm^2	0.1 x 0.1 x 44.8 cm^2	3.2 x 1 x 45 cm^2

CALET: operation in space

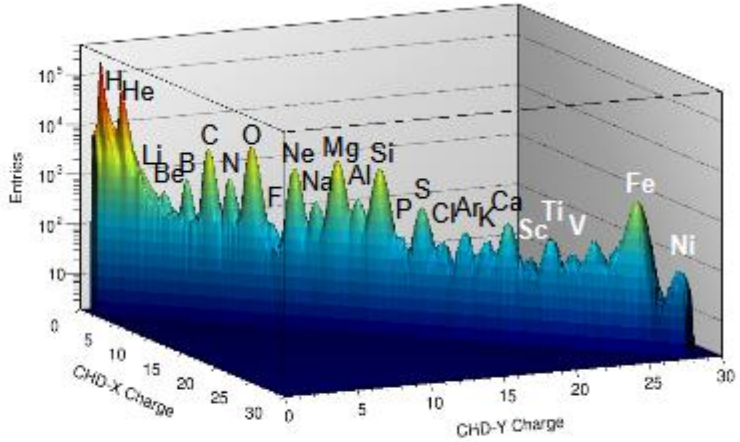
- Main acquisition configurations: high energy trigger.
- High efficiency for electrons > 10 GeV
- Operational time 3123 days (> 8 years) (up to Apr. 30, 2024)
- Live time fraction **~ 86%**
- Exposure of HE trigger **> 275 m²** sr day
- HE-gamma point source exposure ~4.2 m² day (for Crab, Geminga)
- Full acceptance geometrical factor: 1037 cm²sr

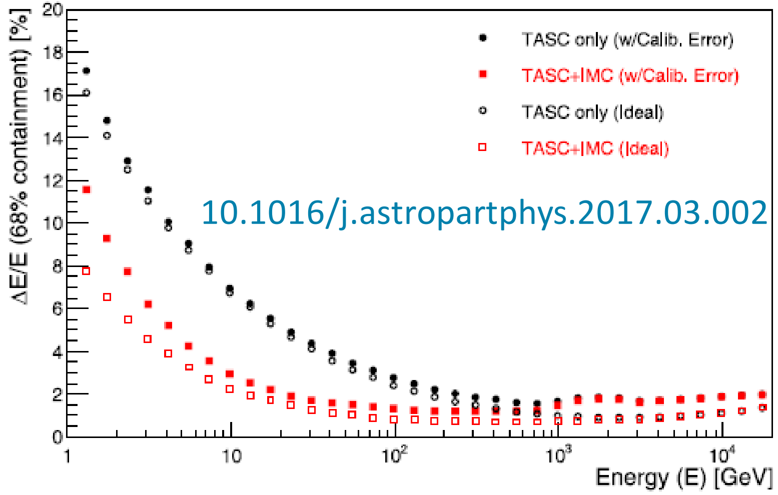


Main reference: Astroparticle Physics 100 (2018) 29–37

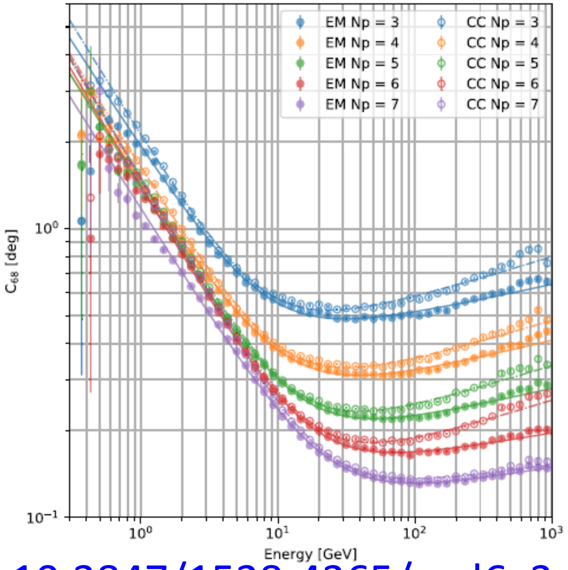
Detector performance

- CHD charge resolution: 0.15 e for C, 0.3 e for Fe
- IMC: provide additional charge information and reconstructs charged particle and gamma ray tracks.
- Angular resolution better than 1 at high energy.
- TASC electron energy resolution: ~2% @ TeV
- Electron proton separation: proton contamination less than 10% up to 7.5 TeV

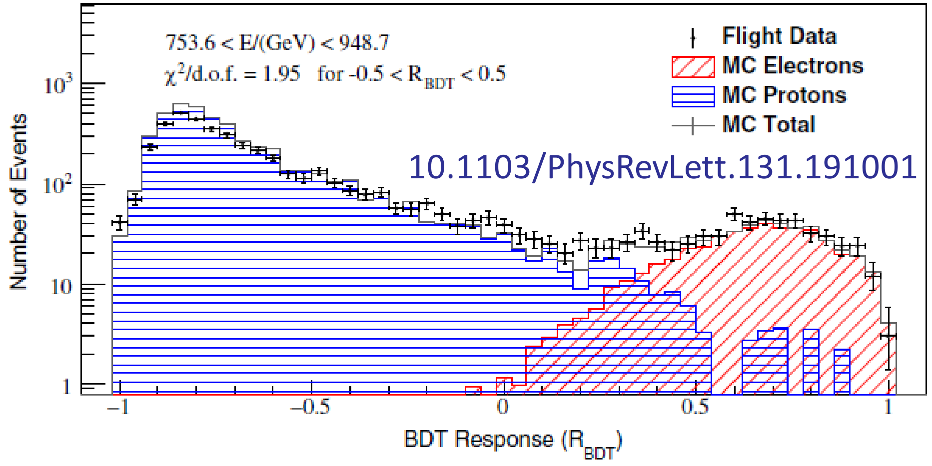




10.1016/j.astropartphys.2017.03.002

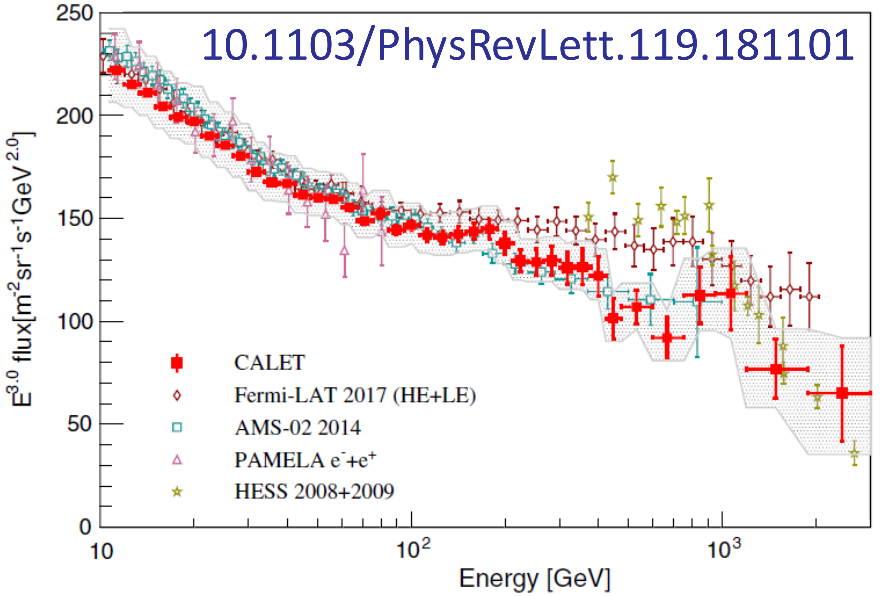


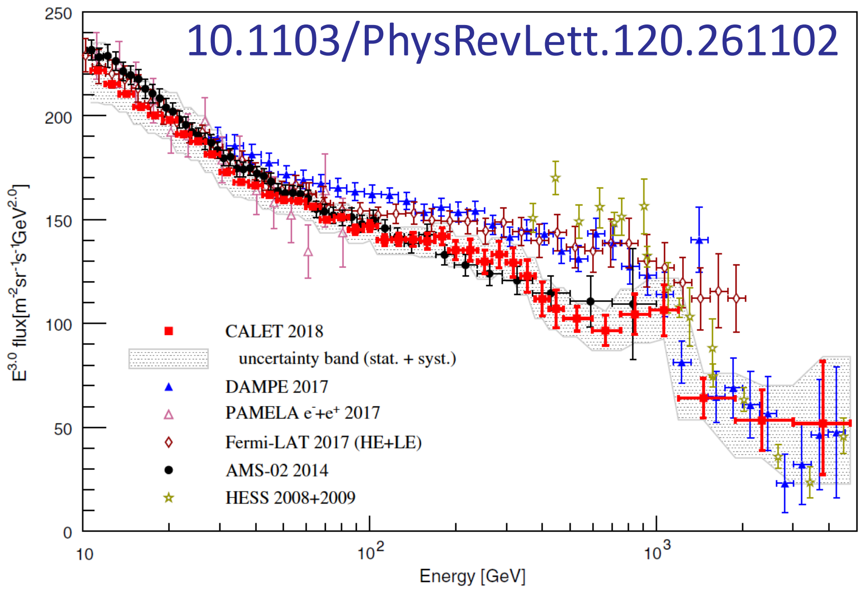
10.3847/1538-4365/aad6a3



10.1103/PhysRevLett.131.191001

First steps of CALET in CR observation

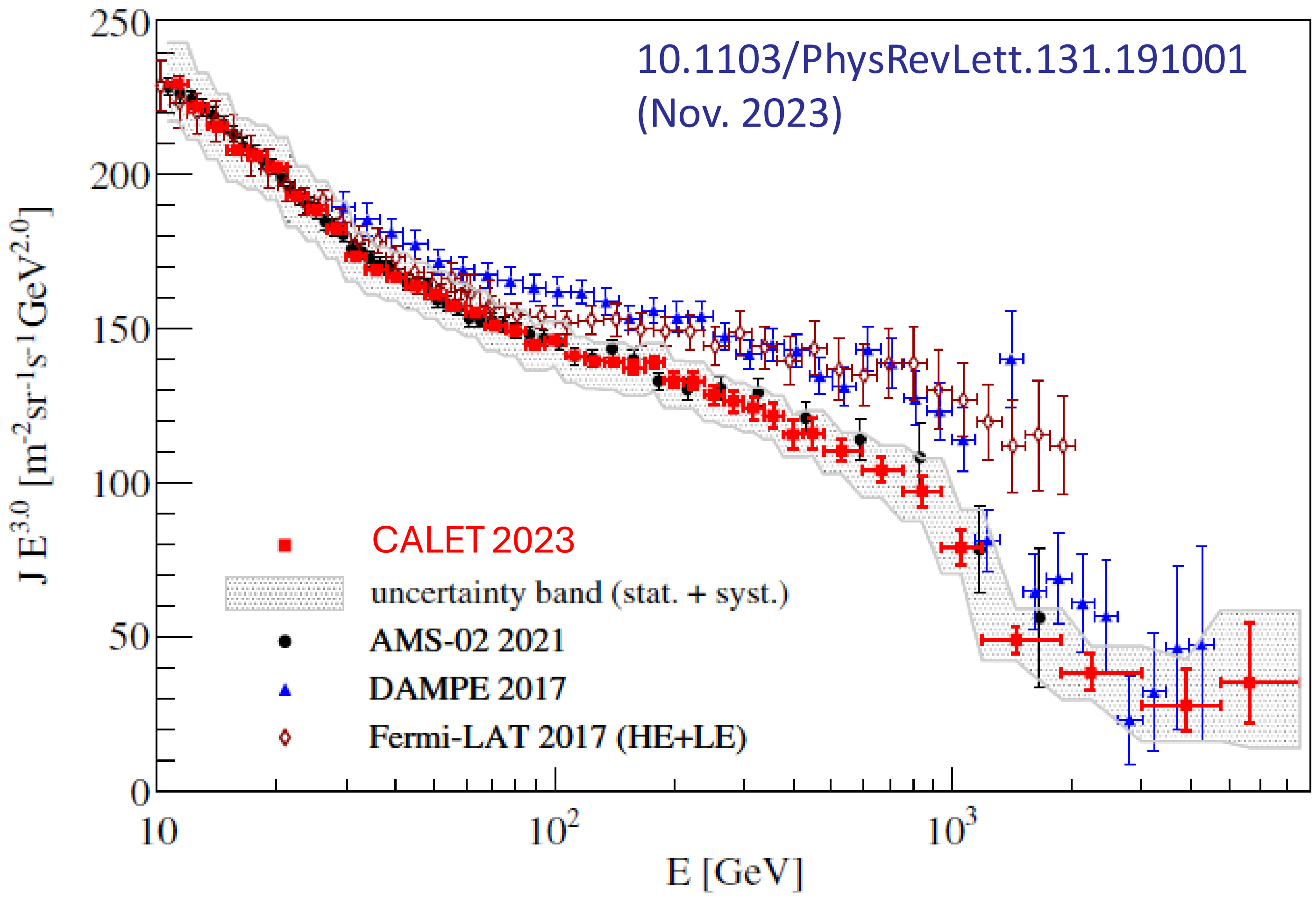




- First steps of our journey in CR direct measurements:

1. PRL publication, electrons up to 3 TeV (Nov. 2017) Electron flux compatible with AMS-02, first observation of 3 TeV
2. PRL publication, electrons up to 5 TeV (June 2018): compatible with the cut-off observed by DAMPE, it rejects the hypothesis of a peak at TeV energies.

First measurement of electrons > 5 TeV



- First observation of all-electron flux up to 7.5 TeV.
- Clear cut-off @ ~TeV is shown.
- Below 1 TeV present measurements clustered into 2 groups:
  - **AMS02 + CALET** and
  - **FERMI+DAMPE**
- possibly indicating the presence of unknown systematics.

All-electron: fit and interpretation.

10.1103/PhysRevLett.131.191001

$$J(E) = C(E/100\ \mathrm{GeV})^{\gamma}[1 + (E + E_b)^{\Delta\gamma/s}]^{-s}$$

SBPL fit result:

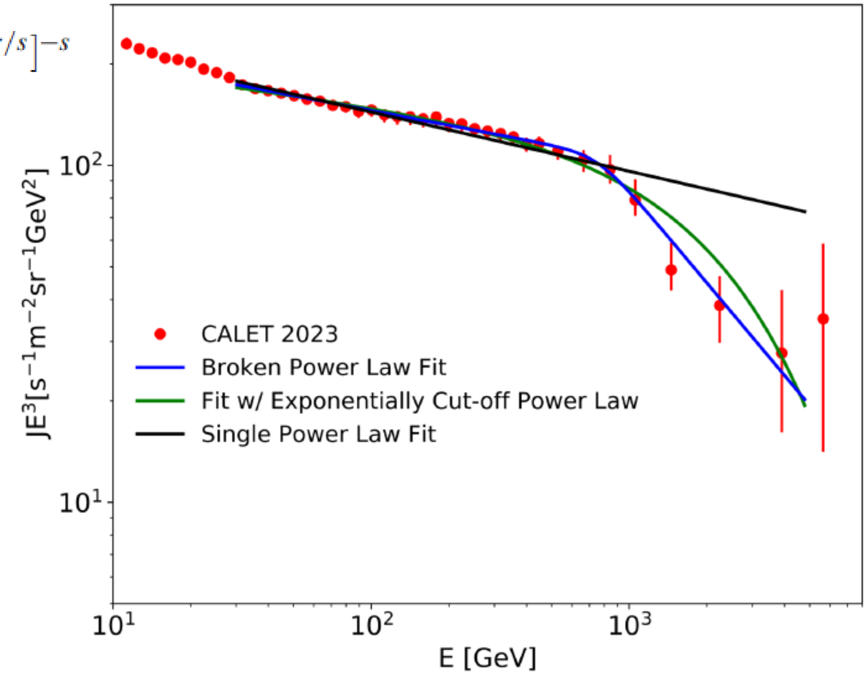
γ = -3.15 ± 0.01

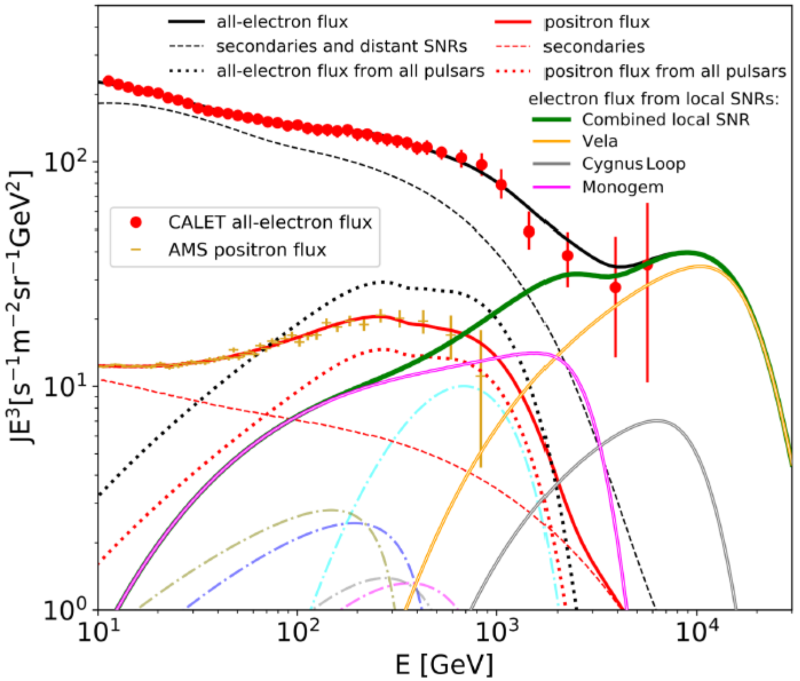
$\Delta\gamma$ = -0.77 ± 0.22

E_b = 761 ± 115 GeV

S = 0.1 (fixed)

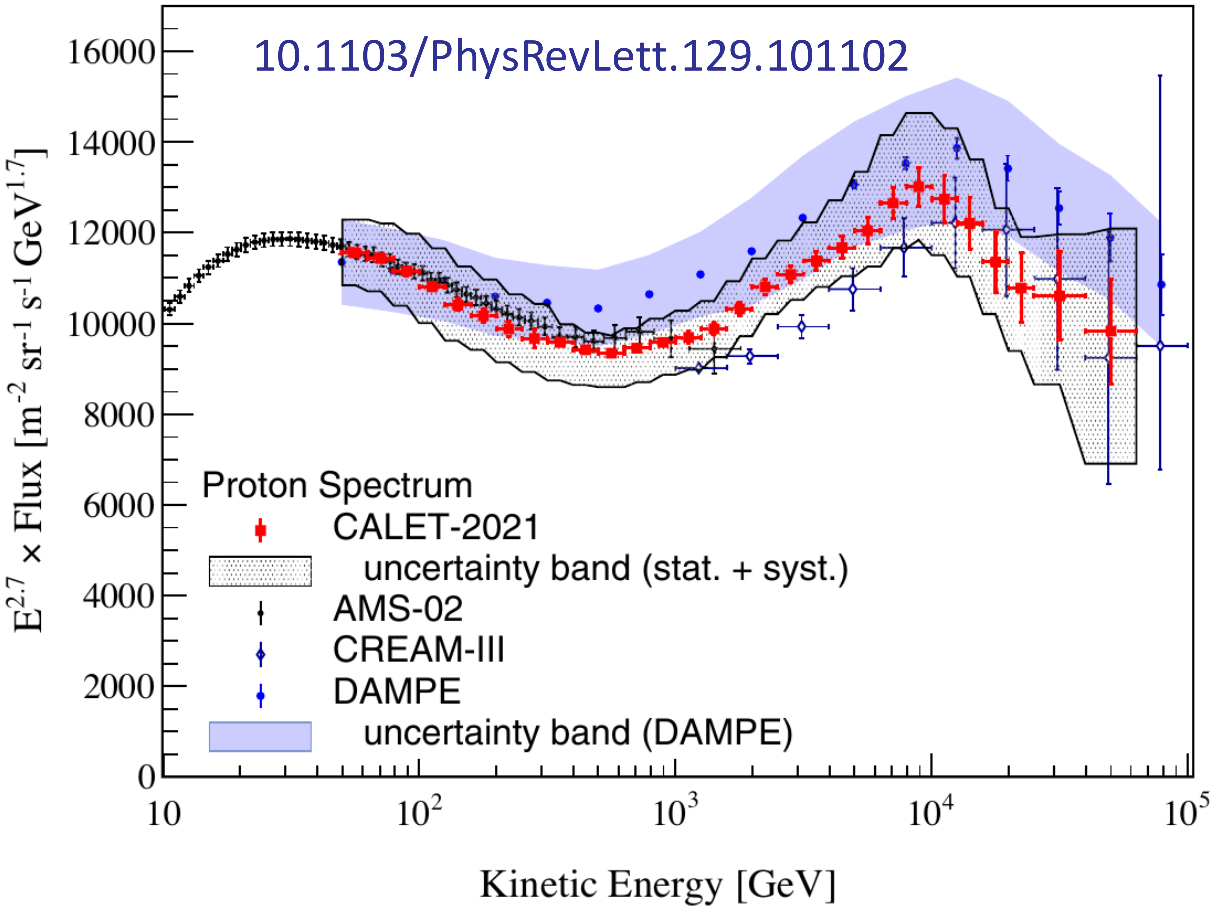
χ^2/dof = 3.6/ 27





- The fit results are consistent with DAMPE.
- A first hint of near-by source observation is present:
  - 9 candidates above 4.8 TeV are consistent with an estimation of the electron flux from the nearby SNRs based on an interpretation model.

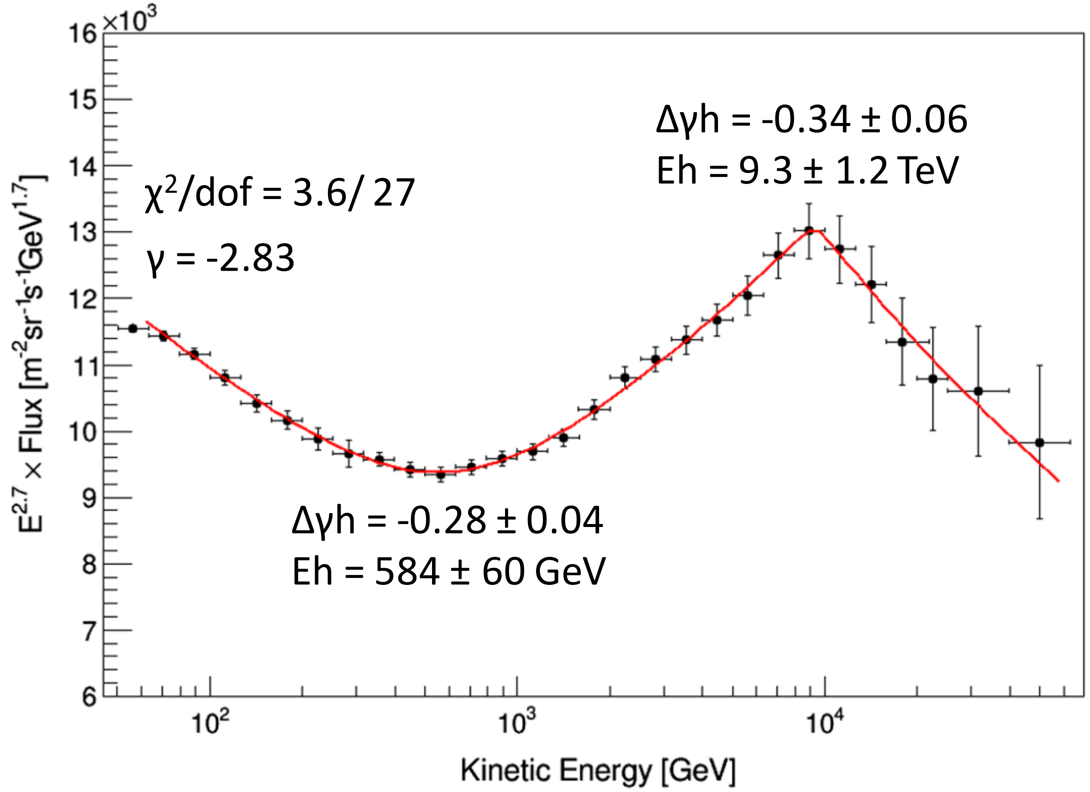
Recent proton spectrum

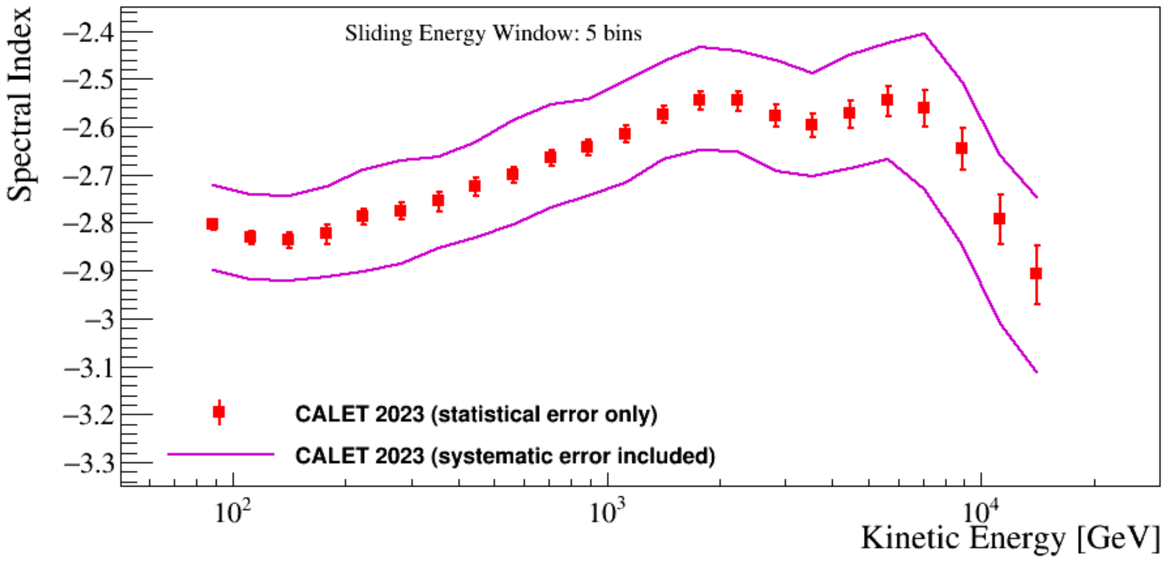


- Measurement range : 50 GeV – 60 TeV.
- Flux consistent with AMS-02, slightly softer than DAMPE one.
- CALET confirms proton spectral hardening above a few hundred GeV (significance > 20σ).
- CALET observes a spectral softening starting around 10 TeV consistent, within the errors, with the measurement reported by DAMPE.

Fit of proton spectrum

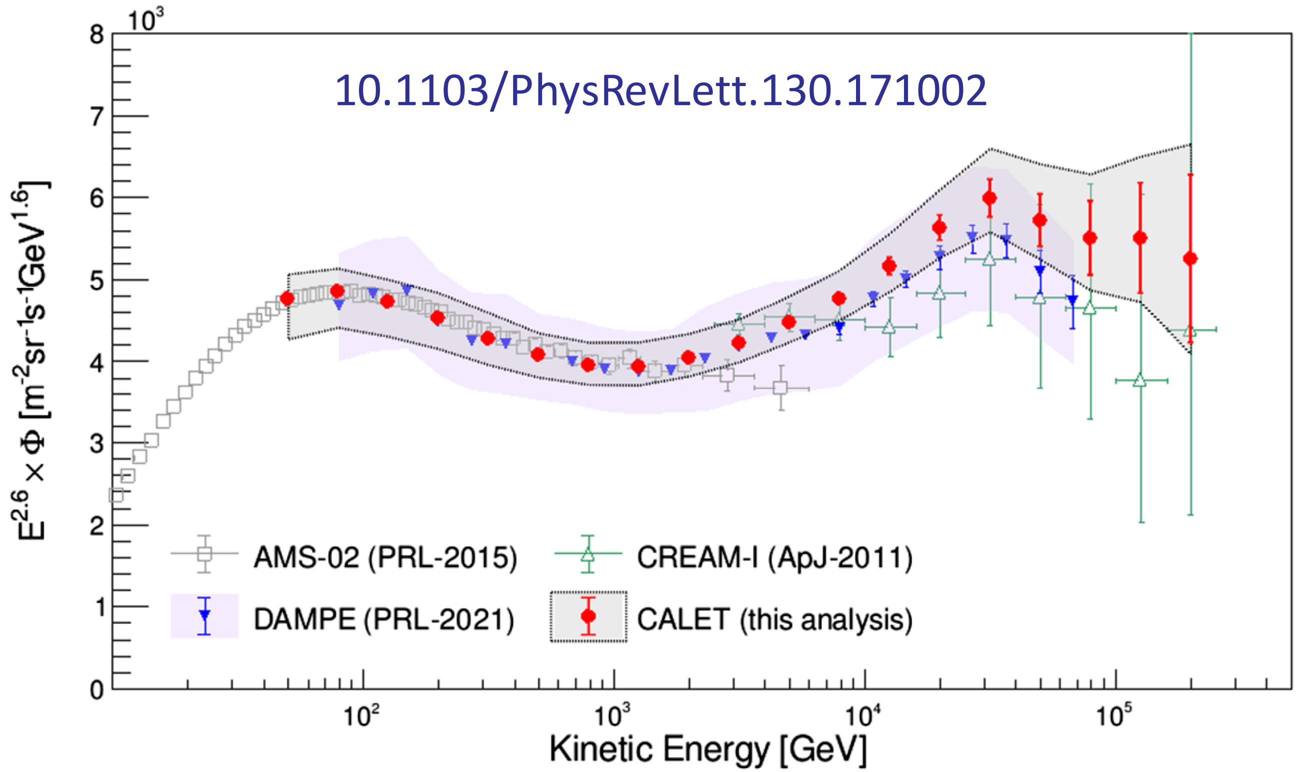
10.1103/PhysRevLett.129.101102





$$\Phi'(E) = E^{2.7} \times C \times \left(\frac{E}{1\ \mathrm{GeV}}\right)^{\gamma} \times \phi(E) \qquad \phi(E) = \left[1 + \left(\frac{E}{E_0}\right)^{s}\right]^{\frac{\Delta\gamma}{s}} \times \left[1 + \left(\frac{E}{E_1}\right)^{s_1}\right]^{\frac{\Delta\gamma_1}{s_1}}$$

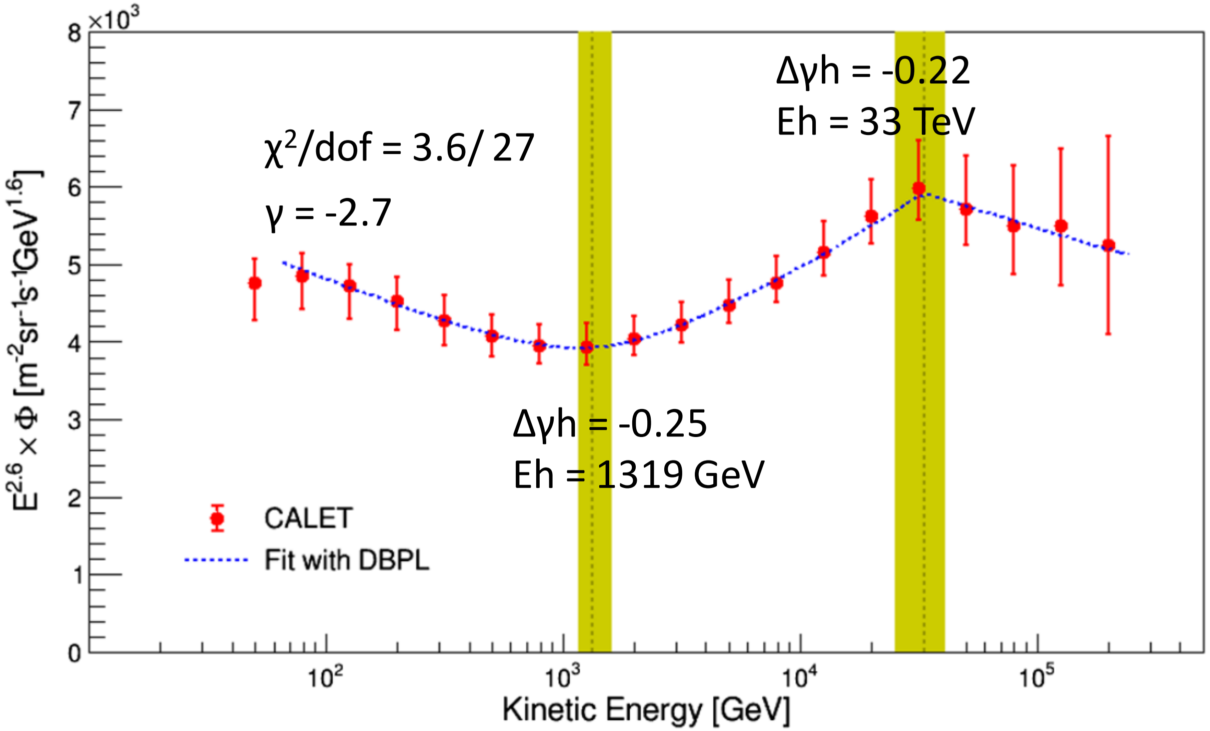
The helium spectrum

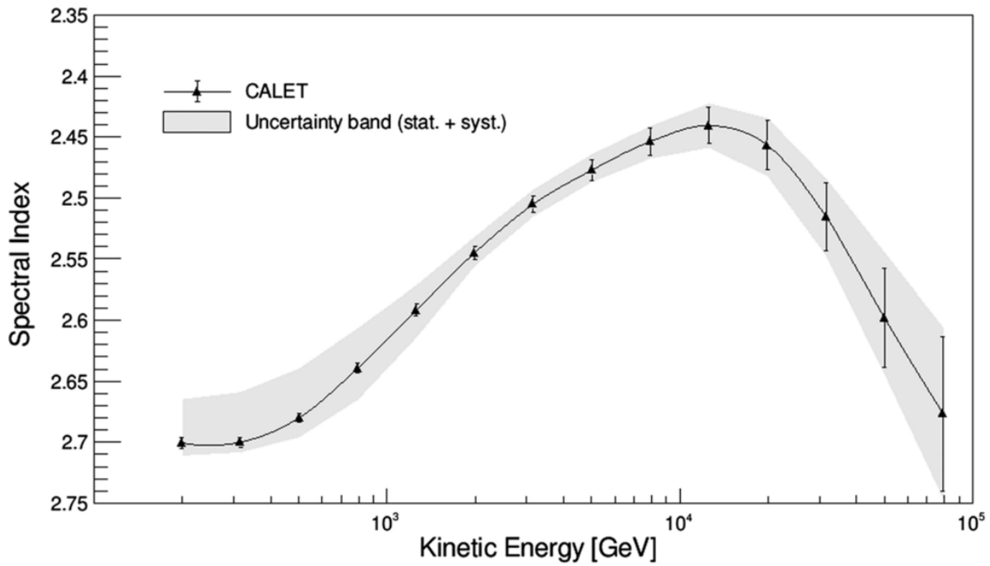


- Measurement range : 40 GeV – 250 TeV.
- Flux consistent with AMS-02, slightly higher than DAMPE above 10 TeV.
- CALET confirms He spectral hardening above a few hundred GeV (significance > 8σ).
- CALET observes a spectral softening starting around tens TeV consistent, within the errors, with the measurement reported by DAMPE.

Fit of helium spectrum

10.1103/PhysRevLett.130.171002





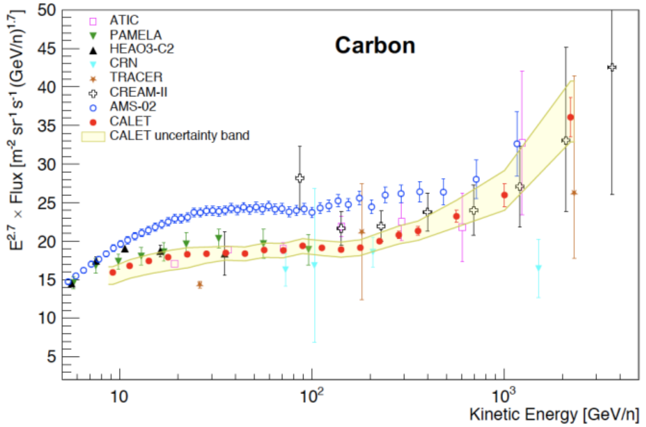
$$\gamma = -2.703^{+0.005}_{-0.006}(stat)^{+0.032}_{-0.009}(syst);\ \Delta\gamma = -0.25^{+0.02}_{-0.01}(stat)^{+0.02}_{-0.03}(syst);$$
$$E_0 = 1319^{+113}_{-93}(stat)^{+267}_{-124}(syst)GeV;\ S = 2.7^{+0.6}_{-0.5}(stat)^{+3.0}_{-0.9}(syst);$$
$$\Delta\gamma_1 = -0.22^{+0.07}_{-0.10}(stat)^{+0.03}_{-0.04}(syst);\ E_1 = 33.2^{+9.8}_{-6.2}(stat)^{+1.8}_{-2.3}(syst)\,TeV;$$

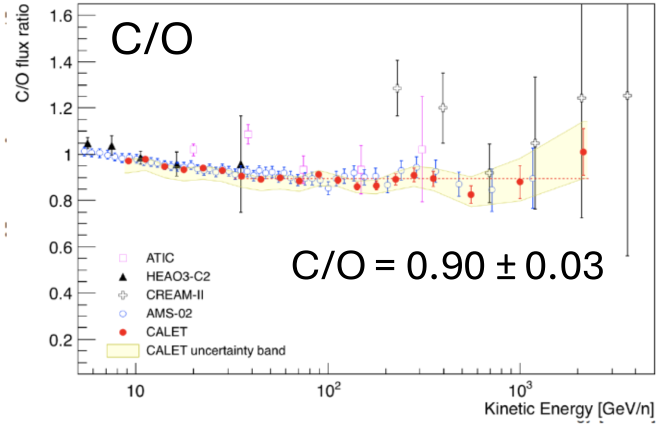
$$\Phi(E) = C\left(\frac{E}{GeV}\right)^{\gamma}\left[1+\left(\frac{E}{E_0}\right)^{S}\right]^{\frac{\Delta\gamma}{S}}\left[1+\left(\frac{E}{E_1}\right)^{S_1}\right]^{\frac{\Delta\gamma_1}{S_1}}$$

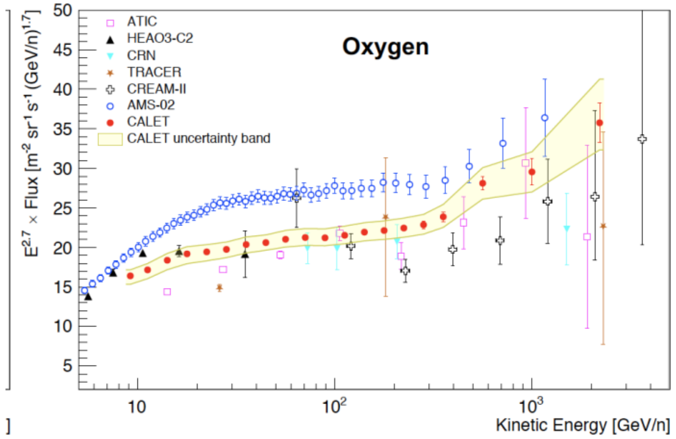
HARDENING SOFTENING

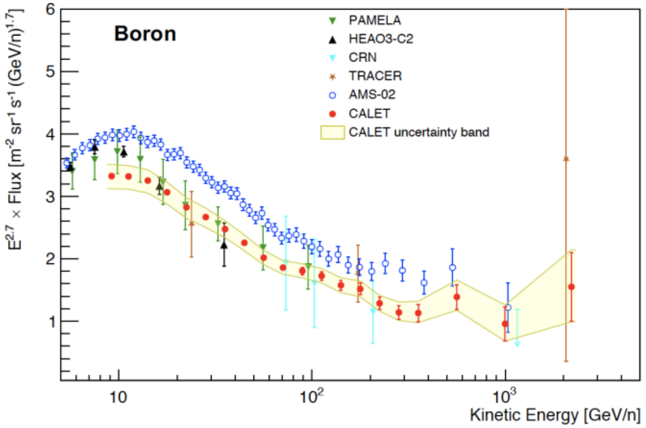
Carbon Oxygen and Boron spectra

Conference proceeding: PoS(ICRC2023)058







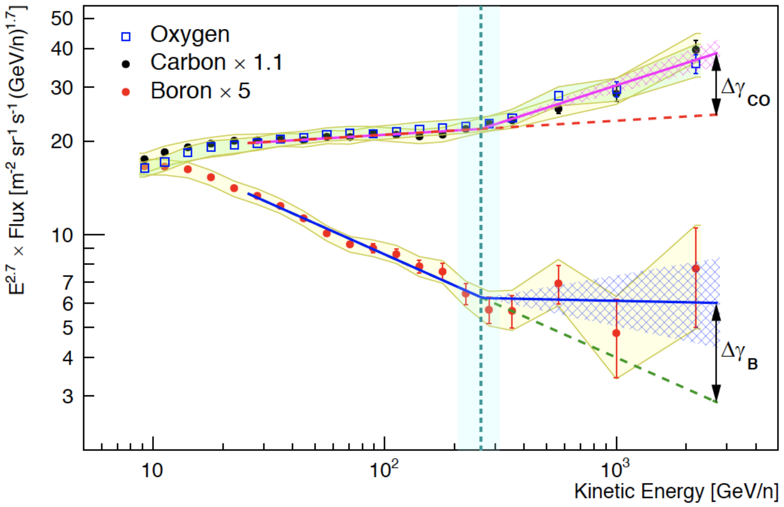


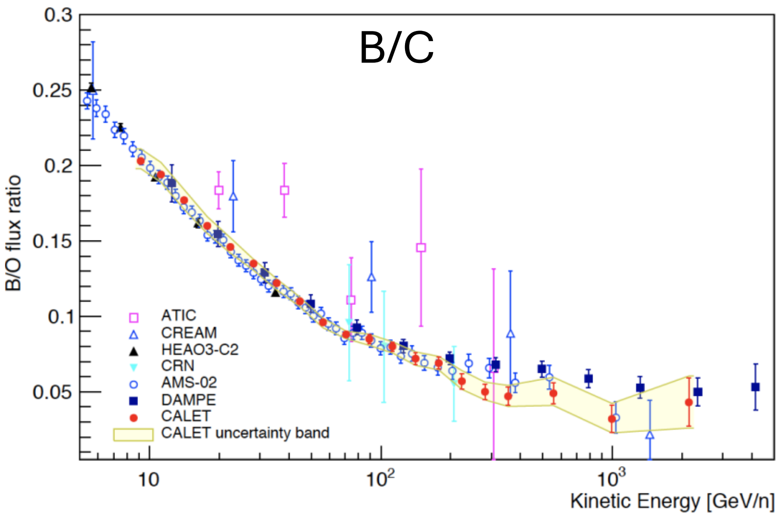
- Normalization of nuclei is smaller than the one of AM-02 (consistent with other experiments, e.g. PAMELA)
- C and O fluxes harden in a similar way above 200 GeV/n.
- B spectrum clearly different from C-O as expected for primary and secondary CR.
- The flux hardens more for B than for C and O above 200 GeV/n, albeit with low statistical significance.
- This suggests that the hardening is mainly due to propagation effects.

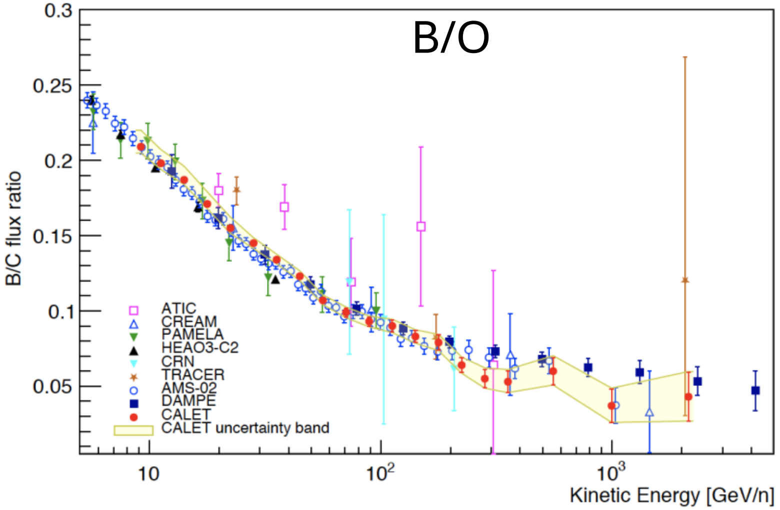
Please cite PRL papers: 10.1103/PhysRevLett.129.251103, 10.1103/PhysRevLett.125.251102

Fit and secondary/primary ratios

Conference proceeding: PoS(ICRC2023)058







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

C-O fit

γ = −2.66 ± 0.02
E_0 = (260 ± 50) GeV/n
$\Delta\gamma$ = 0.19 ± 0.04
χ^2/dof = 23/25

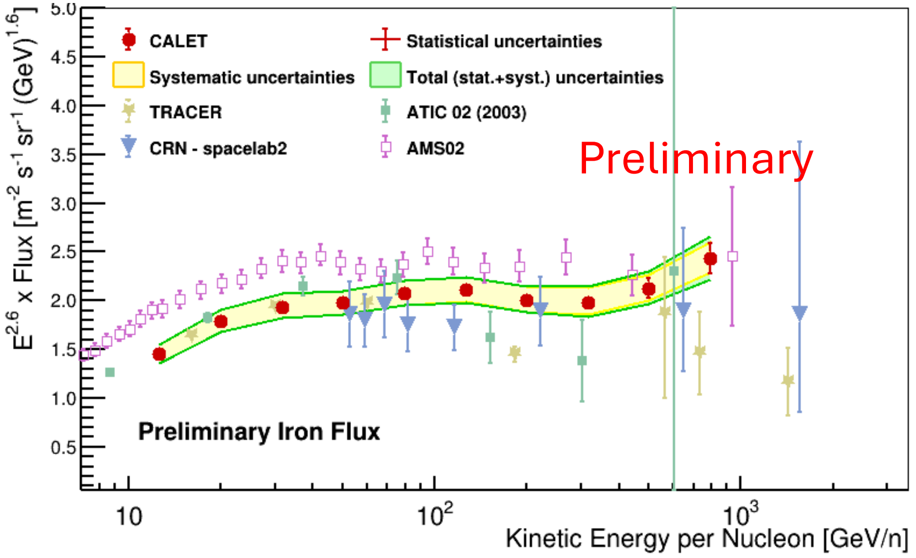
B fit

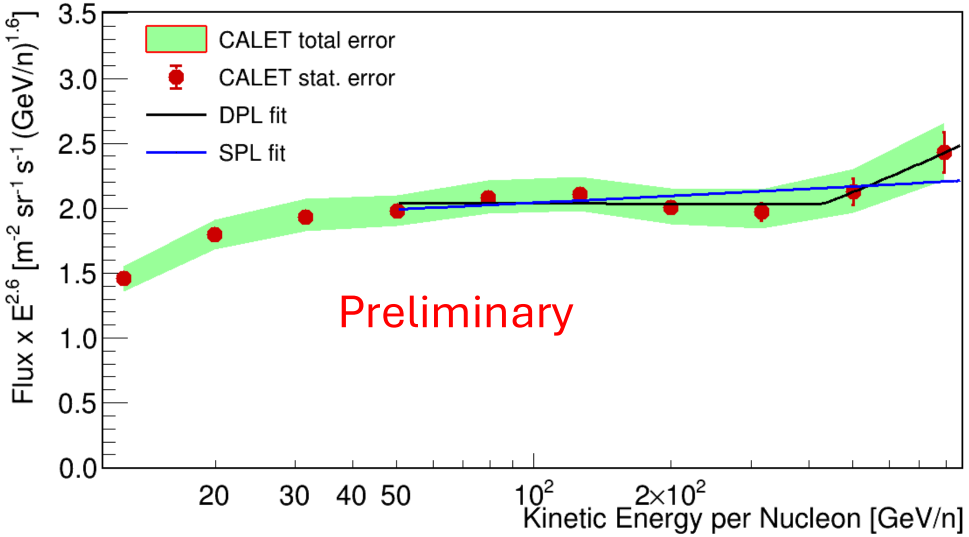
γ = −3.03 ± 0.03
E_0 fixed from C-O
$\Delta\gamma$ = 0.32 ± 0.14
χ^2/dof = 5.2/11

Please cite PRL papers: 10.1103/PhysRevLett.129.251103, 10.1103/PhysRevLett.125.251102

Iron spectrum and fit

Conference proceeding PoS(ICRC2023)061





- It is consistent with CNR and ATIC.
- DPL is preferred over SPL, with small statistical significance.

DPL Fit

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

- $\gamma = -2.60 \pm 0.01(\mathrm{stat}) \pm 0.08(\mathrm{sys})$
- $\chi^2/\mathrm{DOF} = 0.8/3$
- $\Delta\gamma = 0.29 \pm 0.27$
- $E_0 = (428 \pm 314)$ Gev/n

SPL Fit

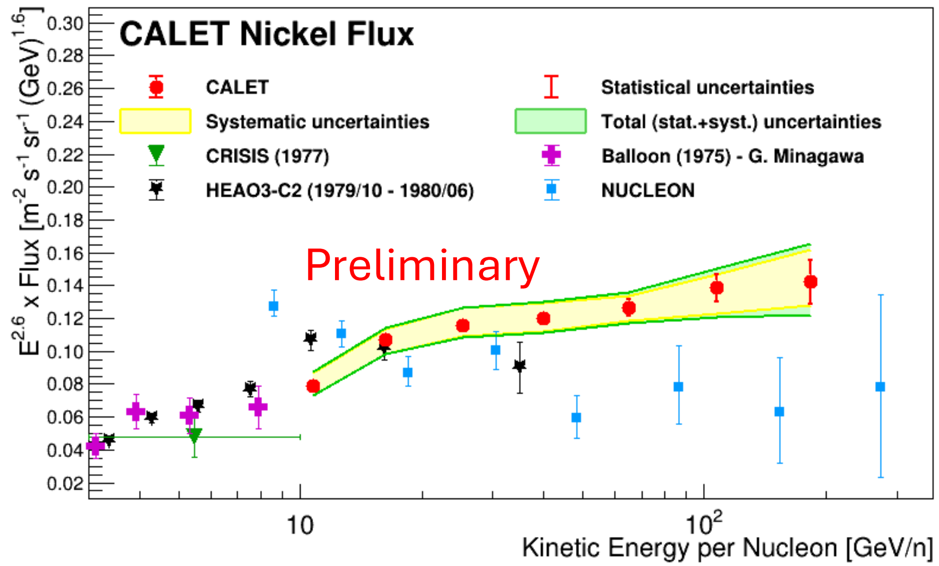
$$\Phi(E) = C\left(\frac{E}{1\ \mathrm{GeV}}\right)^{\gamma}$$

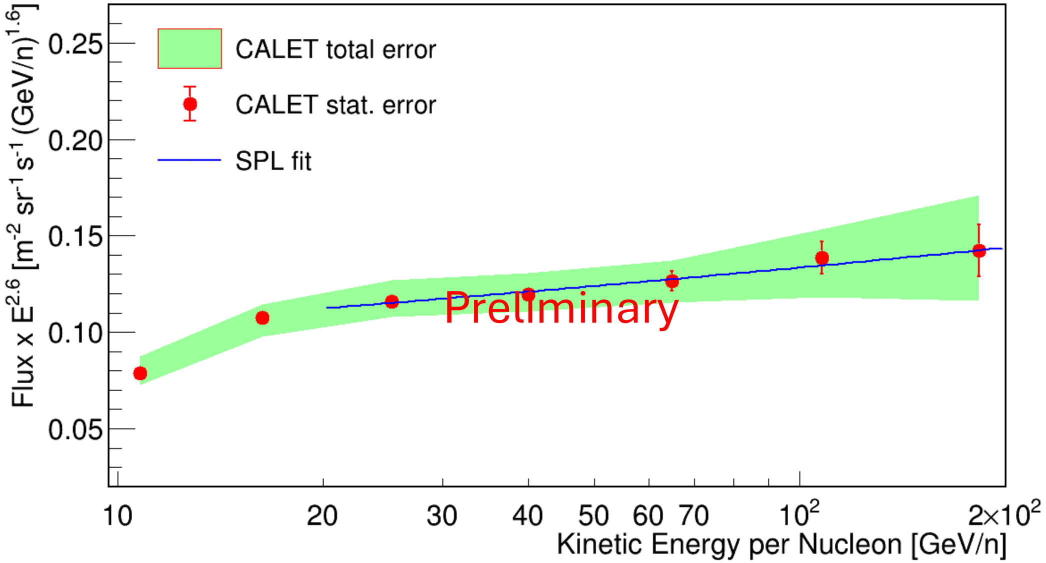
- $\gamma = -2.56 \pm 0.01(\mathrm{stat}) \pm 0.03(\mathrm{sys})$
- $\chi^2/\mathrm{DOF} = 2.7/5$

Please cite PRL paper: 10.1103/PhysRevLett.126.241101

Nickel spectrum and fit

Conference proceeding PoS(ICRC2023)061





- Slightly softer than NUCLEON results
- SPL well consistent with CALET data.

SPL Fit

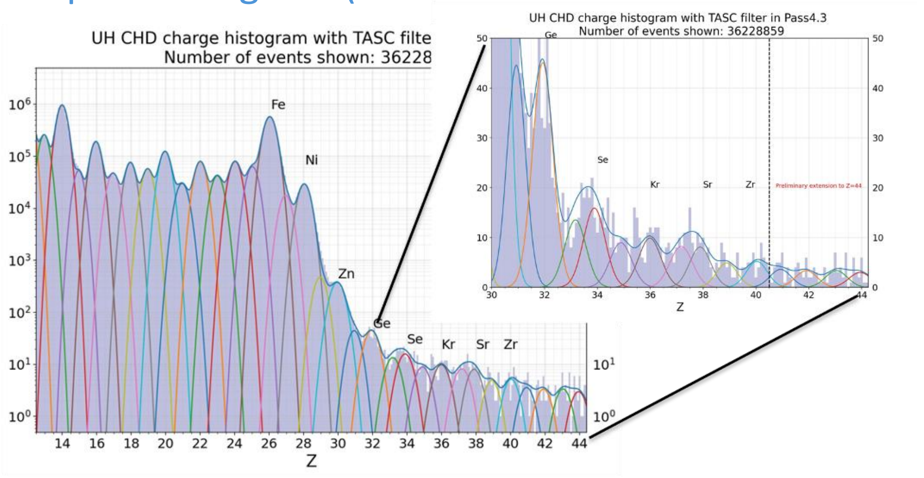
$$\Phi(E) = C\left(\frac{E}{1\ \mathrm{GeV}}\right)^{\gamma}$$

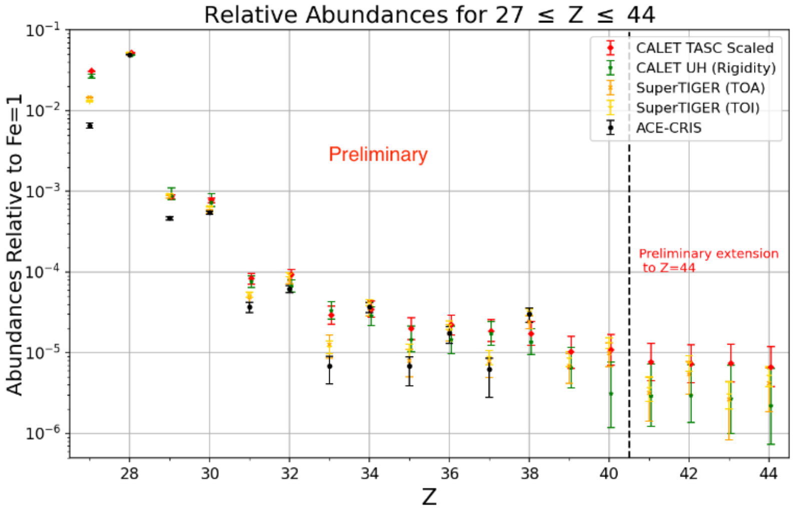
- $\gamma = -2.49 \pm 0.03(\mathrm{stat}) \pm 0.07(\mathrm{sys})$
- $\chi^2/\mathrm{DOF} = 0.1/3$

Please cite PRL paper: 10.1103/PhysRevLett.128.131103

Ultra heavy nuclei (Z>Fe)

Conference proceeding: PoS(ICRC2023)088





- Special UH CR trigger uses the CHD and the first 4 layers of the IMC: **GF ~ 4400 cm^{2}sr** without energy information**.** (~260 million events)
- A subset of events pass through the top of the TASC (~65 million events) with energy information.
- The CALET UH element ratios relative to Fe are consistent with Super-TIGER and ACE abundances.

Gamma and X rays observation

Main references: 10.3847/1538-4365/aad6a3, doi.org/10.3847/1538-4357/ac6f53

- Trigger modes:
  - High-energy (HE) trigger are always active (E > ~10 GeV)
  - low-energy gamma (LEG) trigger are active at low geomagnetic latitudes (E > ~1 GeV)
  - Trigger of CGBM instrument prompts CALET to temporarily activate LEG mode to search for transient counterparts.
- Transient analysis pipeline allows for quick follow-up of GRBs or LIGO/Virgo GW triggers.
- Observations corresponding to triggers in LIGO/Virgo O3-O4 run was analyzed.
- No candidate of EM counterparts was found in CALET data. We obtained upper limits of high energy gamma-ray flux.

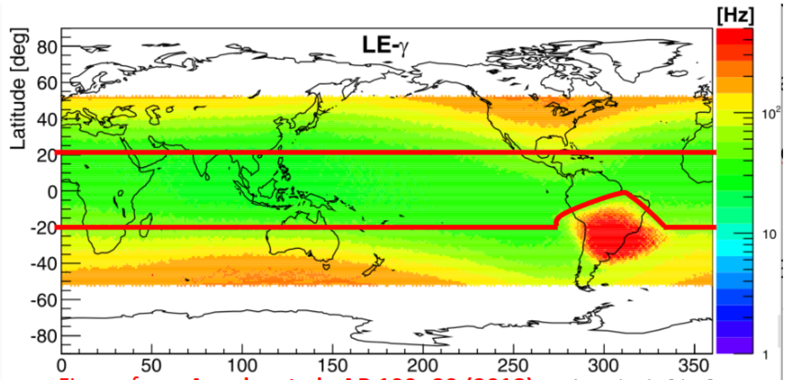
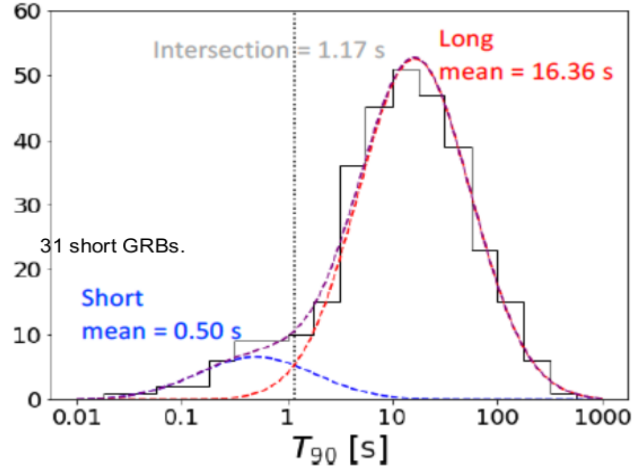


Figure from **Asaoka et al., AP 100, 29 (2018)**

CGBM has detected 327 GRBs as of June 2023.

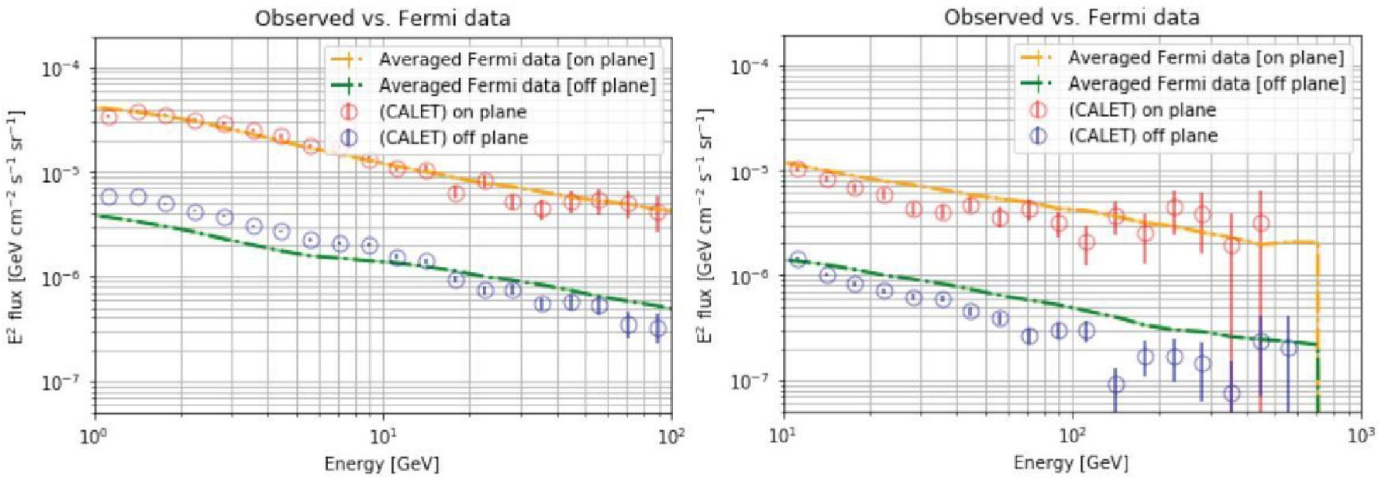
Duration distribution measured by SGM (40 – 1000 keV)

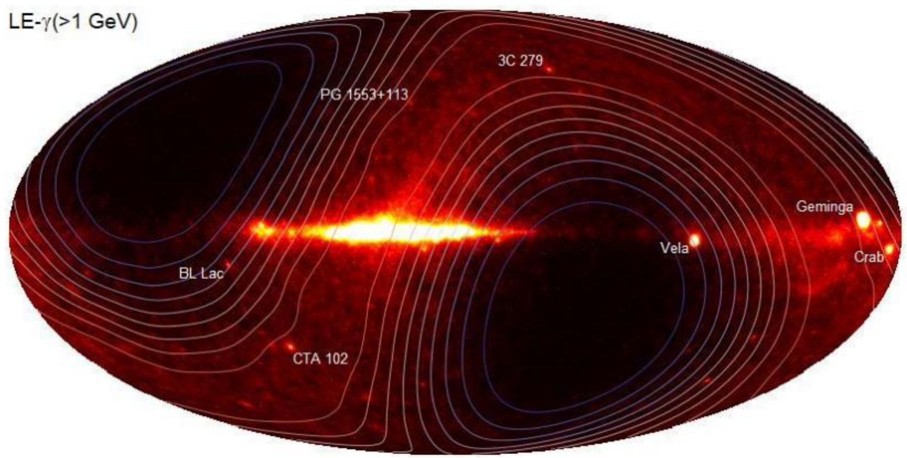


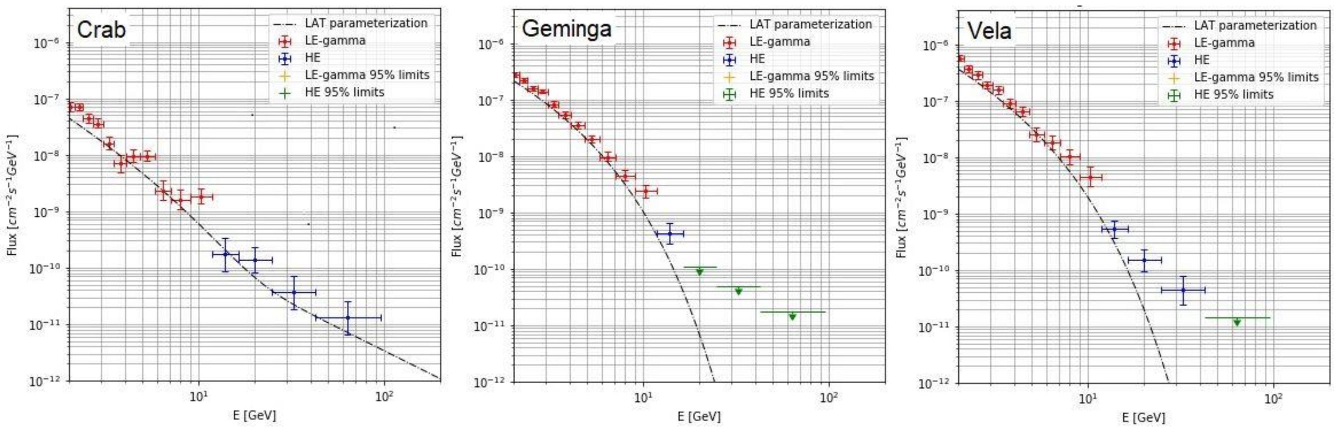
Diffuse and point source spectra

Conference proceeding: PoS(ICRC2023)708

- The spectra for point sources and diffuse components are found to be consistent with those by Fermi-LAT.
- Effective area: ~400 cm^2
- Angular resolution: < 0.2° (> 10 GeV).
- Energy resolution: ~2% (> 10 GeV).



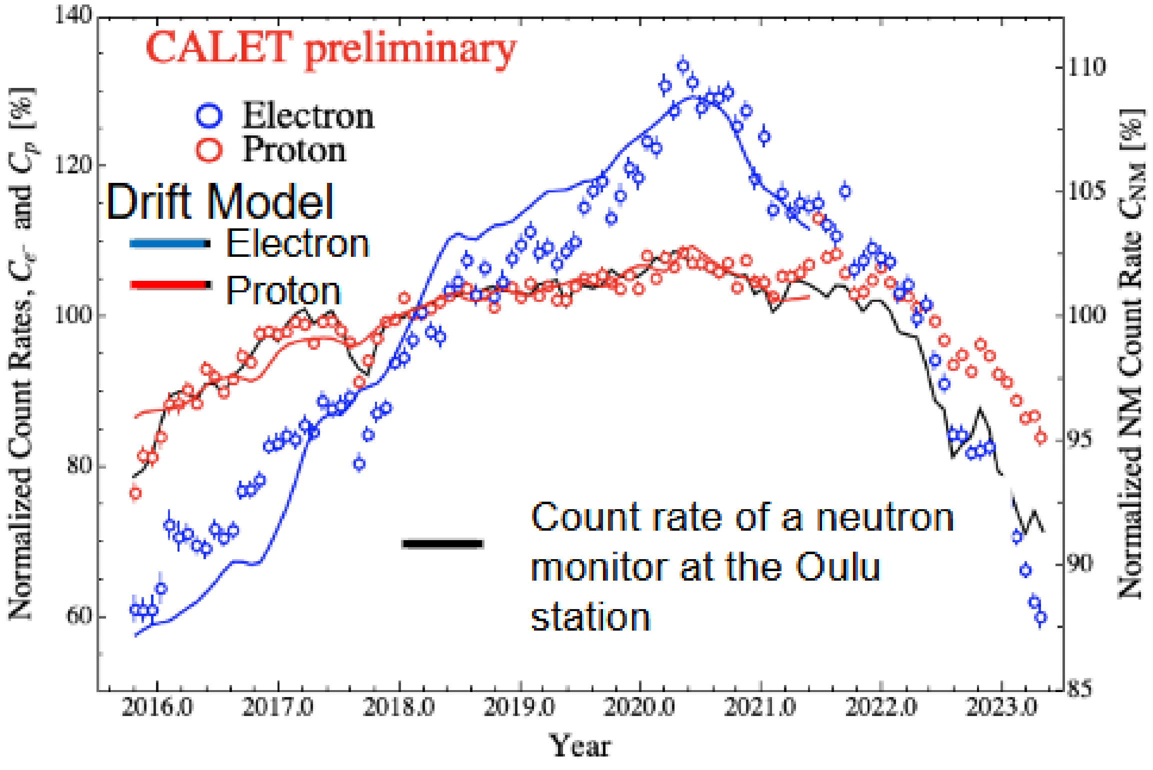




Solar modulation: electron vs protons

- Sine 2015/10, a steady increase in the 1-10 GeV all-electron flux has been observed.
- In ~2020, the flux has reached the maximum flux
- We have observed a clear charge-sign dependence of the solar modulation of GCRs.
- We also have succeeded in reproducing variations of C_{e-} and C_p simultaneously with a numerical drift model of the solar modulation, which implies that the drift effect plays a major role in the long-term modulation of GCRs.

PRL 130 211101 (2023) & PoS(ICRC2023)1253



Conclusion

- Mian observation discussed in this presentation:
  - Electron up to 7.5 TeV, cut-off confirmed and hint of SNR contribution. [PRL 131, 191001 (2023)]
  - Proton up to 70 TeV, hardening and softening confirmed. [PRL 129, 101102 (2022)]
  - Helium up to 250 TeV, hardening and softening confirmed. [PRL 130, 171002 (2023)]
  - Carbon and Oxygen up to 2.2 TeV/n, hardening clearly observed. [PRL 125, 251102 (2020) and ICRC2023]
  - Boron up to 2.2 TeV/n, harden more than C-O. [PRL 129, 251103 (2022) and ICRC2023]
  - Iron up to 2 TeV/n, hint of hardening [PRL 126, 241101 (2021) and ICRC2023]
  - Nickel up to 240 GeV/n, more accurate high energy measurement. [PRL 128, 131103 (2022) and ICRC2023]
  - High energy gamma-rays: diffuse flux, source spectra [ICRC2023]
  - Transient low energy gamma and X-rays: no candidate of EM counterparts. [ApJ 933:85, ApJL 829:L20]
  - Solar modulation: charge sing dependence. [PRL 130, 211001 (2023) and ICRC2023]
  - Ultra heavy nuclei: large acceptance analysis, consistent with S-TIGER [ICRC2023]
- Other important topics were not discussed in this presentation, e.g. space weather (https://doi.org/10.1029/2021GL097529), nuclei ratios (He/p,Ni/C, ….)….
- **Extended operations recently approved by JAXA/NASA/ASI through the end of 2030**

CRIS-MAC 2024

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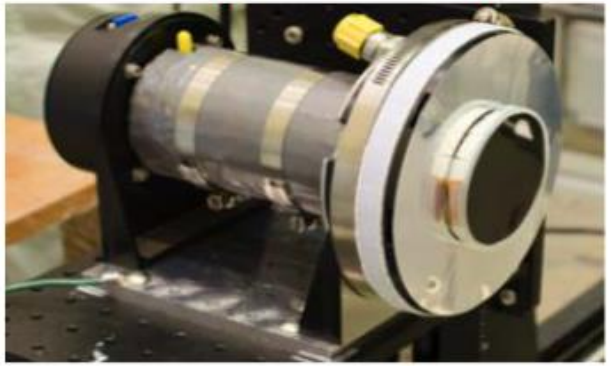
SEZIONE DI FIRENZE

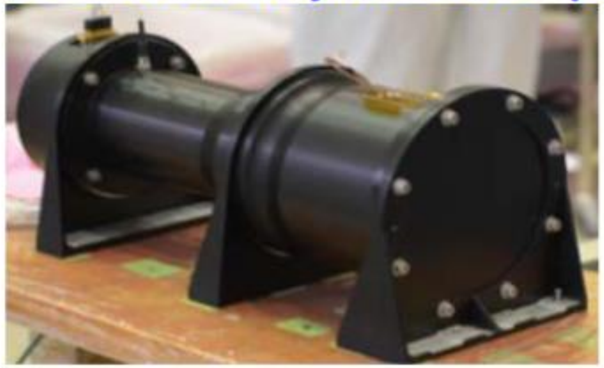
Thank you very much

Calet Gamma-ray Burst Monitor (CGBM)

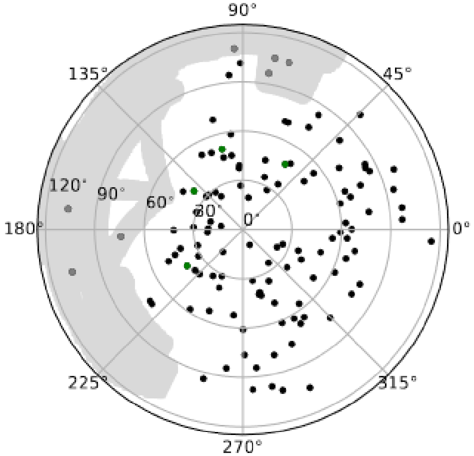
Hard X-ray Monitor (HXM)



Soft Gamma-ray Monitor (SGM)



Field of view (SGM)



- CGBM consists of two HXMs and one SGM.
- Both HXM and SGM are scintillation detectors, LaBr3(Ce) and BGO, respectively.
- CGBM collects light curve data and spectral data for each 1/8 s and 4 s, respectively.
- If CGBM detects a transient, CGBM captures event data (62.5 us, 4096 x 2 energy channels).