P-004

国際宇宙ステーション搭載 CALETによる7年間観測の成果

CALET

Calorimetric
Electron
Telescope

on the International Space Station

田村 忠久
神奈川大学工学部
他CALET国際研究チーム

第23回　宇宙科学シンポジウム（2022年度）

CALET Member list

as of Dec. 01, 2022

O. Adriani,[1, 2] Y. Akaike,[3, 4] K. Asano,[5] Y. Asaoka,[5] E. Berti,[1] G. Bigongiari,[6, 7] W.R. Binns,[8] M. Bongi,[1, 2] P. Brogi,[6, 7] A. Bruno,[9] J.H. Buckley,[8] N. Cannady,[10, 11, 12] G. Castellini,[13] C. Checchia,[6, 7] M.L. Cherry,[14] G. Collazuol,[15, 16] G.A. de Nolfo,[9] K. Ebisawa,[17] A. W. Ficklin,[14] H. Fuke,[17] S. Gonzi,[1, 2] T.G. Guzik,[14] T. Hams,[10] K. Hibino,[18] M. Ichimura,[19] K. Ioka,[20] W. Ishizaki,[5] M.H. Israel,[8] K. Kasahara,[21] J. Kataoka,[22] R. Kataoka, [23] Y. Katayose,[24] C. Kato,[25] N. Kawanaka,[20] Y. Kawakubo,[14] K. Kobayashi,[3, 4] K. Kohri,[26] H.S. Krawczynski, [8] J.F. Krizmanic,[11] P. Maestro,[6, 7] P.S. Marrocchesi,[6, 7] A.M. Messineo,[27, 7] J.W. Mitchell,[11] S. Miyake,[28] A.A. Moiseev,[29, 11, 12] M. Mori,[30] N. Mori,[2] H.M. Motz,[31] K. Munakata,[25] S. Nakahira,[17] J. Nishimura,[17] S. Okuno,[18] J.F. Ormes,[32] S. Ozawa,[33] L. Pacini,[1, 2, 13] P. Papini,[2] B.F. Rauch,[8] S.B. Ricciarini,[13, 2] K. Sakai,[10, 11, 12] T. Sakamoto,[34] M. Sasaki,[29, 11, 12] Y. Shimizu,[18] A. Shiomi,[35] P. Spillantini,[1] F. Stolzi,[6, 7] S. Sugita,[34] A. Sulaj, [6, 7] M. Takita,[5] T. Tamura,[18] T. Terasawa,[5] S. Torii,[3] Y. Tsunesada,[36, 37] Y. Uchihori,[38] E. Vannuccini,[2] J.P. Wefel, [14] K. Yamaoka,[39] S. Yanagita,[40] A. Yoshida,[33] K. Yoshida,[21] and W. V. Zober [8]

PI : Japan
Co-PI : Italy
Co-PI : USA

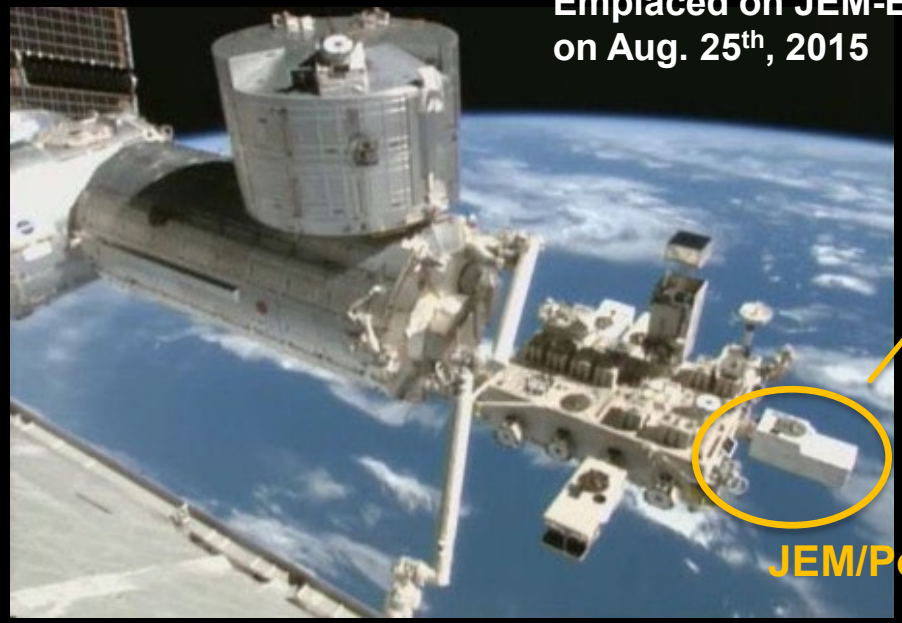
1) University of Florence, Italy
2) INFN Florence, Italy
3) WISE, Waseda University, Japan
4) JEM Utilization Center, JAXA, Japan
5) ICRR, University of Tokyo, Japan
6) University of Siena, Italy
7) INFN Pisa, Italy
8) Washington University, St. Louis, USA
9) Heliospheric Physics Laboratory, NASA/GSFC, USA
10) University of Maryland, Baltimore County, USA
11) Astroparticle Physics Laboratory, NASA/GSFC, USA
12) CRESST, NASA/GSFC, USA
13) IFAC, CNR, Italy
14) Louisiana State University, USA
15) University of Padova, Italy
16) INFN Padova, Italy
17) ISAS, JAXA, Japan
18) Kanagawa University, Japan
19) Hirosaki University, Japan
20) YITP, Kyoto University, Japan
21) Shibaura Institute of Technology, Japan
22) ASE, Waseda University, Japan
23) NIPR, Japan
24) Yokohama National University, Japan
25) Shinshu University, Japan
26) IPNS, KEK, Japan
27) University of Pisa
28) NIT(KOSEN), Ibaraki College, Japan
29) University of Maryland, College Park, USA
30) Ritsumeikan University, Japan
31) GCSE, Waseda University, Japan
32) University of Denver, USA
33) NICT, Japan
34) Aoyama Gakuin University, Japan
35) Nihon University, Japan
36) Osaka Metropolitan University, Japan
37) NITEP, Osaka Metropolitan University, Japan
38) QST, Japan
39) Nagoya University, Japan
40) Ibaraki University, Japan

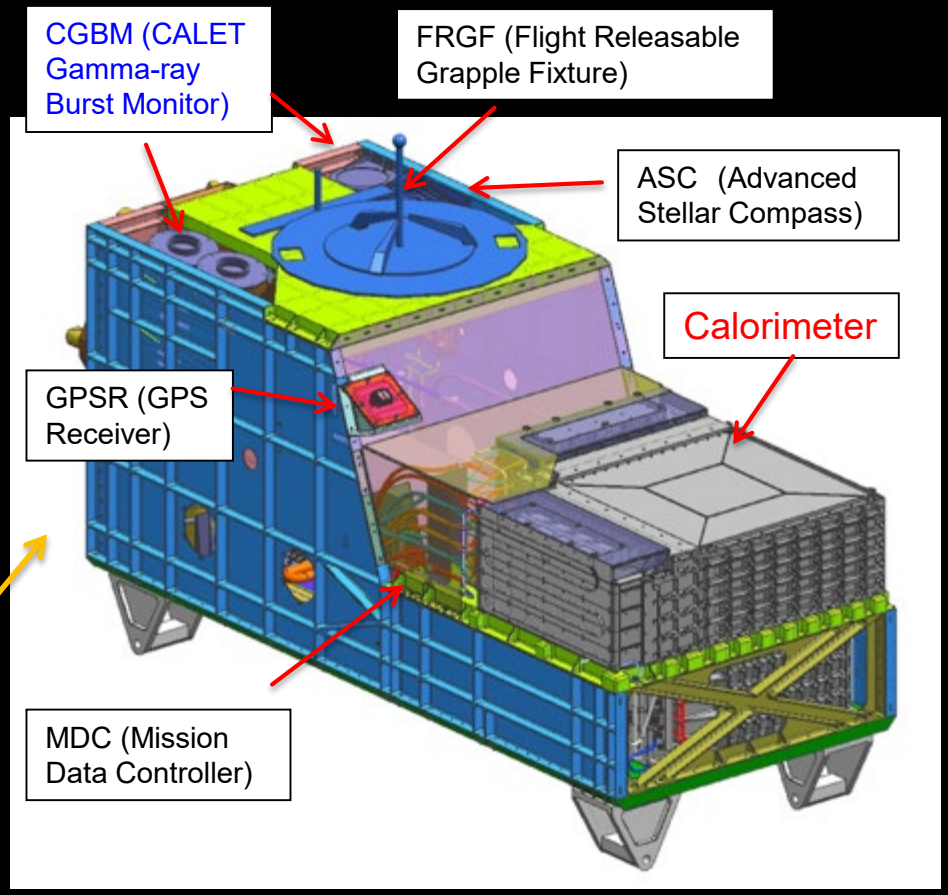
CALET Payload

Kounotori (HTV) 5

Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

Emplaced on JEM-EF port #9 on Aug. 25th, 2015

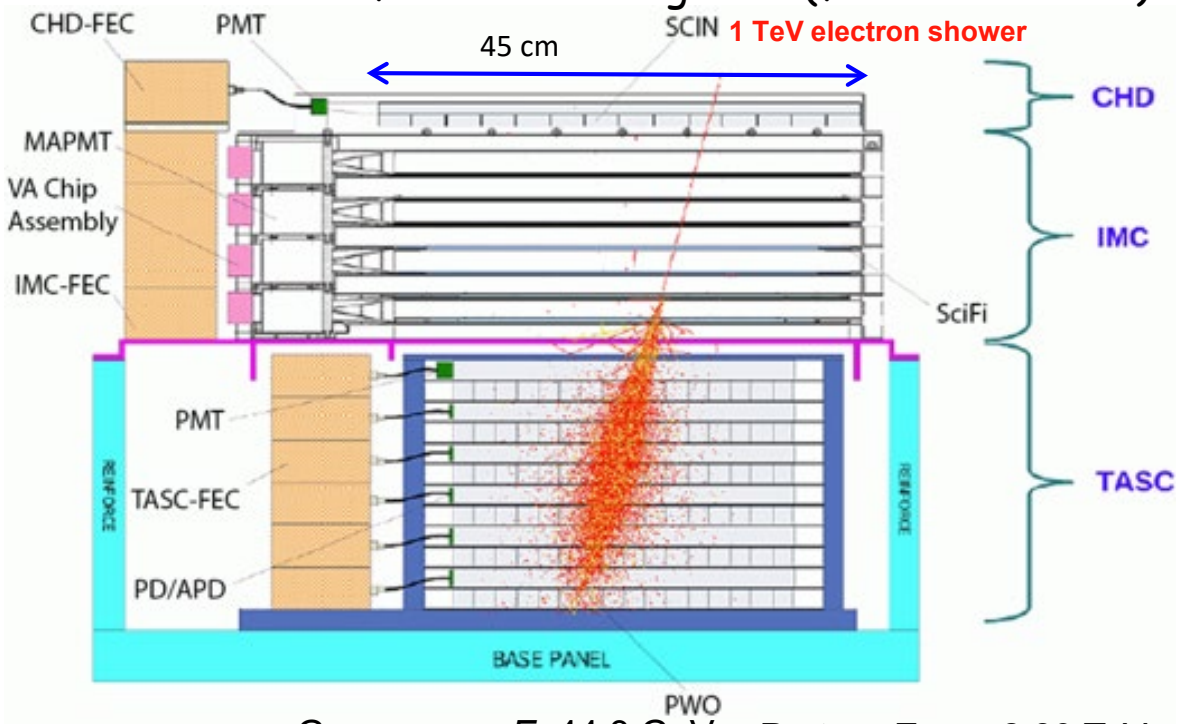




- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W（max）**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

CALET Calorimeter and Capability

Field of view: ~ 45 degrees (from the zenith) Geometrical Factor: ~ 1,040 cm^{2}sr (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

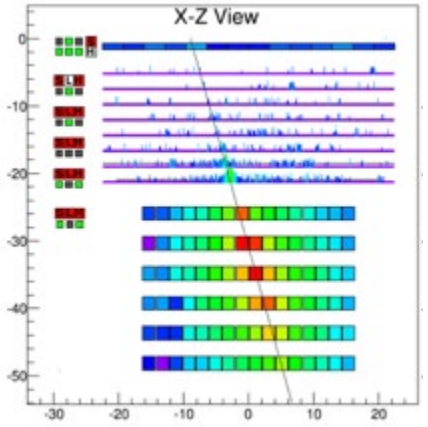
IMC – Imaging Calorimeter

- 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**

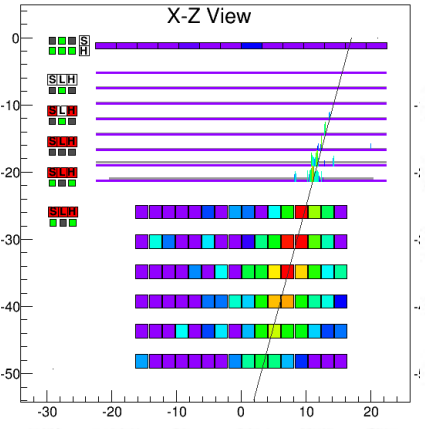
TASC – Total Absorption Calorimeter 27 X_0, 1.2 λ_I

- 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}

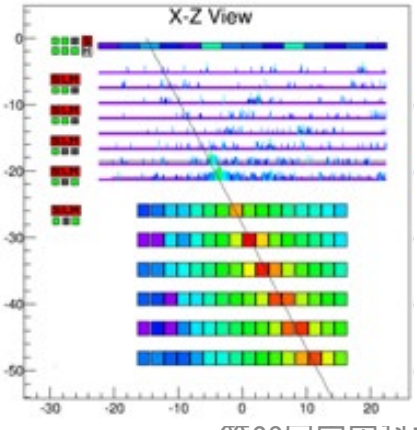
Electron, E=3.05 TeV



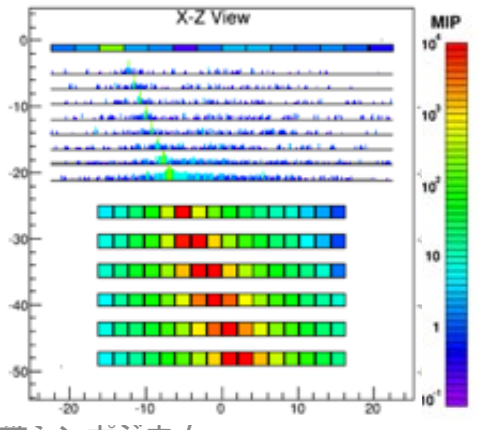
Gamma-ray, E=44.3 GeV



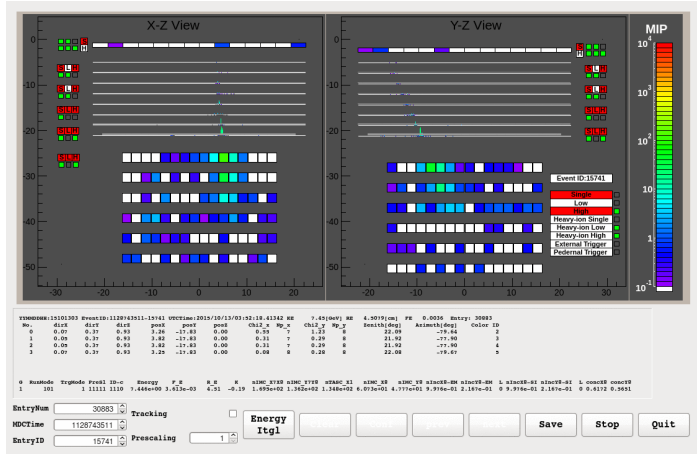
Proton, E_{TASC}=2.89 TeV



Iron, E_{TASC} =9.3 TeV

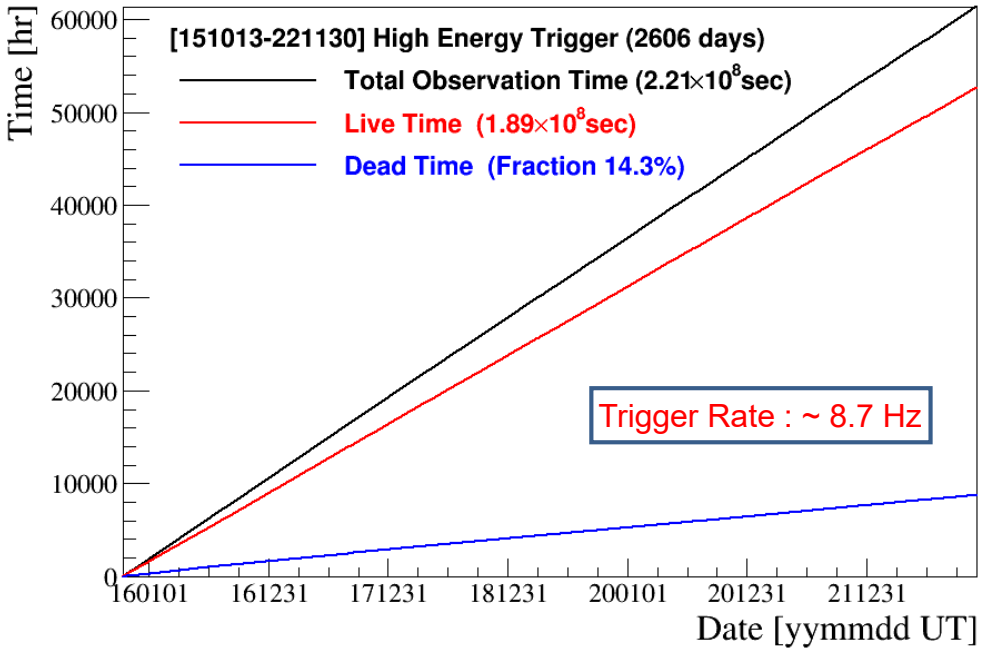


Event Display: Electron Candidate (>100 GeV)



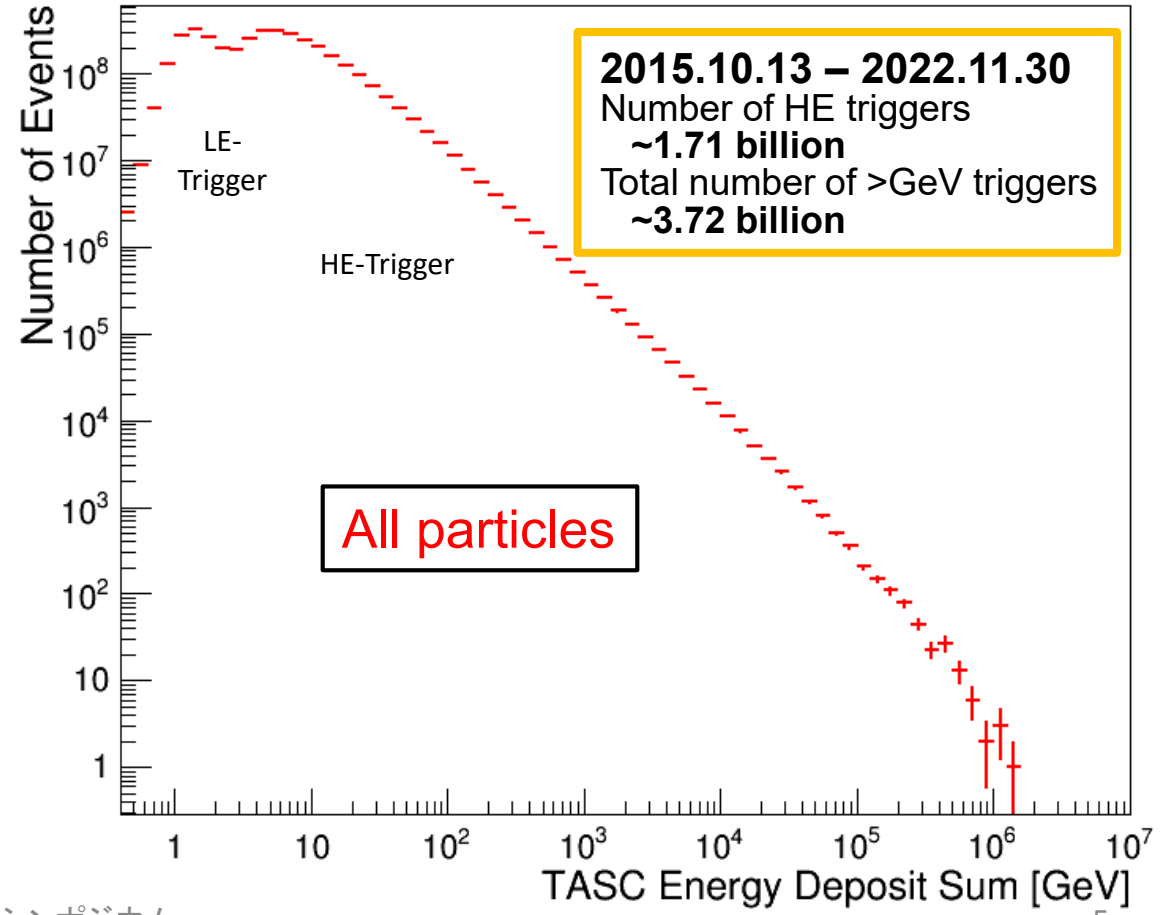
CALET Observations on the ISS（2015.10.13－2022.11.30）

Accumulated observation time (live, dead)



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

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



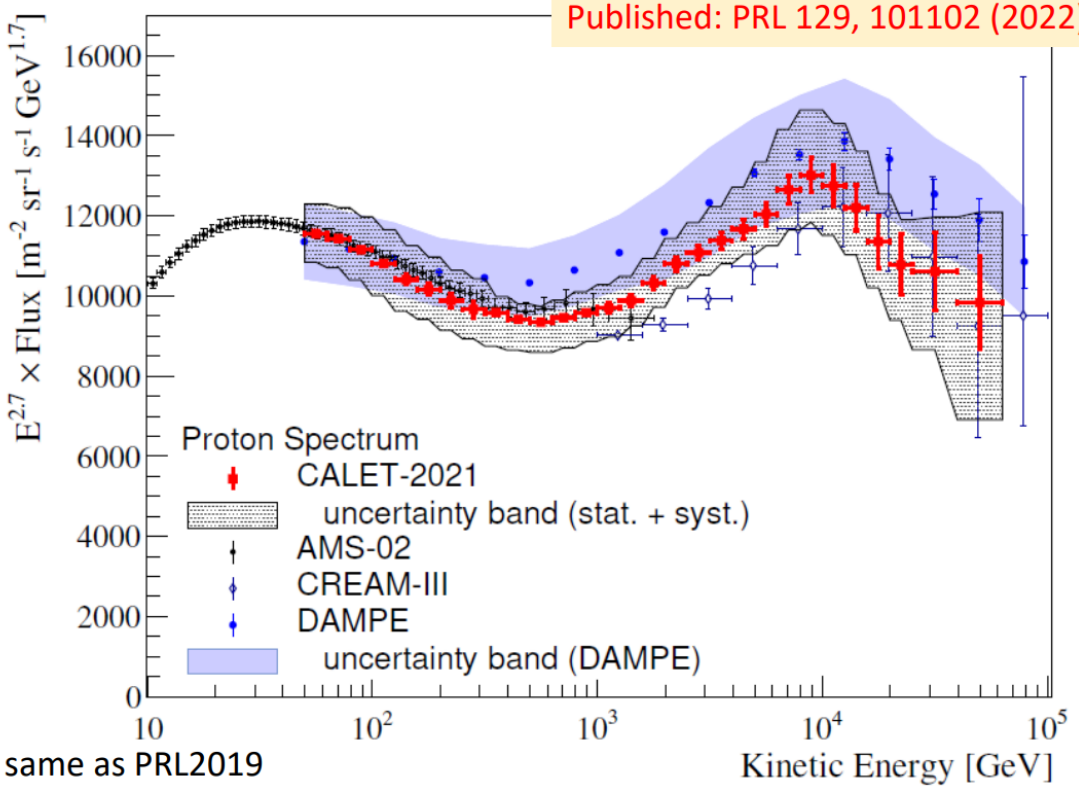
High-energy trigger (> 10 GeV) statistics:
- Operational time > **2606 days**(*)
  (*) as of November 30, 2022
- Live time fraction **> 85%**
- Exposure of HE trigger
  ~229 m² sr day
- HE-gamma point source exposure
  ~4.4 m² day (for Crab, Geminga)

Cosmic-ray Proton Spectrum

Published at PRL 126 241101 (2022.4.1)

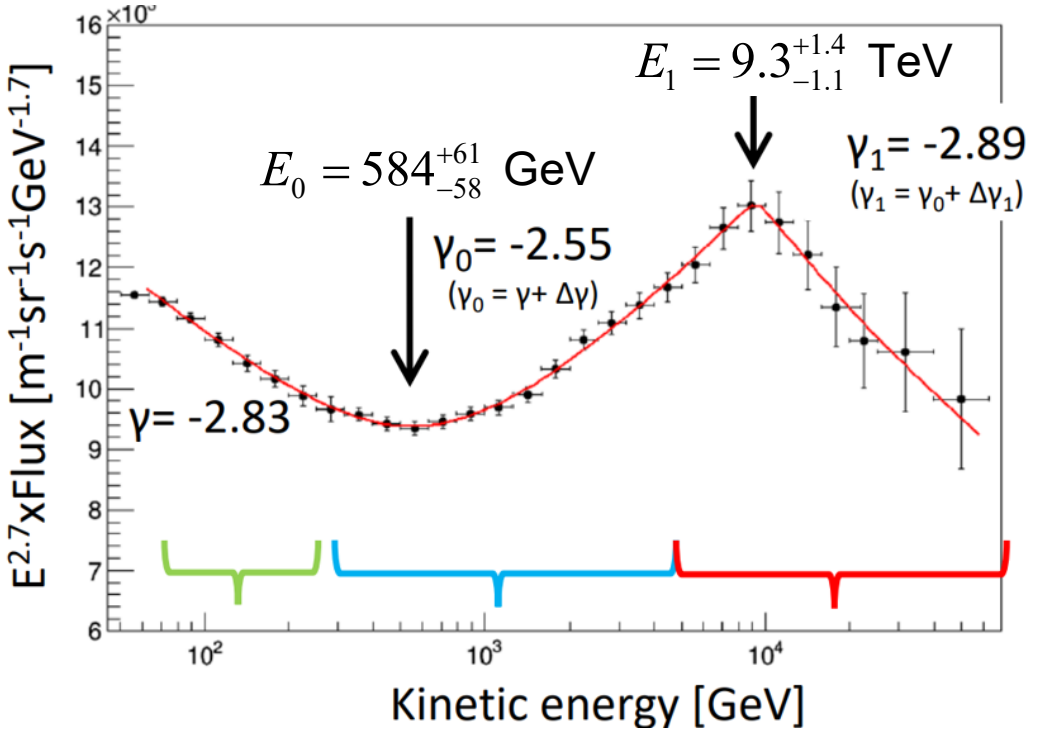
P-003

Published: PRL 129, 101102 (2022)



LE: same as PRL2019

HE: 1925 days of live time (Oct. 2015 – Dec. 2021)



We also observed a spectral softening over 7 TeV.

Fitting function (double broken power law):

$$\Phi = E^{2.7} \times C \times \left(\frac{E}{1}\right)^{\gamma} \times \left(1 + \left(\frac{E}{E_0}\right)^{s}\right)^{\frac{\Delta\gamma}{s}} \times \left(1 + \left(\frac{E}{E_1}\right)^{s_1}\right)^{\frac{\Delta\gamma_1}{s_1}}$$

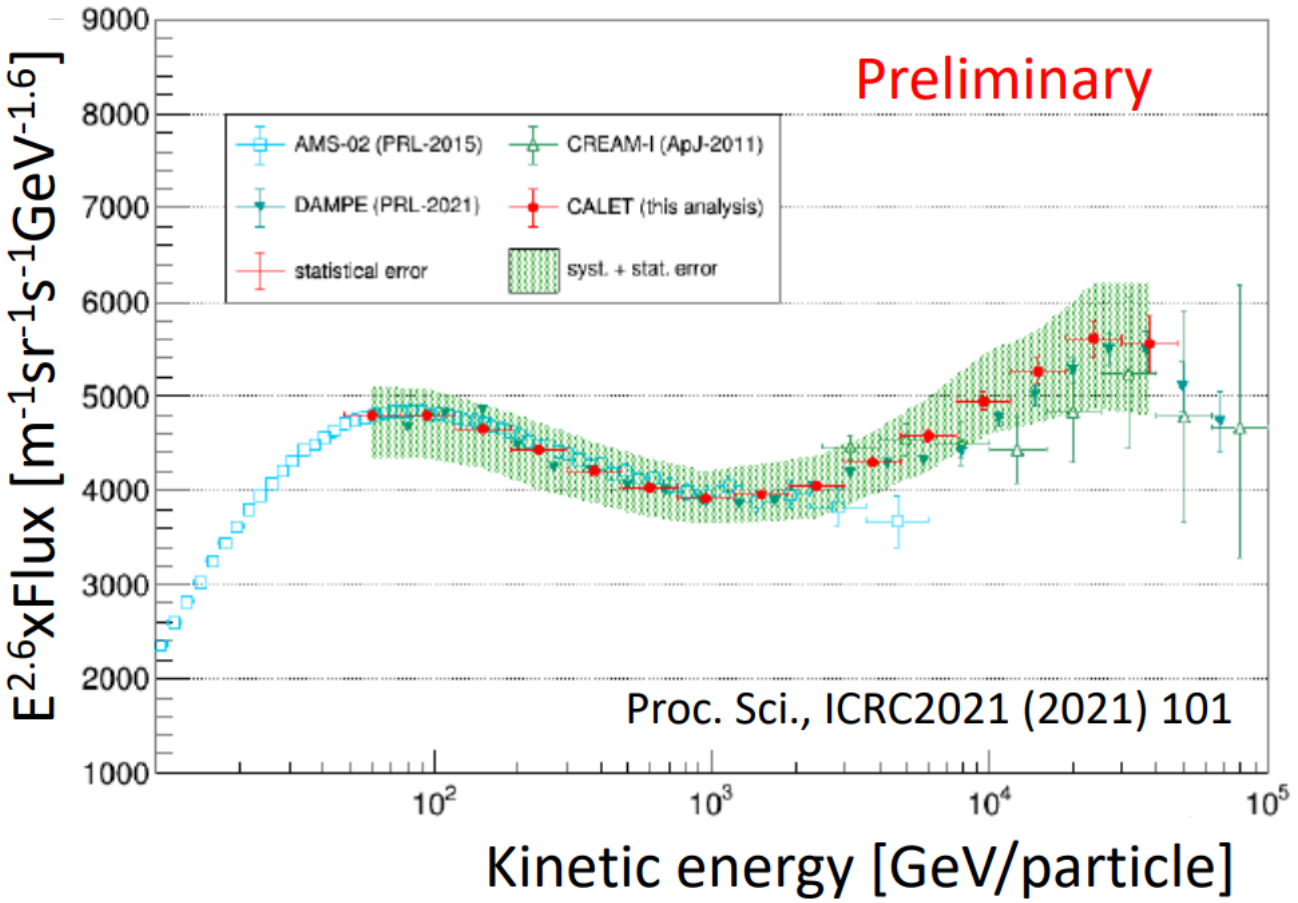
Low energy hardening softening

γ	-2.83+0.01-0.02
S	2.4+0.8-0.6
$\Delta\gamma$	(2.8+0.4-0.2)x10^{-1}
E_0	(5.84+0.61-0.58)x10^{2}
$\Delta\gamma_1$	(-3.4±0.6)x10^{-1}
E_1	(9.3+1.4-1.1)x10^{3}
s_1	~30

Softening is much sharper and the s_1 becomes higher with a large uncertainty.

Cosmic-ray Helium spectrum

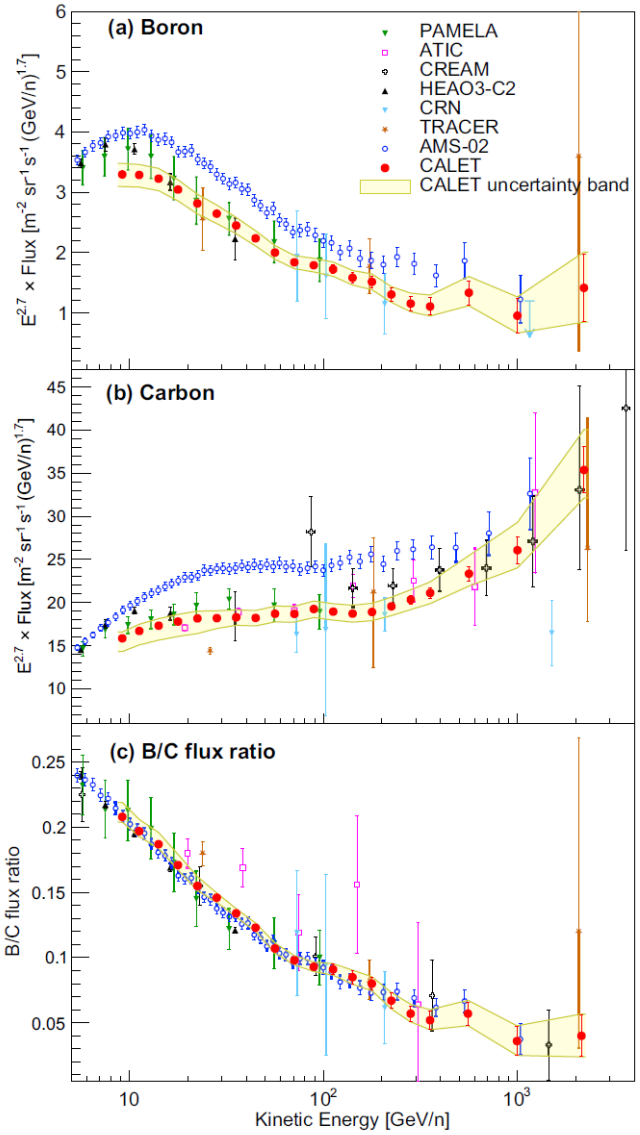
P-003



- We observe the spectral hardening starting at 1.3±0.3TeV. This is consistent with DAMPE result (PRL 2021).

Cosmic-ray Boron and Carbon Flux

Published at PRL 129, 251103 (2022.12.16) **P-001**

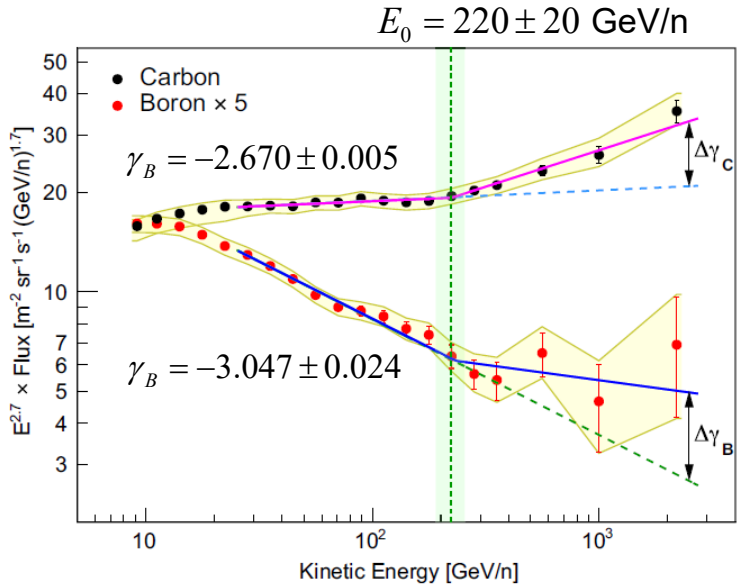


(a) Boron flux

(b) carbon flux

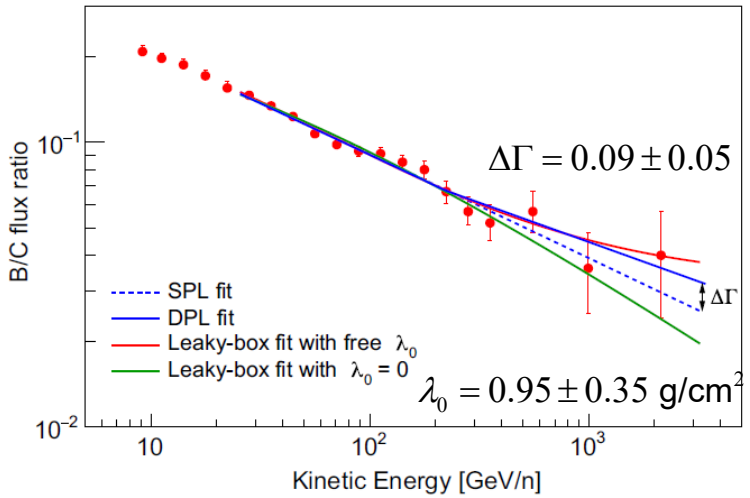
(c) Ratio of boron to carbon

Error bars of CALET data represent the statistical uncertainty only, while yellow band indicates the quadratic sum of statistical and systematic errors.



CALET B and C energy spectra are fitted with double power law functions.

$$\Delta\gamma_B = 0.19 \pm 0.03$$
$$\Delta\gamma_B = 0.25 \pm 0.12$$



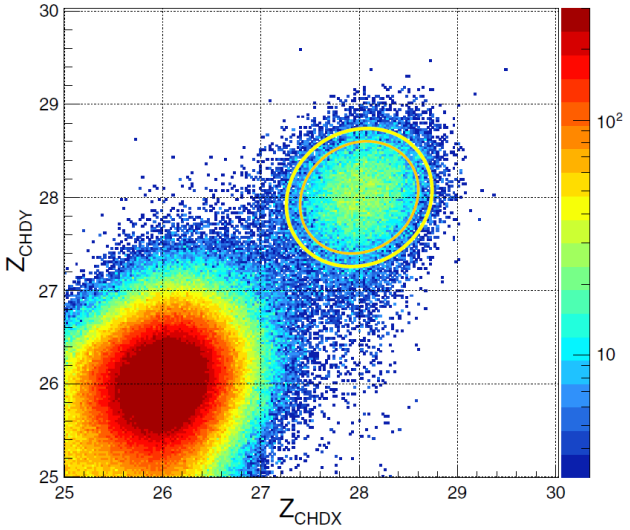
The CALET B/C ratio fitted to a single power law function (SPL), a double power law (DPL) function.

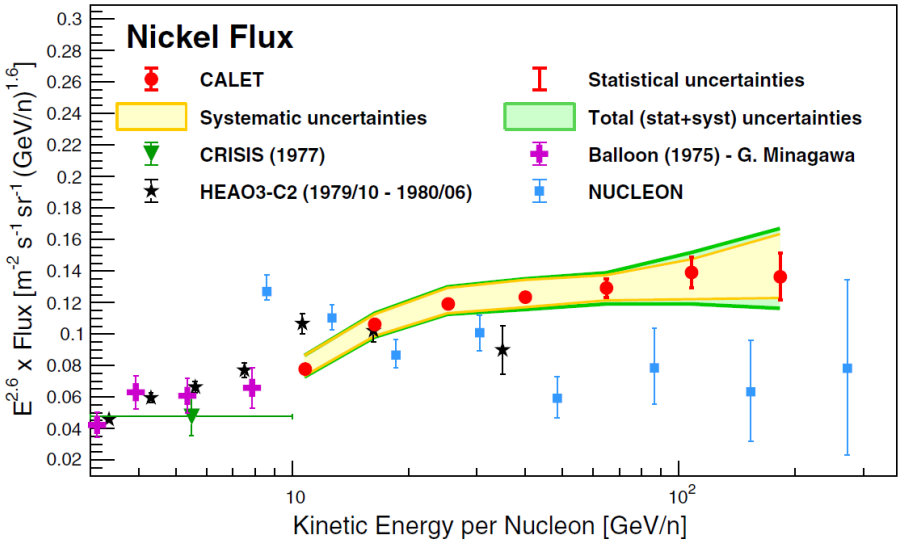
DPL provides a better fit, Suggesting a trend of the data toward a Flattening of B/C at high energy.

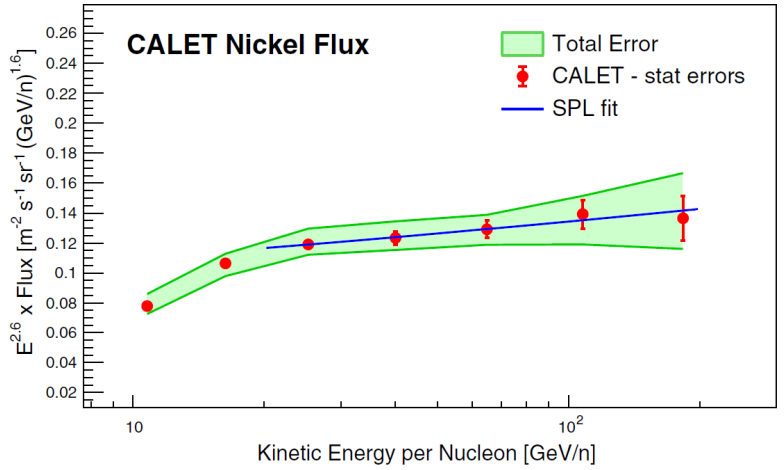
Cosmic-ray Nickel Spectrum

Published at PRL 128, 131103 (2022.4.1)

P-001



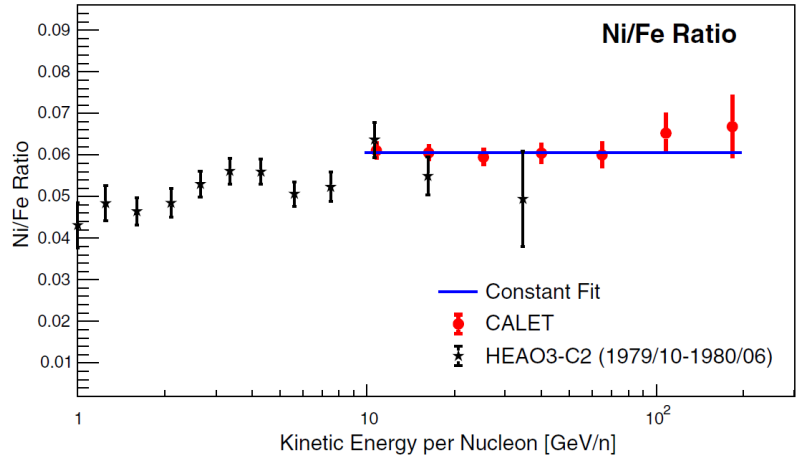




Nickel candidates are selected inside an ellipse with semi minor and major axes 1.4 σ_x and 1.4σ_y , respectively, rotated clockwise by 45 deg.

The maximum and the minimum elliptical selection (depending on the energy) are indicated by the yellow and the orange ellipses.

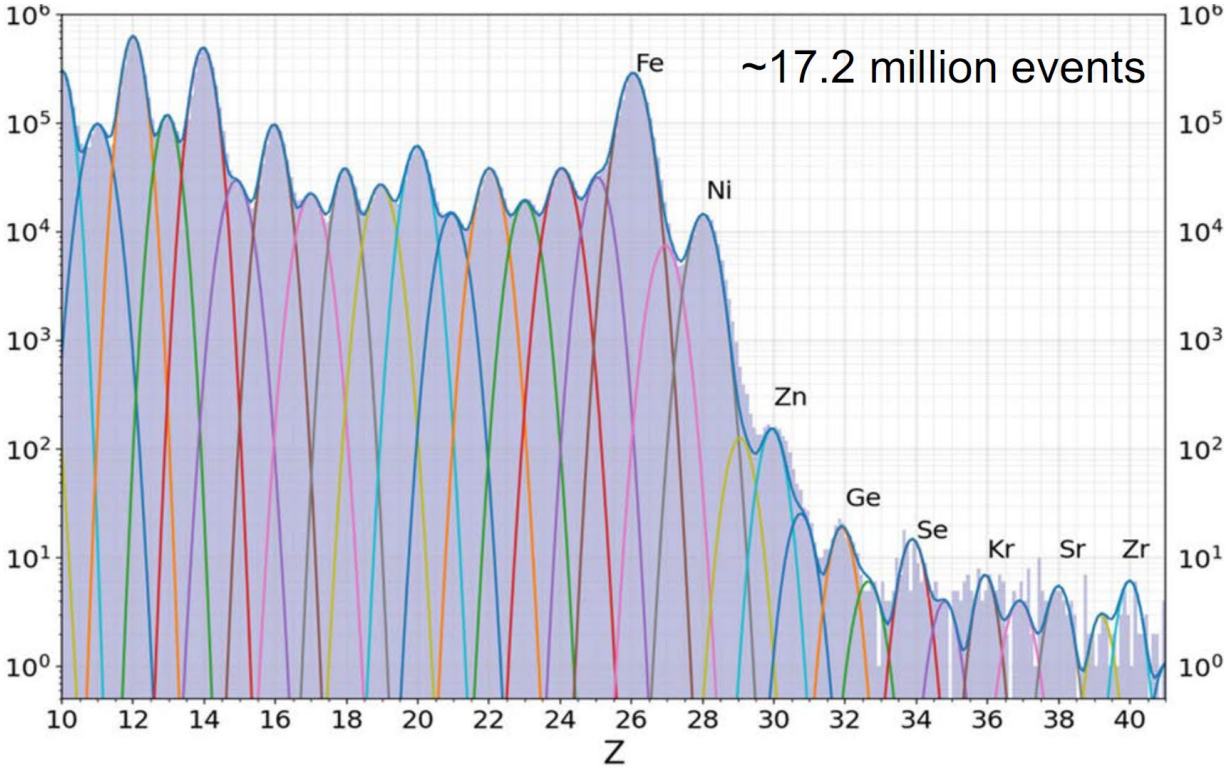
- The measurement improves considerably, both in energy reach and in precision, the present data.
- Below 20 GeV/n: The observed nickel spectrum was found to decrease with energy following a general trend also observed for primaries lighter than nickel.
- Above 20 GeV/n: The present observations are consistent, within our uncertainty band, with the hypothesis of a Single Power Law spectrum up to 240 GeV/n.

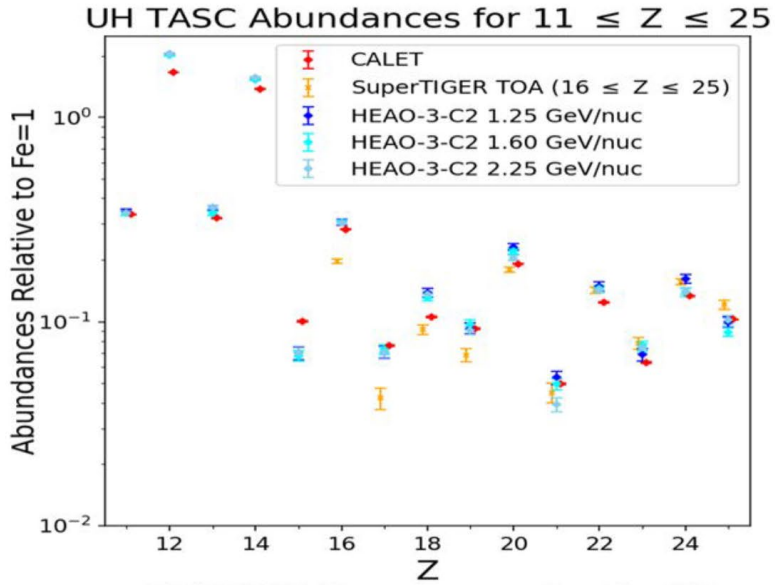


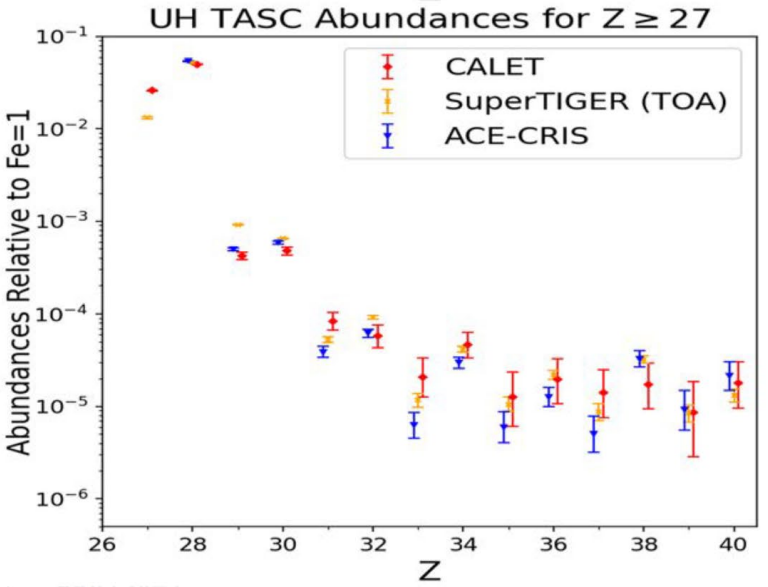
Ultra Heavy Nuclei

COSPAR (2022) : W. Zober

- This analysis uses ~6.5 years of CALET UH-trigger data from 10/2015 through 02/2022.
- We constrain the analysis to events that pass through the TASC. (~38 million events).
- This reduces statistics but the energy information allows for an improved charge assignment. Allowing us to trade statistics for better resolution.



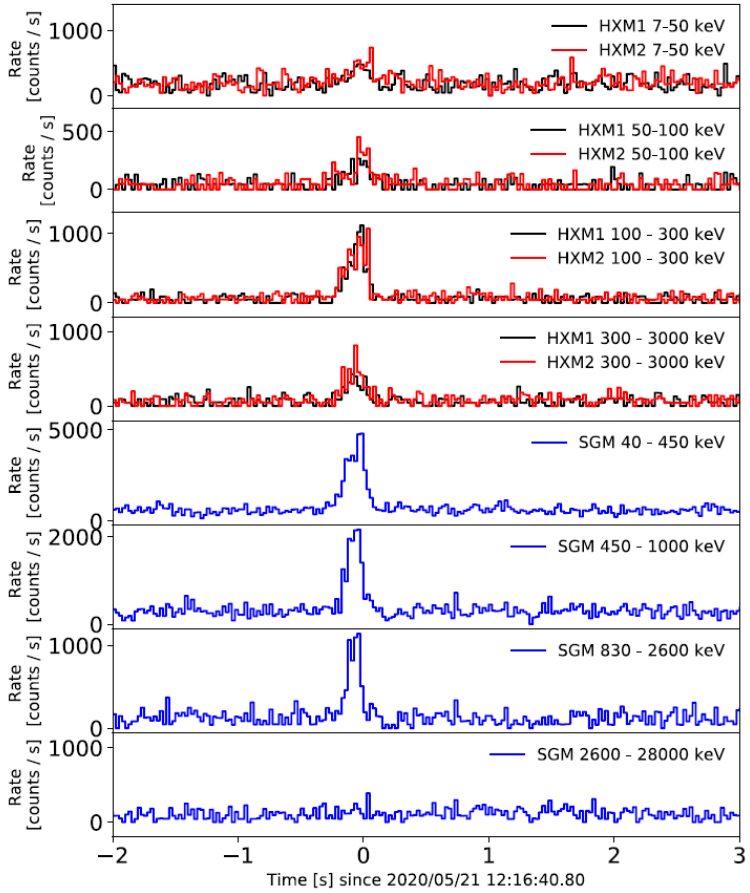




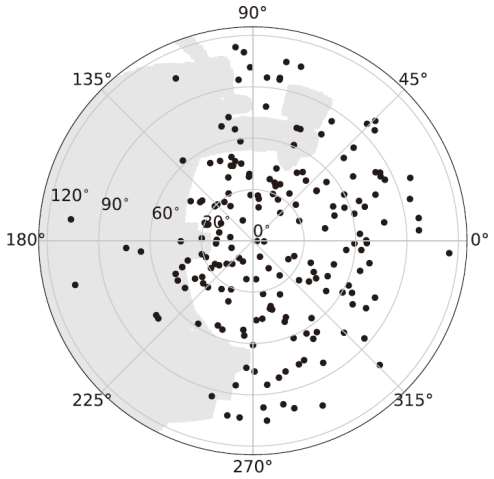
GRB Observation

Published at The Astrophysical Journal, 933:85 (16pp), 2022.7.1

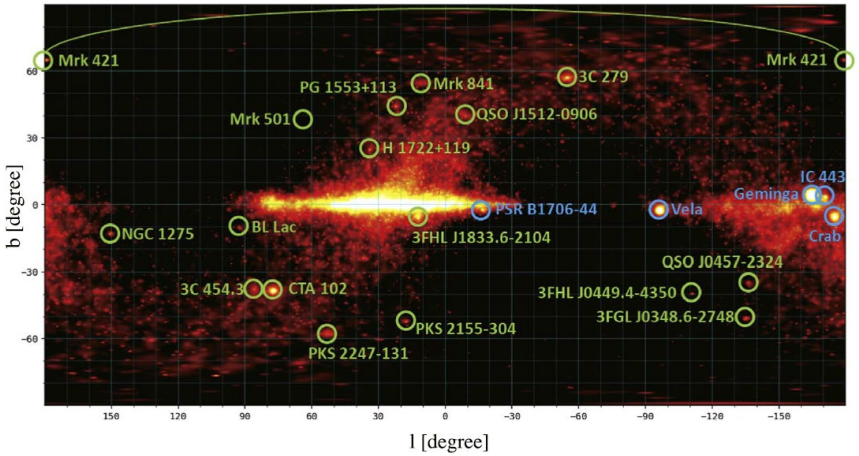
Electromagnetic Counterparts of Gravitational Waves during the LIGO/Virgo O3 Run



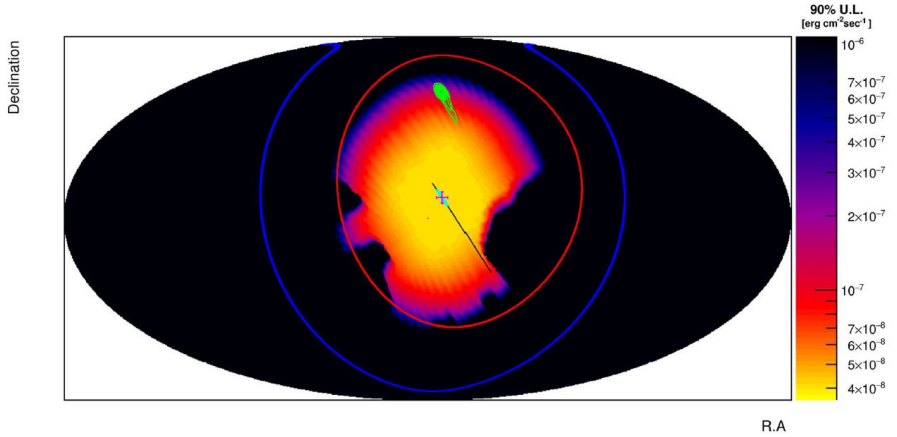
Time histories of counts observed in HXM1, HXM2, and SGM for GRB 200521A



Incident angle distributuion of GRBs in the SGM FOV. Black points are GRB positions in the SGM coordinate. Gray shaded regions show the ISS fixed stuctures viewed from CALET.



Map of the sky above 1 GeV observed by CAL (Cannady et al. 2021).

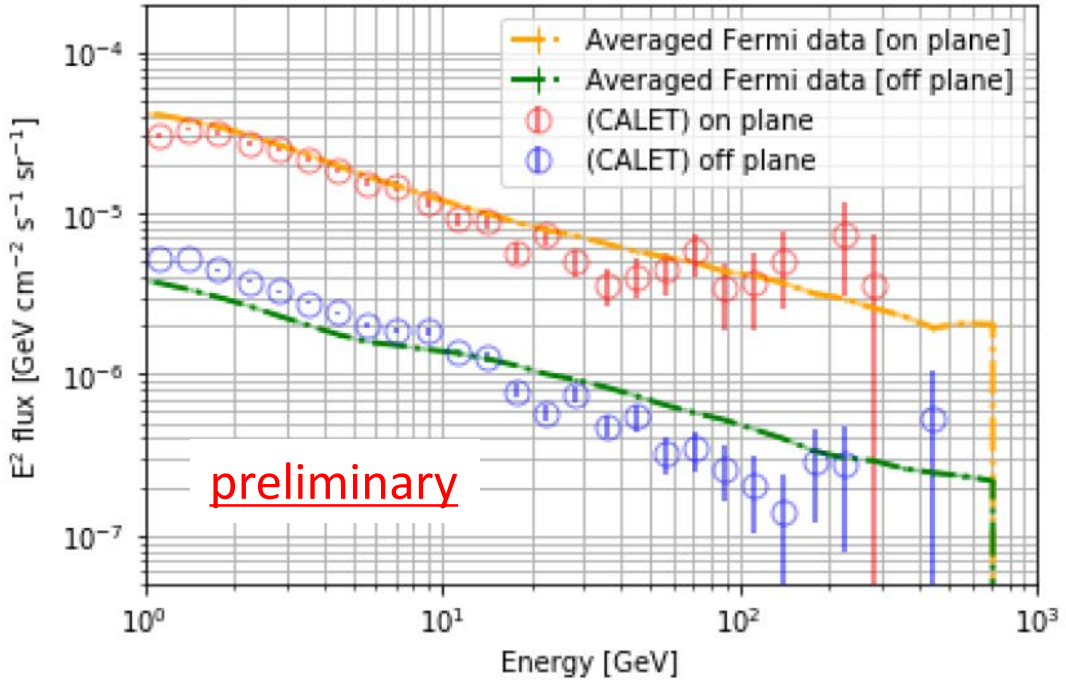


90% confidence level upper limits observed by CAL in the energy range 1-10 GeV during the interval ±60 s around the time of GW 190408an reported by LIG/Virgo. Red and blue circles are the HXM and SGM FOV, respectively.

Diffuse Gamma-ray Flux

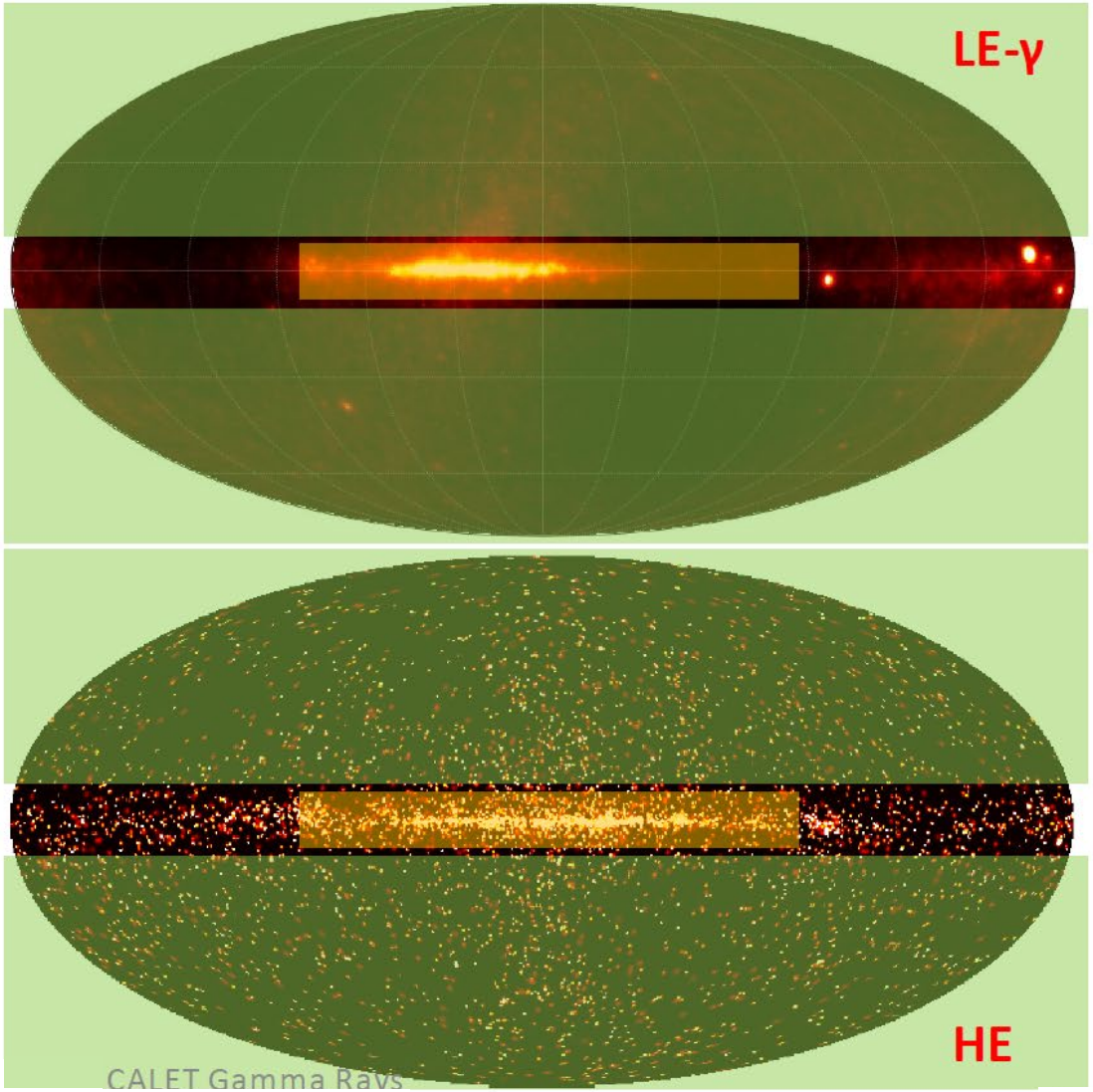
COSPAR (2022) : N. Cannady

Diffuse emission:
on-plane and off-plane (11/2015 – 02/2022)



On-plane: |b| < 8° & |l| < 80°

Off-plane: |b| > 10°



CALET: Summary and Future Prospects

- CALET was successfully launchedon Aug. 19th, 2015. The observation campaign started on Oct. 13th, 2015. Excellent performance and remarkable stability of the instrument were confirmed.
- As of November 30, 2022, total observation time is 2606 days (～7.1 years) with live time fraction close to 86 %. Nearly 3.72 billion events collected with low (> 1 GeV) & high (> 10 GeV) energy triggers.
- Accurate calibrations have been performed with non-interacting p & He events + linearity in the energy measurements established in 1 GeV – 1 PeV.
- Following results have been obtained by now (works published in 2022 are presented in this presentation).
  - Measurement of electron + positron spectrum in 11 GeV – 4.8 TeV
  - Direct measurement of proton and Lehlium in 50 GeV ～ 60 or 50 TeV energy range, and of Carbon and Oxygen spectra in 10 GeV/n – 2.2 TeV/n: Spectral hardening observed at ～600 GV.
  - Heavy primary cosmic-ray elecmnts up to Iron and Nickel are successfully observed, and these spectra are published in PRL.
  - Continous observations of gamma-ray bursts, solar modulation and REP events are successfully carried out.
- CALET observation has been carried out over 7 years, and is approved to be extended until the end of 2024 at the JAXA review held on March 12, 2021.

✓ We greatly appreciate JAXA staffs for perfect support of the CALET operation at the TKSC of JAXA !!

✓ This work is partially supported by JSPS KAKENHI Kiban (S) Grant Number 19H05608 (2019-2023 FY)