飛翔体観測(CALET)による
高エネルギー宇宙線加速天体の研究
～CALET4年間の軌道上観測成果～

研究代表者：鳥居祥二
早稲田大学理工学術院総合研究所
神奈川大学工学部

CALET

令和元年宇宙線研究所共同利用研究成果発表会　2019.12.13

共同利用研究概要(2019)

- 共同研究内容
  - CALET観測最適化のためのシミュレーション計算及びデータ解析
- 発表概要
  - CALET概要
  - 観測現状
  - 観測データ解析
  - まとめと展望
- 予算 旅費　200千円
  支出(予定)内容: 研究打ち合わせ、小研究会
- 共同利用　計算機(シミュレーション計算)

参加研究者及び研究補助

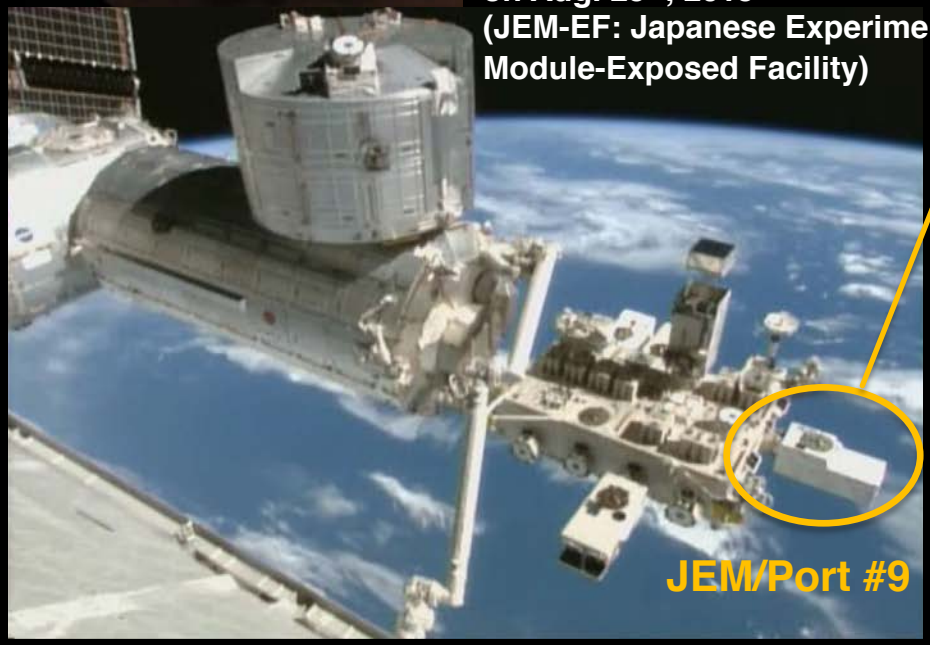
早稲田大学	笠原克昌、寺澤敏夫、浅岡陽一、Motz H Martin		
宇宙線研究所	浅野勝晃	神奈川大学	田村忠久, 清水雄輝
横浜国立大学	片寄祐作	芝浦工業大学	吉田健二
立命館大学	森正樹	弘前大学	市村雅一
信州大学	宗像一起	茨城大学	柳田昭平
茨城高専	三宅晶子	CRESST/NASA/GSFC	赤池陽水

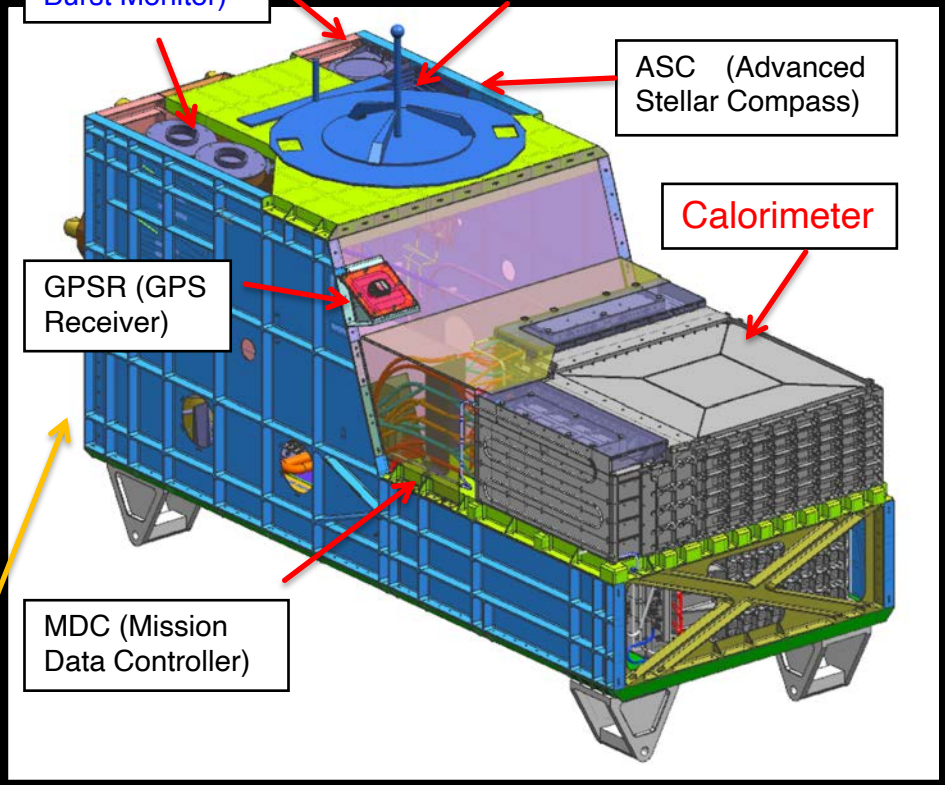
CALET Payload

Kounotori (HTV) 5

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

Emplaced on JEM-EF port #9 on Aug. 25th, 2015 (JEM-EF: Japanese Experiment Module-Exposed Facility)





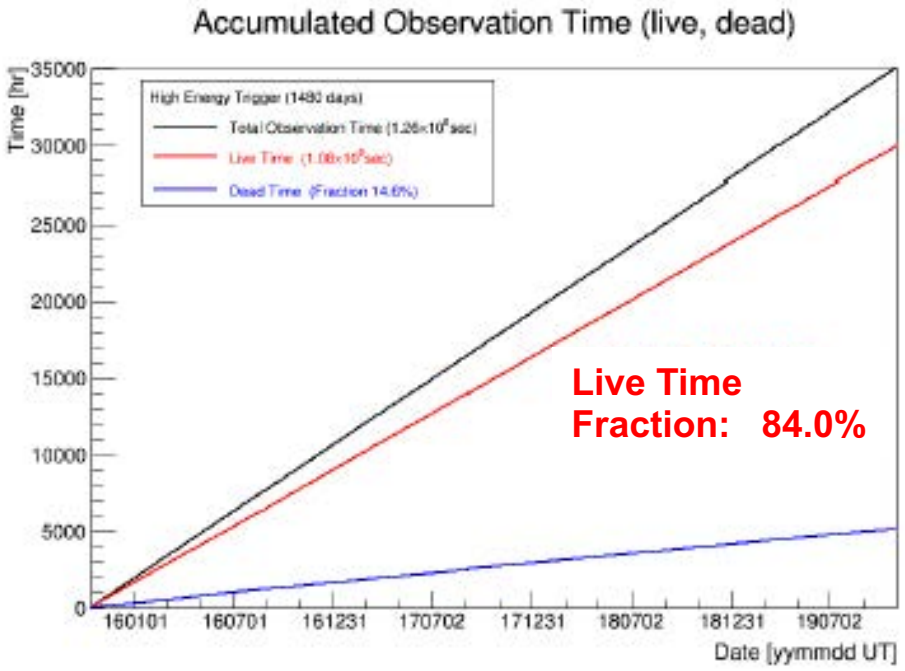
- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W（max）**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

Observation with High Energy Trigger (>10GeV)

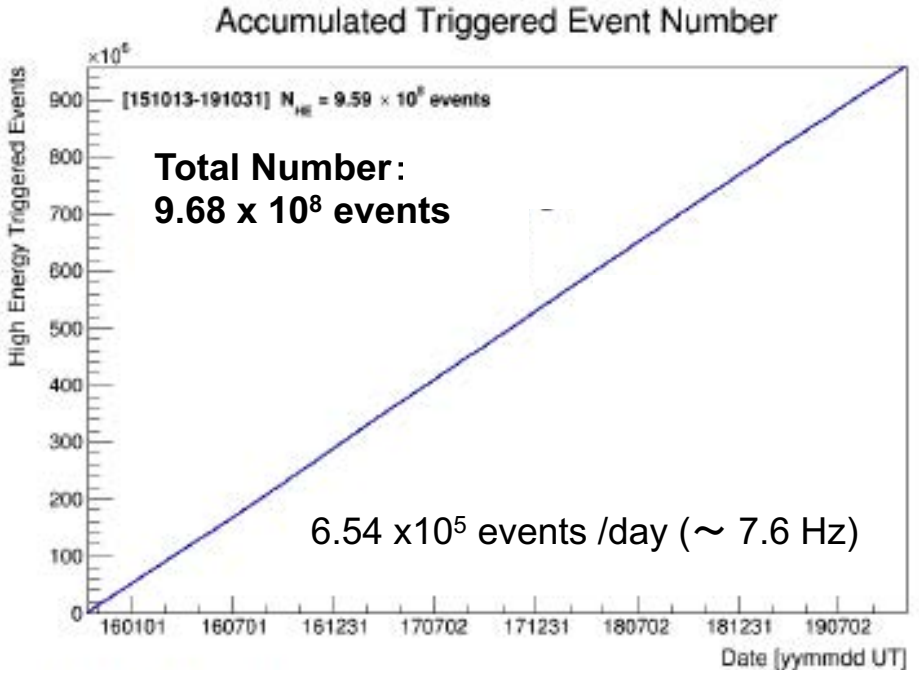
Observation by High Energy Trigger for 1480 days : Oct.13, 2015 – Oct. 31, 2019

- The exposure, SΩT, has reached to ~ 150 m^2 sr day for electron observations by continuous and stable operations.
- Total number of triggered events is ~ 970 million with a live time fraction of about 84.0 %.

Accumulated observation time (live, dead)

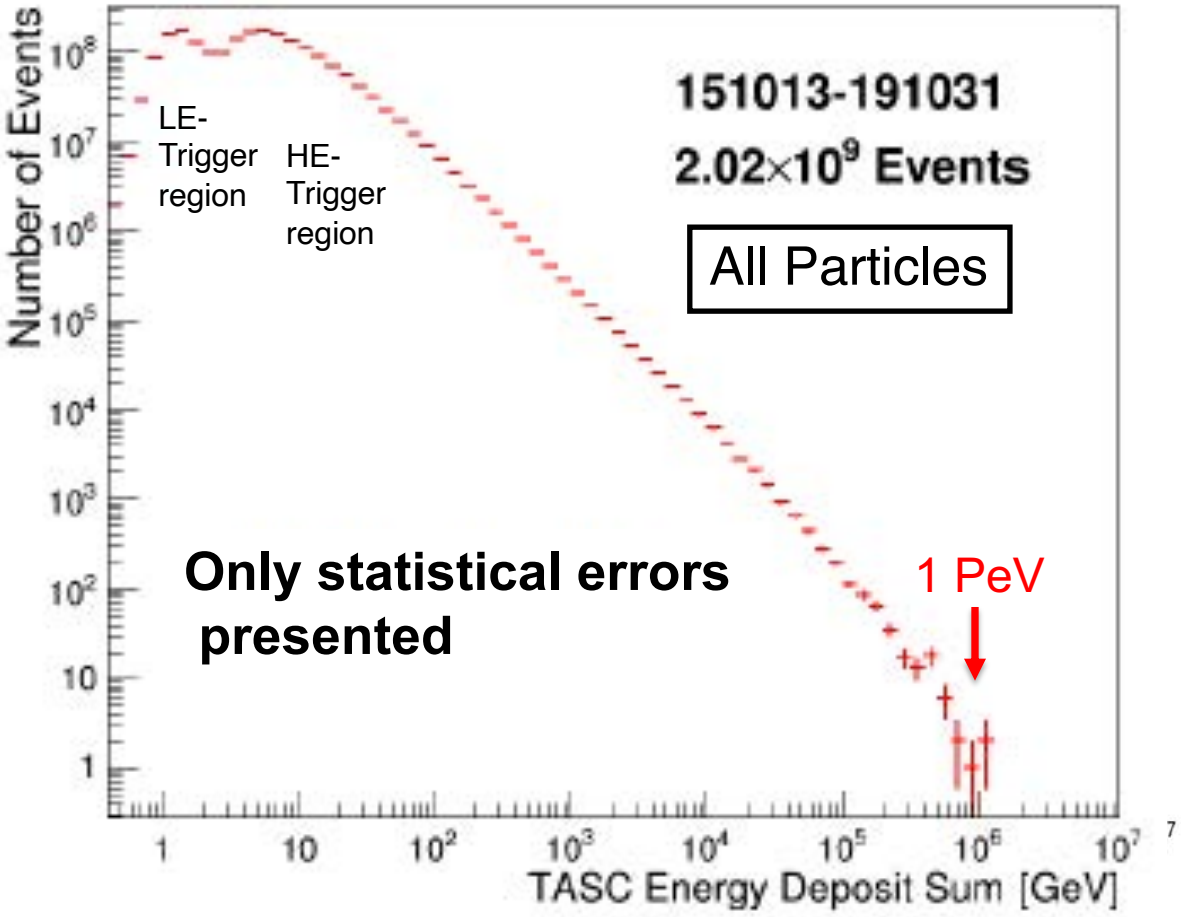


Accumulated triggered event number



TASC Energy Deposit Distribution of All Triggered-Events

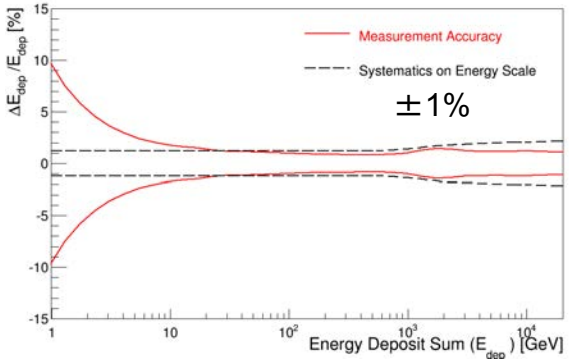
Distribution of deposit energies (ΔE) in TASC



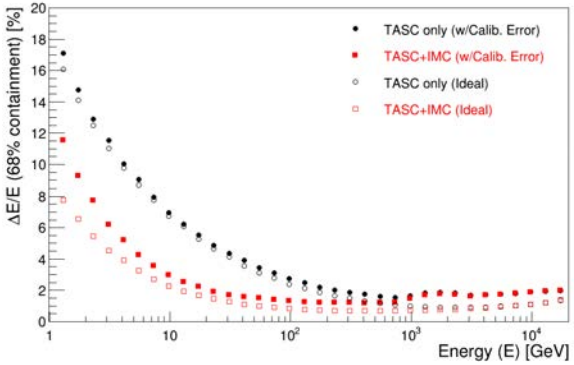
The TASC energy measurements have successfully been carried out in the dynamic range of 1 GeV – 1 PeV.

Y.Asaoka, et al. (CALET Collaboration), Astroparticle Physics 91 (2017) 1.

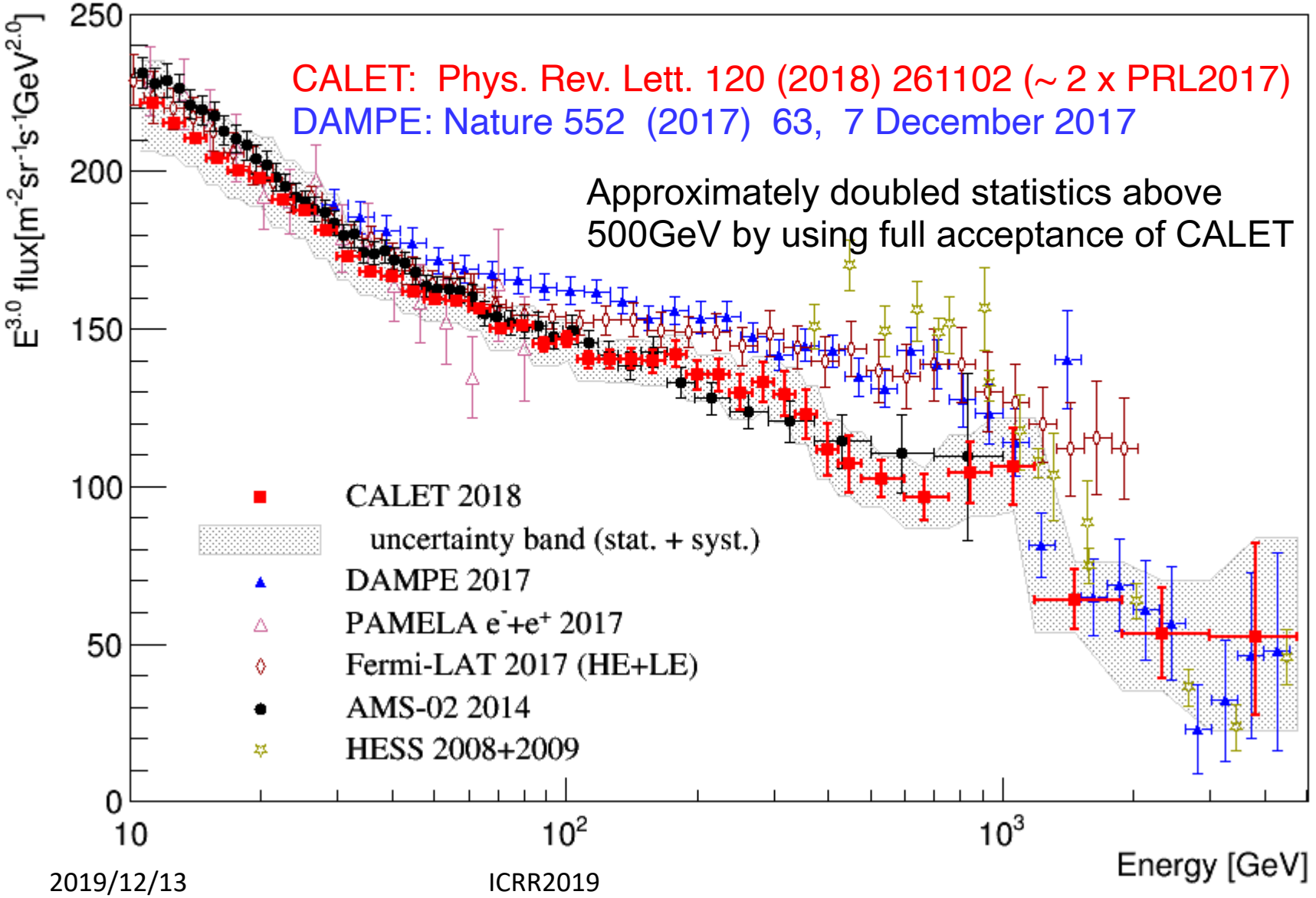
Performance of electron energy measurement in 1GeV-20TeV



Energy resolution for electrons (TASC+IMC):
< 3% over 10 GeV; <2% over 20GeV

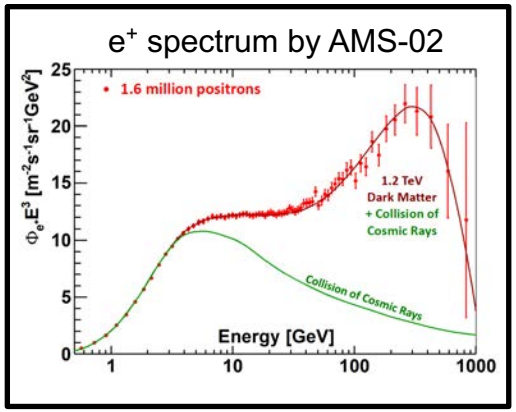


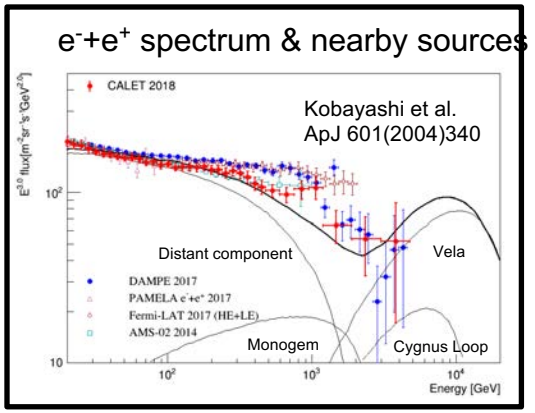
All-Electron Spectrum Measured with CALET from 11 GeV to 4.8TeV



Future prospects: Search for new sources

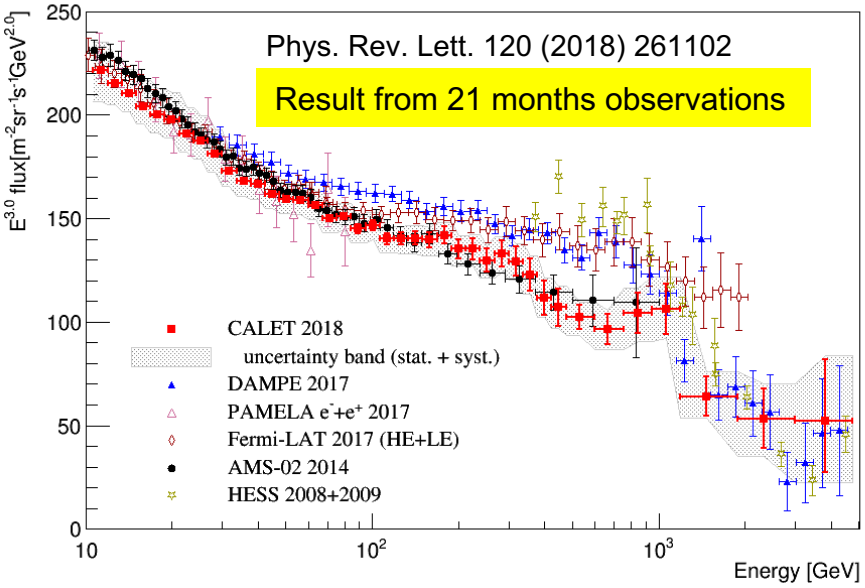
- Investigation of CR nearby sources by electron observations at the TeV region
  - Direct detection of nearby sources
  - Acceleration limit and escape process from SNR
- Search for Dark Matter signature in the electron spectrum structure
  - Detection of unknown primary source of electron and positron: Pulsar(s) or Dark Matter ?



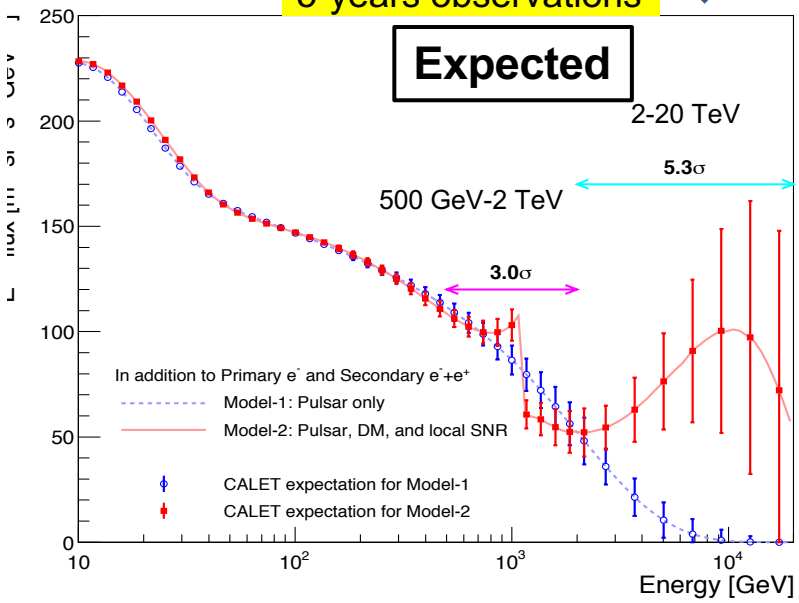


Detection of primary source of e+ & e-

Search for nearby source(s)

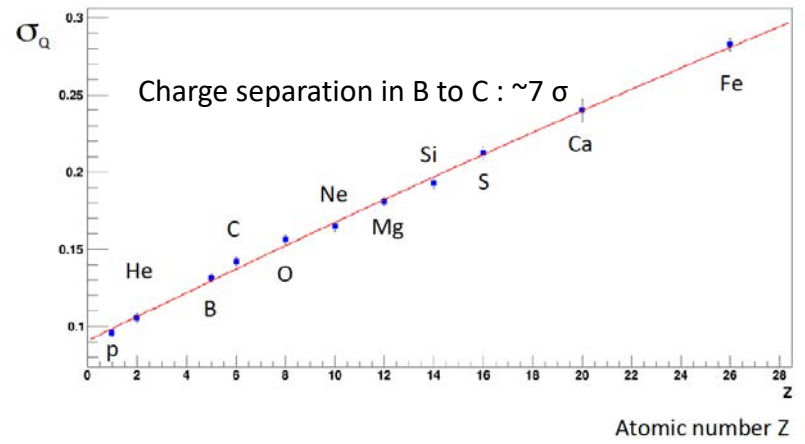


5-years observations

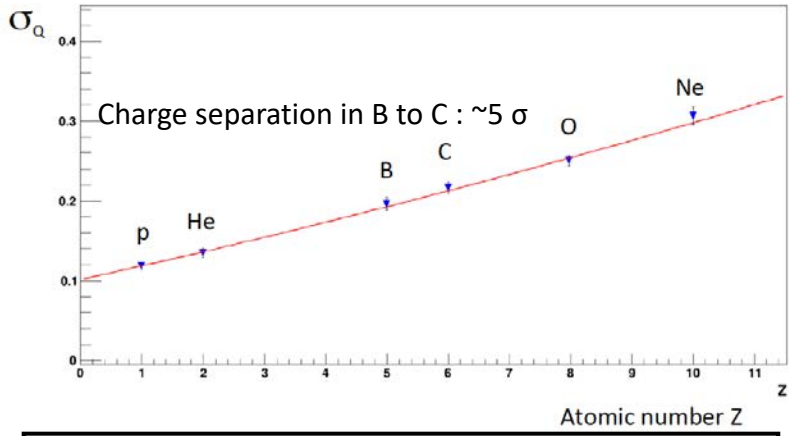


Charge Identification with CHD and IMC

CHD charge resolution (2 layers combined) vs. Z

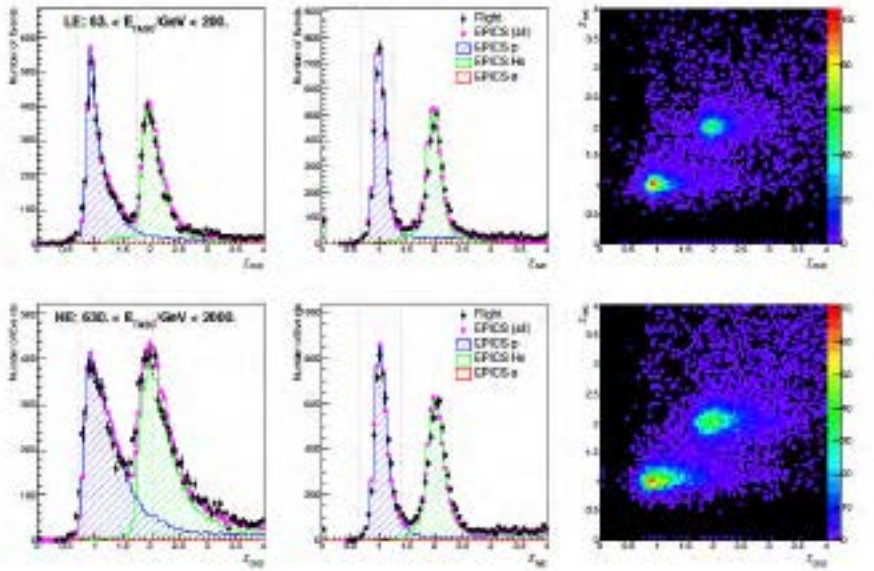


Charge resolution using multiple dE/dx measurements from the IMC scintillating fibers.

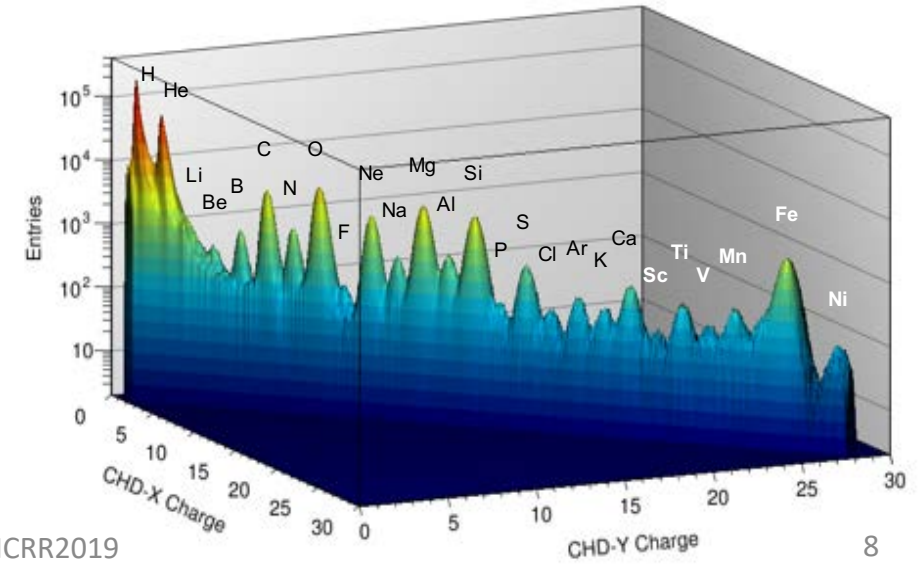


Non-linear response to Z^2 is corrected both in CHD and IMC using a core + halo ionization model (Volz).

Combined CHD-IMC proton-Helium charge-ID



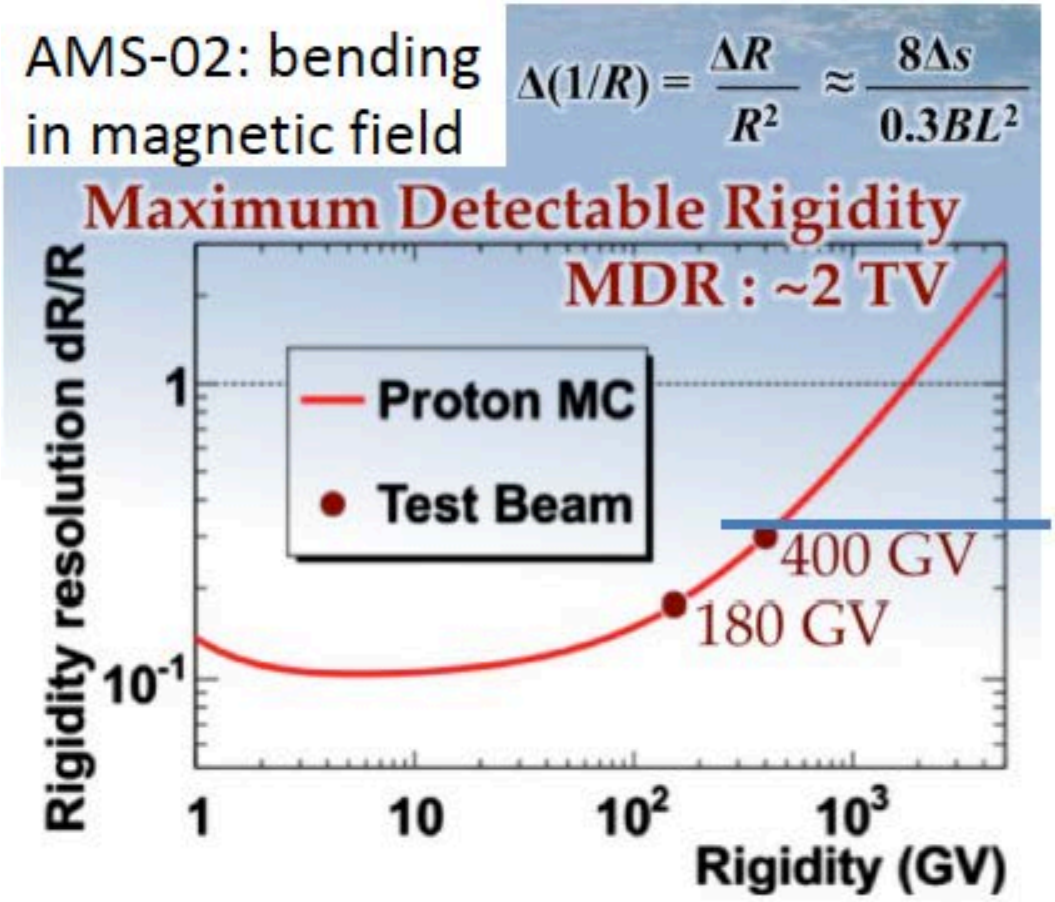
CHDx-y charge-ID up to Z=28



Energy Measurement of Protons: Magnetic Spectrometer vs Calorimeter

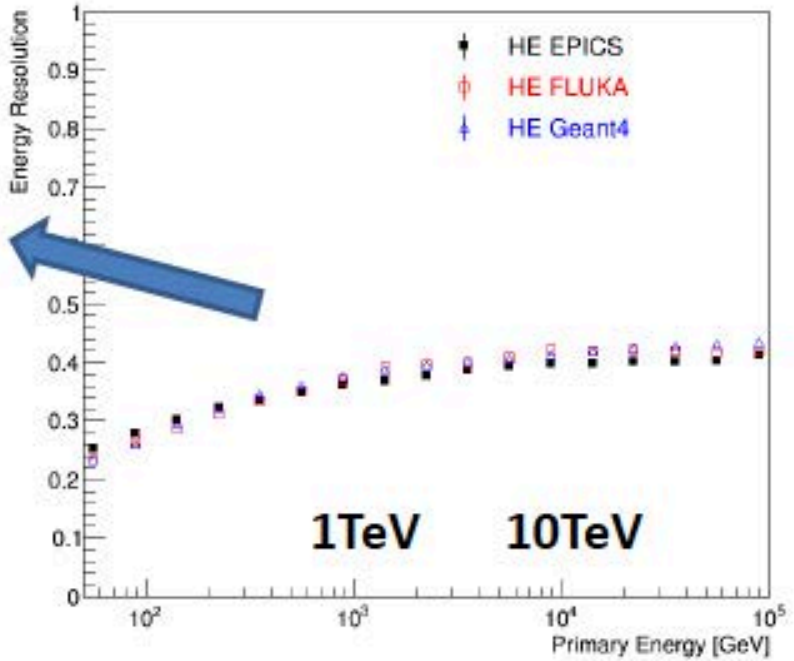
AMS-02: bending in magnetic field

$$\Delta(1/R) = \frac{\Delta R}{R^2} \approx \frac{8\Delta s}{0.3BL^2}$$

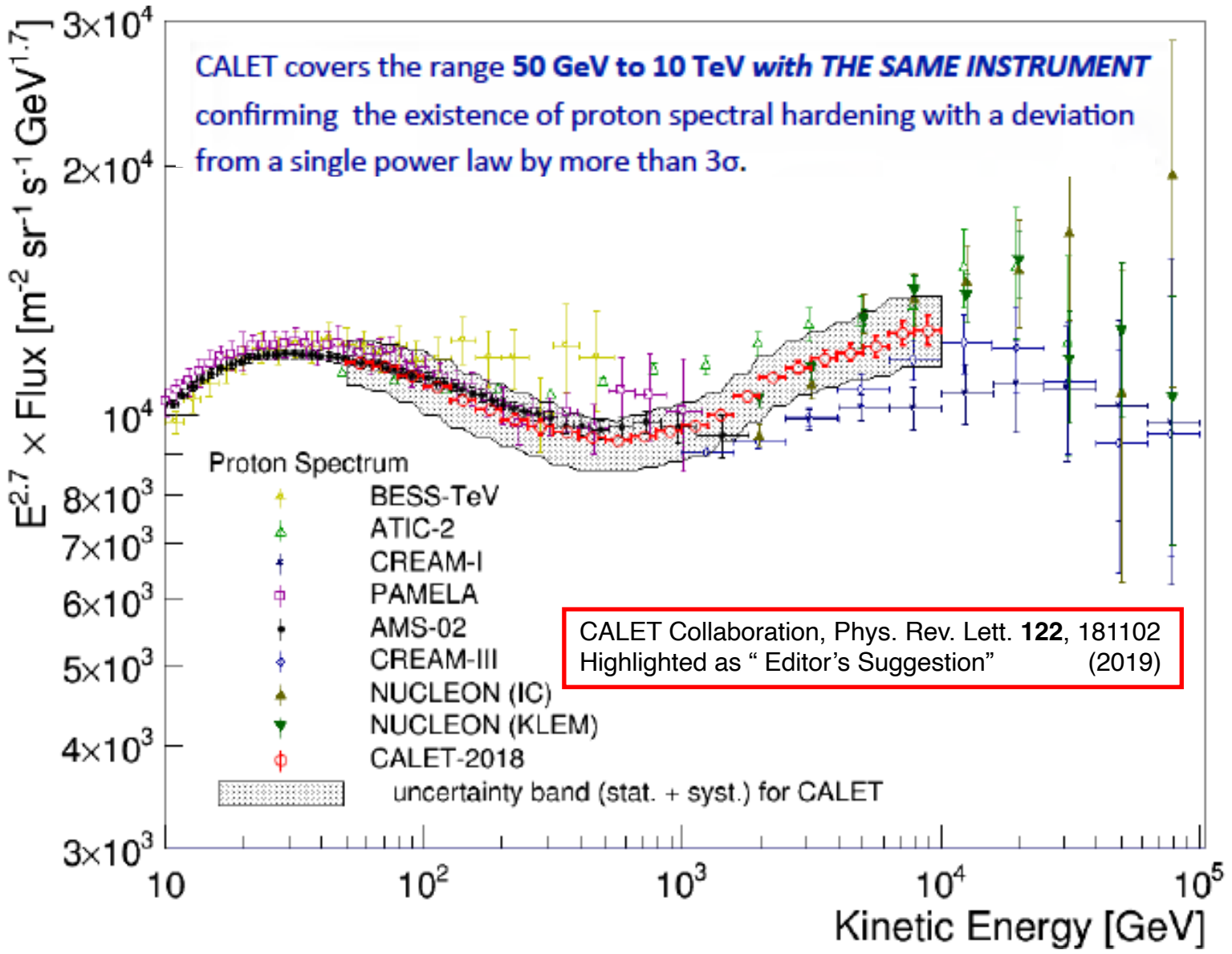


Ref: Haino 2014

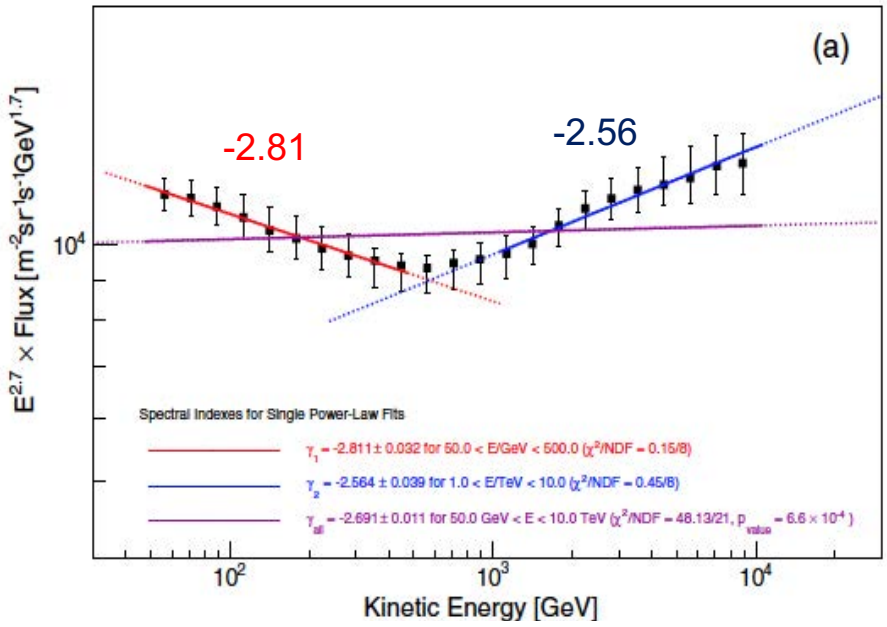
CALET: shower energy
Better resolution at E>500 GeV.
Very stable above E>1TeV. Small dependence on MC models.

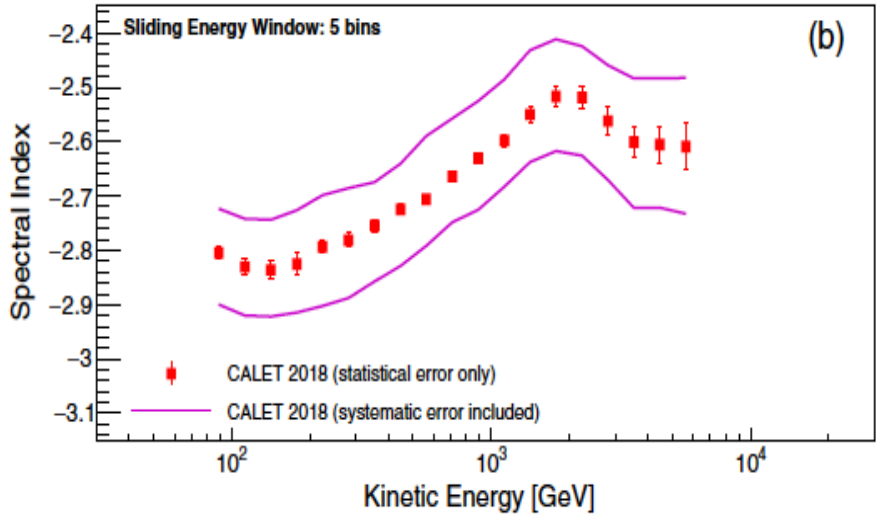


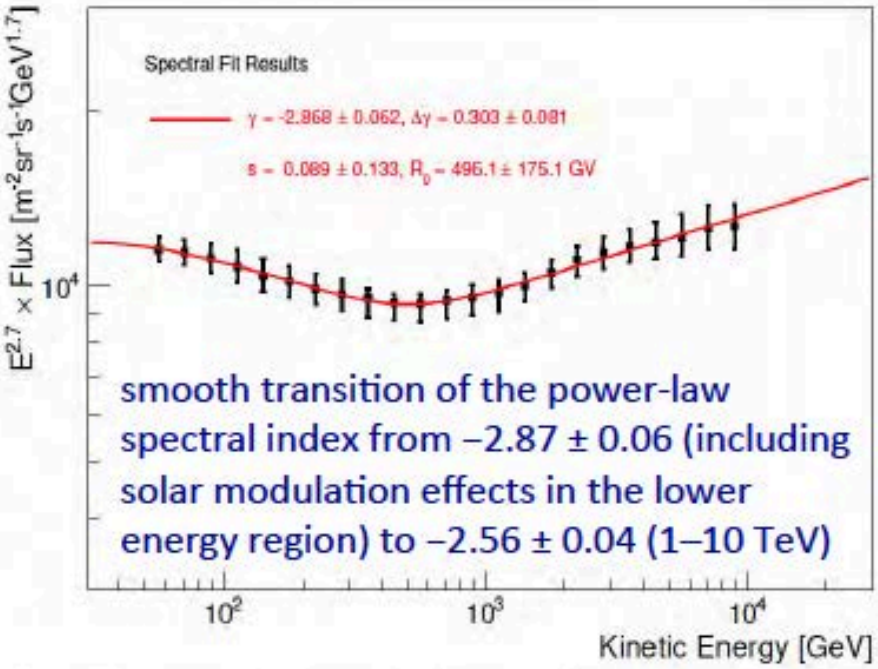
Direct Measurement of Proton Spectrum by CALET



Spectral Behavior of Proton Flux

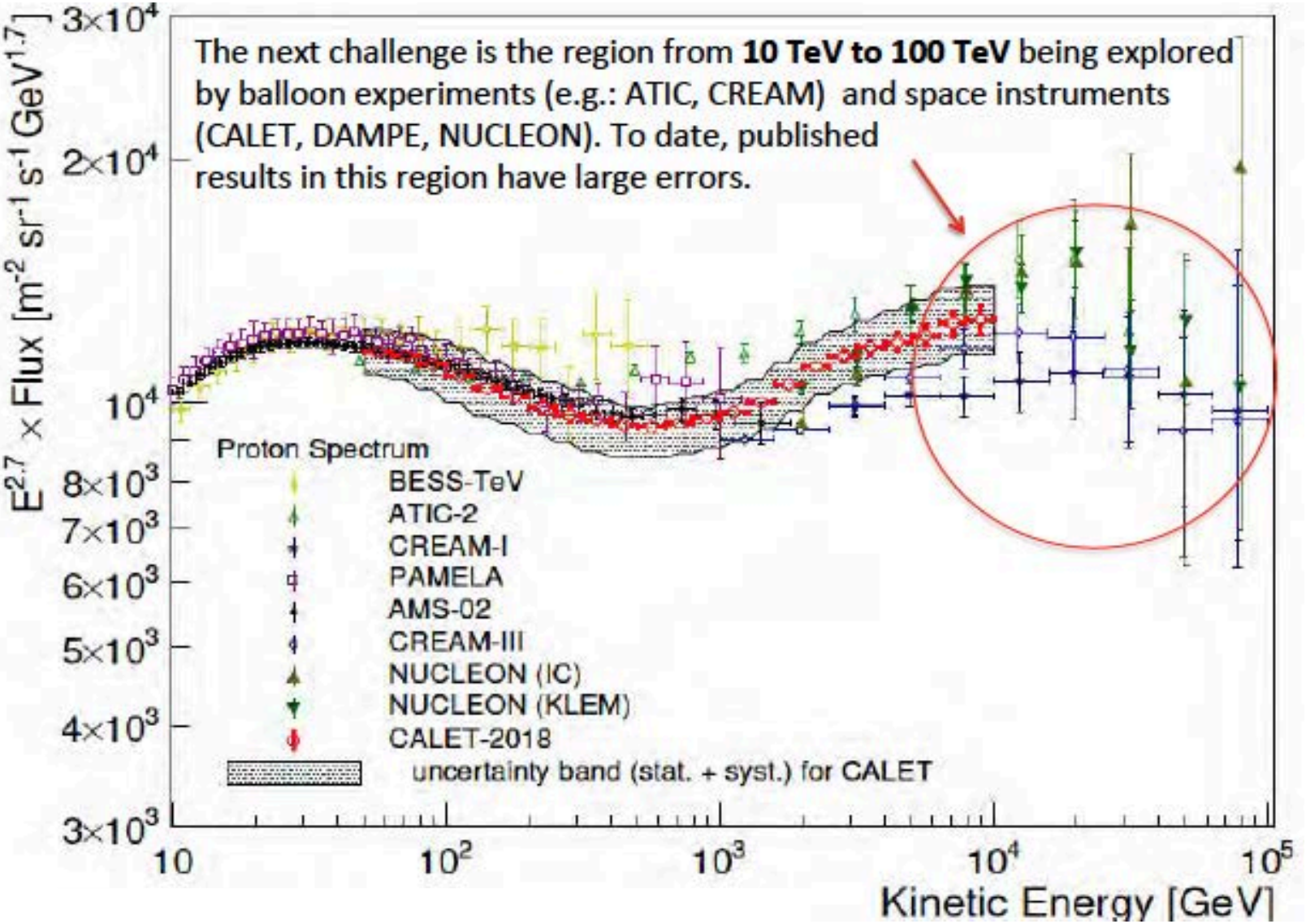






1. Subranges of 50—500GeV, 1-10TeV can be fitted with single power law function, but not the whole range (significance > 3σ).
2. Progressive hardening up to the TeV region was observed.
3. "smoothly broken power-law fit" gives power law index consistent with AMS-02 in the low energy region, but shows larger index change and higher break energy than AMS-02.

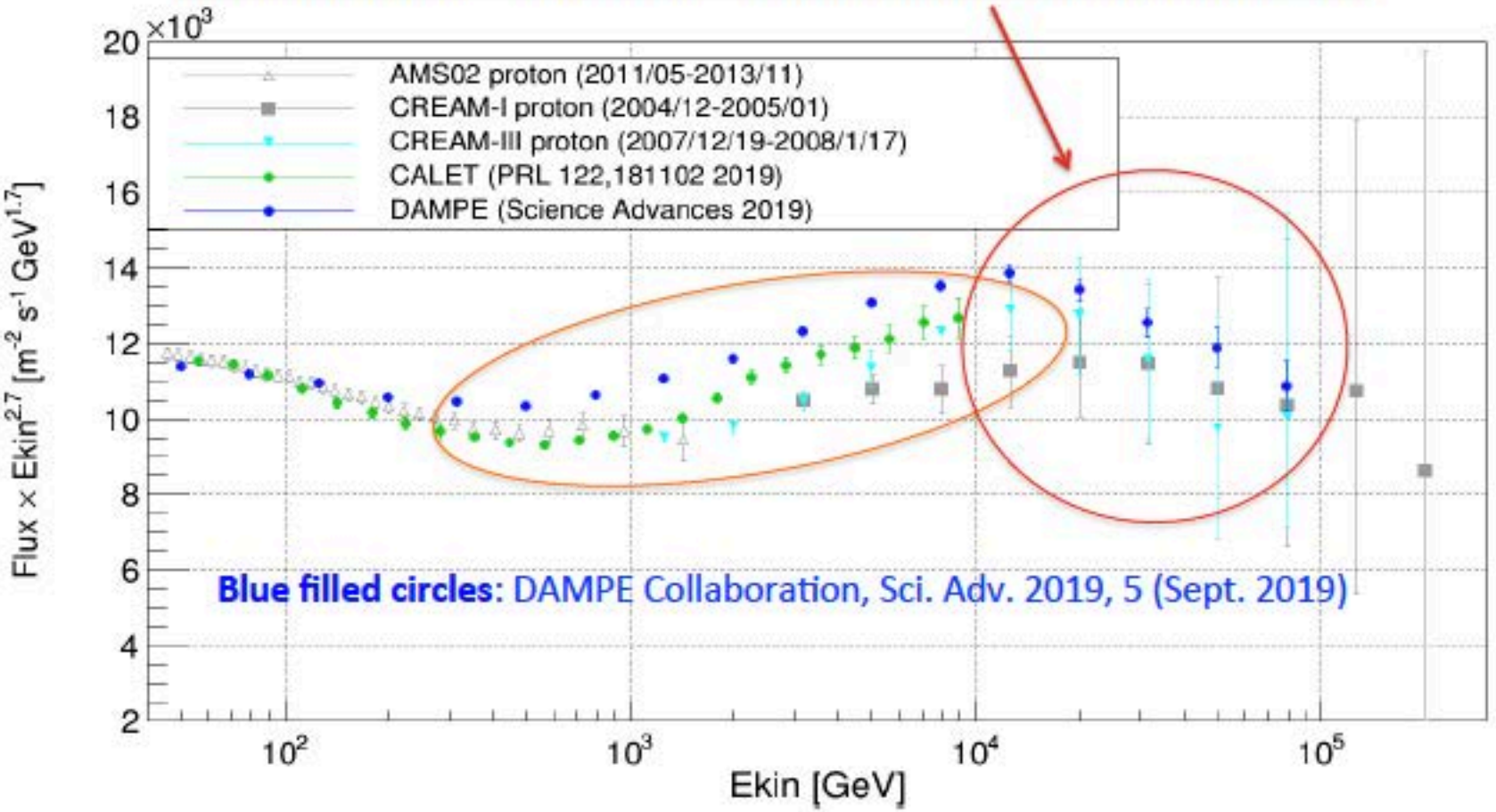
Direct Measurements of Proton Spectrum before Sep. 2019



Recent Direct Measurements of Proton Spectrum

Recent paper by DAMPE collaboration (Sept 2019) from 40 GeV to 100 TeV:

- flux higher than AMS02 and CALET above 200 – 300 GeV
- flux higher than CREAM-III (and CREAM-I) in the region 1 TeV to 10 TeV approx.
- flux reduction above 13.6 TeV (spectral index changes from ~2.60 to ~2.85)



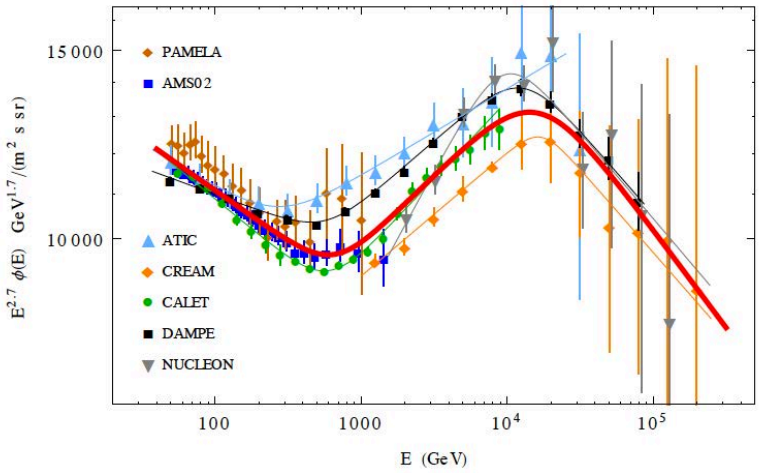
Possible Connection of Proton Spectrum to Air Shower Observations

The shape of the cosmic ray proton spectrum

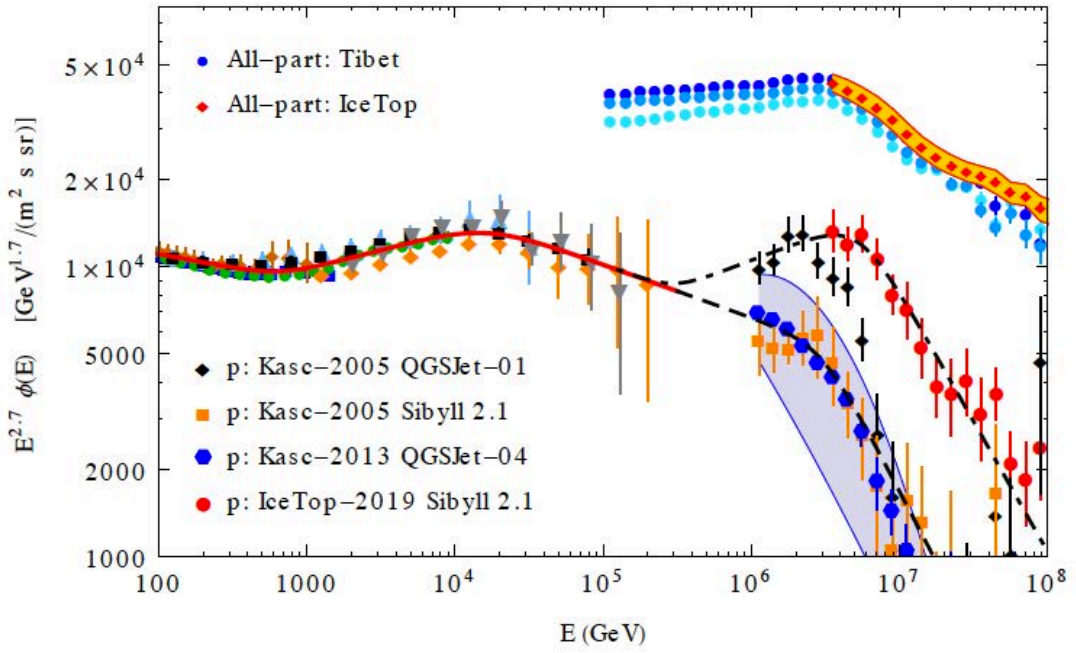
Paolo Lipari[1] and Silvia Vernetto[2]

[1]INFN, Sezione Roma "Sapienza", Piazzale Aldo Moro 2, 00185 Roma, Italy
[2]OATO–INAF, INFN Sezione Torino, Via Pietro Giuria 1, 10124 Torino, Italy

4th November 2019



arXiv:1911.01311v1 [astro-ph.HE] 4 Nov 2019



Preliminary Flux of Primary Components

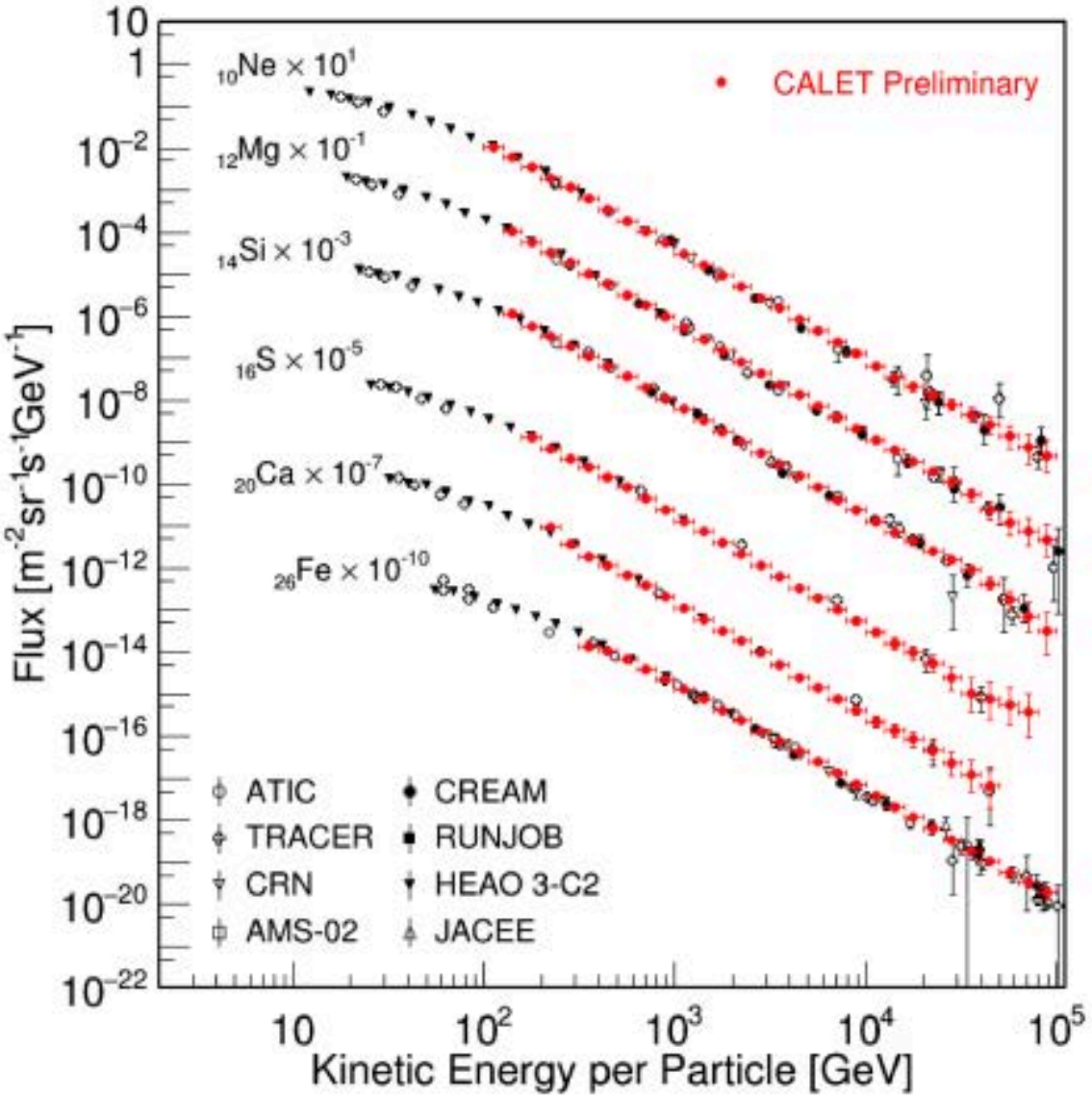
Flux measurements:

$$\Phi(E) = \frac{N(E)}{S\Omega\varepsilon(E)T\Delta E}$$

$N(E)$: Events in unfolded energy bin
$S\Omega$: Geometrical acceptance
$\varepsilon(E)$: Efficiency
T : Live Time
ΔE : Energy bin width

Observation period:
Oct.13 2015 – Dec.31 2018
(1,176 days)

6.8 x 10 ^{6} events (C-Fe ΔE>10 GeV)
[Y. Akaike et al., ICRC2019]



CALET Gamma-ray Sky (>1GeV)

Instrument characterized using EPICS simulations

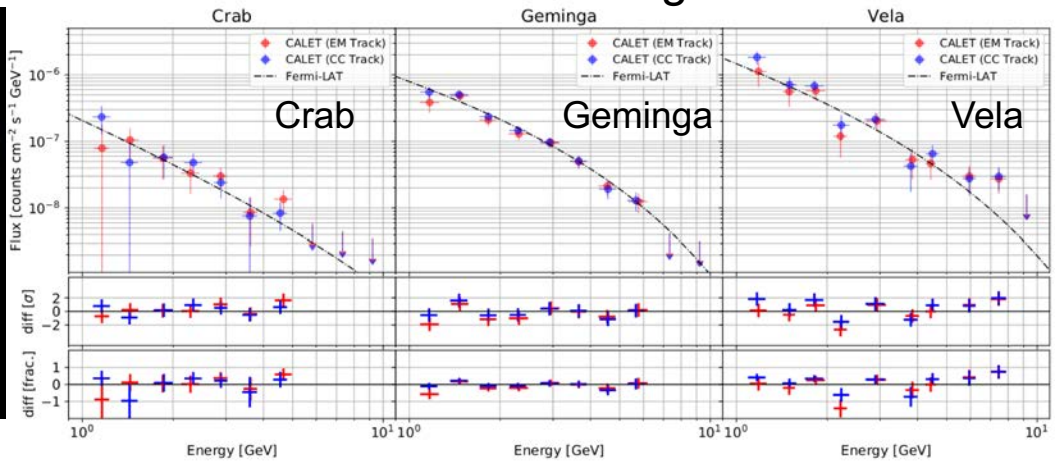
- Effective area ~400 cm² above 2 GeV
- Angular resolution < 2° above 1 GeV (< 0.2° above 10 GeV)
- Energy resolution ~12% at 1 GeV (~5% at 10 GeV)

Simulated IRFs consistent with 2 years of flight data

Consistency in signal-dominated regions with Fermi-LAT

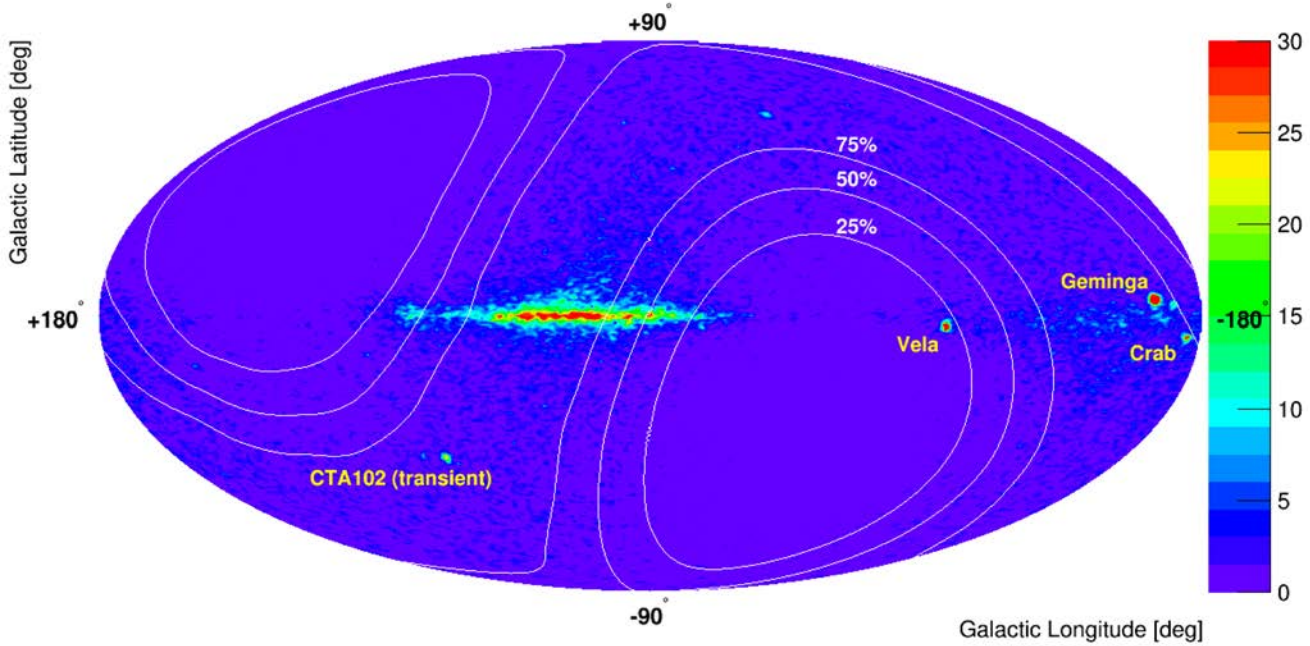
Residual background in low-signal regions

Flux validation with bright sources

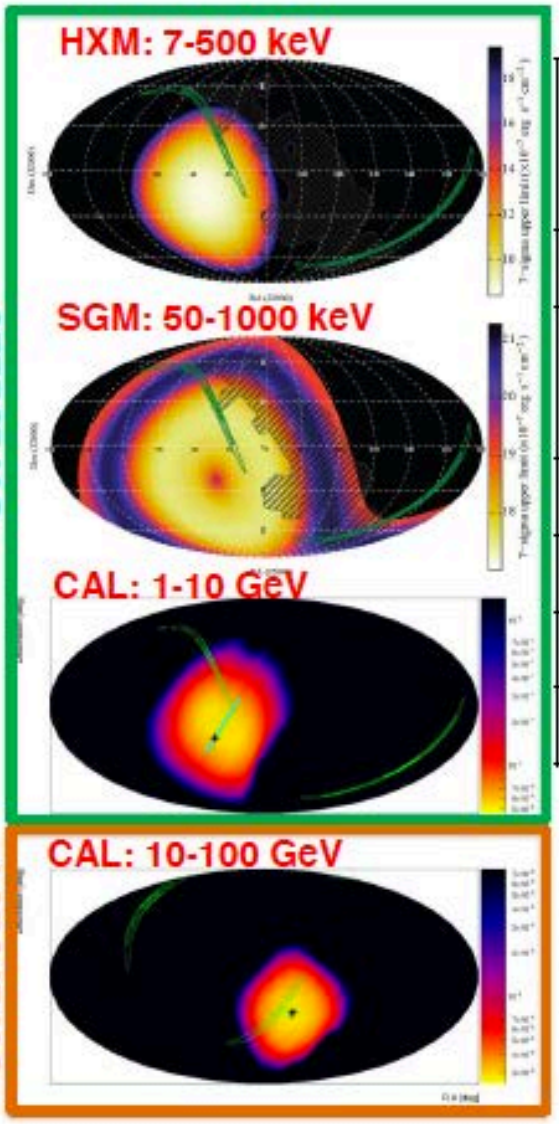


Gamma-ray Sky Map

LE-γmode,
from 2015 November
to 2018 May



Complete Search Results for GW Events during O1&O2



GW151226: O. Adriani et al. (CALET Collaboration), ApJL 829:L20 (2016).
All O1 & O2: O. Adriani et al. (CALET Collaboration), ApJ 863 (2018) 160.

Event	Type	Mode	Sum. LIGO prob.	Obs. time	Upper limits	
					Ene. Flux erg cm^{-2} s^{-1}	Lum. erg s^{-1}
GW150914	BH-BH	Before operation				
GW151226	BH-BH	LE HXM SGM	15%	T_0-525 – T_0+211	9.3×10^{-8} 1.0×10^{-6} 1.8×10^{-6}	2.3×10^{48} $3\text{-}5 \times 10^{49}$
GW170104	BH-BH	HE	30%	T_0-60 – T_0+60	6.4×10^{-6}	6.2×10^{50}
GW170608	BH-BH	HE	0%	T_0-60 – T_0+60	Out of FOV	
GW170814	BH-BH	HE	0%	T_0-60 – T_0+60	Out of FOV	
GW170817	NS-NS	HE	0%	T_0-60 – T_0+60	Out of FOV	

- CALET can search for EM counterparts to LIGO/Virgo triggers
- All O1 and O2 triggers checked – no signal in CGBM or CAL
- Upper limits set for GW151226 for CGBM+CAL in 2016 paper
- Upper limits for the CAL set using refined LE selection for triggers to-date in the 2018 paper

CALET: Summary and Future Prospects

- CALET was successfully launched on Aug. 19th, 2015. The observation campaign started on Oct. 13th, 2015. **Excellent performance and remarkable stability of the instrument were confirmed.**
- As of Oct. 31st, 2019, total observation time is 1480 days with live time fraction to total time close to 84%. **Nearly 2.0 billion events collected with low (> 1 GeV) + high energy (> 10 GeV) triggers.**
- **Accurate calibrations** have been performed with non-interacting p & He events + linearity in the energy measurements established **up to 1 PeV.**
- Following results have been obtained by now.
  - Measurement of **electron + positron spectrum in 11 GeV- 4.8 TeV.**
  - Direct measurement **of proton spectrum in 50 GeV- 10 TeV energy range**, spectral hardening observed above a few hundred GeV.
  - **Preliminary analysis of primary elements up to Fe.**
  - Study of diffuse and point sources of gamma-rays. **Follow-up observations of GW events** in X-ray and gamma-ray bands.
- After an initial period of 2 years, CALET observation time has been extended to **5.5 years at least.**

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

Publication List in FY 2017-2019（refereed journal)

1. Relativistic electron precipitation at International Space Station: Space weather monitoring by Calorimetric Electron Telescope
   R. Kataoka et al., *Geophysical Research Letters*, 43, 4119-4125 (2016)
2. CALET Upper Limits on X-ray and Gamma-ray Counterparts of GW 151226
   O. Adriani et al., *Astrophysical Journal Letters*, 829, L20 (5pp) (2016)
3. Energy Calibration of CALET Onboard the International Space Station
   Y. Asaoka et al., *Astroparticle Physics,* 91, 1-10 (2017)
4. Energy Spectrum of Cosmic-ray Electron + Positron from 10 GeV to 3 TeV Observed with the Calorimetric Electron Telescope on the International Space Station
   O. Adriani et al., *Physical Review Letters*, 119, 181101 (2017)
5. Detection of the thermal component in GRB 160107A
   Y. Kawakubo et al., *Publications of the Astronomical Society of Japan*, 70, 6 (1-10) (2018)
6. On-orbit Operations and Offline Data Processing of CALET onboard the ISS
   Y. Asaoka et al., *Astroparticle Physics*, 100, 29-37 (2018)
7. Extended measurement of cosmic-ray electron and positron spectrum from 11 GeV to 4.8 TeV with the calorimetric electron telescope on the International Space Station
   O. Adriani et al., *Physical Review Letters*, 120, 261102 (2018)
8. Search for GeV gamma-ray counterparts of gravitational wave events by CALET
   O. Adriani et al., *Astrophysical Journal*, 863, 160 (9pp) (2018)
9. Characteristics and Performance of the Calorimetric Electron Telescope (CALET) Calorimeter for Gamma-ray Observation
   O. Adriani et al., *Astrophysical Journal Supplement*, 238, 5 (16pp) (2018)
10. Measurements of Heavy Cosmic-Ray Nuclei Spectra with CALET on the ISS
    Y. Akaike et al., *Journal of Physics: Conf. Series* 1181 (2019) 012042
11. Direct Measurement of the Cosmic-Ray Proton Spectrum from 50 GeV to 10 TeV with the Calorimetric Electron Telescope on the International Space Station
    O. Adriani et al., *Physical Review Letters*, 122, 181102 (2019)