

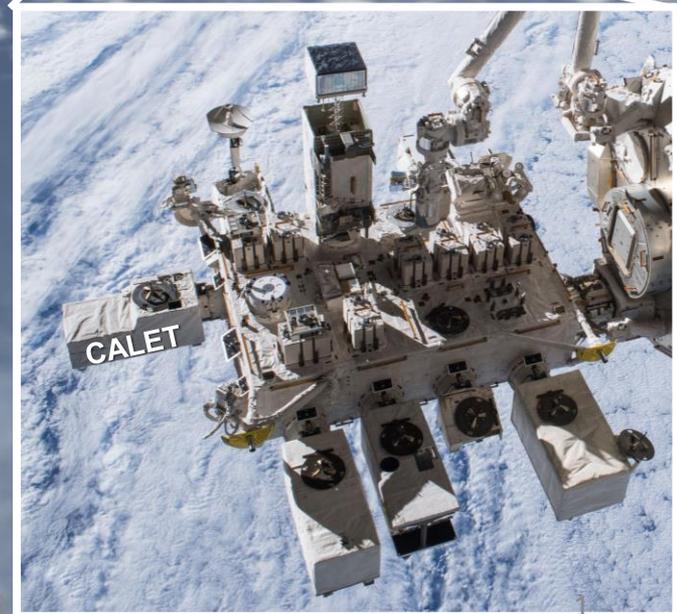


The CALorimetric Electron Telescope (CALET) on the International Space Station (ISS)

Yoichi Asaoka
for the CALET collaboration
WISE, Waseda University

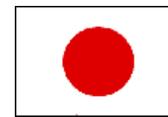


Highlight Talk (CRD H7) 27 July 2019





CALET Collaboration Team



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- 3) CRESST/NASA/GSFC and University of Maryland, USA
- 4) Hirosaki University, Japan
- 5) Ibaraki National College of Technology, Japan
- 6) Ibaraki University, Japan
- 7) ICRR, University of Tokyo, Japan
- 8) ISAS/JAXA Japan
- 9) JAXA, Japan
- 10) Kanagawa University, Japan
- 11) Kavli IPMU, University of Tokyo, Japan
- 12) KEK, Japan
- 13) Louisiana State University, USA
- 14) Nagoya University, Japan
- 15) NASA/GSFC, USA
- 16) National Inst. of Radiological Sciences, Japan
- 17) National Institute of Polar Research, Japan

- 18) Nihon University, Japan
- 19) Osaka City University, Japan
- 20) Ritsumeikan University, Japan
- 21) Saitama University, Japan
- 22) Shibaura Institute of Technology, Japan
- 23) Shinshu University, Japan
- 24) University of Denver, USA
- 25) University of Florence, IFAC (CNR) and INFN, Italy
- 26) University of Padova and INFN, Italy
- 27) University of Pisa and INFN, Italy
- 28) University of Rome Tor Vergata and INFN, Italy
- 29) University of Siena and INFN, Italy
- 30) University of Tokyo, Japan
- 31) Waseda University, Japan
- 32) Washington University-St. Louis, USA
- 33) Yokohama National University, Japan
- 34) Yukawa Institute for Theoretical Physics, Kyoto University, Japan



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S. Yanagita⁶, A. Yoshida¹, and K. Yoshida²²





Outline

1. Introduction

2. Calibration

→ Y.Asaka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al.
(CALET Collaboration), *Astropart. Phys.* 91 (2017) 1.

3. Operations

→ Y.Asaka, S.Ozawa, S.Torii et al.
(CALET Collaboration), *Astropart. Phys.* 100 (2018) 29.

4. Results

— Electrons

→ O.Adriani et al. (CALET Collaboration),
Phys.Rev.Lett. 119 (2017) 181101.

— Hadrons

→ O.Adriani et al. (CALET Collaboration),
Phys.Rev.Lett. 120 (2018) 261102.

— Gamma-Rays

→ O.Adriani et al. (CALET Collaboration),
Phys.Rev.Lett. 120 (2018) 261102.

— Space Weather

→ O.Adriani et al. (CALET Collab.), *ApJL* 829 (2016) L20.
O.Adriani et al. (CALET Collab.), *ApJ* 863 (2018) 160.
N.Cannady, Y.Asaka et al. (CALET Collab.),
ApJS 238 (2018) 5.

5. Summary

→ R.Kataoka et al., *JGR*,
10.1002/2016GL068930 (2016).

Direct measurements of cosmic rays : little room for “unknown” systematics

Four major factors in the spectrum measurements:

1. Acceptance $\Rightarrow S\Omega$
 - Geometrical Factor
2. Energy determination $\Rightarrow \Delta E/E$ (resolution)
Energy Scale
Typically:
 - Magnet spectrometer
 - Calorimeter
3. Particle identification $\Rightarrow r_{BG}$ (contamination ratio)
 - Rejection of background cosmic rays
4. Detection efficiency $\Rightarrow \epsilon$
 - Losses in the detector

Question: How “direct” each measurement is?

Larger corrections leave more rooms for “unknown” systematics

ISS as Cosmic Ray Observatory



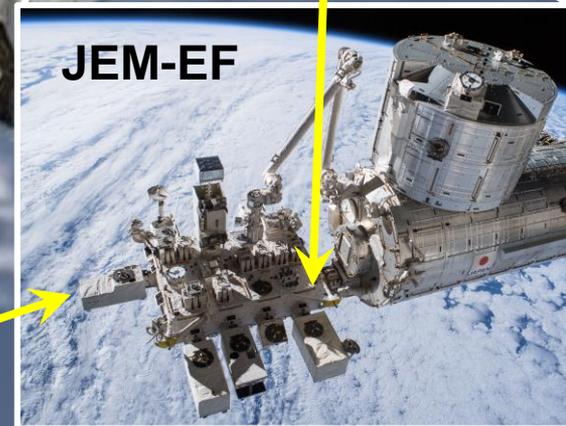
AMS Launch
May 16, 2011



ISS-CREAM Launch
August 14, 2017



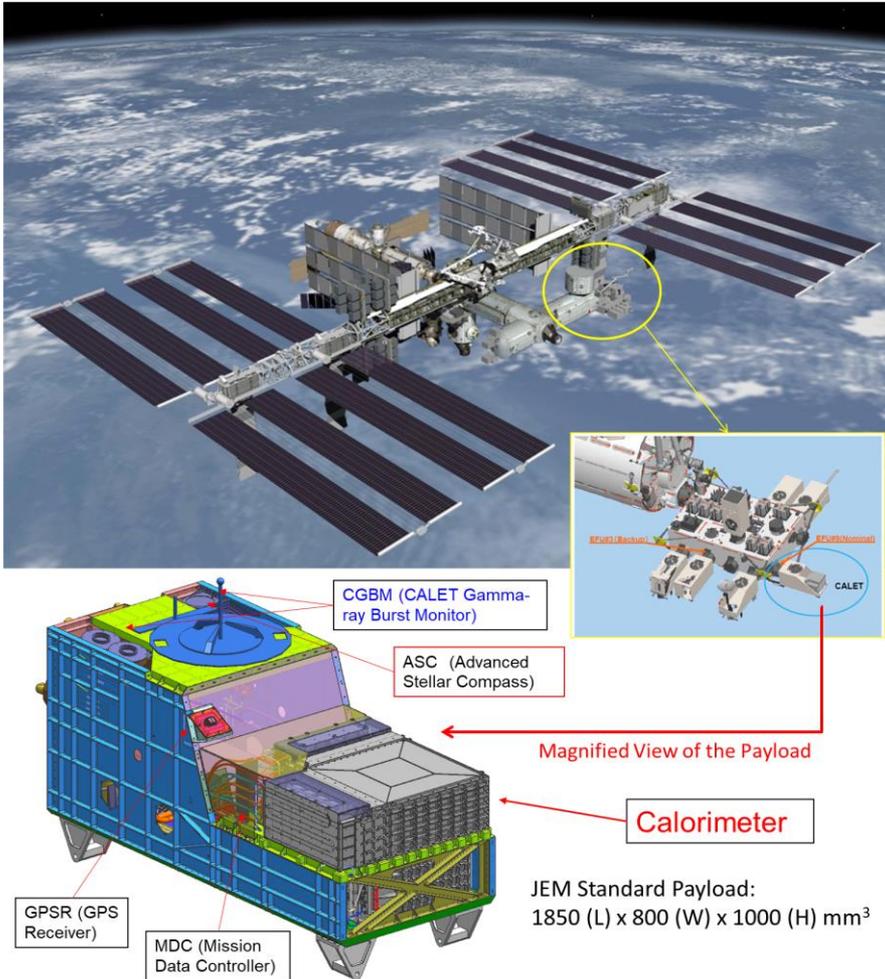
CALET Launch
August 19, 2015



JEM-EF



CALET: Cosmic Ray Detector onboard the ISS



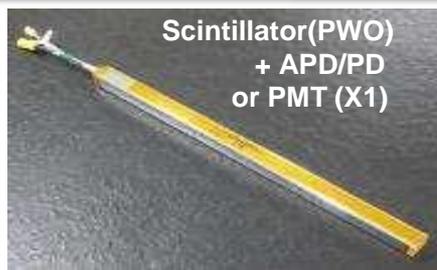
Overview of CALET Observations

- Direct cosmic ray observations in space at the highest energy region by combining:
 - ✓ A large-size detector
 - ✓ Long-term observation onboard the ISS (5 years or more is expected)
- Electron observation in the 1 GeV - 20 TeV energy range, with high energy resolution owing to optimization for electron detection
 - ⇒ **Search for Dark Matter and Nearby Sources**
- Observation of cosmic-ray nuclei in the 10 GeV - 1 PeV energy range.
 - ⇒ **Unravelling the CR acceleration and propagation mechanism**
- Detection of transients in space by long-term stable observations
 - ⇒ **EM radiation from GW sources, Gamma-ray burst, Solar flare, etc.**

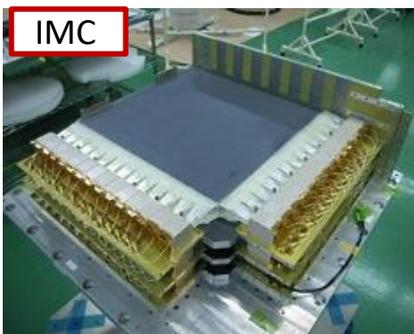
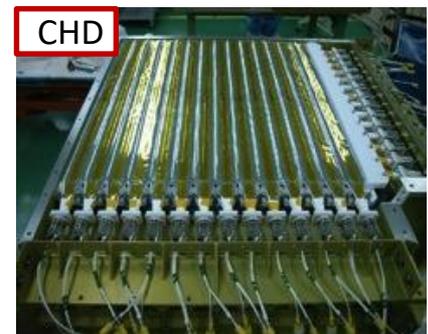
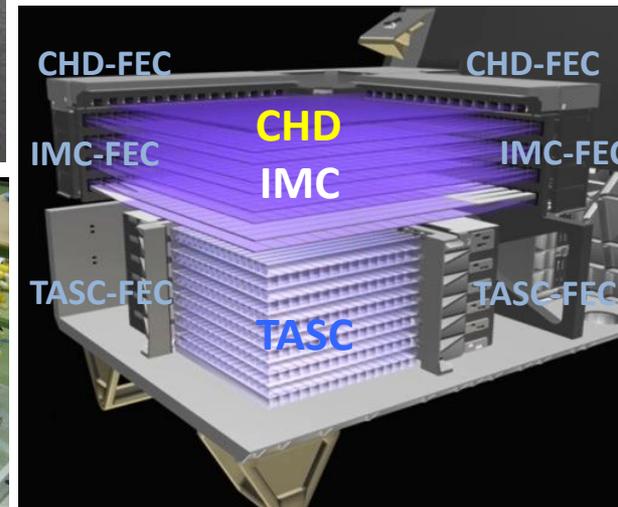
Continues stable observation since Oct. 13, 2015 and collected ~1.8 billion events so far.



CALET Instrument



CALORIMETER

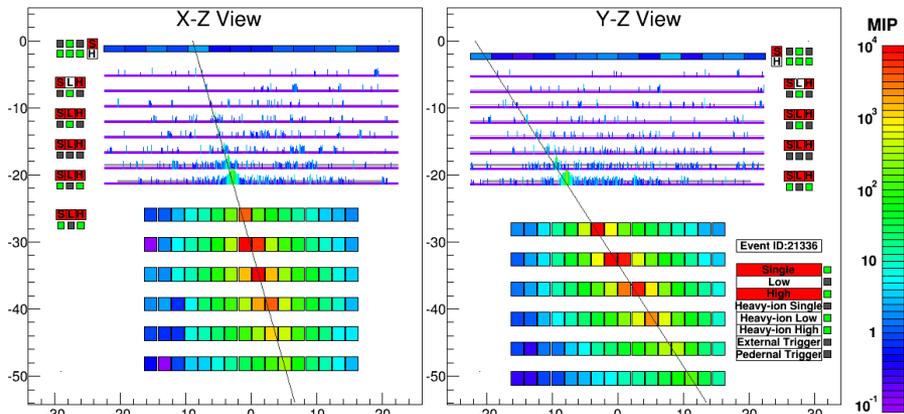


	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	Charge ($Z=1-40$)	Tracking, Particle ID	Energy, e/p Separation
Geometry (Material)	Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm ³	448 Scifi x 16 layers (X,Y) : 7168 Scifi 7 W layers ($3X_0$): $0.2X_0 \times 5 + 1X_0 \times 2$ Scifi size : 1 x 1 x 448 mm ³	16 PWO logs x 12 layers (x,y): 192 logs log size: 19 x 20 x 326 mm ³ Total Thickness : $27 X_0$, $\sim 1.2 \lambda_1$
Readout	PMT+CSA	64-anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)@top layer



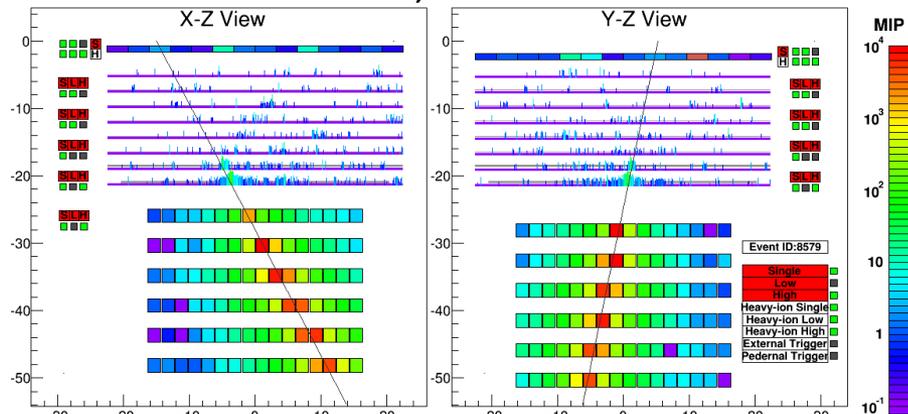
Event Examples of High-Energy Showers

Electron, $E=3.05$ TeV



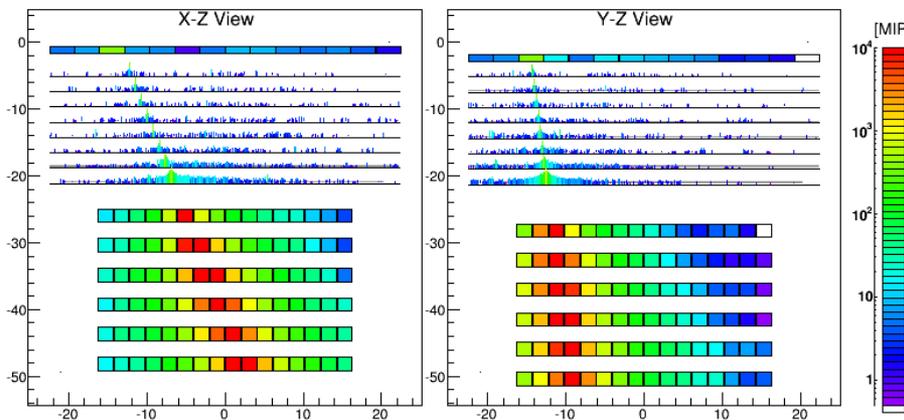
fully contained even at 3TeV

Proton, $\Delta E=2.89$ TeV



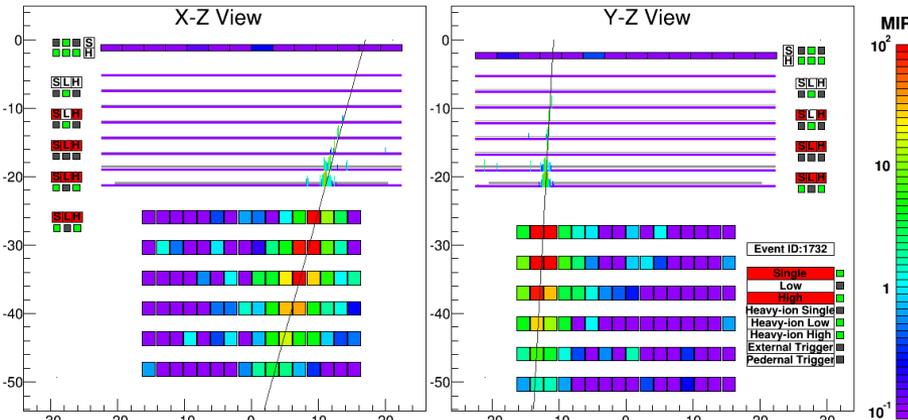
clear difference from electron shower

Fe($Z=26$), $\Delta E=9.3$ TeV



energy deposit in CHD consistent with Fe

Gamma-ray, $E=44.3$ GeV

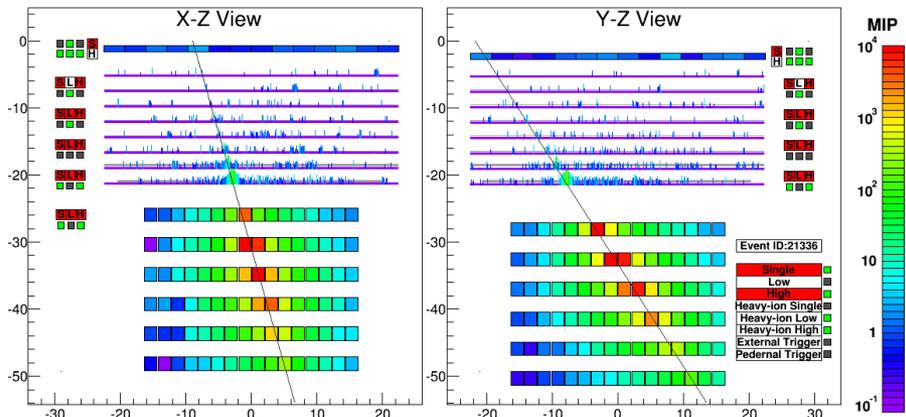


no energy deposit before pair production



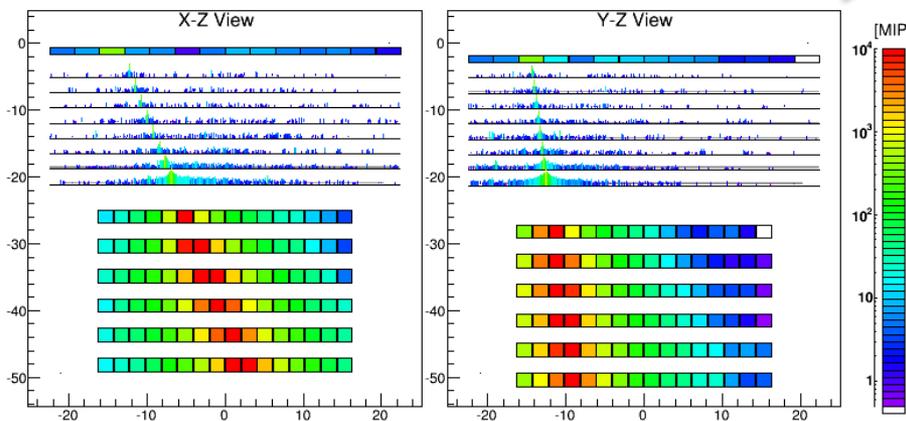
Event Examples of High-Energy Showers

Electron, $E=3.05$ TeV



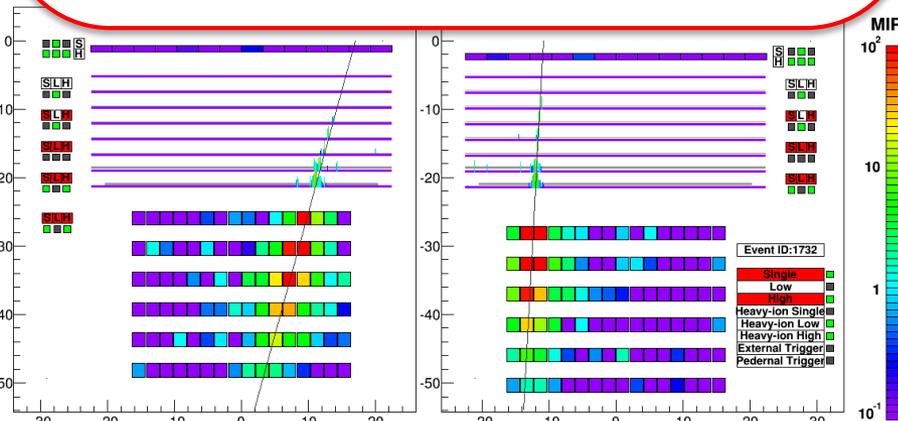
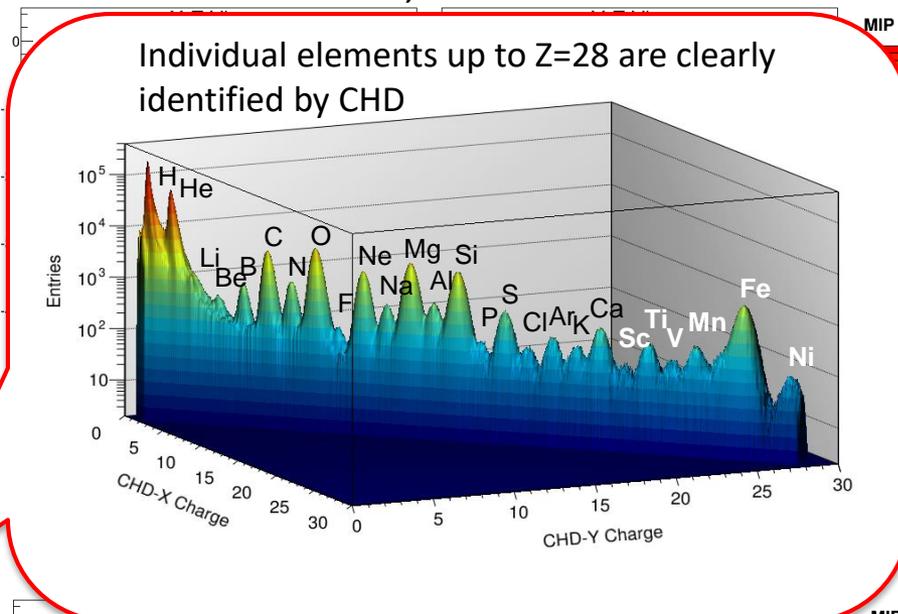
fully contained even at 3TeV

Fe($Z=26$), $\Delta E=9.3$ TeV



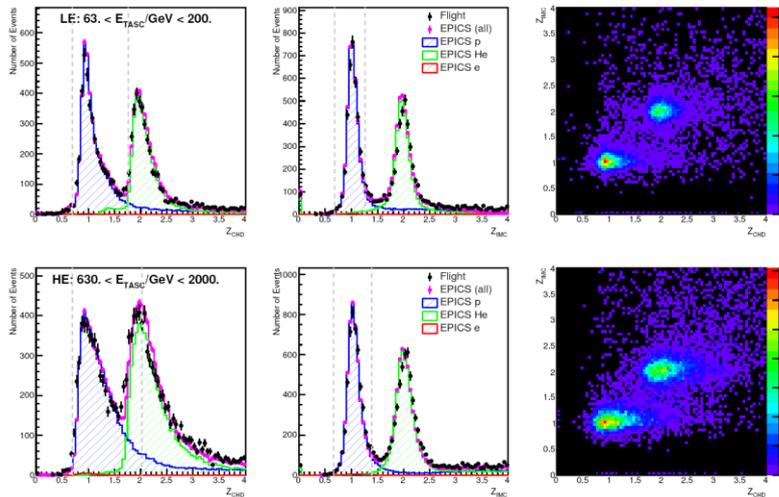
energy deposit in CHD consistent with Fe

Proton, $\Delta E=2.89$ TeV



no energy deposit before pair production

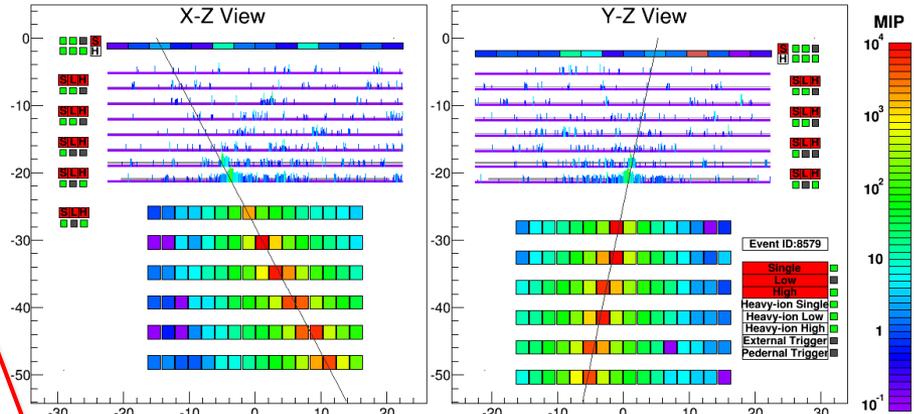
Event Examples of High-Energy Showers



Proton/helium separation using CHD/IMC charge

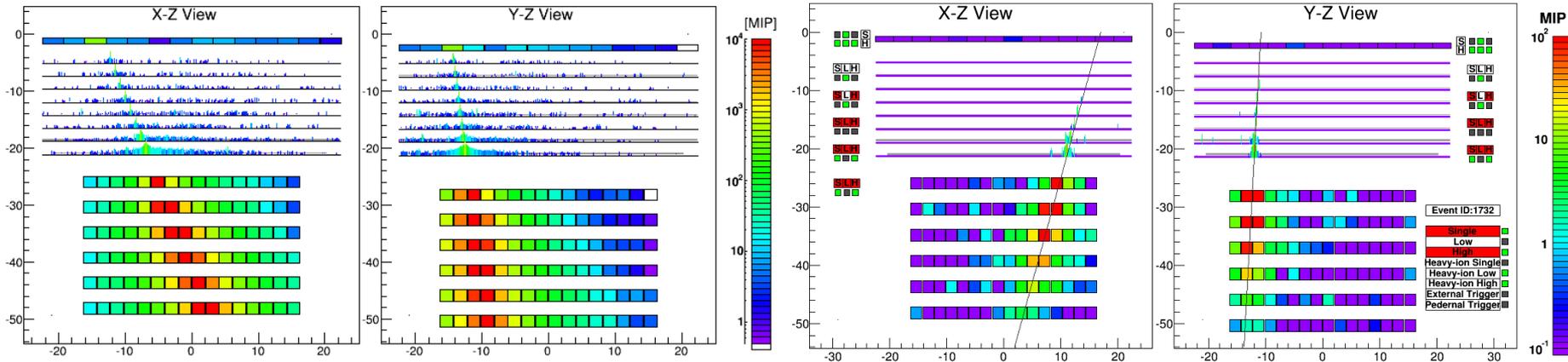
Fe(Z=26), $\Delta E=9.3$ TeV

Proton, $\Delta E=2.89$ TeV



clear difference from electron shower

Gamma-ray, $E=44.3$ GeV



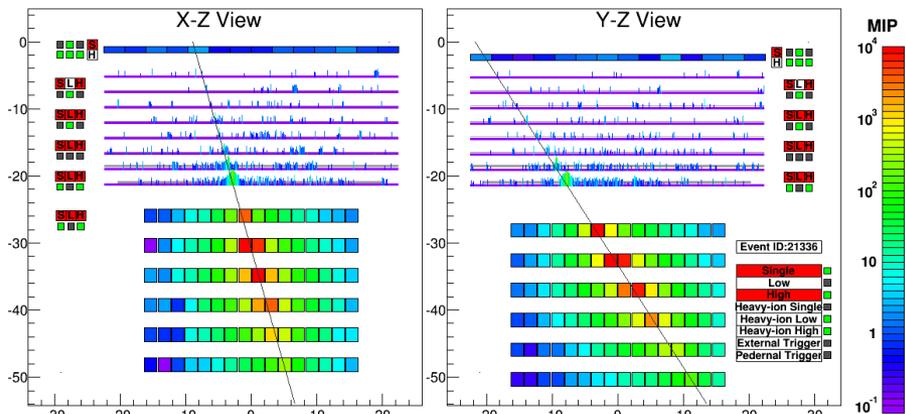
energy deposit in CHD consistent with Fe

no energy deposit before pair production



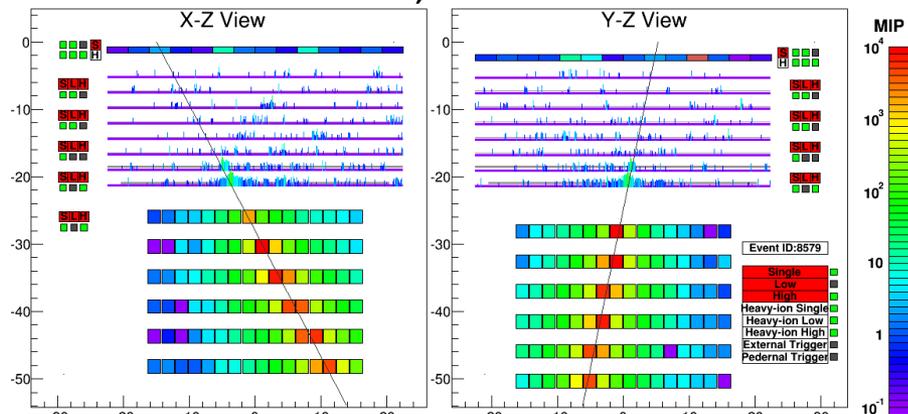
Event Examples of High-Energy Showers

Electron, $E=3.05$ TeV



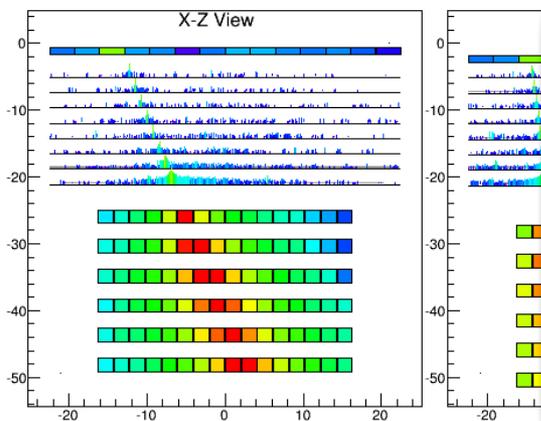
fully contained even at 3TeV

Proton, $\Delta E=2.89$ TeV



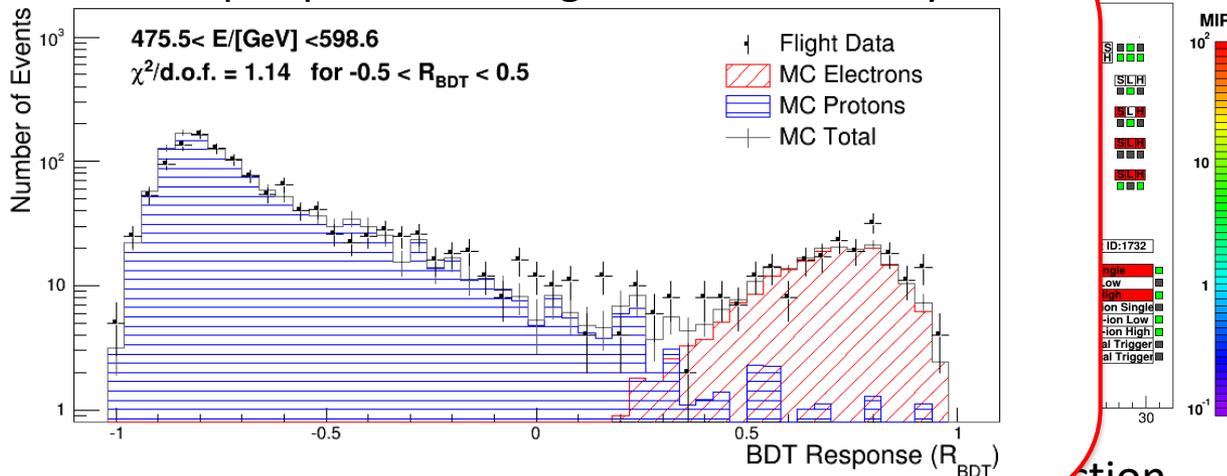
clear difference from electron shower

Fe($Z=26$), $\Delta E=9.2$ TeV



energy deposit in CHD cons.

Clear e/p separation using multivariate analysis



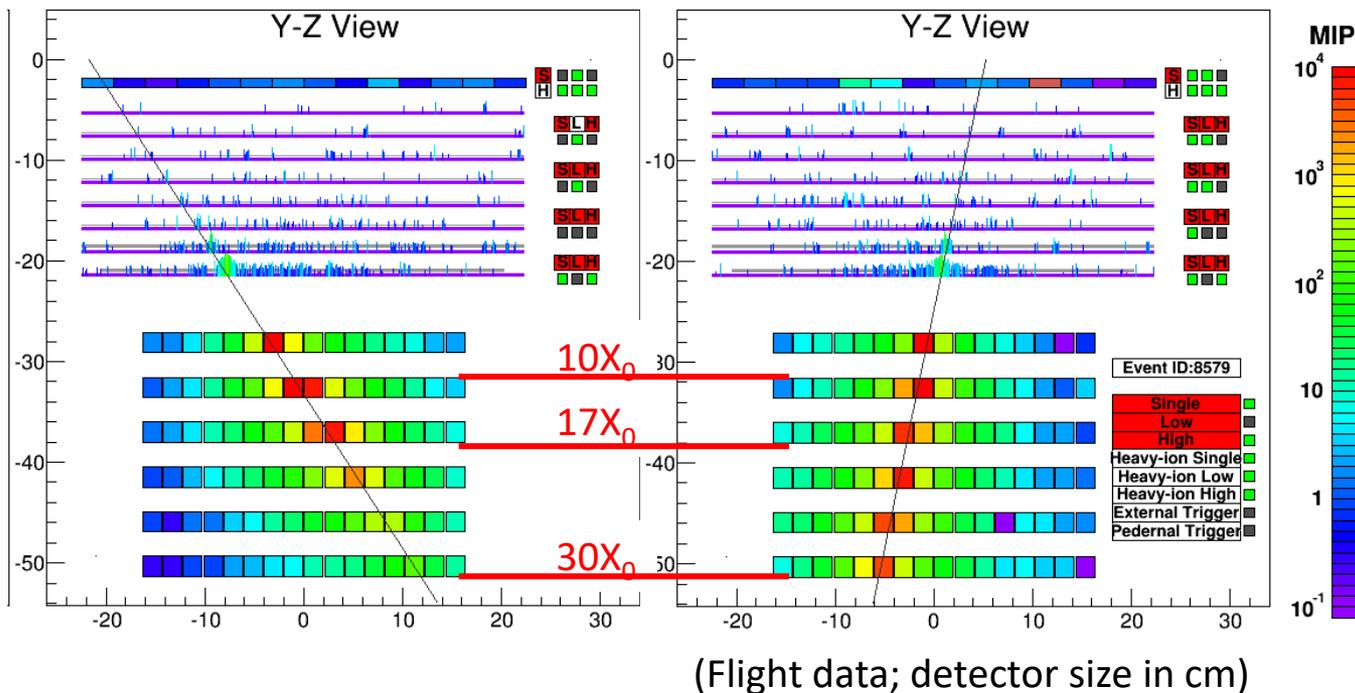
action



All-Electron Measurement with CALET

3TeV Electron Candidate

Corresponding Proton Background



1. **Reliable tracking**
well-developed
shower core
2. **Fine energy resolution**
full containment
of TeV showers
3. **High-efficiency electron ID**
30X₀ thickness,
closely packed logs

⇒ CALET is best suited for observation of **possible fine structures** in the all-electron spectrum up to the trans-TeV region.

All-Electron Measurement with CALET: room for “unknown” systematics

1. Acceptance
 - Geometrical factor

⇒ well defined $S\Omega$
because of reliable tracking
2. Energy determination
 - Magnet Spectrometer
 - **Calorimeter**

⇒ $\Delta E/E \sim 2\%$ ($E > 20\text{GeV}$)
absolute energy scale calibrated
by geomagnetic rigidity cutoff
3. Particle identification
 - Contamination

⇒ $r_{BG} < 5\%$ ($E < 1\text{TeV}$)
 $r_{BG} \sim 10\text{--}20\%$ ($1 < E < 5\text{TeV}$)
4. Detection efficiency
 - Losses in the detector

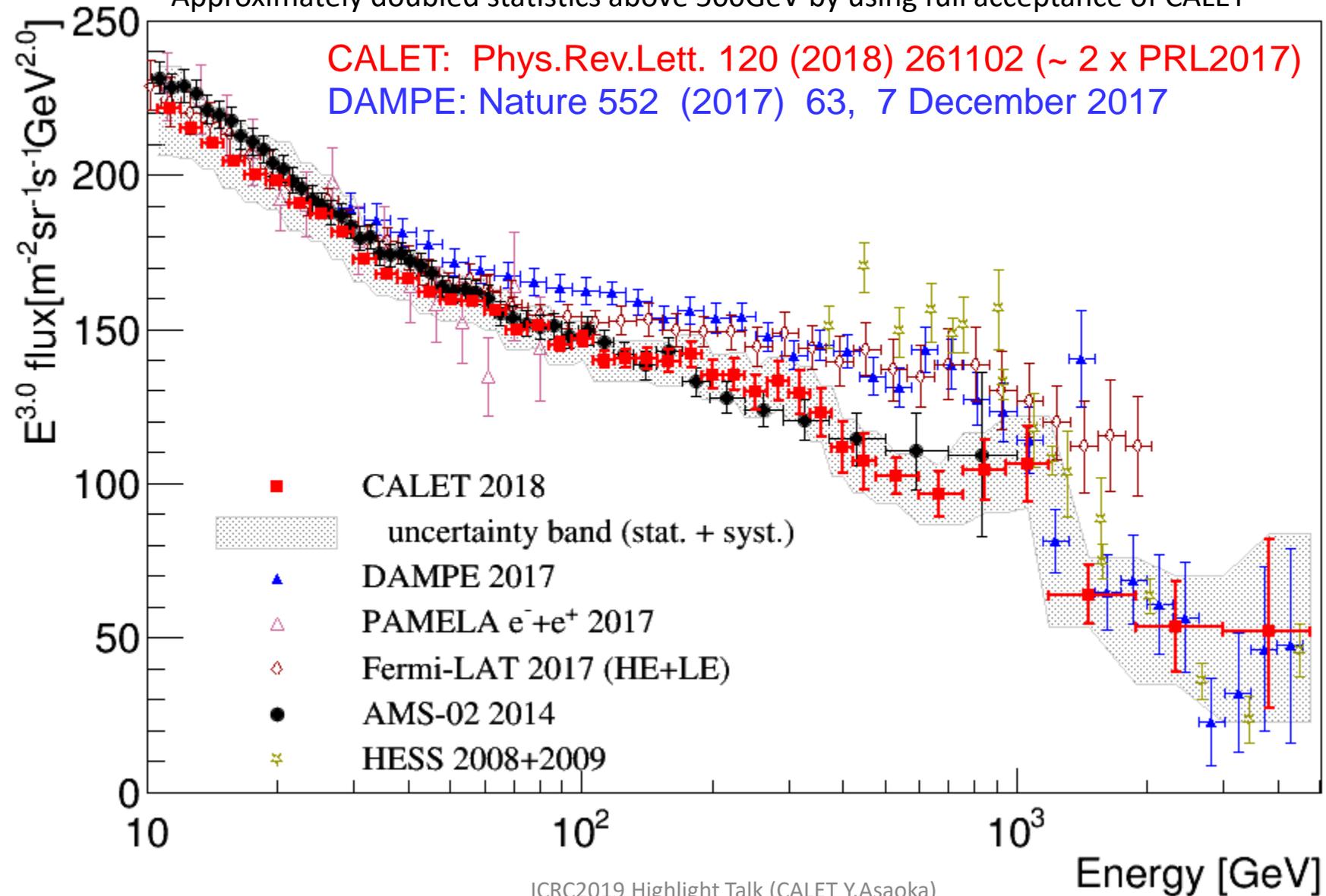
⇒ $\varepsilon > 70\%$ ($E > 30\text{GeV}$)
keeps constant value

⇒ Leaves little room for “unknown” systematics
combined with detailed systematic studies (see PRLs + SM)



All Electron Spectrum: Extended Measurement by CALET

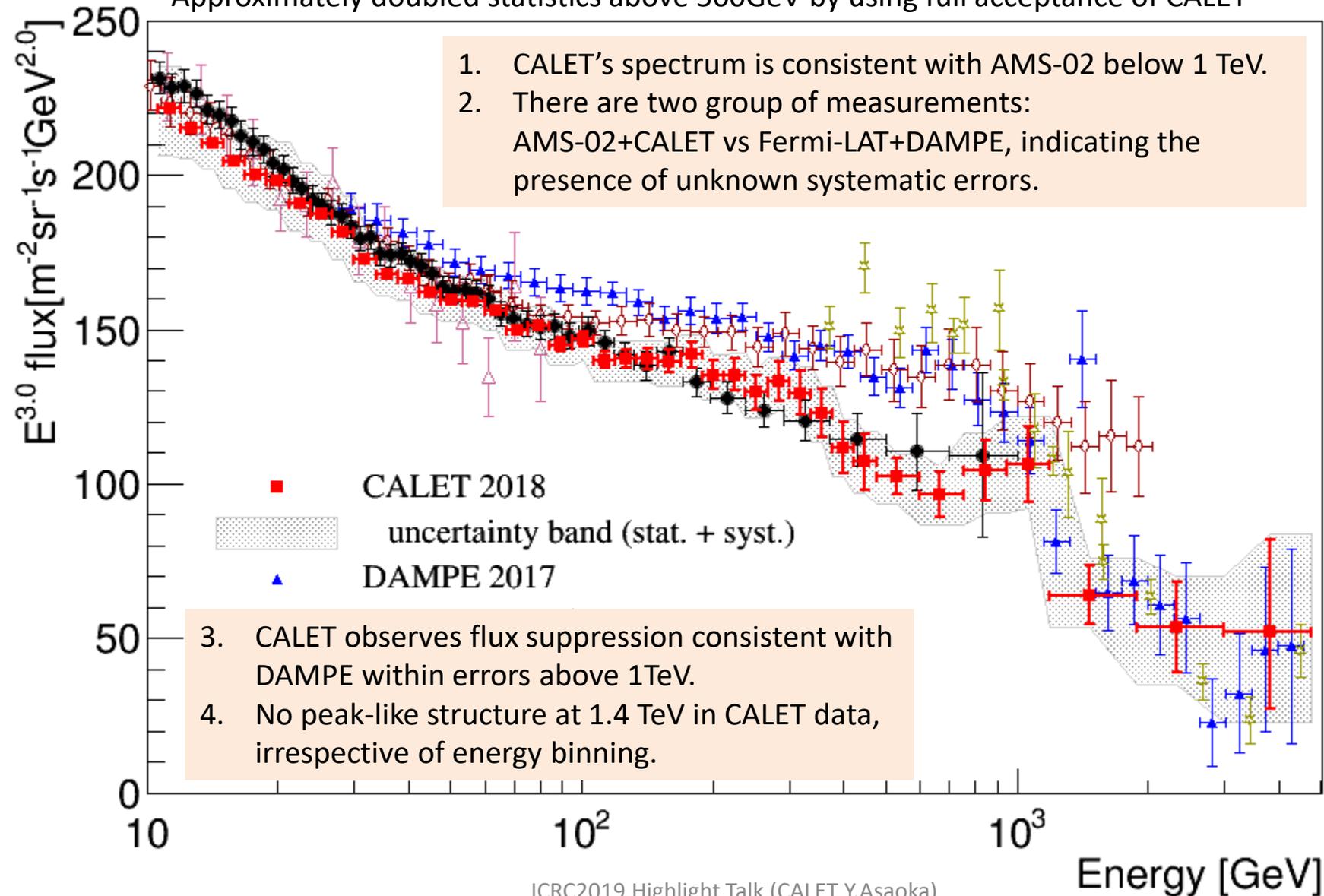
Approximately doubled statistics above 500GeV by using full acceptance of CALET





All Electron Spectrum: Extended Measurement by CALET

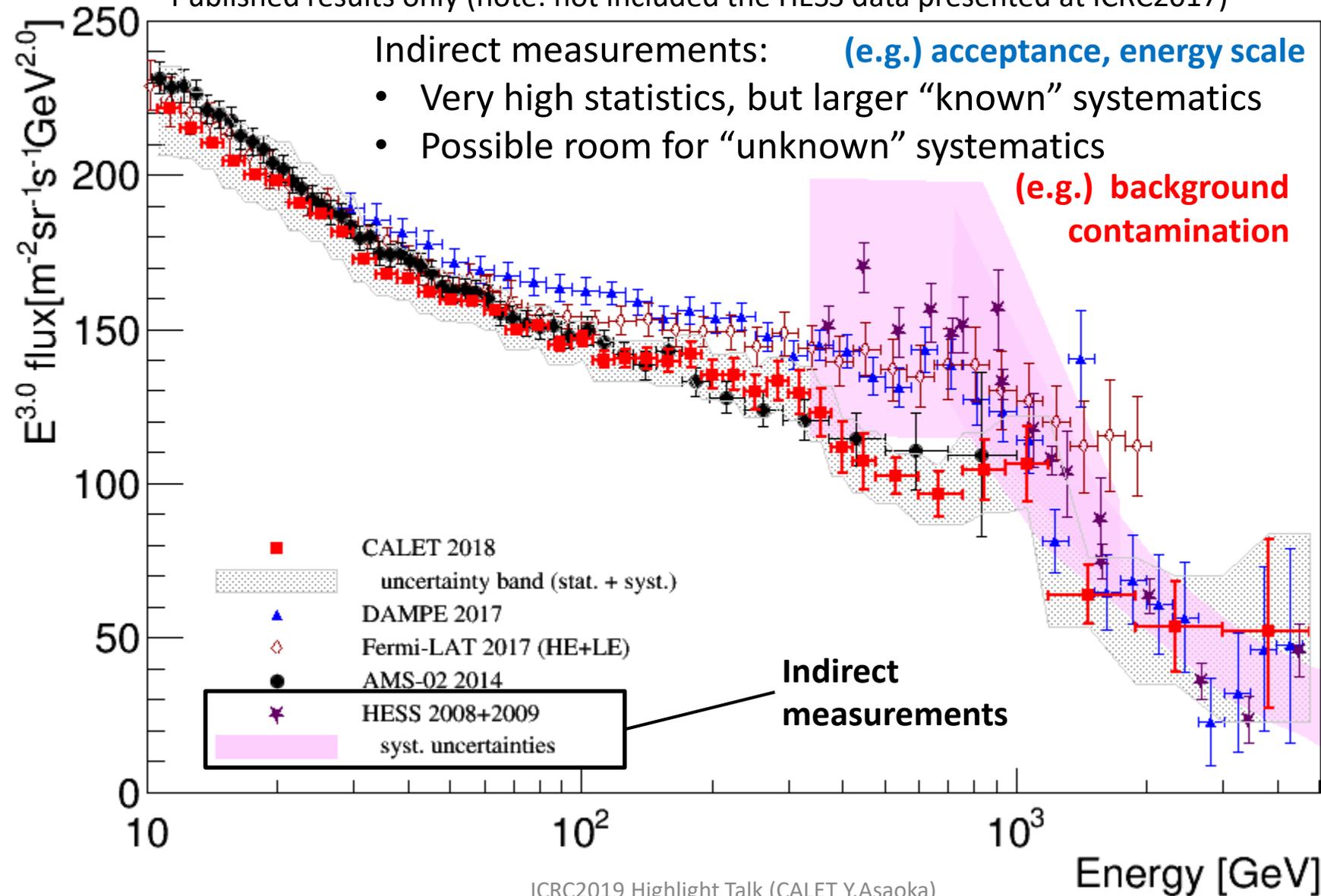
Approximately doubled statistics above 500GeV by using full acceptance of CALET





All Electron Spectrum: Comparison with Indirect Measurements

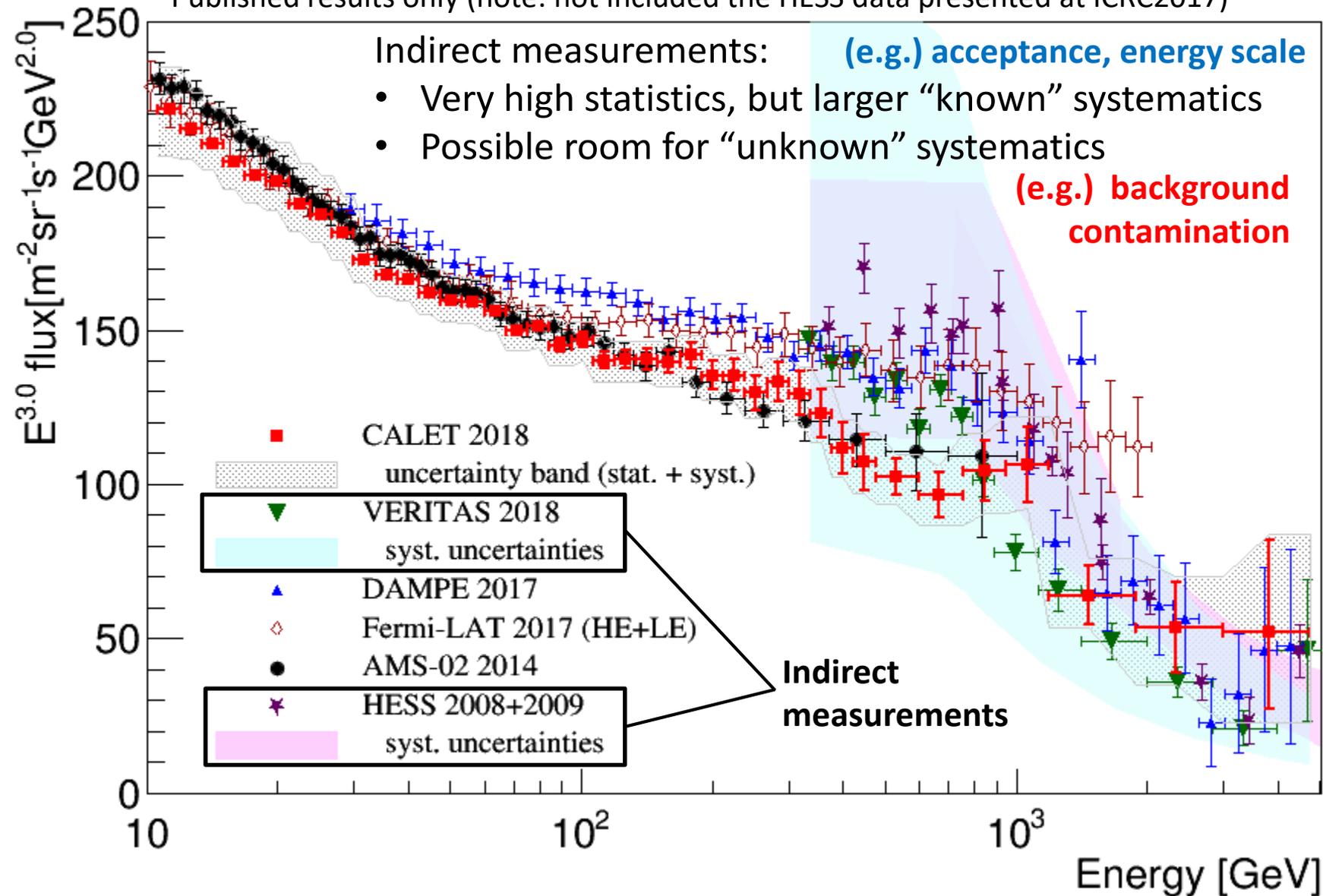
Published results only (note: not included the HESS data presented at ICRC2017)





All Electron Spectrum: Comparison with Indirect Measurements

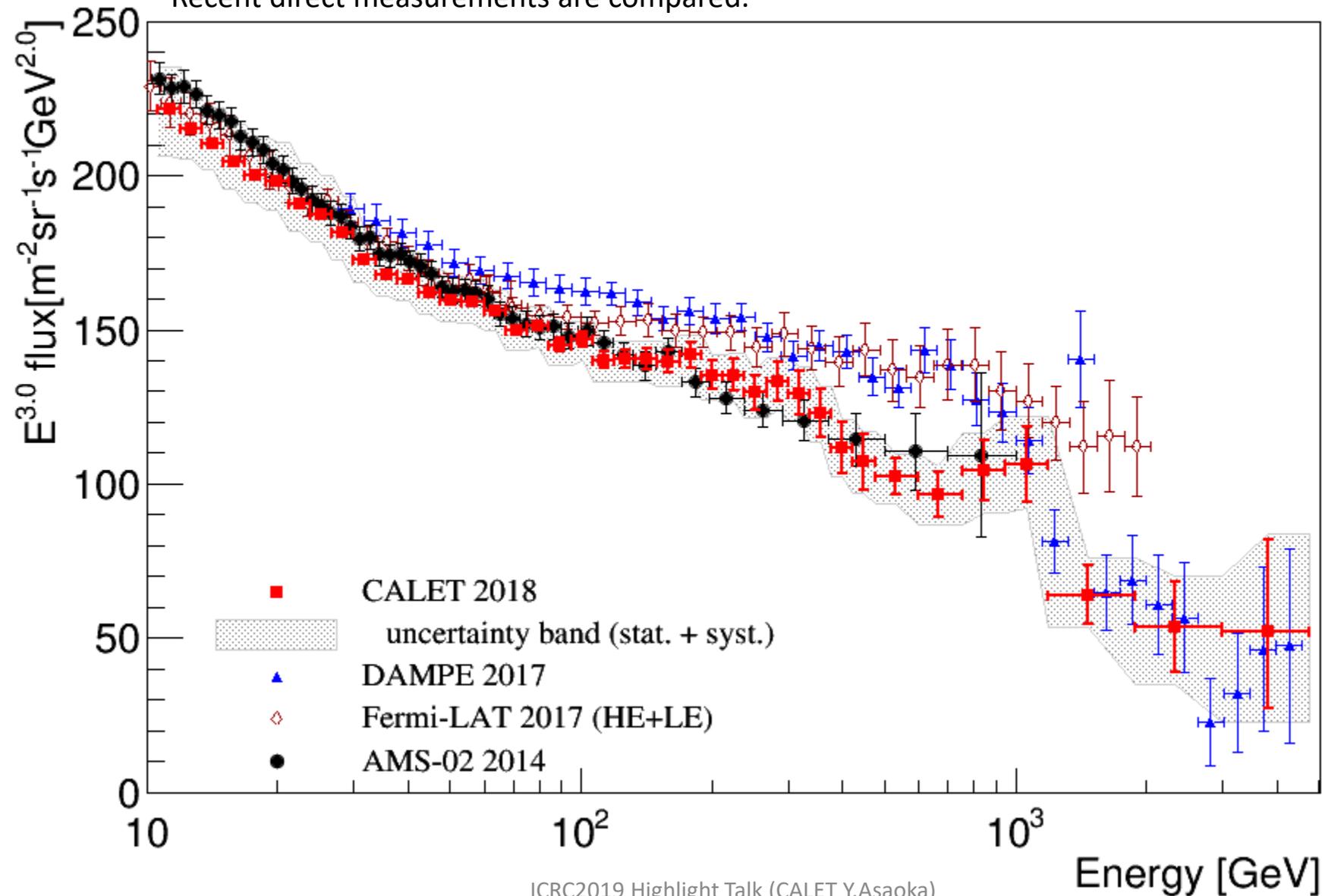
Published results only (note: not included the HESS data presented at ICRC2017)





All Electron Spectrum: Comparison between Recent Direct Measurements

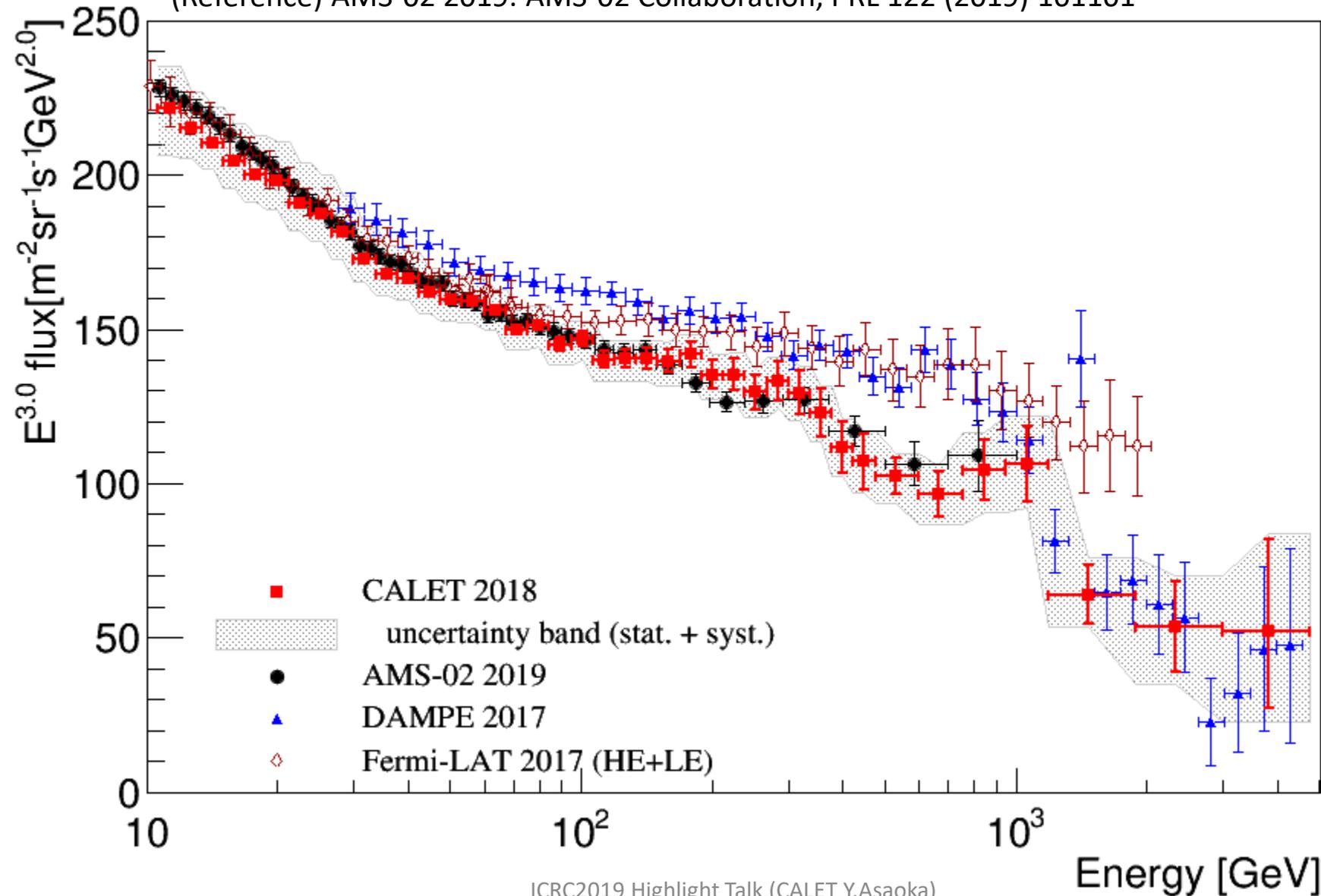
Recent direct measurements are compared.





All Electron Spectrum: Comparison with the Updated AMS-02 Result

(Reference) AMS-02 2019: AMS-02 Collaboration, PRL 122 (2019) 101101





All Electron Spectrum: Comparison between updated AMS-02 & CALET

Exactly the same analysis applied, data up to the end of May 2019 are used.

S. Torii ICRC2019 Jul. 25 (CRD2c)

Very good agreement obtained just by adding data:

- Low energy region: solar modulation
- High energy region: statistics matters.

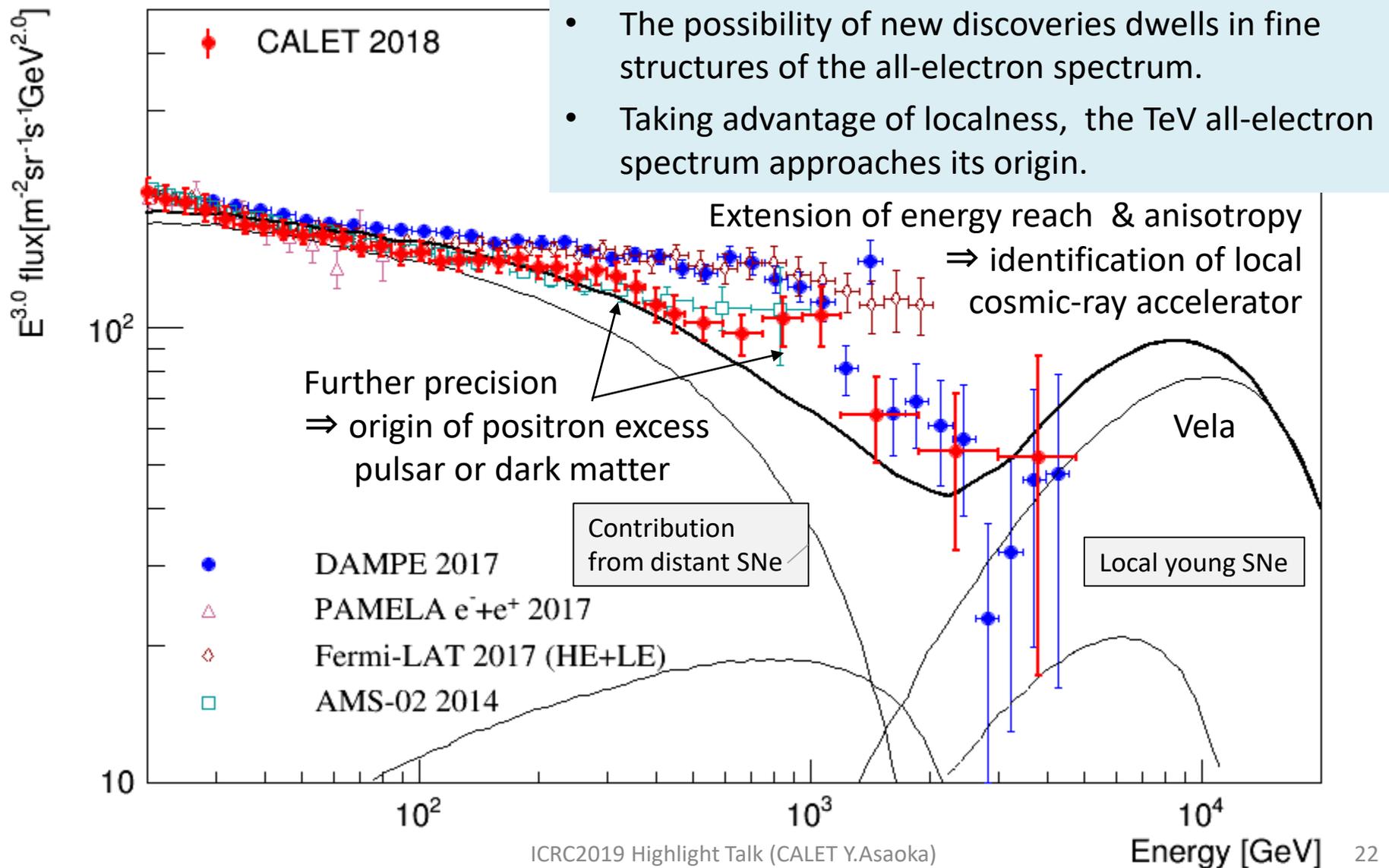
CALET Preliminary
(Statistical Error ONLY)

Sorry, please refer to our forthcoming publication

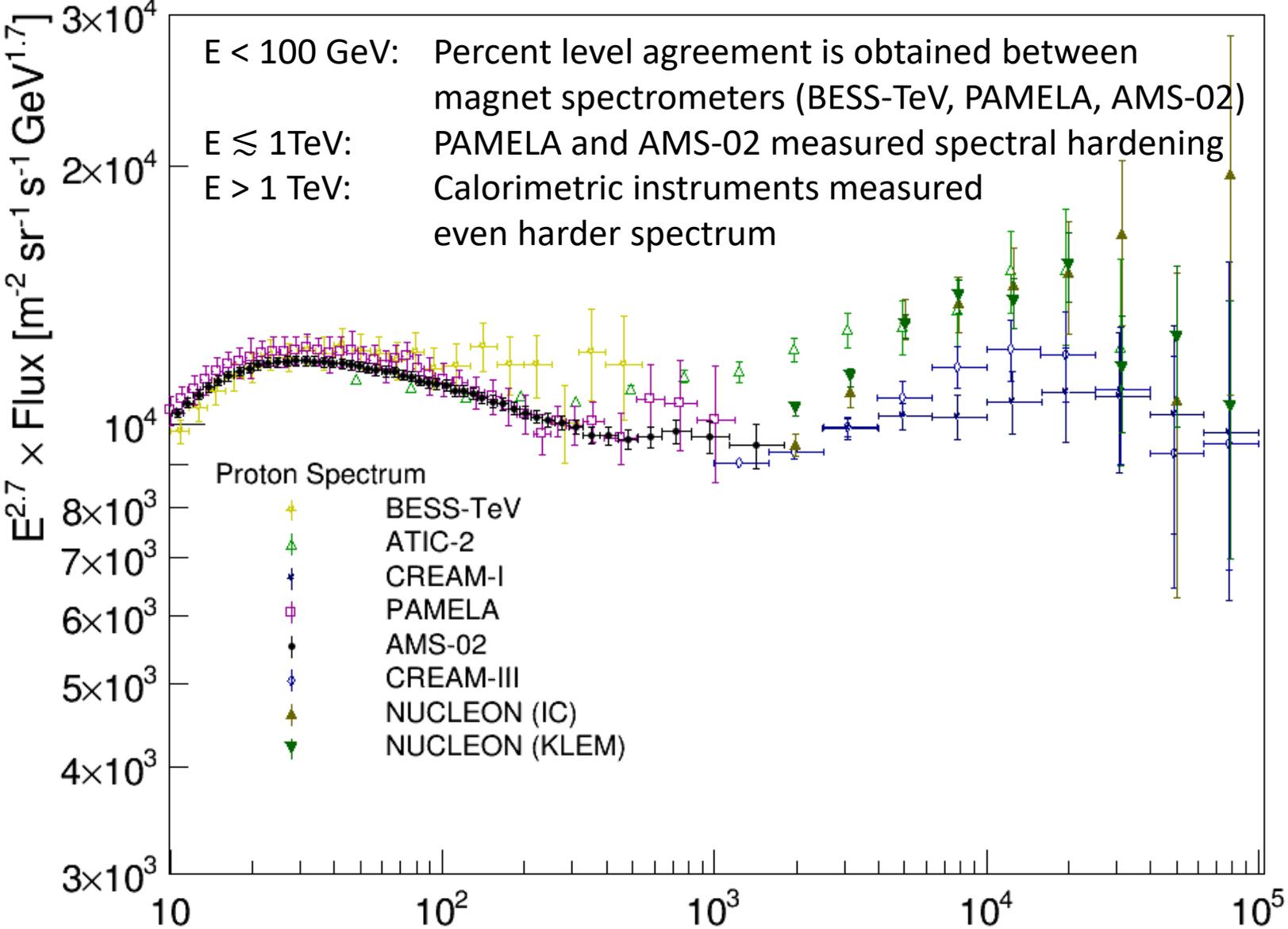


Prospects for the CALET All-Electron Spectrum

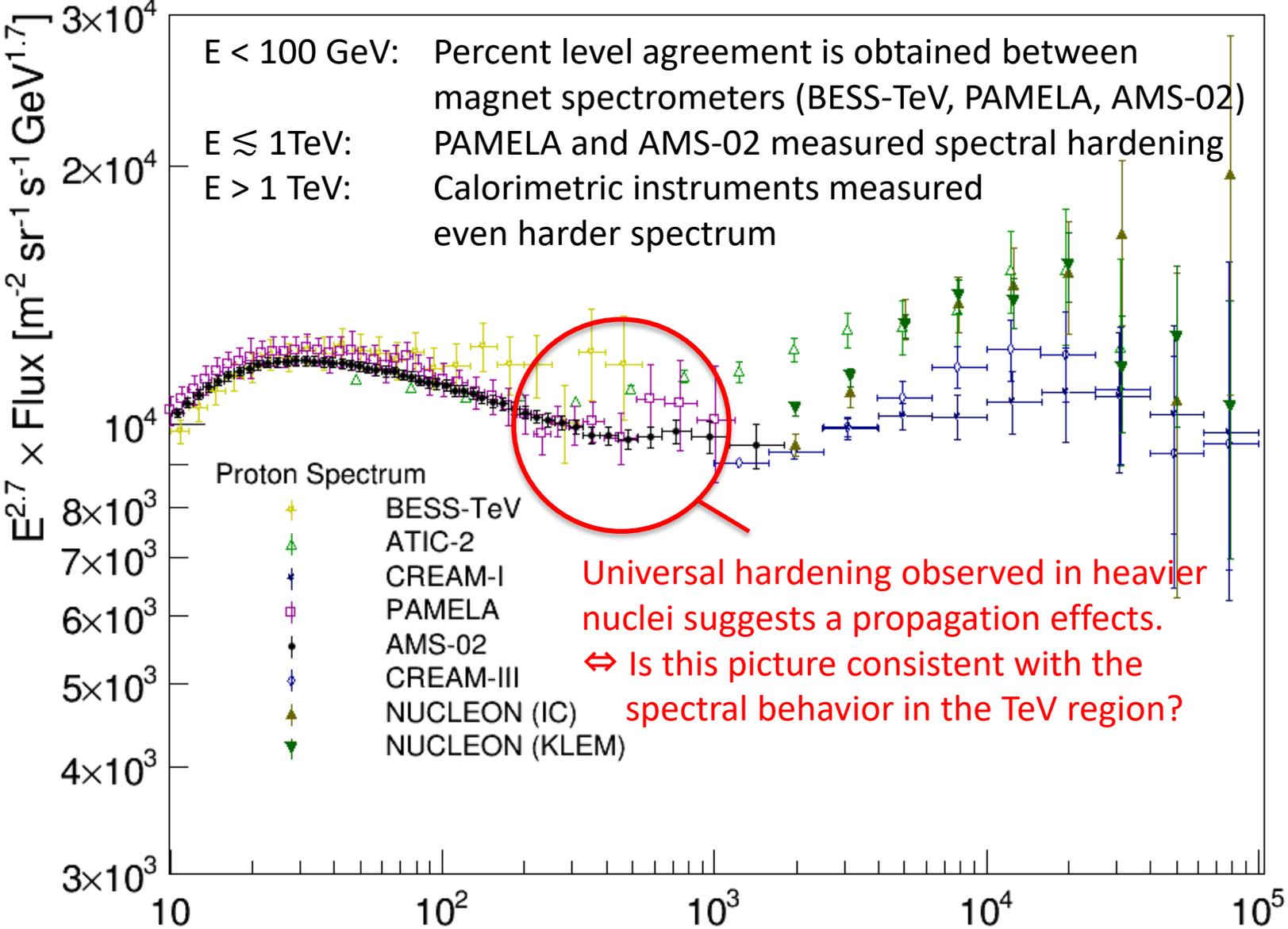
Five years or more observations \Rightarrow 3 times more statistics, reduction of systematic errors



Status of Cosmic-Ray Proton Spectrum Measurements



Status of Cosmic-Ray Proton Spectrum Measurements

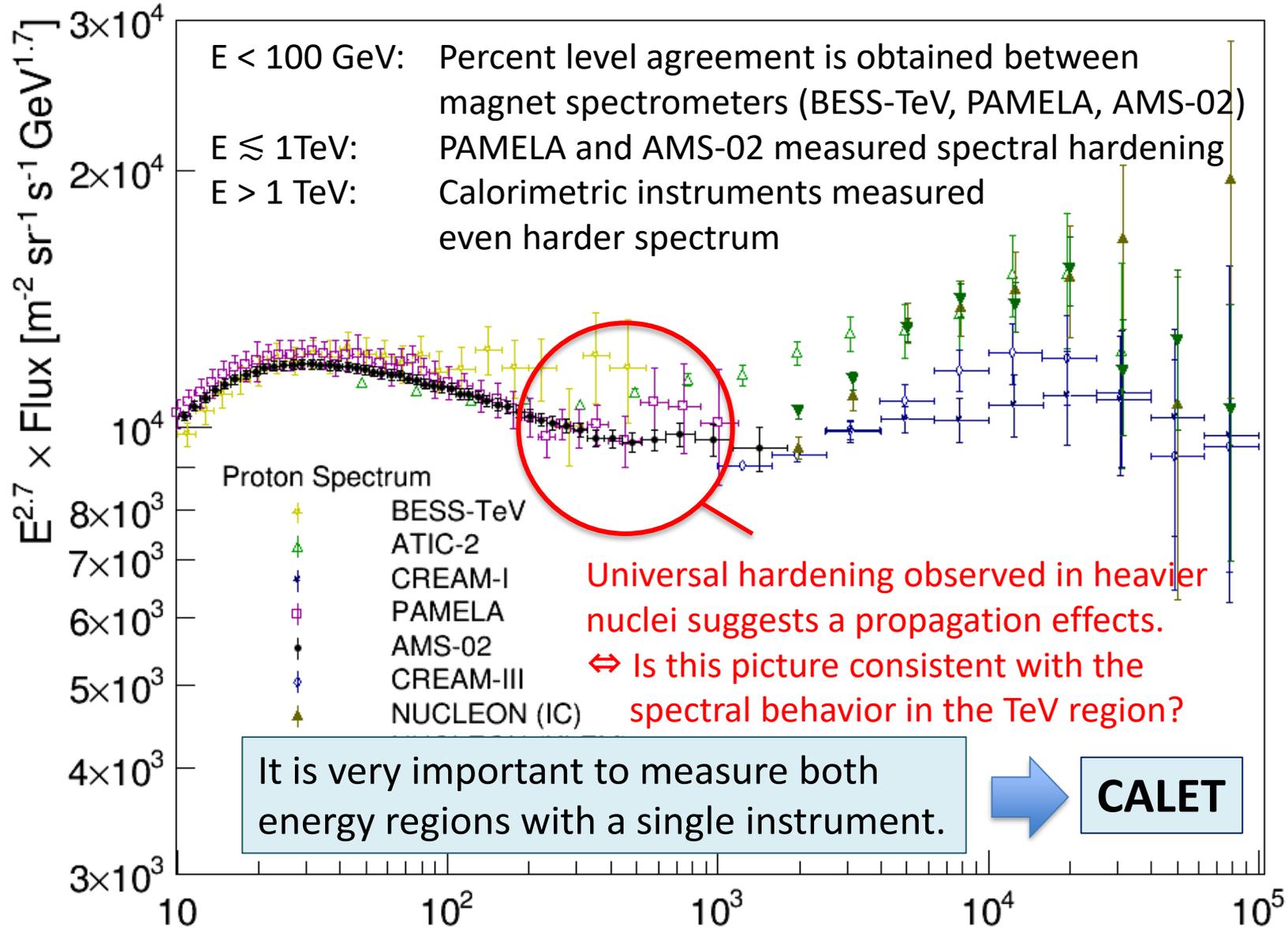


$E < 100 \text{ GeV}$: Percent level agreement is obtained between magnet spectrometers (BESS-TeV, PAMELA, AMS-02)
 $E \approx 1\text{TeV}$: PAMELA and AMS-02 measured spectral hardening
 $E > 1 \text{ TeV}$: Calorimetric instruments measured even harder spectrum

- Proton Spectrum
- ★ BESS-TeV
 - ▲ ATIC-2
 - ★ CREAM-I
 - PAMELA
 - AMS-02
 - ◆ CREAM-III
 - ▲ NUCLEON (IC)
 - ▼ NUCLEON (KLEM)

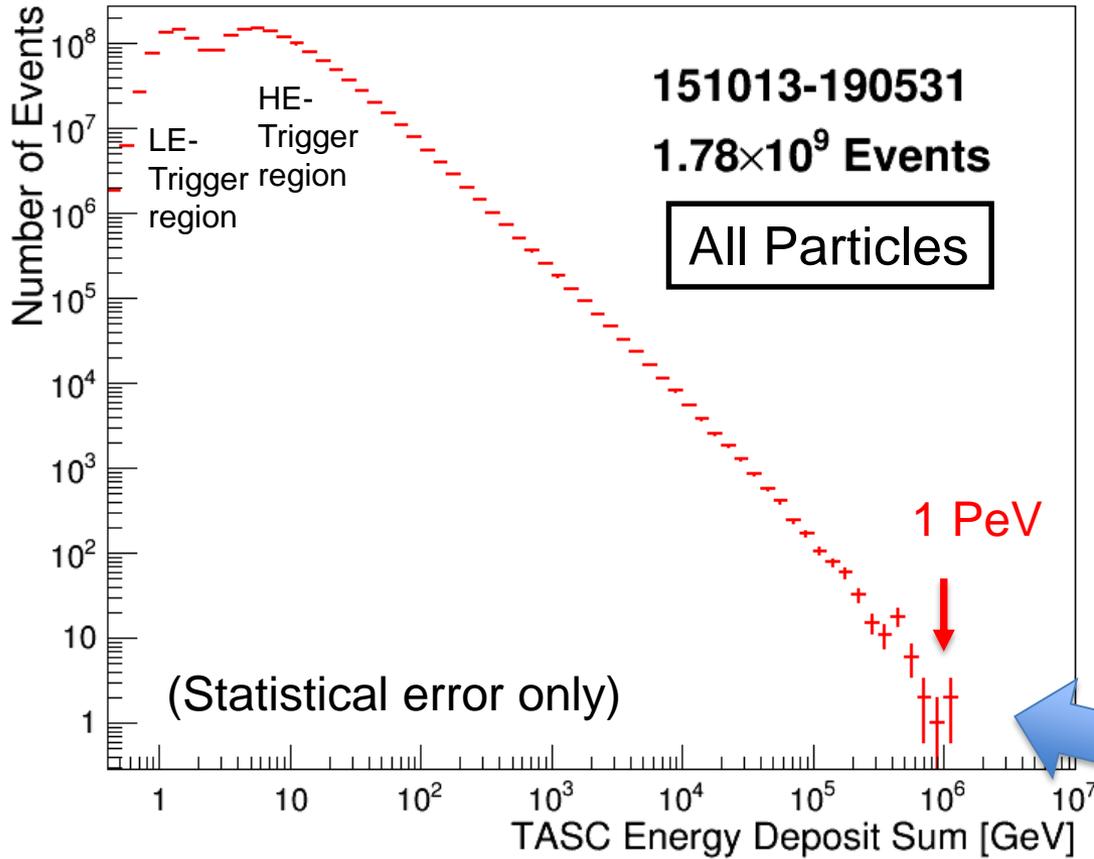
Universal hardening observed in heavier nuclei suggests a propagation effects.
 ⇔ Is this picture consistent with the spectral behavior in the TeV region?

Status of Cosmic-Ray Proton Spectrum Measurements

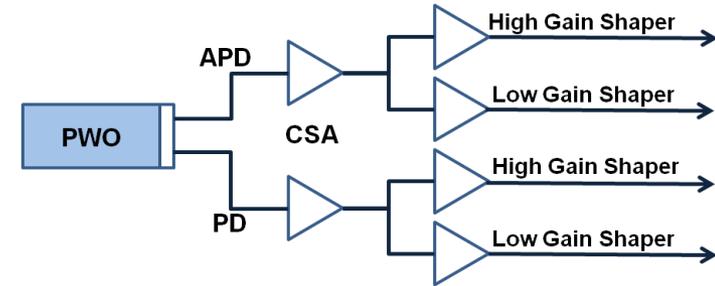
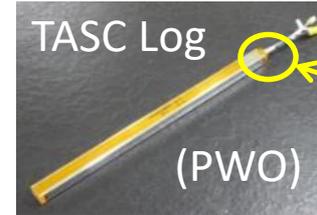


Wide Dynamic Range Energy Measurement

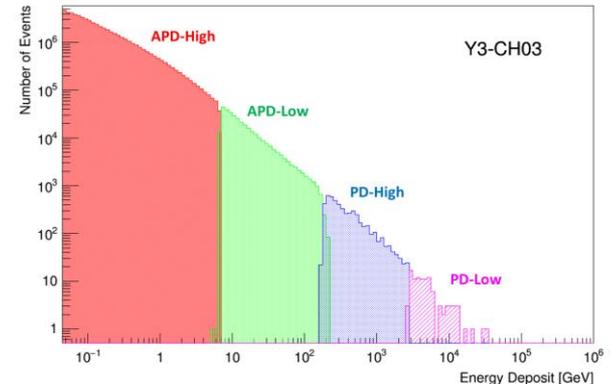
Distribution of TASC energy deposit sum



Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), *Astropart. Phys.* 91 (2017) 1.



An example of gain connection in one PWO log:

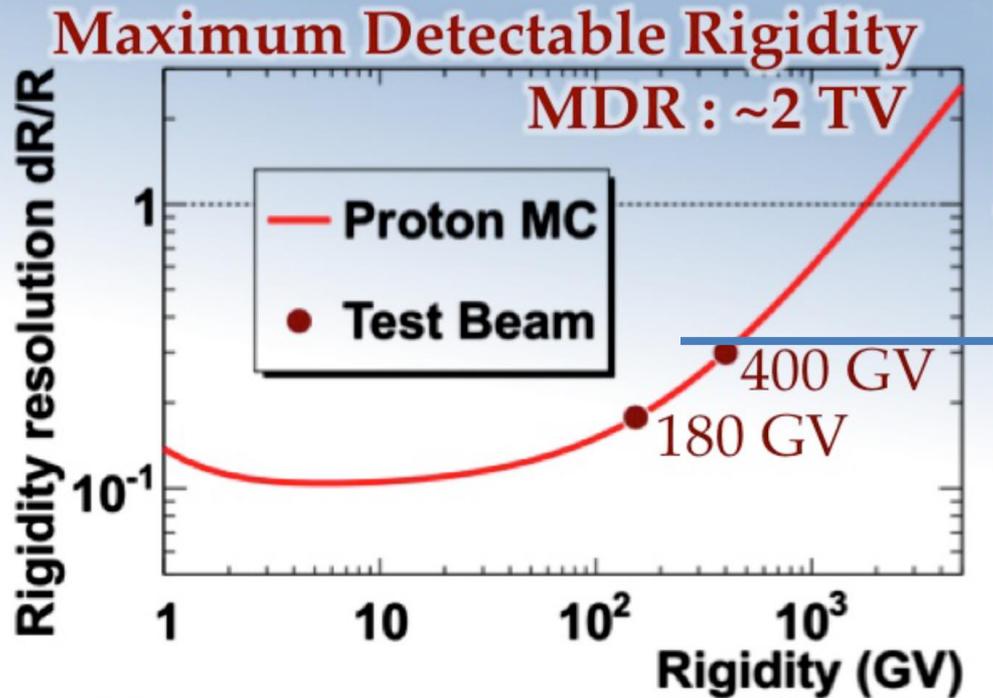


The smooth distribution clearly reflects the power-law nature of cosmic-rays, demonstrating the reliability of the energy measurement over a wide energy range.

Energy Measurement of Protons: Magnetic Spectrometer vs Calorimeter

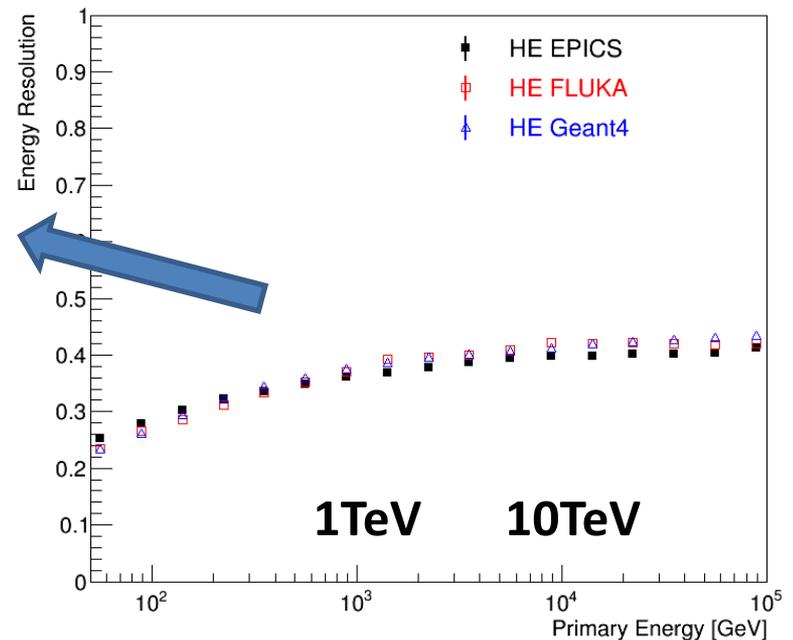
AMS-02: bending
in magnetic field

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



Ref: Haino 2014

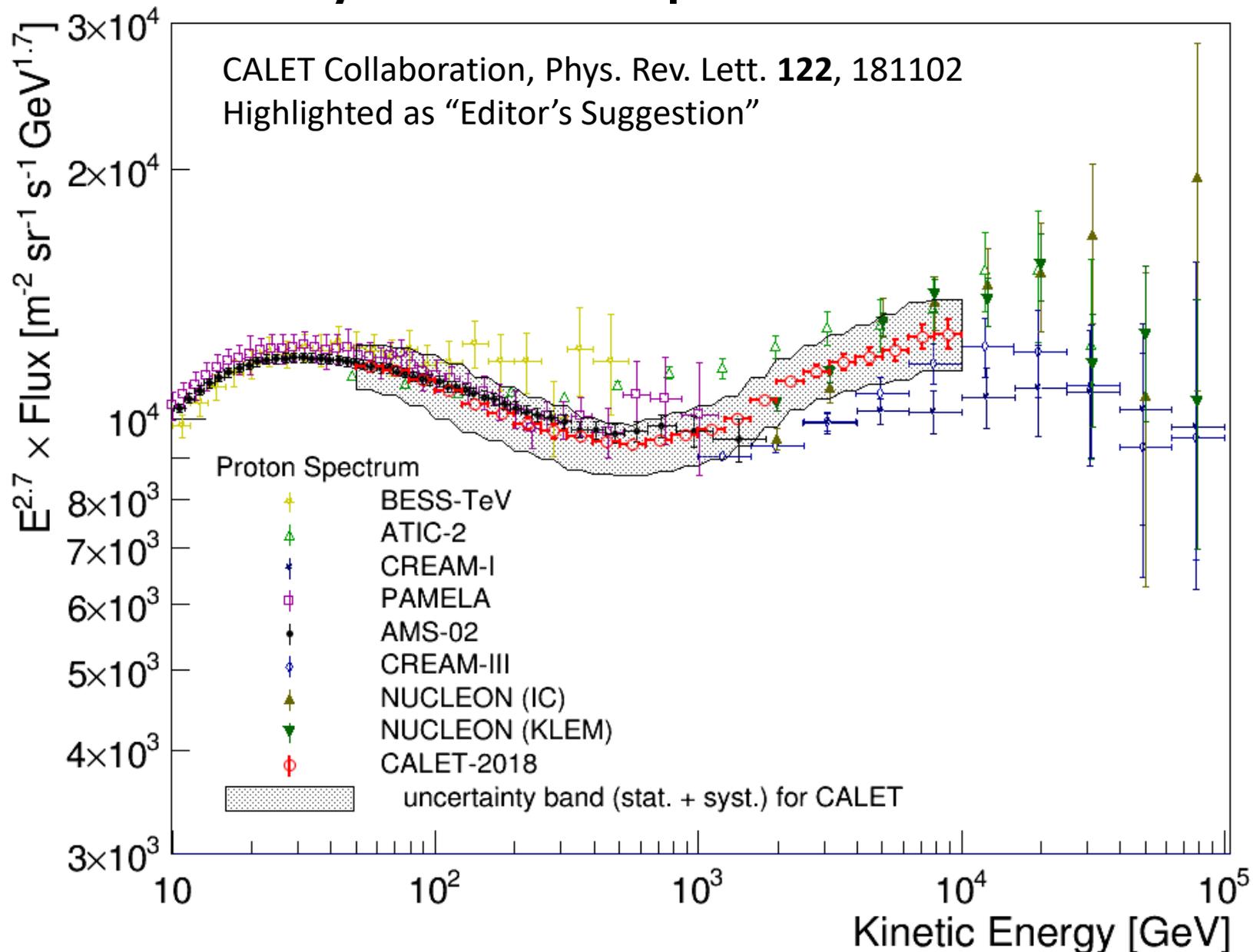
CALET: shower energy
Better resolution at $E > 500$ GeV.
Very stable above $E > 1$ TeV. Small
dependence on MC models.



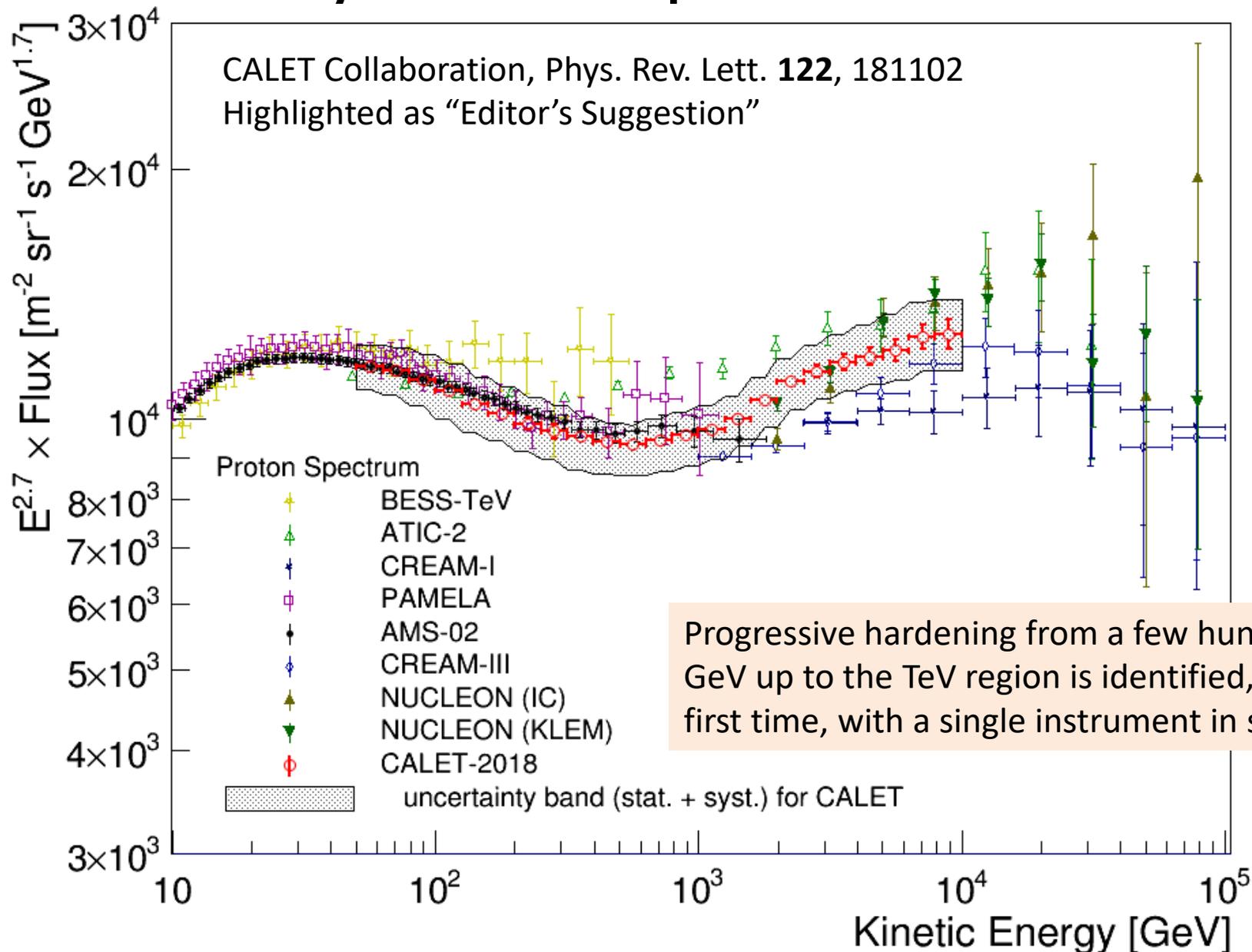
Proton Measurement with CALET: room for “unknown” systematics

1. Acceptance \Rightarrow well defined $S\Omega$
 - Geometrical factor \Rightarrow because of KF tracking and event selection
 2. Energy determination \Rightarrow limited energy resolution but constant response, and confirmed by test beam
 - Magnet Spectrometer
 - **Calorimeter**
 3. Particle identification \Rightarrow excellent charge separation capability
 - Contamination
 4. Detection efficiency \Rightarrow low efficiency, but confirmed by test beam
 - Losses in the detector
- \Rightarrow Needs special care for “unknown” systematics
detailed systematic studies are carried out
(see the Supplement Material of PRL 122, 181102)

Cosmic-Ray Proton Spectrum from CALET

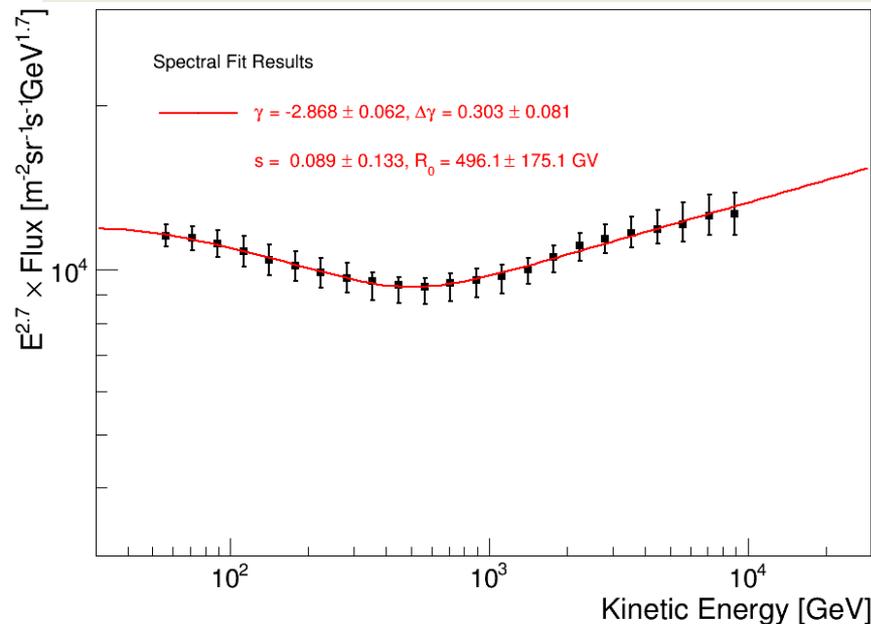
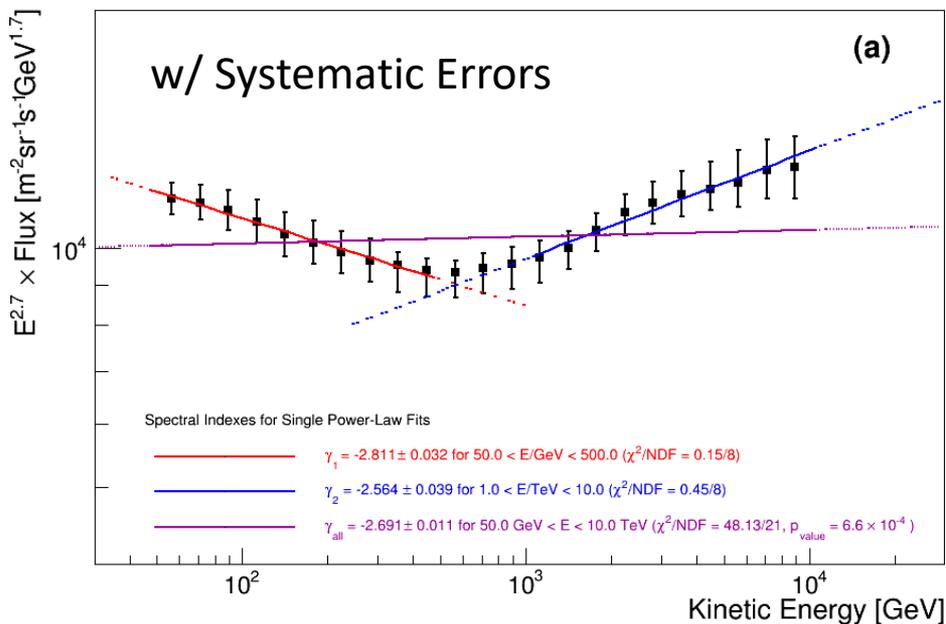


Cosmic-Ray Proton Spectrum from CALET



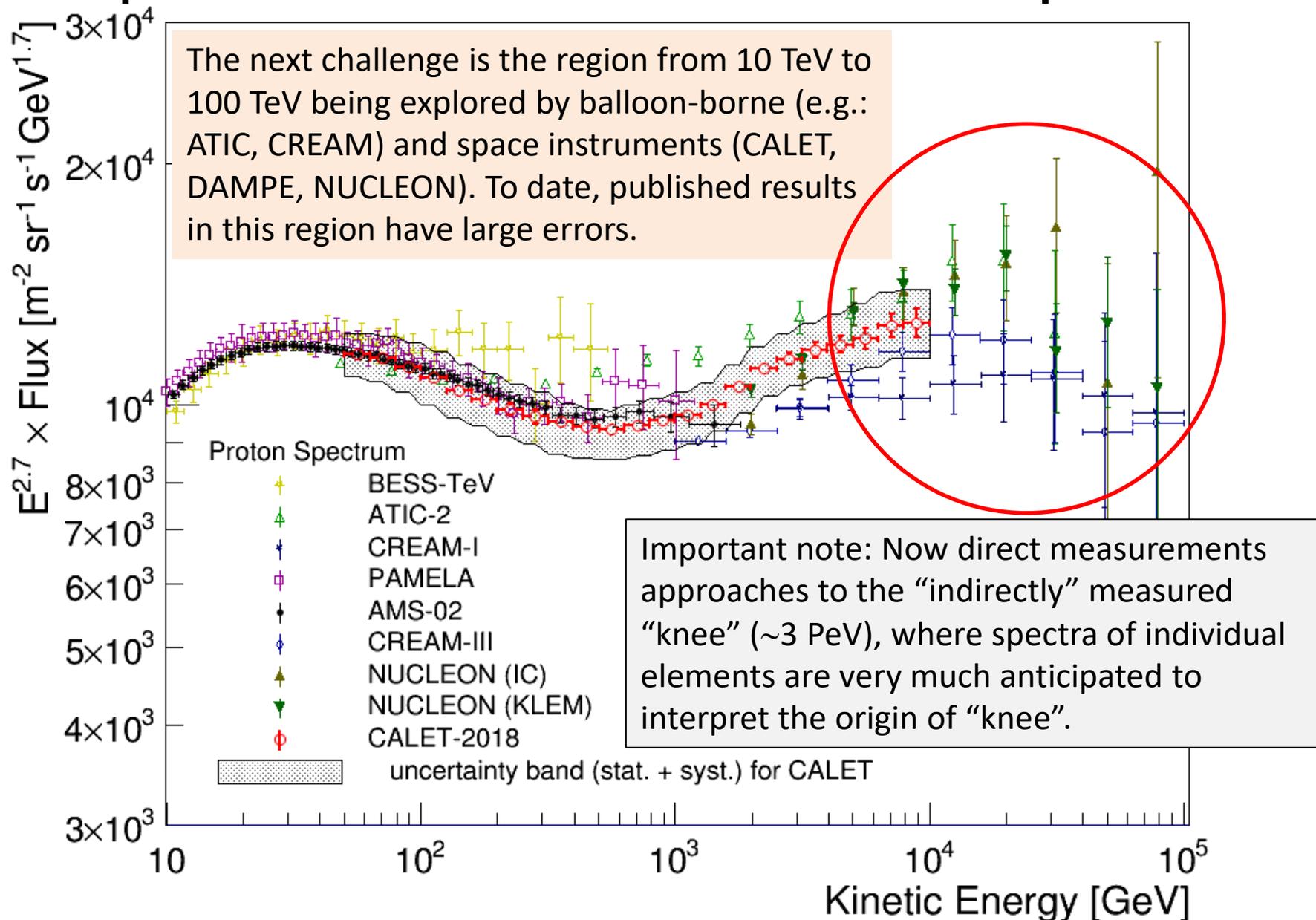
Spectral Behavior of Proton Flux

P. S. Marrocchesi ICRC2019 Jul. 30 (CRD8e)



1. Subranges of 50—500GeV, 1-10TeV can be fitted with single power law function, but not the whole range (significance $> 3\sigma$).
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.

Prospects for the CALET Proton Spectrum

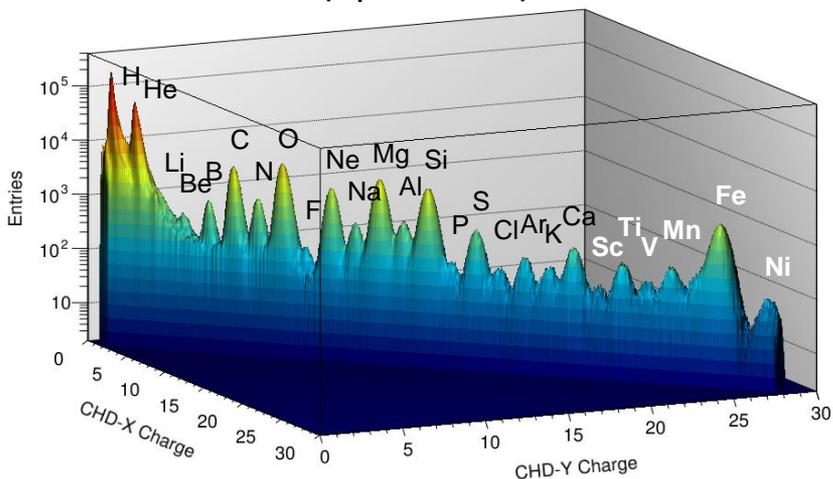




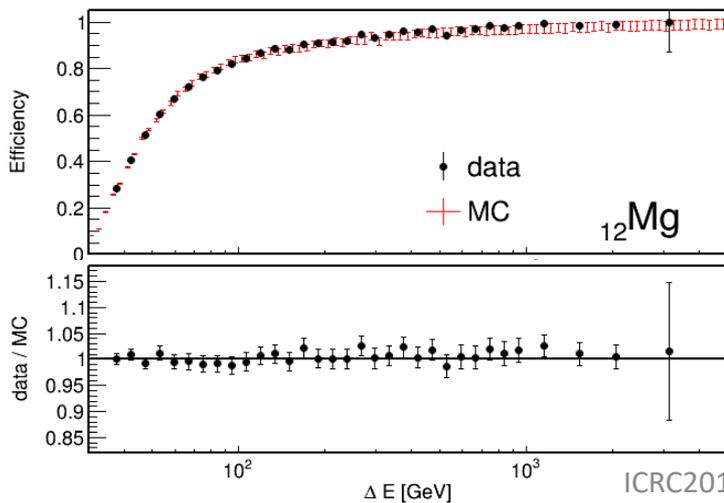
Preliminary Spectra of Primary Components

Charge Separation only with CHD

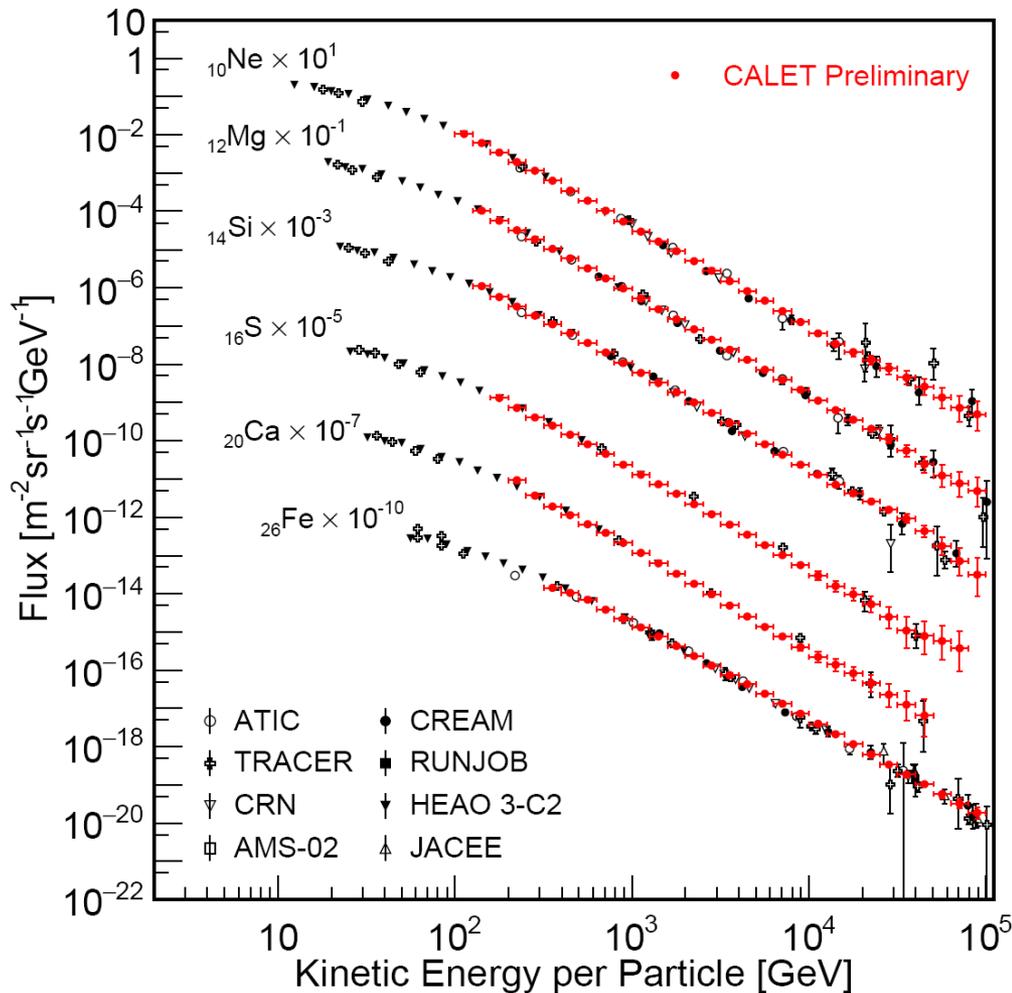
Clear separation of protons, helium to iron and nickel (up to Z=40).



Trigger Efficiency Measurement



Y. Akaike ICRC2019 Jul. 26 (CRD3b)

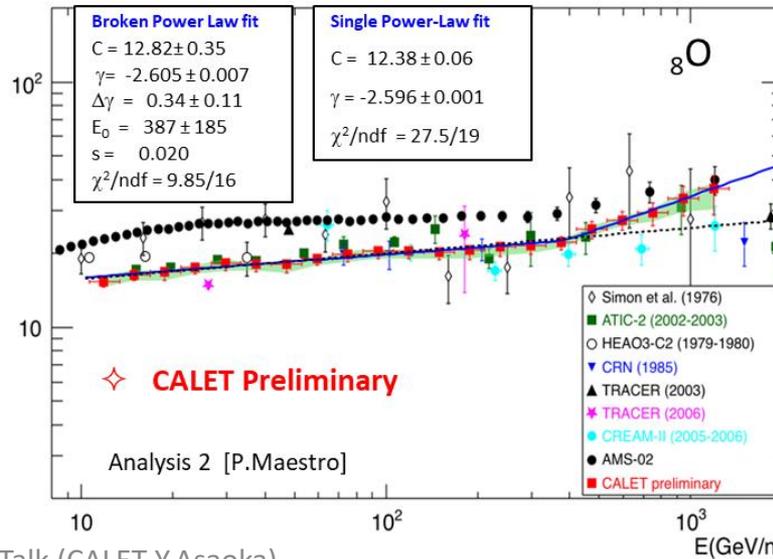
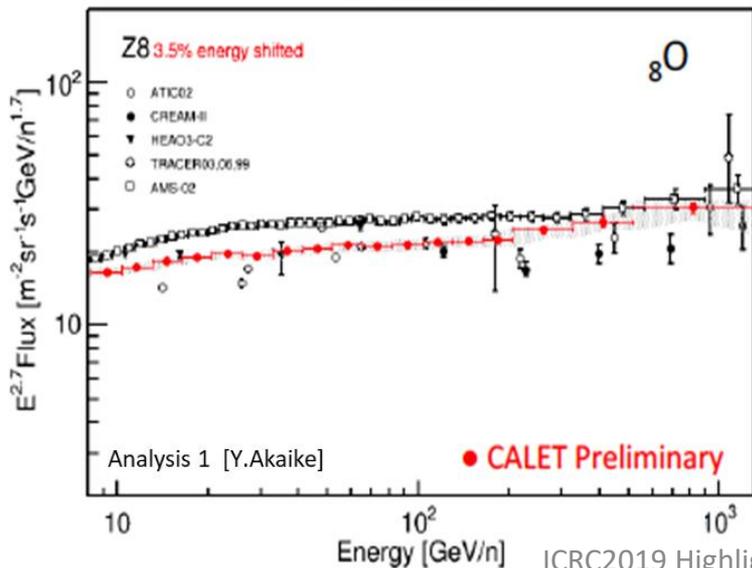
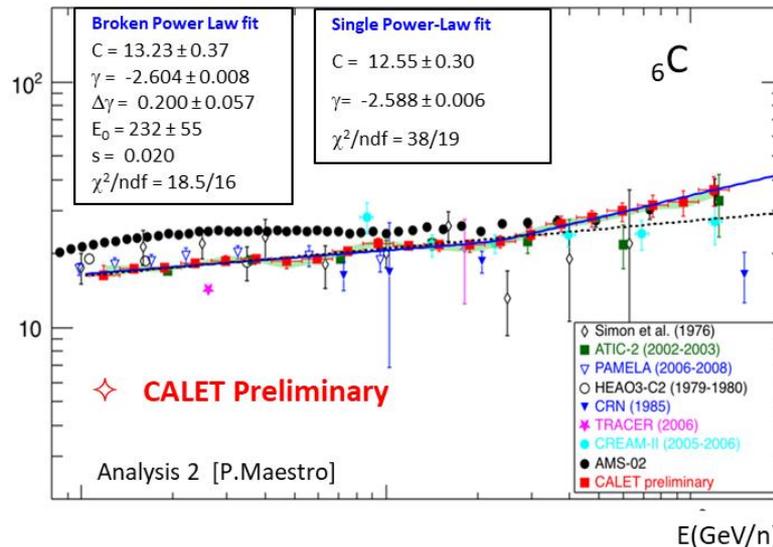
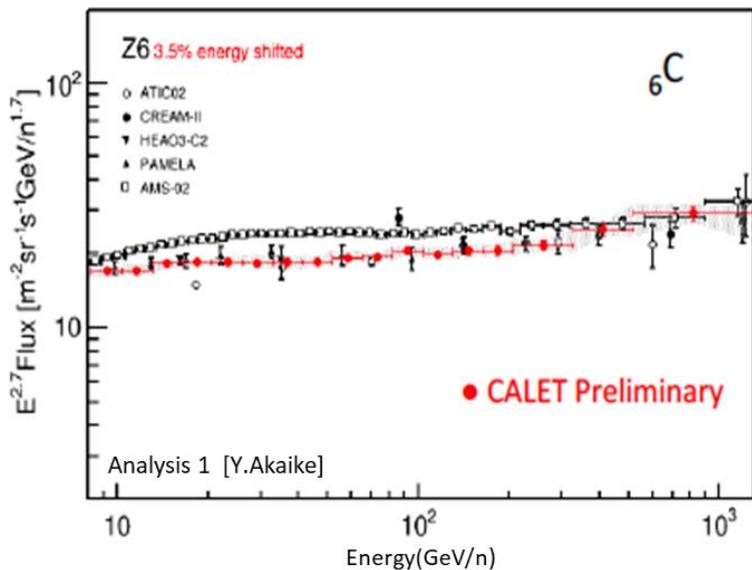




Preliminary Energy Spectra of Carbon and Oxygen

(2 independent CALET analyses)

P. Maestro ICRC2019 Jul. 30 (CRD8f)



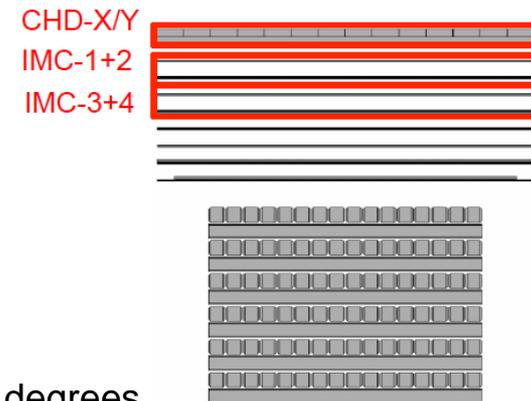


Ultra Heavy Nuclei Analysis (Z>26, up to 40)

B. Rauch ICRC2019 Jul. 26 (CRD3c)

Onboard trigger for UH events

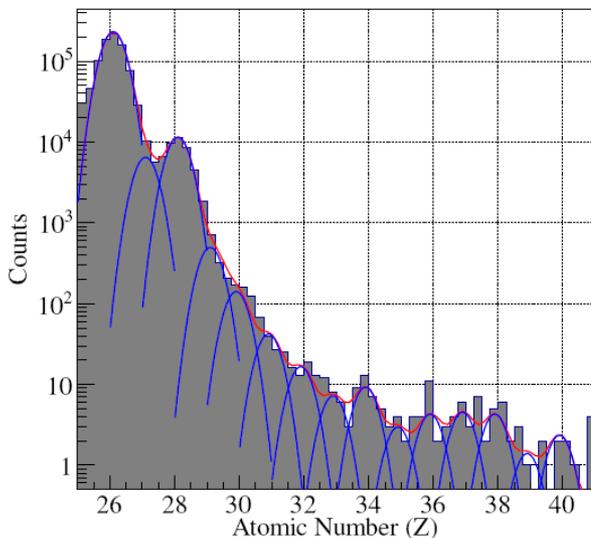
- CALET measures the relative abundances of ultra heavy nucle through $_{40}\text{Zr}$
- Trigger for ultra heavy nuclei: CHD, IMC1+2 and IMC3+4 are required
 \Rightarrow an expanded geometrical acceptance (4000 cm^2sr)
- Energy threshold depends on the geomagnetic cutoff rigidity



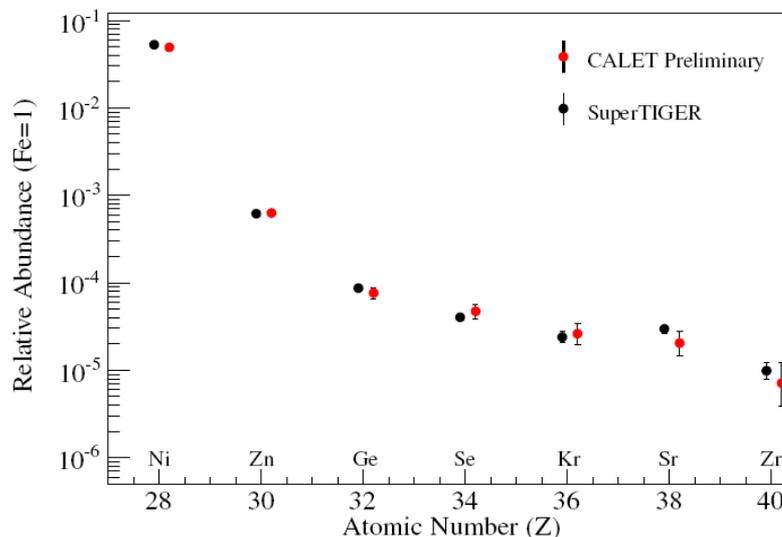
Data analysis

- Event Selection: Vertical cutoff rigidity > 4GV & Zenith Angle < 60 degrees
- Contamination from neighboring charge are determined by multiple-Gaussian function

Charge Distribution



Relative Abundance (Fe=1)



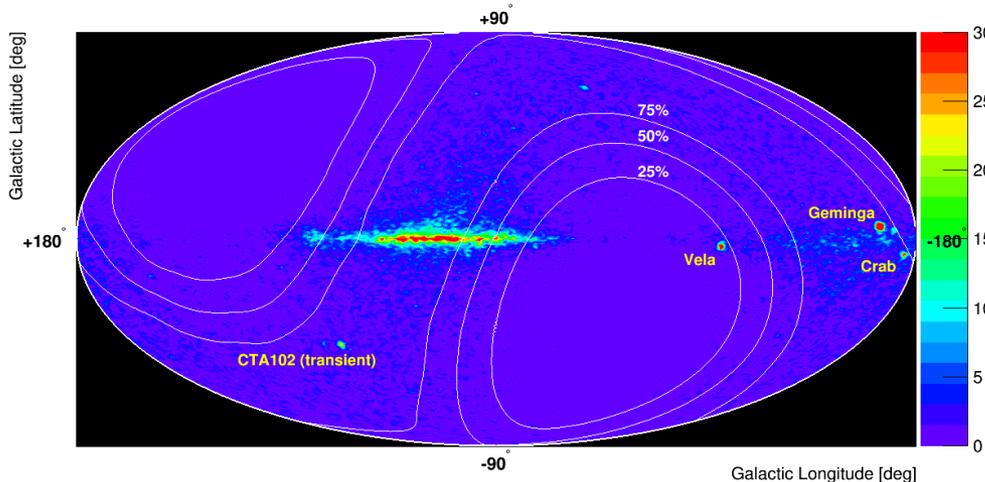


Gamma-Ray Observations

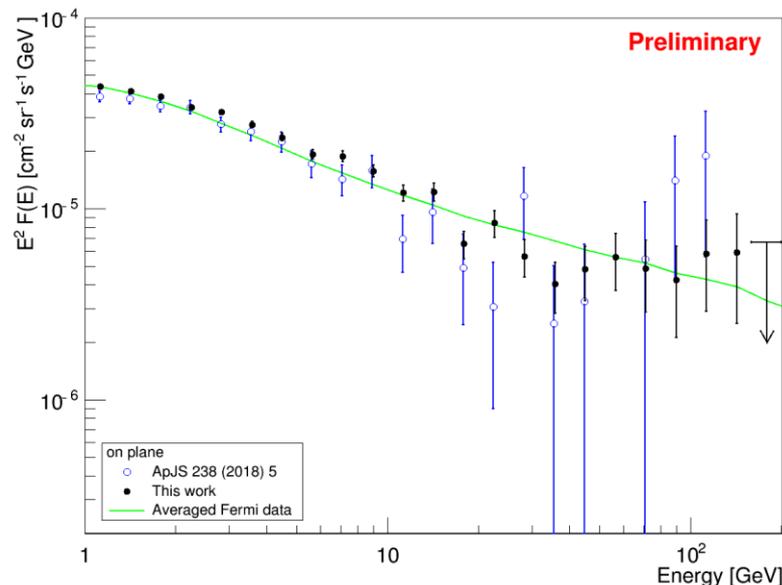
M. Mori ICRC2019 Jul. 29 (GAD5d)

N. Cannady ICRC2019 Jul. 31 (PS3-243)

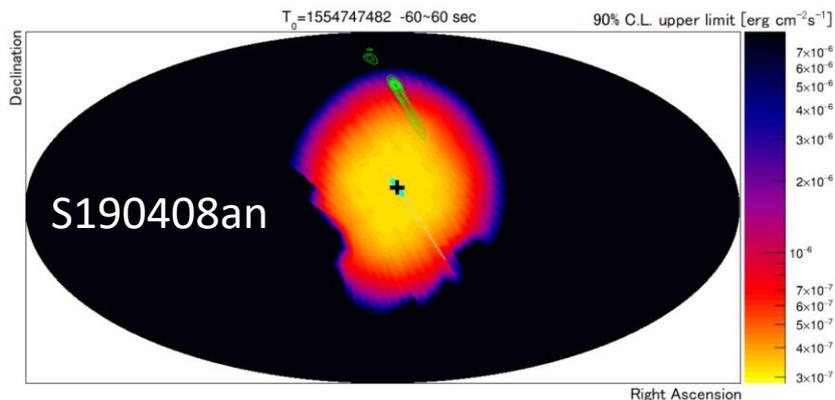
Sky map obtained with LE- γ trigger



Average flux from galactic plane



GeV γ -ray counterpart search for GW events



GCN No.	LIGO/Virgo trigger	Trigger time T_0 (2019)	Events $T_0 \pm 60$ s	90% C.L. U.L.	Summed probability	CAL α ($^\circ$)	CAL δ ($^\circ$)
24088	S190408an	04-08 18:18:02.288 UTC	0	$2.3 \times 10^{-6} \ddagger$	80%	352.9	8.3
24218	S190425z	04-25 08:18:05.017 UTC	0	1.0×10^{-4}	5%	131.3	-43.6
24276	S190426c	04-26 15:21:55.337 UTC	0	2.5×10^{-5}	10%	183	-50.9
24403	S190503bf	05-03 18:54:04.294 UTC	0	4.2×10^{-5}	10%	169	-45.5
24495	S190510g	05-10 02:59:39.292 UT	0	-	No	295.7	50.8
24531	S190512at	05-12 18:07:14.422 UT	0	1.9×10^{-5}	10%	214.9	37.7
24548	S190513bm	05-13 20:54:28.747 UT	0	$6.0 \times 10^{-5} \ddagger$	5%	348	4.4
24593	S190517h	05-17 05:51:01.831 UT	0	-	No	126.2	-31.9
24617	S190519bj	05-19 15:35:44.398 UT	0	-	No	243.1	51.1
24648	S190521g	05-21 03:02:29.447 UT	0	6.0×10^{-6}	30%	205.7	49.2
24649	S190521r	05-21 07:43:59.463 UT	0	-	No	225.3	51.4
24735	S190602aq	06-02 17:59:27.089 UT	0	2.9×10^{-4}	5%	127.5	45.1

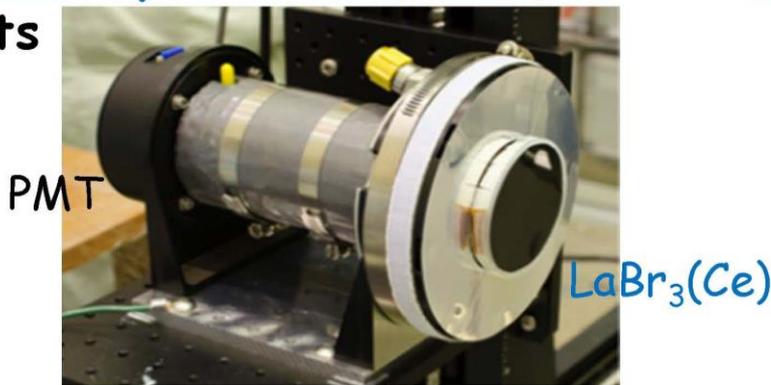


CALET Gamma-Ray Burst Monitor (CGBM)

Y. Kawakubo ICRC2019 Jul. 25-26 (GAD PS1-249)

Hard X-ray Monitor (HXM)

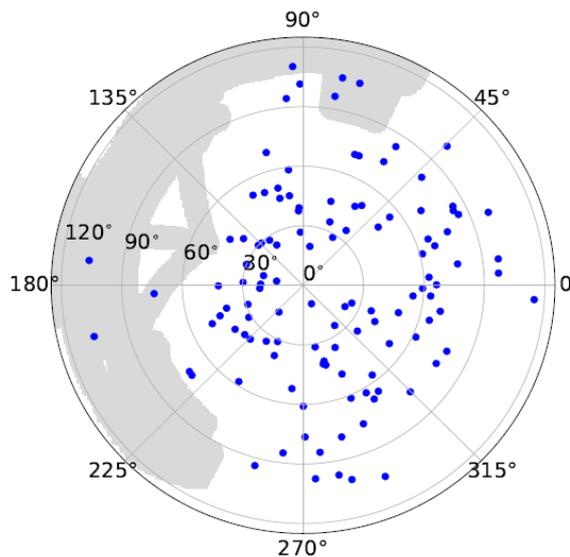
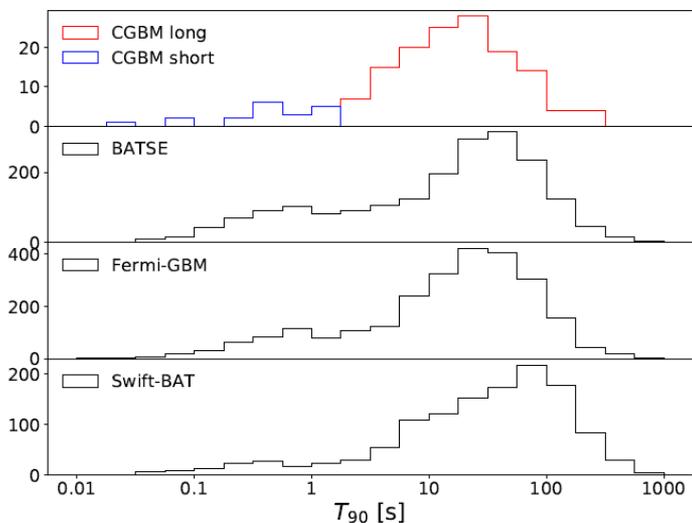
2 units



Soft Gamma-ray Monitor (SGM)



T90 distribution for CGBM detected GRBs



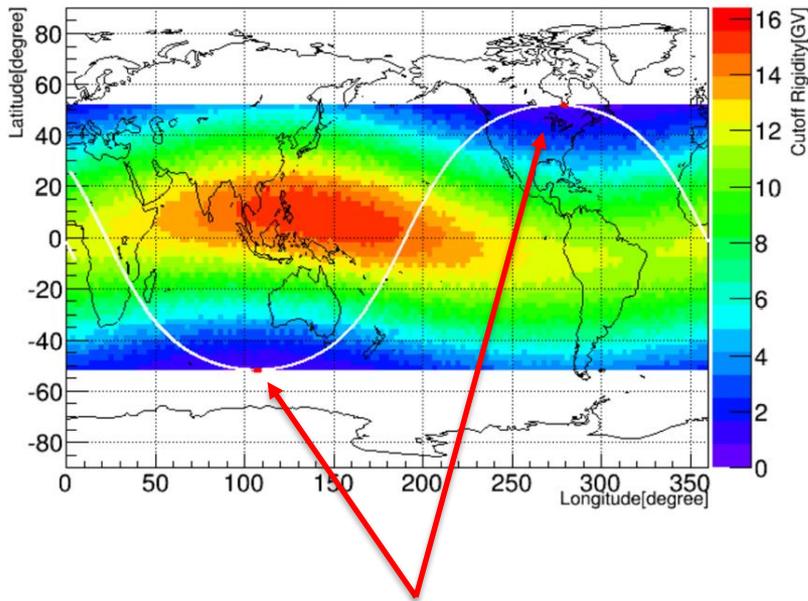
CGBM detected nearly 43 GRBs (~12% short GRB among them) per year in the energy range of 7 keV—20 MeV



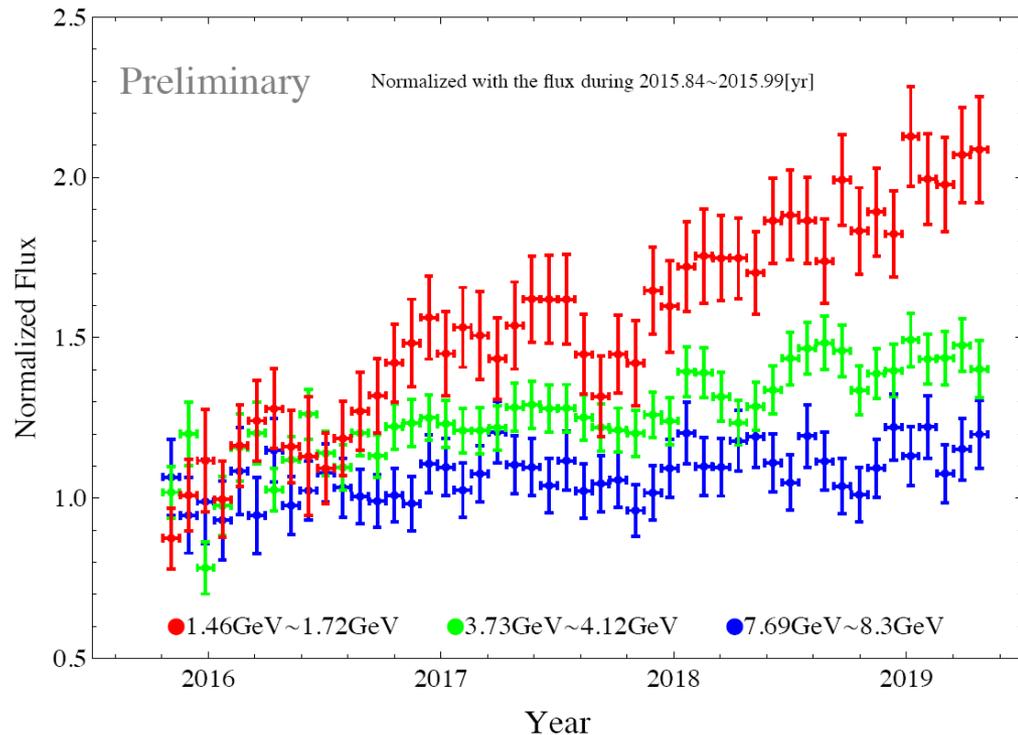
Solar Modulation of Cosmic-Ray Electrons

S. Miyake ICRC2019 Jul. 25 (SH2a)

Color map: cutoff rigidity



Low-energy electron trigger ($E > 1\text{GeV}$) is activated for 90 s at the lowest rigidity cutoff region for each passage of the high latitude region (north and south).



Time profile of the normalized flux of the low-energy electrons from October 2015 to April 2019.



Observations of SEPs during September 2017

CALET Observations

A. Bruno ICRC2019 Jul. 27,29 (SH PS2-4)

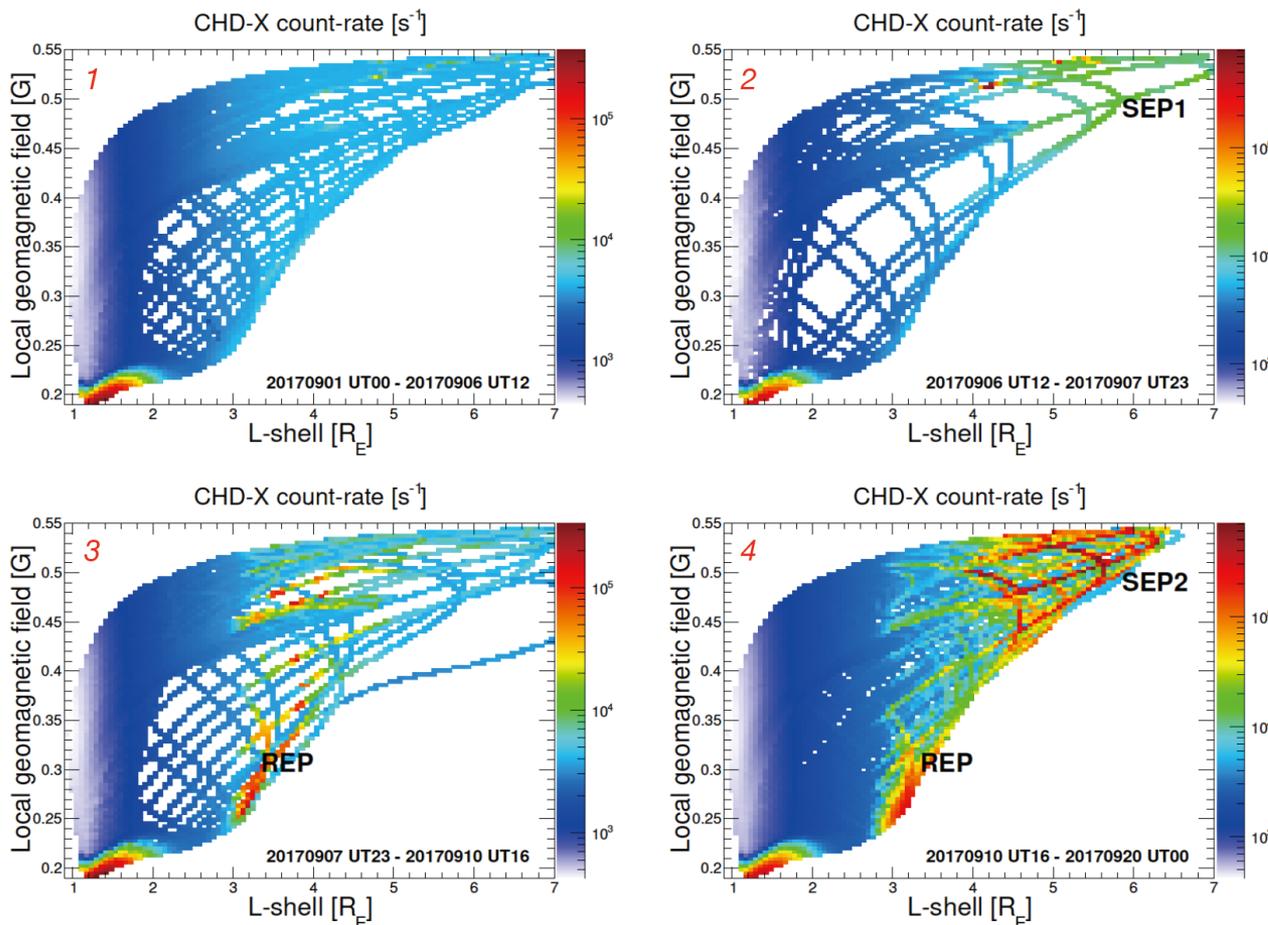


Figure 4: Count-rate measured by the CALET top detector (CHD-X) as a function of local geomagnetic field intensity B and L-shell, during four different intervals of early September 2017 (see labels). The enhancements relative to SEP and REP events are indicated.

Measurements by GEOS-16, SOPO, YKTK and MGDN

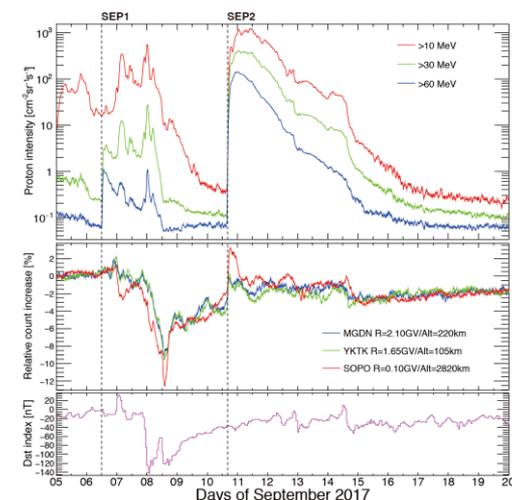


Figure 1: Time profiles (5–19 September 2017) of proton intensities measured by GOES-15 at three different energy thresholds (top; 1-hour running averages), count-rate increases registered by the SOPO, YKTK and MGDN neutron monitors at different geomagnetic cutoff rigidities / altitudes (middle; 1-hour running averages), and Dst index (bottom; 1-hour resolution). The vertical dashed lines mark the onset of the 6 and 10 September SEP events.

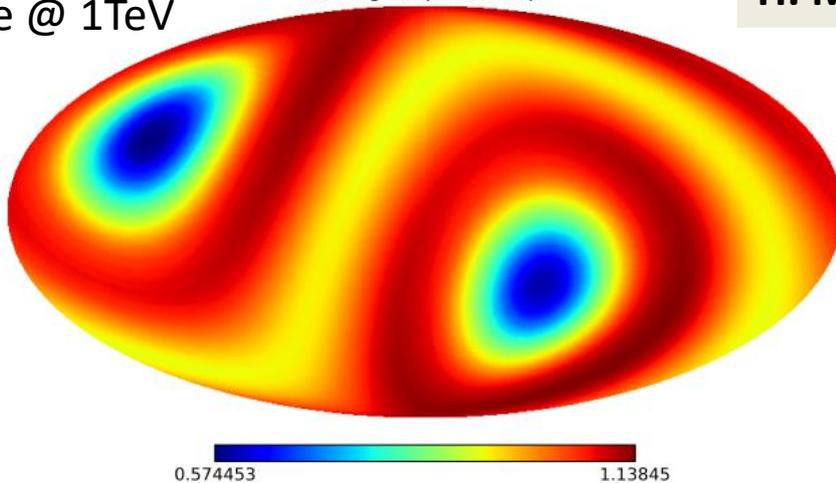
SEP: Solar Energetic Particle
 REP: Relativistic Electron Precipitation



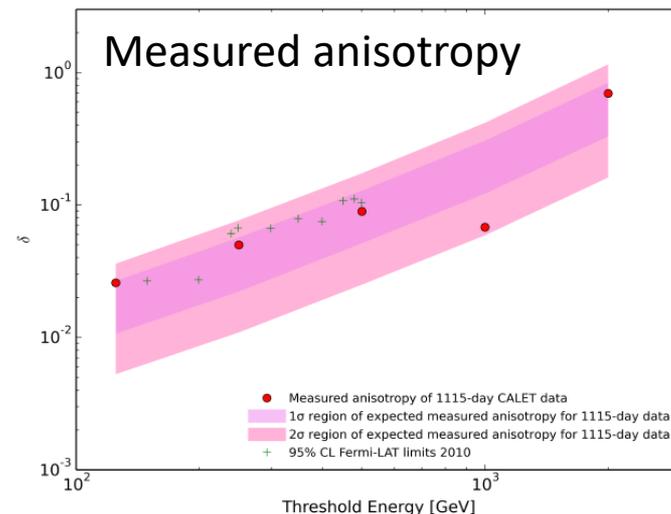
Electron Anisotropy

Exposure @ 1TeV

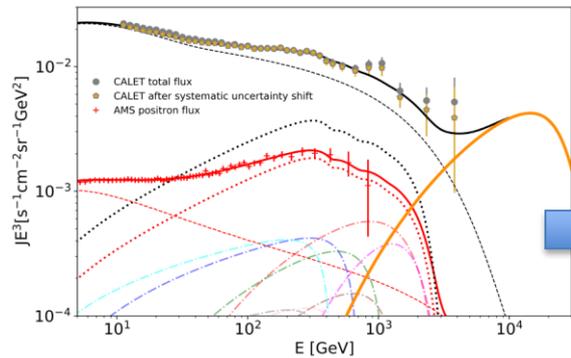
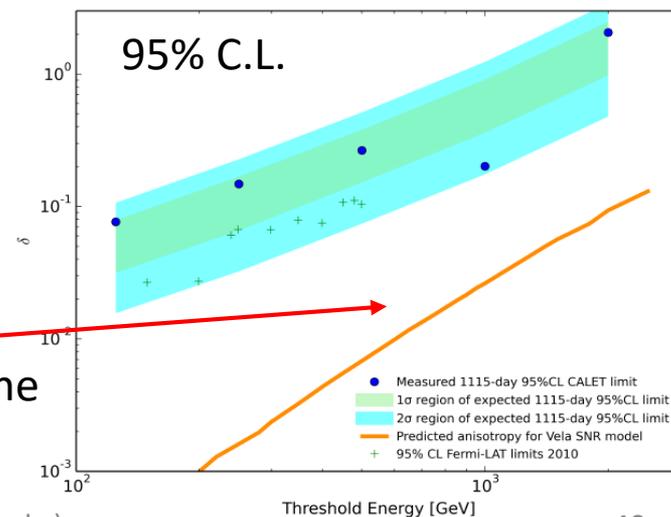
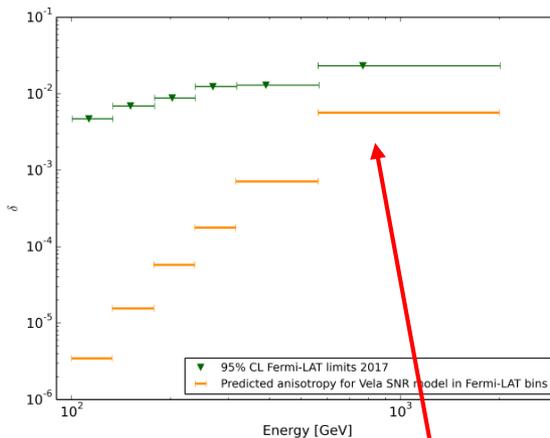
average exposuremap



H. Motz ICRC 2019, Jul 25-26 (CRD PS1-20)



Fermi-LAT limit from PRL 118, 091103 (2017)



Calculated with the same Vela model



Summary/Prospects and Other CALET Talks at ICRC2019

- ❑ CALET continues very stable observation since Oct. 2015, for more than 3.5 years.
- ❑ We have published all-electron spectrum (11 GeV – 4.8 TeV) and proton spectrum (50 GeV – 10 TeV) including the detailed assessment of systematic errors.
- ❑ Many more results including preliminary ones will be presented in this conference.
- ❑ The so far excellent performance of CALET and the outstanding quality of the data suggest that a 5-year (or more) observation period is likely to provide a wealth of new interesting results.

No.	Presenter	Title	Session	Date
1	S. Torii	Extended Measurement of Cosmic-Ray Electron and Positron Spectrum from CALET on the ISS	CRD2c	Jul. 25
2	P.S. Marrocchesi	Measurement of the Proton Spectrum with CALET on the ISS	CRD8e	Jul. 30
3	Y. Akaike	Measurements of Heavy Cosmic Ray Nuclei Fluxes with CALET	CRD3b	Jul. 26
4	P. Maestro	Measurement of the energy spectra of carbon and oxygen nuclei in cosmic rays with CALET	CRD8f	Jul. 30
5	B. Rauch	CALET Ultra Heavy Cosmic Ray Observations on the ISS	CRD3c	Jul. 26
6	M. Mori	High-Energy Gamma-ray Observations Using the CALorimetric Electron Telescope (CALET) on the ISS	GAD5d	Jul. 29
7	N. Cannady	CALET Upper Limits on GeV-energy Gamma-Ray Burst Emission	GAD PS3-243	Jul. 31
8	A. Bruno	Space Weather Observations during September 2017 with CALET on the International Space Station	SH PS2-4	Jul. 27,29
9	Y. Kawakubo	Gamma-ray burst observations with the CALET Gamma-ray Burst Monitor	GAD PS1-249	Jul. 25-26
10	H. Motz	Analysis of CALET Data for Anisotropy in Electron+Positron Cosmic Rays	CRD PS1-20	Jul. 25-26
11	S.Miyake	Solar Modulation of Galactic Cosmic-Ray Electrons Measured with CALET	SH2a	Jul. 25