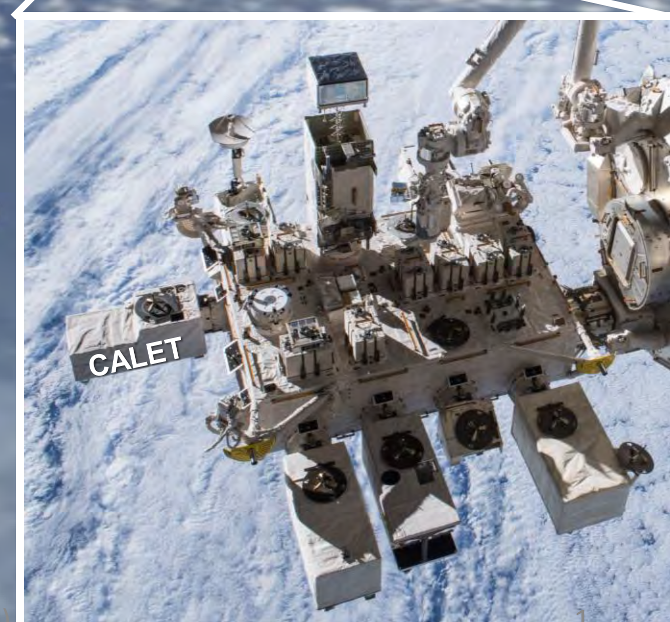
The CALorimetric Electron Telescope (CALET) on the International Space Station (ISS)



Yoichi Asaoka
for the CALET collaboration
WISE, Waseda University

Highlight Talk (CRD H7) 27 July 2019

ICRC2019 36th International Cosmic Ray Conference · Madison, WI, USA
THE ASTROPARTICLE PHYSICS CONFERENCE

CALET Collaboration Team

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17) National Institute of Polar Research, Japan
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Outline

1. Introduction
2. Calibration → Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), Astropart. Phys. 91 (2017) 1.
3. Operations → Y.Asaoka, 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. O.Adriani et al. (CALET Collaboration), Phys.Rev.Lett. 120 (2018) 261102.
   - Hadrons → O.Adriani et al. (CALET Collaboration), Phys.Rev.Lett. 120 (2018) 261102.
   - Gamma-Rays → O.Adriani et al. (CALET Collab.), ApJL 829 (2016) L20. O.Adriani et al. (CALET Collab.), ApJ 863 (2018) 160. N.Cannady, Y.Asaoka et al. (CALET Collab.), ApJS 238 (2018) 5.
   - Space Weather → R.Kataoka et al., JGR, 10.1002/2016GL068930 (2016).
5. Summary

Direct measurements of cosmic rays : little room for "unknown" systematics

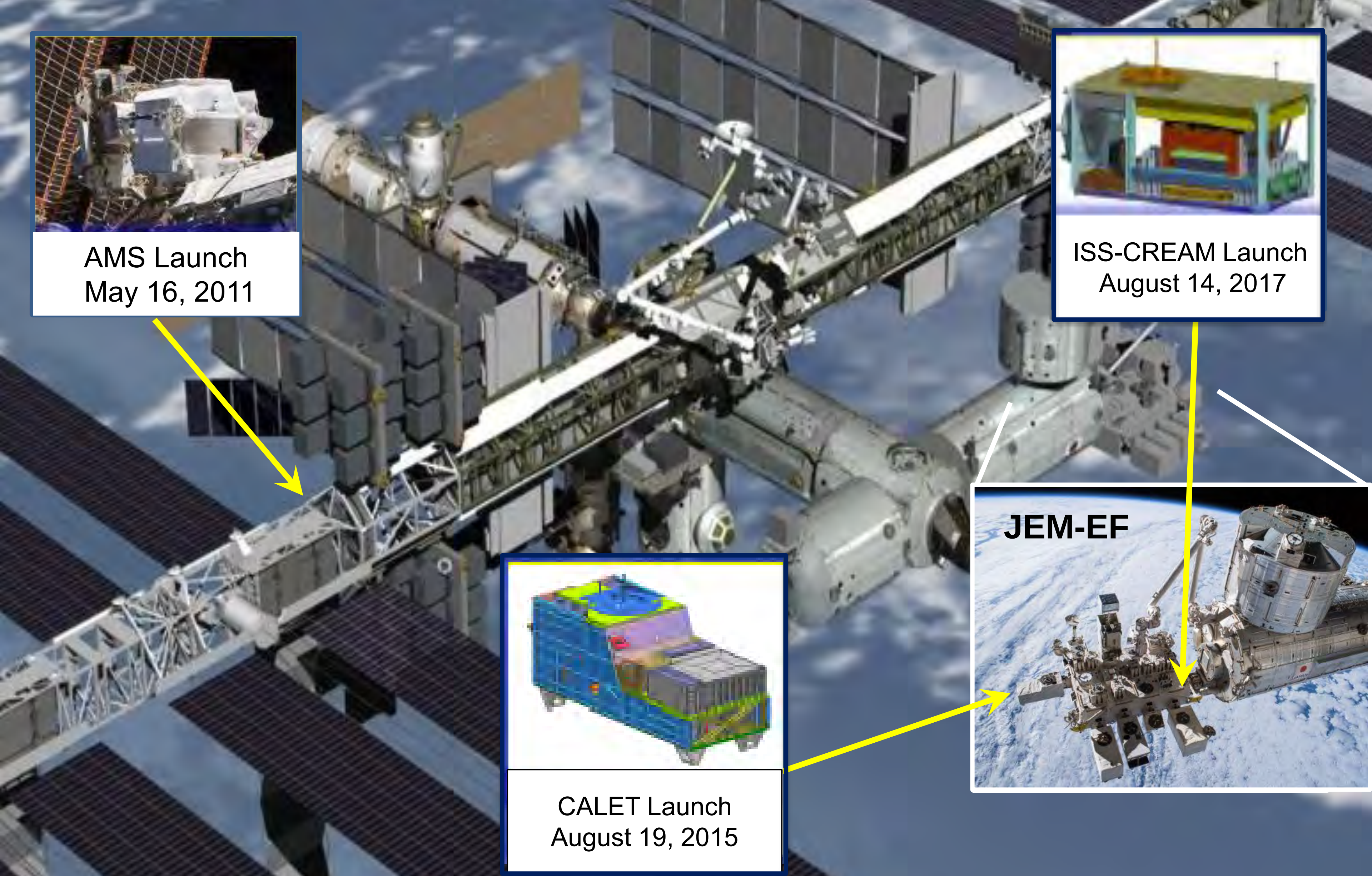
Four major factors in the spectrum measurements:

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 $\Rightarrow$ **ε**
   – Losses in the detector

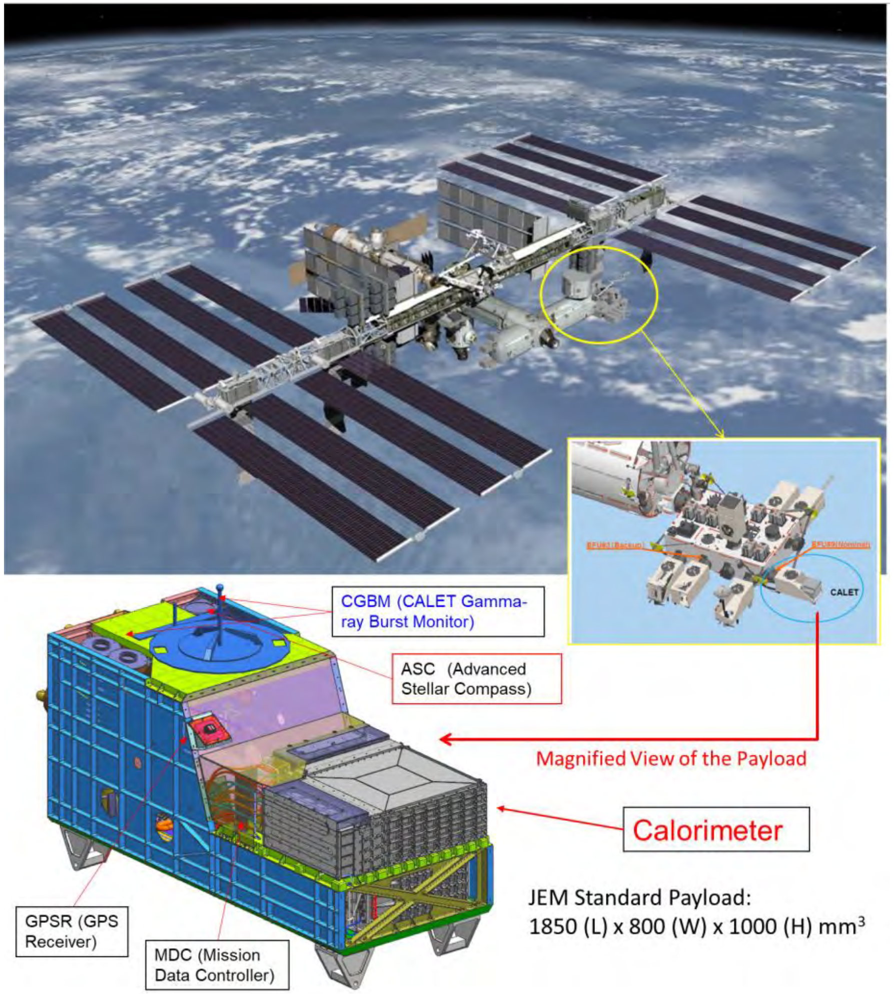
Question: How "direct" each measurement is?

Larger corrections leave more rooms for "unknown" systematics

ISS as Cosmic Ray Observatory



CALET: Cosmic Ray Detector onboard the ISS



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

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

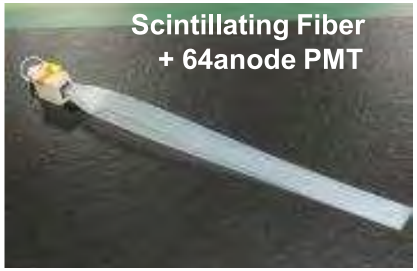
- Observation of cosmic-ray nuclei in the 10 GeV - 1 PeV energy range.

⇨ Unravelling the CR acceleration and propagation mechanism

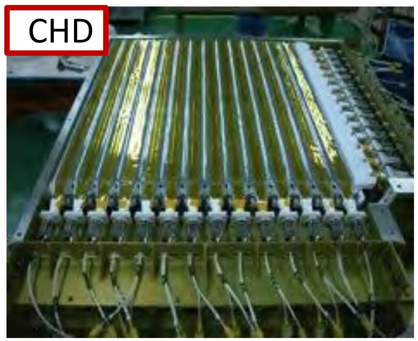
- Detection of transients in space by long-term stable observations

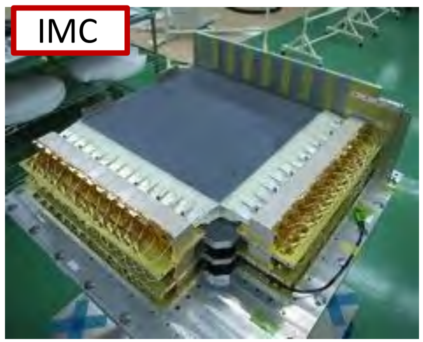
⇨ EM radiation from GW sources, Gamma-ray burst, Solar flare, etc.

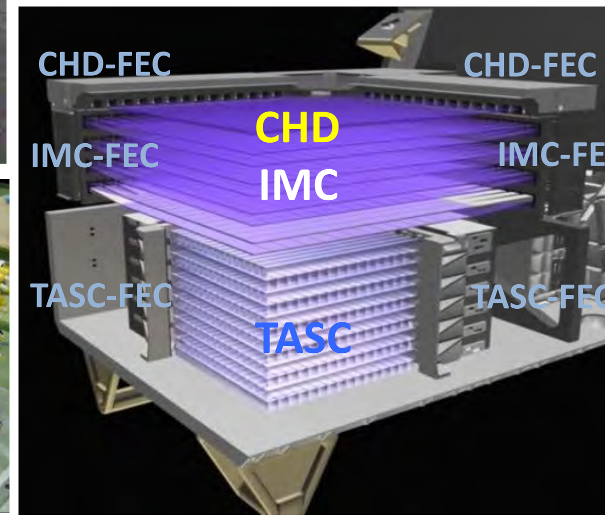
CALET Instrument



CALORIMETER



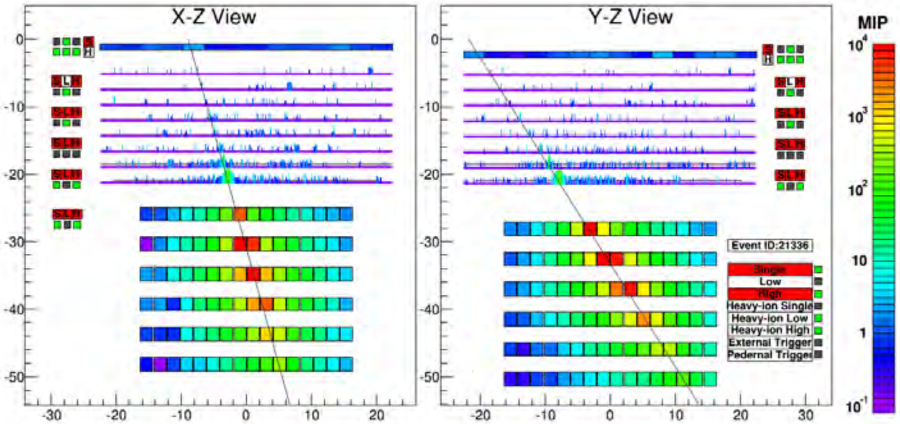




	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers (X,Y) : 7168 Scifi 7 W layers (3X_0): 0.2X_0 x 5 + 1X_0 x2 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 , ~1.2 λ_I**
Readout	**PMT+CSA**	**64-anode PMT+ ASIC**	**APD/PD+CSA PMT+CSA (for Trigger)@top layer**

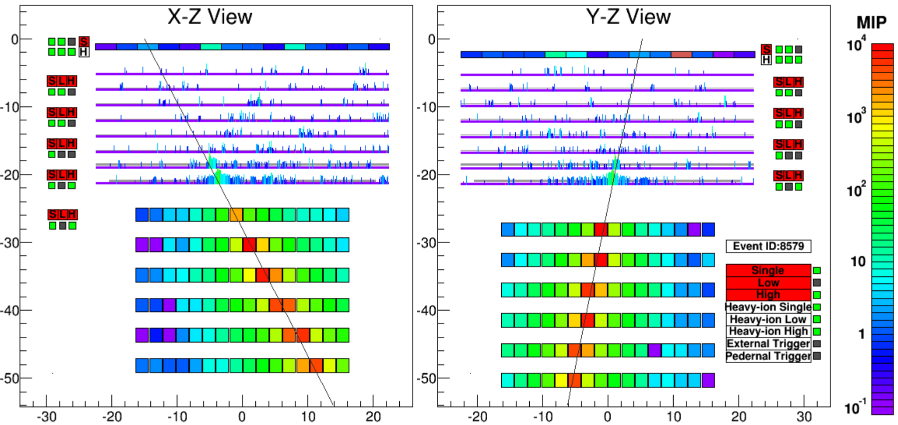
Event Examples of High-Energy Showers

Electron, E=3.05 TeV



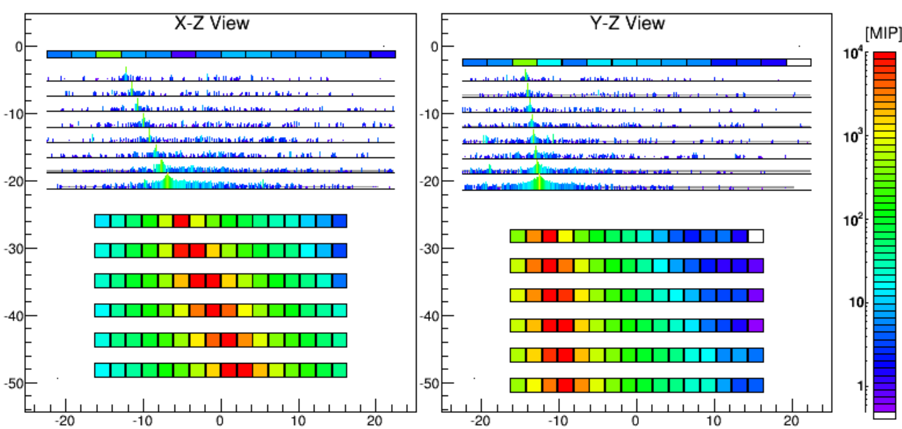
fully contained even at 3TeV

Proton, ΔE=2.89 TeV



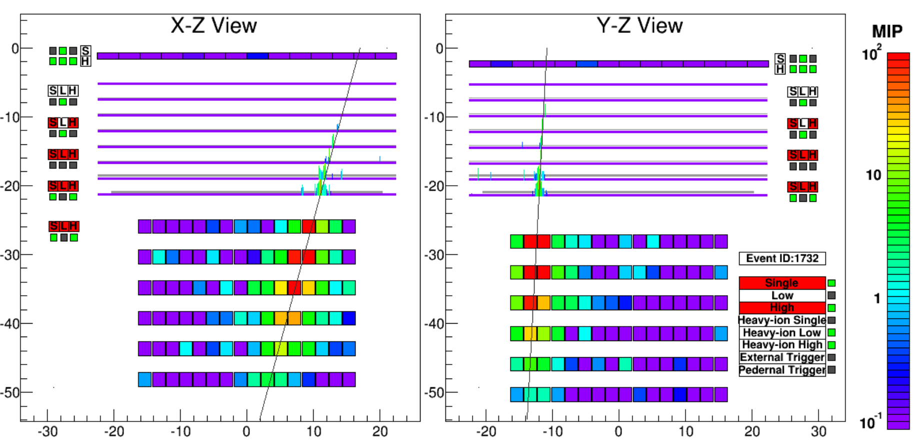
clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

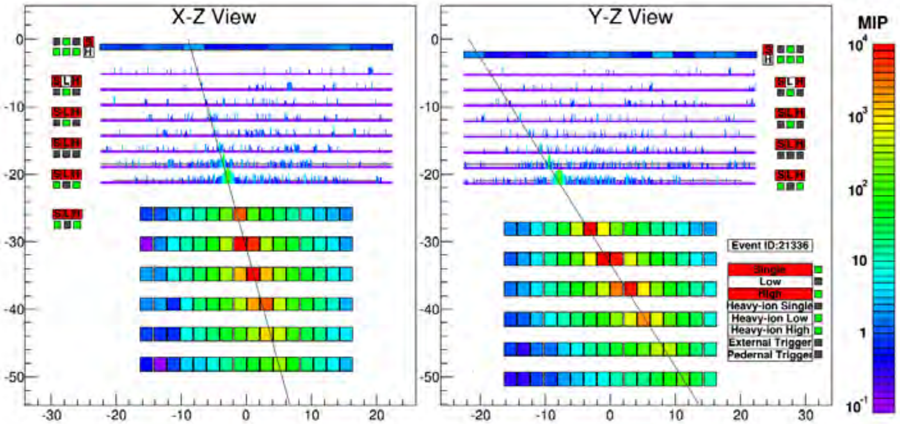
Gamma-ray, E=44.3 GeV



no energy deposit before pair production

Event Examples of High-Energy Showers

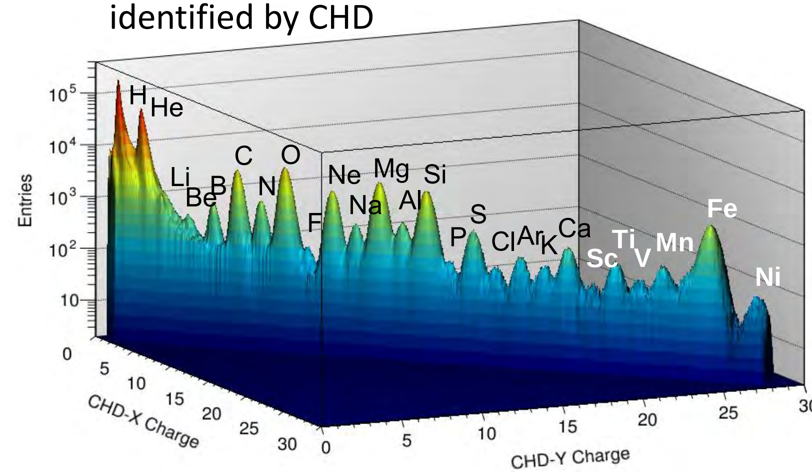
Electron, E=3.05 TeV



fully contained even at 3TeV

Proton, ΔE=2.89 TeV

Individual elements up to Z=28 are clearly identified by CHD



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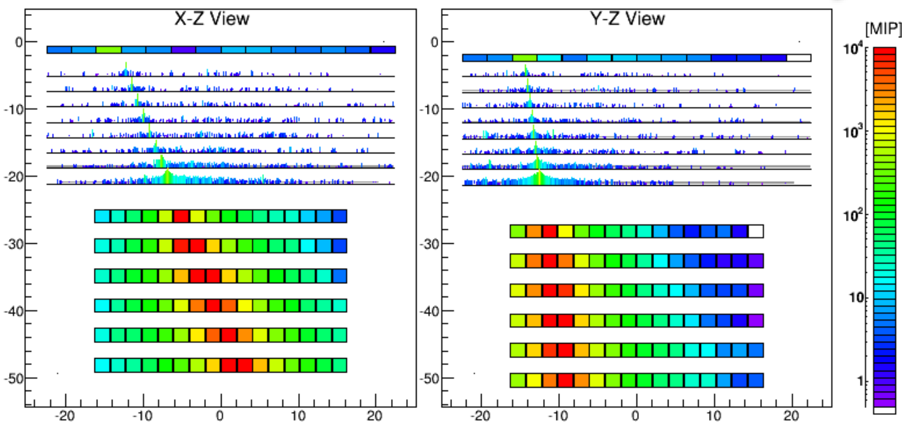
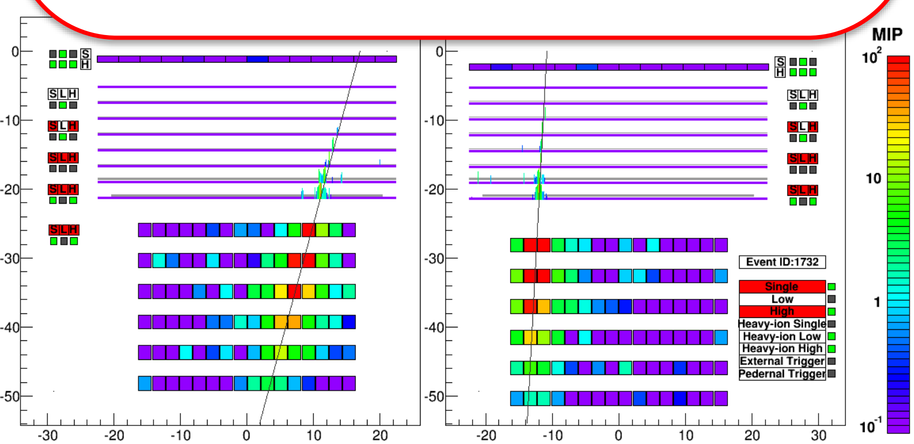
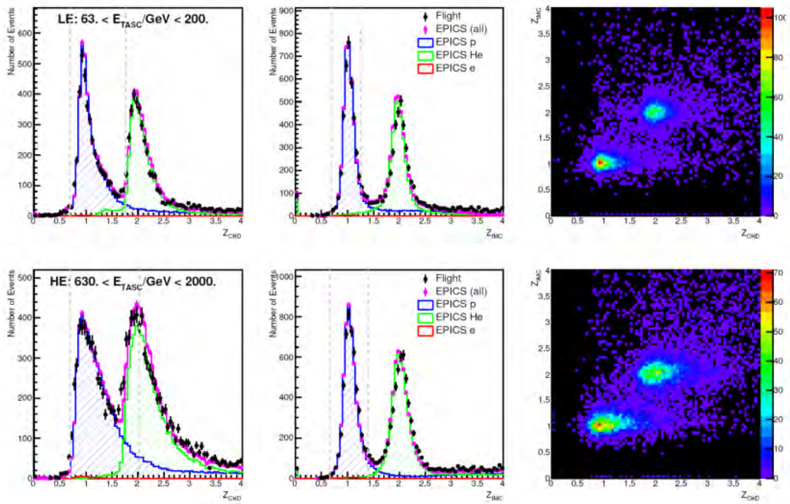


energy deposit in CHD consistent with Fe



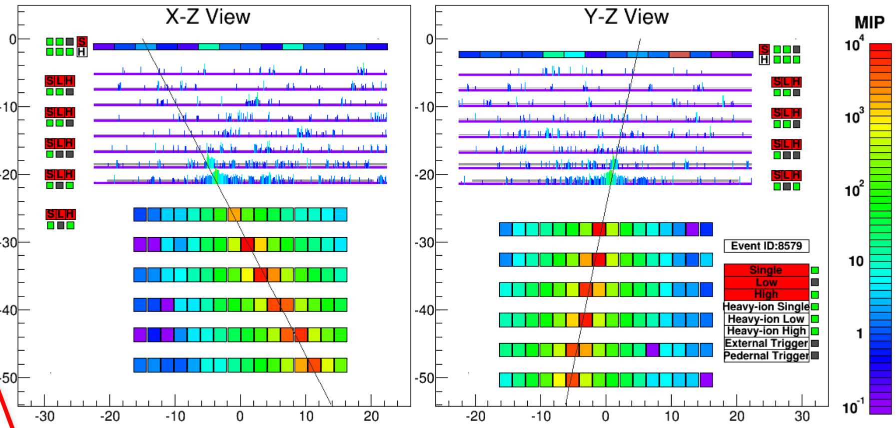
no energy deposit before pair production

Event Examples of High-Energy Showers



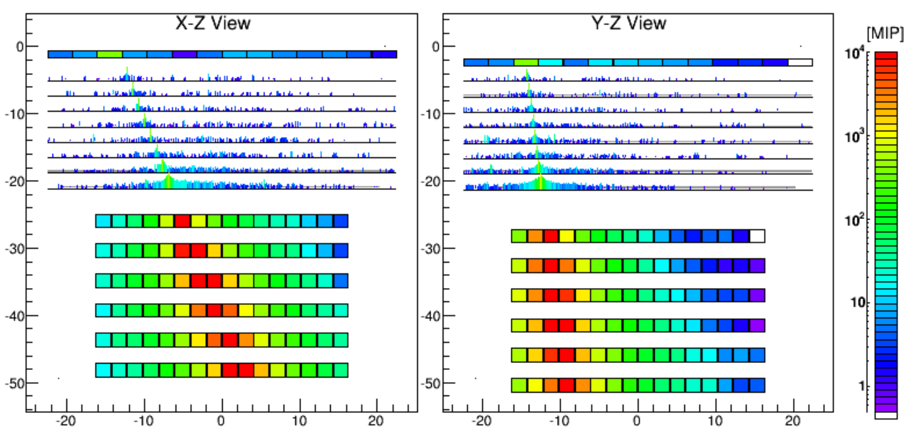
Proton/helium separation using CHD/IMC charge

Proton, ΔE=2.89 TeV



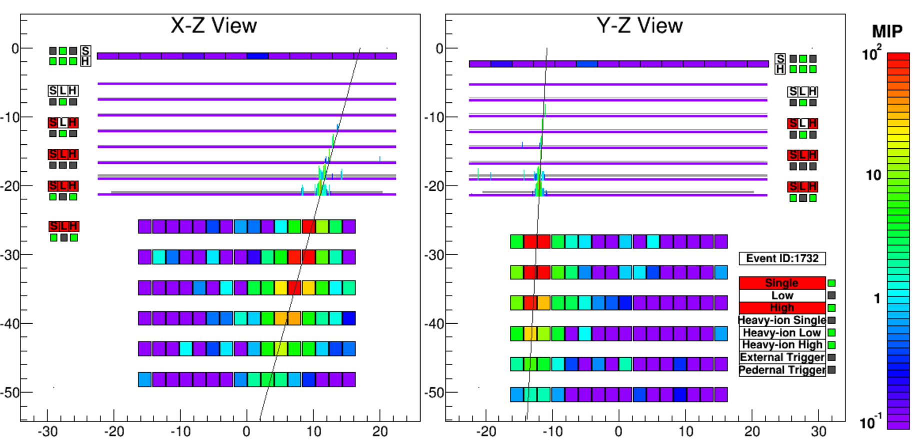
clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

Gamma-ray, E=44.3 GeV

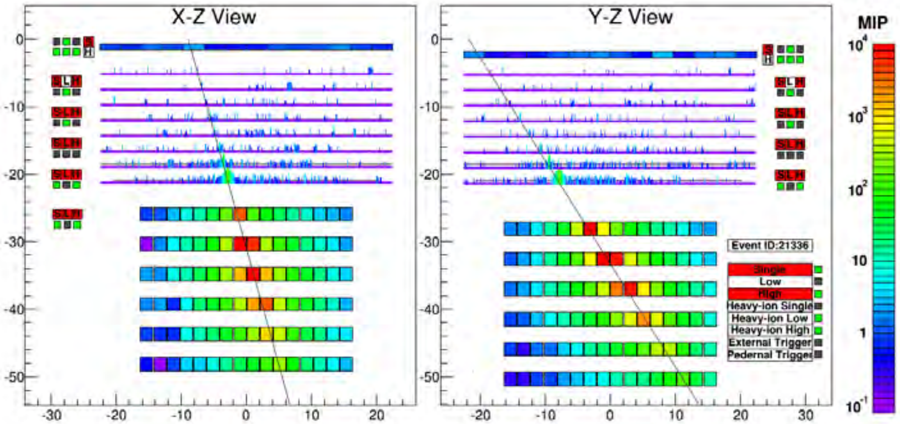


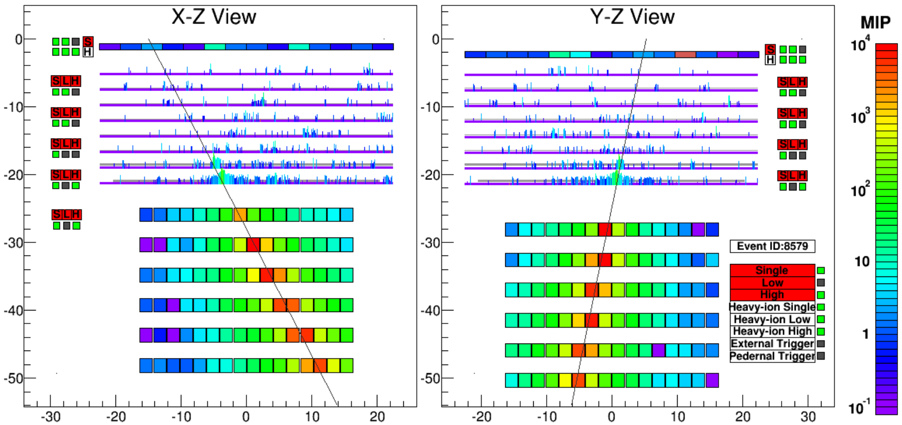
no energy deposit before pair production

Event Examples of High-Energy Showers

Electron, E=3.05 TeV

Proton, ΔE=2.89 TeV

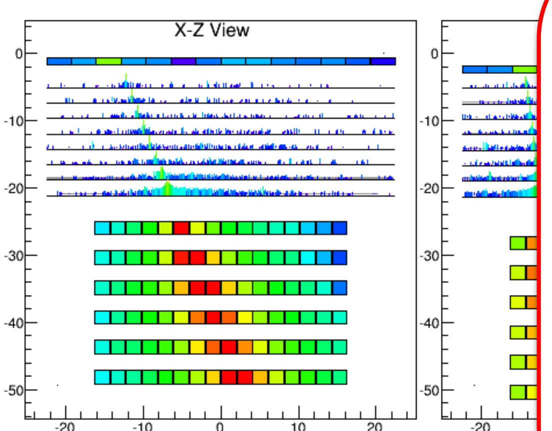




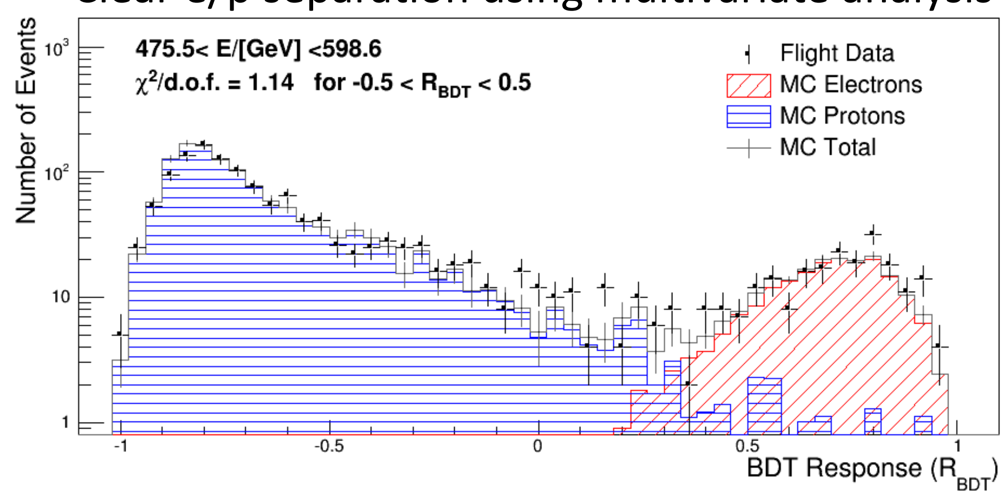
fully contained even at 3TeV

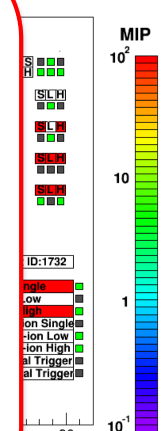
clear difference from electron shower

Fe(Z=26), ΔE=9.



Clear e/p separation using multivariate analysis





energy deposit in CHD cons

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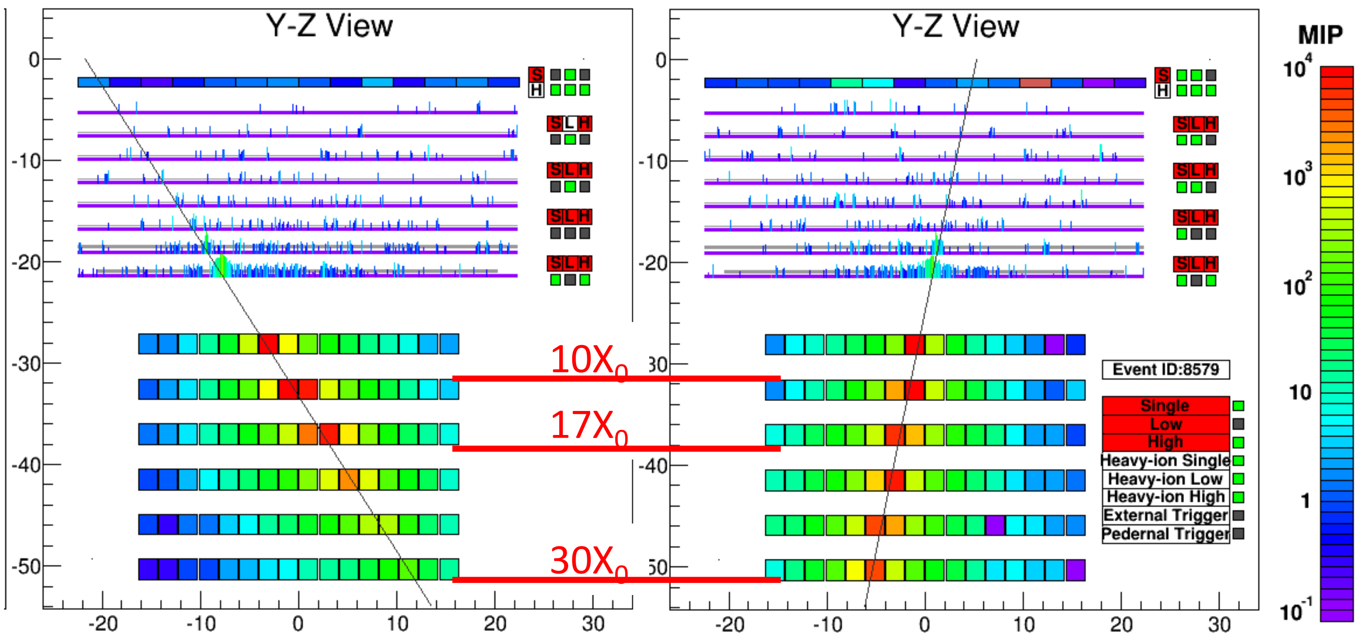
All-Electron Measurement with CALET

3TeV Electron Candidate

Corresponding Proton Background



(Flight data; detector size in cm)

1. **Reliable tracking**
   well-developed shower core
2. **Fine energy resolution**
   full containment of TeV showers
3. **High-efficiency electron ID**
   $30X_0$ 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

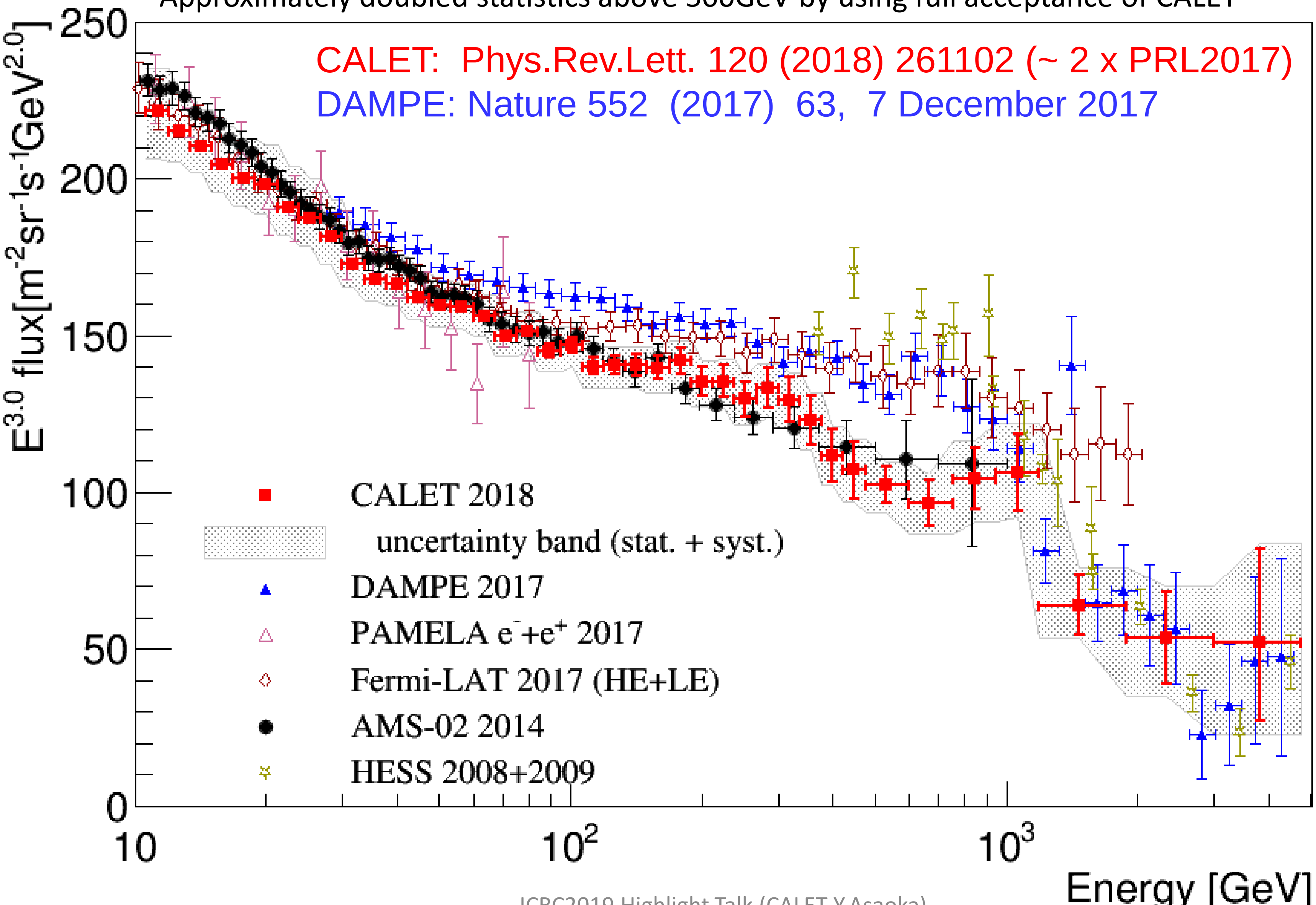
1. Acceptance ⇒ **well defined SΩ because of reliable tracking**
   - Geometrical factor
2. Energy determination ⇒ **$\Delta E/E$ ~ 2% (E>20GeV) absolute energy scale calibrated by geomagnetic rigidity cutoff**
   - Magnet Spectrometer
   - **Calorimeter**
3. Particle identification ⇒ **r_{BG} < 5% (E<1TeV) r_{BG} ~ 10—20% (1<E<5TeV)**
   - Contamination
4. Detection efficiency ⇒ **ε > 70% (E>30GeV) keeps constant value**
   - Losses in the detector

⇒ **Leaves little room for "unknown" systematics**

combined with detailed systematic studies (see PRLs + SM)

All Electron Spectrum: Extended Measurement by CALET

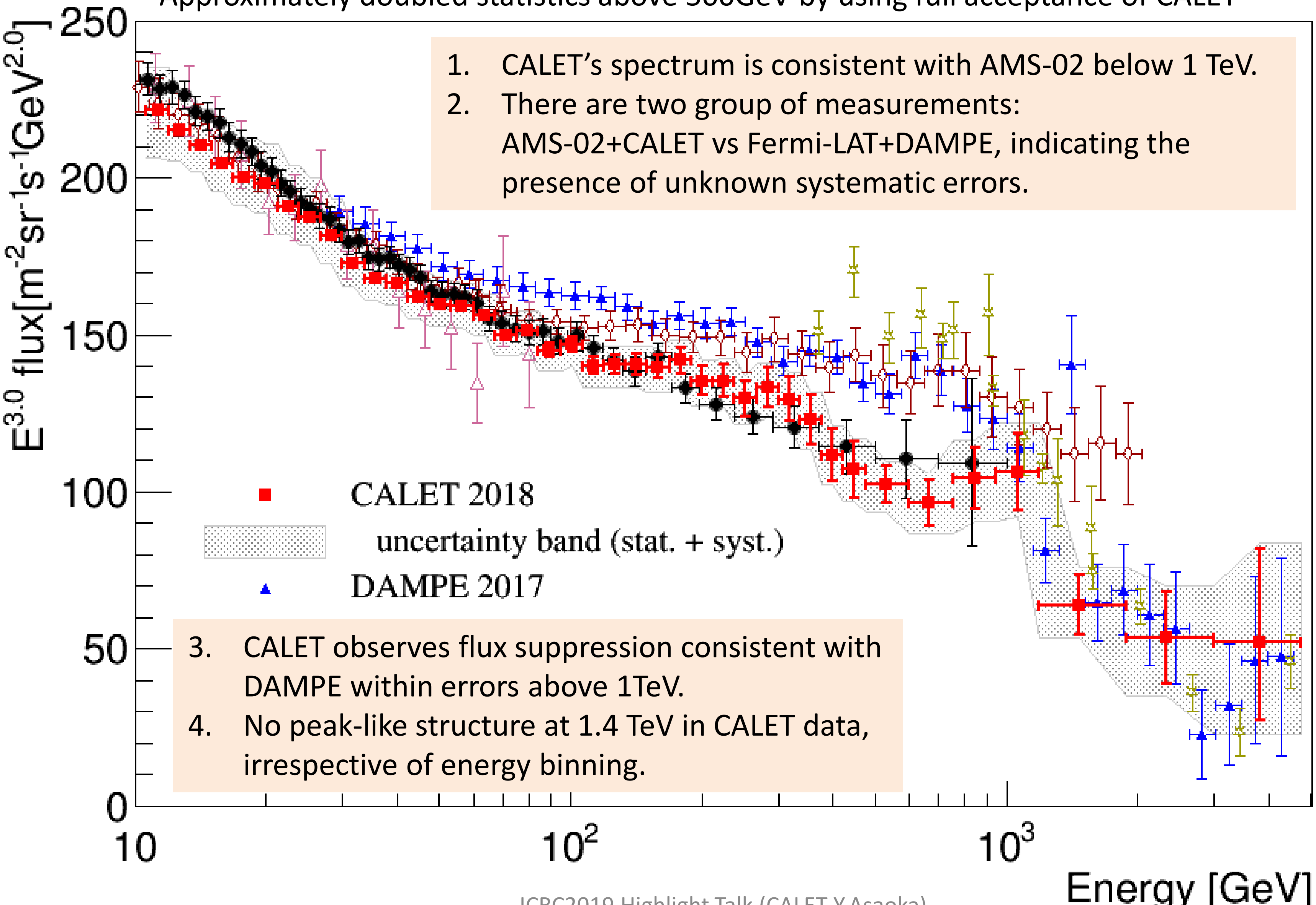
Approximately doubled statistics above 500GeV by using full acceptance of CALET



All Electron Spectrum: Extended Measurement by CALET

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

1. CALET's spectrum is consistent with AMS-02 below 1 TeV.
2. There are two group of measurements: AMS-02+CALET vs Fermi-LAT+DAMPE, indicating the presence of unknown systematic errors.



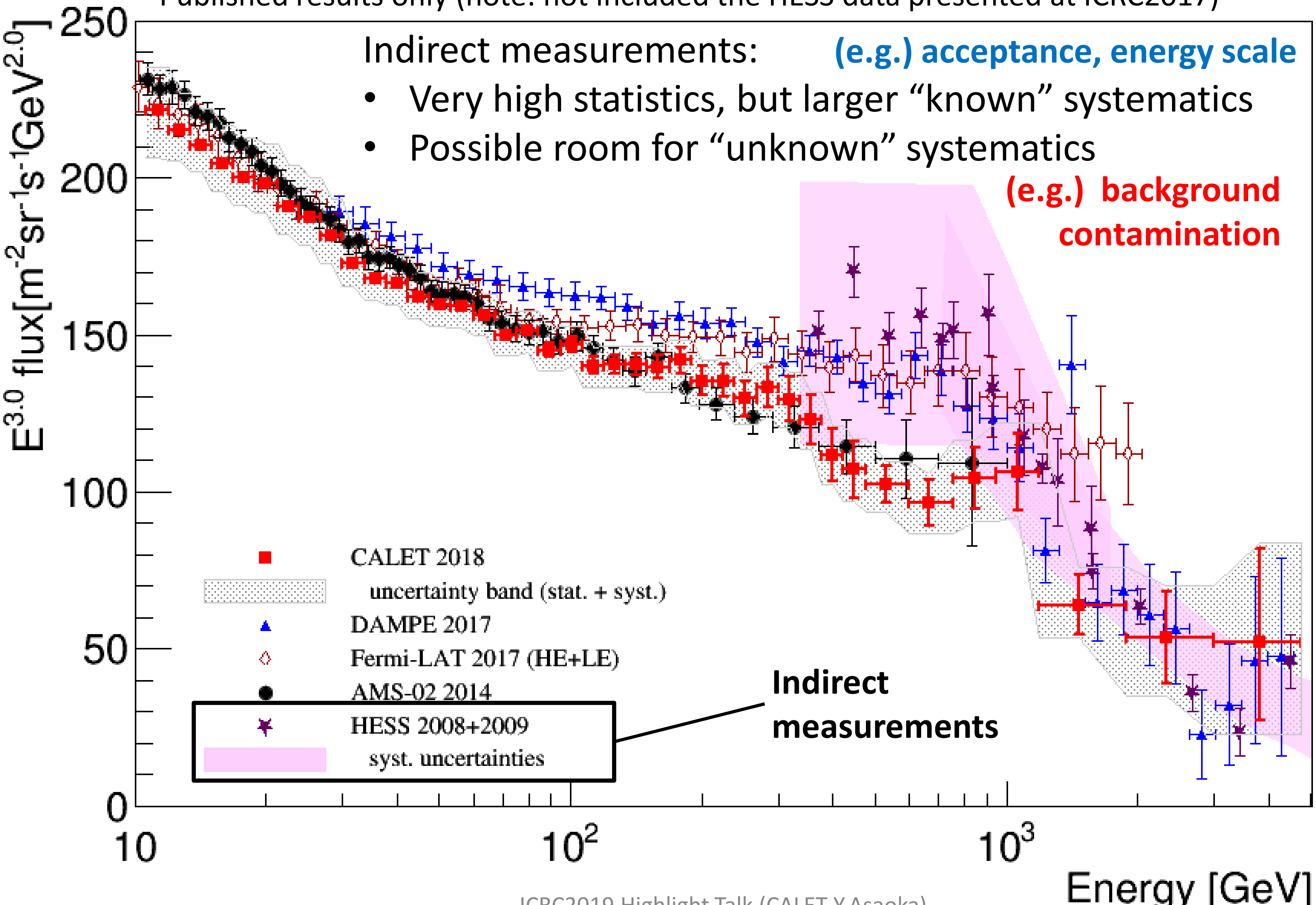
3. CALET observes flux suppression consistent with DAMPE within errors above 1TeV.
4. No peak-like structure at 1.4 TeV in CALET data, irrespective of energy binning.

All Electron Spectrum:
Comparison with Indirect Measurements

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

Indirect measurements: (e.g.) acceptance, energy scale

- Very high statistics, but larger "known" systematics
- Possible room for "unknown" systematics



All Electron Spectrum: Comparison with Indirect Measurements

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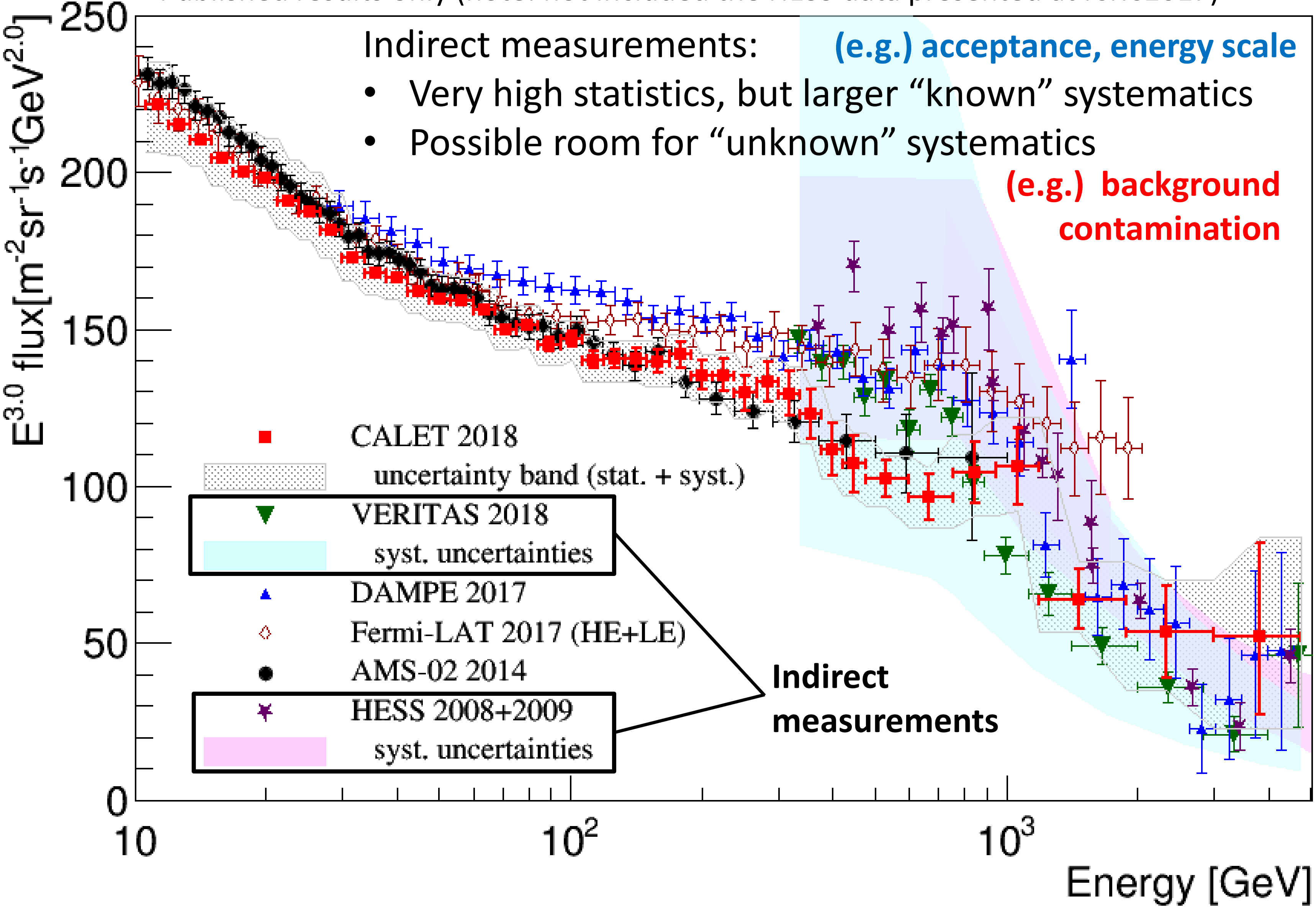
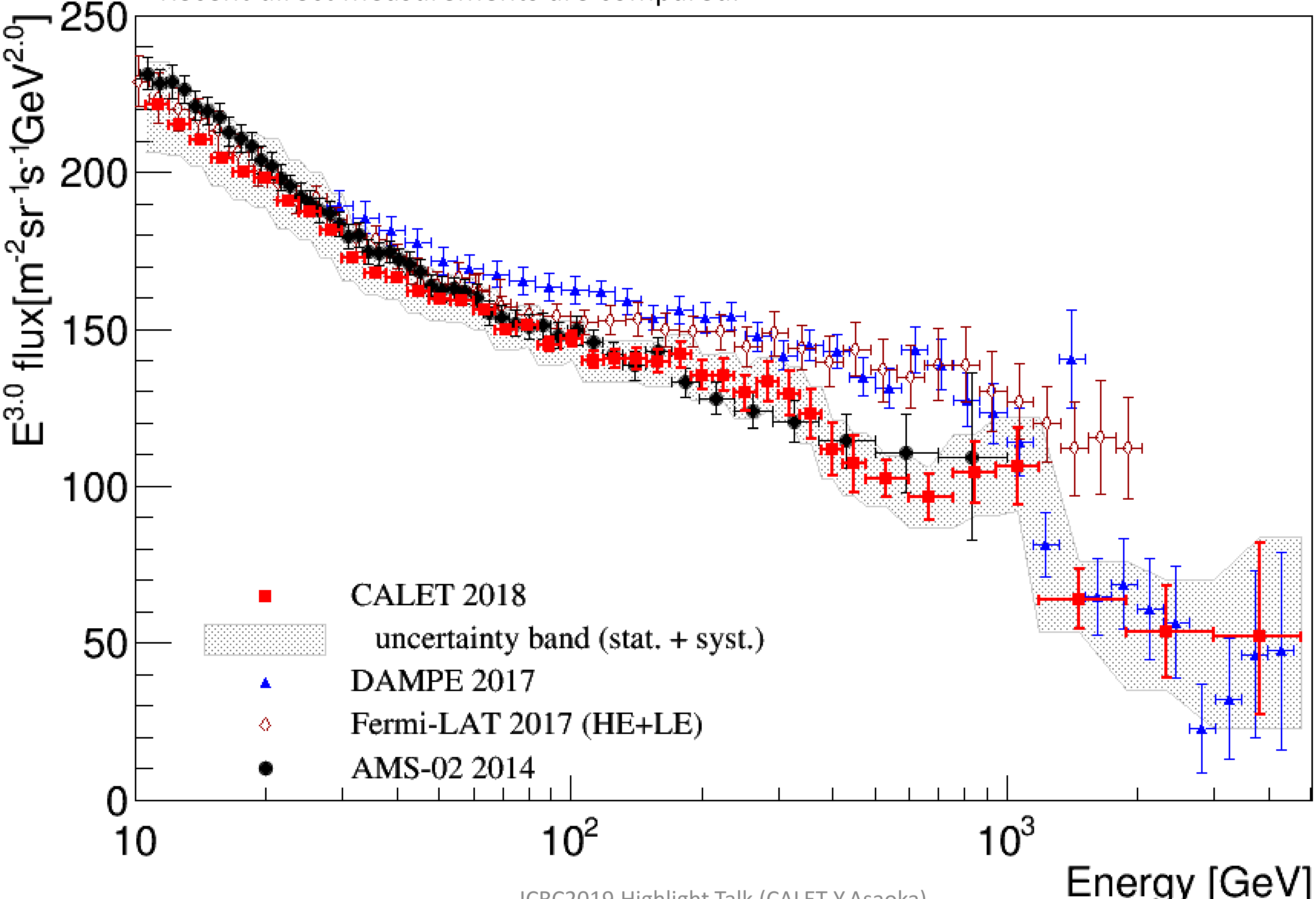


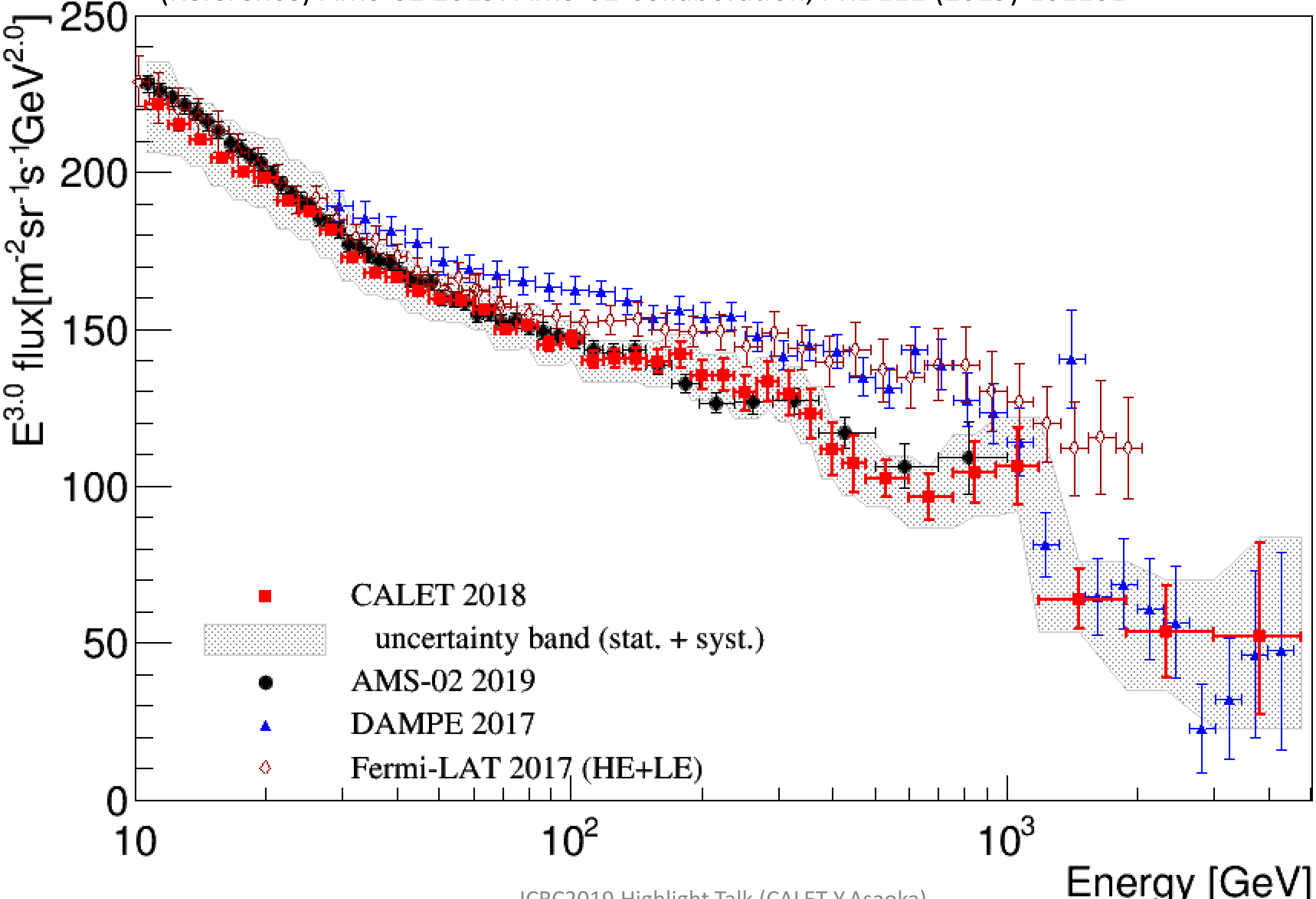
All Electron Spectrum: Comparison between Recent Direct Measurements

Recent direct measurements are compared.



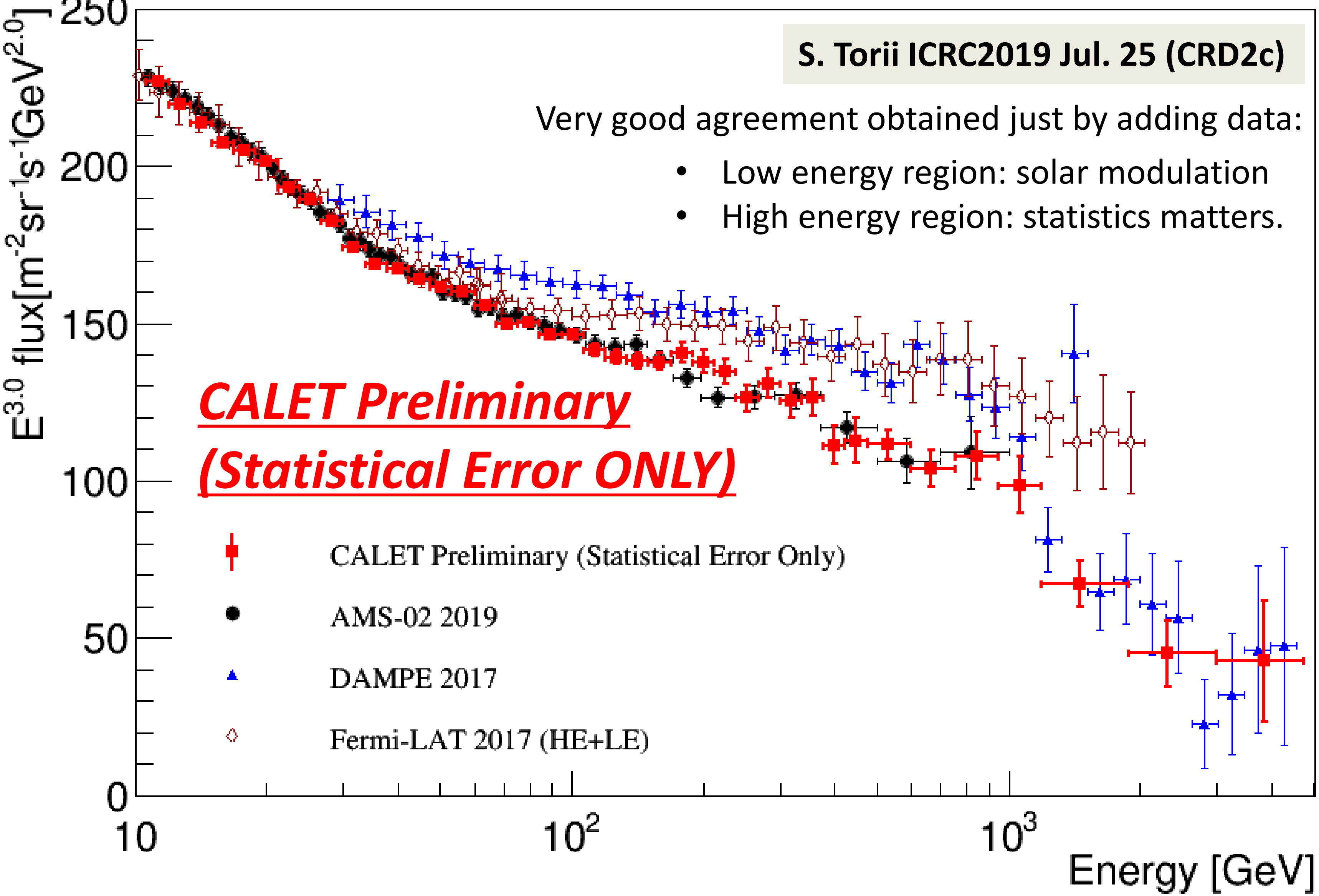
All Electron Spectrum: Comparison with the Updated AMS-02 Result

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



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

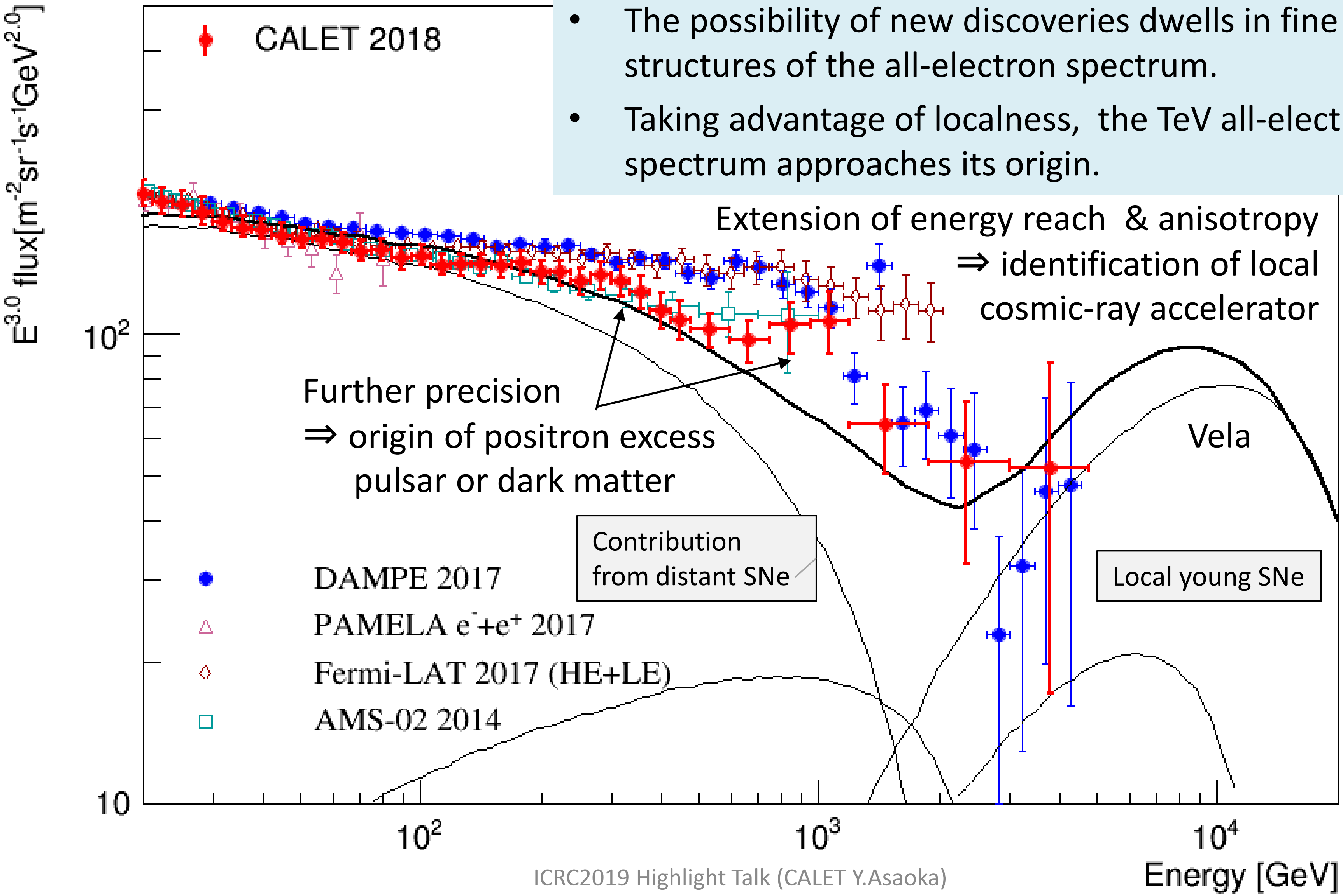
Exactly the same analysis applied, data up to the end of May 2019 are used.



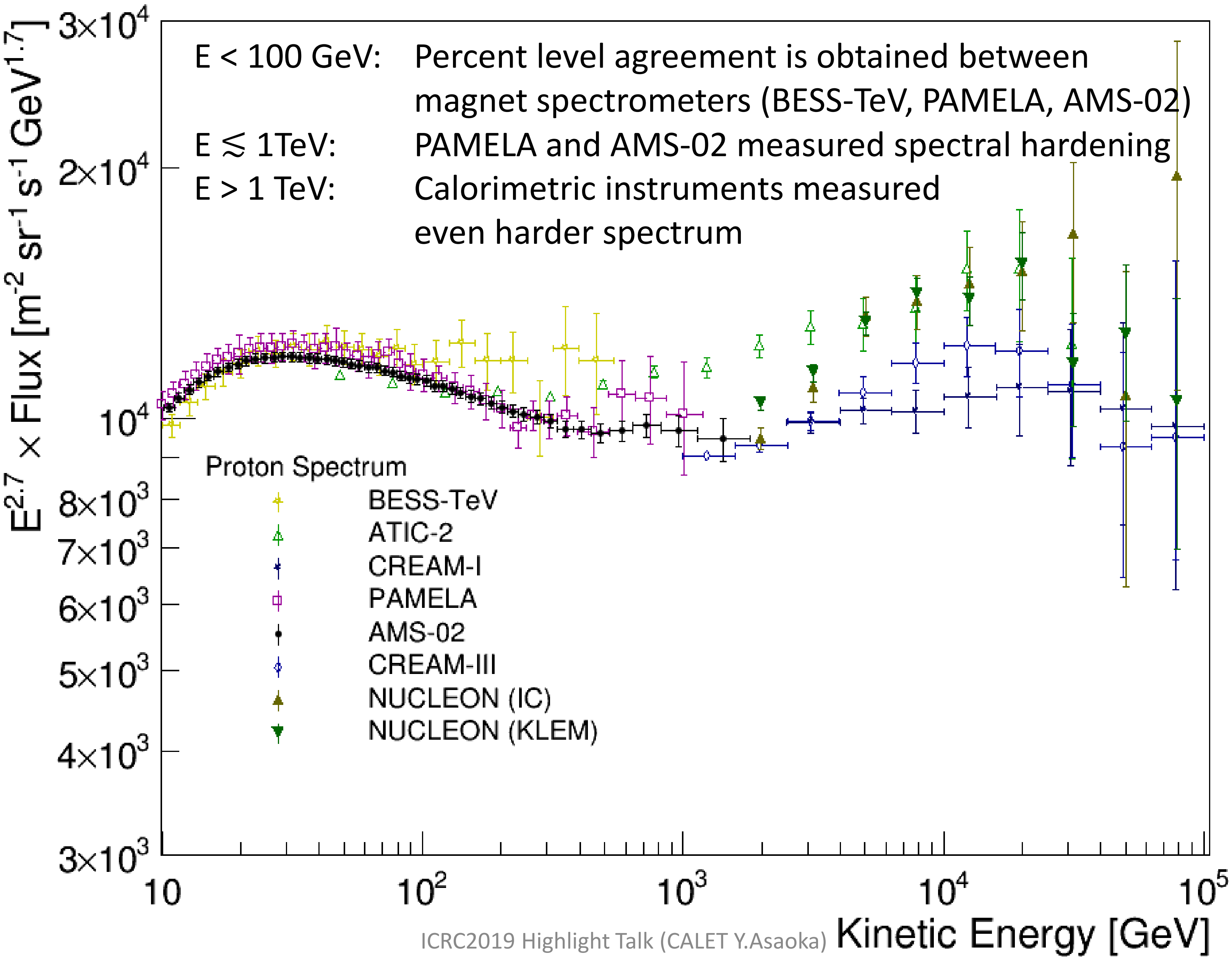
Prospects for the CALET All-Electron Spectrum

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

- The possibility of new discoveries dwells in fine structures of the all-electron spectrum.
- Taking advantage of localness, the TeV all-electron spectrum approaches its origin.



Status of Cosmic-Ray Proton Spectrum Measurements



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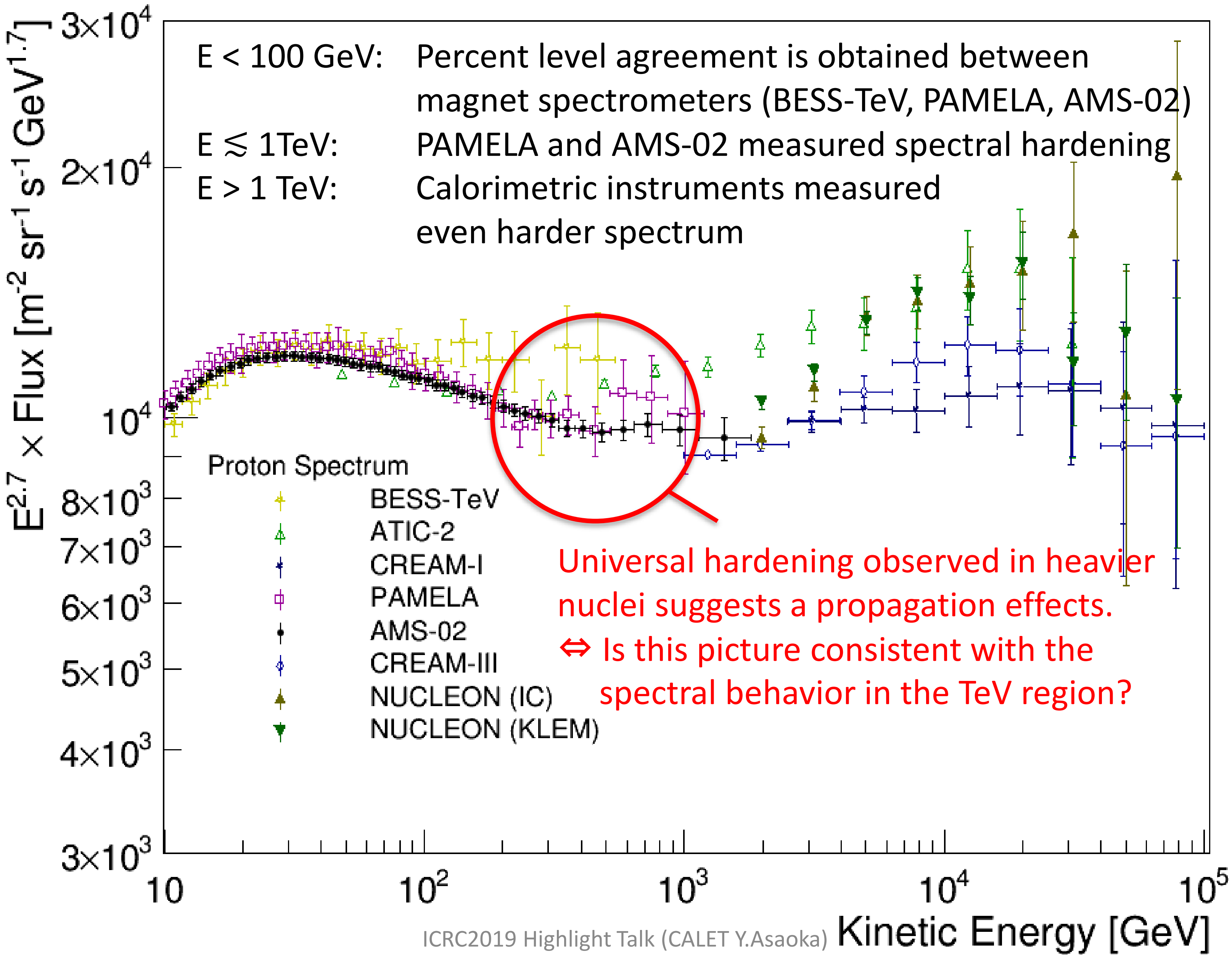

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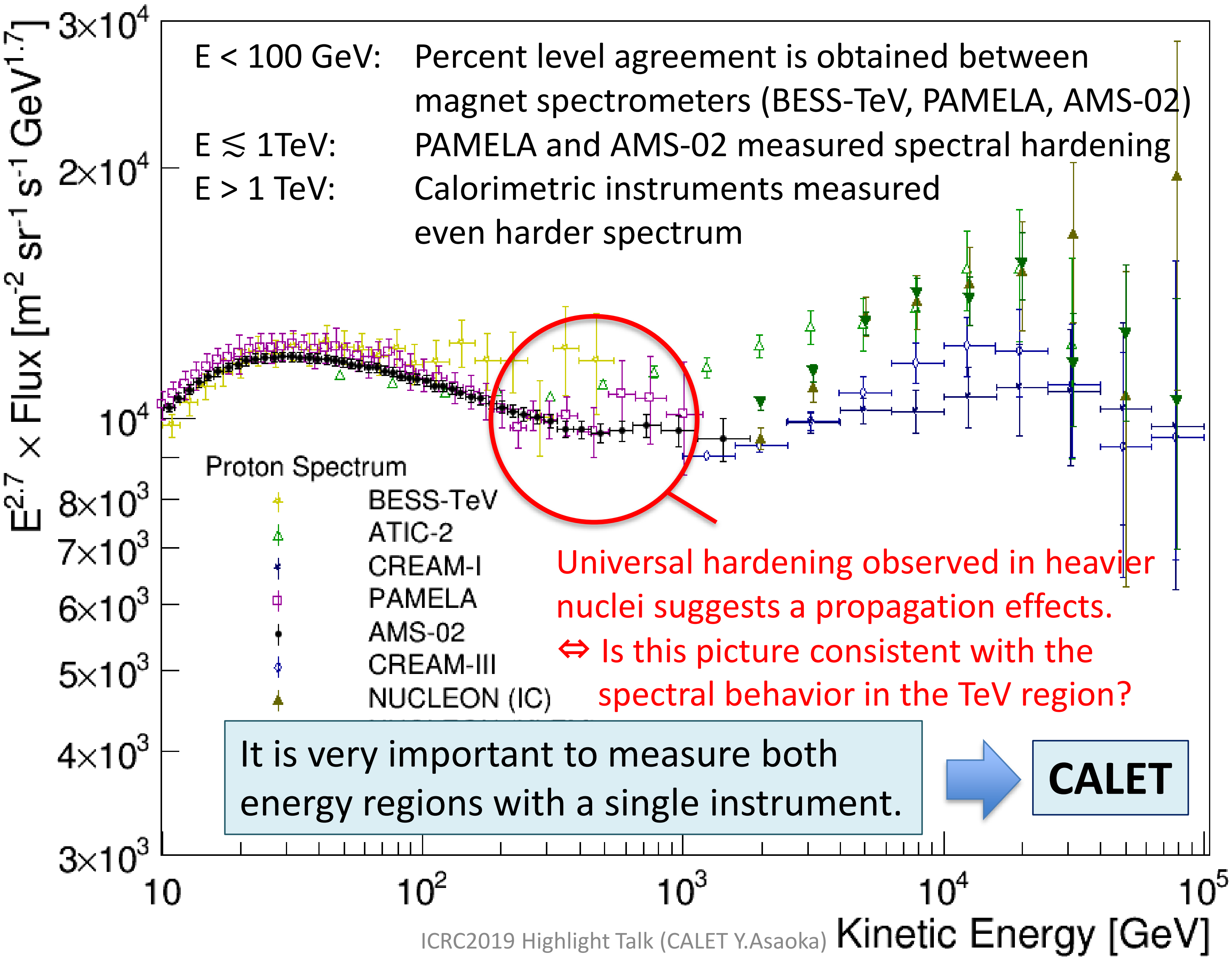
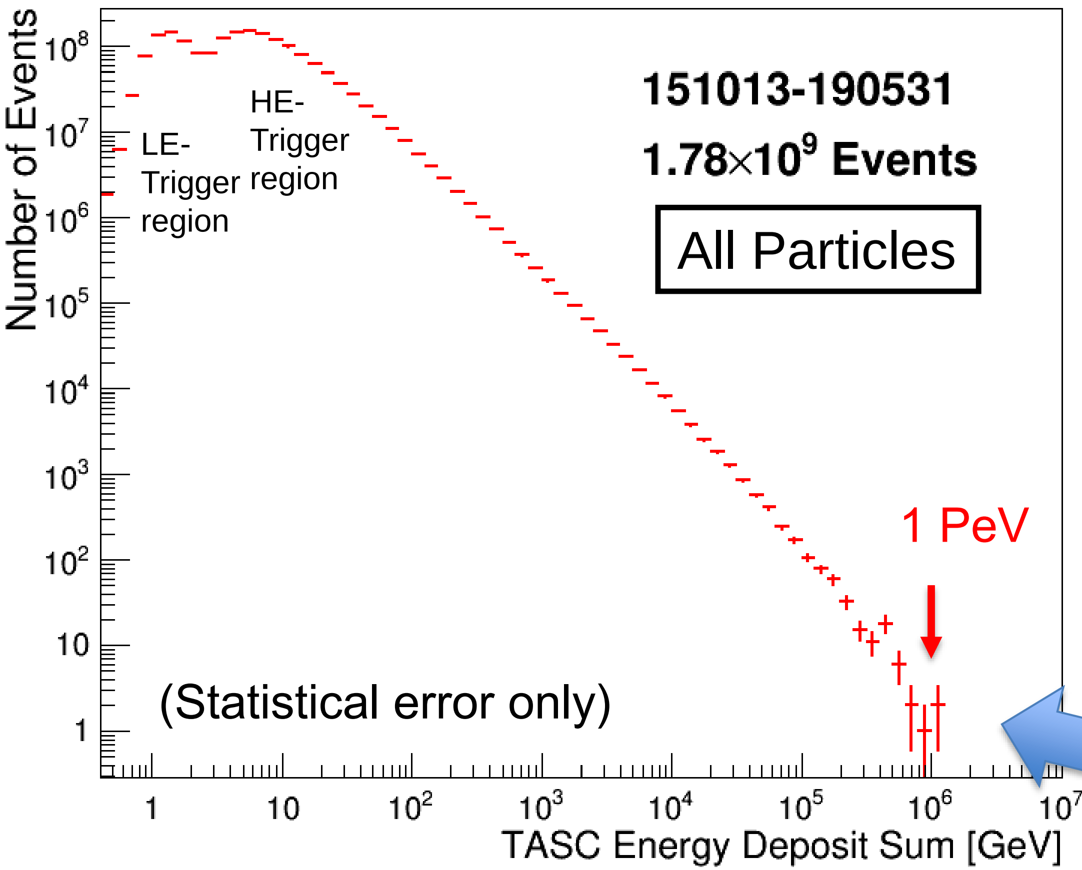
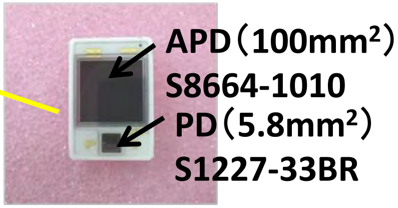


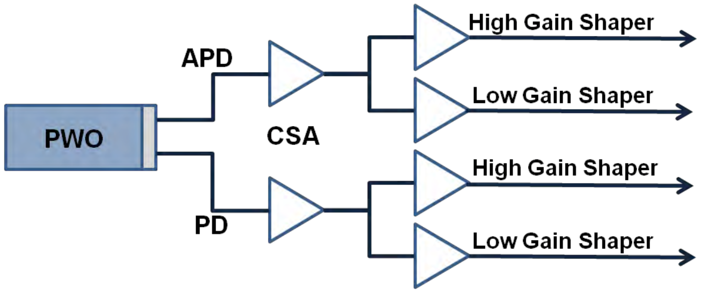
Wide Dynamic Range Energy Measurement

Distribution of TASC energy deposit sum

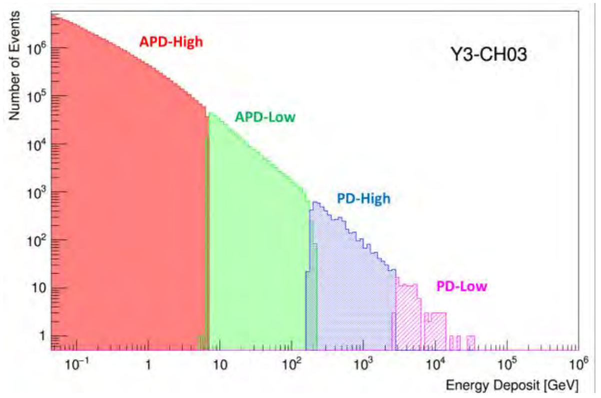


Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), Astropart. Phys. 91 (2017) 1.





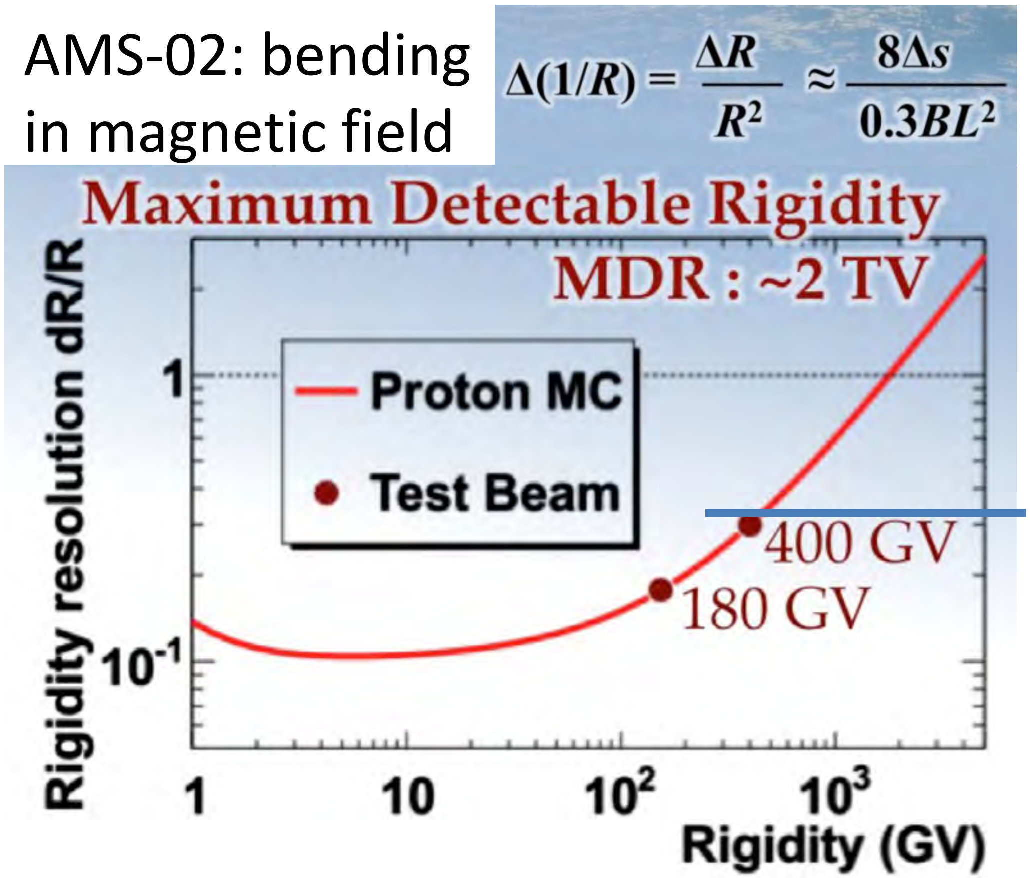
An example of gain connection in one PWO log:



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

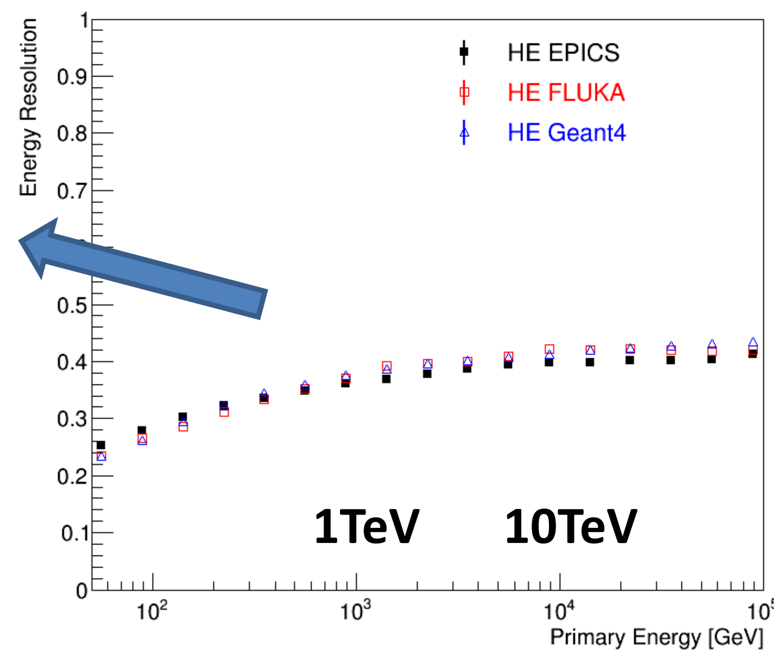
AMS-02: bending in magnetic field



Ref: Haino 2014

CALET: shower energy

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



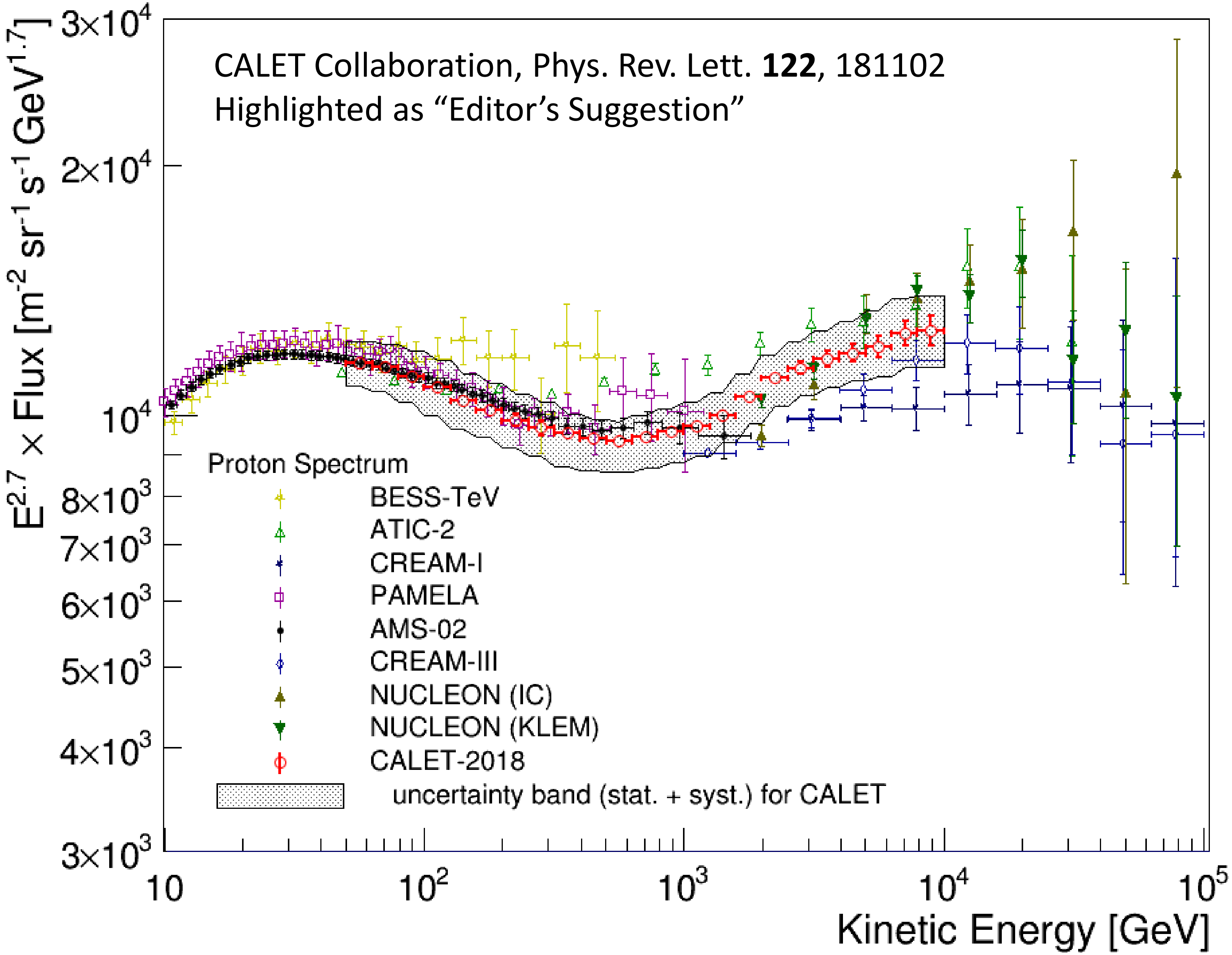
Proton Measurement with CALET: room for "unknown" systematics

1. Acceptance ⇒ **well defined SΩ**
   – Geometrical factor — **because of KF tracking and event selection**
2. Energy determination ⇒ **limited energy resolution but constant response, and confirmed by test beam**
   – Magnet Spectrometer
   – **Calorimeter**
3. Particle identification ⇒ **excellent charge separation capability**
   – Contamination
4. Detection efficiency ⇒ **low efficiency, but confirmed by test beam**
   – Losses in the detector

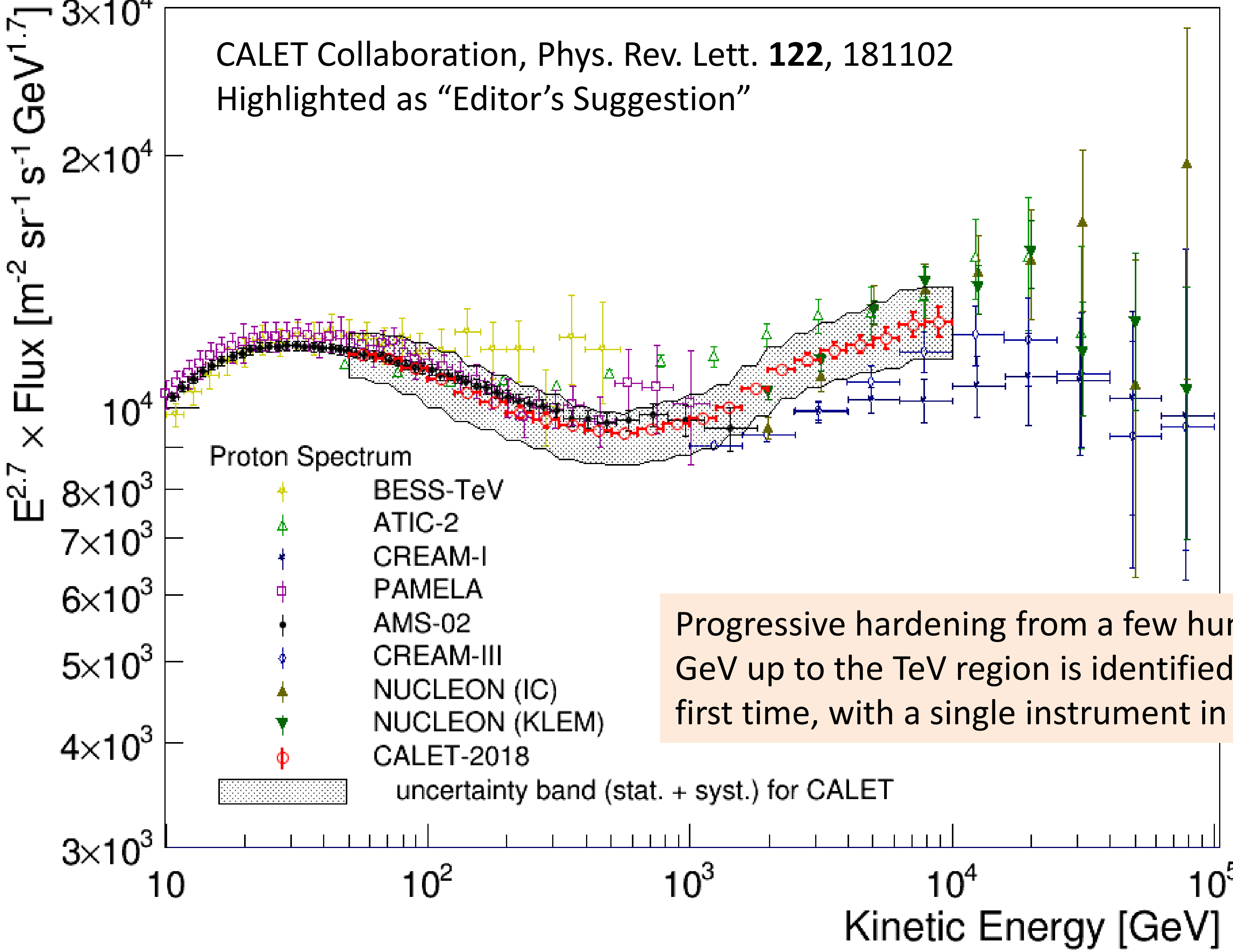
⇒ **Needs special care for "unknown" systematics**

detailed systematic studies are carried out
(see the Supplement Material of PRL 122, 181102)

Cosmic-Ray Proton Spectrum from CALET



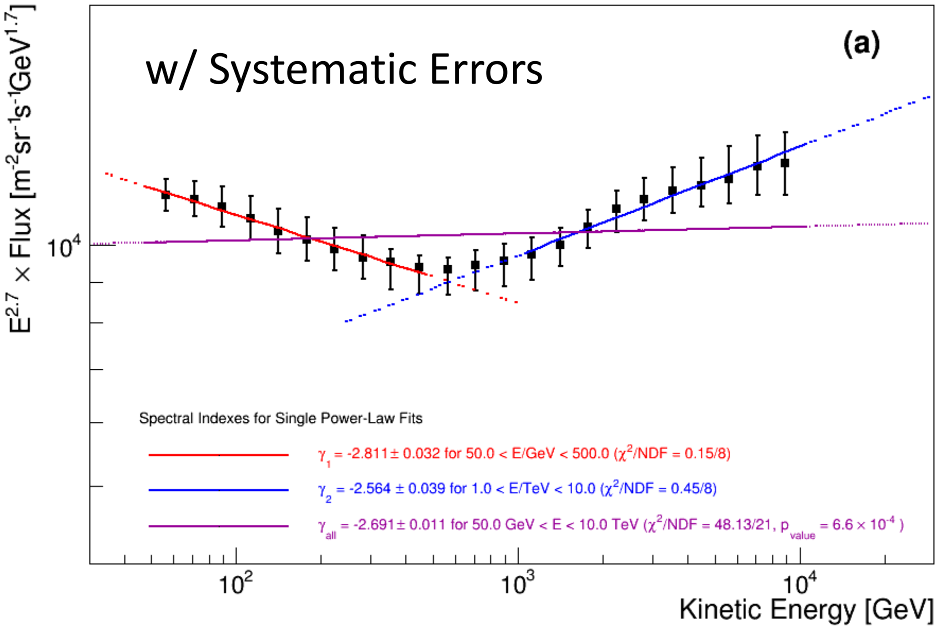
Cosmic-Ray Proton Spectrum from CALET

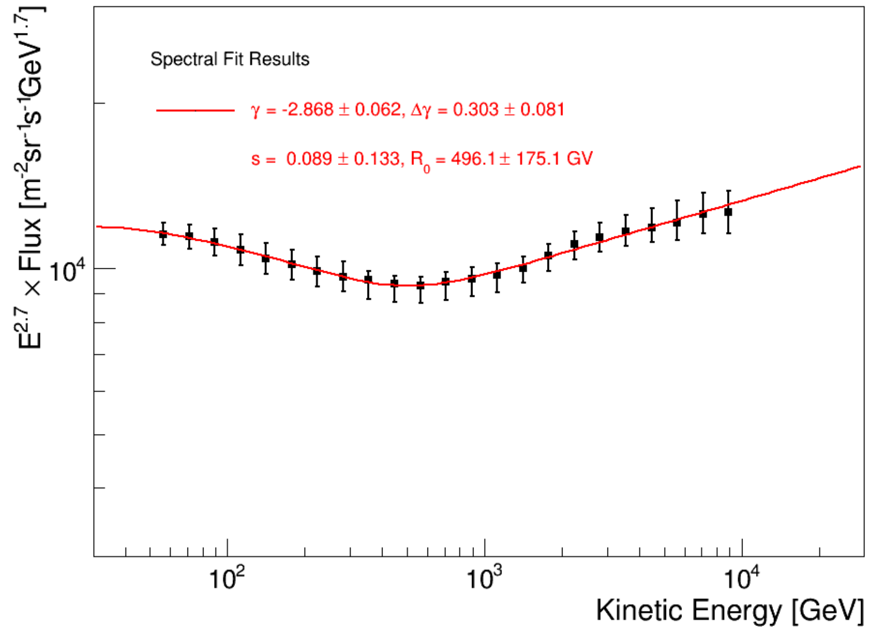


Progressive hardening from a few hundred GeV up to the TeV region is identified, for the first time, with a single instrument in space

Spectral Behavior of Proton Flux

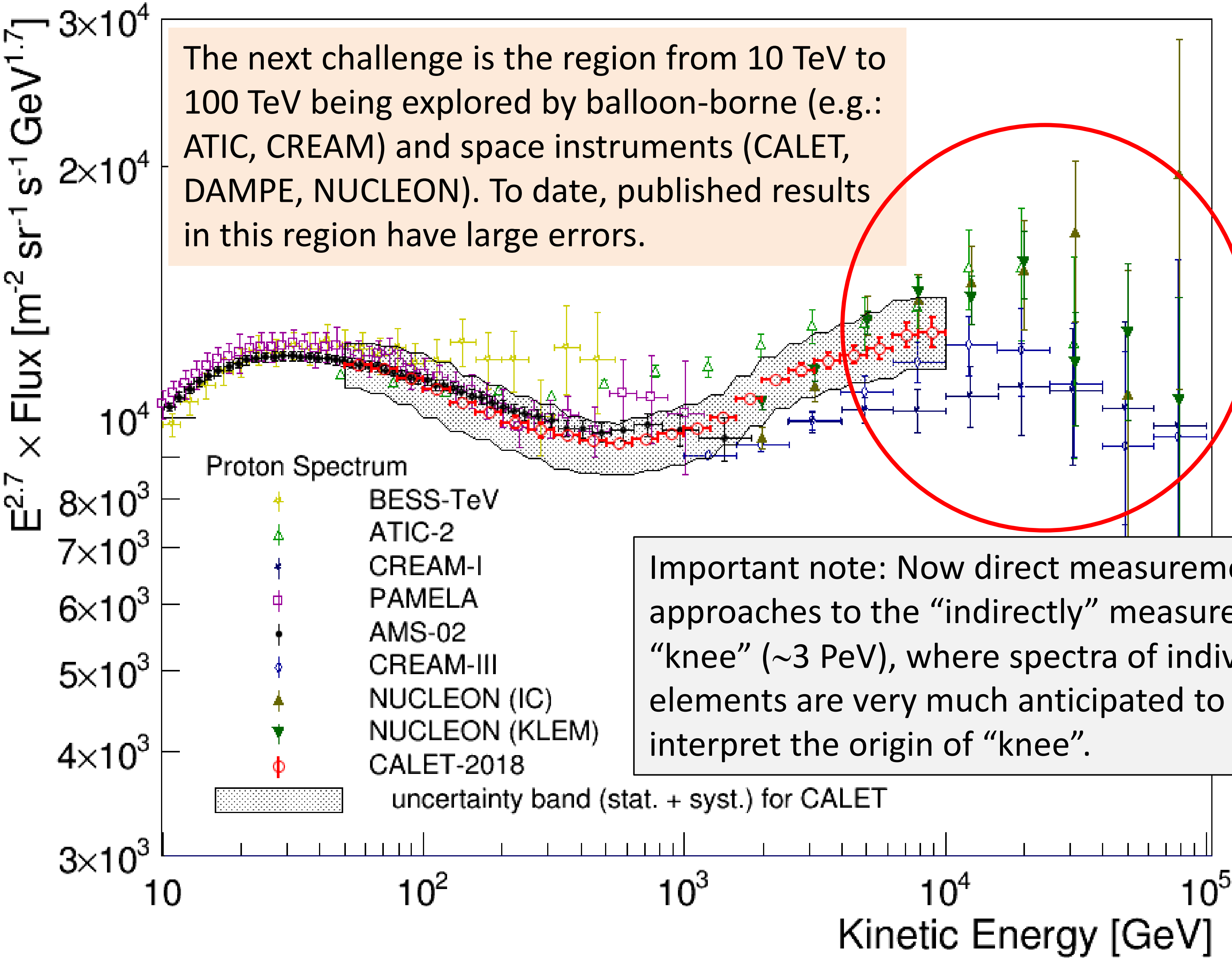
P. S. Marrocchesi ICRC2019 Jul. 30 (CRD8e)





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

Prospects for the CALET Proton Spectrum



The next challenge is the region from 10 TeV to 100 TeV being explored by balloon-borne (e.g.: ATIC, CREAM) and space instruments (CALET, DAMPE, NUCLEON). To date, published results in this region have large errors.

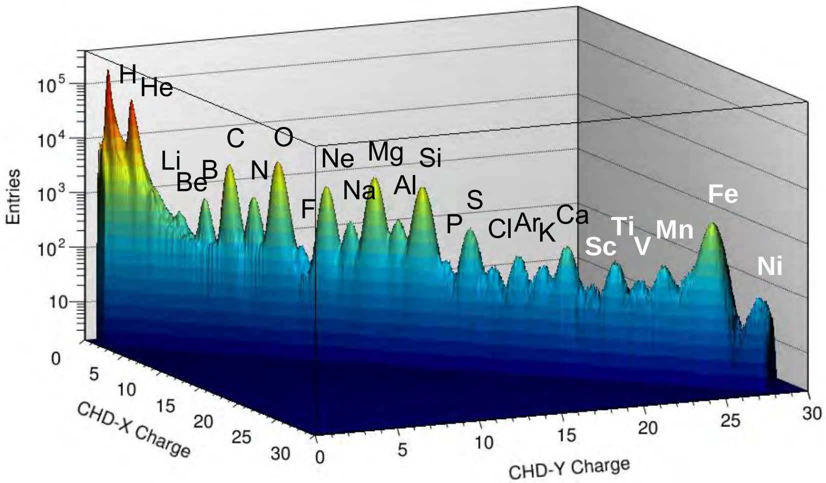
Important note: Now direct measurements approaches to the “indirectly” measured “knee” (~3 PeV), where spectra of individual elements are very much anticipated to interpret the origin of “knee”.

Preliminary Spectra of Primary Components

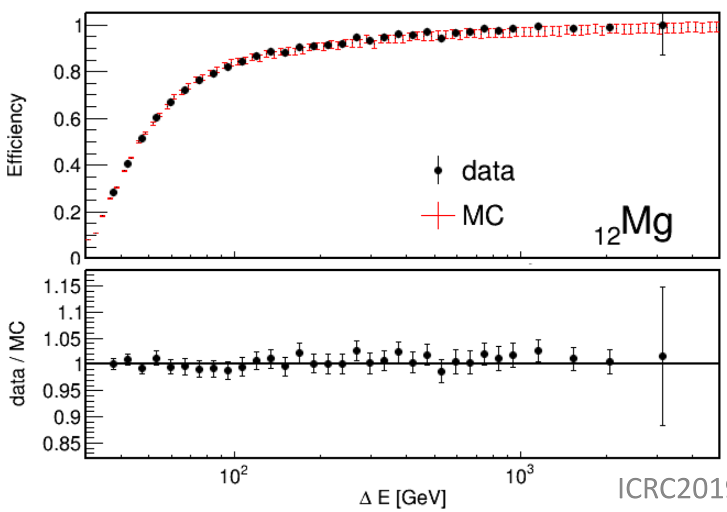
Y. Akaike ICRC2019 Jul. 26 (CRD3b)

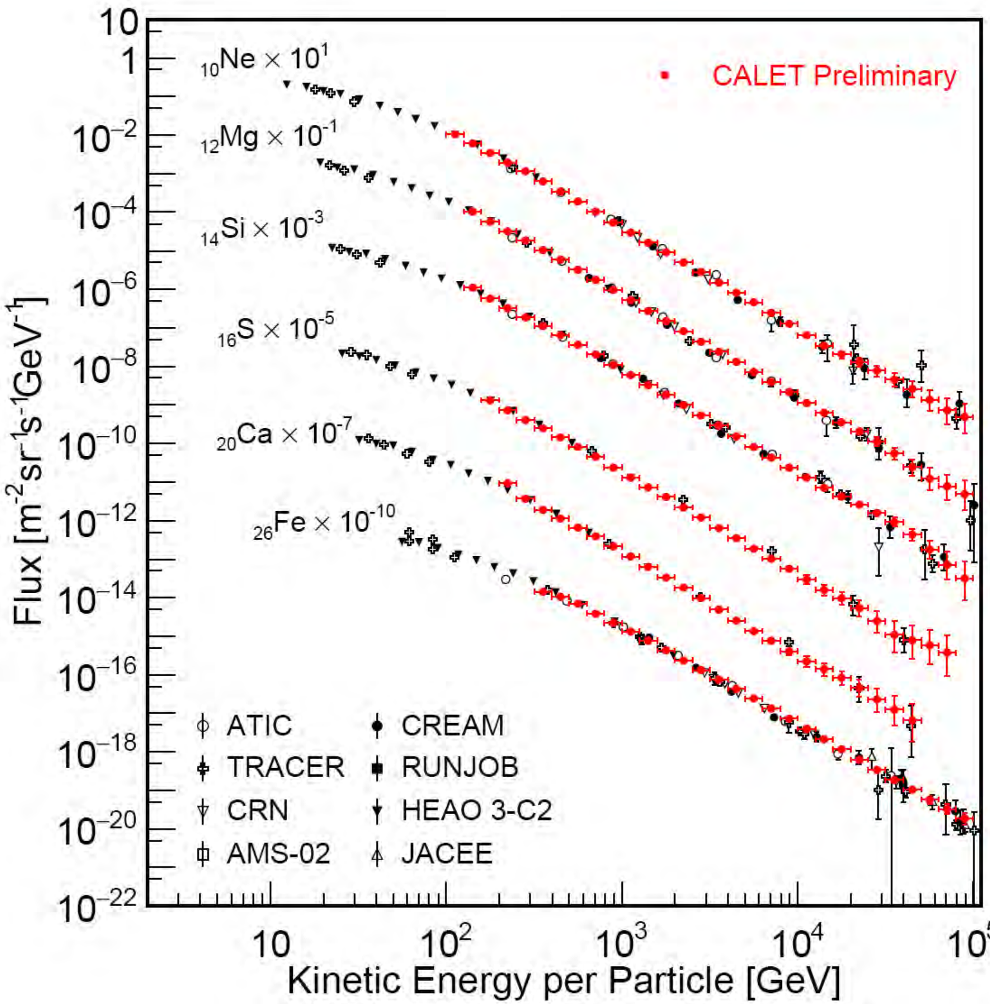
Charge Separation only with CHD

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



Trigger Efficiency Measurement

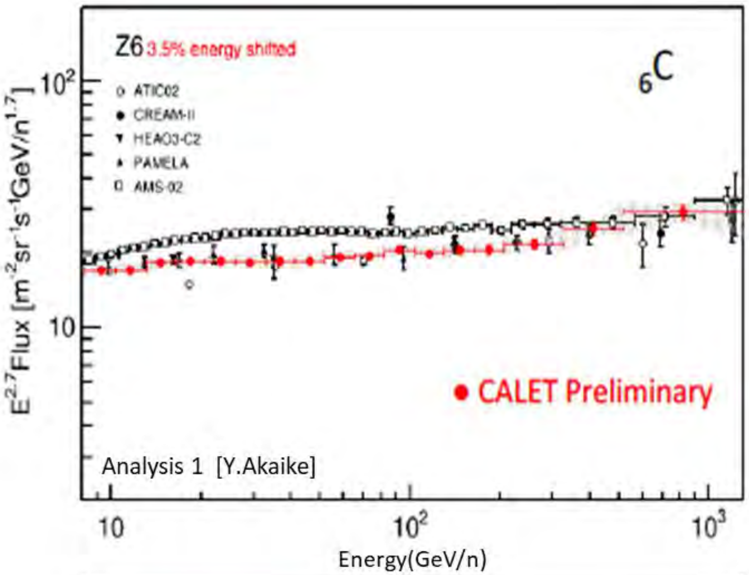


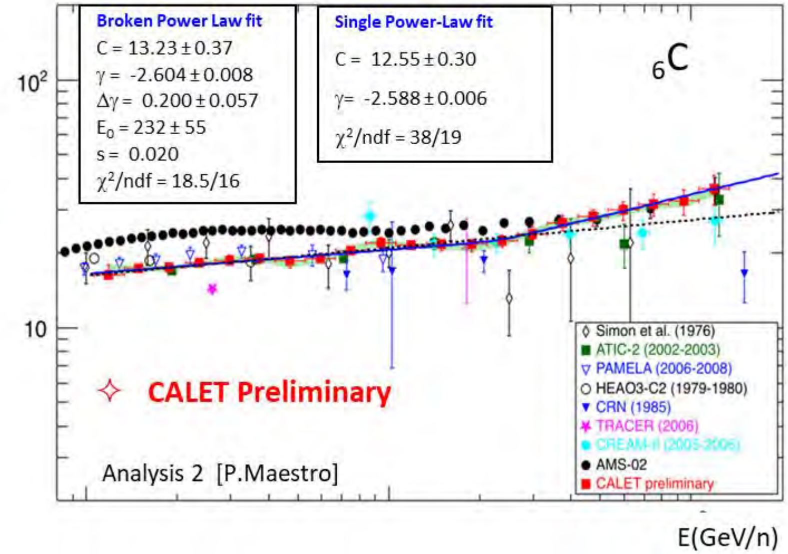


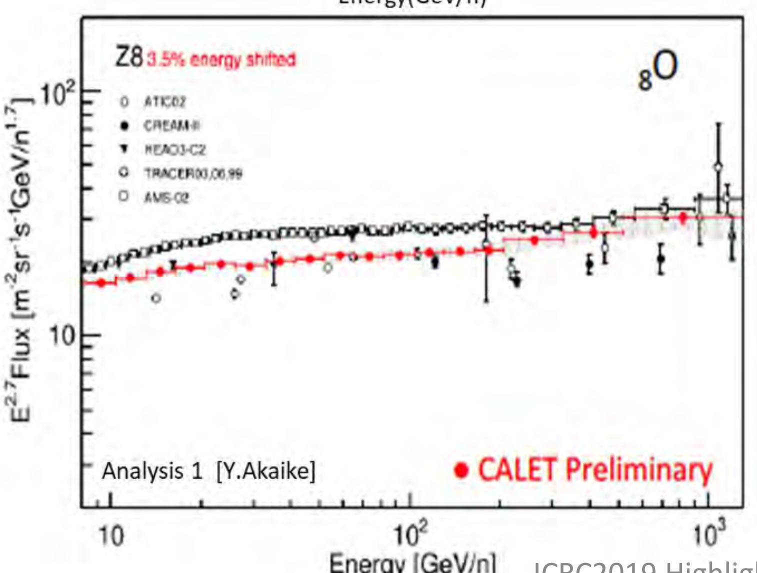
Preliminary Energy Spectra of Carbon and Oxygen

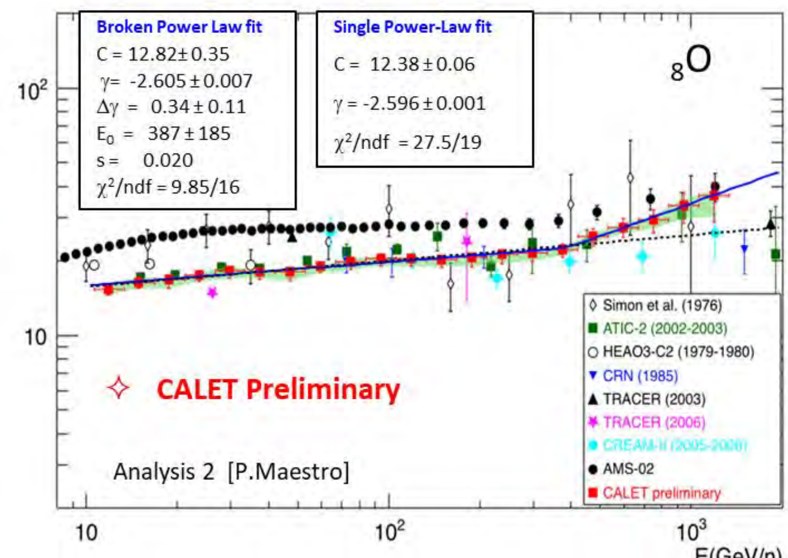
(2 independent CALET analyses)

P. Maestro ICRC2019 Jul. 30 (CRD8f)







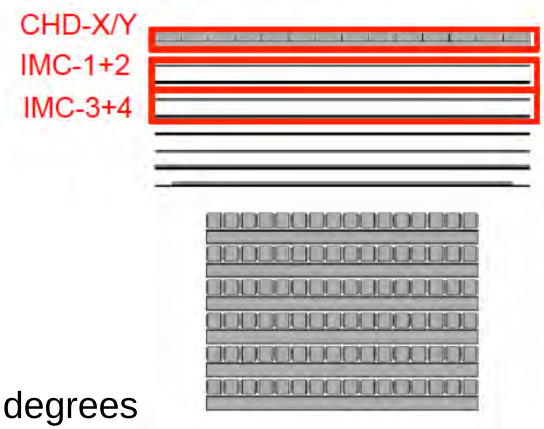


Ultra Heavy Nuclei Analysis (Z>26, up to 40)

B. Rauch ICRC2019 Jul. 26 (CRD3c)

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

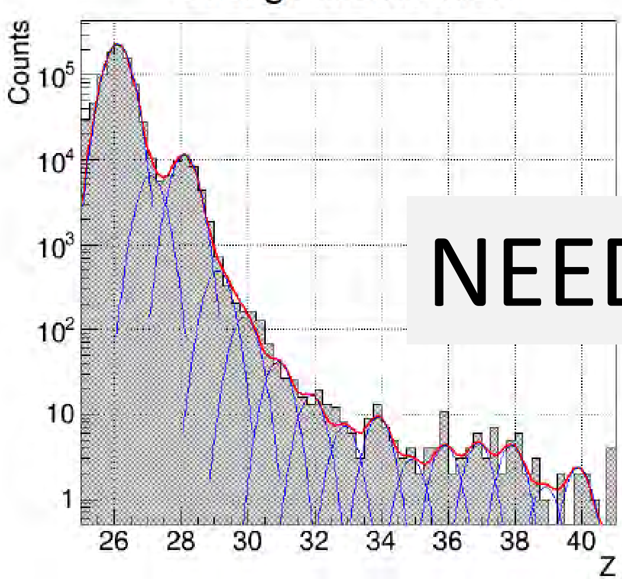
Onboard trigger for UH events



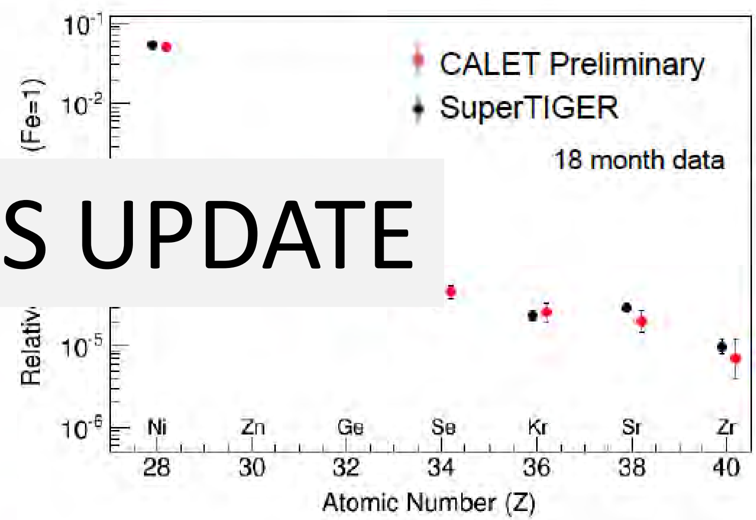
Data analysis

- ☐ 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)



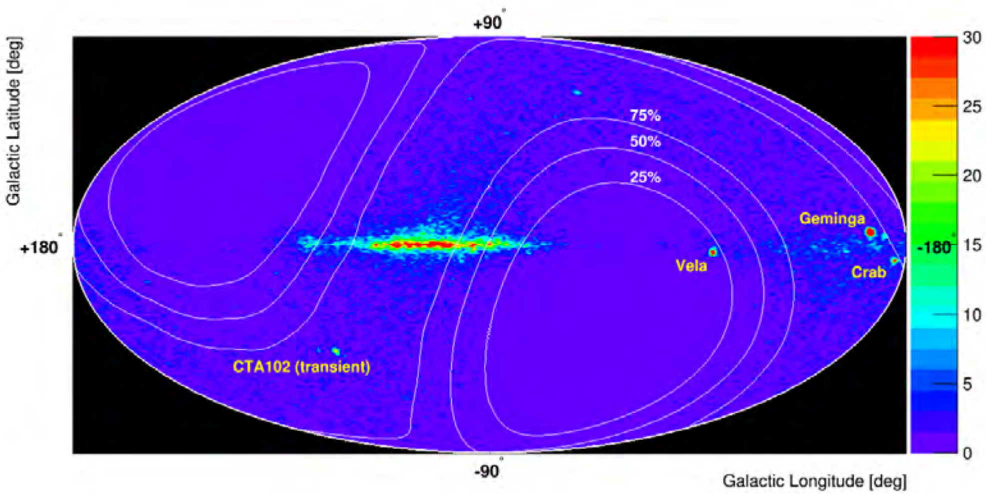
NEEDS UPDATE

Gamma-Ray Observations

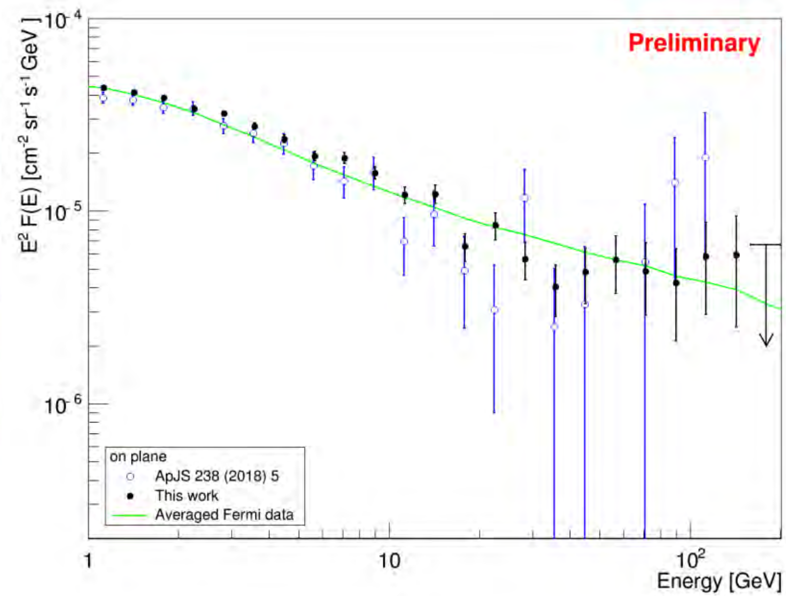
M. Mori ICRC2019 Jul. 29 (GAD5d)

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

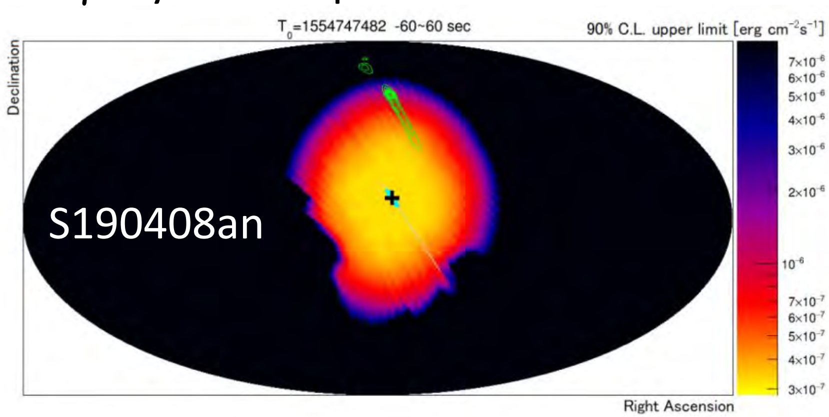
Sky map obtained with LE-γ trigger



Average flux from galactic plane



GeV γ-ray counterpart search for GW events



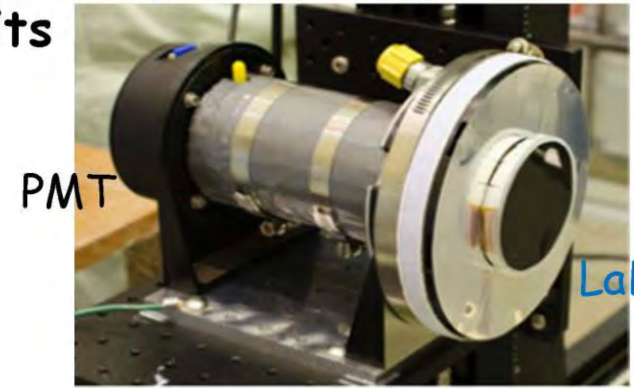
GCN No.	LIGO/Virgo trigger	Trigger time T_0 (2019)	Events $T_0 \pm 60$ s	90% C.L. U.L.	Summed probability	CAL α (°)	CAL δ (°)
24088	S190408an	04-08 18:18:02.288 UTC	0	2.3×10^{-6}†	80%	352.9	8.3
24218	S190425z	04-25 08:18:05.017 UTC	0	1.0×10^{-4}	5%	131.3	-43.6
24276	S190426c	04-26 15:21:55.337 UTC	0	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	6.0×10^{-5}†	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)

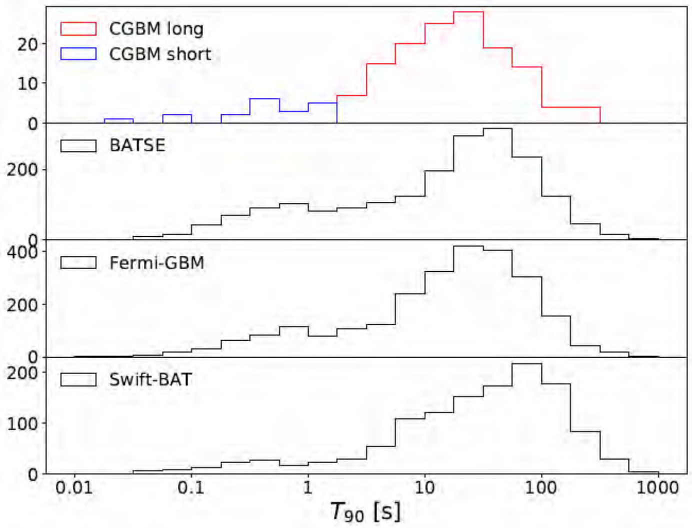
Hard X-ray Monitor (HXM)

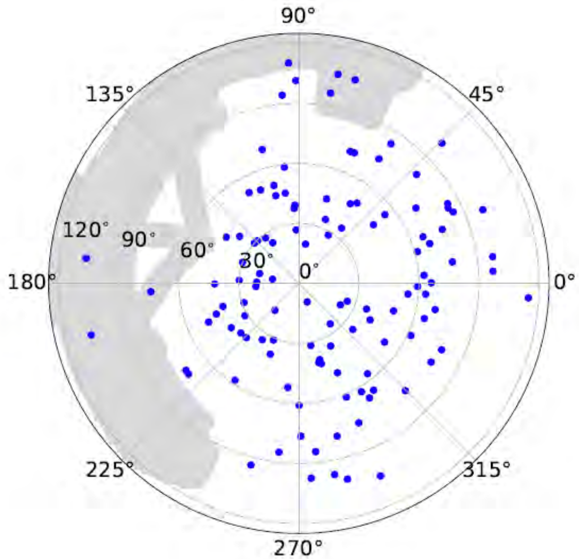
2 units



Soft Gamma-ray Monitor (SGM)

T90 distribution for CGBM detected GRBs



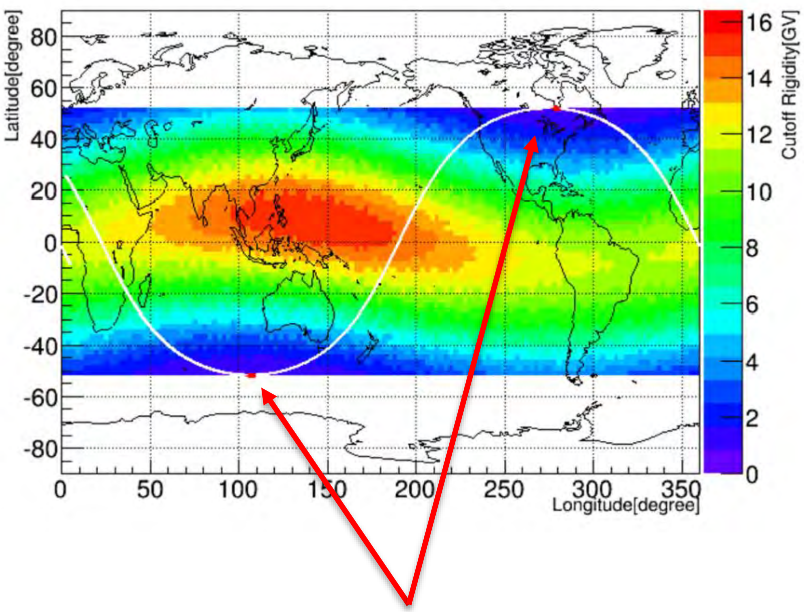


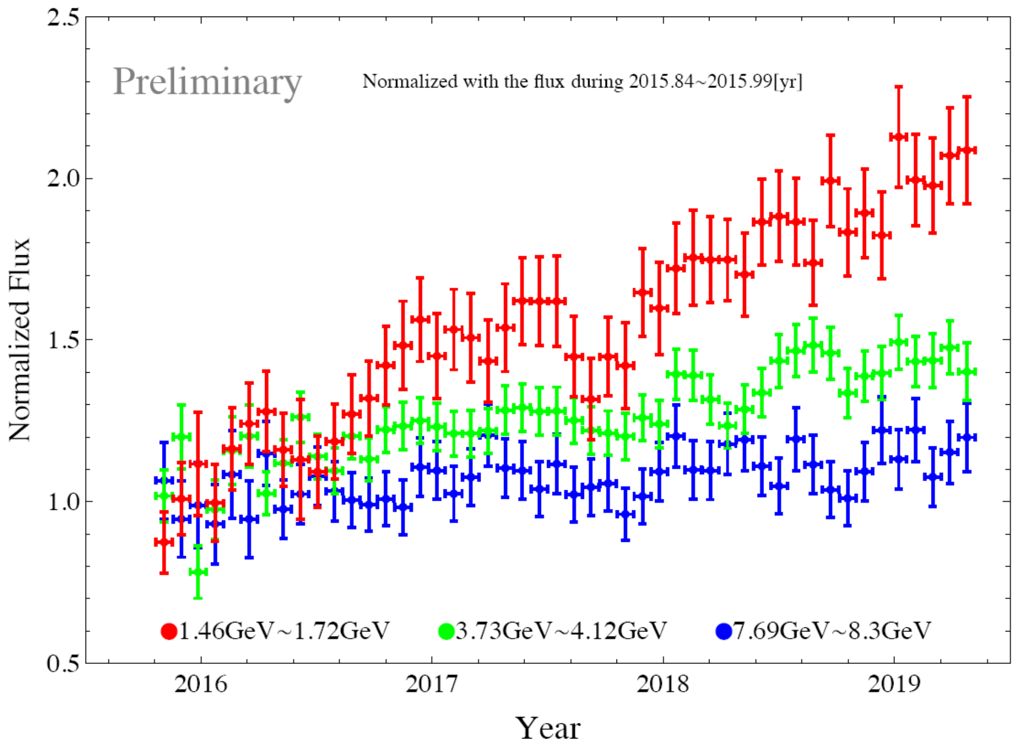
CGBM detected nearly 43 GRBs (~12% short GRB among them) per year in the energy range of 7 keV—20 MeV

Solar Modulation of Cosmic-Ray Electrons

S. Miyake ICRC2019 Jul. 25 (SH2a)

Color map: cutoff rigidity





Low-energy electron trigger (E>1GeV) 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

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

CALET Observations

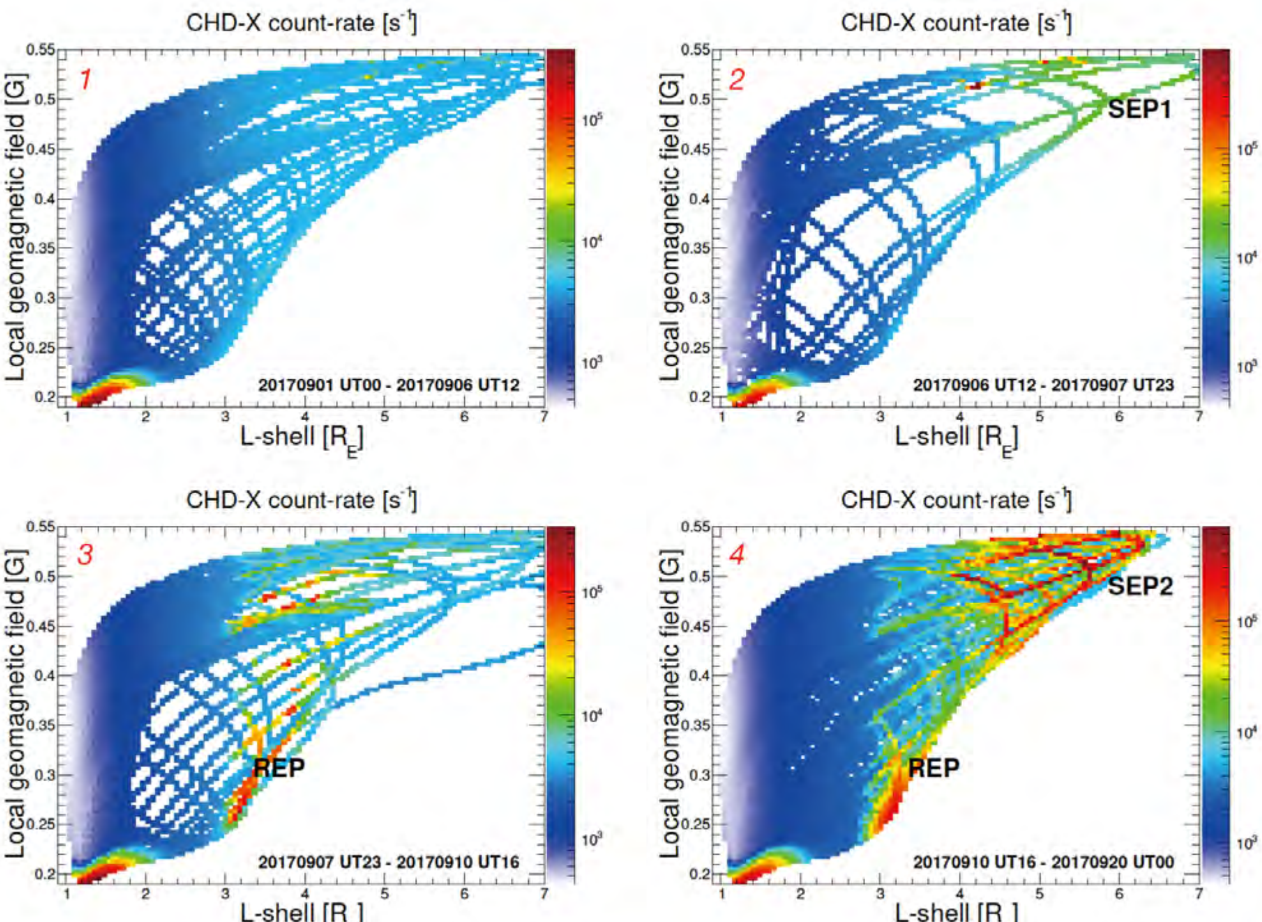


Figure 4: Count-rate measured by the CALET top detector (CHD-X) as a function of local geomagnetic field intensity B and L-shell, during four different intervals of early September 2017 (see labels). The enhancements relative to SEP and REP events are indicated.

Measurements by GEOS-16, SOPO, YKTK and MGDN

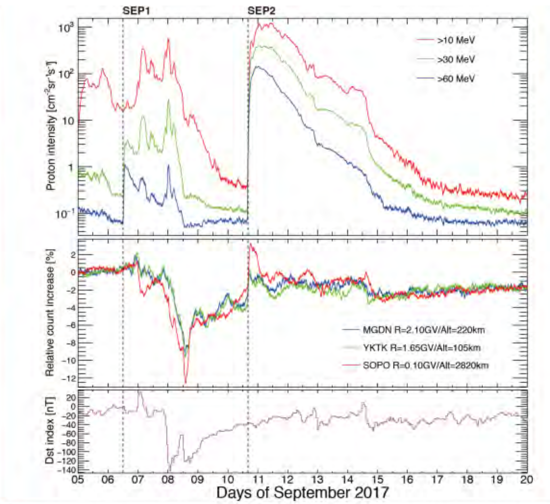


Figure 1: Time profiles (5–19 September 2017) of proton intensities measured by GOES-15 at three different energy thresholds (top; 1-hour running averages), count-rate increases registered by the SOPO, YKTK and MGDN neutron monitors at different geomagnetic cutoff rigidities / altitudes (middle; 1-hour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

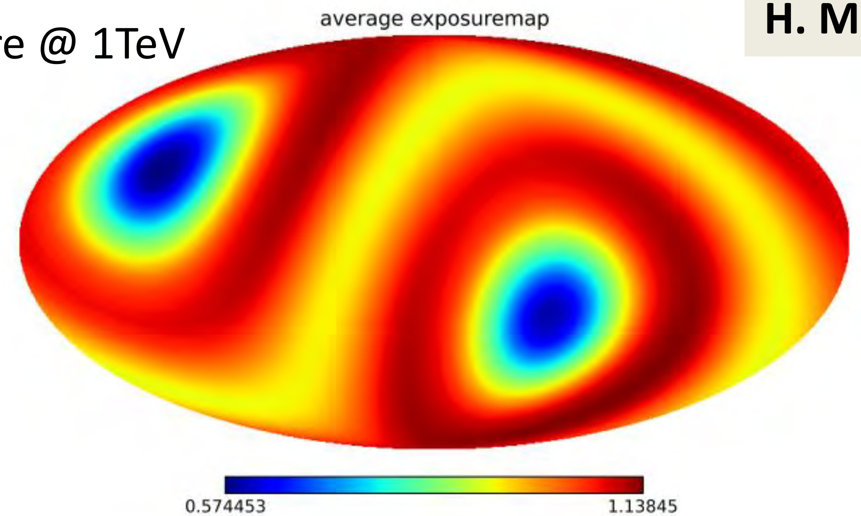
SEP: Solar Energetic Particle

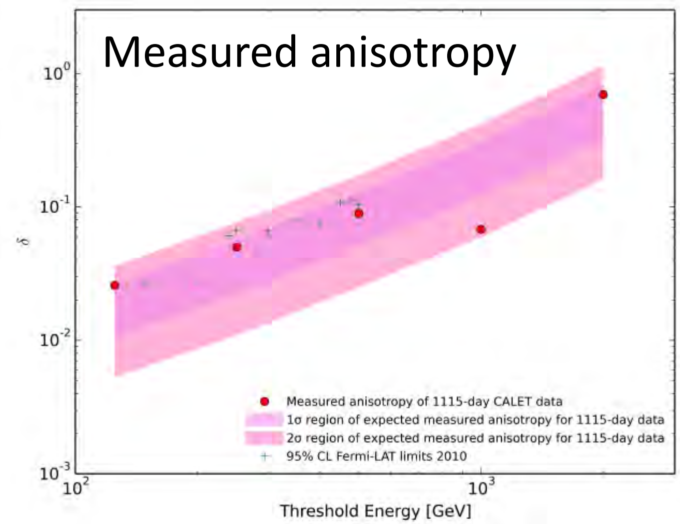
REP: Relativistic Electron Precipitation

Electron Anisotropy

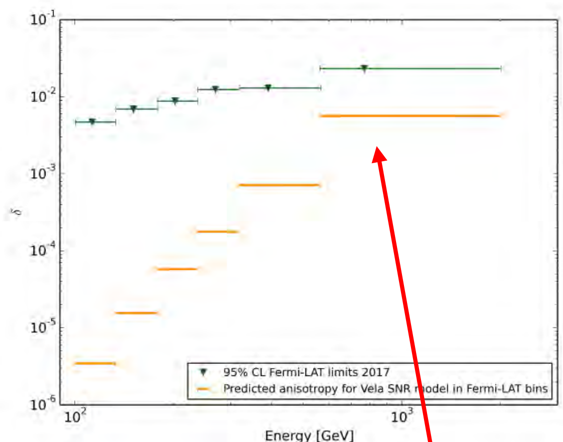
H. Motz ICRC 2019, Jul 25-26 (CRD PS1-20)

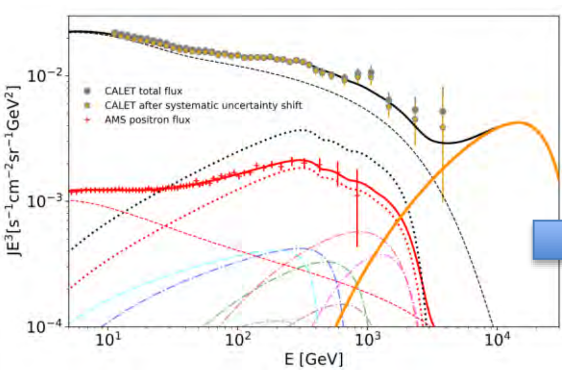
Exposure @ 1TeV



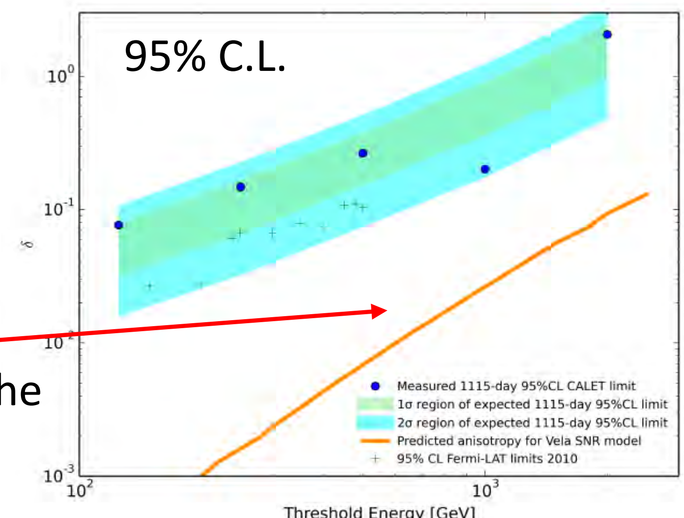


Fermi-LAT limit from
PRL 118, 091103 (2017)





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

Complete List of CALET Talks at ICRC2019

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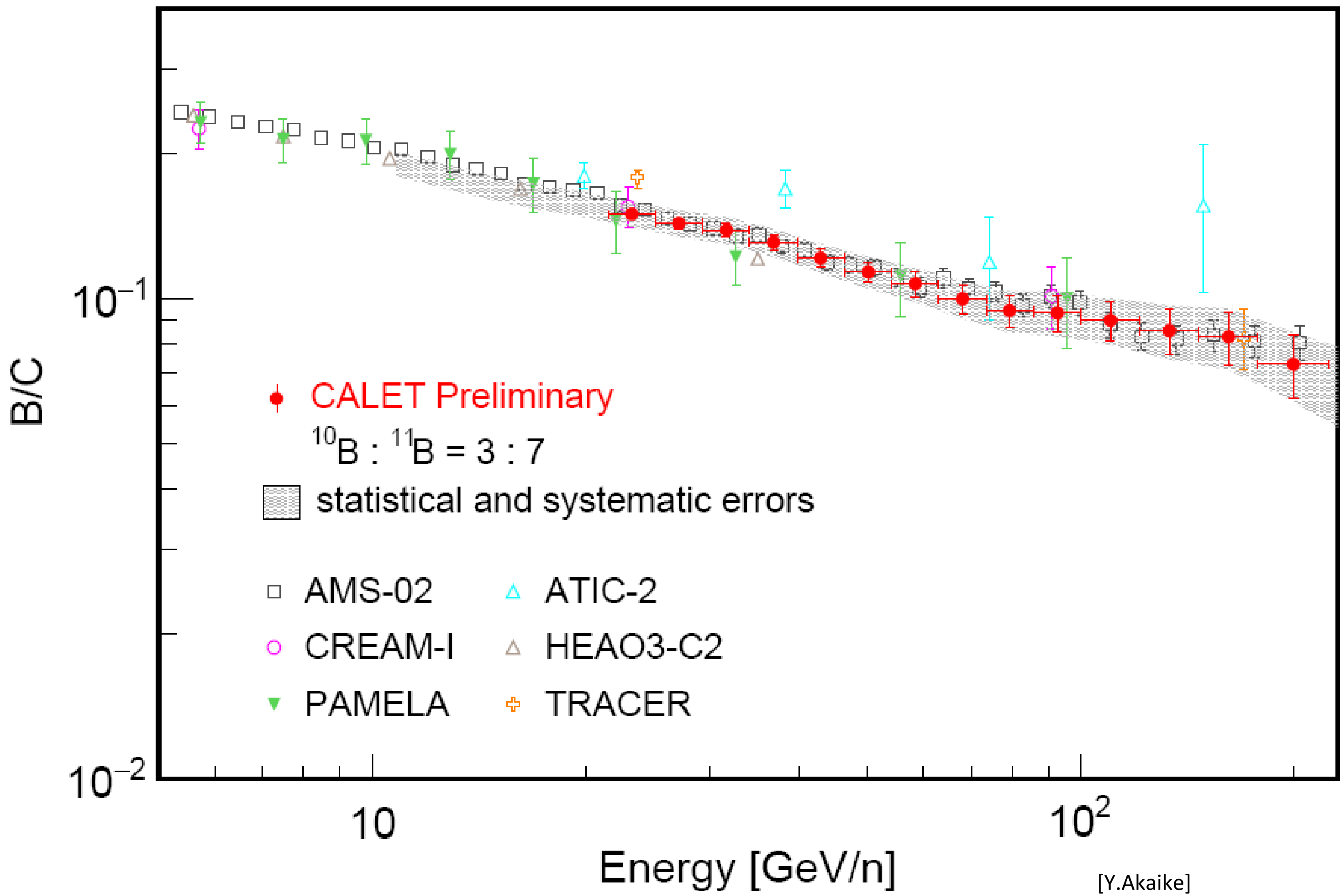
11	S.Miyake	Solar Modulation of Galactic Cosmic-Ray Electrons Measured with CALET	SH2a	Jul. 25

Backup

Preliminary Boron-to-Carbon Flux Ratio



[Y.Akaike]