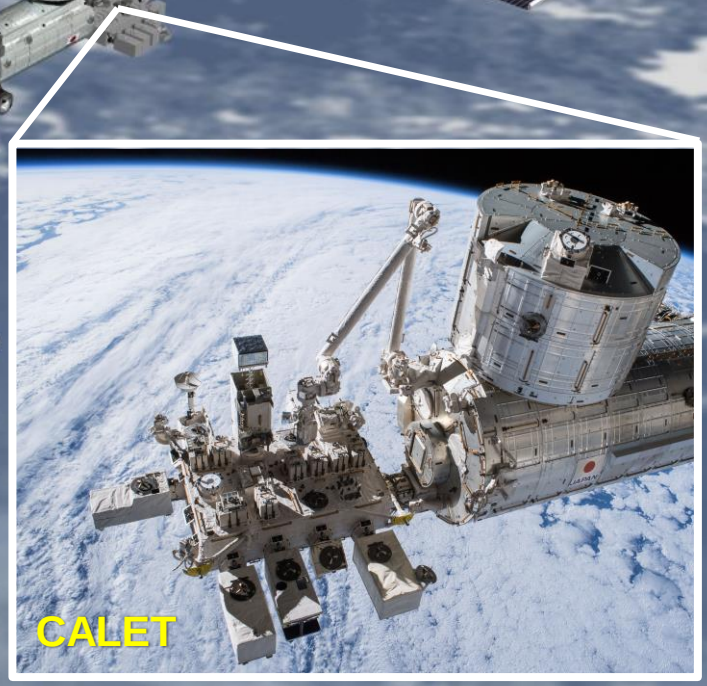
Direct Measurement of Cosmic-Ray Acceleration Limit in Supernovae

using the CALorimetric Electron Telescope (CALET) onboard the International Space Station (ISS)

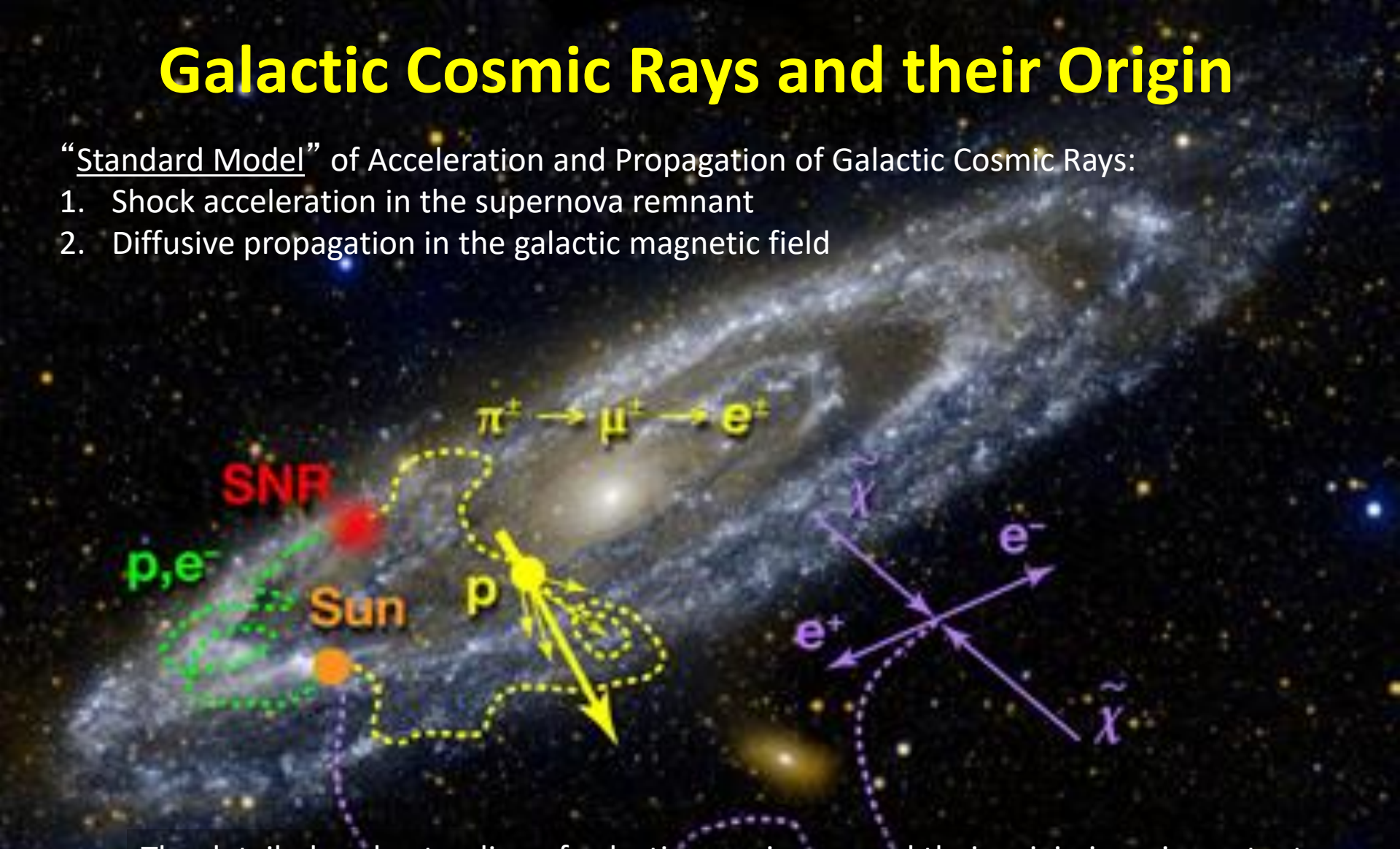


Yoichi Asaoka
for the CALET collaboration
WISE, Waseda University

Galactic Cosmic Rays and their Origin

"Standard Model" of Acceleration and Propagation of Galactic Cosmic Rays:

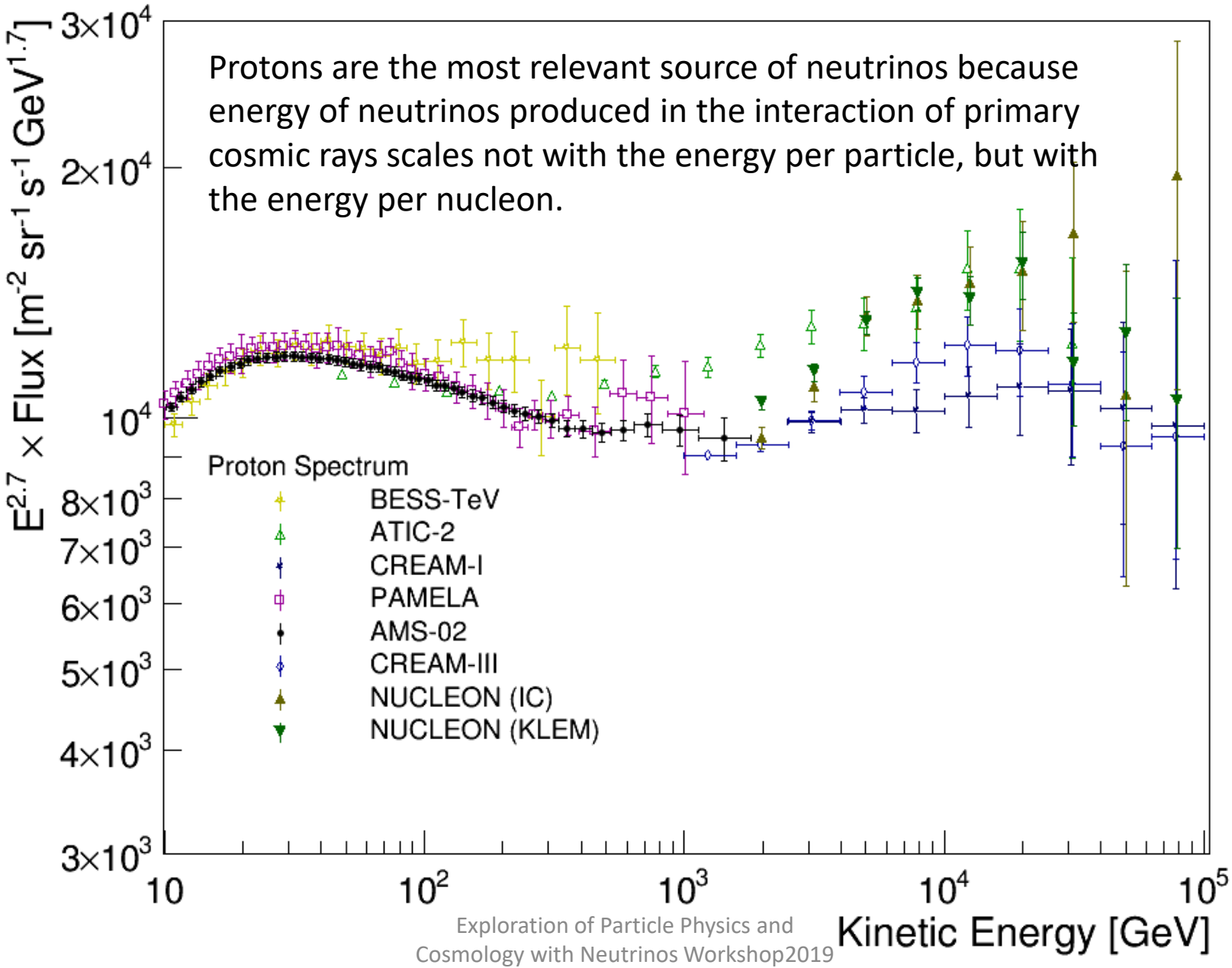
1. Shock acceleration in the supernova remnant
2. Diffusive propagation in the galactic magnetic field



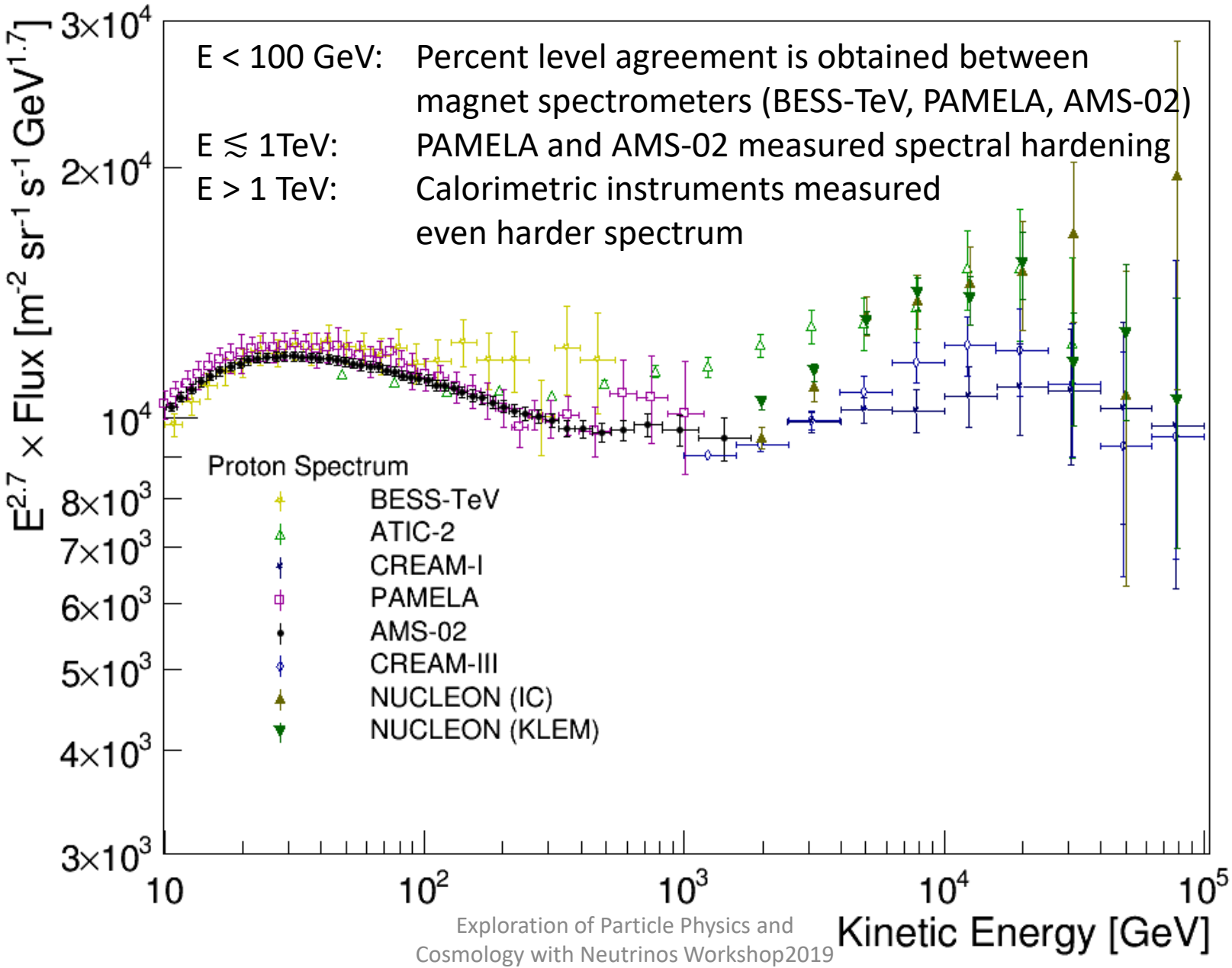
The detailed understanding of galactic cosmic rays and their origin is an important foundation for calculations of **atmospheric and cosmogenic neutrinos**, as well as for calculations used in gamma-ray physics, and indirect searches of dark matter.

https://physics.aps.org/articles/v6/40

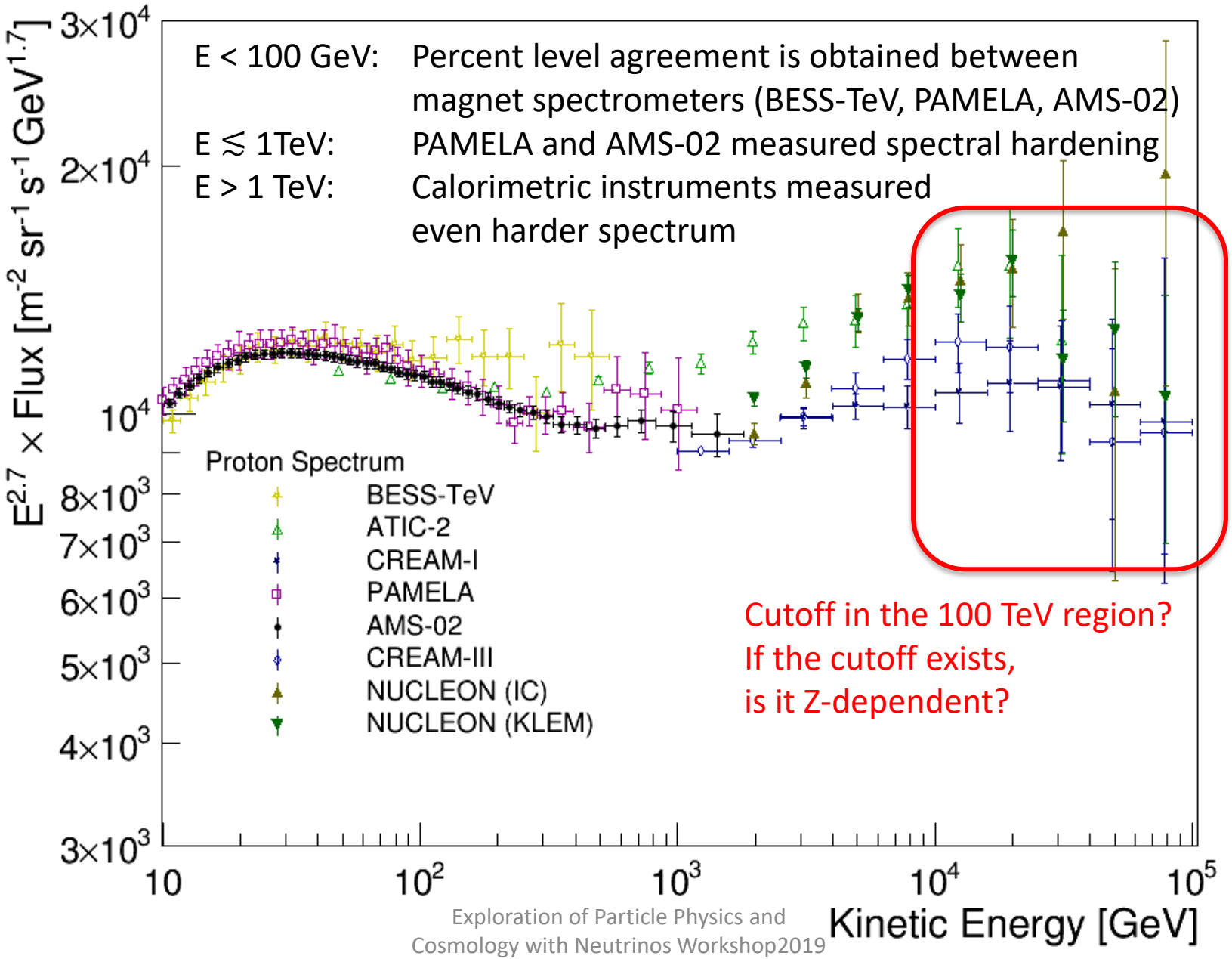
Direct Measurements of Cosmic-Ray Proton Spectrum



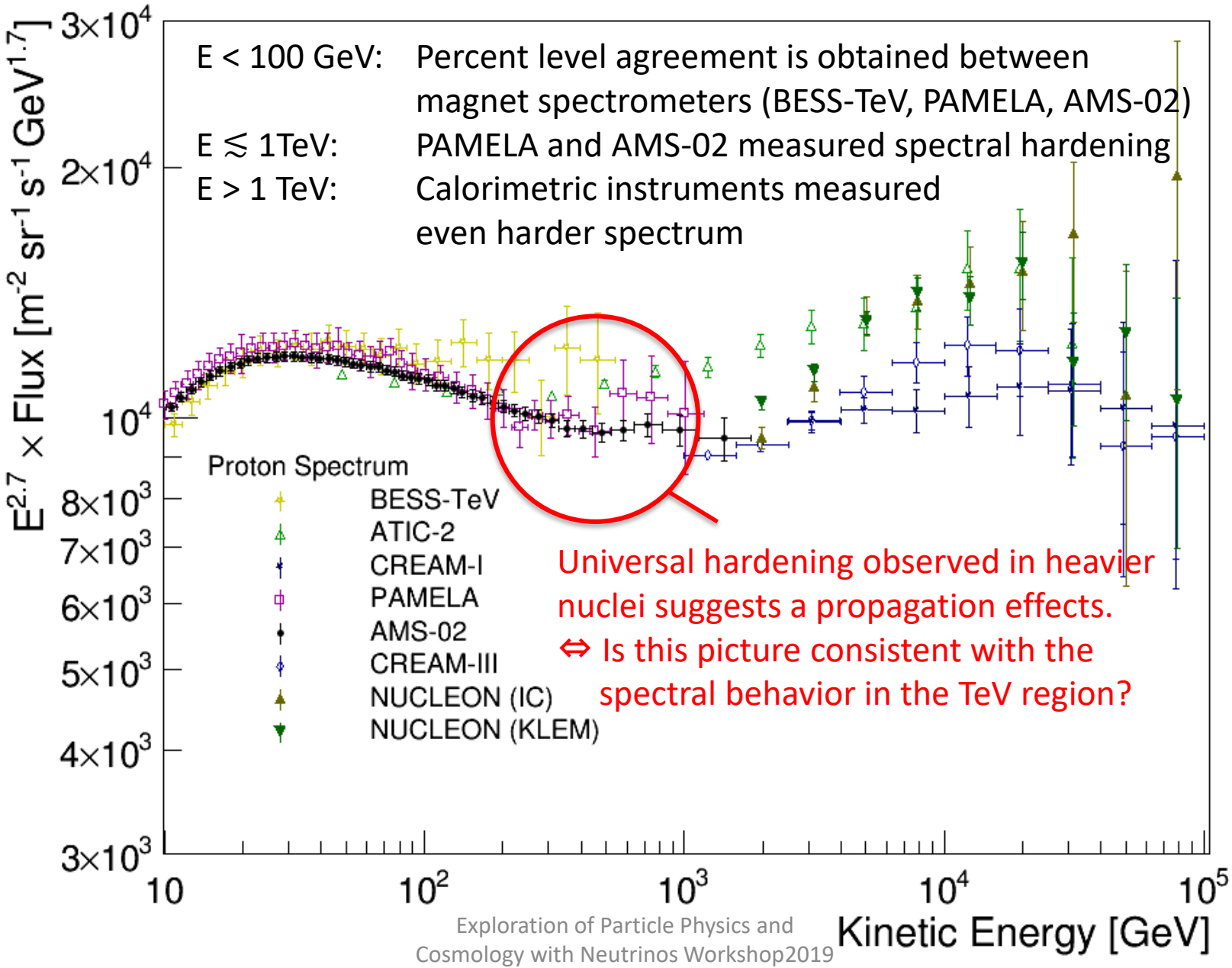
Status of Cosmic-Ray Proton Spectrum Measurements



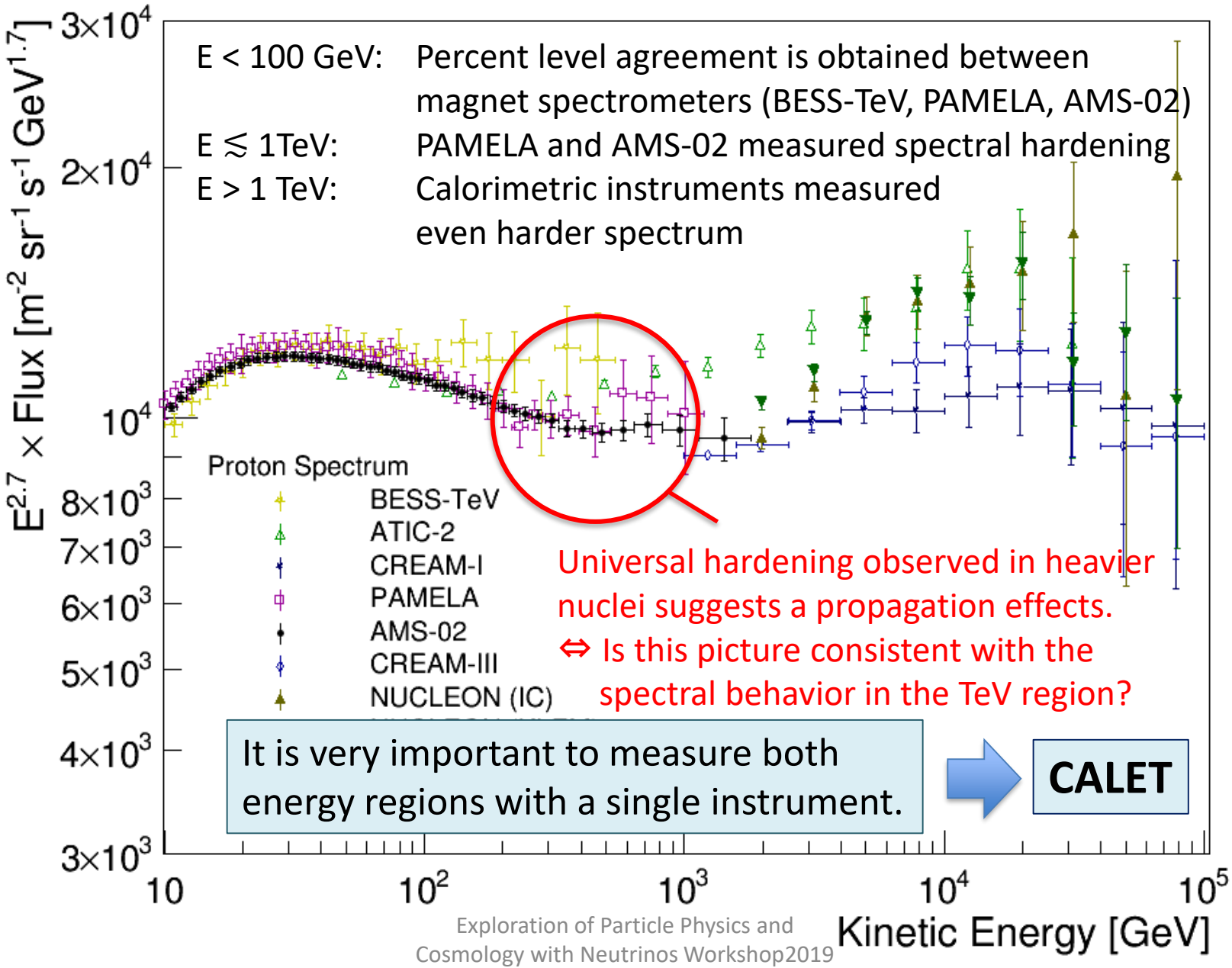
Status of Cosmic-Ray Proton Spectrum Measurements



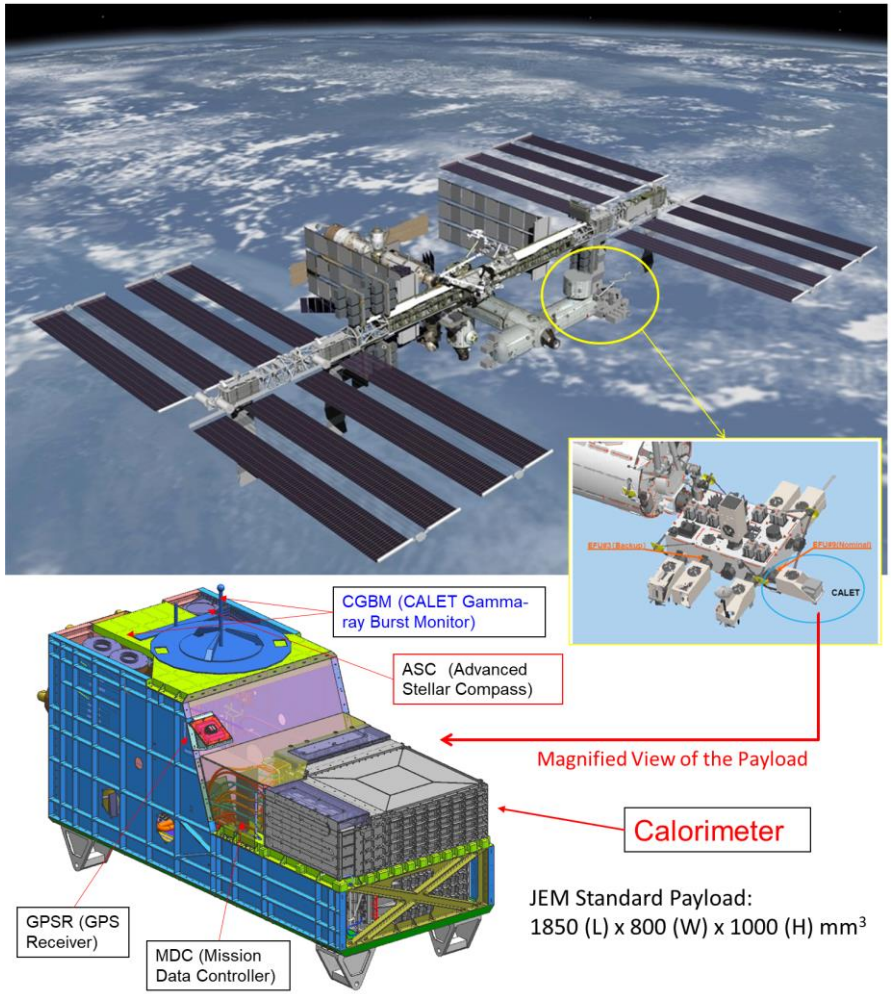
Status of Cosmic-Ray Proton Spectrum Measurements



Status of Cosmic-Ray Proton Spectrum Measurements



CALET: Cosmic Ray Detector onboard the ISS



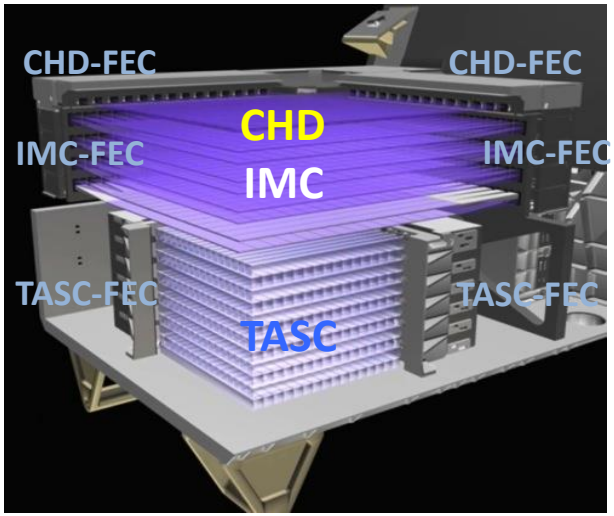
CALET is attached to the Japan Experiment Module (JEM) Exposed Facility port #9

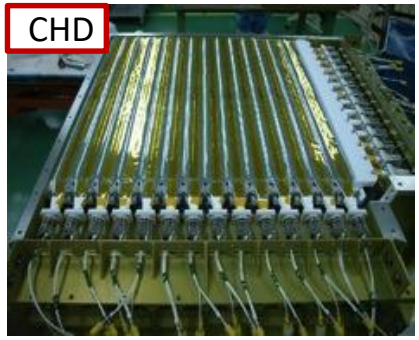
Overview of CALET Observations

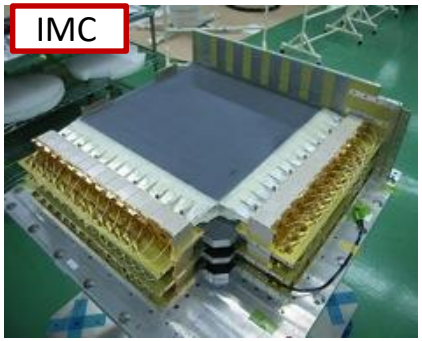
- Direct cosmic ray observations in space at the highest energy region by combining:
  - ✓ A large-size detector
  - ✓ Long-term observation onboard the ISS (5 years or more is expected)
- Electron observation in the 1 GeV - 20 TeV energy range, with high energy resolution owing to optimization for electron 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



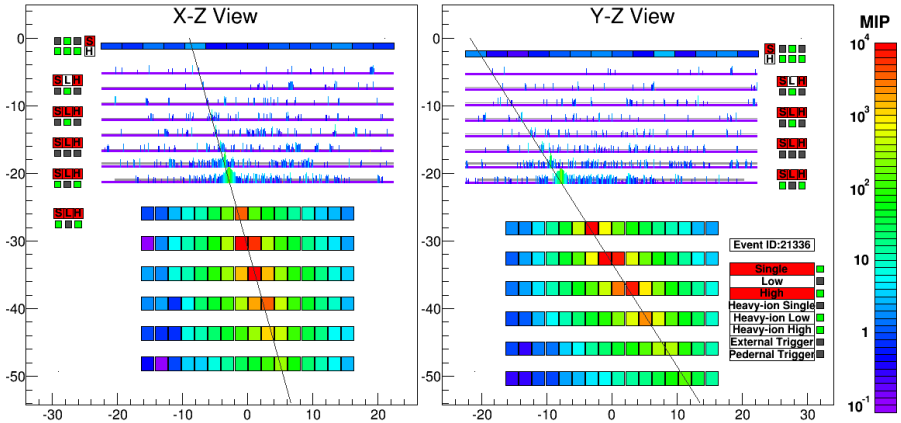




	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Measure	**Charge (Z=1-40)**	**Tracking , Particle ID**	**Energy, e/p Separation**
Geometry (Material)	**Plastic Scintillator 14 paddles x 2 layers (X,Y): 28 paddles Paddle Size: 32 x 10 x 450 mm^3**	**448 Scifi x 16 layers (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**

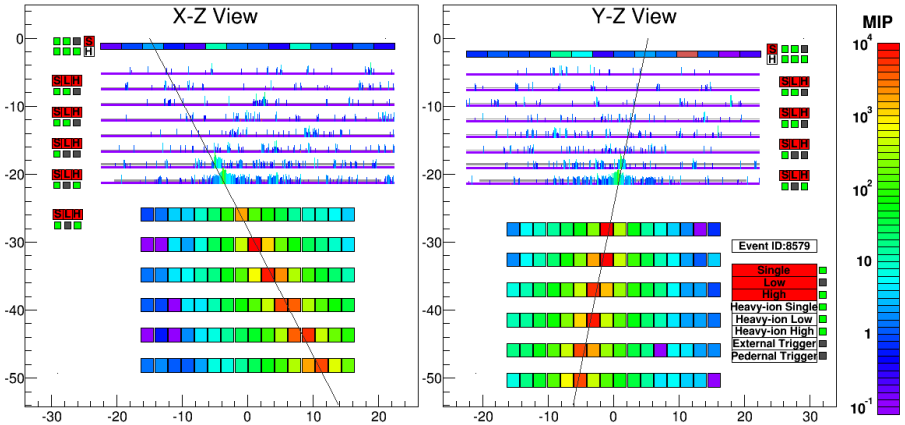
Event Examples of High-Energy Showers

Electron, E=3.05 TeV



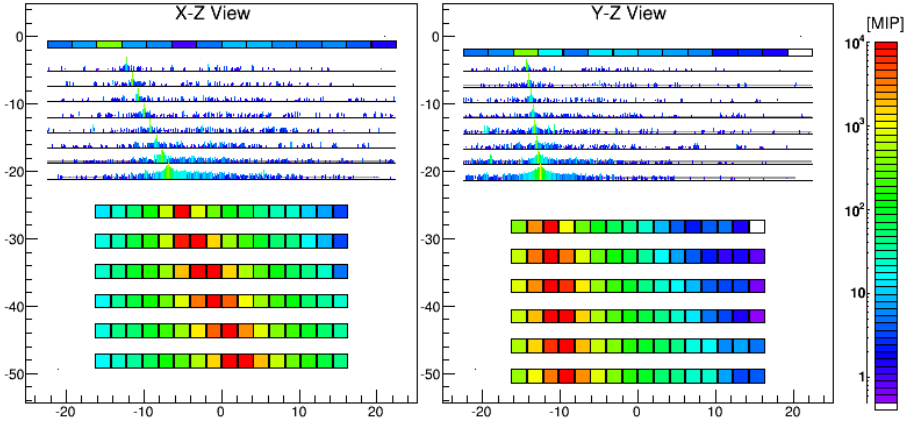
fully contained even at 3TeV

Proton, ΔE=2.89 TeV



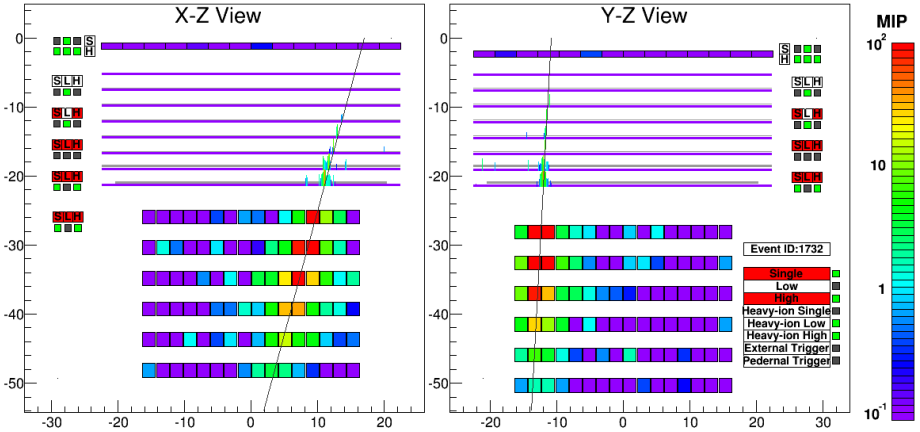
clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

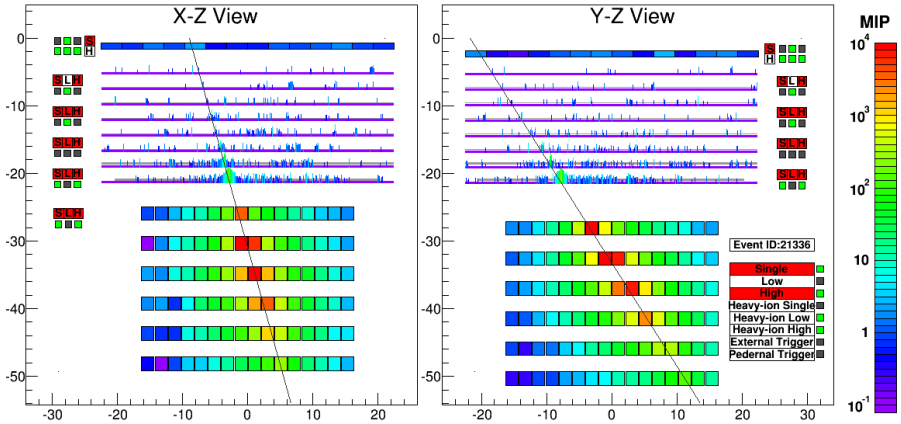
Gamma-ray, E=44.3 GeV



no energy deposit before pair production

Event Examples of High-Energy Showers

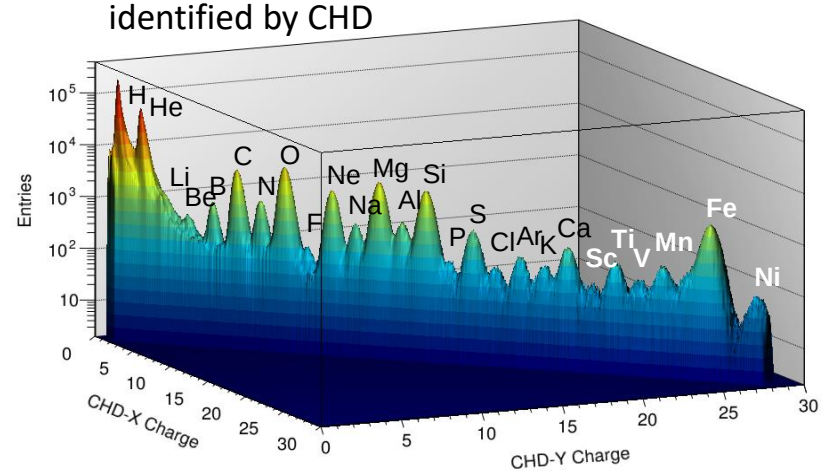
Electron, E=3.05 TeV



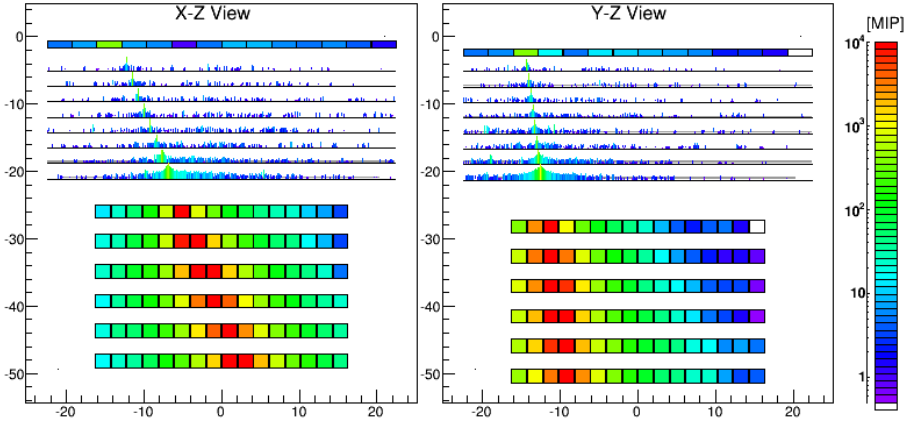
fully contained even at 3TeV

Proton, ΔE=2.89 TeV

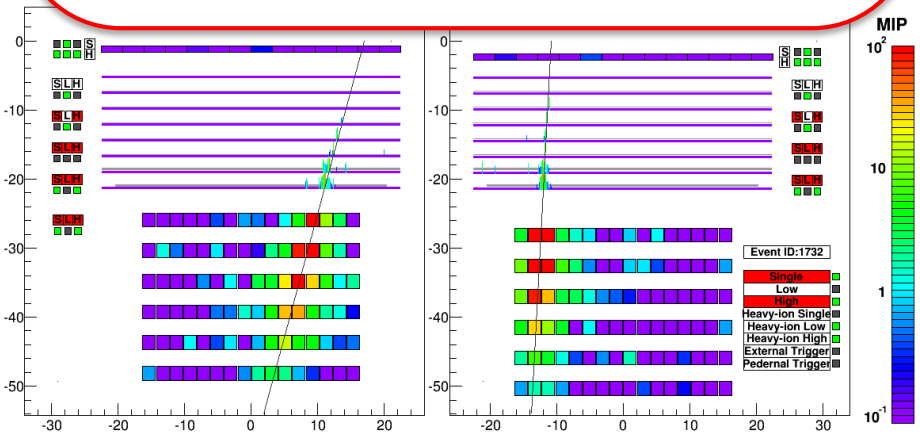
Individual elements up to Z=28 are clearly identified by CHD



Fe(Z=26), ΔE=9.3 TeV

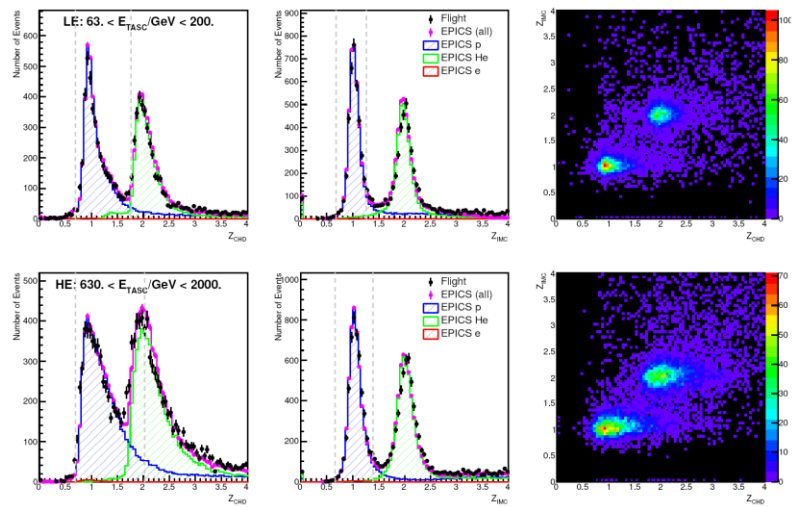


energy deposit in CHD consistent with Fe



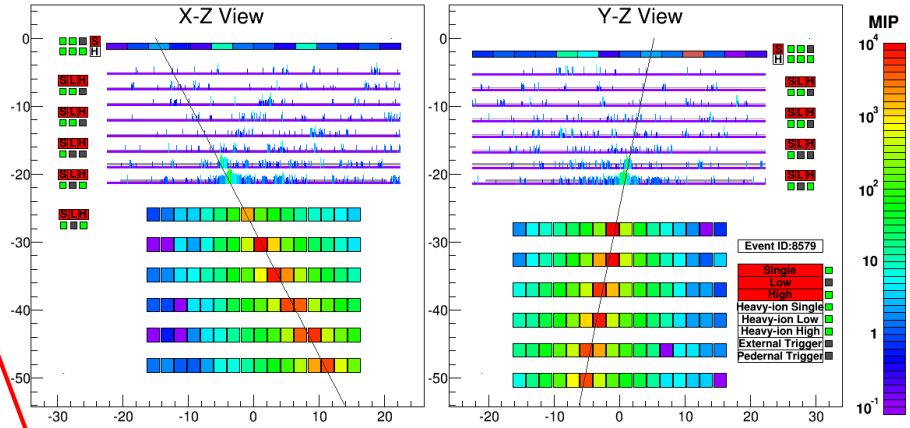
no energy deposit before pair production

Event Examples of High-Energy Showers



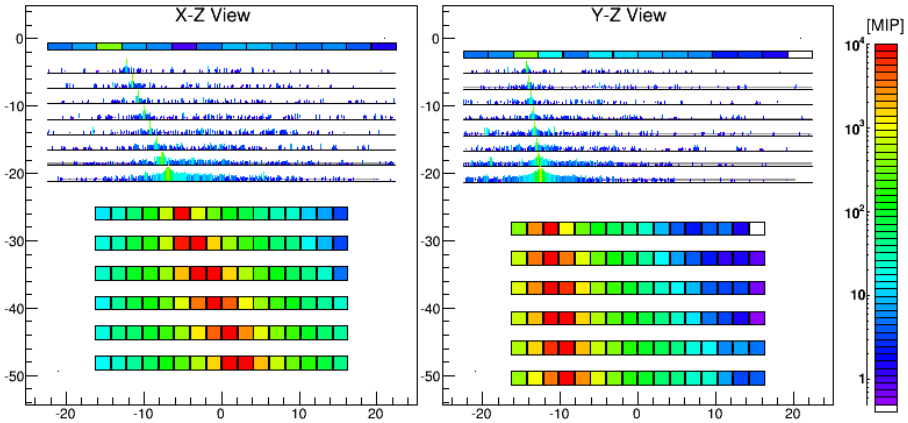
Proton/helium separation using CHD/IMC charge

Proton, ΔE=2.89 TeV



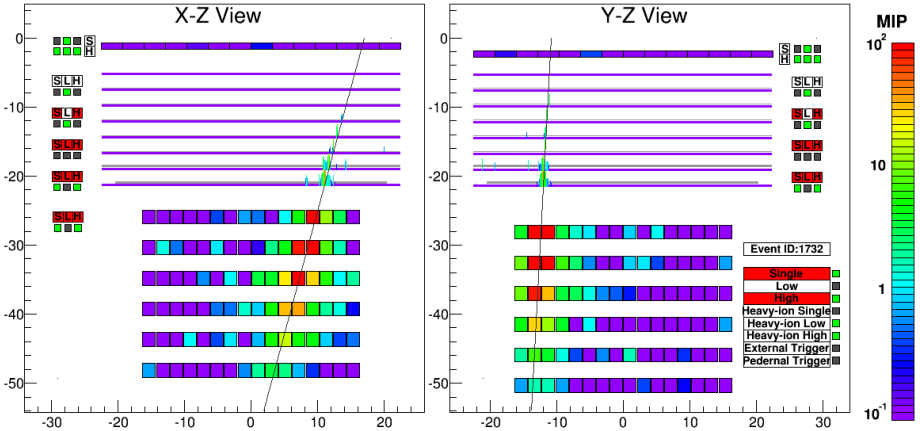
clear difference from electron shower

Fe(Z=26), ΔE=9.3 TeV



energy deposit in CHD consistent with Fe

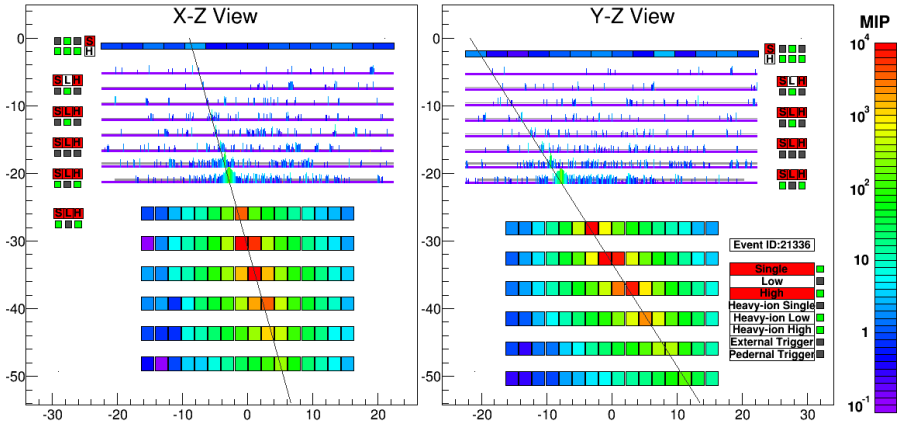
Gamma-ray, E=44.3 GeV



no energy deposit before pair production

Event Examples of High-Energy Showers

Electron, E=3.05 TeV



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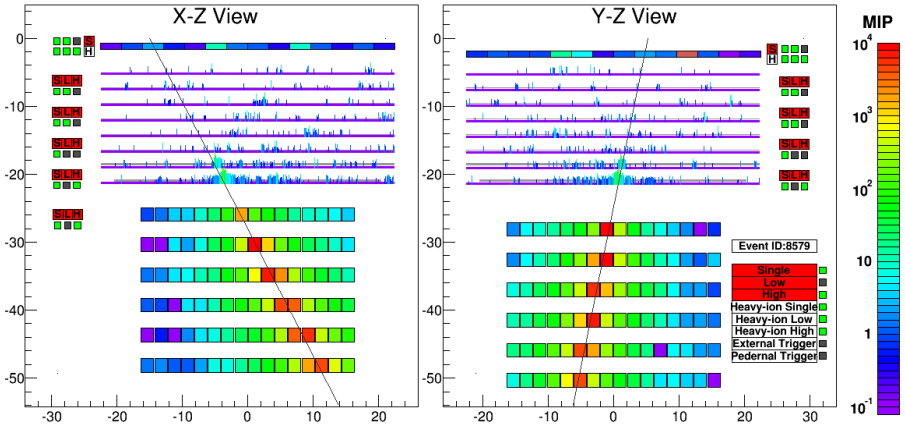
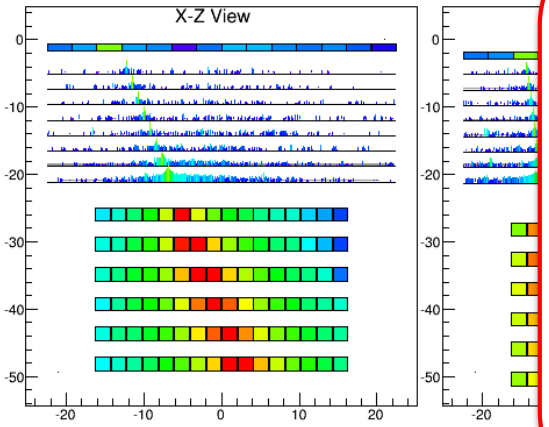
Proton, ΔE=2.89 TeV



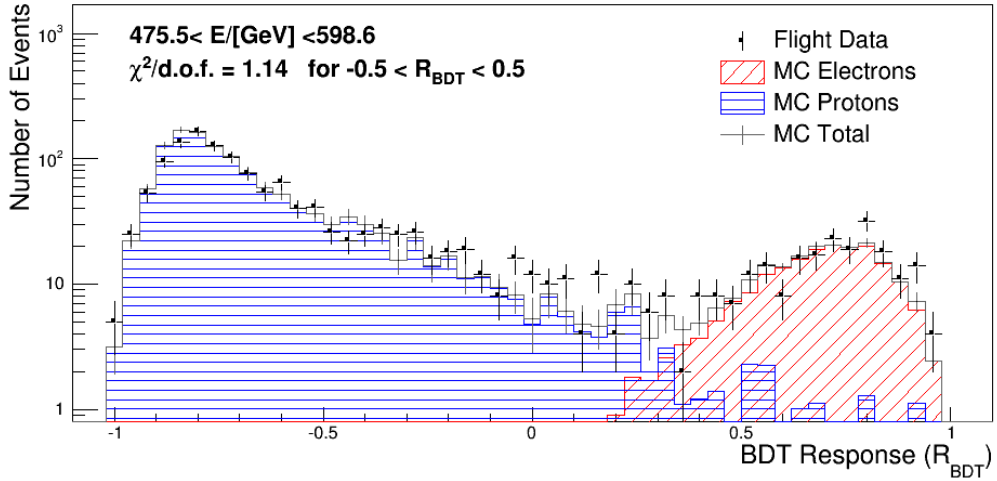
clear difference from electron shower

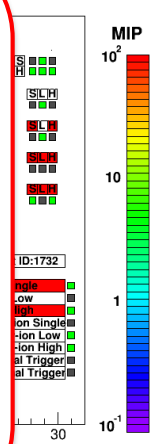
Fe(Z=26), ΔE=9.3



energy deposit in CHD cons

Clear e/p separation using multivariate analysis





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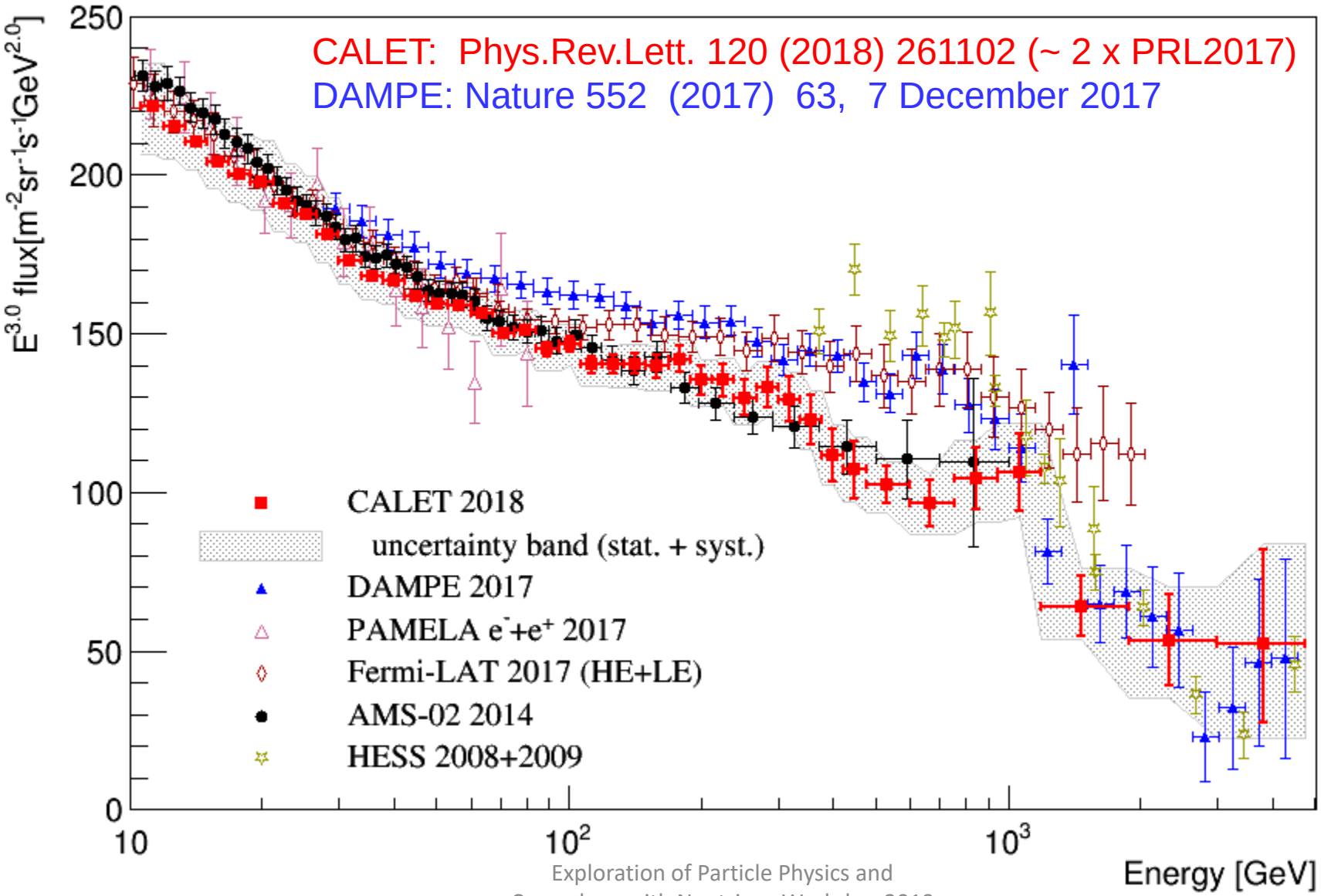
All Electron Spectrum: Extended Measurement by CALET

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



All Electron Spectrum: Extended Measurement by CALET

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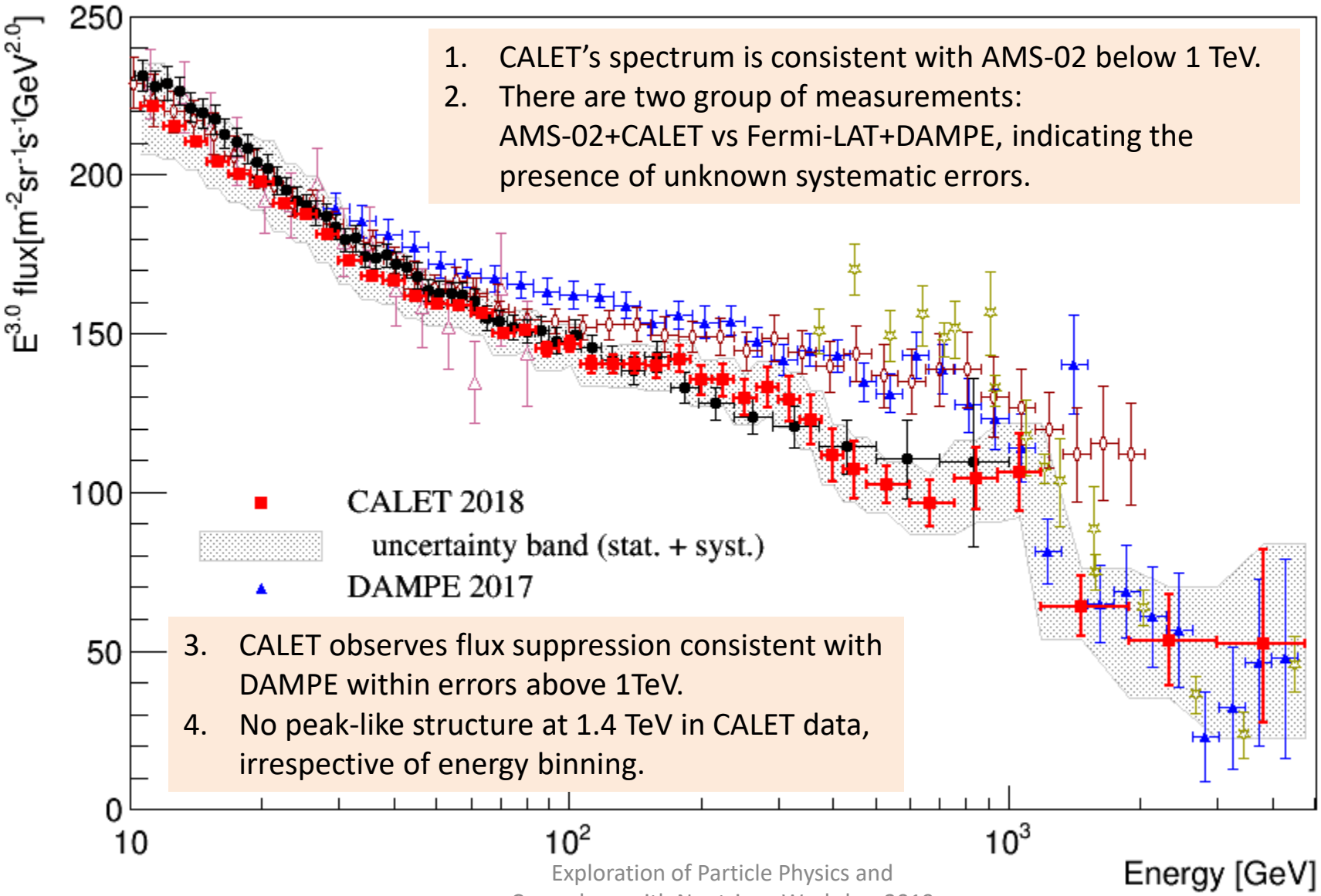


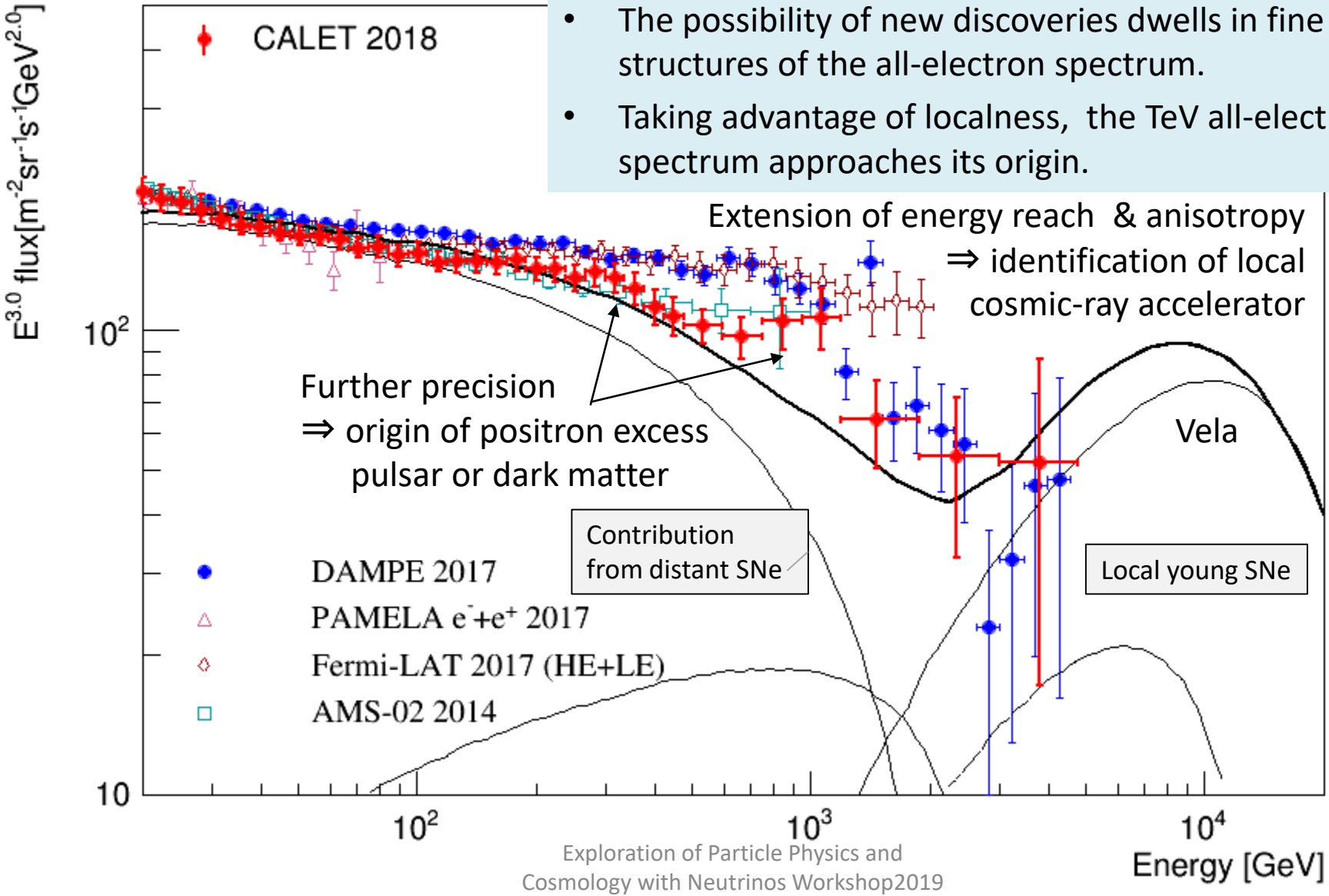
1. CALET's spectrum is consistent with AMS-02 below 1 TeV.
2. There are two group of measurements: AMS-02+CALET vs Fermi-LAT+DAMPE, indicating the presence of unknown systematic errors.

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.

Prospects for CALET All-Electron Spectrum

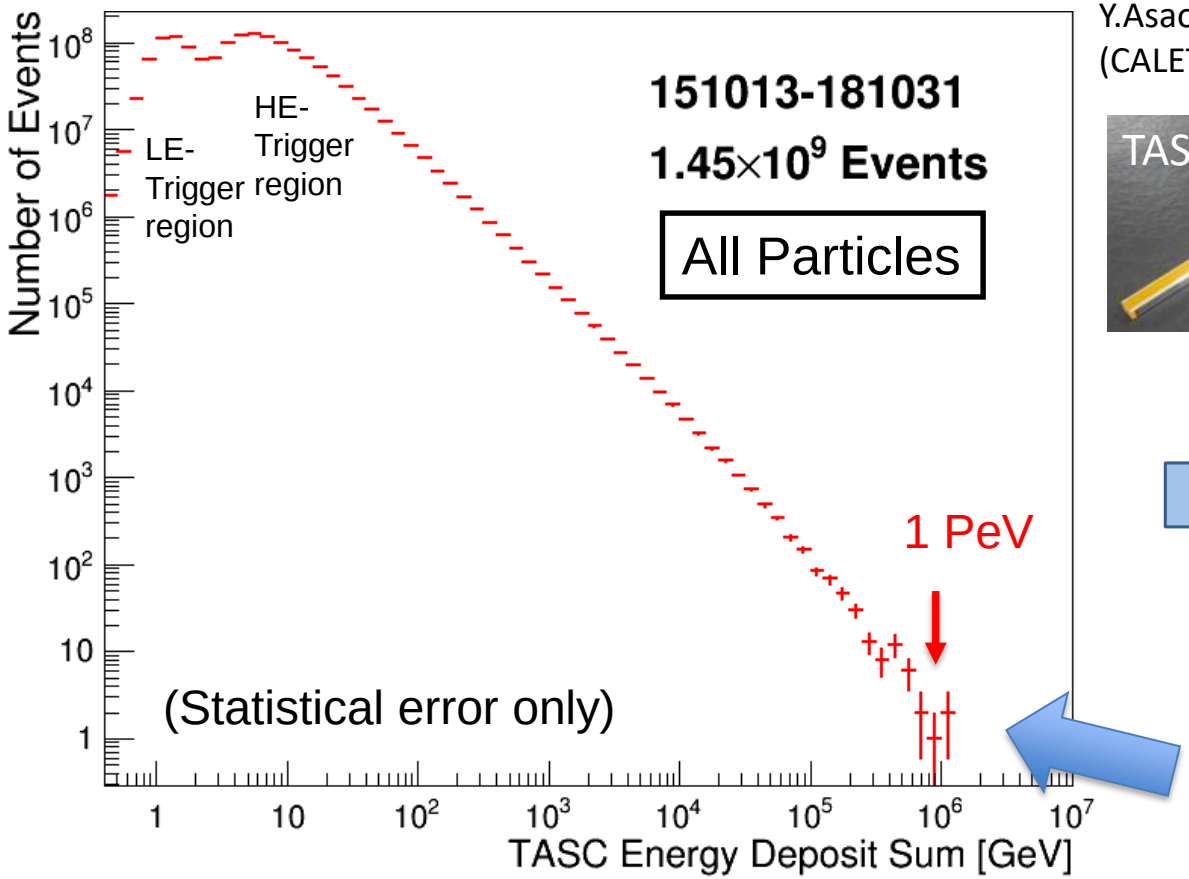
Five years or more observations ⇒ 3 times more statistics, reduction of systematic errors

- 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.

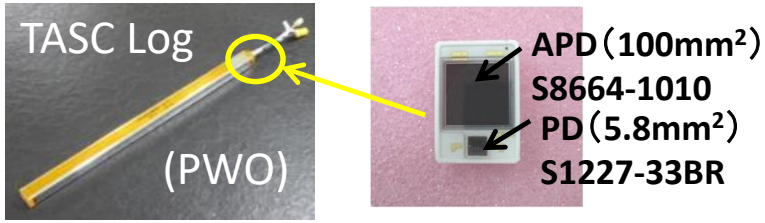


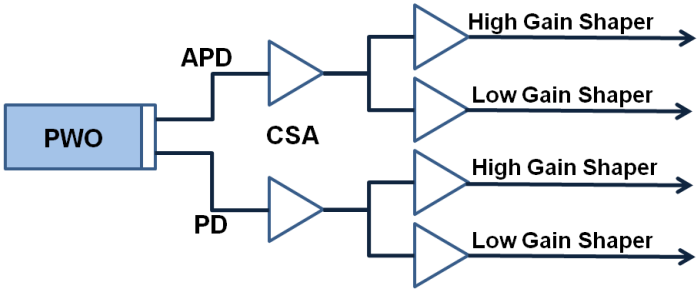
Wide Dynamic Range Energy Measurement

Distribution of TASC energy deposit sum

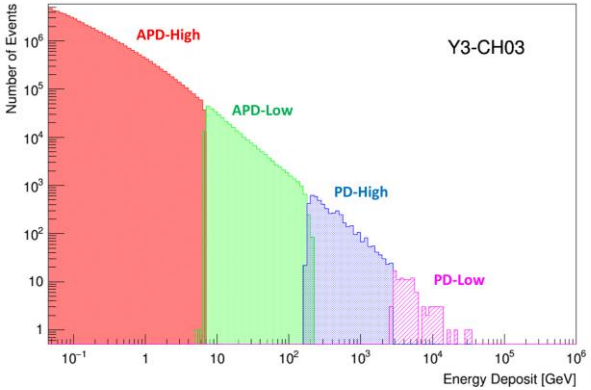


Y.Asaoka, Y.Akaike, Y.Komiya, R.Miyata, S.Torii et al. (CALET Collaboration), Astropart. Phys. 91 (2017) 1.



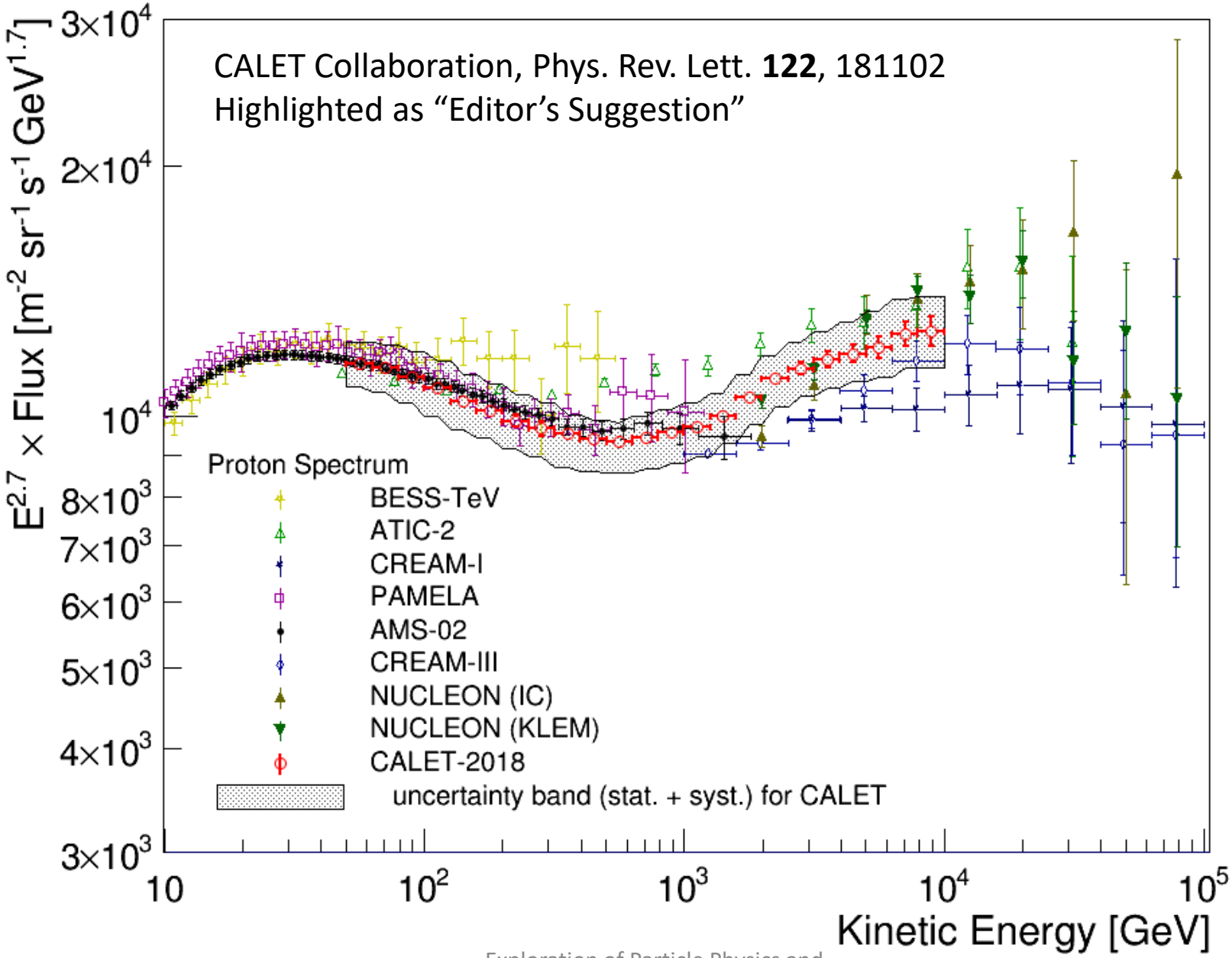


An example of gain connection in one PWO log:



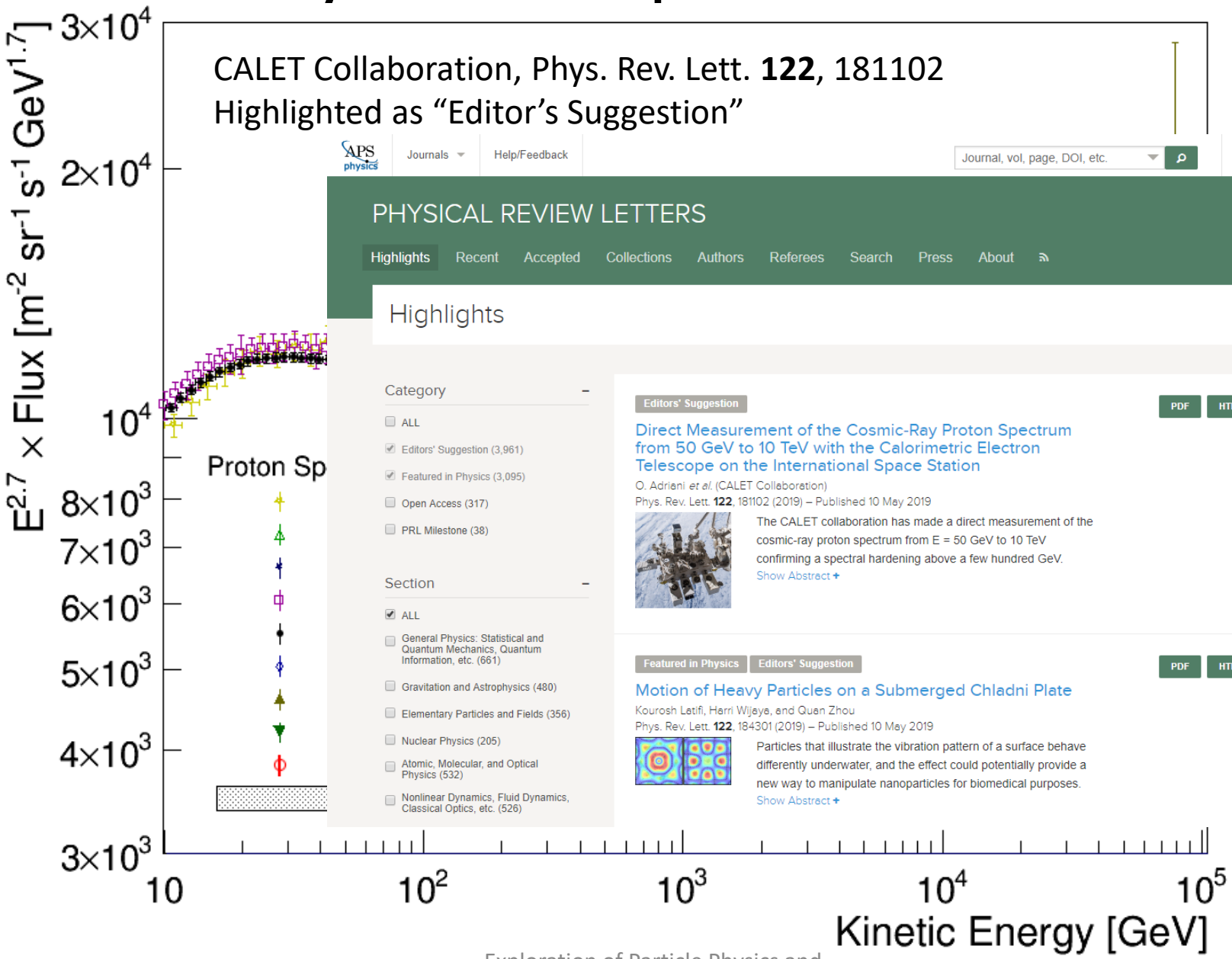
The smooth distribution clearly reflects the power-law nature of cosmic-rays, demonstrating the reliability of the energy measurement over a wide energy range.

Cosmic-Ray Proton Spectrum from CALET



Cosmic-Ray Proton Spectrum from CALET

CALET Collaboration, Phys. Rev. Lett. **122**, 181102
Highlighted as "Editor's Suggestion"



APS physics | Journals | Help/Feedback | Journal, vol, page, DOI, etc. | Yoichi Asaoka

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Highlights

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- Featured in Physics (3,095)
- Open Access (317)
- PRL Milestone (38)

Section
- ALL
- General Physics: Statistical and Quantum Mechanics, Quantum Information, etc. (661)
- Gravitation and Astrophysics (480)
- Elementary Particles and Fields (356)
- Nuclear Physics (205)
- Atomic, Molecular, and Optical Physics (532)
- Nonlinear Dynamics, Fluid Dynamics, Classical Optics, etc. (526)

Editors' Suggestion — PDF | HTML

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.* (CALET Collaboration)
Phys. Rev. Lett. **122**, 181102 (2019) – Published 10 May 2019

The CALET collaboration has made a direct measurement of the cosmic-ray proton spectrum from E = 50 GeV to 10 TeV confirming a spectral hardening above a few hundred GeV.
Show Abstract +

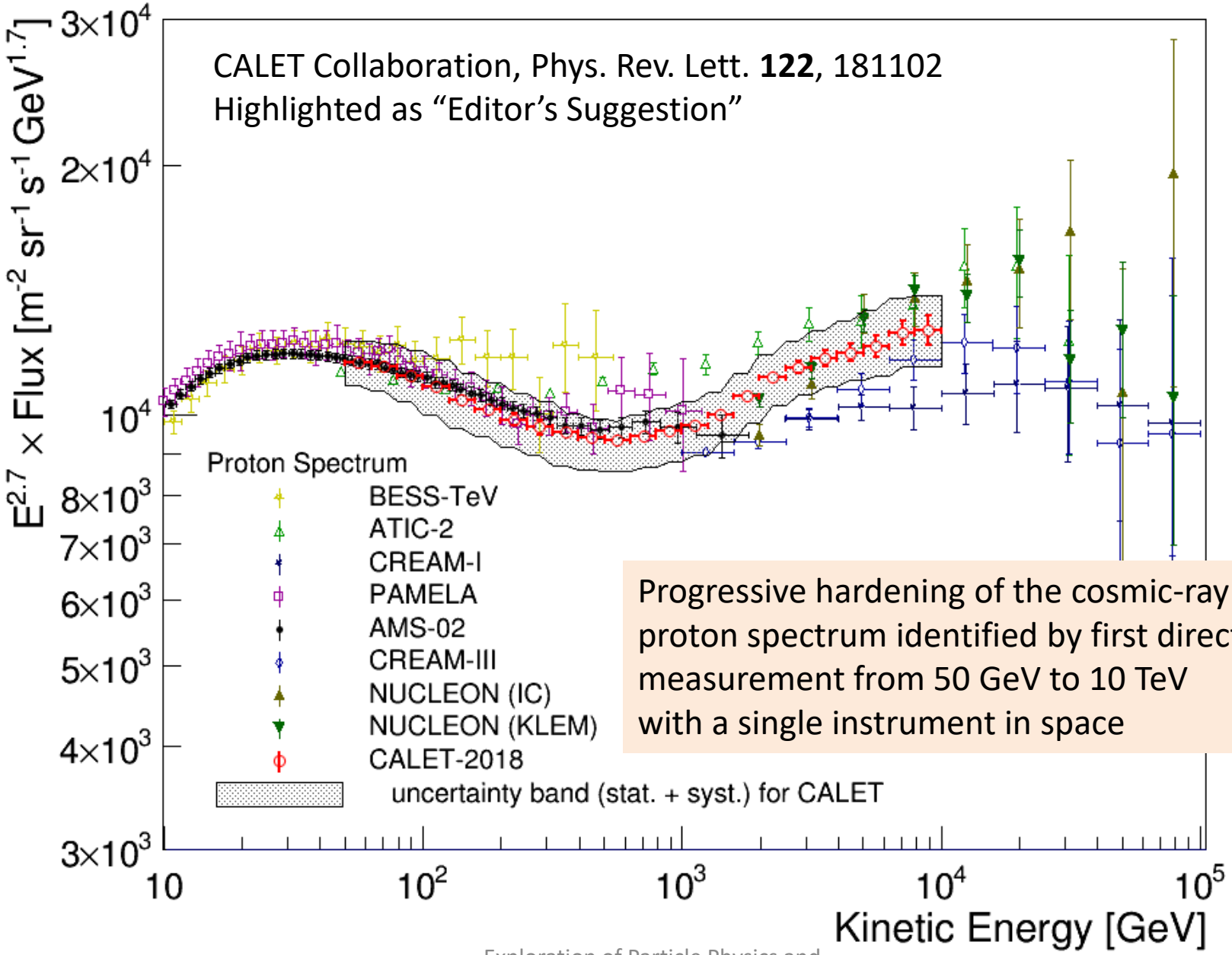
Featured in Physics | Editors' Suggestion — PDF | HTML

Motion of Heavy Particles on a Submerged Chladni Plate

Kourosh Latifi, Harri Wijaya, and Quan Zhou
Phys. Rev. Lett. **122**, 184301 (2019) – Published 10 May 2019

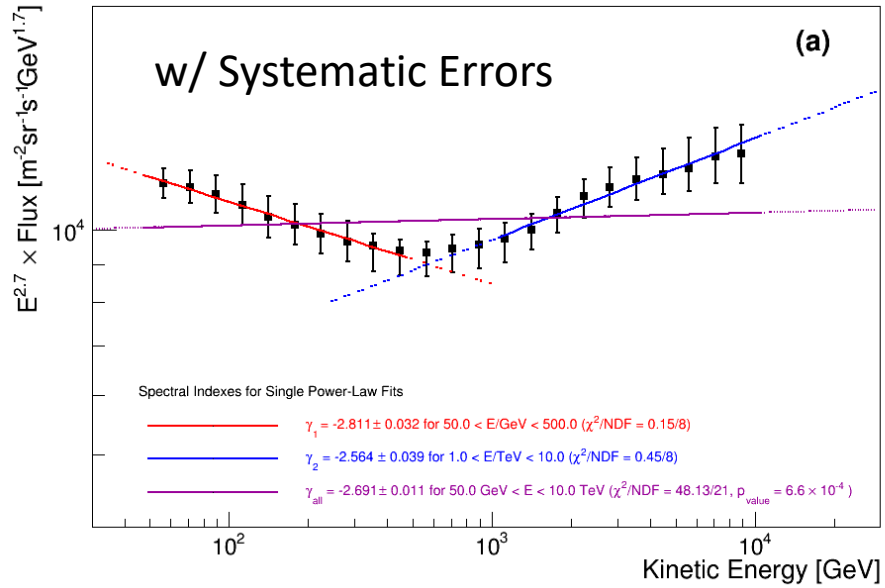
Particles that illustrate the vibration pattern of a surface behave differently underwater, and the effect could potentially provide a new way to manipulate nanoparticles for biomedical purposes.
Show Abstract +

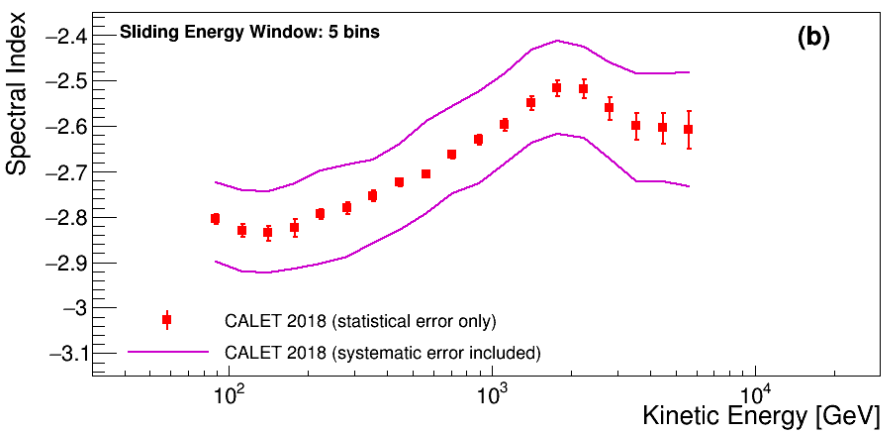
Cosmic-Ray Proton Spectrum from CALET

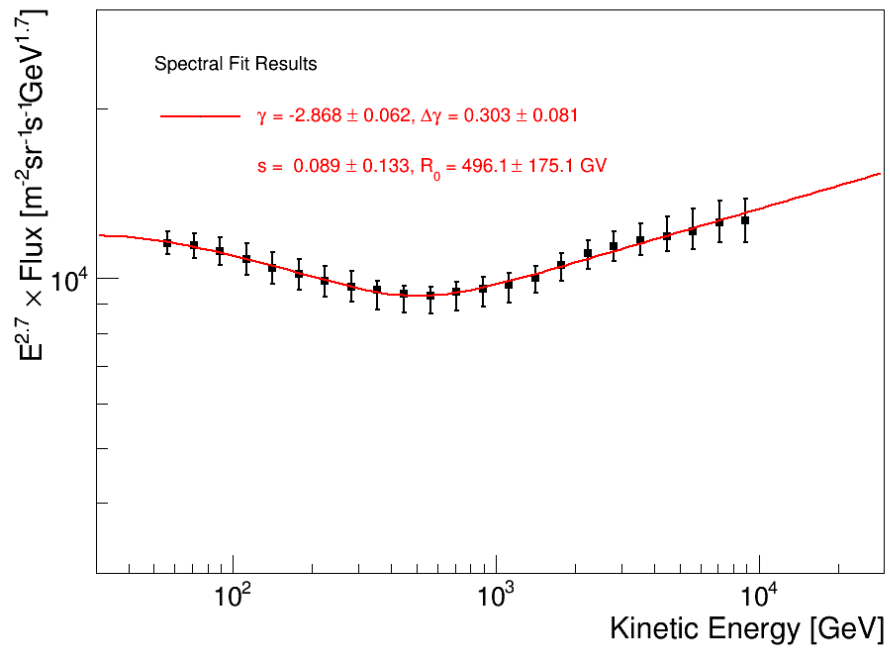


Progressive hardening of the cosmic-ray proton spectrum identified by first direct measurement from 50 GeV to 10 TeV with a single instrument in space

Spectral Behavior of Proton Flux







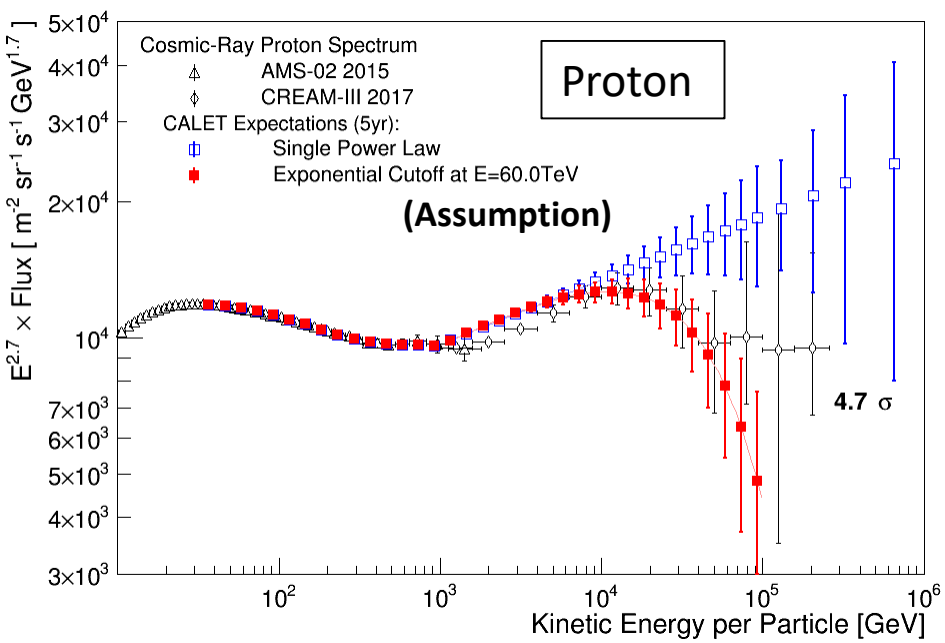
1. Subranges of 50—500GeV, 1-10TeV can be fitted with single power law function, but not the whole range (significance > 3σ).
2. Progressive hardening up to the TeV region was observed.
3. “smoothly broken power-law fit” gives power law index consistent with AMS-02 in the low energy region, but shows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

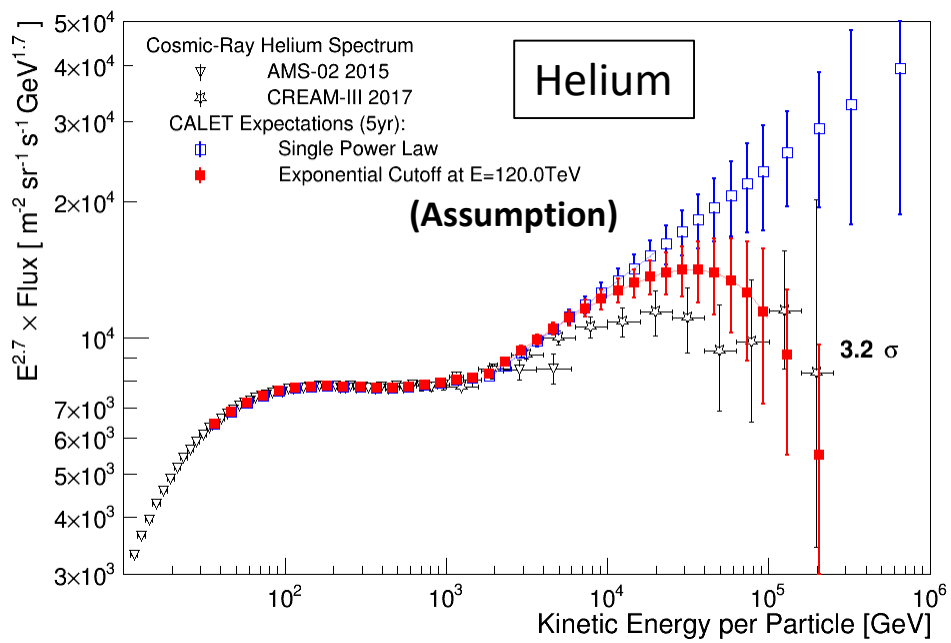
Summary and Prospects

- CALET's proton spectrum covers for the first time in space the whole energy interval previously investigated in separate sub-ranges by magnet spectrometers and calorimeters, making it possible to discuss the spectral behavior in detail.
  - Includes the assessment of systematic uncertainties.
  - Measured smoothness and extent of the spectral index change should have a strong impact on the interpretation of the spectral hardening.
- The future main target is to verify the charge-dependent acceleration limit of supernovae by precisely measuring the spectra of protons and helium up to the 100 TeV region.

$$E_{\max} = 6\times10^{13}\,\mathrm{eV}\,Z\left(\frac{B}{10^{-6}\,\mathrm{G}}\right)\left(\frac{u_1}{10^4\,\mathrm{km/s}}\right)^2\left(\frac{t_{\mathrm{free}}}{200\,\mathrm{year}}\right)$$

Phys. Soc. Japan vol67.12 p834 (Ohira, Yamazaki, Terasawa) in Japanese





Summary and Prospects

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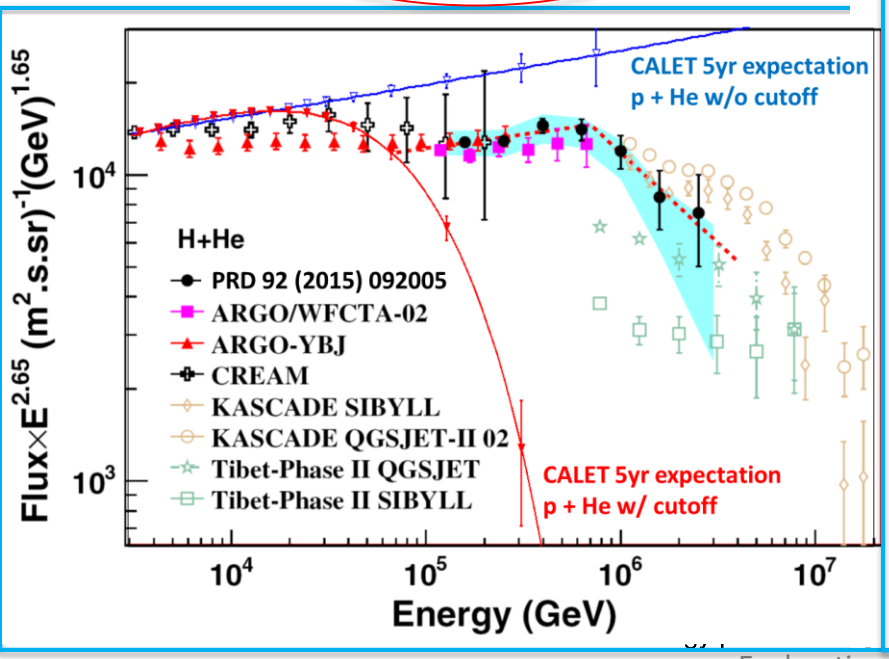
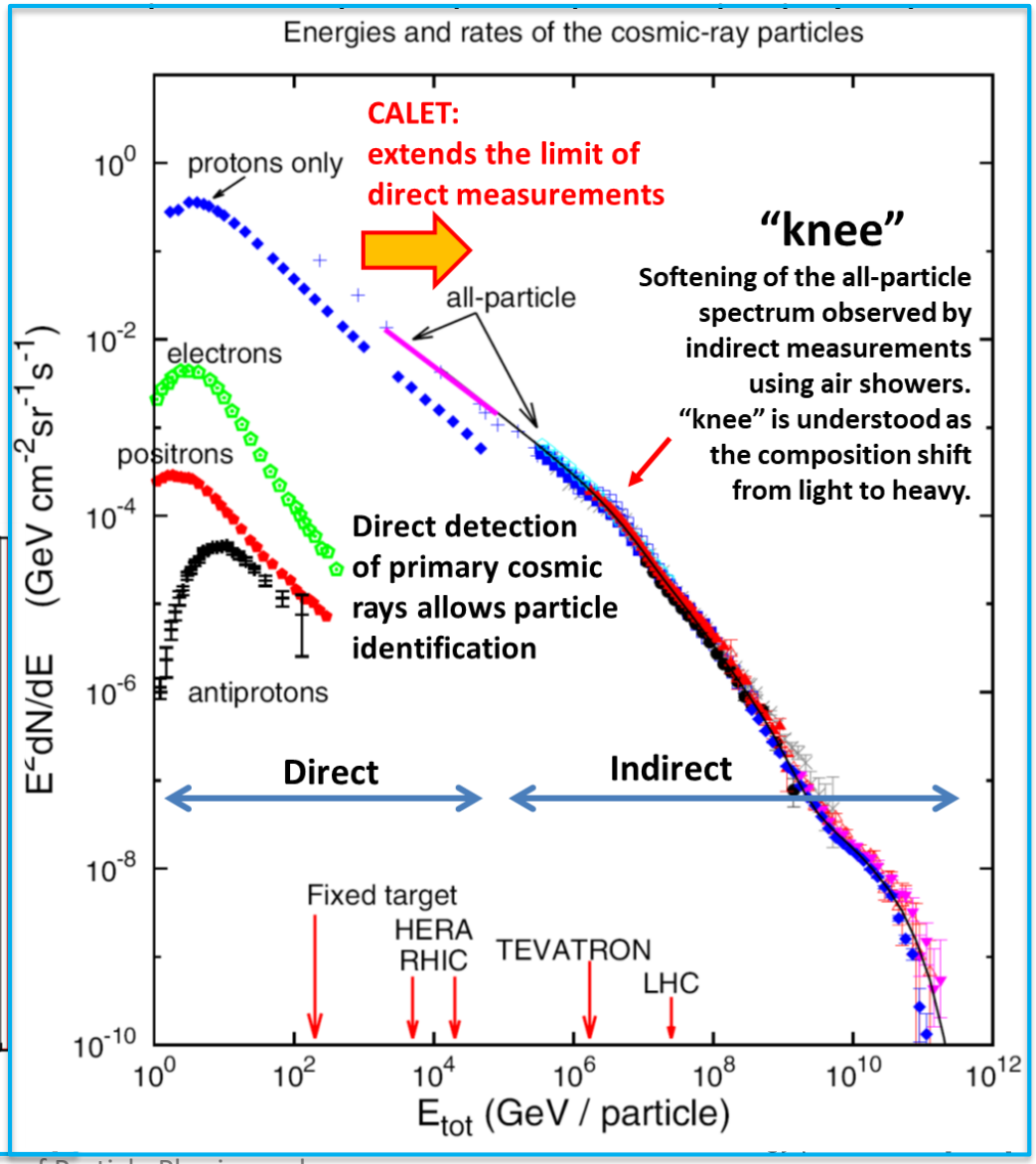
  –
  –
- The futur arget is to verify the by precisely m asuring the spectra of

The maximum energy extracted from typical supernova parameters are much smaller than the "knee" energy (3 PeV)

$$E_{max} = 6\times10^{13}\ \text{eV}\ Z\left(\frac{B}{10^{-6}\ \text{G}}\right)\left(\frac{}{10^{}}\right.$$





CALET Collaboration Team

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CALET Publication List

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)