ISS搭載CALETによる
5年間の観測の最新成果報告

CALET

Calorimetric
Electron
Telescope
on the International Space Station

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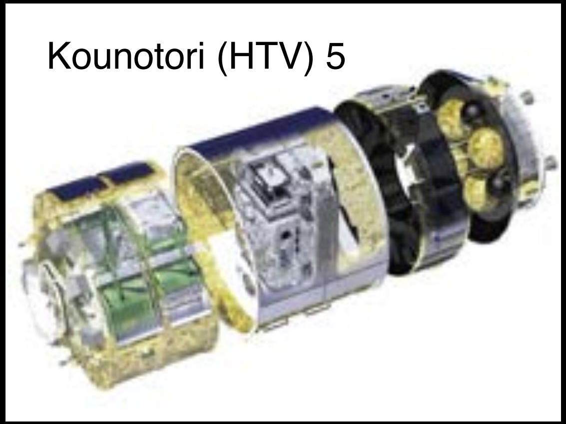
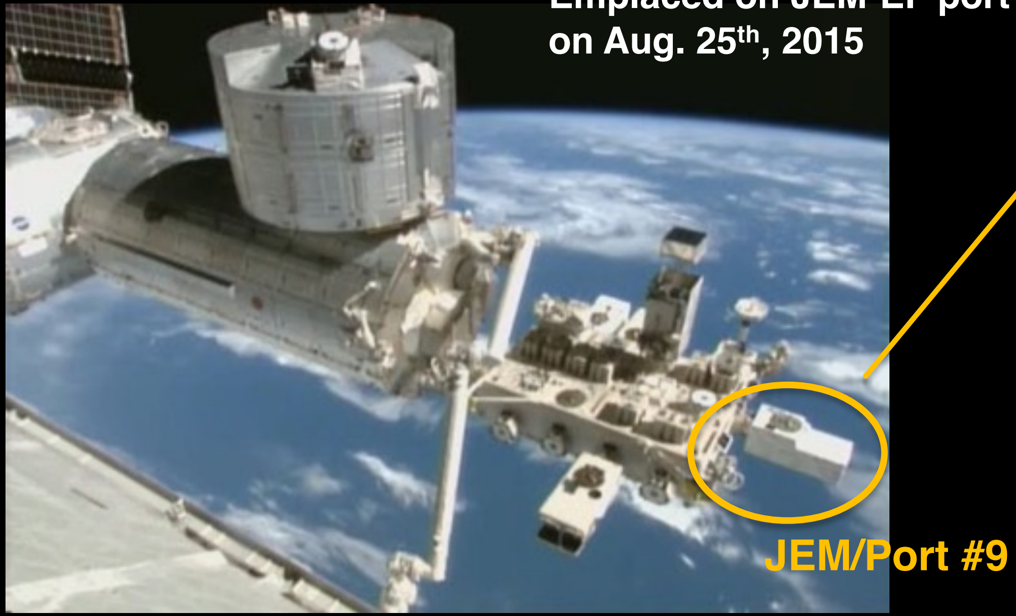
PI : Japan
Co-PI : Italy
Co-PI : USA

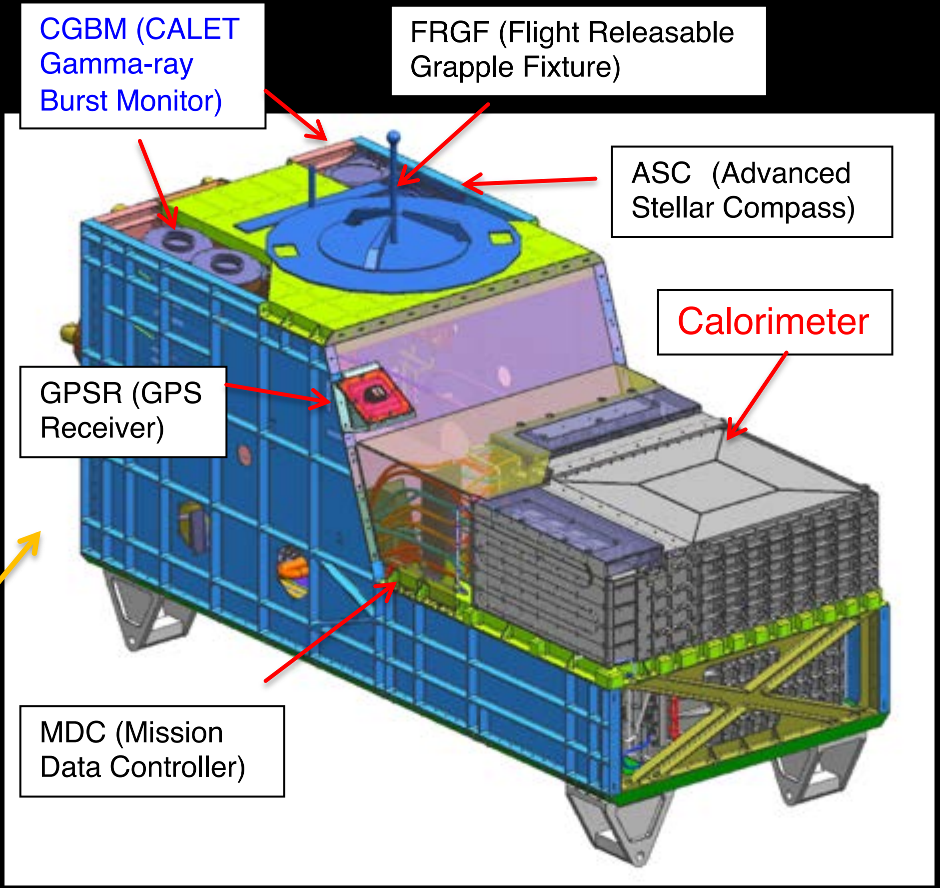
CALET Payload



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

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

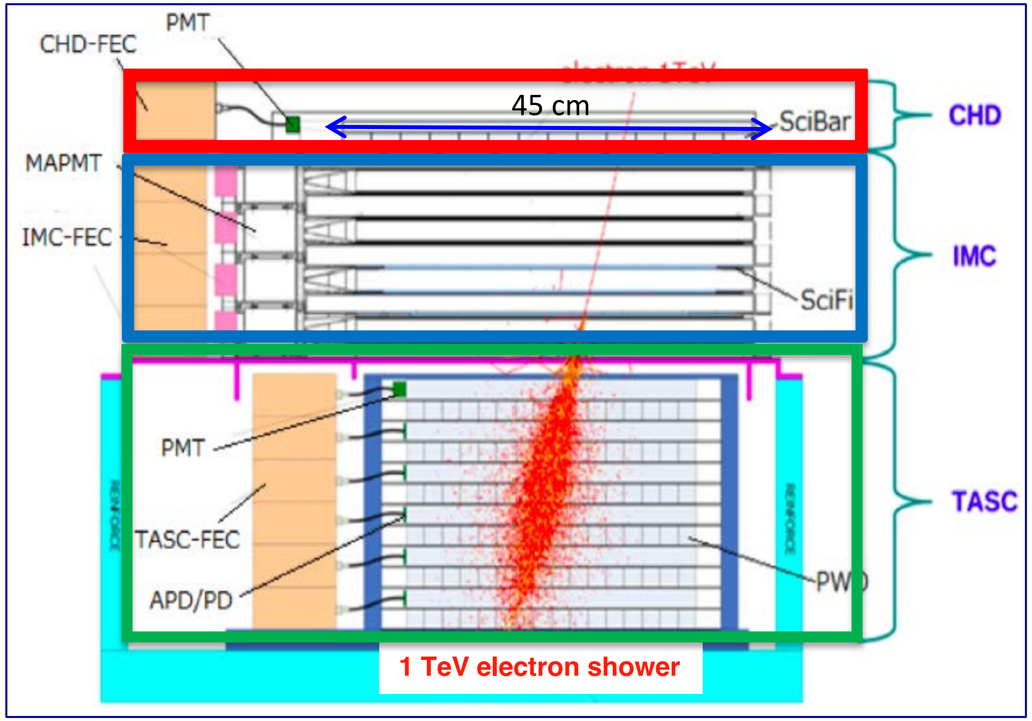




- **Mass: 612.8 kg**
- **JEM Standard Payload Size:**
  1850mm(L) × 800mm(W) × 1000mm(H)
- **Power Consumption: 507 W（max）**
- **Telemetry:**
  Medium 600 kbps (6.5GB/day) / Low 50 kbps

CALET Instrument

Field of view: ~ 45 degrees (from the zenith) Geometrical Factor: ~ 1,040 cm^2sr (for electrons) Thickness: 30 X_0 , 1.2 λ_I

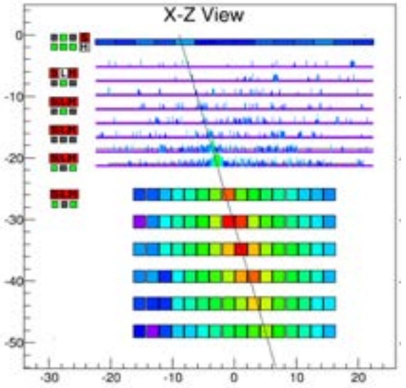


CHD – Charge Detector
- 2 layers x 14 plastic scintillating paddles
- single element charge ID from p to Fe and above (Z = 40)
- charge resolution ~0.1-0.3 e

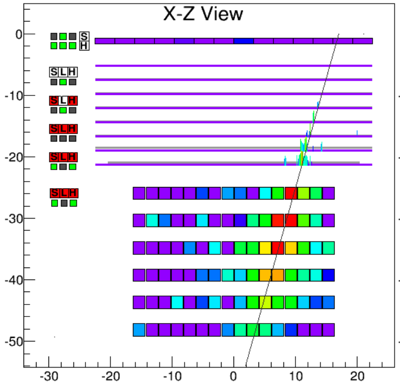
IMC – Imaging Calorimeter
- Scifi + Tungsten absorbers: 3 X_0 at normal incidence
- 8 x 2 x 448 plastic scintillating fibers (1mm) **readout individually**
- **Tracking** (~0.1° angular resolution) + **Shower imaging**

TASC – Total Absorption Calorimeter 27 X_0, 1.2 λ_I
- 6 x 2 x 16 lead tungstate ($PbWO_4$) logs
- **Energy resolution:** ~2 % (>10GeV) for e , γ ~30-35% for p, nuclei
- **e/p separation:** $\sim 10^{-5}$

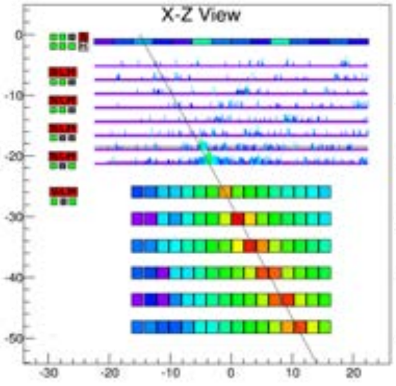
Electron, E=3.05 TeV



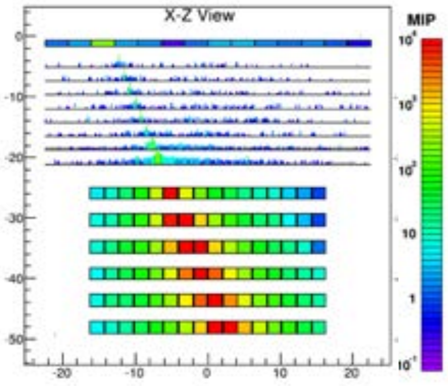
Gamma-ray, E=44.3 GeV



Proton, E_{TASC}=2.89 TeV



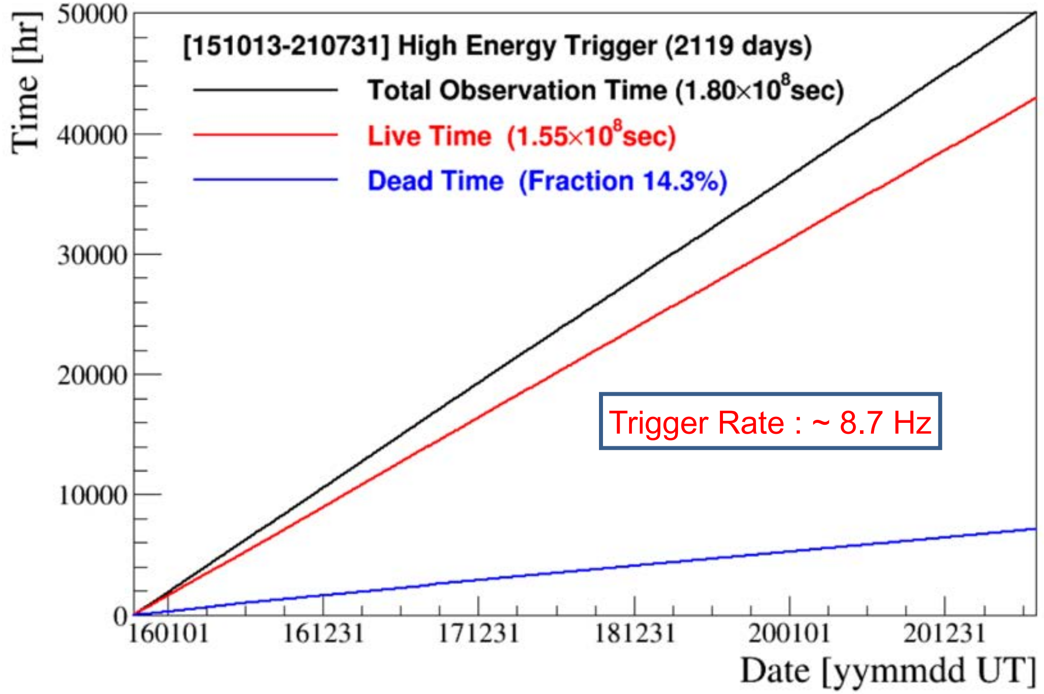
Iron, E_{TASC} =9.3 TeV



Event Display: Electron Candidate (>100 GeV)

CALET Observations on the ISS

Accumulated observation time (live, dead)



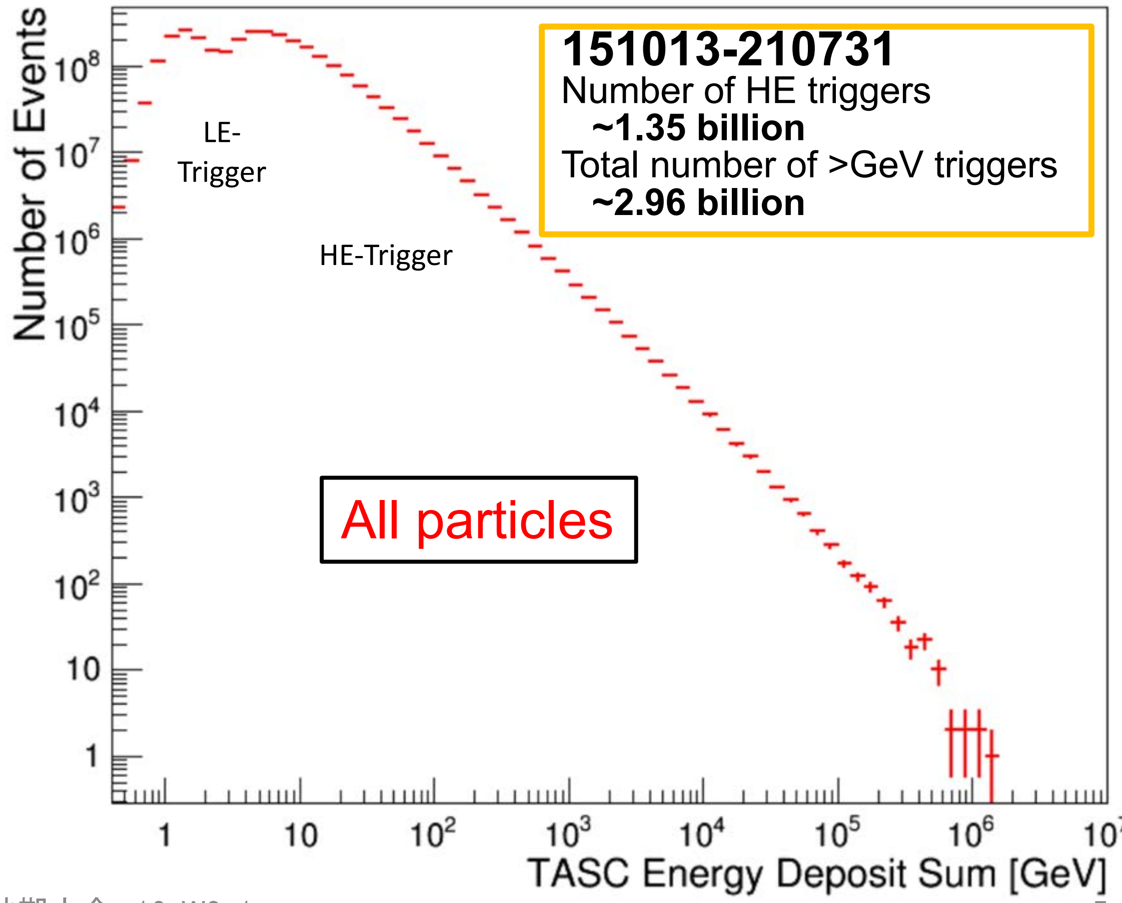
High-energy trigger (> 10 GeV) statistics:

- Operational time > **2119 days**(*)
  (*) as of July 31, 2021
- Live time fraction **> 85%**
- Exposure of HE trigger
  ~186 m^2 sr day
- HE-gamma point source exposure
  ~3.6 m^2 day (for Crab, Geminga)

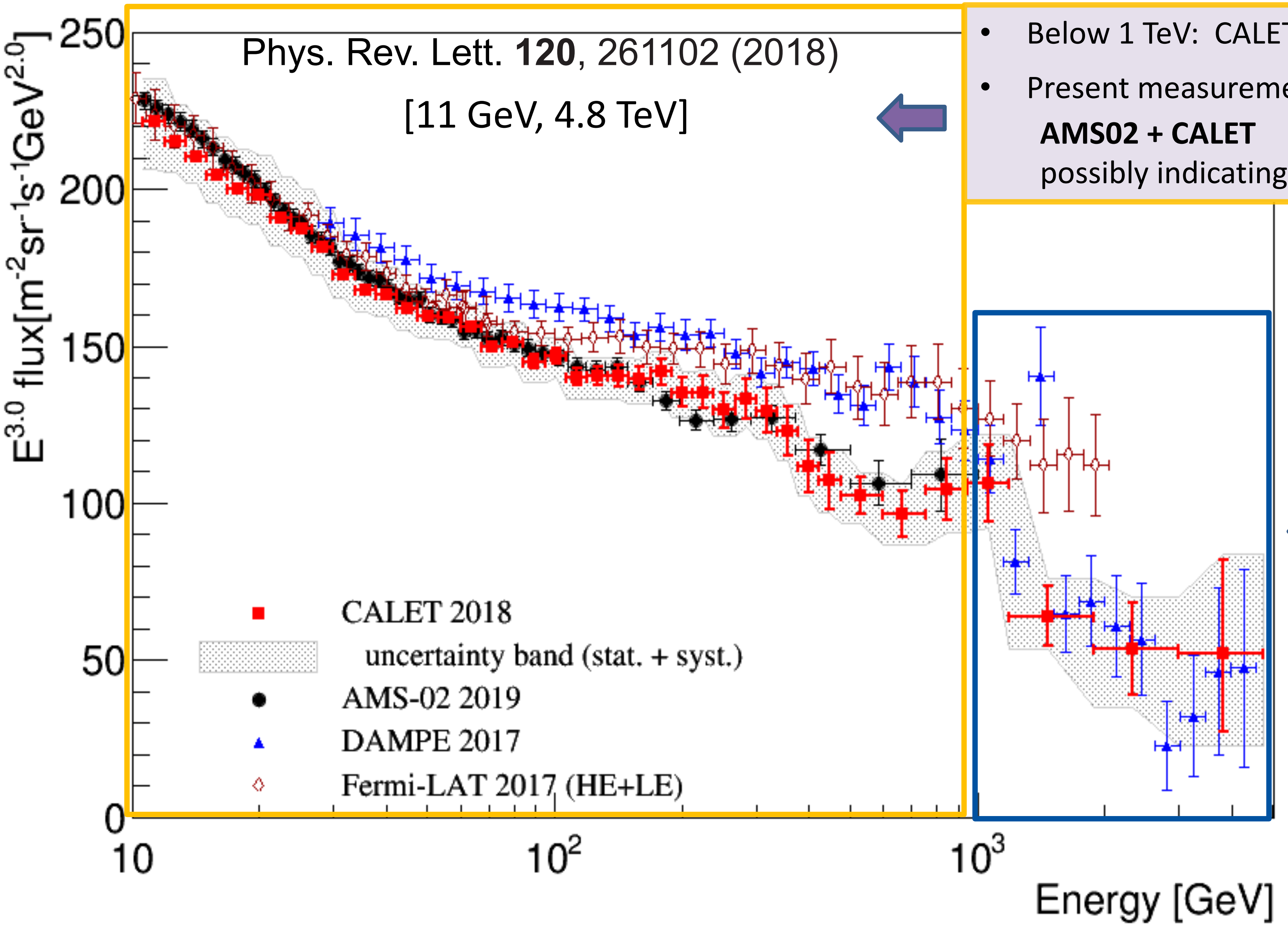
Geometrical Factor:

- 1040 cm^2 sr for electrons, light nuclei
- 1000 cm^2 sr for gamma-rays
- 4000 cm^2sr for ultra-heavy nuclei

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



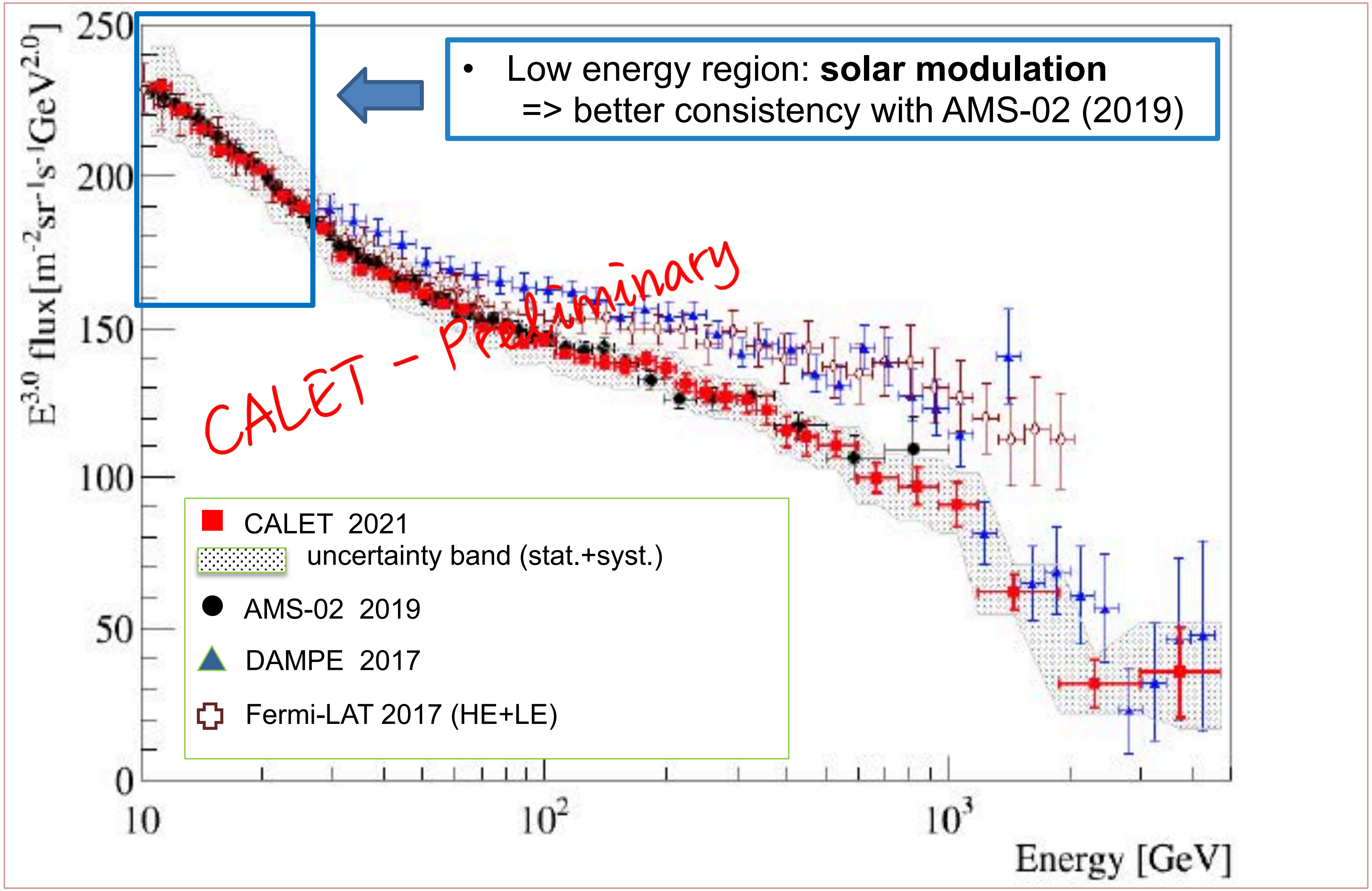
Cosmic-ray All-electron Spectrum



- Below 1 TeV: CALET spectrum is consistent with AMS-02
- Present measurements cluster into 2 groups:
  AMS02 + CALET and **FERMI + DAMPE**
  possibly indicating the presence of unkown systematics

- Above 1 TeV CALET observes a suppression of the flux consistent with DAMPE within errors
- No peak-like structure at 1.4 TeV in CALET measurement irrespective of binning

Cosmic-ray All-electron Spectrum (update: as of Sep.30, 2020)



- Low energy region: **solar modulation**
  => better consistency with AMS-02 (2019)

Preliminary spectrum is **updated** after 1815 days of CALET observations: Oct.13, 2015 - Sep.30, 2020

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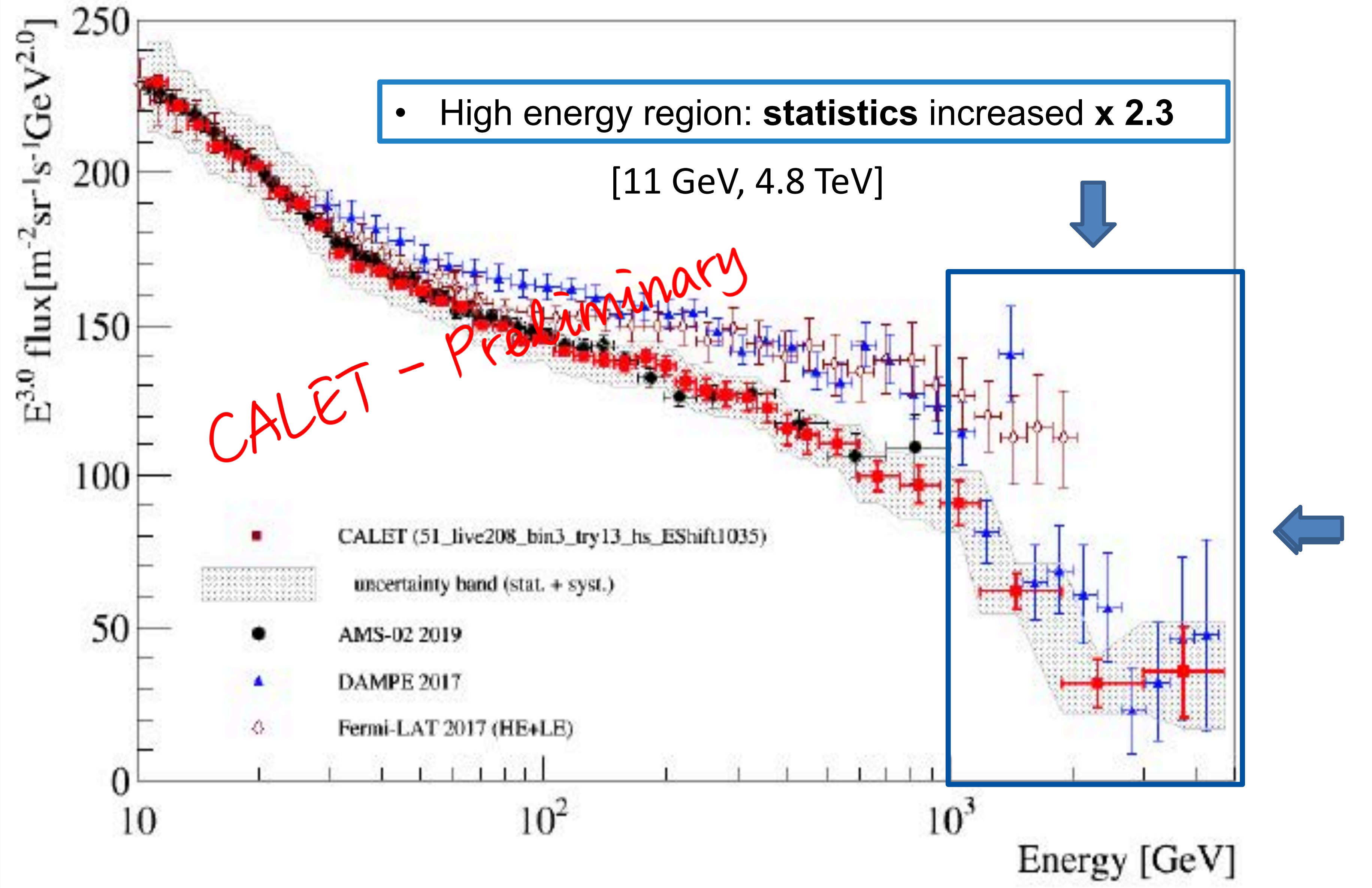
Cosmic-ray All-electron Spectrum (update: as of Sep.30, 2020)



- High energy region: **statistics** increased **x 2.3**

[11 GeV, 4.8 TeV]

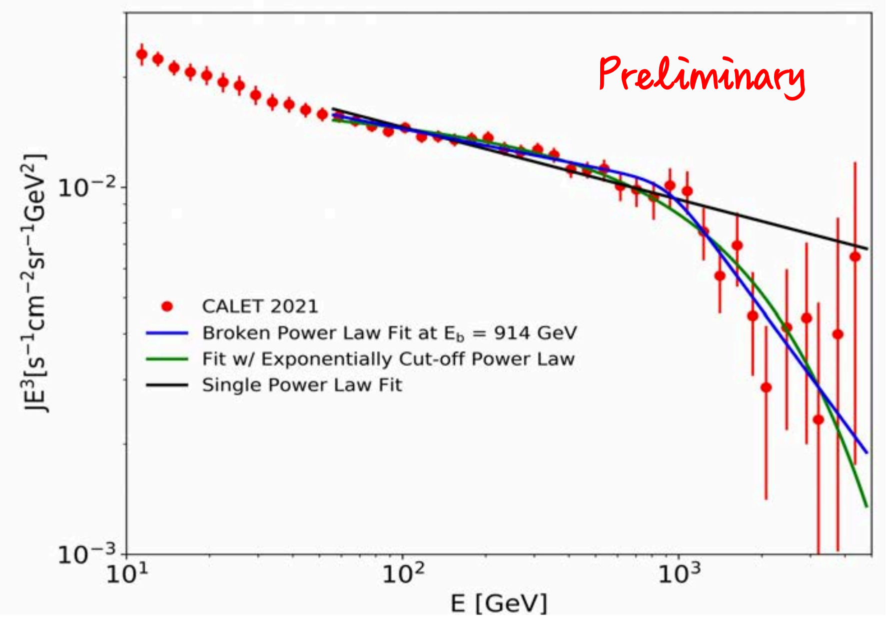
CALET observes a flux suppression above 1 TeV with a **significance > 6.5 σ**, a considerable improvement with respect to the result published in PRL2018 (~4 σ)

Towards an Interpretation of the CALET All-electron Spectrum

16aW2-4: Motz

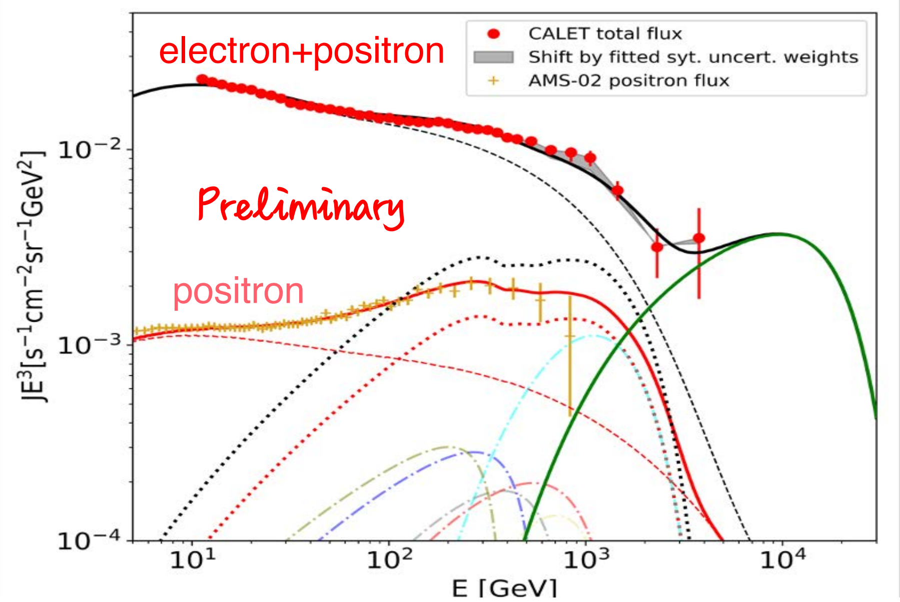
- Fits of the CALET all-electron spectrum in 55 GeV - 4.8 TeV, using the same energy binning as DAMPE [Nature, 2017]
  - Broken power law used in DAMPE
    γ= - 3.151 ⇨ - 4.024 (χ^2 /NDF=11.64/29)
  - Exponential cut-off power law [PRL, 2018]
    γ= - 3.054 with E_c= 2.17 TeV (χ^2 /NDF=11.25/29)
  - Single power law
    γ=-3.197 (χ^2 /NDF=54.50/30)

The significance of both fits of softening spectrum is considerably improved: 4 σ (PRL2018) => nearly 6.5 σ,



- Tentative spectral fit in 11 GeV-4.8 TeV including pulsars and a possible Vela SNR contribution.
  - Positron flux(AMS): secondaries+ nearby pulsars
  - Electron flux (CALET-AMS):
    Secondaries + Distant SNRs (black dashed line)
    + Vela SNR (green line).

A possible contribution from the Vela SNR:
Energy output of 2.08×10^{48} erg in electron CR above 1 GeV.



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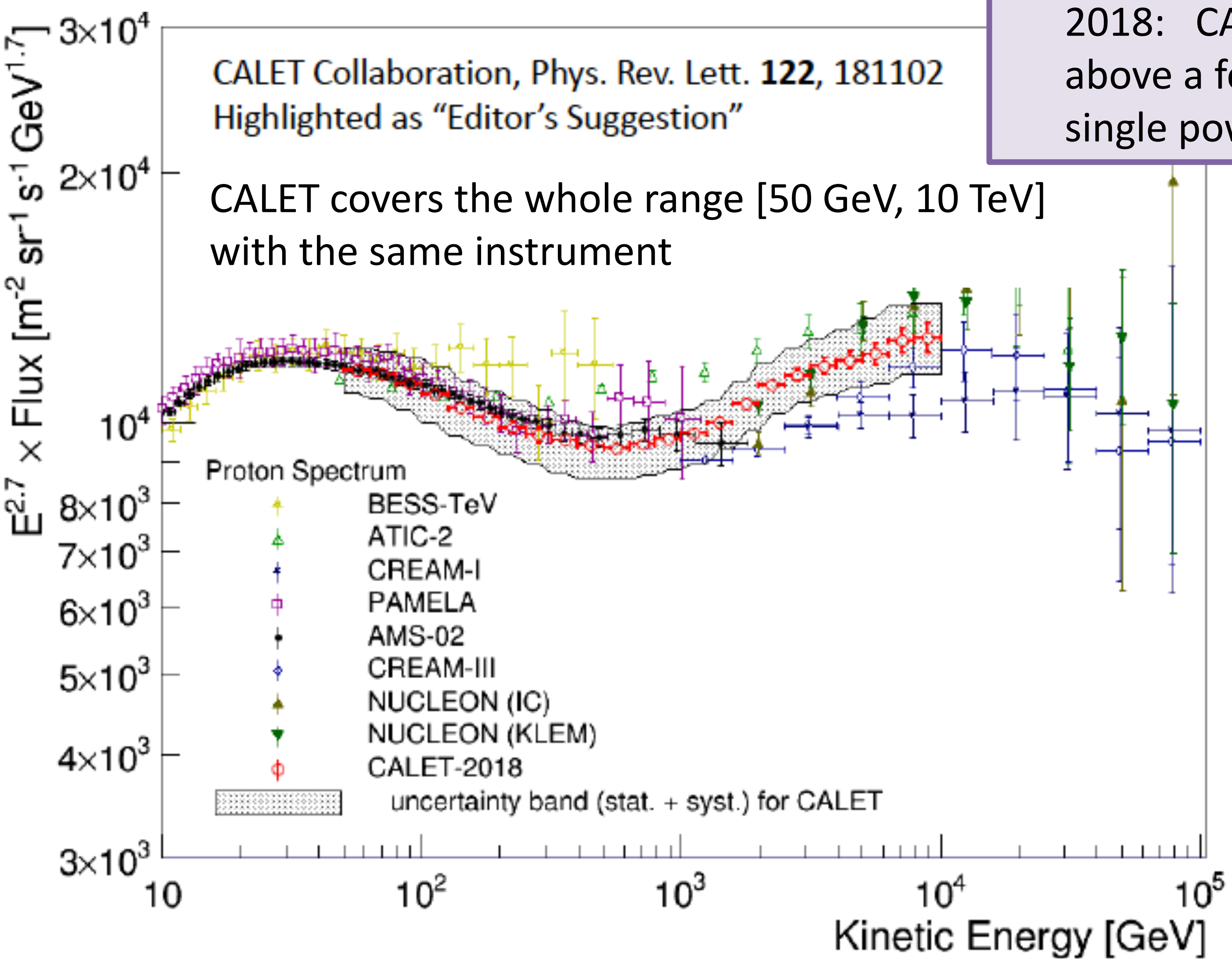
Cosmic-ray Proton Spectrum

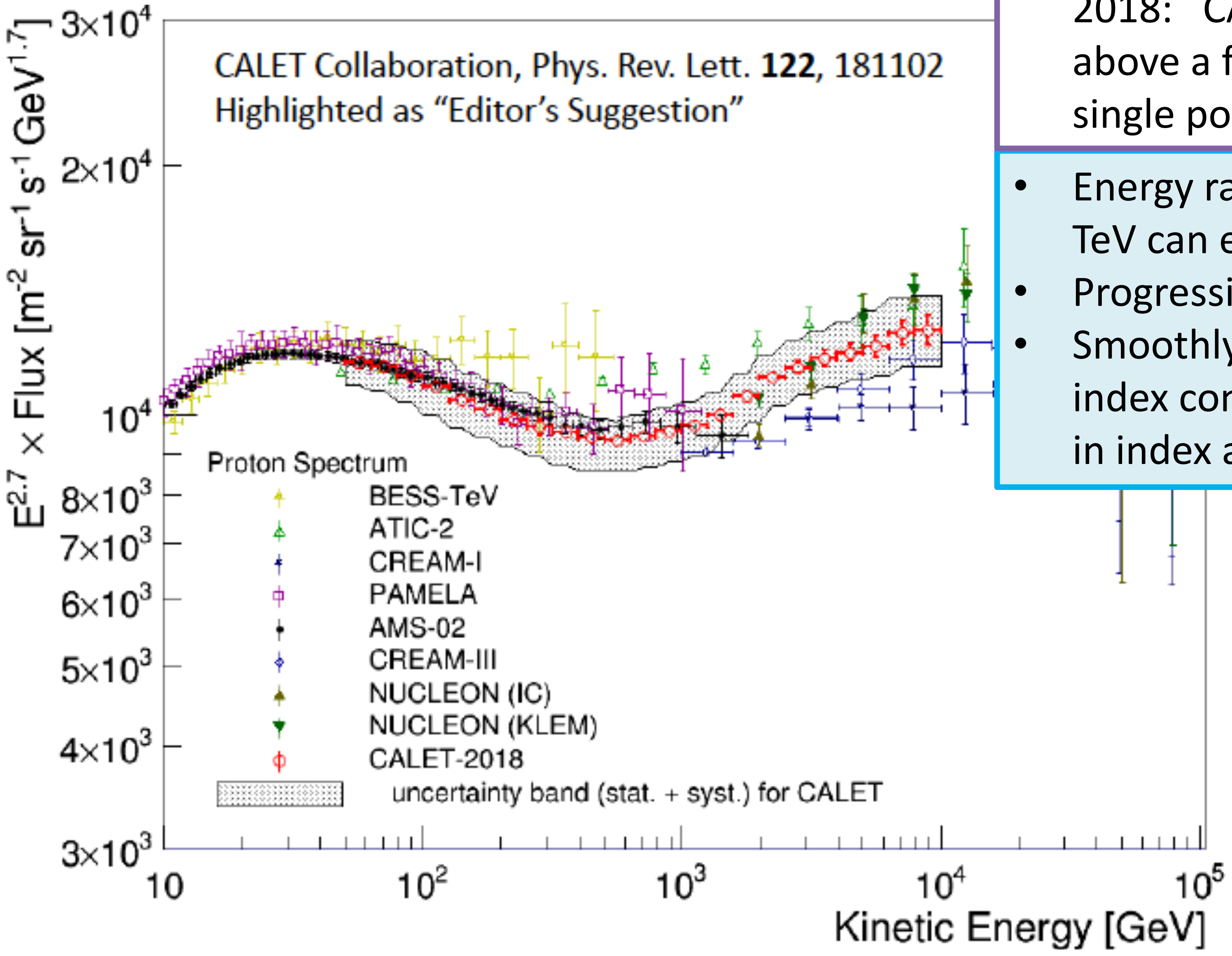
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

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

CALET covers the whole range [50 GeV, 10 TeV] with the same instrument

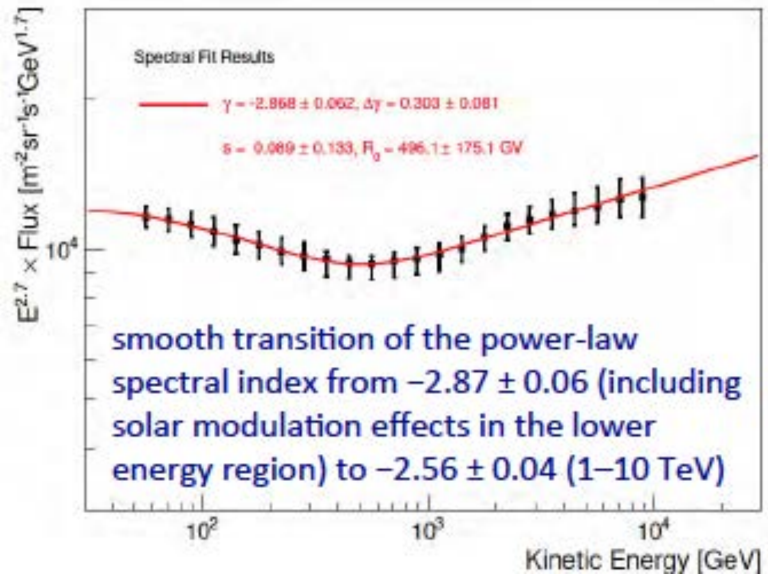


Cosmic-ray Proton Spectrum



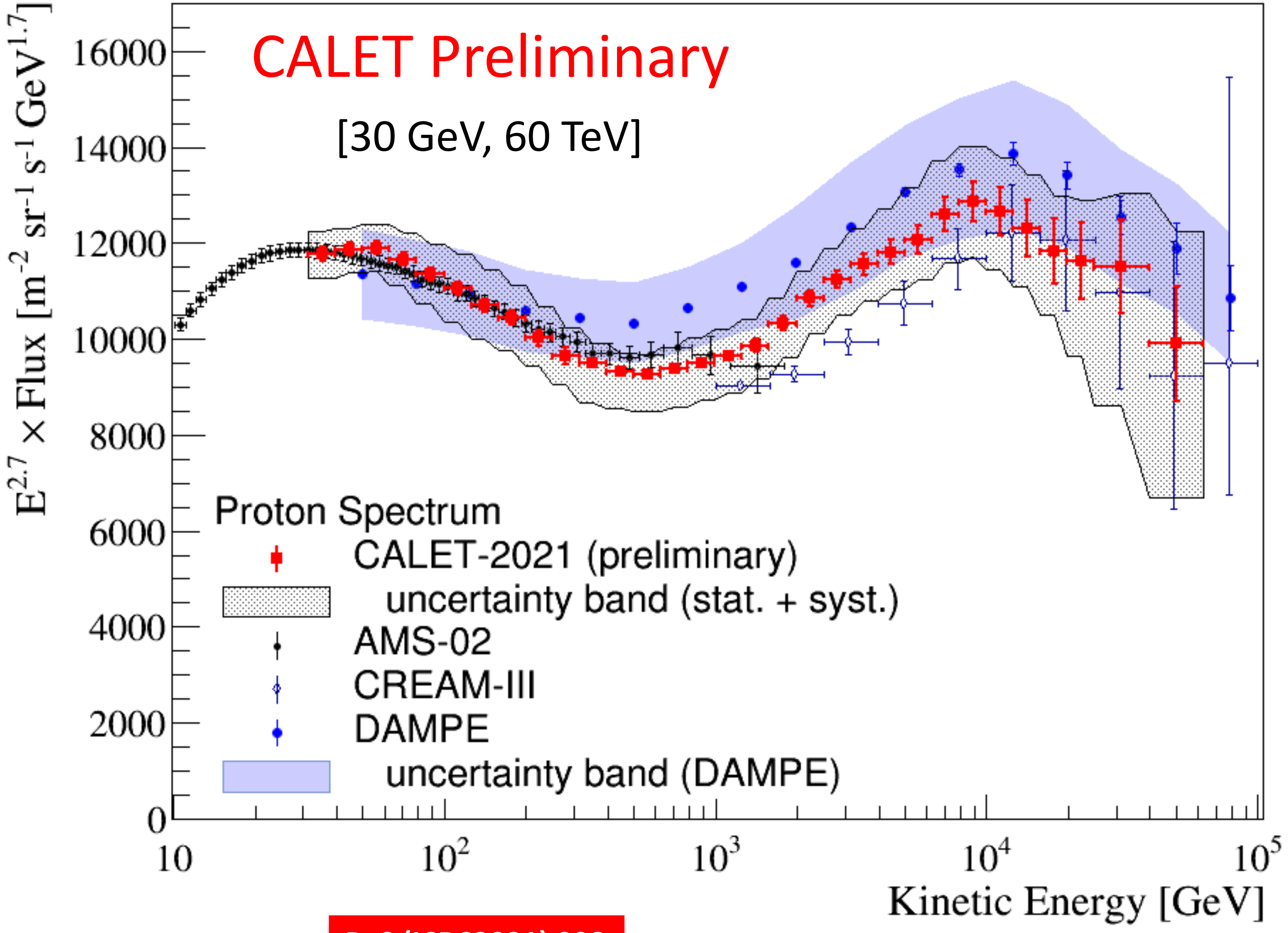
2018: CALET confirms proton spectral hardening above a few hundred GeV with a deviation from a single power law at >3σ

- Energy ranges 50 GeV – 500 GeV and 1 TeV – 10 TeV can each be fitted with single power laws
- Progressive hardening up to TeV energies
- Smoothly-broken power law fit gives low energy index consistent with AMS-02, but larger change in index and higher break energy



Cosmic-ray Proton Spectrum (update: as of Sep.30, 2020)

16aW2-3: Kobayashi



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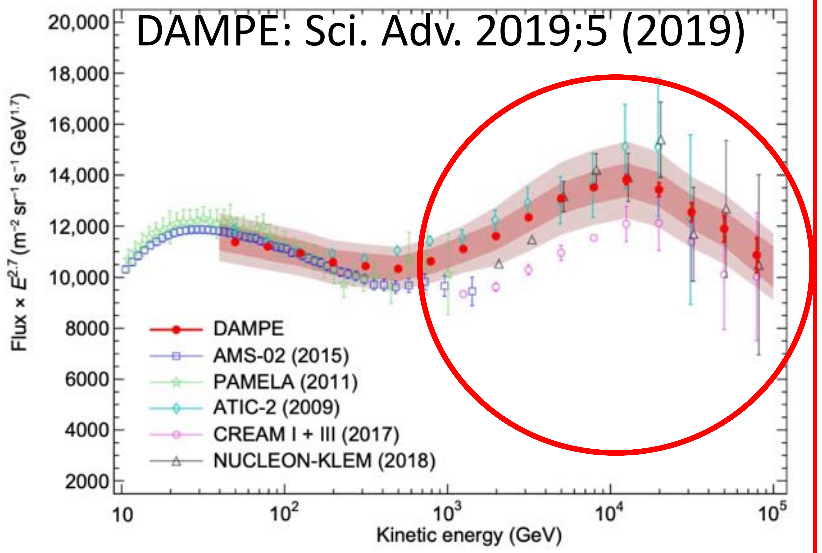
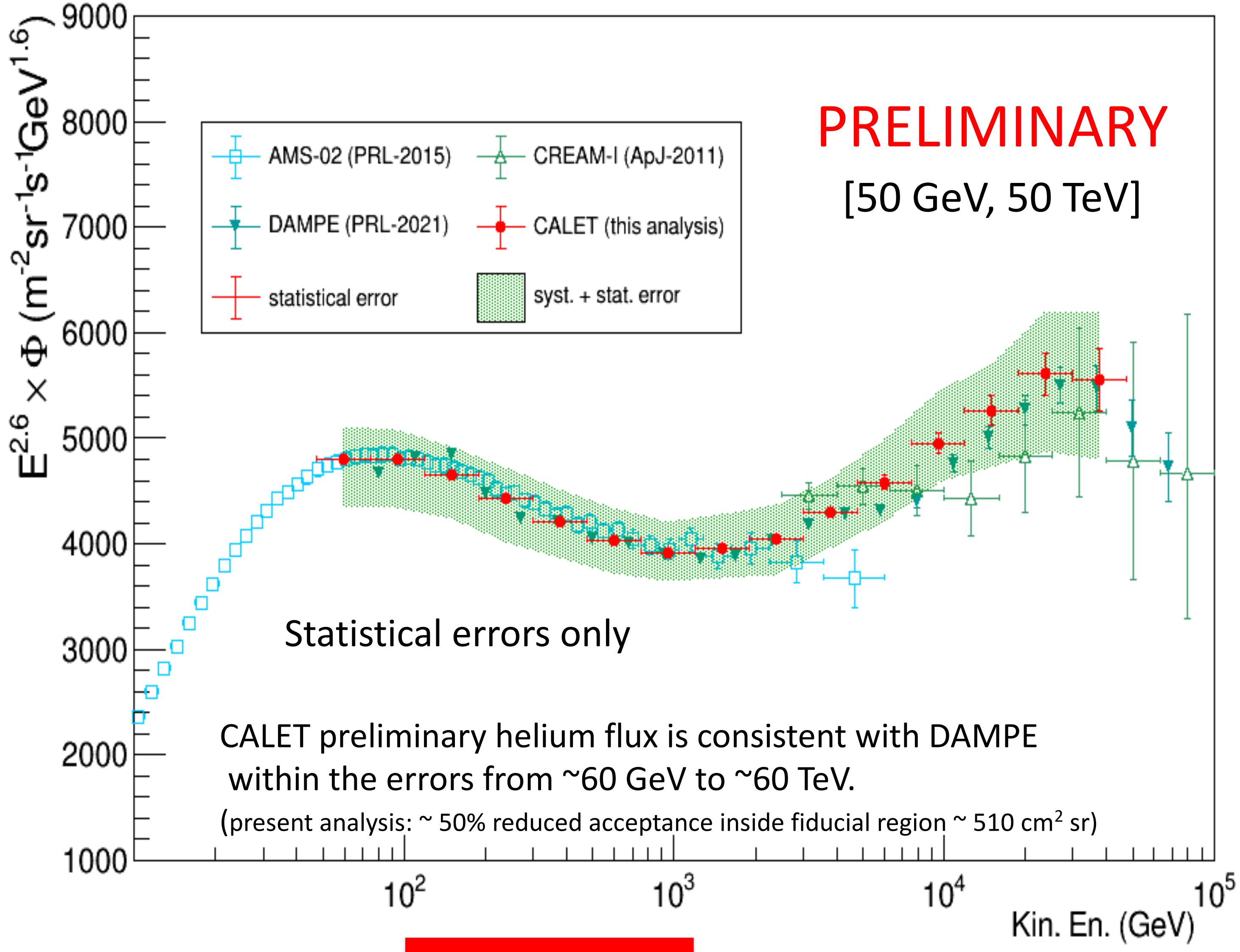


- DAMPE reported a spectral index softening $\Delta\gamma = -0.25 \pm 0.07$ from ~-2.60 to ~-2.85. above 10 TeV at E_{break} = $13.6^{+4.1}_{-4.8}$ TeV with ~30% error.
- DAMPE flux is consistent with AMS-02 and CALET up to 200 GeV. Above, the flux is higher (close to the limit of the systematic error band).

Cosmic-ray Helium Spectrum (preliminary)

16aW2-3: Kobayashi



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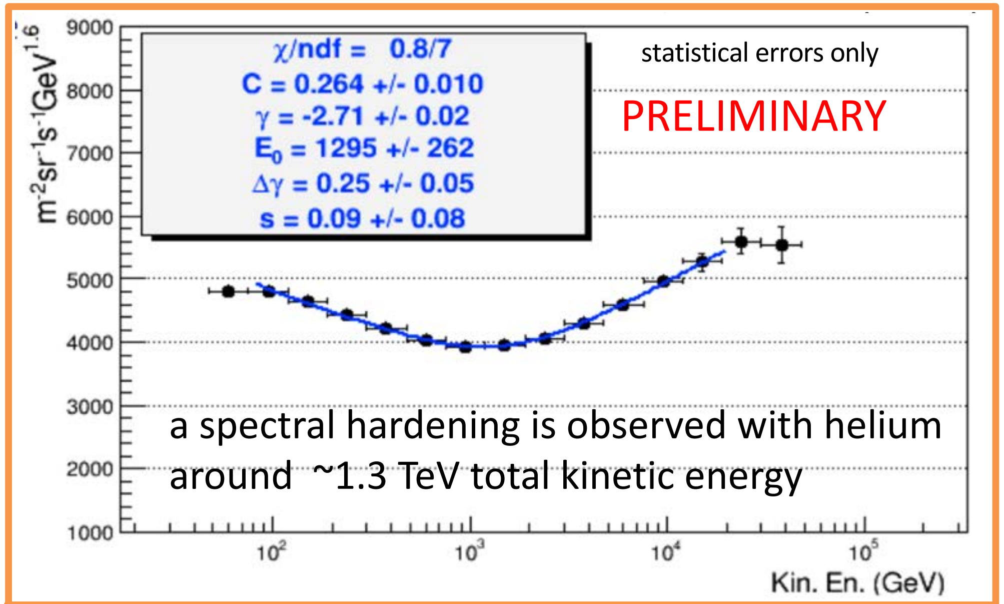
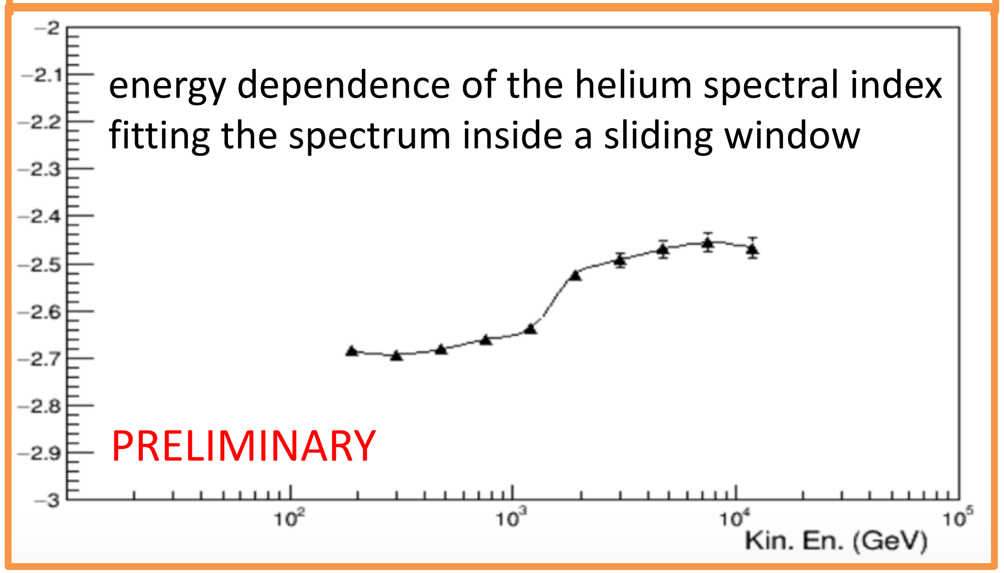
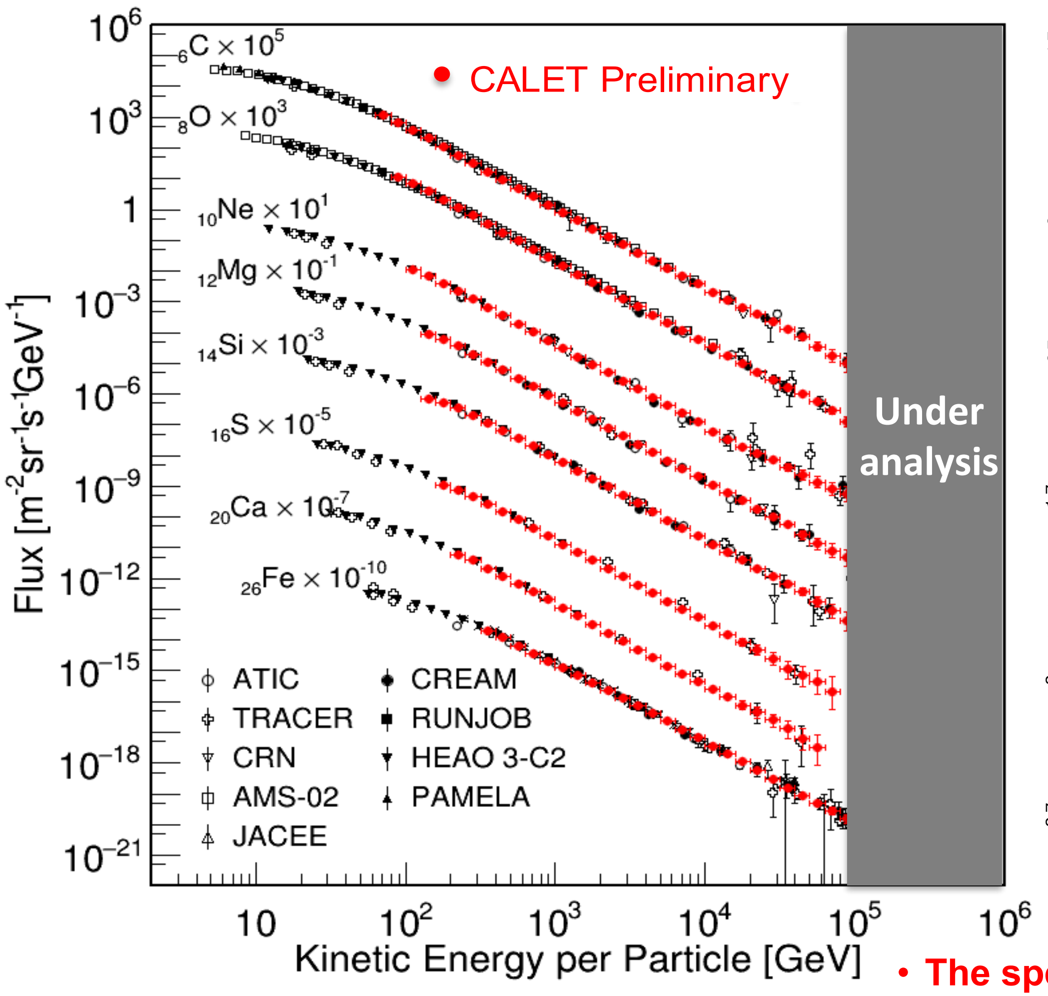




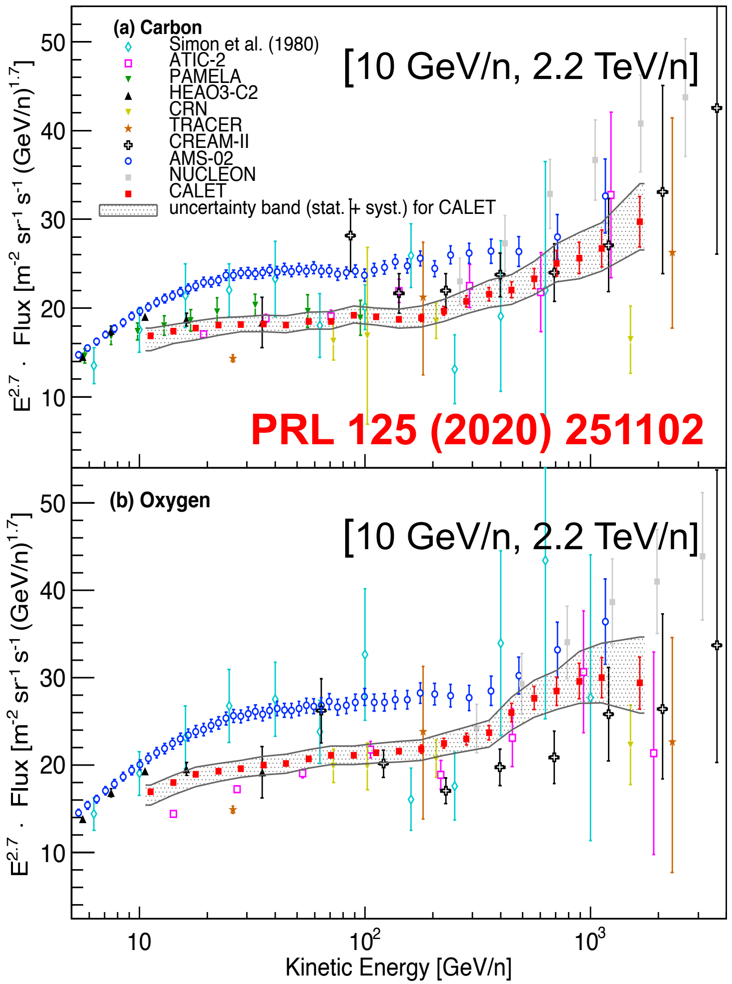
Spectra of Cosmic-ray Nuclei from C to Fe

16aW2-2: Akaike

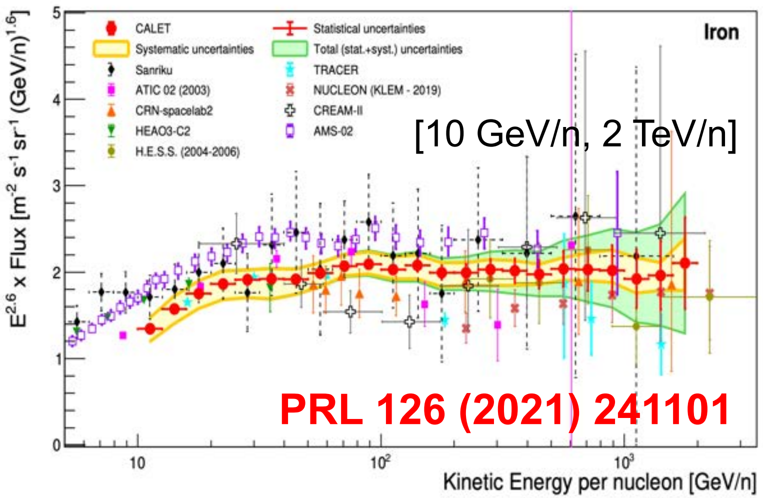
Preliminary Spectra of Carbon – Iron



Carbon and oxygen energy spectra



Iron energy spectrum

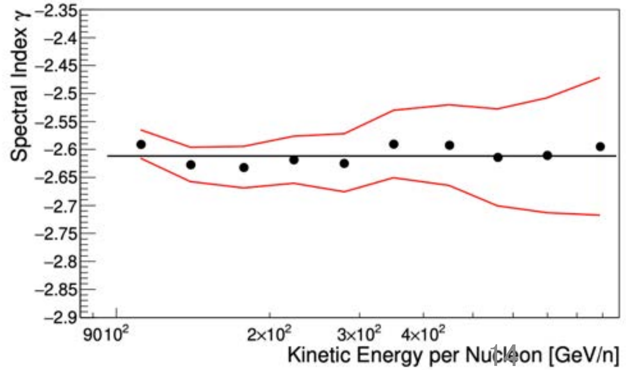


Iron Single Power Law fit:

50 GeV/n, 2.0 TeV/n

$\gamma = -2.60 \pm 0.02(stat) \pm 0.02(sys)$

with $\chi^2/d.o.f. = 4.2/14$

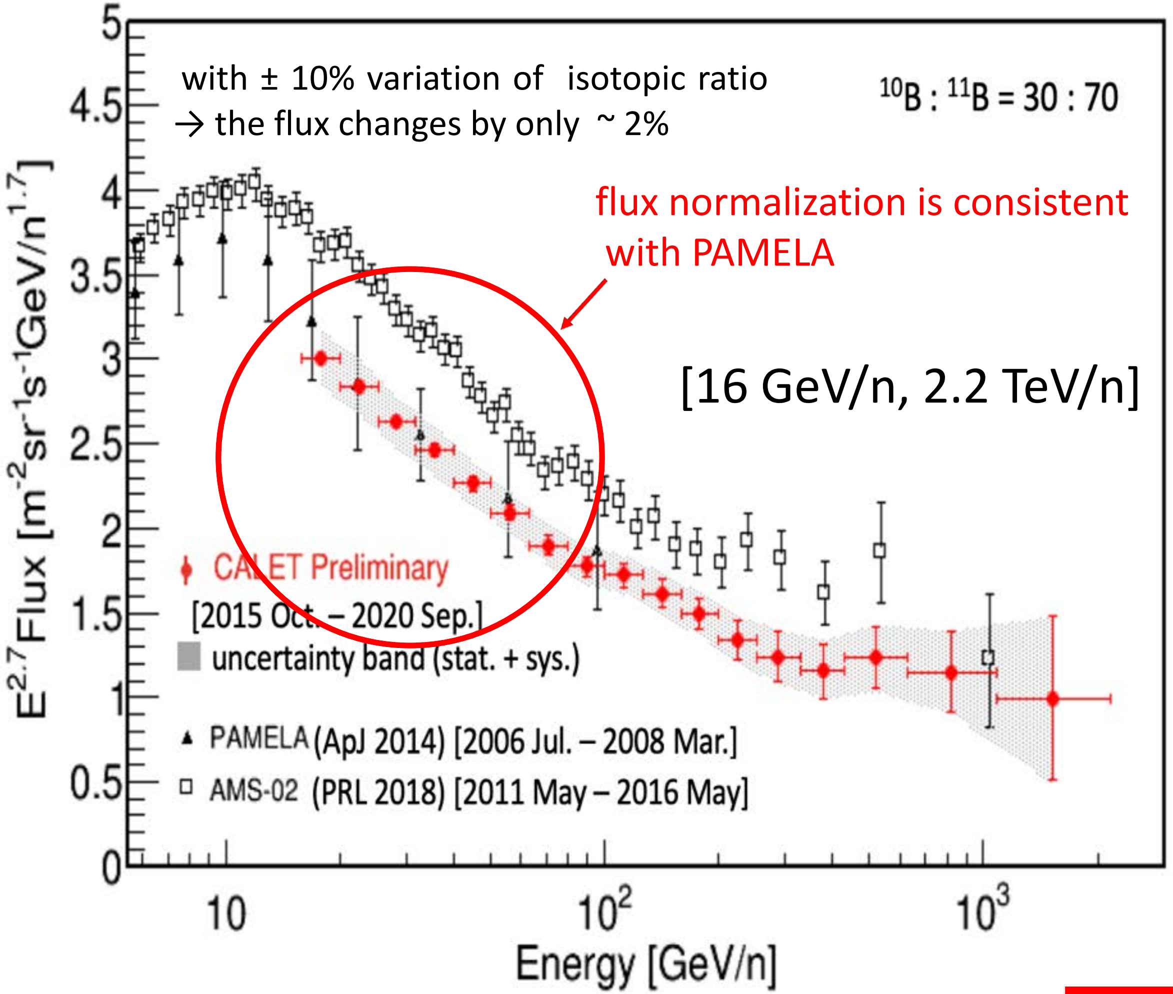


- **The spectra show a clear hardening around 200 GeV/n**
- They have shapes similar to AMS-02 but the absolute normalization is significantly lower (~ 27%)

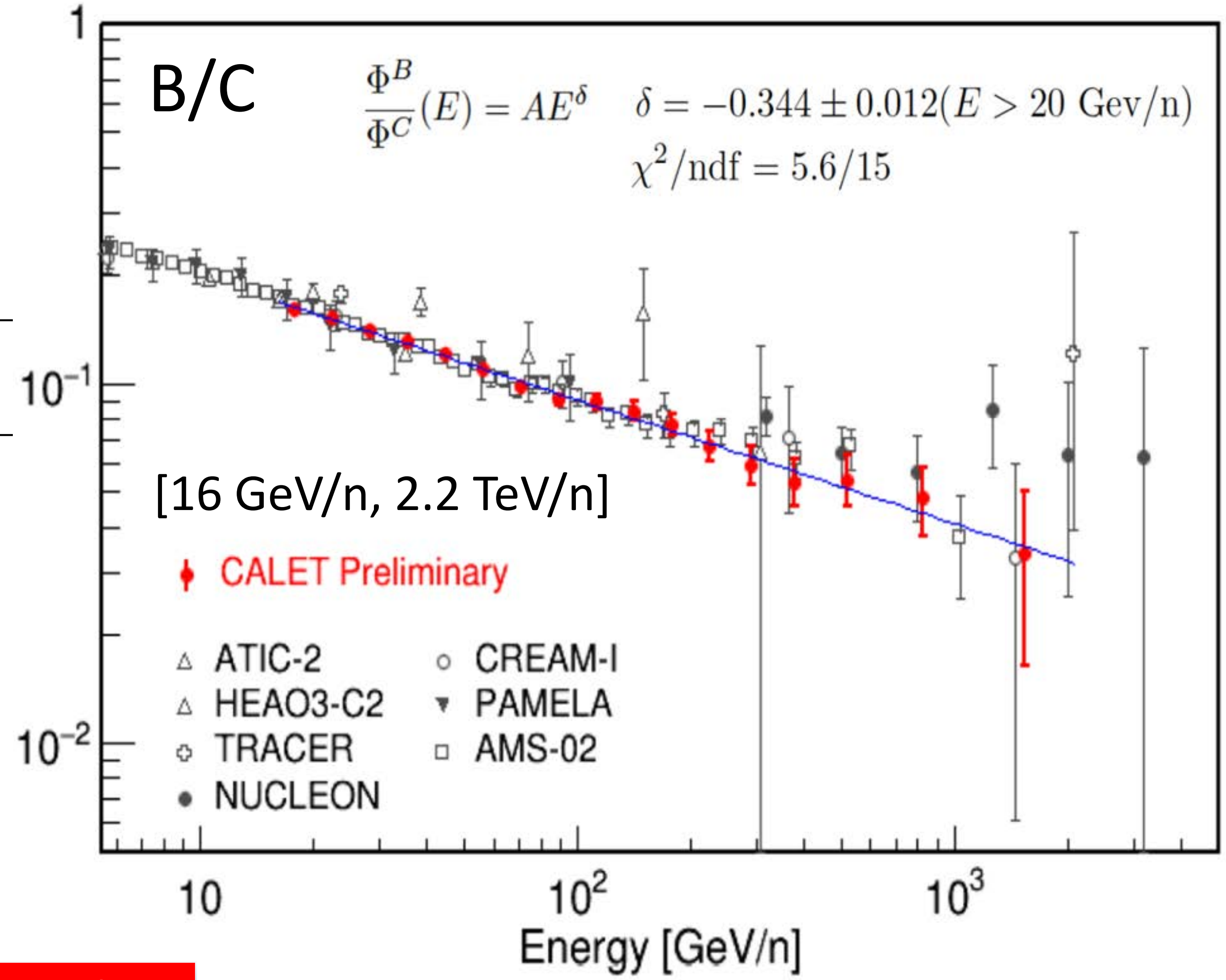
Boron Spectrum and B/C Ratio (preliminary)

16aW2-2: Akaike

Boron energy spectrum



B/C ratio



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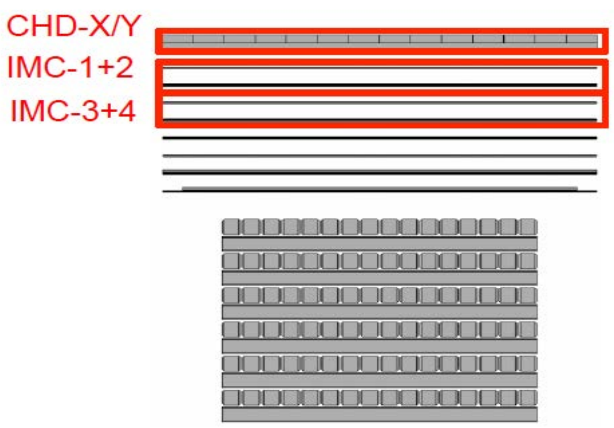
Ultra-heavy Cosmic-ray Nuclei (26 < Z ≤ 40)

Onboard trigger for UH events



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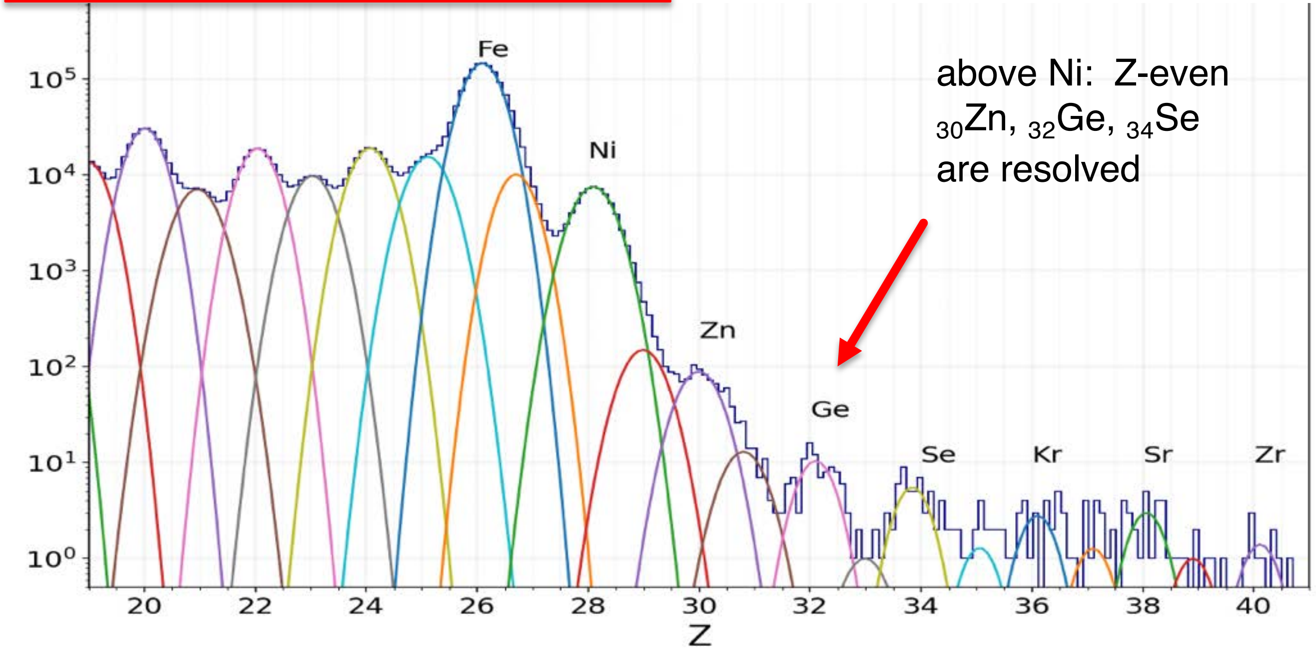
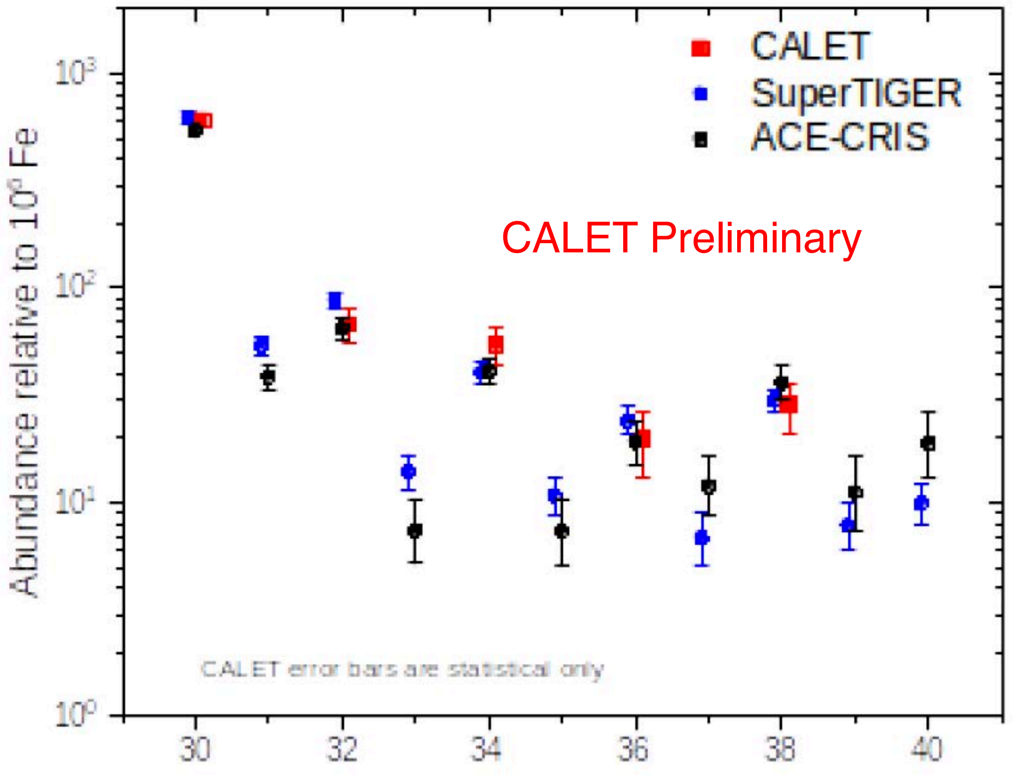
A special UH CR trigger uses the CHD and the first 4 layers of the IMC to achieve an expanded x 4 geometric factor
GF ~ 4400 cm² sr



above Ni: Z-even $_{30}$Zn, $_{32}$Ge, $_{34}$Se are resolved

Measurement of the relative abundances elements above Fe through $_{40}$Zr



The CALET UH element ratios relative to Fe are consistent with Super-TIGER and ACE abundances.

CALET γ–ray Sky (>1GeV) ,GRBs, GW follow-up, DM limits

16aW2-5: Mori
16aW2-6: Kawakubo

- Effective area: ~400 cm^2 above 2 GeV
- Angular resolution: < 0.2° above 10 GeV
- Energy resolution: ~5% at 10 GeV

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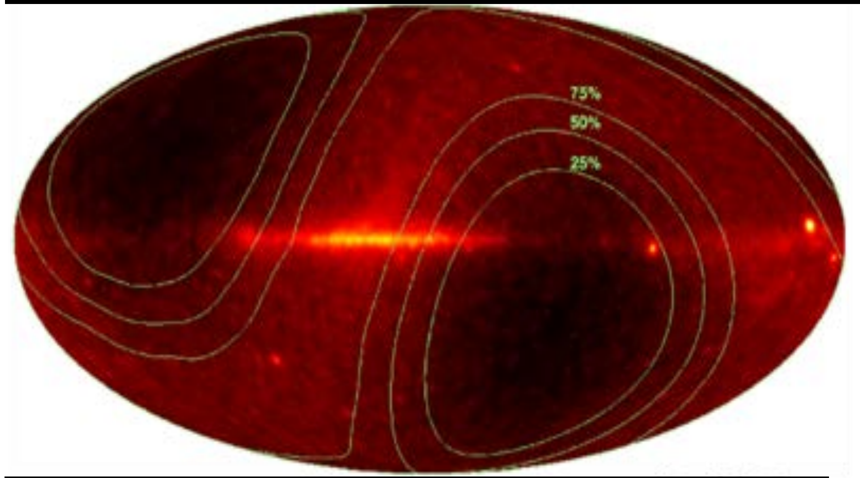
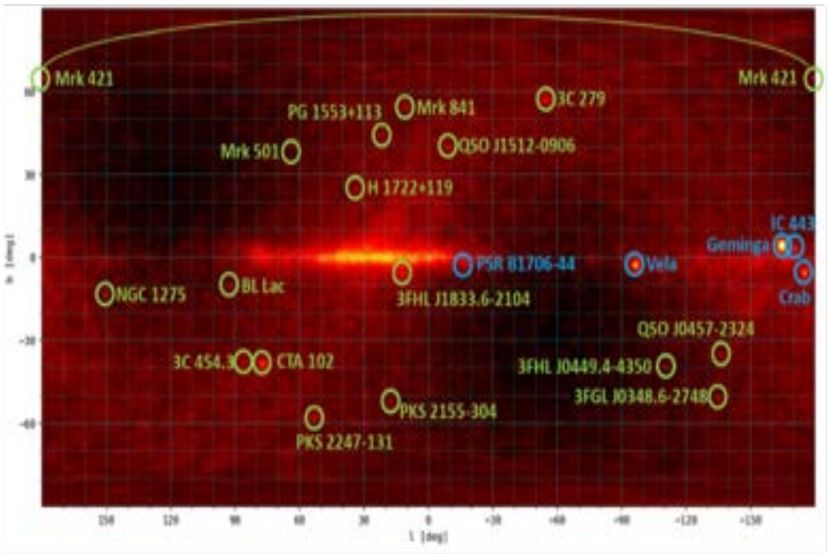
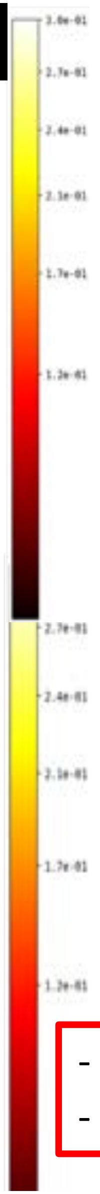
PoS (ICRC2021) 619
PoS (ICRC2021) 957

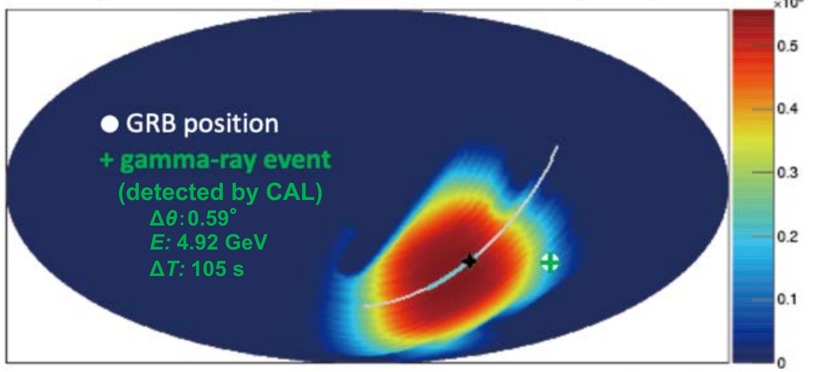
Gamma-ray sky map LE-γ trigger (E >1 GeV)



Identified bright point-sources (E >1 GeV)







CGBM: dedicated Gammay-Ray Burst Monitor with energy range 7 keV-20 MeV

from 2015-10-05 to 2021-07-23
264 GRBs (45.5 GRBs / year)
233 Long (88%) **31 Short (12%)**

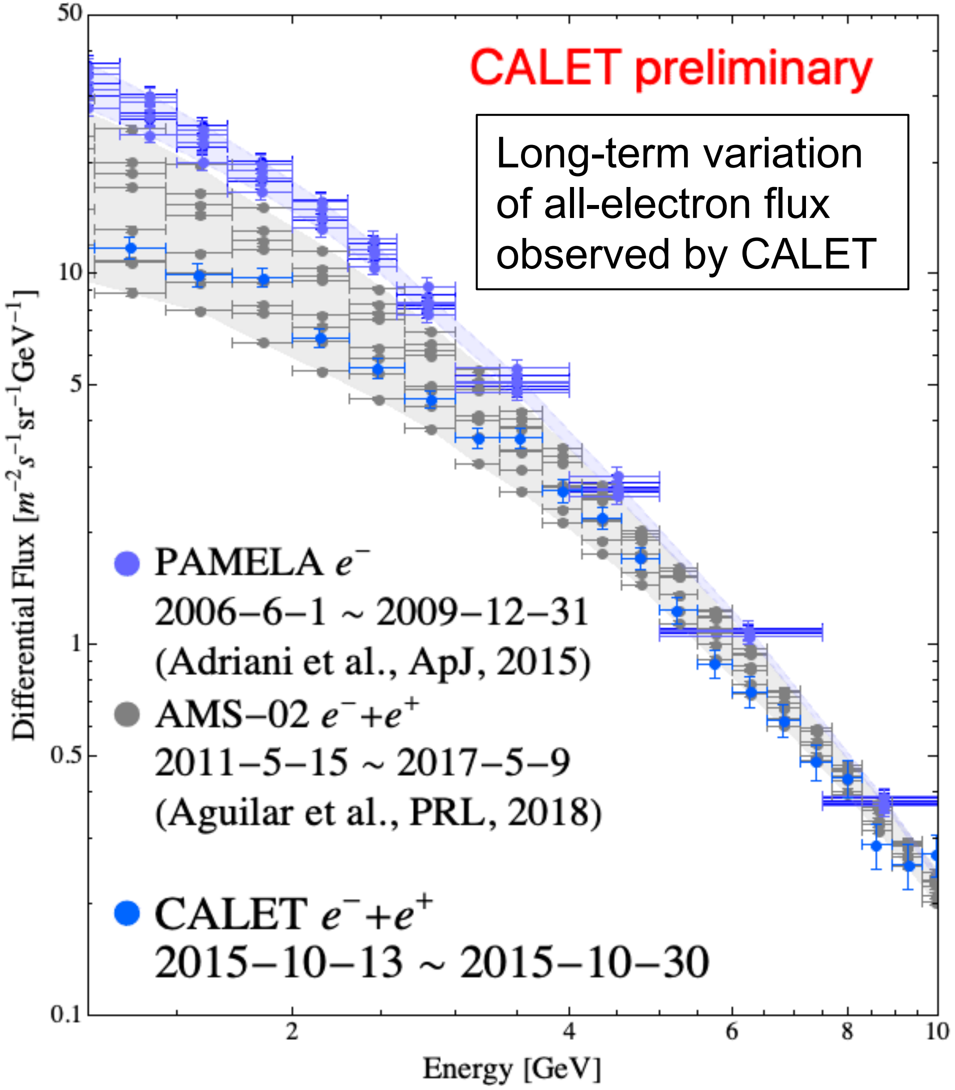
- **Follow-up** of LIGO/Virgo **GW** observations
  - X-ray and γ-ray bands
  - high-energy γ-in calorimeter

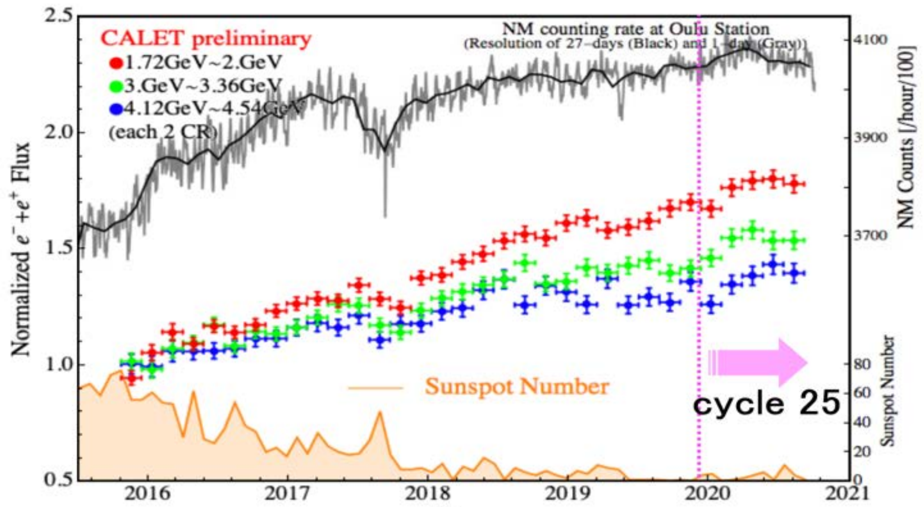
- **Limits on DM** annihilation into γγ: $\langle\sigma v\rangle < 10^{-28}$-$10^{-25} cm^{-3}s^{-1}$
- Limits on DM decay $\chi \rightarrow \gamma\nu$ etc.: $\tau_{DM} > 10^{30}$s (m_{DM}>100 GeV)

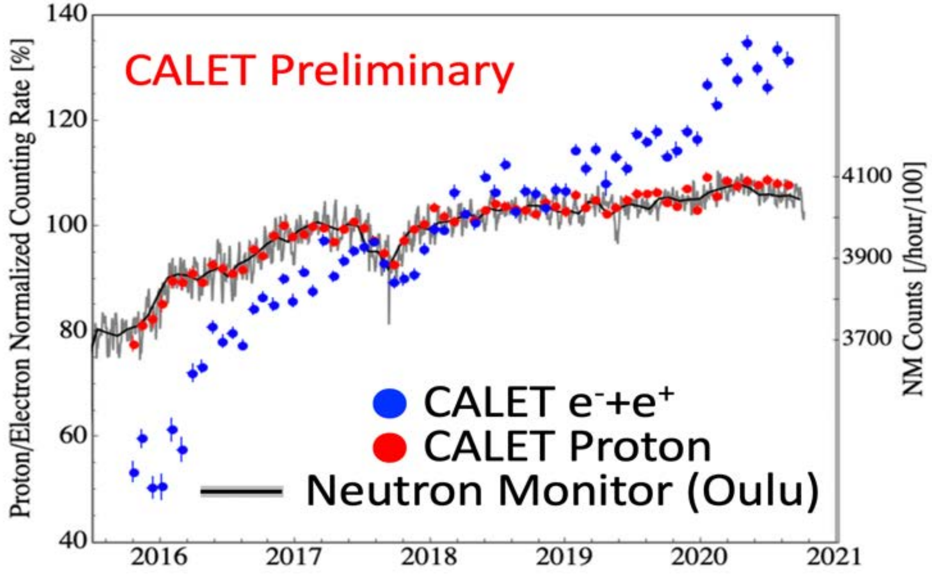
Solar Modulation

16aW2-7: Miyake

- **Since the start of observations in 2015/10, a steady increase in the 1-10 GeV all-electron flux has been observed.**
- **In the past two years, the flux has reached the maximum flux observed with PAMELA during the previous solar minimum.**







Good correlation of NM counting rate at Oulu station (black points) with the CR e^- + e^+ flux increase in the 1-10 GeV until ~half a year after the beginning the new solar cycle 25. The flux has now started decreasing.

The count rate increase of CR e^- + e^+ is found to be larger than that of CR protons. Consistent with the expected CHARGE SIGN dependence of the solar modulation.

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Main Science Goals and Status of the Analysis

Scientific Objectives	Observables	Energy Reach	Reported	Reference	ICRC2021	#
Cosmic-ray origin and acceleration	**Electron spectrum**	1 GeV – 20 TeV	to 4.8 TeV	PRL 120, 261102 (2018)	**11 GeV – 4.8 TeV**	**737, 628**
	Proton spectrum	10 GeV – 1 PeV	to 10 TeV	PRL 122, 181102 (2019)	**30 GeV – 60 TeV**	**390**
	Helium spectrum	10 GeV – 1 PeV	preliminary	preliminary	**50 GeV – 50 TeV**	**512**
	Carbon and oxygen spectra	10 GeV – 1 PeV	to 2.2 TeV/n	PRL 125, 251102 (2020)	**10 GeV/n – 2.2 TeV/n**	**260**
	Iron spectrum	10 GeV – 1 PeV	to 2 TeV/n	PRL 125,241101 (2021)	**10 GeV/n – 2 TeV/n**	**797**
	Elemental spectra of primaries	10 GeV – 1 PeV	to 100 TeV	ICRC 2019, 034	10 GeV – 100 TeV	**786**
	Ultra-heavy abundances	> 600 MeV/n	> 600 MeV/n	ICRC 2019, 130	> 600 MeV/n	**1044, 657**
CR propagation	**B/C and secondary-to-primary ratios**	Up to some TeV/n	to 200 GeV/n	ICRC 2019, 034	**16 GeV/n – 2.2 TeV/n**	**842**
Nearby electron sources	**Electron spectral shape**	100 GeV – 20 TeV	to 4.8 TeV	ICRC 2019, 142	to 4.8 TeV	**737, 492**
Dark matter	**Signatures in e/γ spectra**	100 GeV–20TeV (e) 10 GeV-10TeV (γ)	to 4.8 TeV (e) to 600 GeV (γ)	ICRC2019 , 533	to 4.8 TeV	**517**
Gamma rays	**Diffuse & point sources**	1 GeV – 10 TeV	1 GeV – 1 TeV	ApJS 238:5 (2018)	1 GeV – 1 TeV	**322, 517**
Heliospheric physics	**Solar modulation**	1 GeV – 10 GeV	1 – 10 GeV	ICRC 2019, 1126	**1 – 10 GeV**	**332**
Gamma-ray transients	**GW follow-up and GRB analysis**	7 keV–20MeV (CGBM) 1 GeV-1TeV (ECAL)	7 KeV-20MeV	ApJL 829:L20 (2016)	7 keV–20MeV (CGBM) > 1 GeV (ECAL)	**817**
Space weather	**Relativistic electron precipitation**	> 1.5 MeV	> 1.5 MeV	Geophys.Res.Lett,43 (2016)	> 1.5 MeV	**959**

CALET: Summary and Future Prospects

- CALET was successfully launched on Aug. 19th, 2015
- More than 5.5 years of excellent performance and remarkable stability of the instrument
- Linearity in the energy measurements established up to 10^6 MIP
  ⇨ [Astropart. Phys. 91, 1 – 10 (2017)]
- Continuous on-orbit calibration updates
- HE trigger operational for > 2000 days with > 85% live time fraction
- Total number of > GeV triggers ~3.0 billion

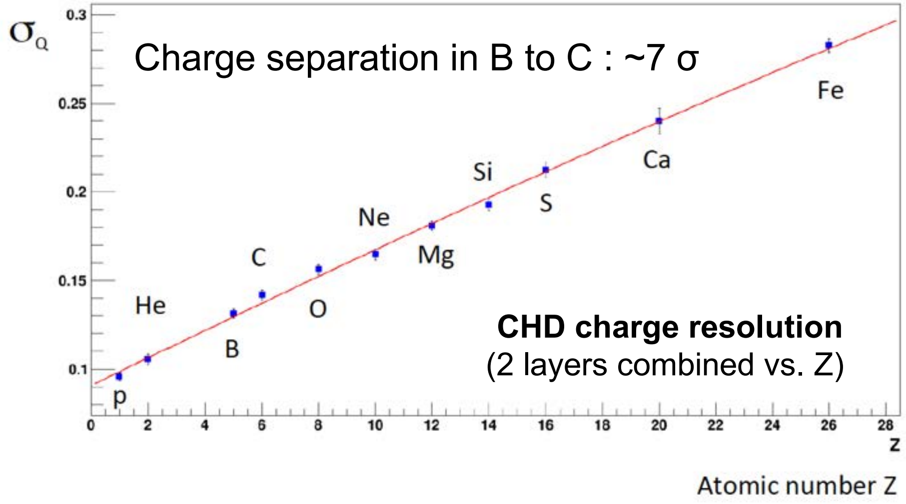
Extended operations approved by JAXA/NASA/ASI in March 2021 through the end of 2024

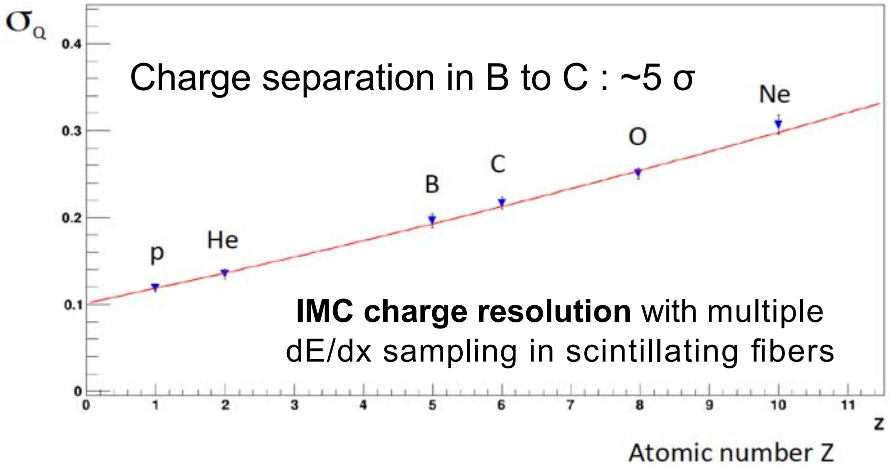
※ This work is partially supported by JSPS KAKENHI Kiban (S) Grant Number 19H05608 (2019-2023FY).

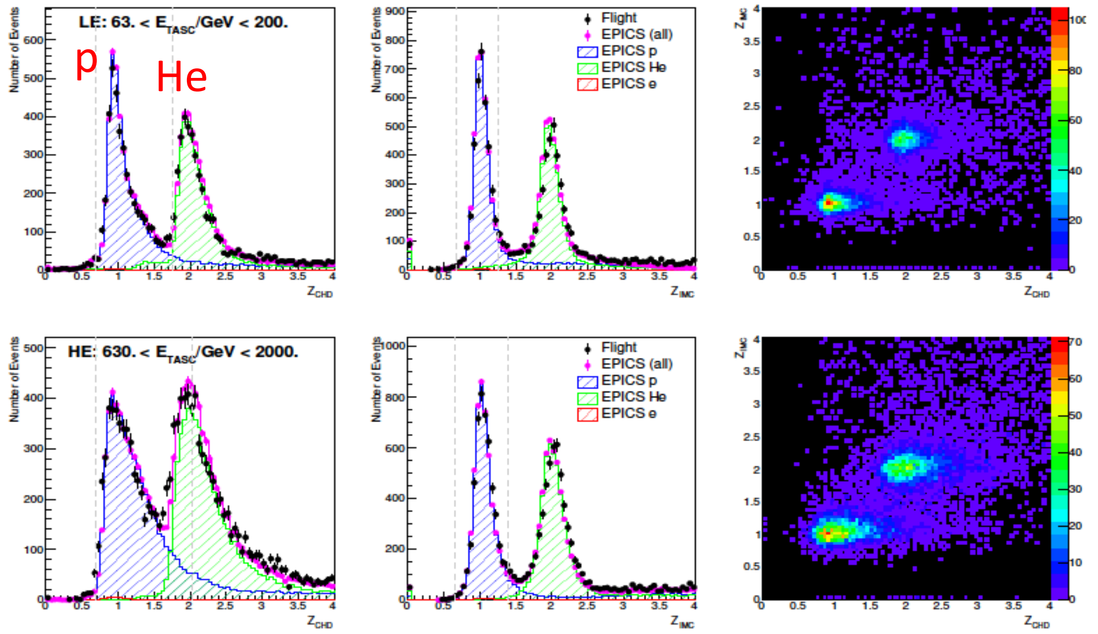
BACKUP

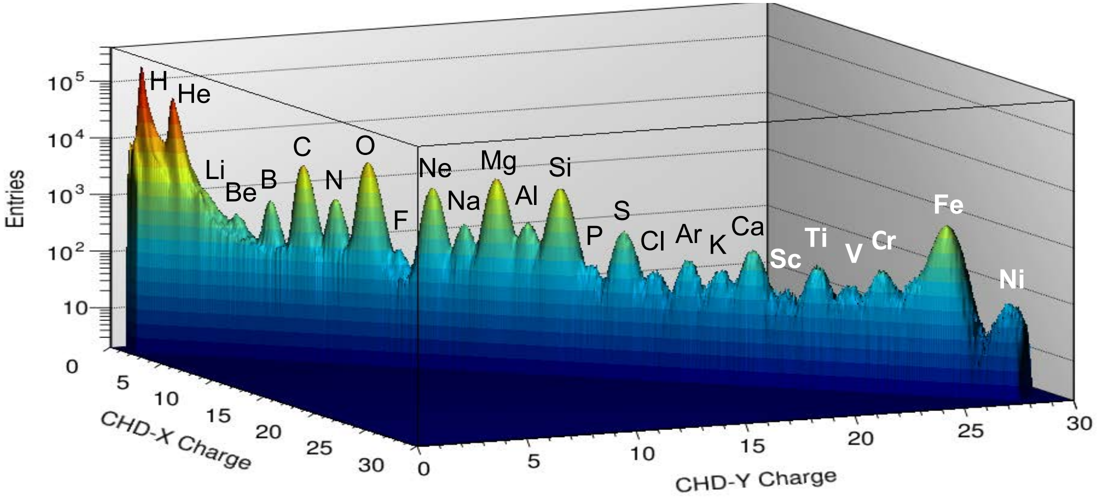
Charge Identification with CHD and IMC

Single element identification for p, He and light nuclei is achieved by CHD+IMC charge analysis.





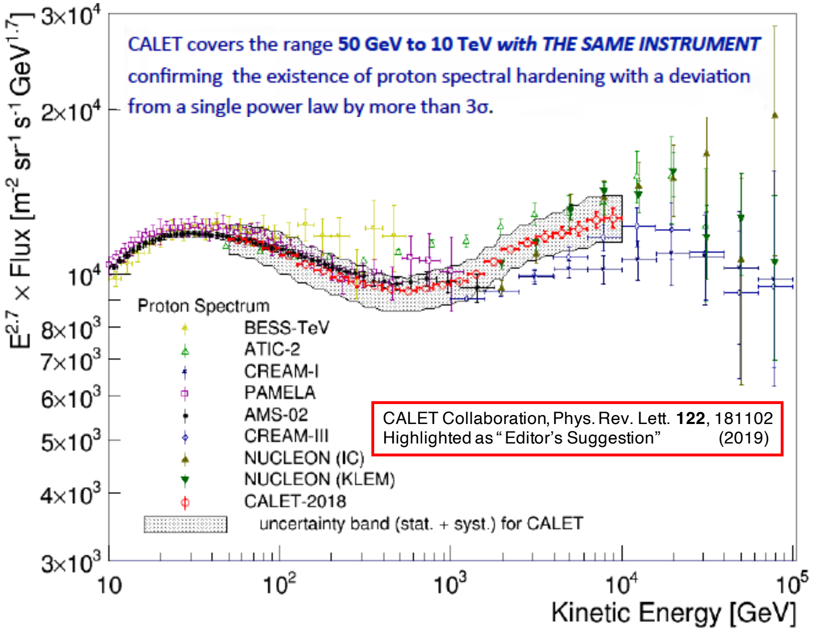




Deviation from Z^2 response is corrected both in CHD and IMC using a core + halo ionization model (Voltz)

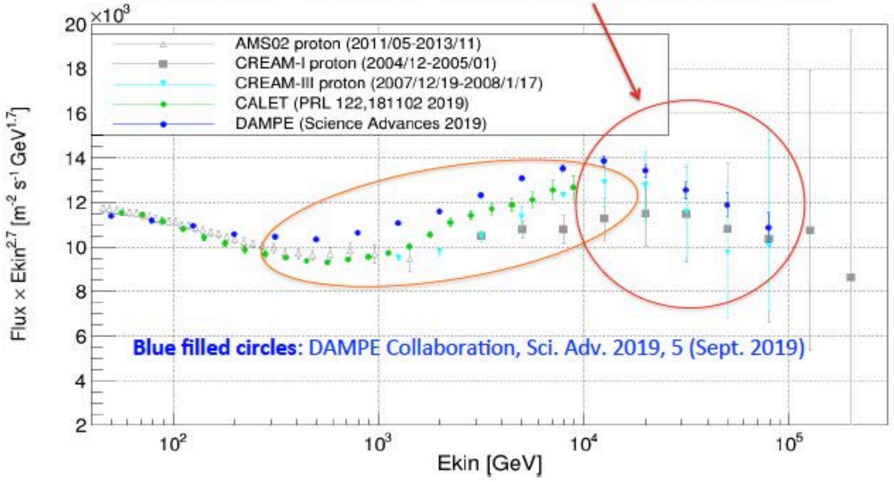
Direct Measurement of Proton Spectrum and AS Observations

Direct Measurements of Proton Spectrum ⇨



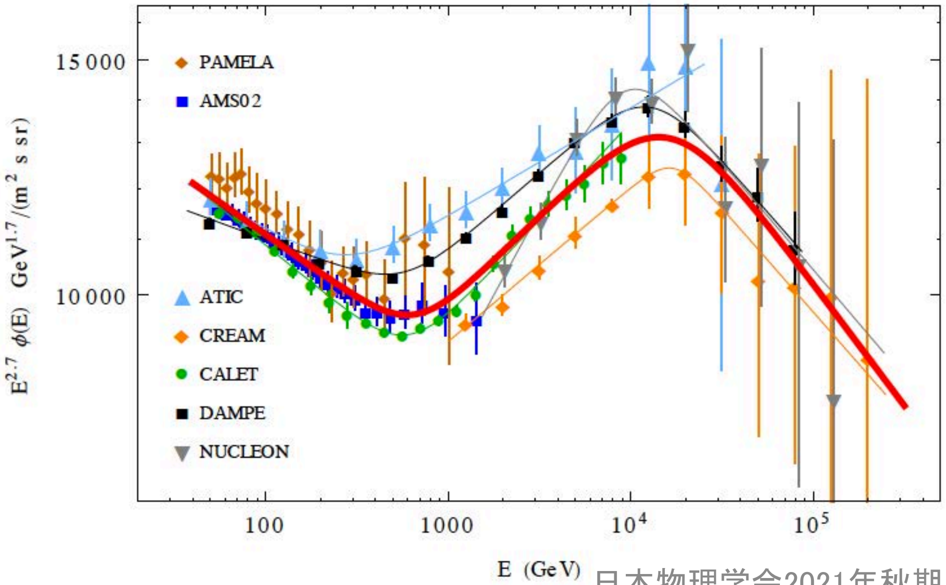
Recent paper by DAMPE collaboration (Sept 2019) from 40 GeV to 100 TeV:

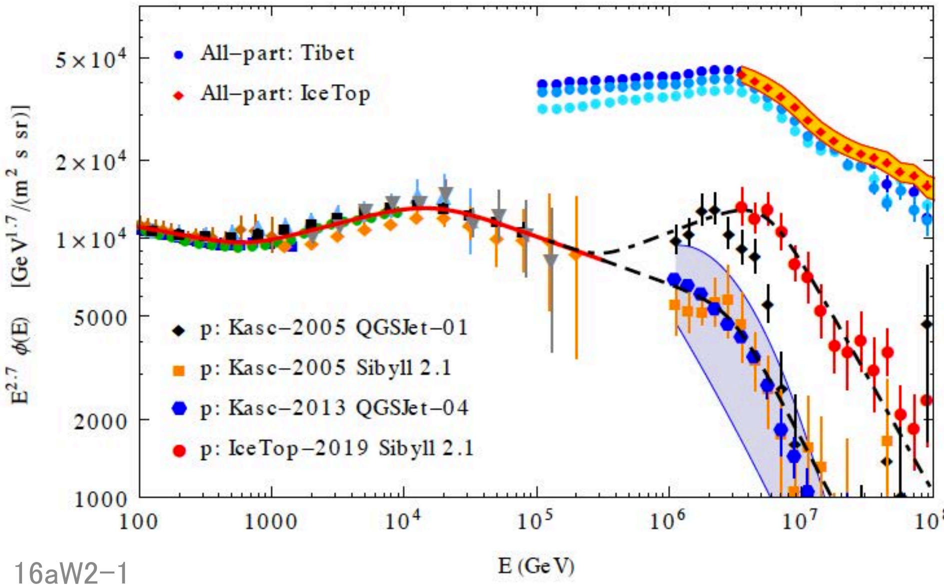
- flux higher than AMS02 and CALET above 200 – 300 GeV
- flux higher than CREAM-III (and CREAM-I) in the region 1 TeV to 10 TeV approx.
- flux reduction above 13.6 TeV (spectral index changes from ~2.60 to ~2.85)



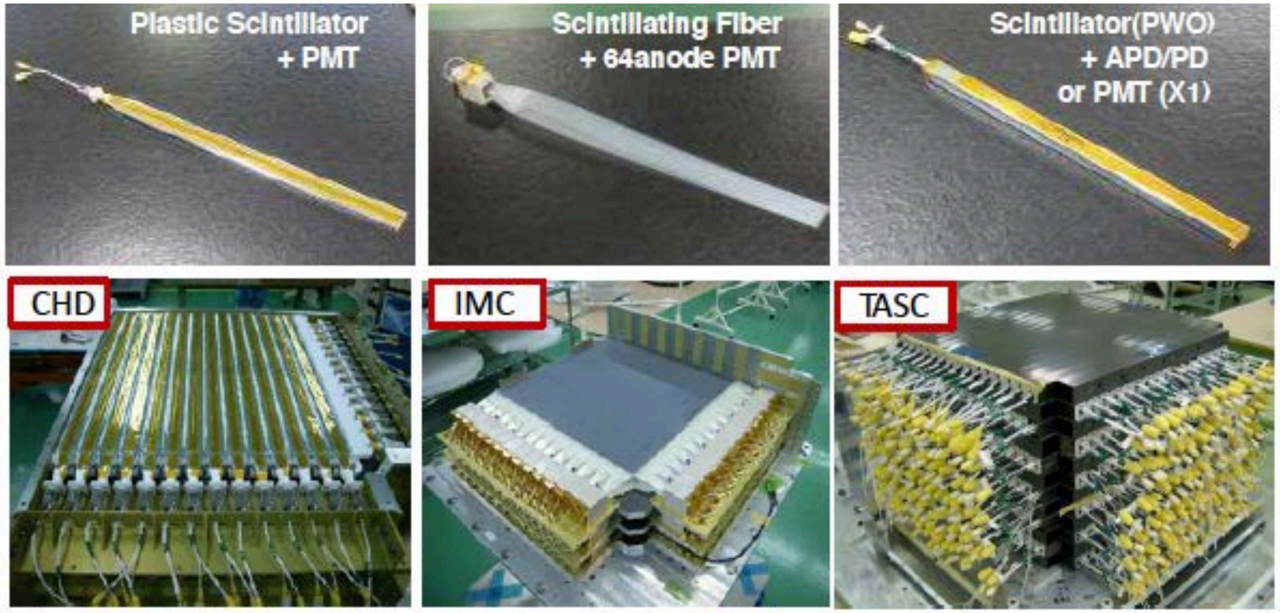
Possible Connection of Proton Spectrum to Air Shower Observations ⇨

Paolo Lipari and Silvia Vernetto
arXiv:1911.01311v1 [astro-ph.HE]
4 Nov 2019

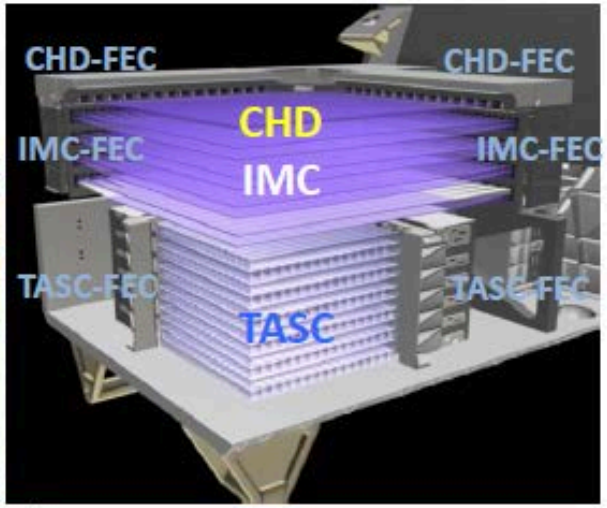




Detector Components



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 (VA32—HDR)**	**APD/PD+CSA PMT+CSA (for Trigger)@top layer**