飛翔体観測(CALET)による高エネルギー宇宙線加速天体の研究

赤池陽水, 他CALETチーム
早稲田大学理工学術院総合研究所

CALET

令和三年度東京大学宇宙線研究所共同利用研究成果発表会

共同利用研究概要 (2021)

- 共同研究内容
  - CALET観測最適化のためのシミュレーション計算及びデータ解析
- 発表概要
  - CALET概要
  - 観測現状
  - 観測データ解析
  - まとめと展望
- 予算: 旅費 190千円 ➡ 全額繰越予定
- 共同利用:　計算機(シミュレーション計算)

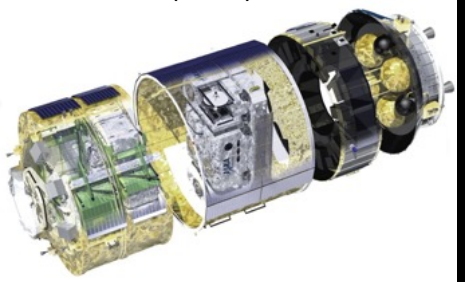
研究代表者　　早稲田大学　鳥居祥二

参加研究者及び研究補助

早稲田大学	赤池陽水, 小林兼好, Motz H. Margin	芝浦工業大学	笠原克昌
宇宙線研究所	寺澤敏夫, 浅野勝晃	弘前大学	市村雅一
神奈川大学	田村忠久, 清水雄輝	信州大学	宗像一起
立命館大学	森正樹	茨木高専	三宅晶子
横浜国立大学	片寄祐作	大阪市立大学	常定芳基
ルイジアナ州立大学	川久保裕太	NASA/GSFC	Nick Cannady
INFN-Pisa	Pier S. Marrocchesi		

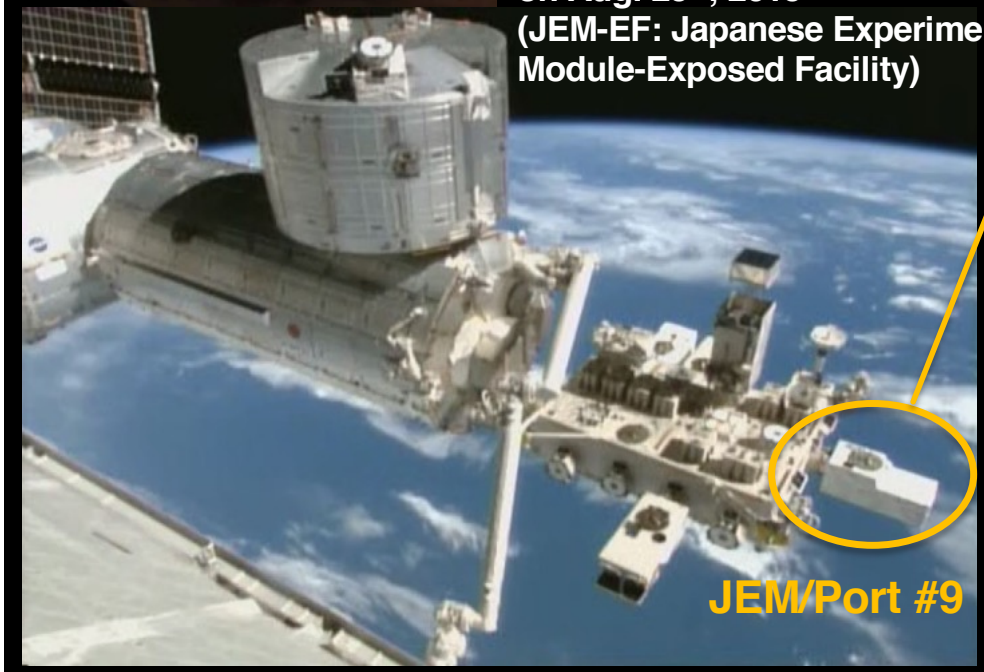
CALET Payload

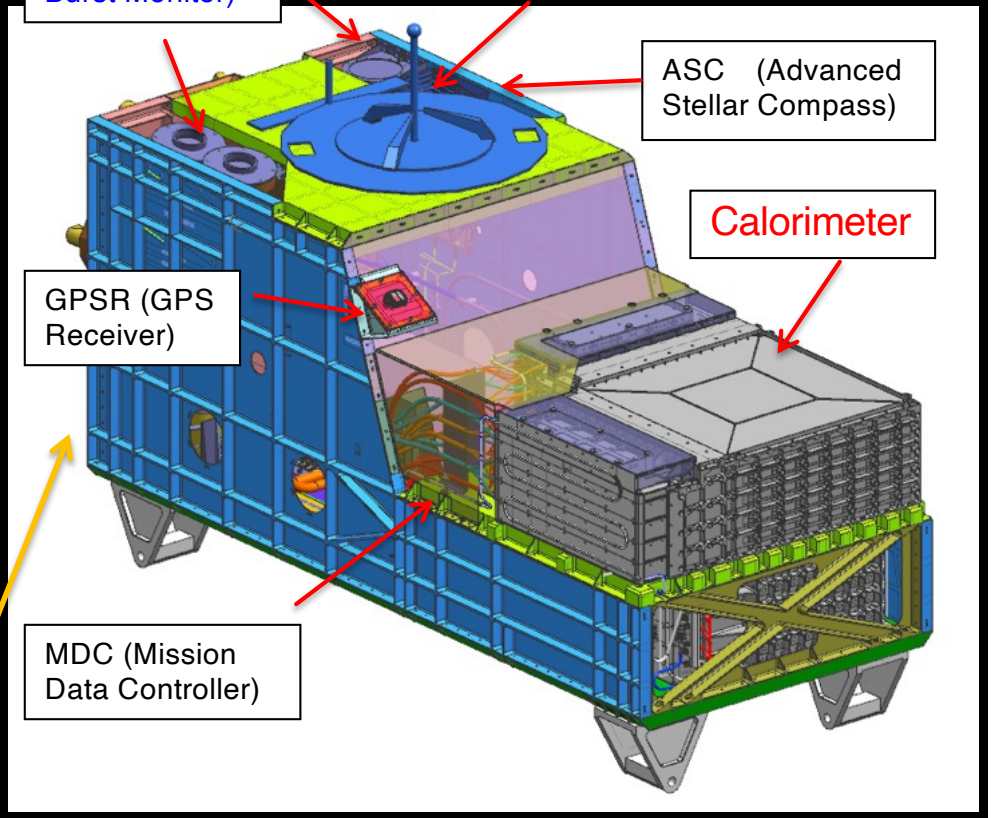
Kounotori (HTV) 5



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

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





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

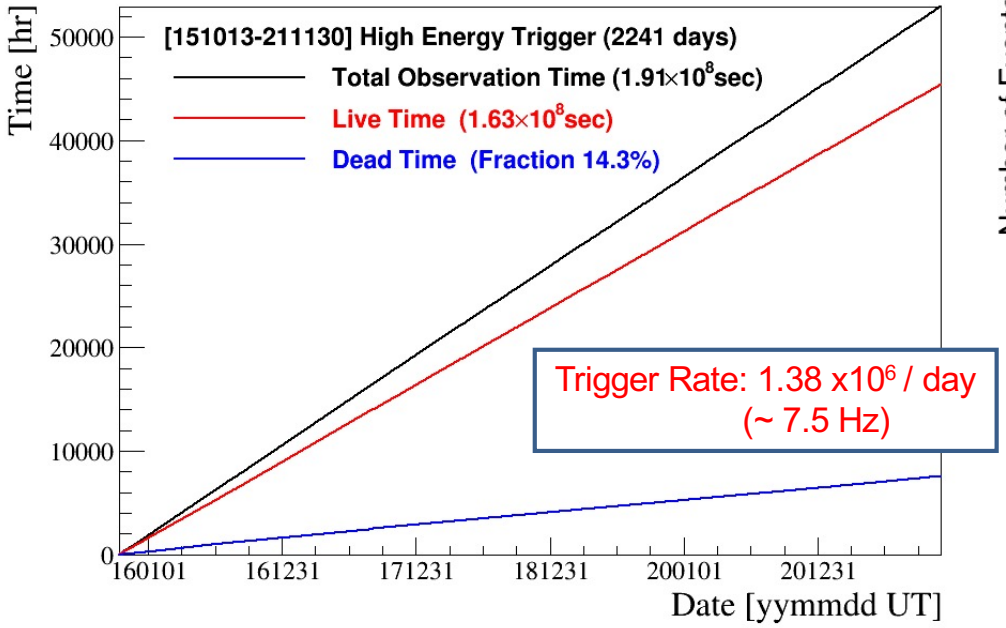
Observations with High Energy Trigger (>10GeV)

Observation by High Energy Trigger for 2,241 day : Oct.13, 2015 – Nov. 30, 2021

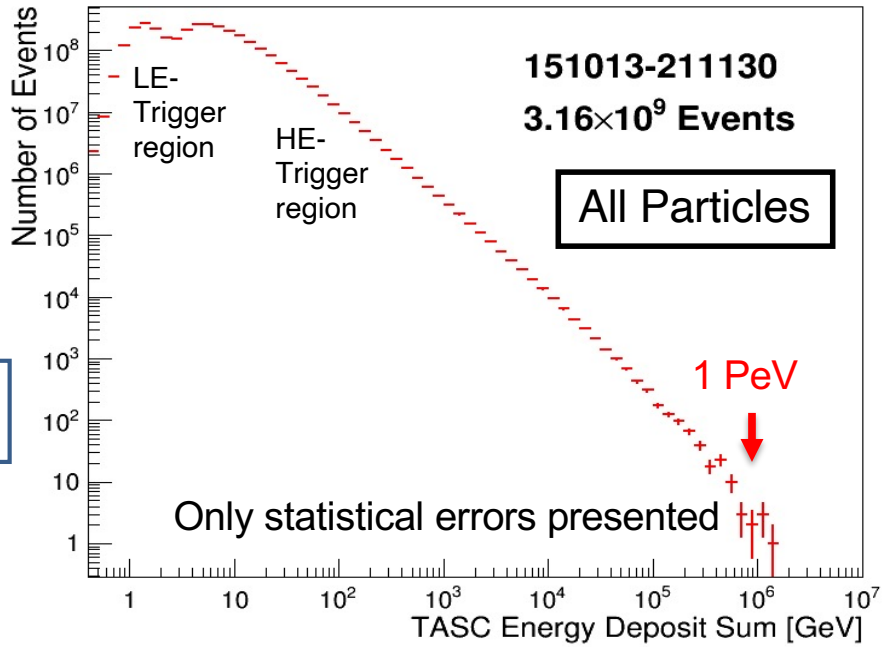
Over 6-year observation has been achieved !!

- The exposure, SΩT, has reached to ~200 m^2 sr day for electron observations by continuous and stable operations.
- Event number of HE triggered events (>10 GeV) is ~1.4 billion with a live time fraction of about 86 %. Total event number triggered over 1 GeV is ~3.2 billion.

Accumulated observation time (live, dead)



Distribution of deposit energies (ΔE) in TASC



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**
	Proton spectrum	10 GeV – 1 PeV	to 10 TeV	PRL 122, 181102 (2019)	**30 GeV – 60 TeV**
	Helium spectrum	10 GeV – 1 PeV	preliminary	preliminary	**50 GeV – 50 TeV**
	Carbon and oxygen spectra	10 GeV – 1 PeV	to 2.2 TeV/n	PRL 125, 251102 (2020)	**10 GeV/n – 2.2 TeV/n**
	Iron spectrum	10 GeV – 1 PeV	to 2 TeV/n	PRL 125,241101 (2021)	**10 GeV/n – 2 TeV/n**
	Elemental spectra of primaries	10 GeV – 1 PeV	to 100 TeV	ICRC 2019, 034	10 GeV – 100 TeV
	Ultra-heavy abundances	> 600 MeV/n	> 600 MeV/n	ICRC 2019, 130	> 600 MeV/n
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**
Nearby electron sources	**Electron spectral shape**	100 GeV – 20 TeV	to 4.8 TeV	ICRC 2019, 142	to 4.8 TeV
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
Gamma rays	**Diffuse & point sources**	1 GeV – 10 TeV	1 GeV – 1 TeV	ApJS 238:5 (2018)	1 GeV – 1 TeV
Heliospheric physics	**Solar modulation**	1 GeV – 10 GeV	1 – 10 GeV	ICRC 2019, 1126	**1 – 10 GeV**
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)
Space weather	**Relativistic electron precipitation**	> 1.5 MeV	> 1.5 MeV	Geophys.Res.Lett,43 (2016)	> 1.5 MeV

Main Science Goals and Status of the Analysis

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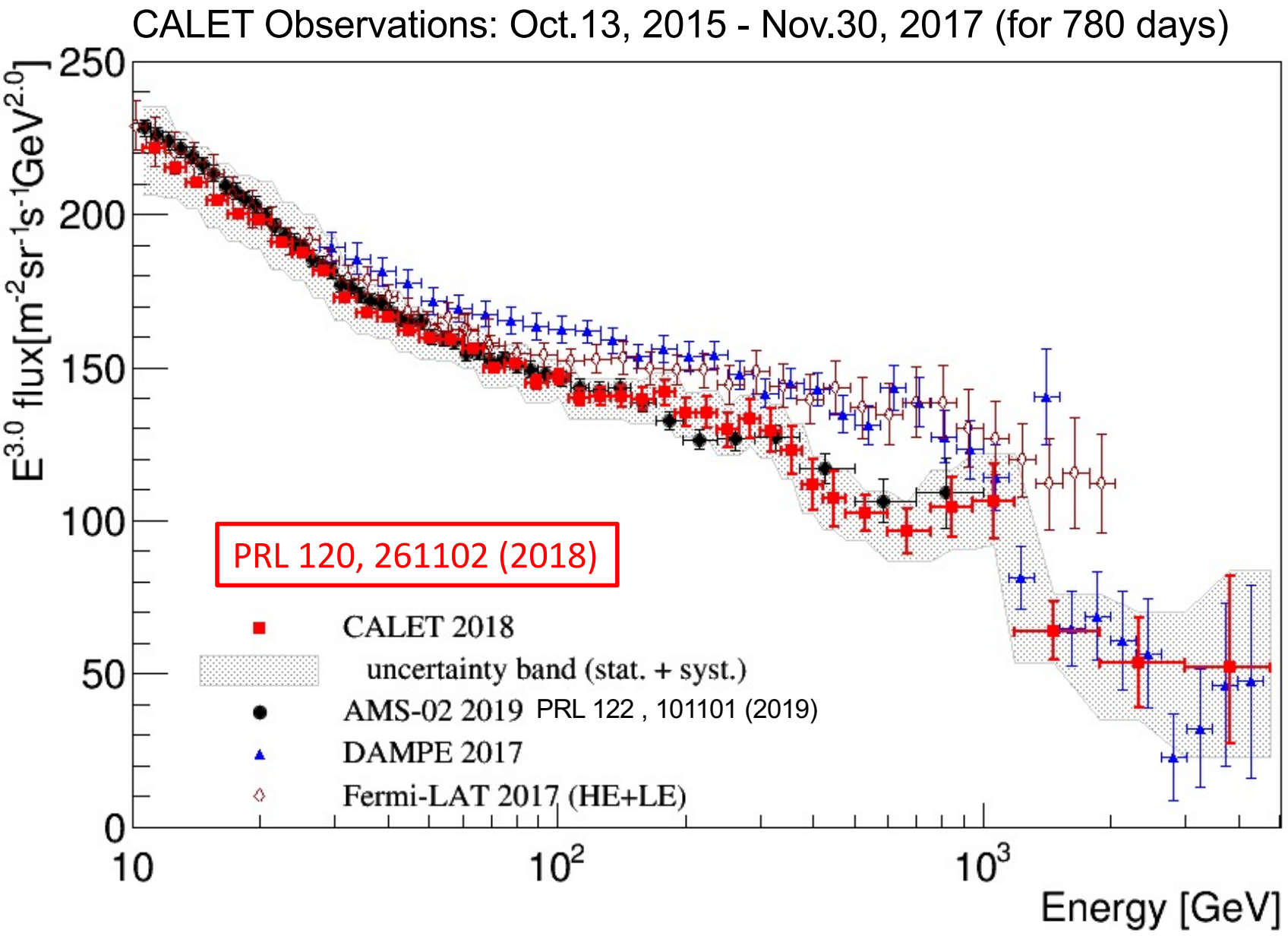
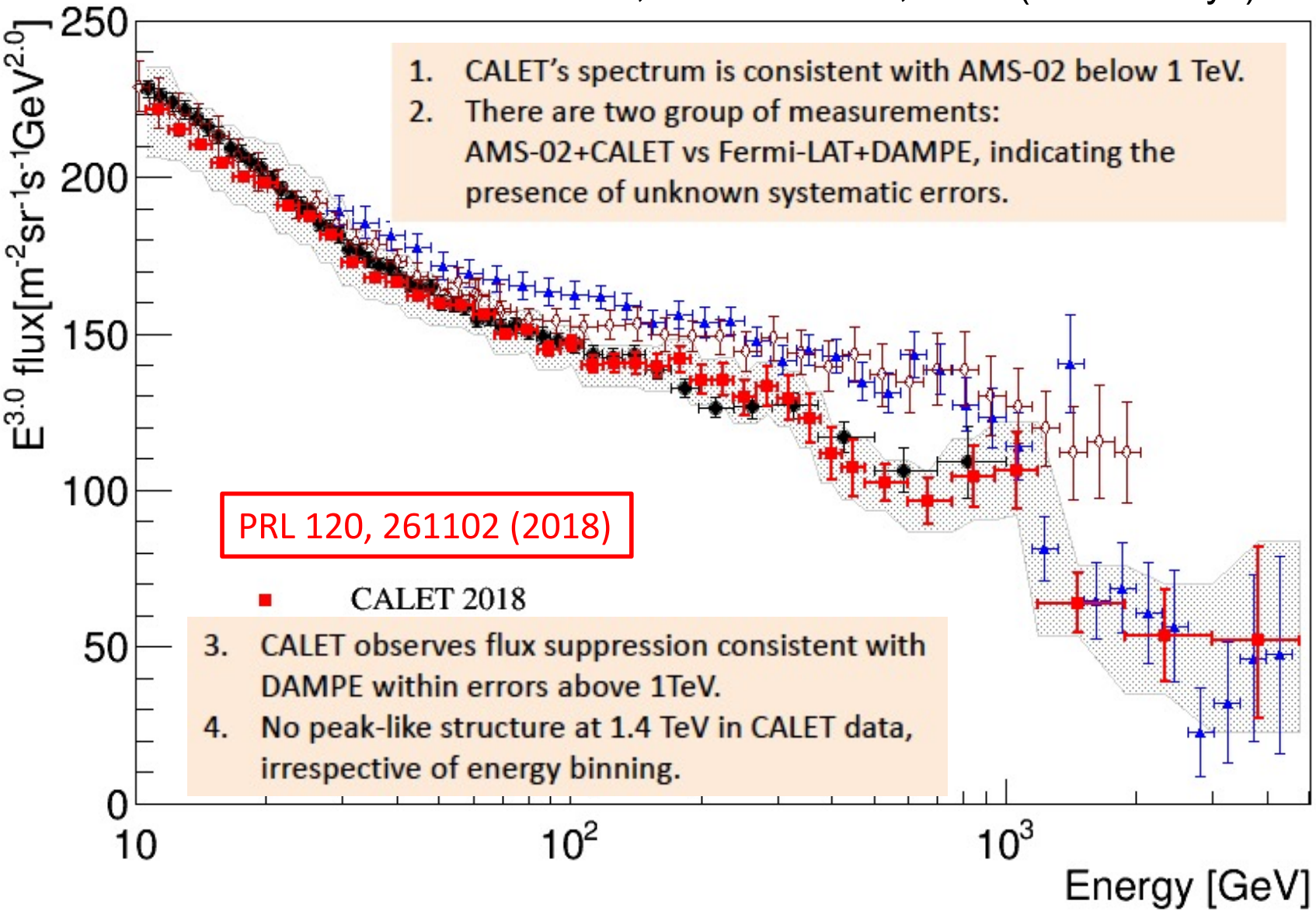
✔: report in this presentation

Electron Spectrum

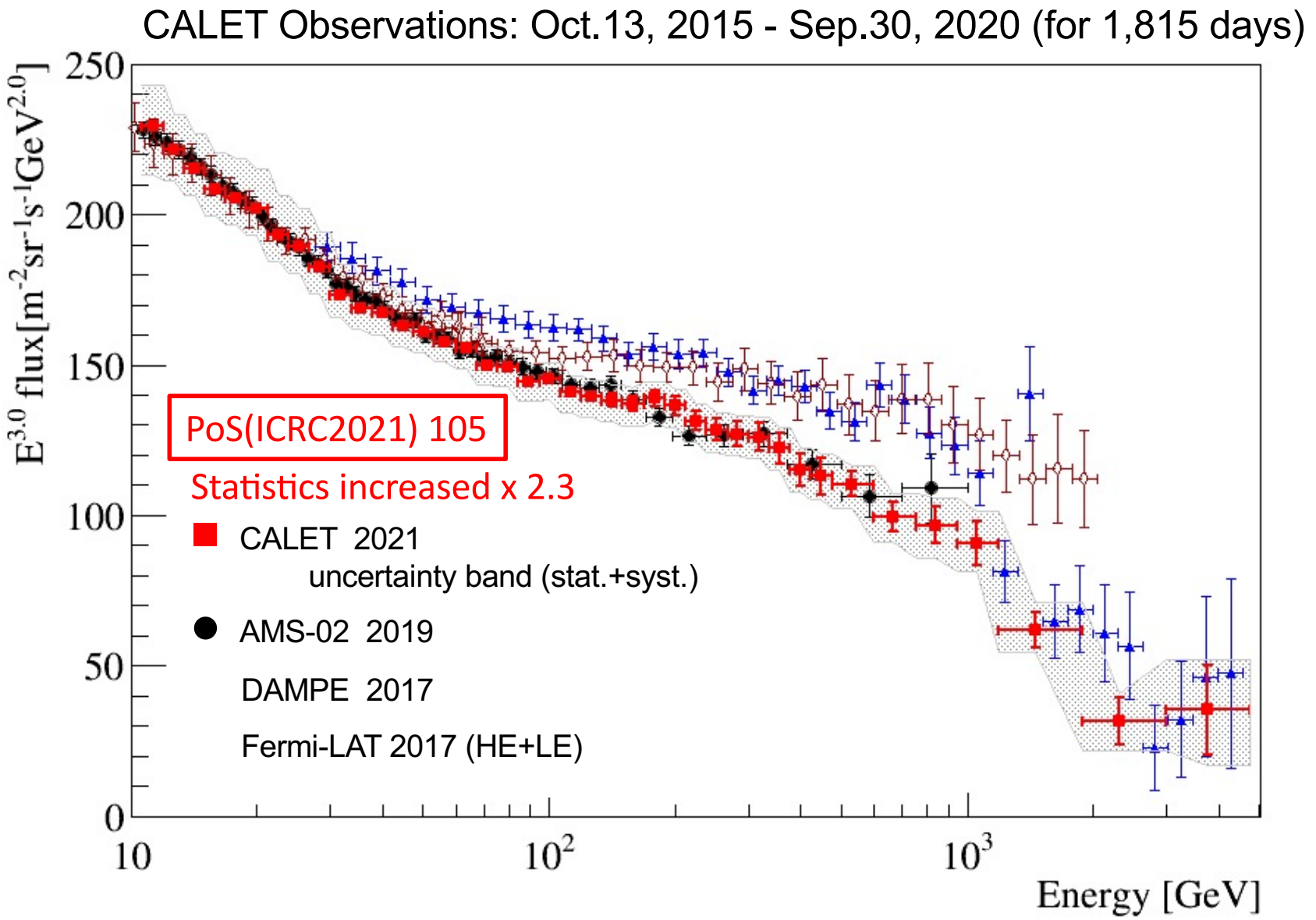


Electron Spectrum

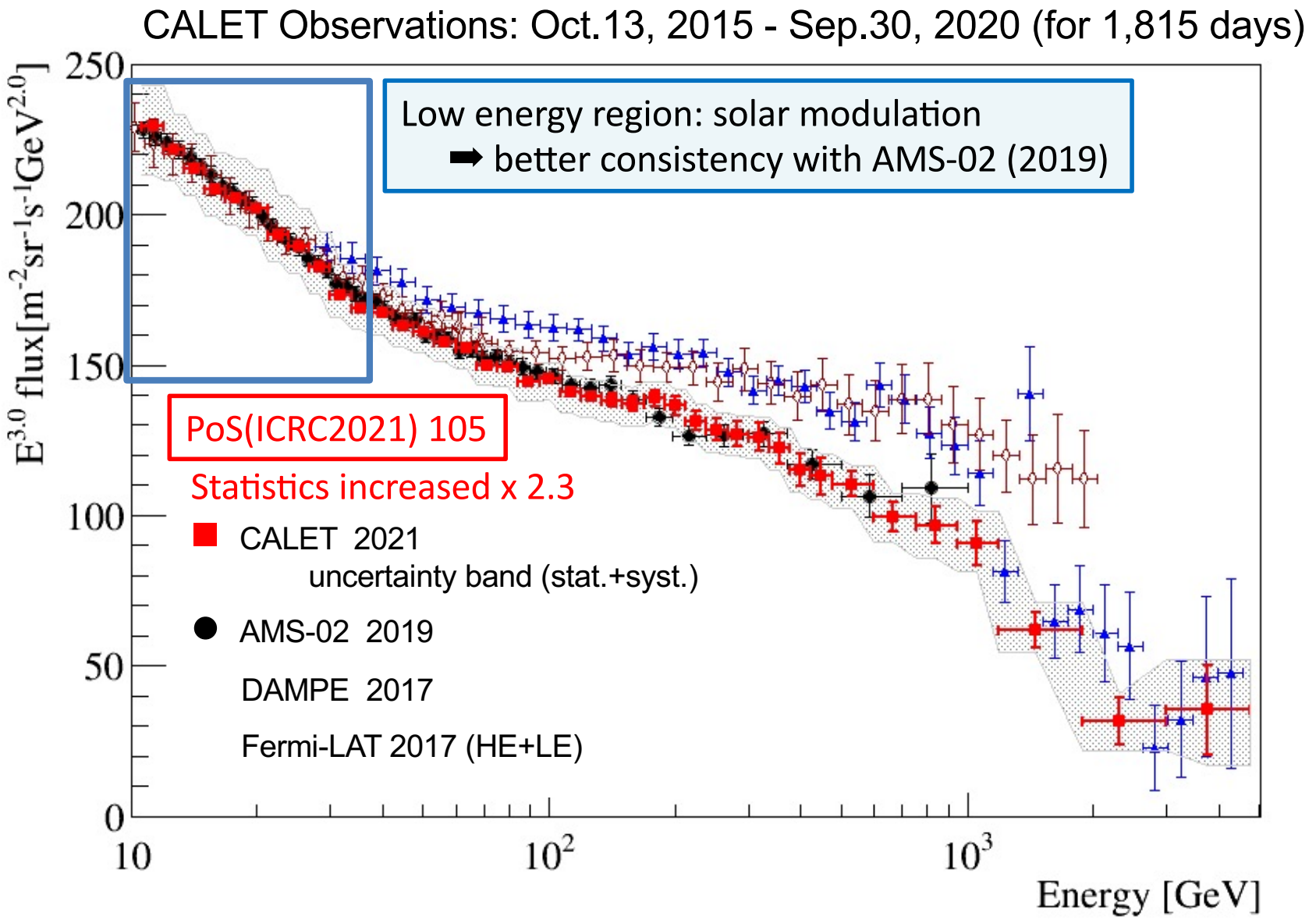
CALET Observations: Oct.13, 2015 - Nov.30, 2017 (for 780 days)



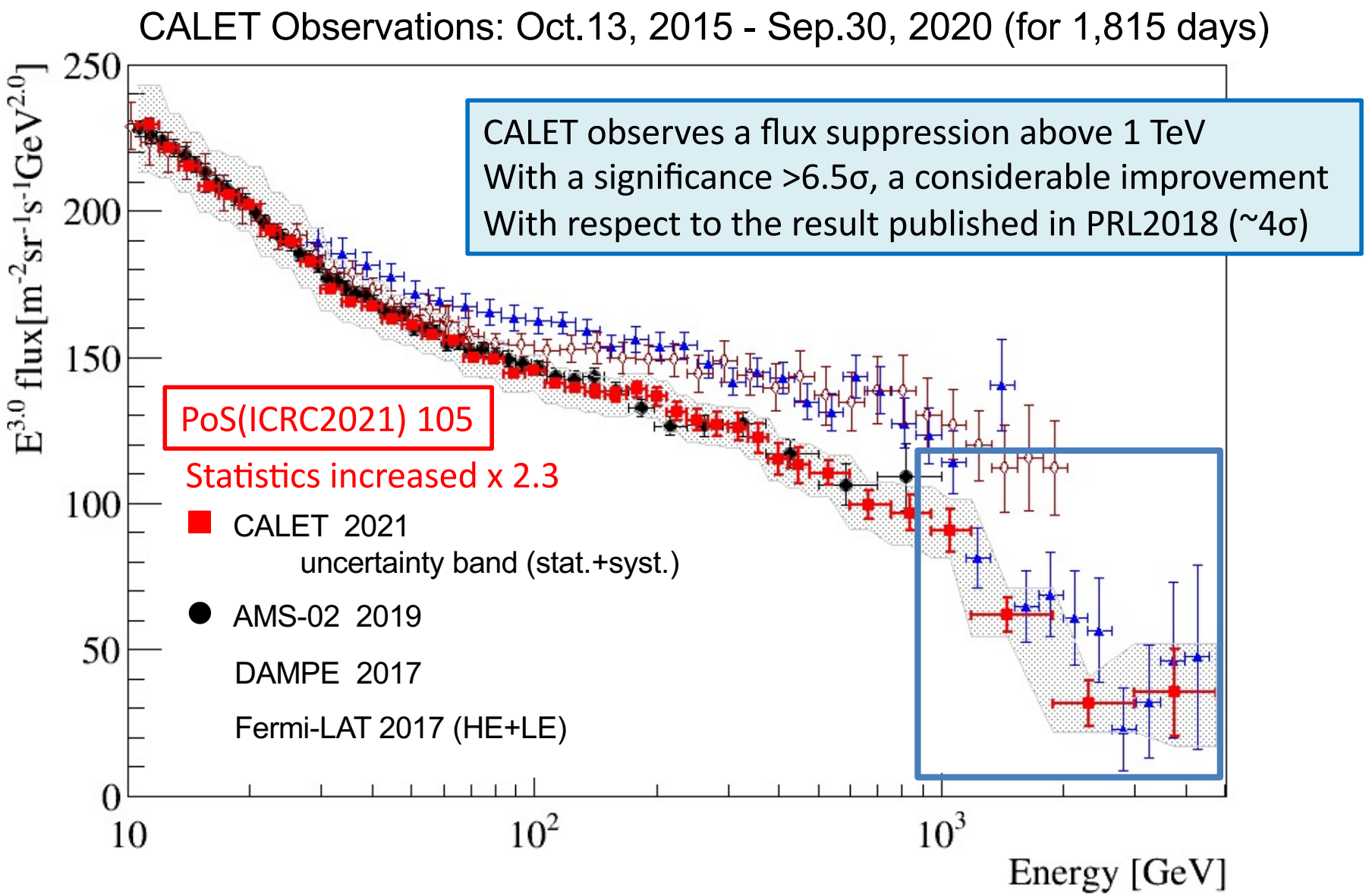
Electron Spectrum



Electron Spectrum



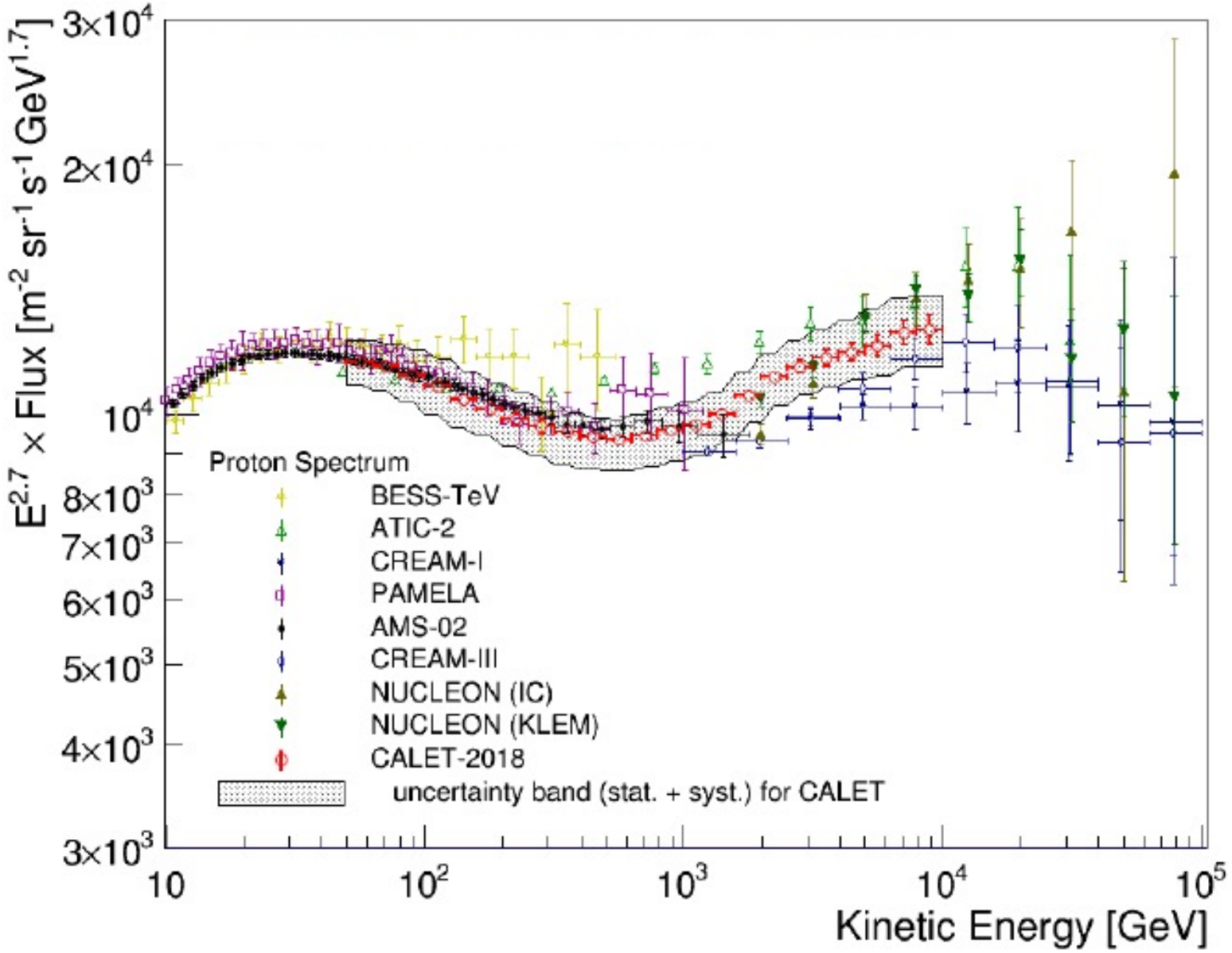
Electron Spectrum



Proton Spectrum

PRL 122, 181102 (2019)

CALET Observations: Oct.13,2015- Aug.31,2018 (for 1,056 days)



Proton Spectrum

PRL 122, 181102 (2019)

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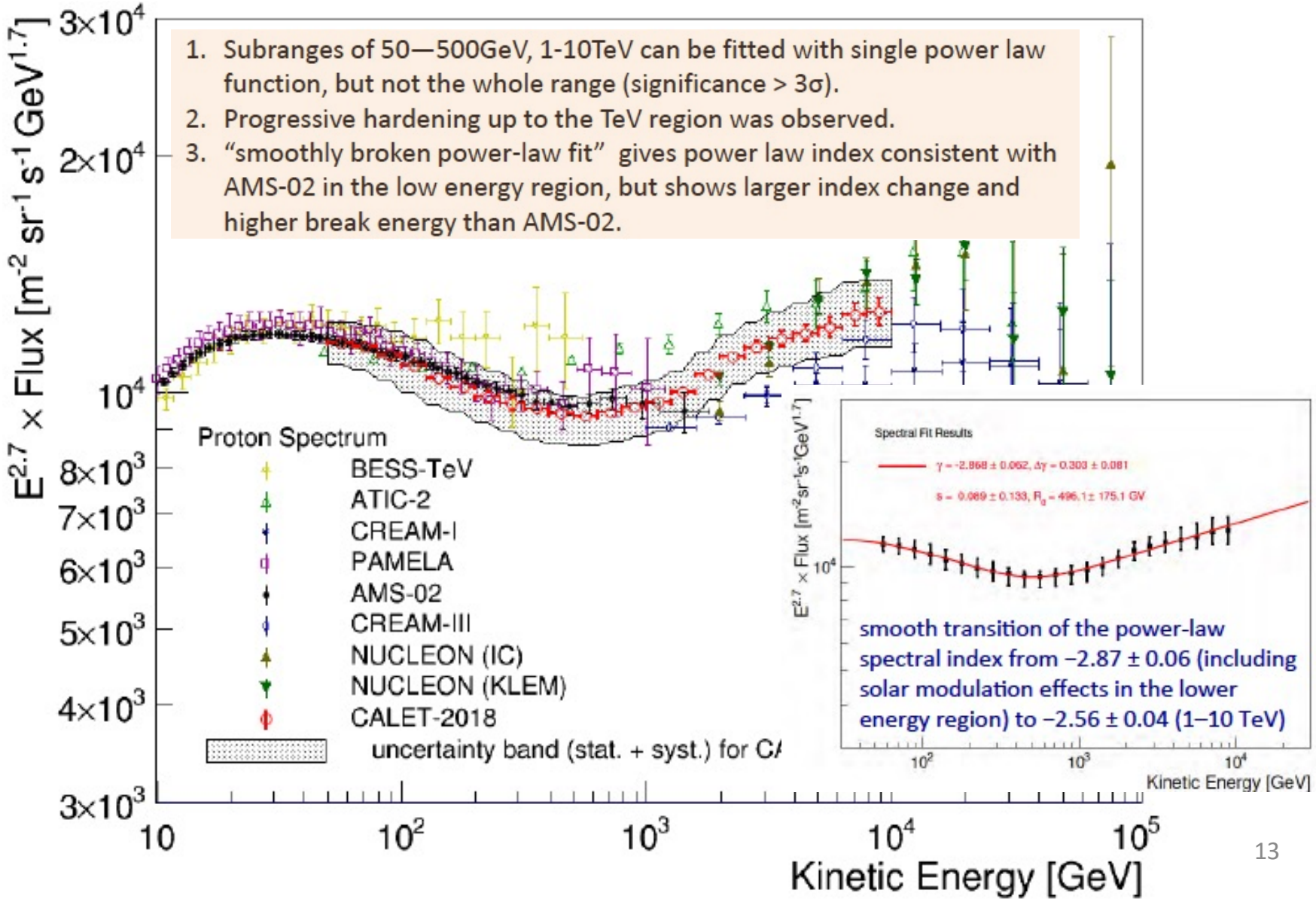
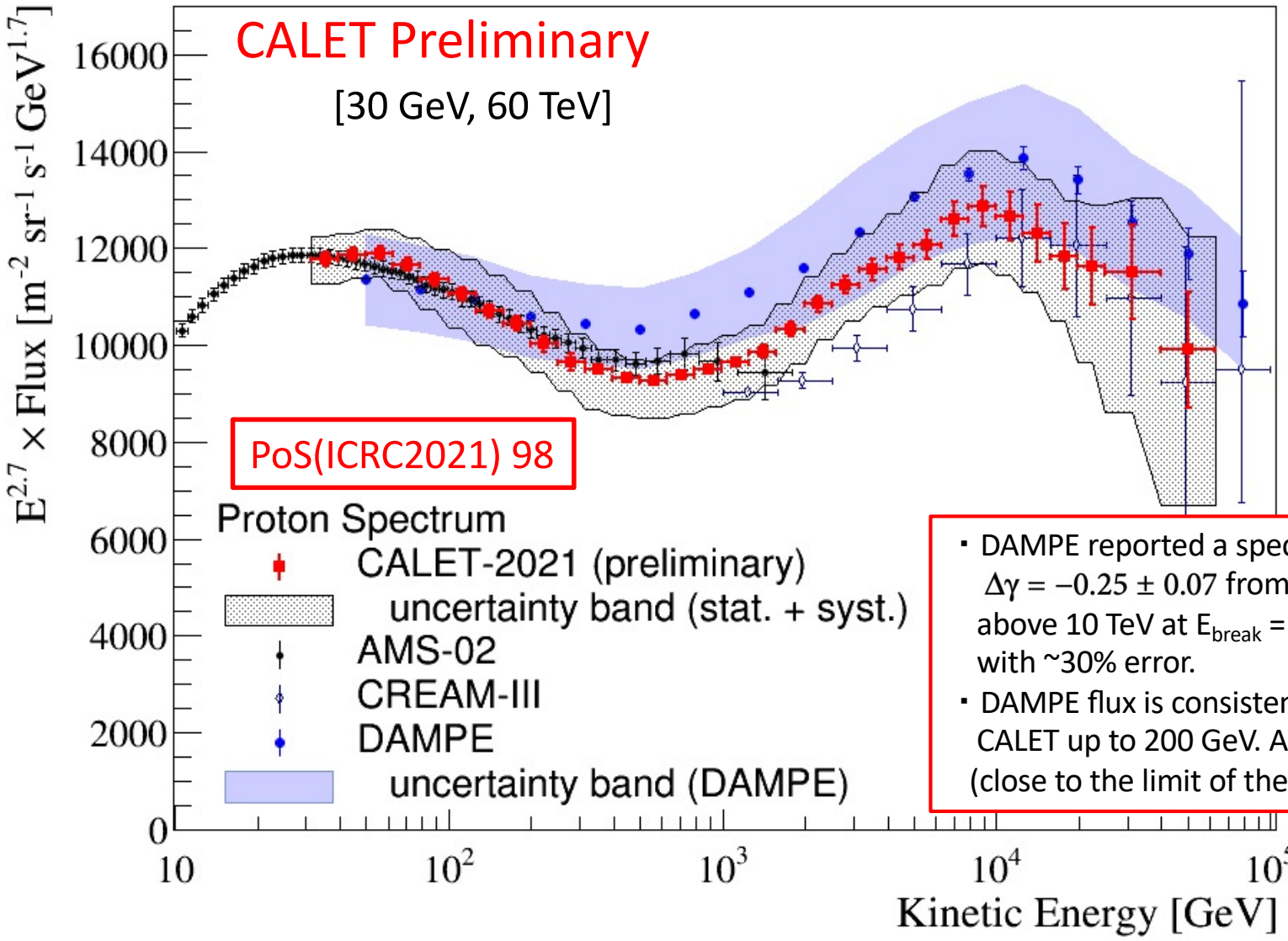


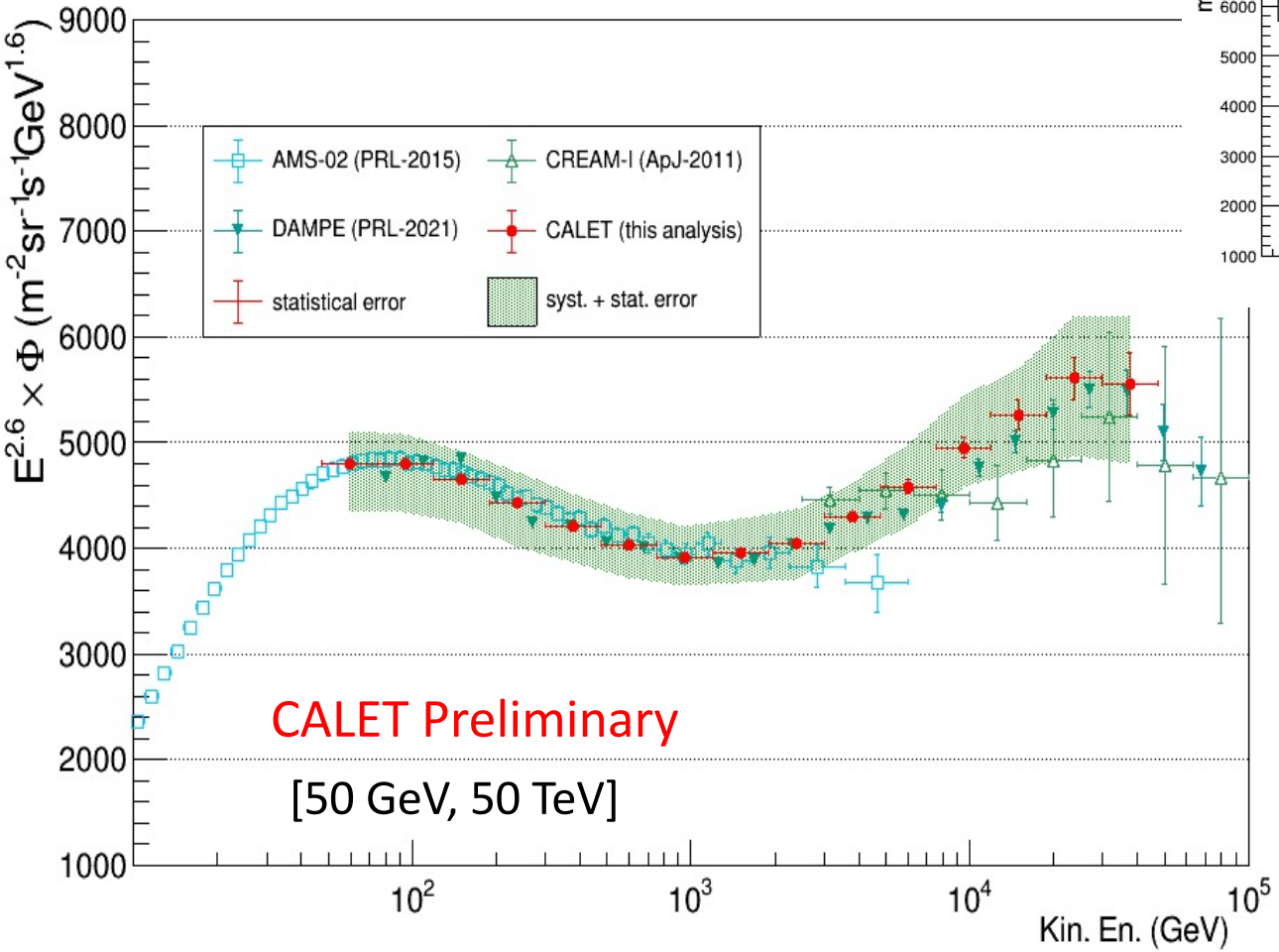
Proton Spectrum

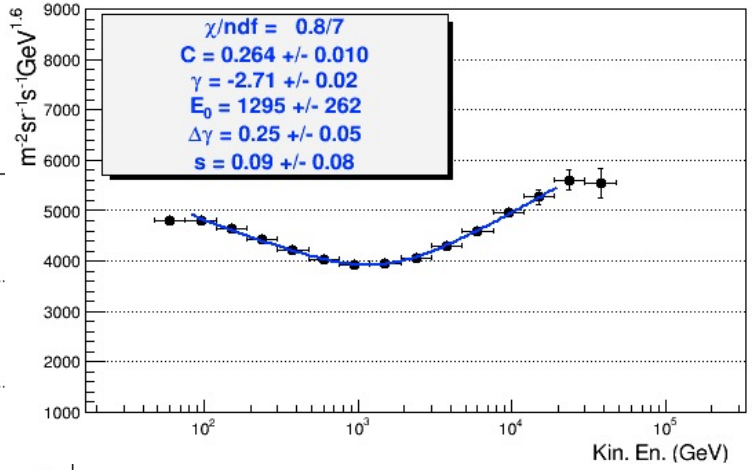


- DAMPE reported a spectral index softening $\Delta\gamma = -0.25 \pm 0.07$ from ~-2.60 to ~-2.85. above 10 TeV at $E_{break} = 13.6^{+4.1}_{-4.8}$ TeV with ~30% error.
- DAMPE flux is consistent with AMS-02 and CALET up to 200 GeV. Above, the flux is higher (close to the limit of the systematic error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

Helium Spectrum

PoS(ICRC2021) 101

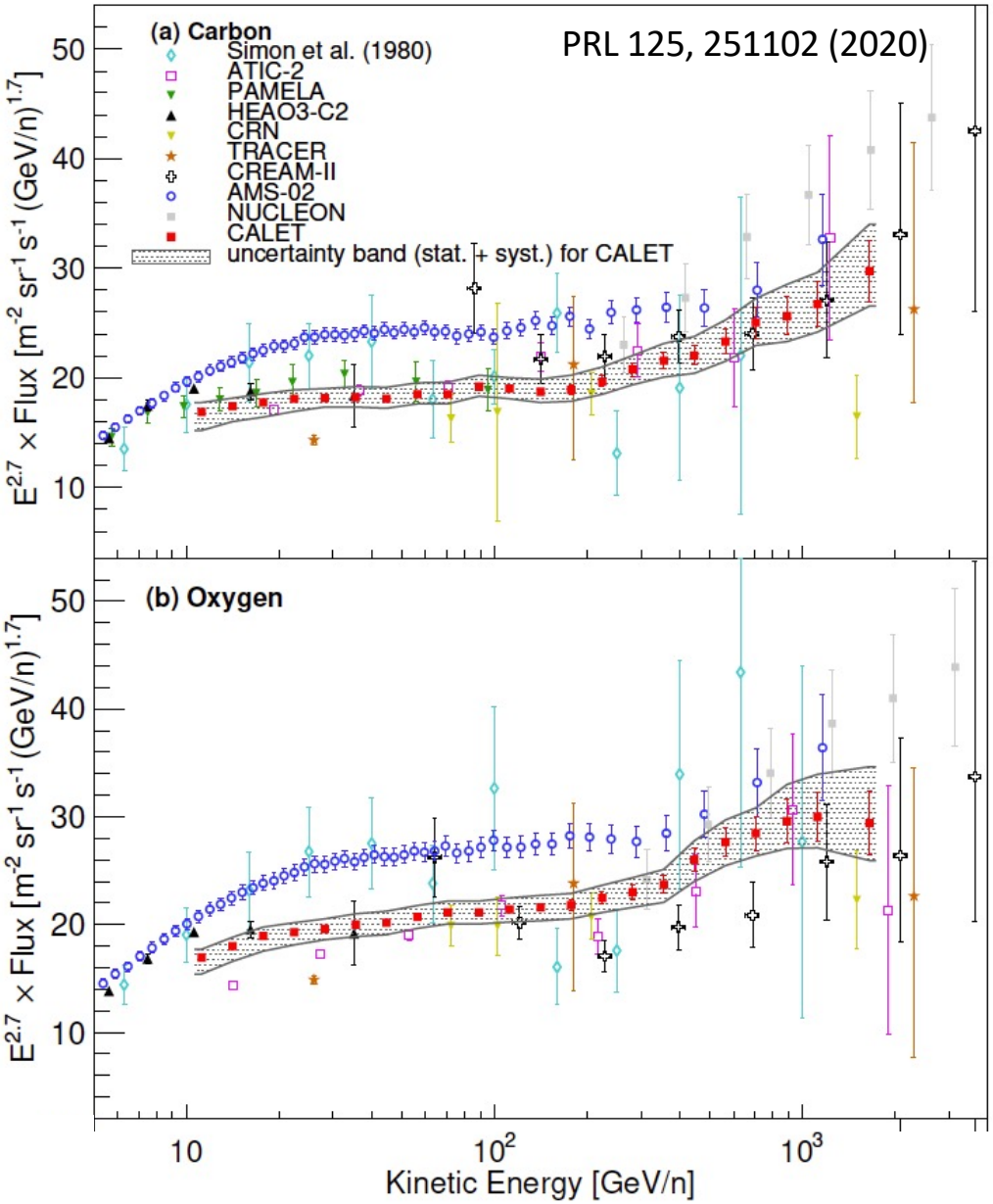


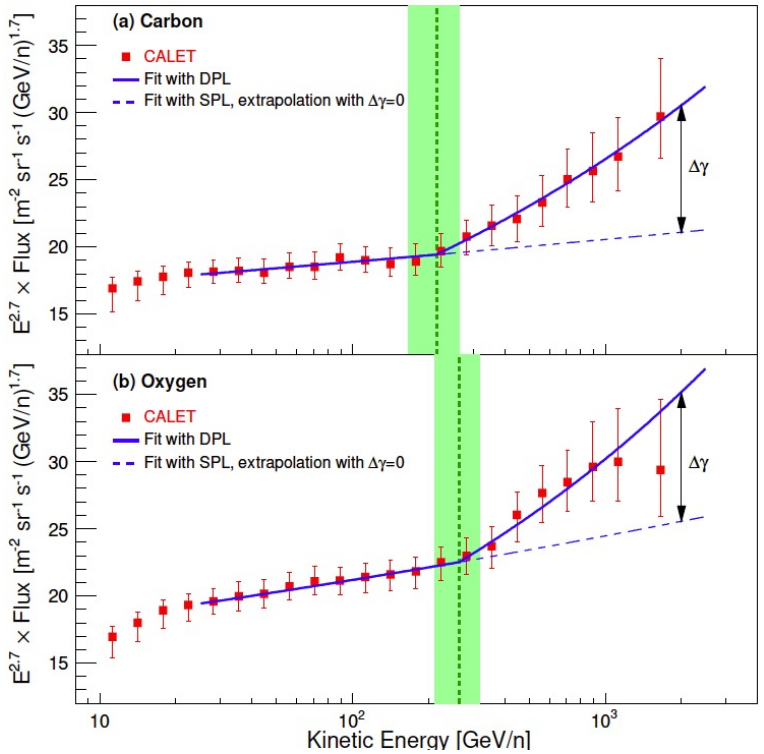


"Smoothly broken power-law fit" gives power law index (γ), Δγ and break energy (E_0) consistent with the recent results from DAMPE.

Carbon and Oxygen Spectra

PRL 125, 251102 (2020)
PoS(ICRC2021) 93





$$\Phi(E) = \begin{cases} C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma} & E \le E_0 \\ C\left(\frac{E}{\mathrm{GeV}}\right)^{\gamma}\left(\frac{E}{E_0}\right)^{\Delta\gamma} & E > E_0 \end{cases}$$

Carbon

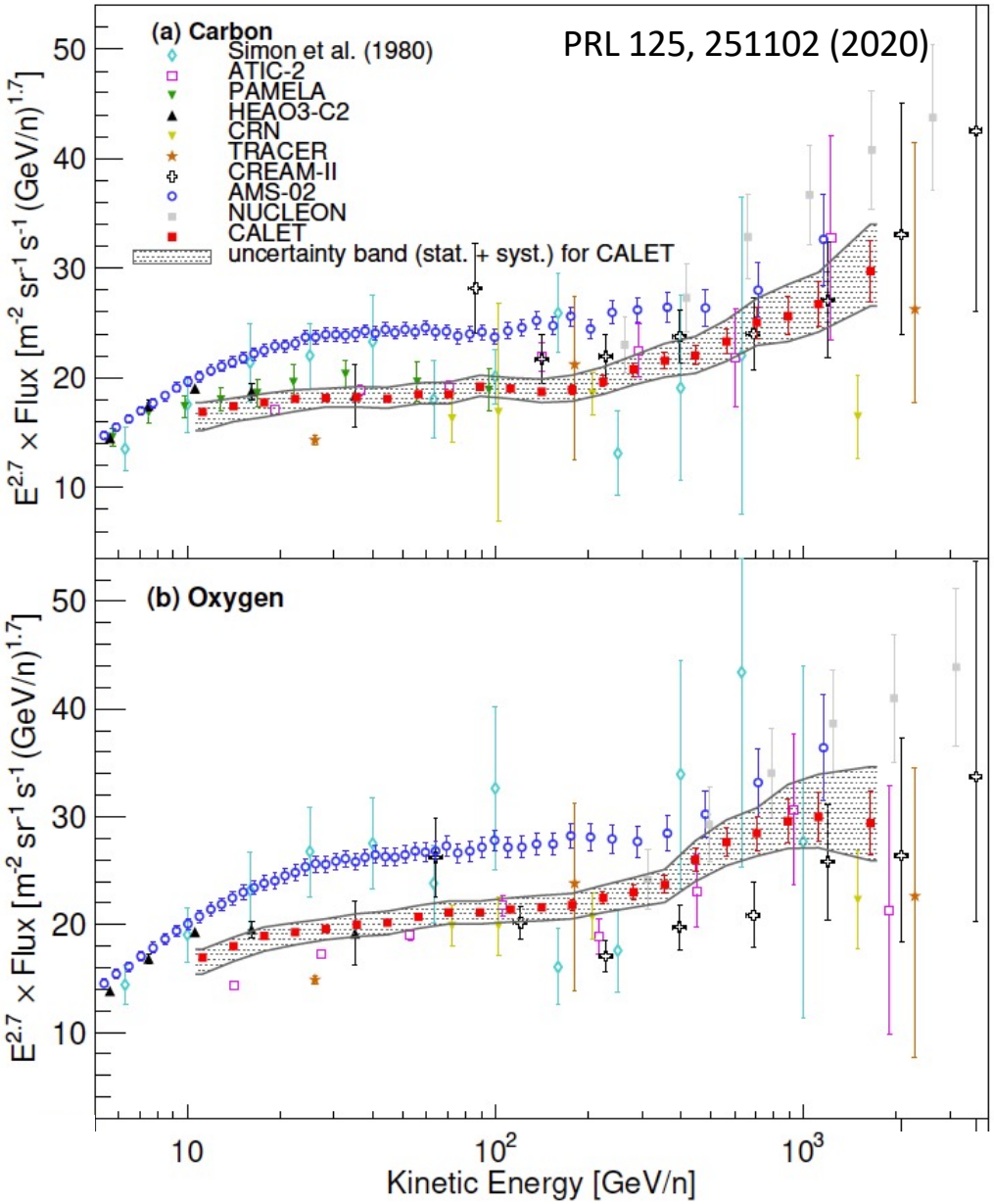
$\gamma = -2.663 \pm 0.014$
$E_0 = 215 \pm 54\,\mathrm{GeV/n}$
$\Delta\gamma = 0.166 \pm 0.042 \;\; (4.0\,\sigma)$
with $\chi^2/\mathrm{d.o.f.} = 9.0/8$

Oxygen

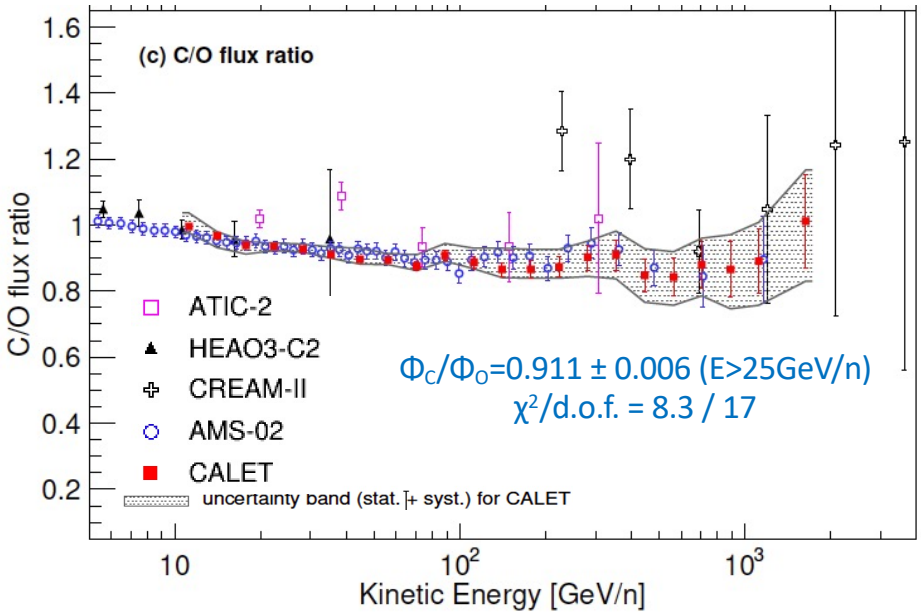
$\gamma = -2.637 \pm 0.009$
$E_0 = 264 \pm 53\,\mathrm{GeV/n}$
$\Delta\gamma = 0.158 \pm 0.053 \;\; (3.0\,\sigma)$
with $\chi^2/\mathrm{d.o.f.} = 3.0/8$

Carbon and Oxygen Spectra

PRL 125, 251102 (2020)
PoS(ICRC2021) 93



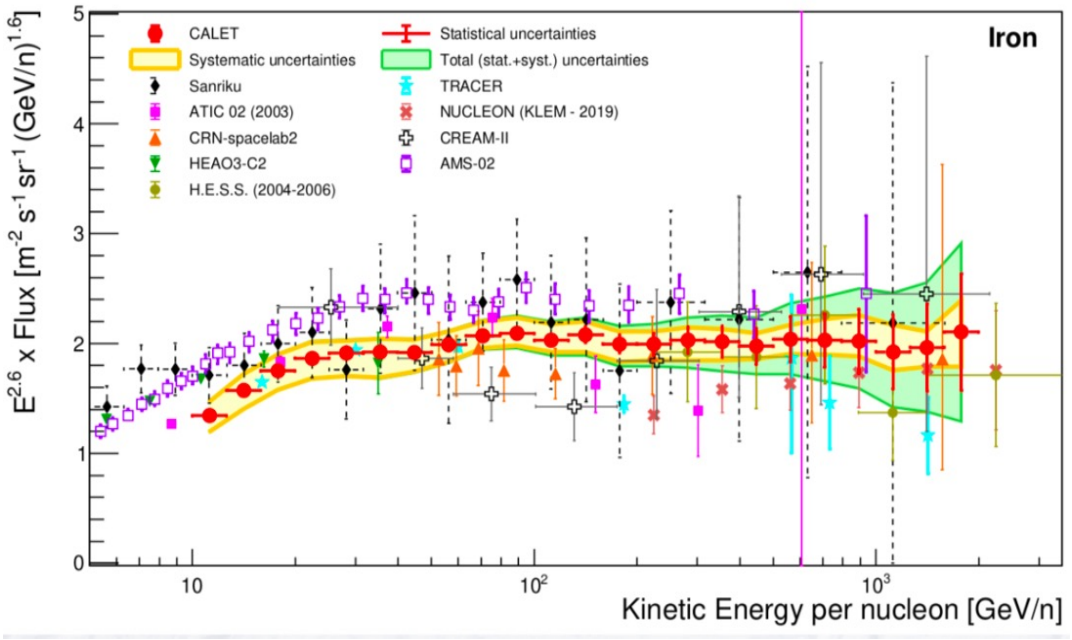
CALET Observations:
Oct.13,2015- Oct.31,2019 (for 1,480 days)

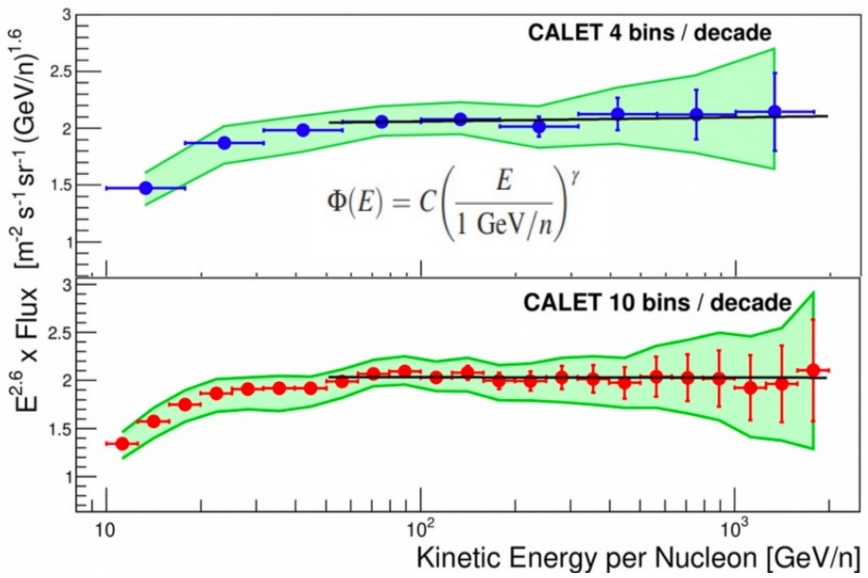


The carbon to oxygen flux ratio is well fitted to a constant value above 25 GeV/n, indicating that the two fluxes have the same energy dependence

Iron Spectrum

PRL 126, 241101 (2021)
PoS(ICRC2021) 109





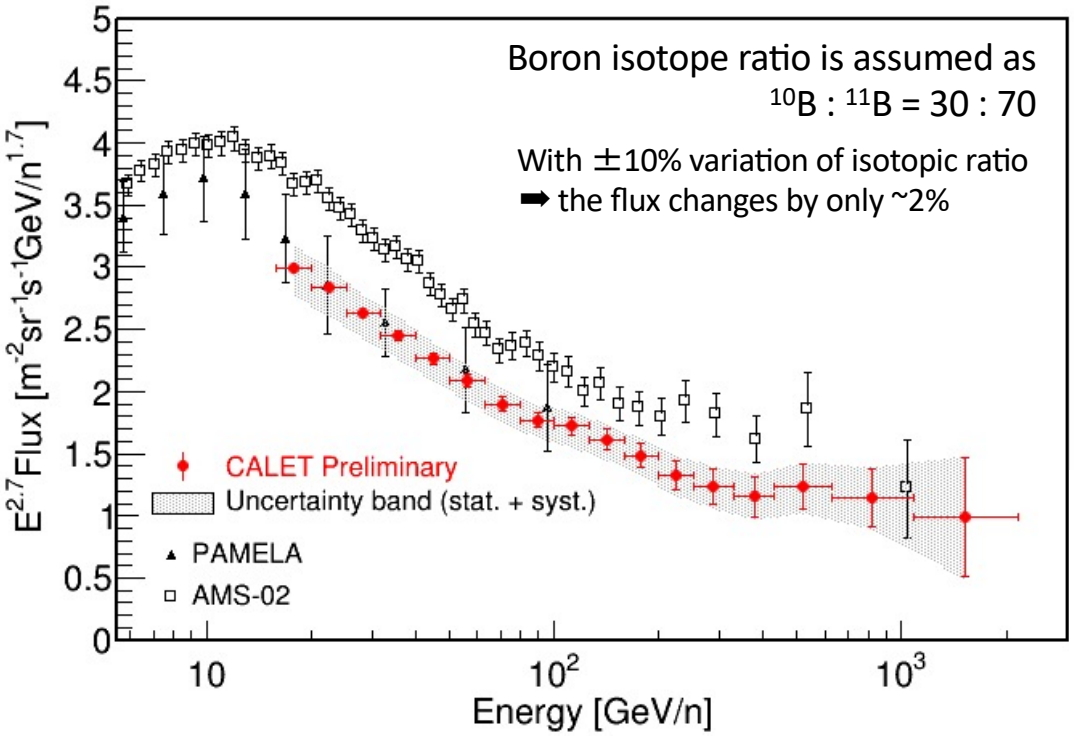
10bins/dec: γ=-2.60 ± 0.02 (stat) + 0.02 (sys)
4bins/dec: γ=-2.59 ± 0.02 (stat) + 0.04 (sys)

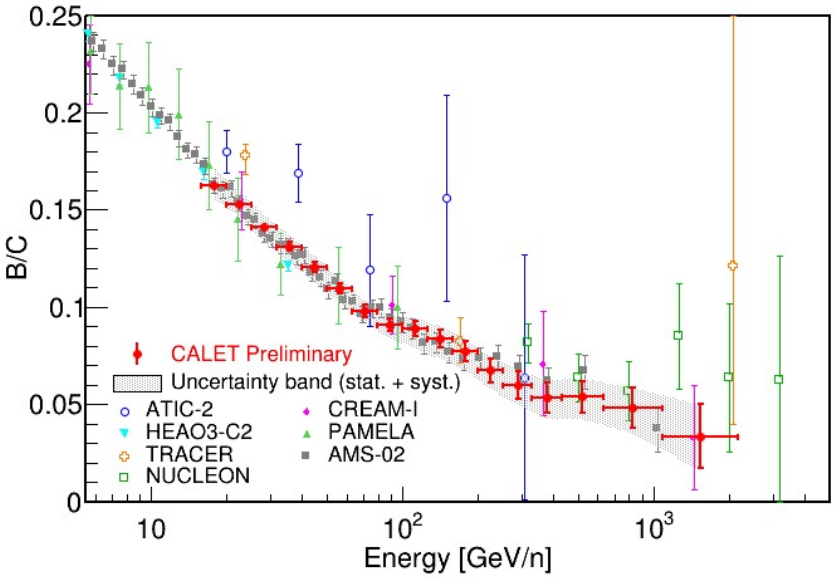
➡ stable when larger energy bins are used

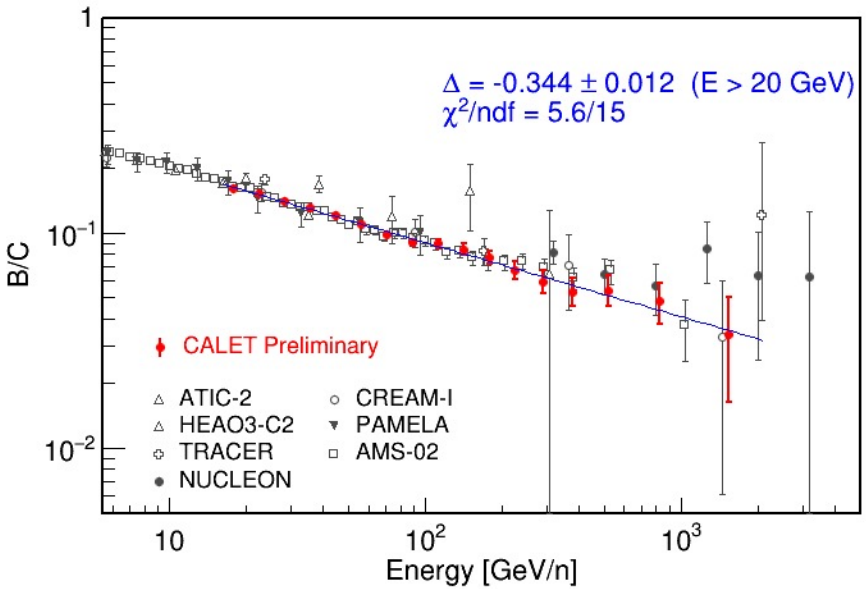
The iron flux, above 50 GeV/n, is compatible within the errors with a single power law
Analysis for the nickel spectrum is ongoing

Boron Spectrum and B/C ratio

PoS(ICRC2021) 112





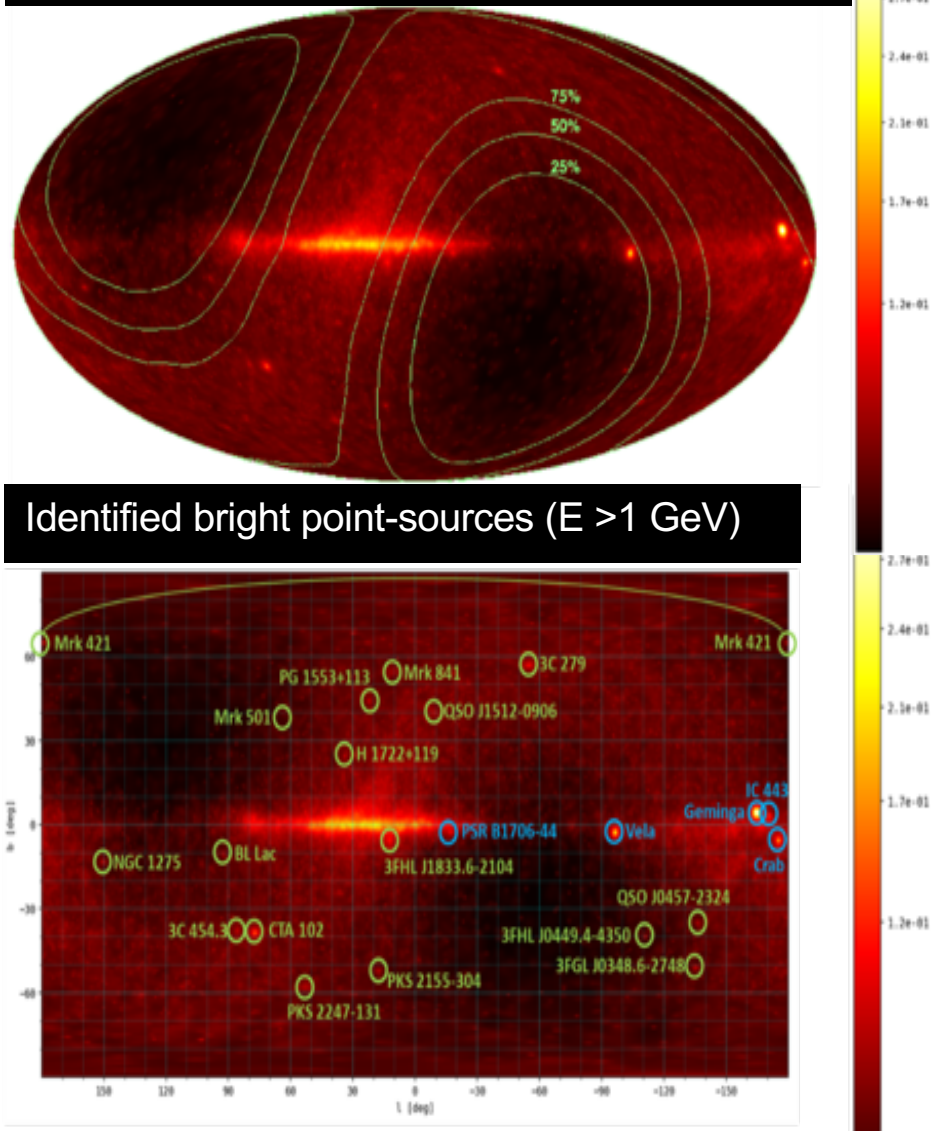


- Preliminary CALET result is consistent with PAMELA, but lower than AMS-02
- B/C ratio is well consistent with other experiments

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

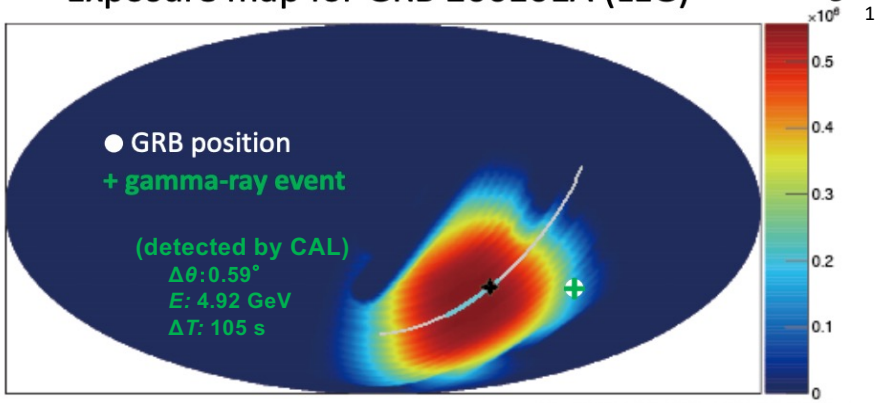
PoS(ICRC2021) 112
PoS(ICRC2021) 604
PoS(ICRC2021) 1619

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



Identified bright point-sources (E >1 GeV)

Exposure map for GRB 200101A (LEG) cm² s erg⁻¹



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

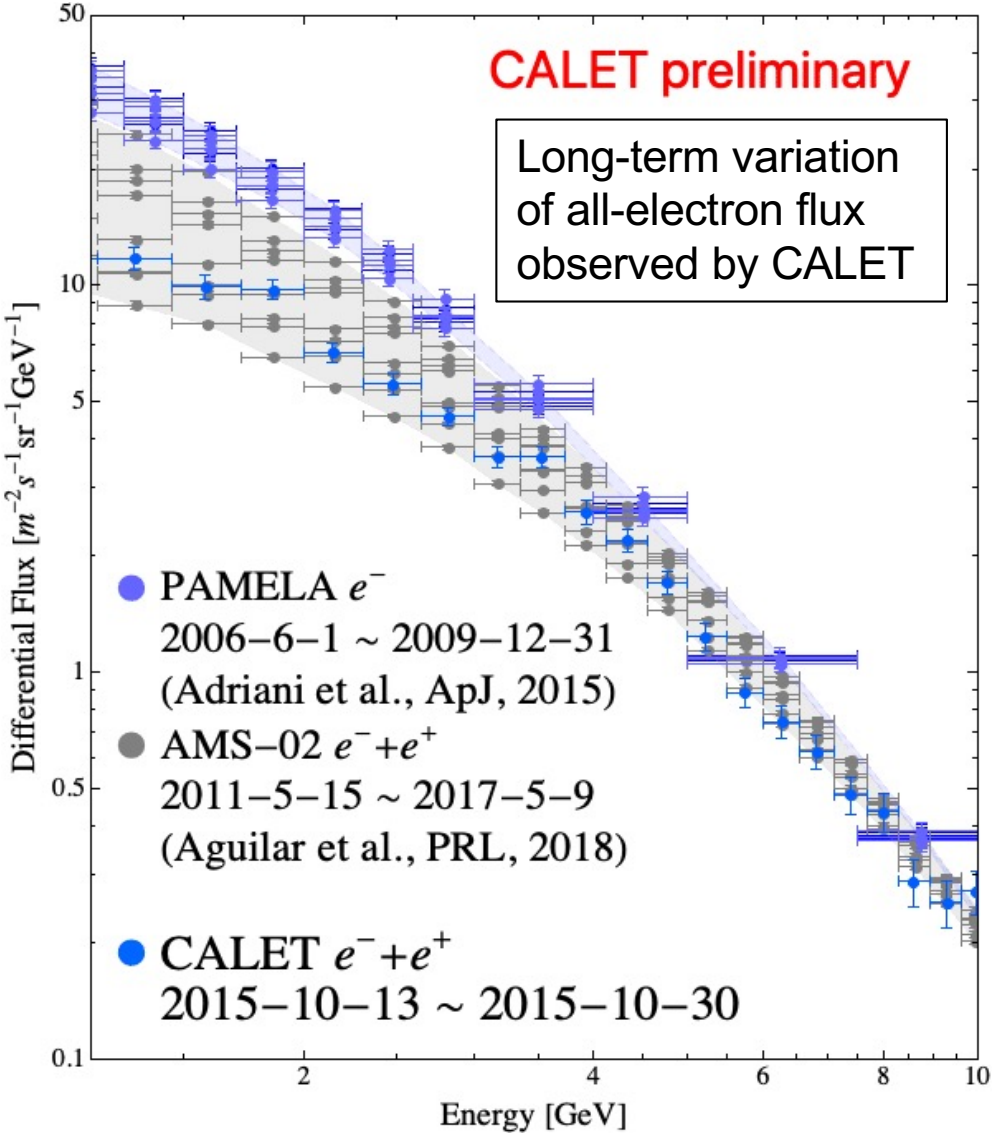
from 2015-10-05 to 2021-07-23
259 GRBs (44.9 GRBs / year)
228 Long (88%) **31 Short (12%)**

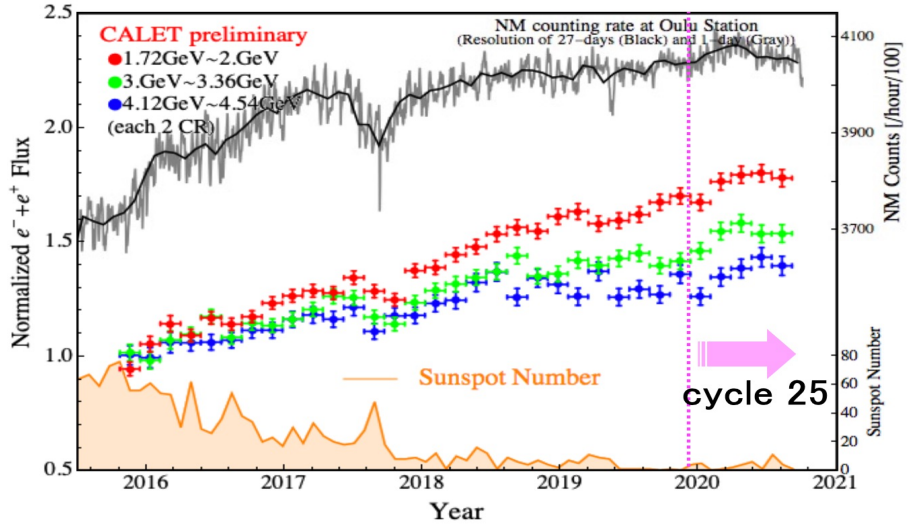
- **Follow-up** of LIGO/Virgo **GW** observations in:
  - X-ray and γ-ray bands
  - high-energy γ-in calorimeter
- DM limit

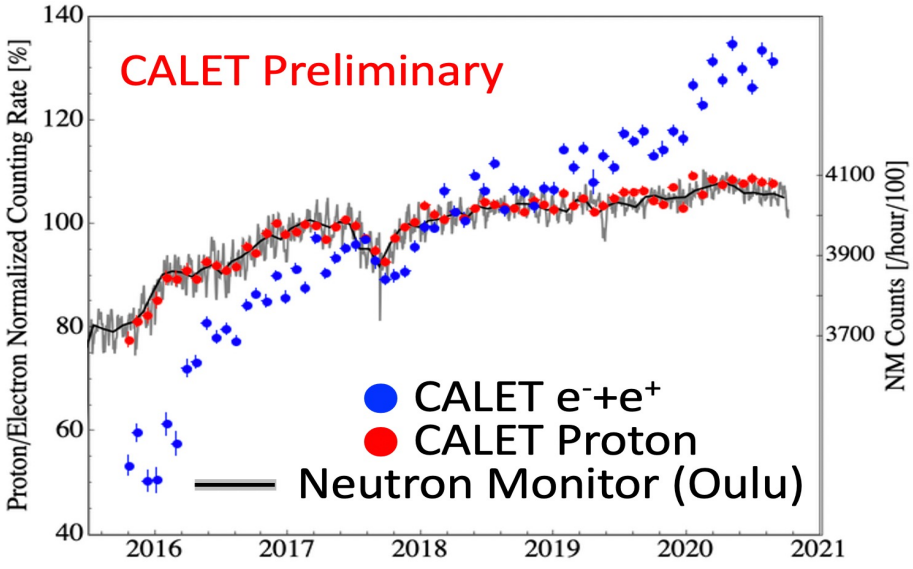
- **Limits on DM** annihilation into γγ: $\langle\sigma v\rangle < 10^{-28}$-$10^{-25}$cm^{-3}s^{-1}
- Limits on DM decay $\chi \rightarrow \gamma\nu$ etc.: $\tau_{DM} > 10^{30}$s (m_{DM}>100 GeV)

Solar Modulation

PoS(ICRC2021) 1270







Summary

- CALET has been accumulating scientific data for over 6 years with excellent performance since October 13, 2015
- Linearity in the energy measurements established up to 10^6 MIP and continuous on-orbit calibration updates
- Following results have been achieved by now
  - Cosmic ray spectra
    - Electron and positron: 11 GeV – 4.8 TeV
    - Proton: 30 GeV – 60 TeV
    - Helium: 50 GeV – 50 GeV
    - Carbon, oxygen and C/O ratio : 10 GeV/n – 2.2 TeV/n
    - Iron: 10 GeV/n – 2.0 TeV/n
    - Boron and B/C ratio: 10 GeV/n – 2.2 TeV/n
  - Study on solar modulation over 5 years
  - Observation of diffuse and point sources (+Sun) of gamma-rays
  - Gamma-ray burst detections and follow-up observation of GW events
- CALET mission is planed by the end of 2024 by approval of JAXA/NASA/ASI