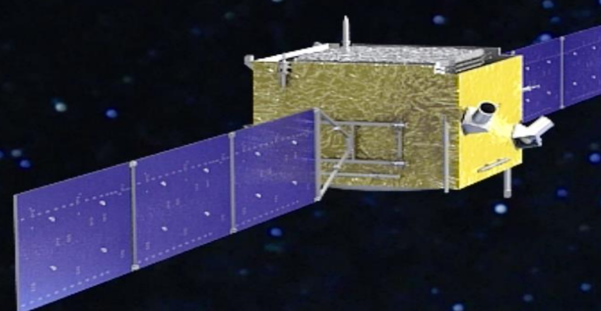
The 2nd LHAASO SYMPOSIUM
21-24 MARCH 2025
HONG KONG, CHINA

Cosmic ray spectrum below the knee

Yi-Zhong Fan (范一中)
Purple Mountain Observatory, Chinese Academy of Sciences

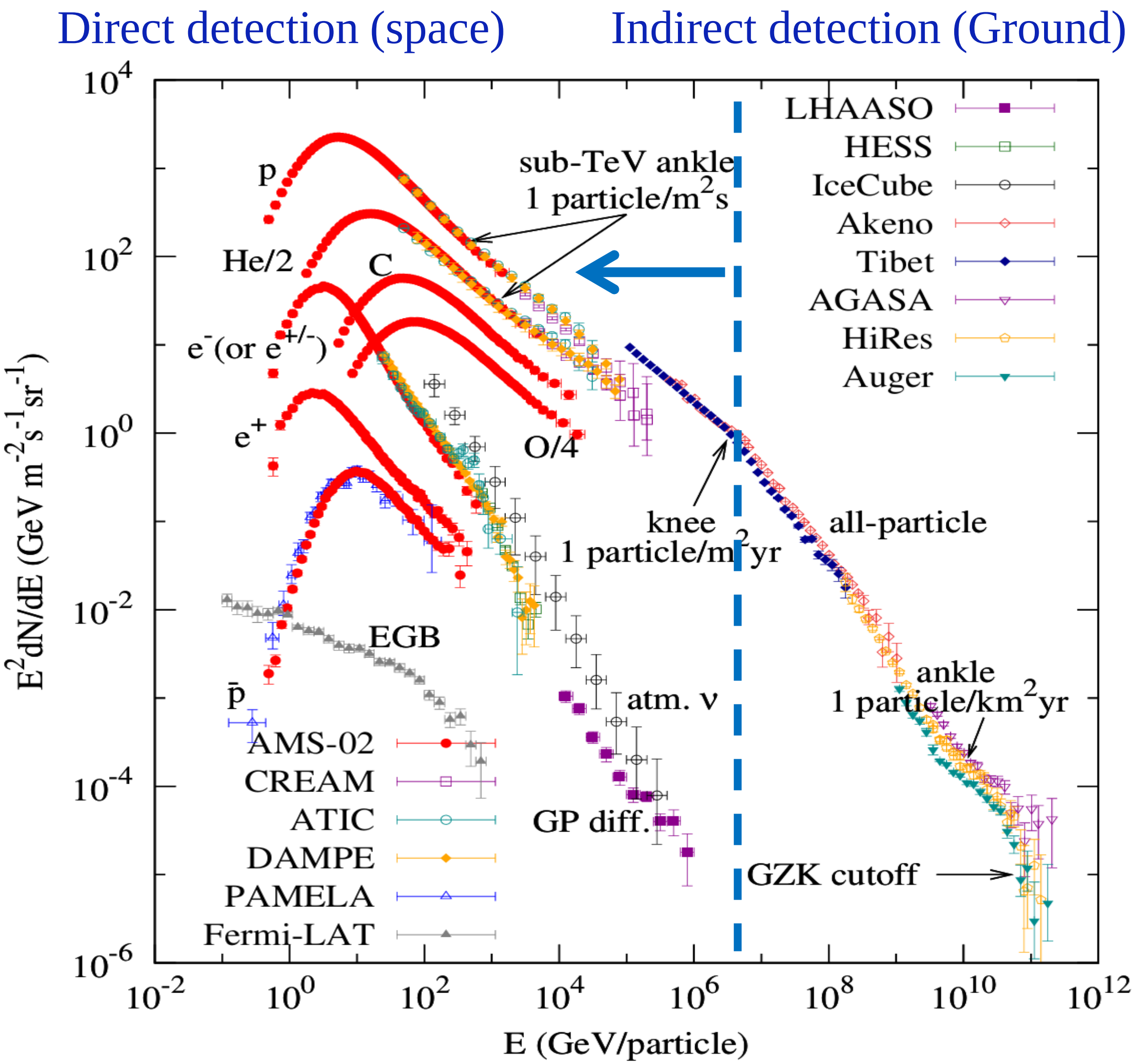


March 23rd, 2025

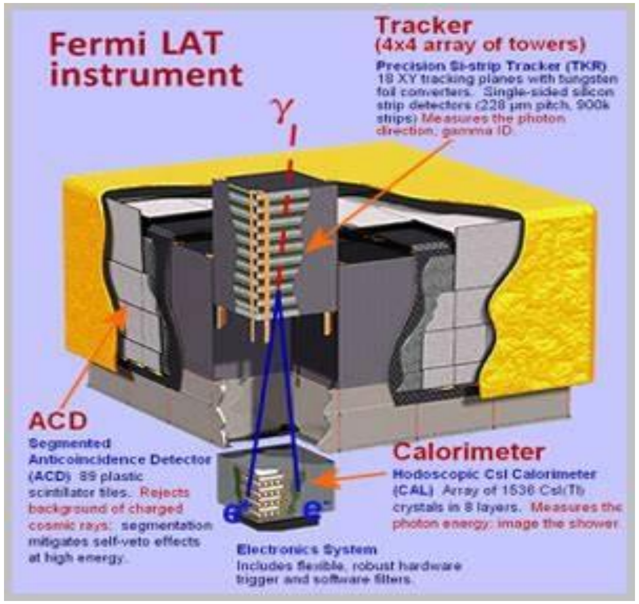
Outline

- Introduction
- Some interesting international results
- DAMPE and its recent results
- Summary

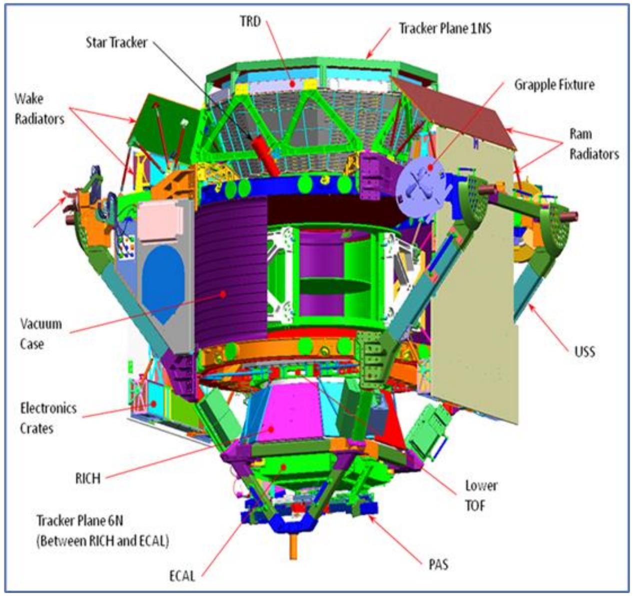
The cosmic ray spectra



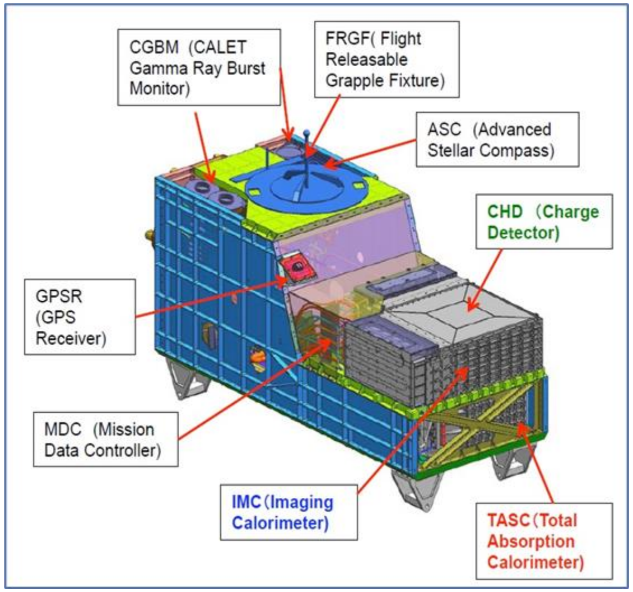
Some space experiments



Fermi-LAT (2008)



AMS-02 (2011)

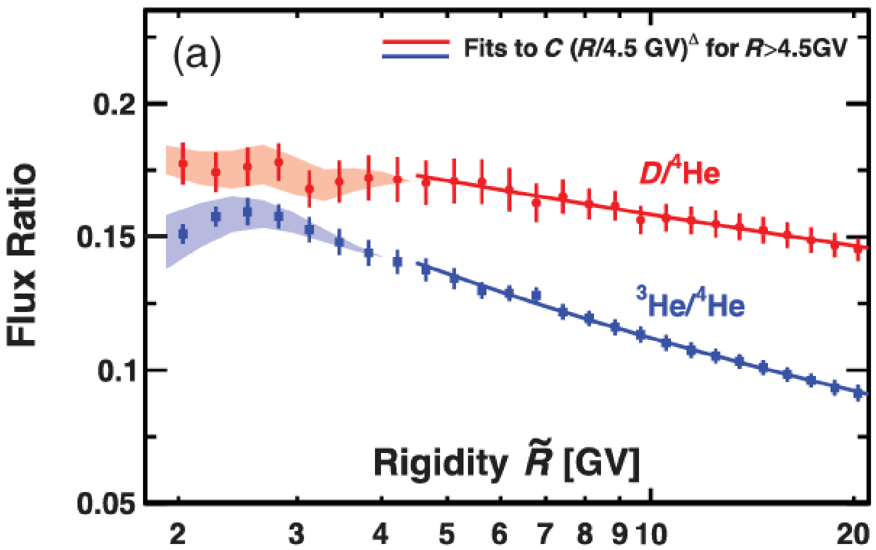


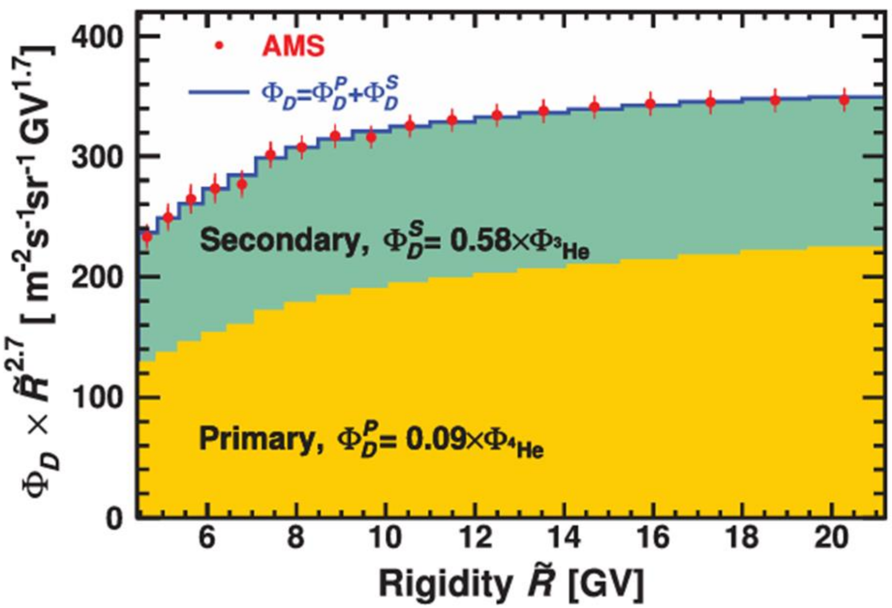
CALET (2015)

Outline

- Introduction
- Some interesting international results
- DAMPE and its recent results
- Summary

AMS-02: primary Deuterons?





Background: Observations of D/He can limit or measure the intrinsic primordial abundance because D is thought to be destroyed by stars. No reliable astrophysical channel can effectively produce primary D

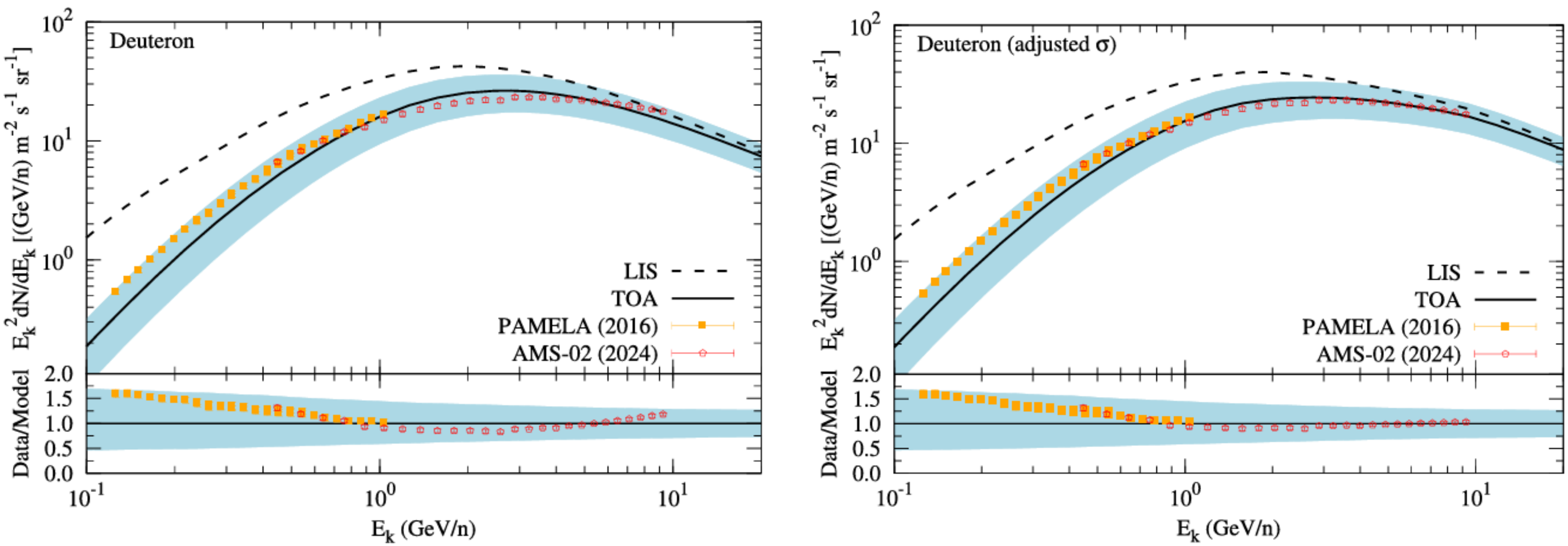
Observation: There is a primary D component (AMS-02 Collaboration. 2024 PRL)! A crisis of the nuclear physics?

AMS-02: primary Deuterons?

The Astrophysical Journal Letters, 974:L14 (6pp), 2024 October 10
https://doi.org/10.3847/2041-8213/ad7e2c

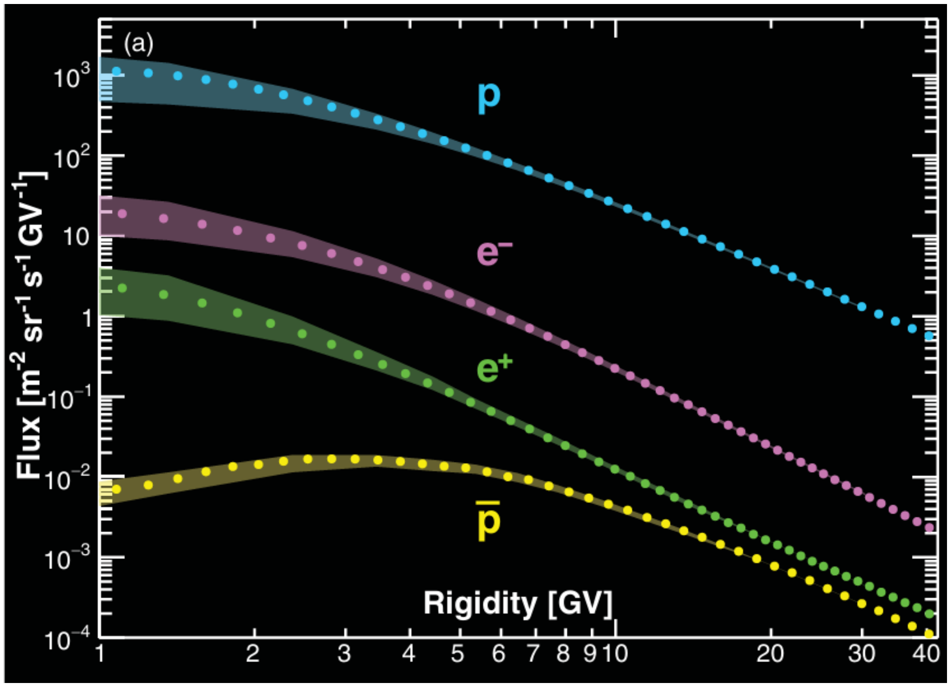
The AMS-02 Cosmic-Ray Deuteron Flux is Consistent with a Secondary Origin

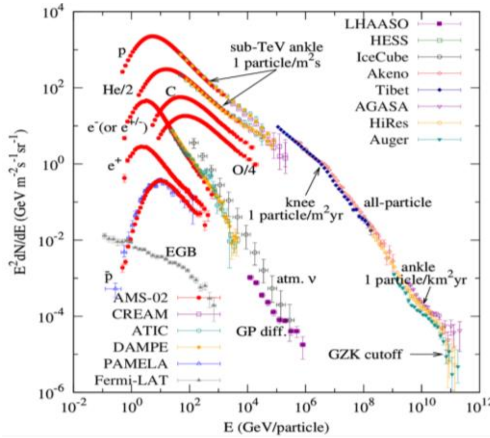
Qiang Yuan[1,2] and Yi-Zhong Fan[1,2]

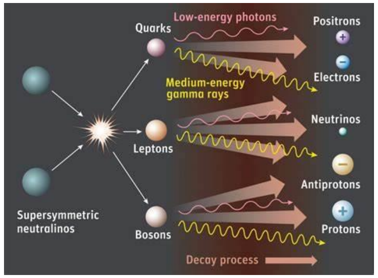


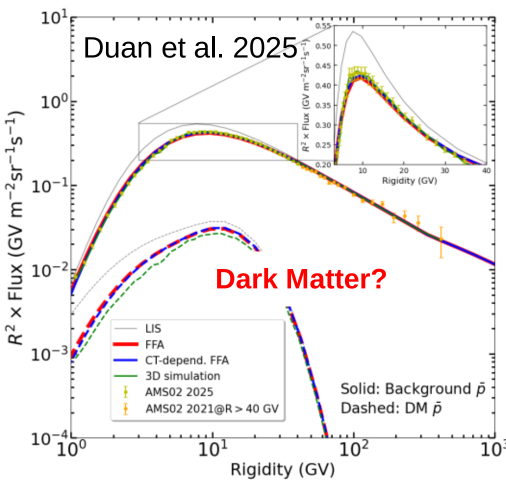
No evidence for a primary D component if one takes into account the more advanced cross sections of the fragmentation of the heavy nuclei into D from B. Coste et al. 2012

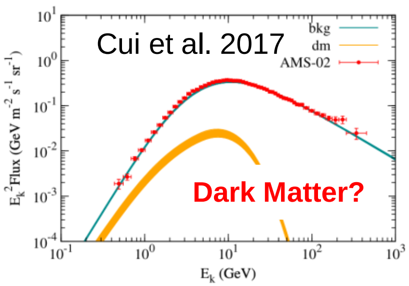
AMS-02: antiproton excess?





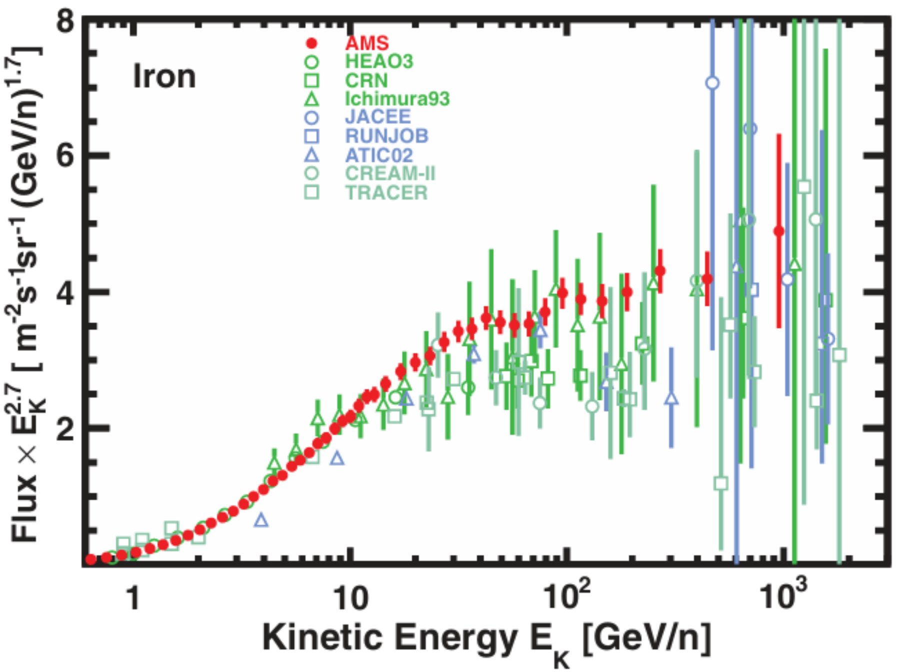




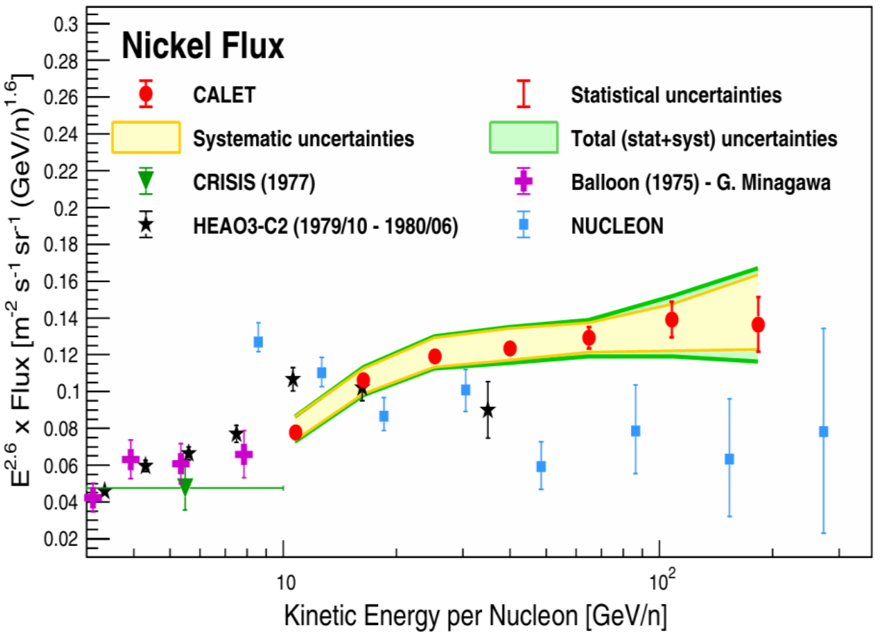


Left panel: the 11-yr time-averaged flux of antiprotons (AMS-02 Collaboration. 2025 PRL)
Right panels: an additional component from ~80 GeV dark matter annihilation into bb? (Duan et al. 2025 in prep.; see also Cui et al. 2017 PRL and Zhu et al. 2022 PRL for evidence in earlier data)

AMS-02 & CALET: Iron & Nickel

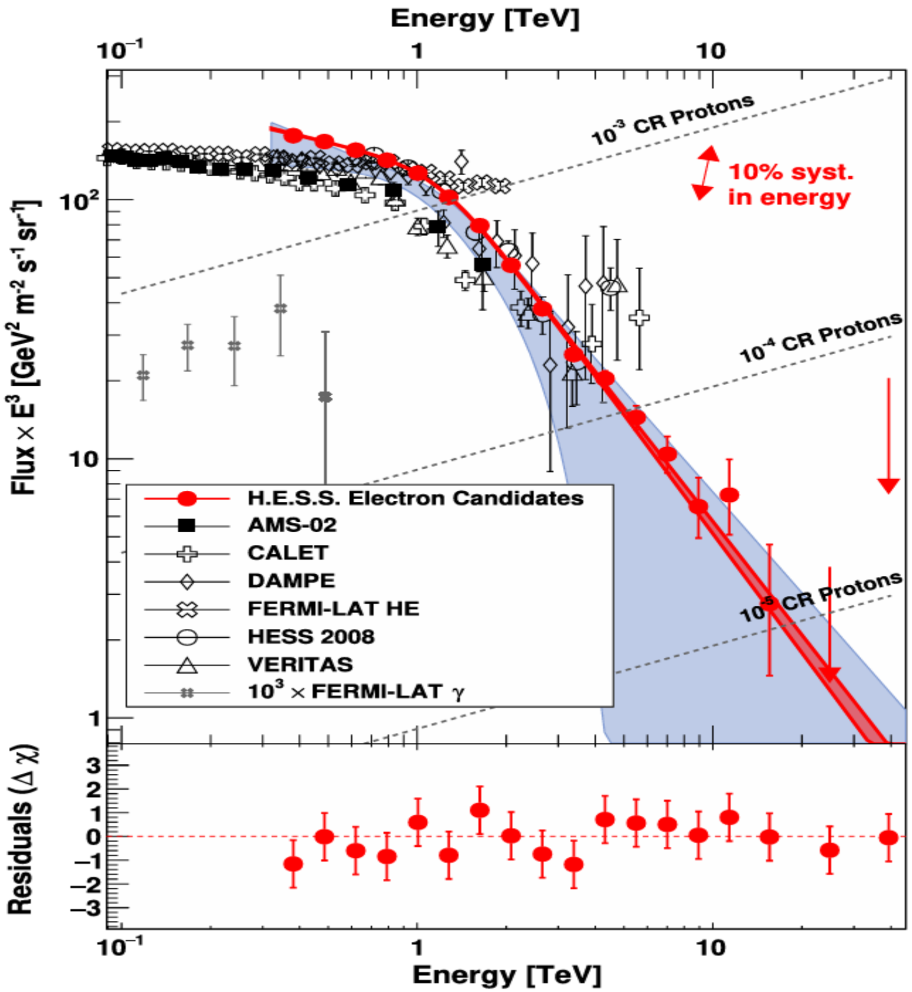


(2021 PRL 126, 041104)



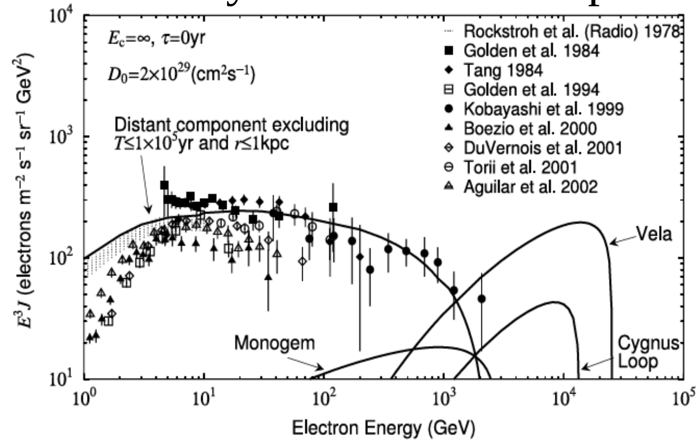
(2024 PRL 128, 131103)

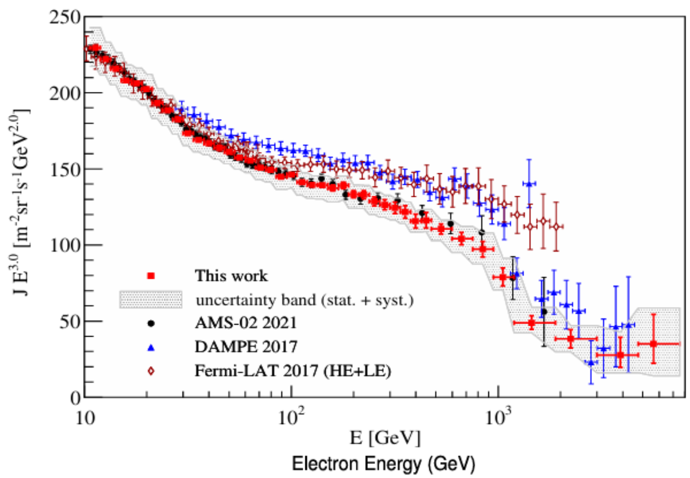
HESS: simple electron spectrum?



HESS Collaboration. 2024 PRL

Kobayashi et al. 2004 ApJ





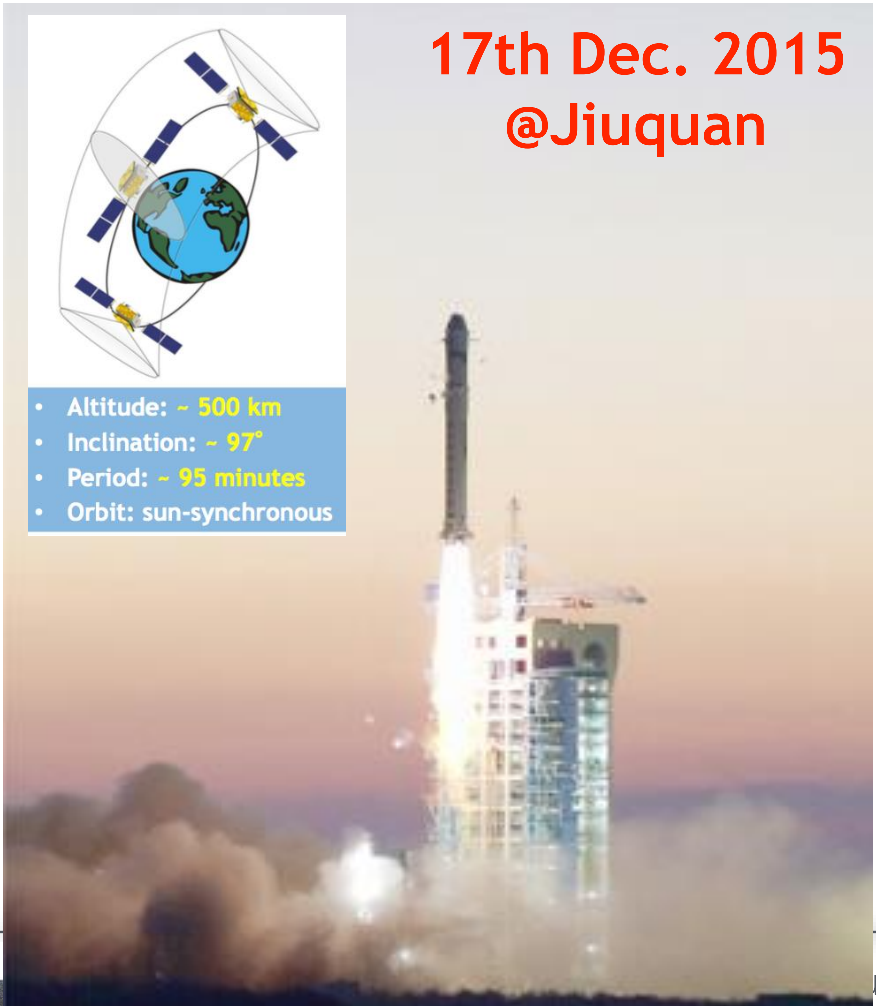
CALET Collaboration 2023 PRL

Outline

- Introduction
- Some interesting international results
- DAMPE and its recent results
- Summary

DAMPE Collaboration

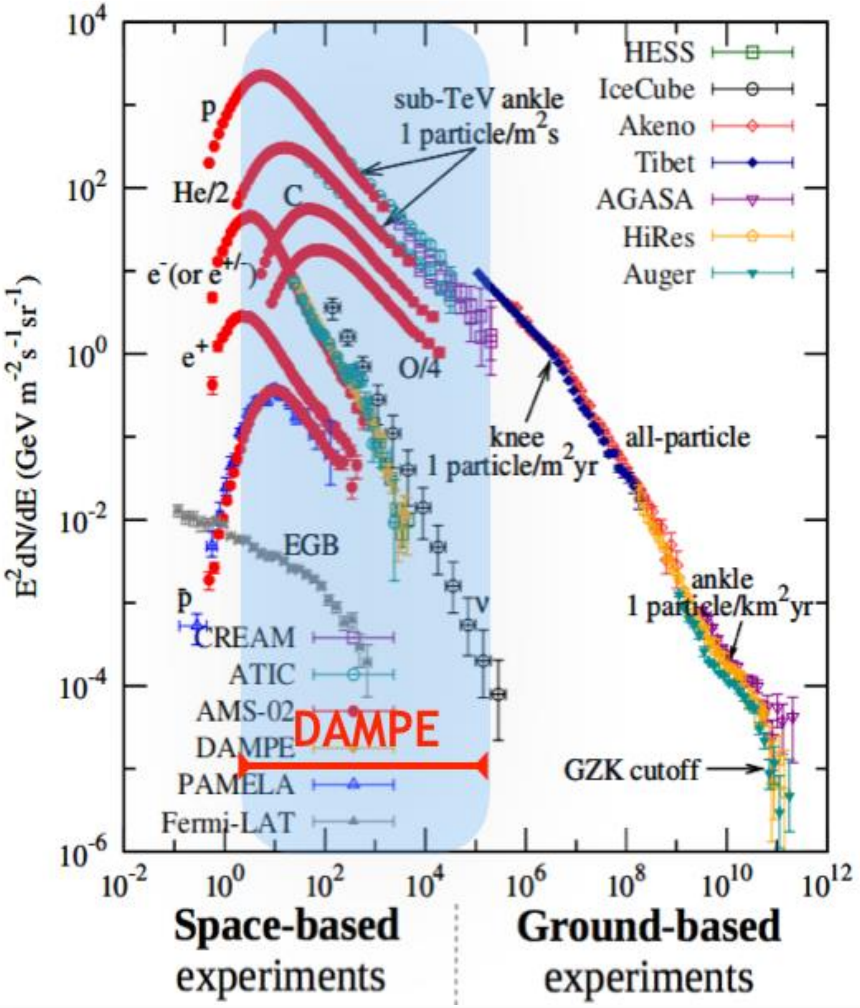
DAMPE ("Wukong"悟空) is a satellite-borne particle detector proposed in the framework of the Strategic Pioneer Program on Space Science, promoted by the **Chinese Academy of Sciences (CAS)**.



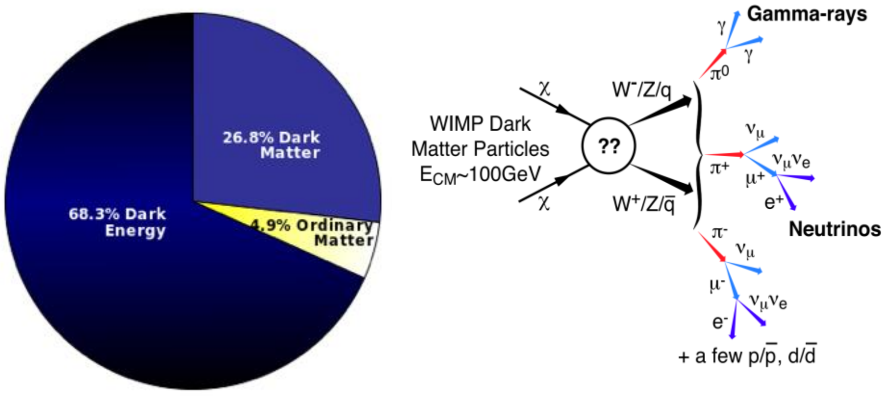
- CHINA
  - Purple Mountain Observatory, CAS, Nanjing
  - Institute of High Energy Physics, CAS, Beijing
  - National Space Science Center, CAS, Beijing
  - University of Science and Technology of China, Hefei
  - Institute of Modern Physics, CAS, Lanzhou
- ITALY
  - INFN Perugia and University of Perugia
  - INFN Bari and University of Bari
  - INFN Lecce and University of Salento
  - INFN LNGS and Gran Sasso Science Institute
- SWITZERLAND
  - University of Geneva

Scientific objects

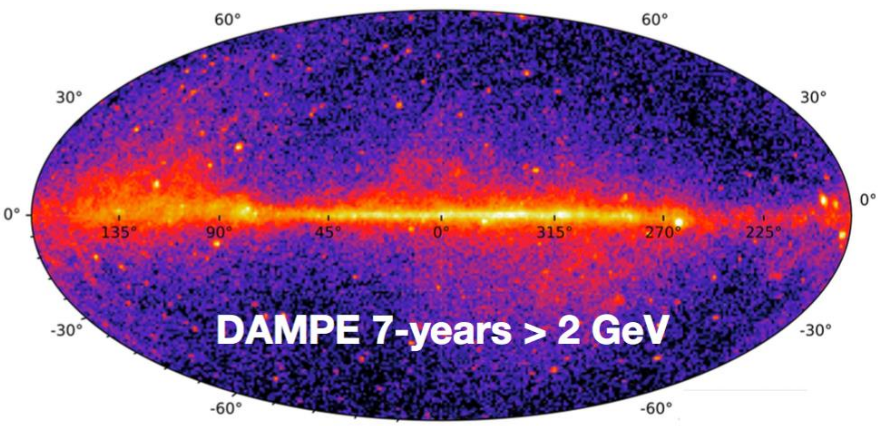
Cosmic-ray detection



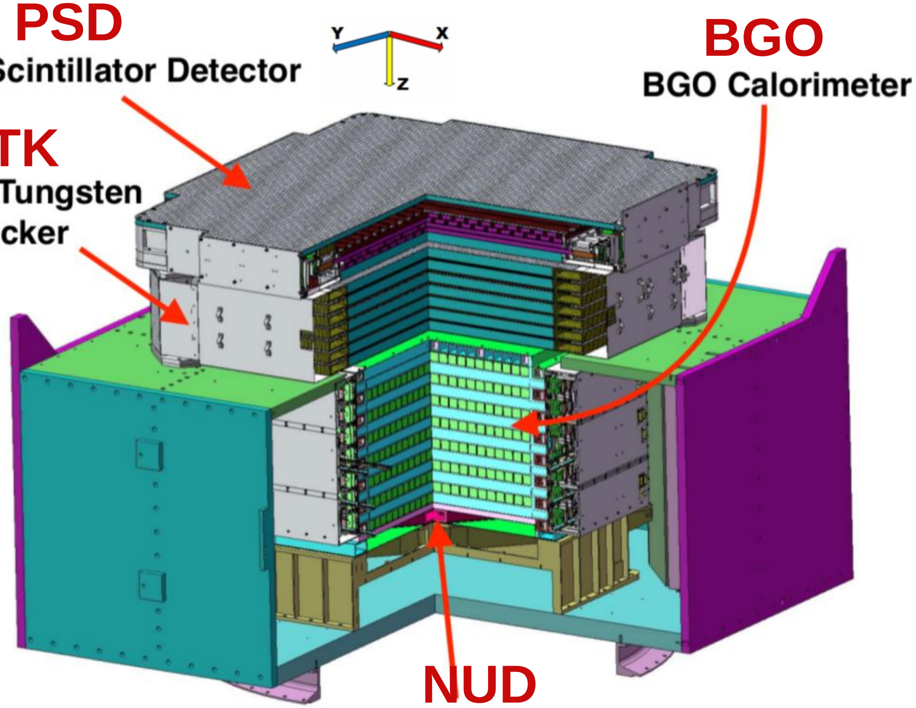
Indirect DM detection



Gamma-ray astronomy



DAMPE detector



Parameter	Value
Energy range (e/γ)	5 GeV to 10 TeV
Energy resolution (e/γ)	1.5% at 800 GeV
Energy range (p/ion)	50 GeV to 500 TeV
Energy resolution (p)	40% at 800 GeV
Geometric factor (e)	0.3 m^2 sr above 30 GeV
Angular resolution (γ)	0.1 degree at 100 GeV
Field of view	1.0 sr

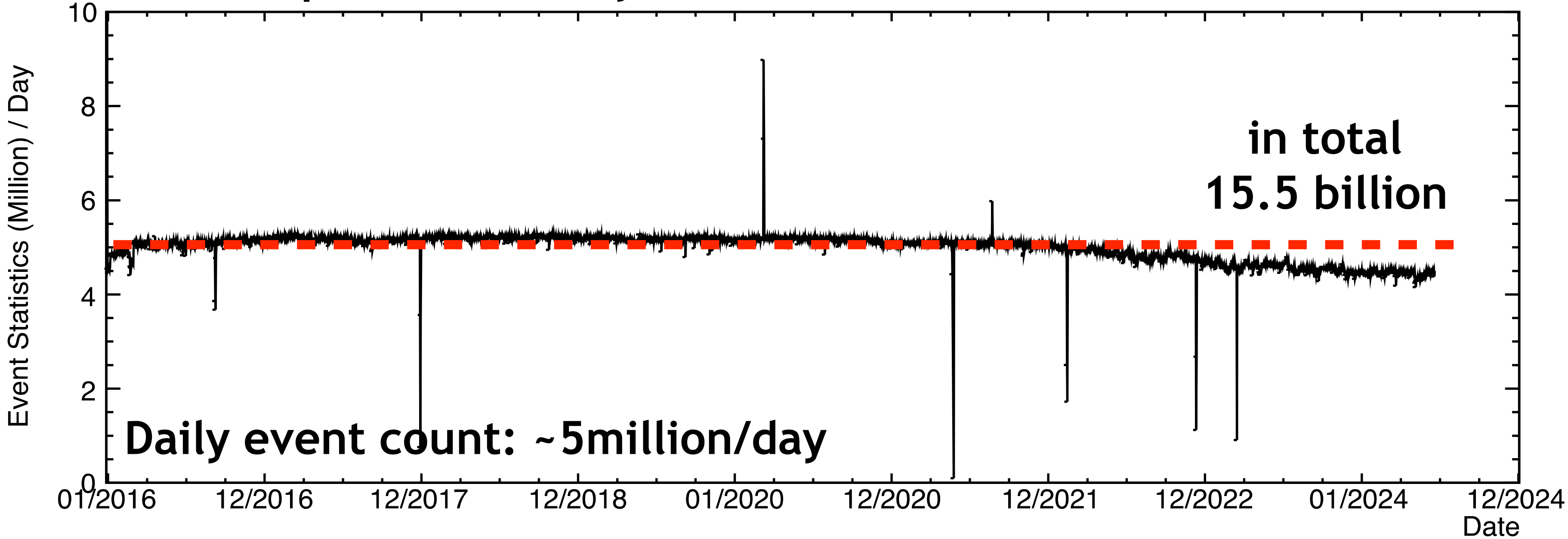
Weight: 1.4 tons in total
Power: ~400 W

- PSD: Charge measurement via dE/dx and ACD for photons
- STK: Track, charge, and photon converter
- BGO: Energy measurement, particle (e/p) identification
- NUD: Additional e/p identification above 1 TeV

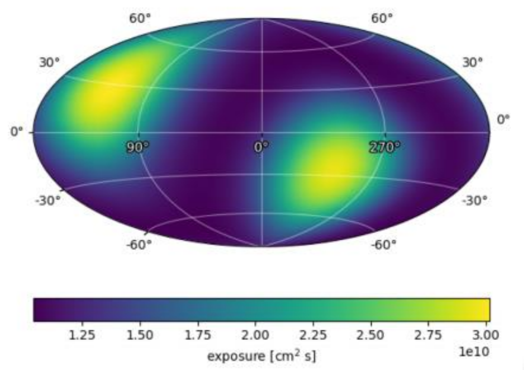
(Chang et al. Astropart.Phys. 2017, 95, 6-24)

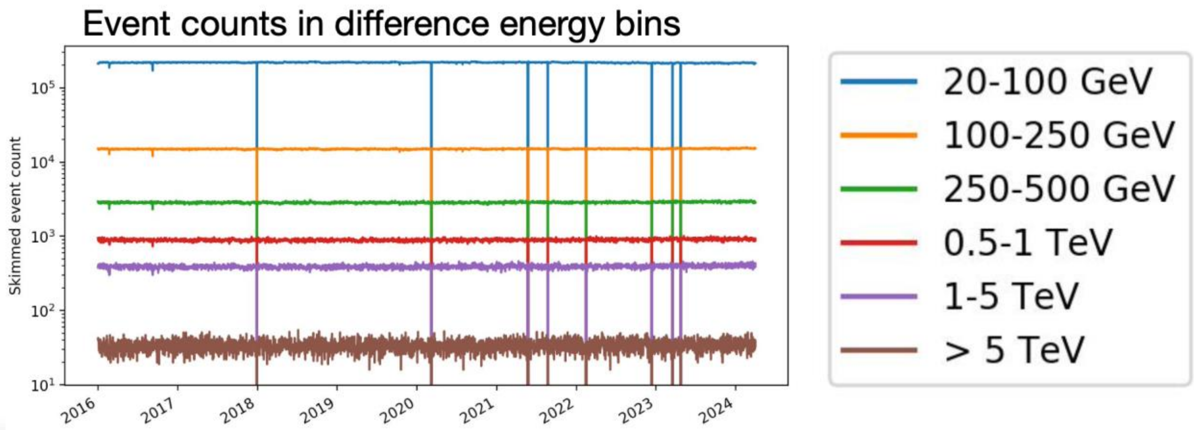
On-orbit operation

Smooth operation for 9 years since launch in Dec. 2015

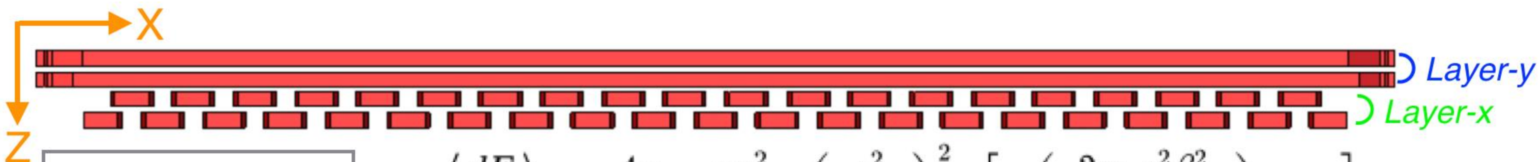


All sky exposure

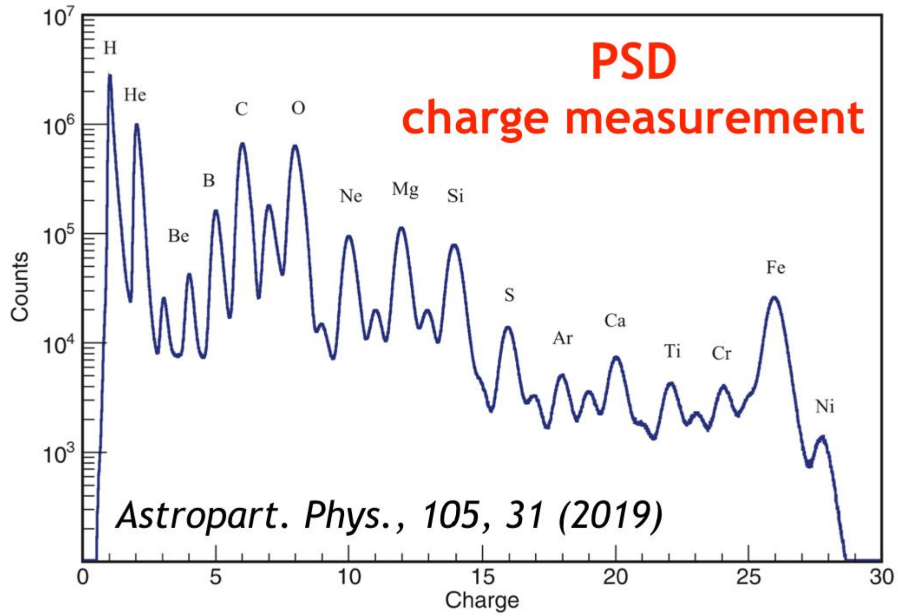




Charge measurement



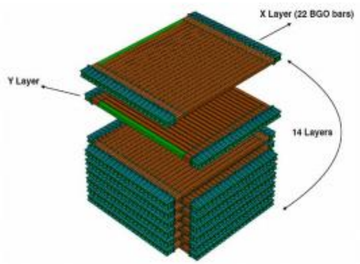
Bethe-Bloch $$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

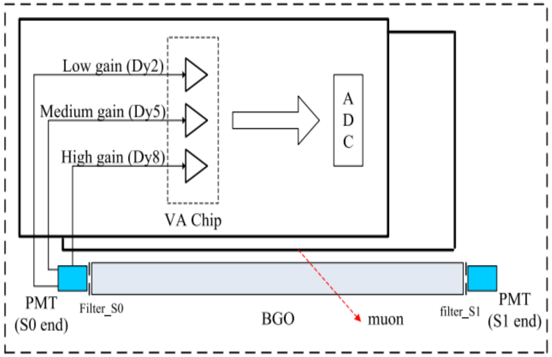


Element	σ_Z	Element	σ_Z	Element	σ_Z	Element	σ_Z
Li	0.14	C	0.18	Ne	0.21	S	0.25
Be	0.21	N	0.21	Mg	0.22	Ca	0.29
B	0.17	O	0.20	Si	0.25	Fe	0.30

Energy calibration

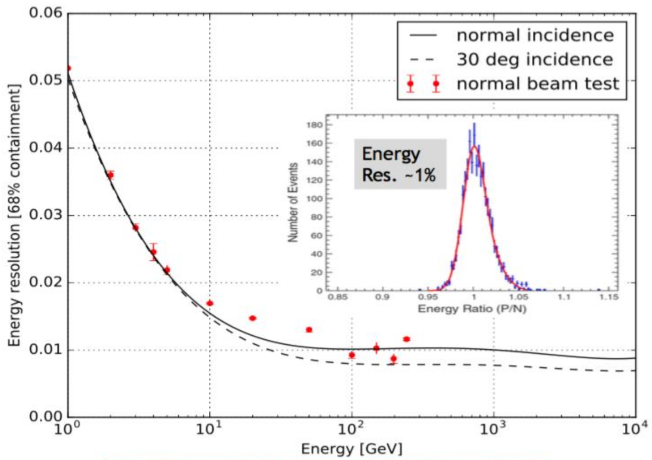
BGO calorimeter | 308 BGO bars | 616 PMTs



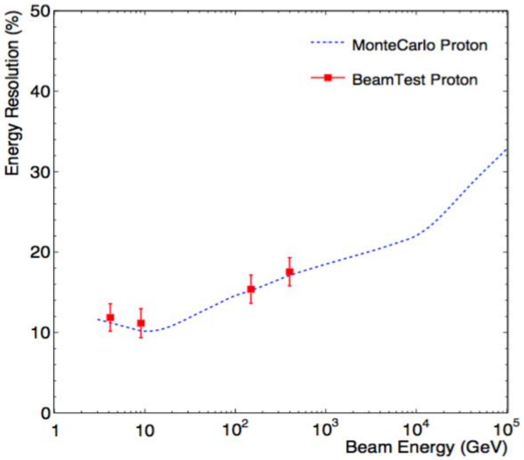


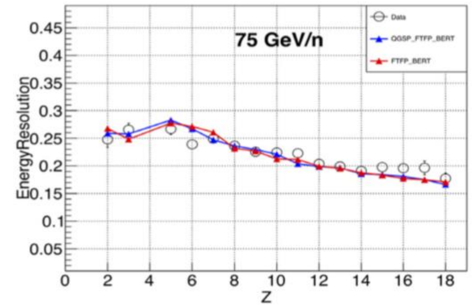
Beam tests at CERN PS & SPS

- Electrons (protons): few GeV — 250 (400) GeV, ions: 40 GeV/n, 75 GeV/n
- Energy resolution: ~1% (e/γ) at 100 GeV and above, 20%—30% for protons/ions



DAMPE collab., Astropart. Phys. 95 (2017) 6-24





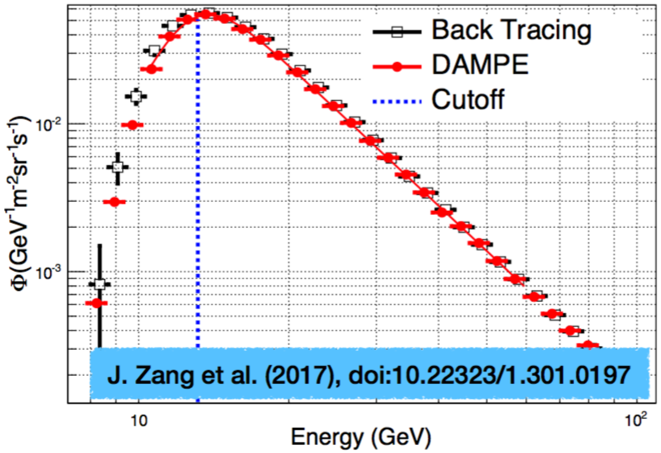
Y. Wei et al. NIMA 922 (2019)

Energy calibration

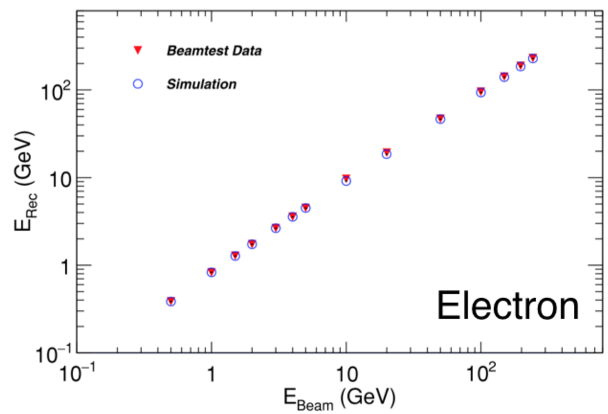
- On-orbit energy scale verified with **geomagnetic cut-off**
- Good linearity to ~2.5 (100) TeV with electron (nuclei) events

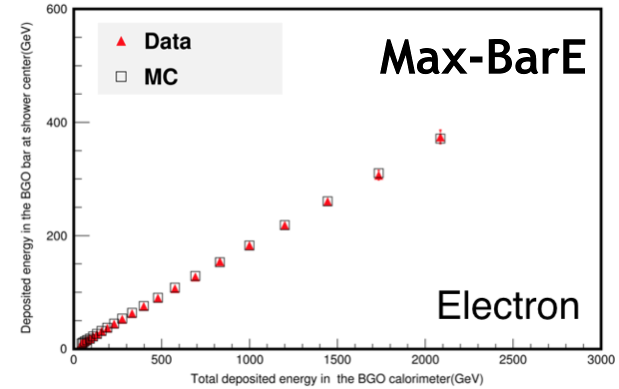
C. Zhao et al. NIMA 1092, 166453 (2022)

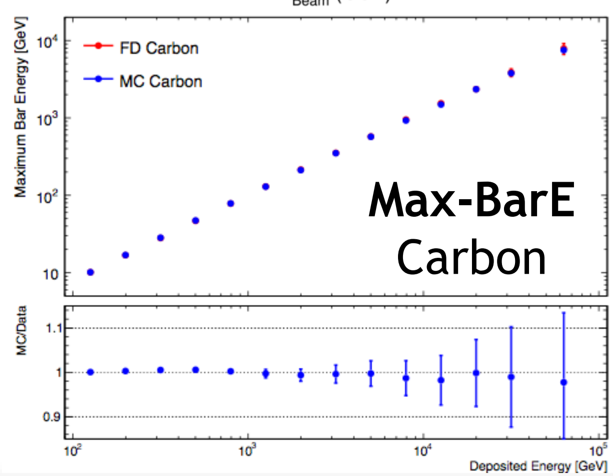
cosmic-ray electron
geomagnetic cut-off

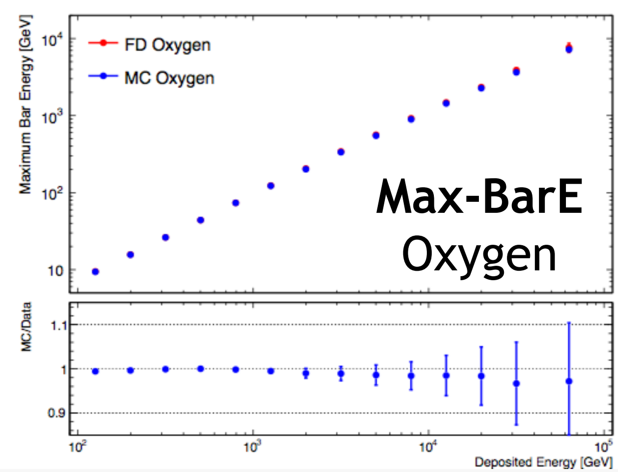


E scale in flight: **+ 1.25%** ± 1.75%(stat) ± 1.34%(sys)



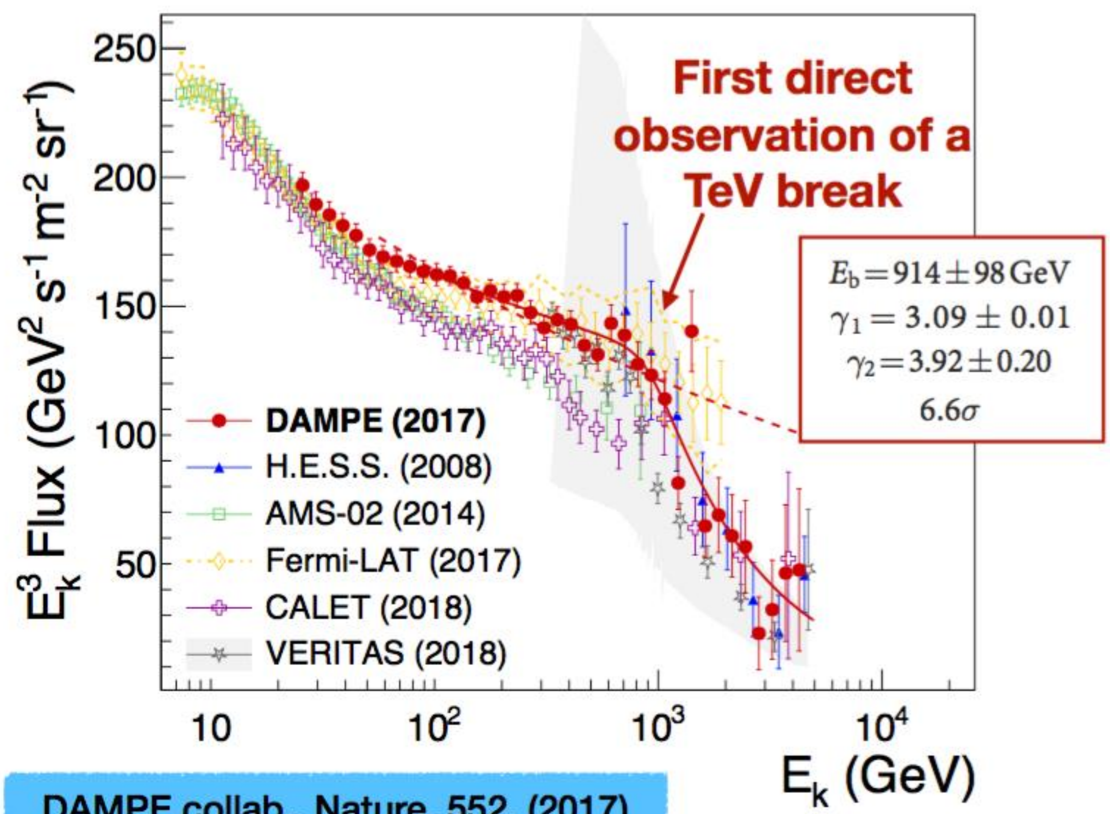




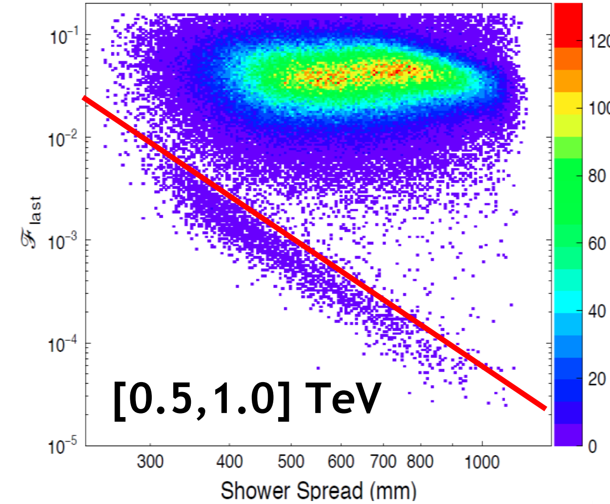


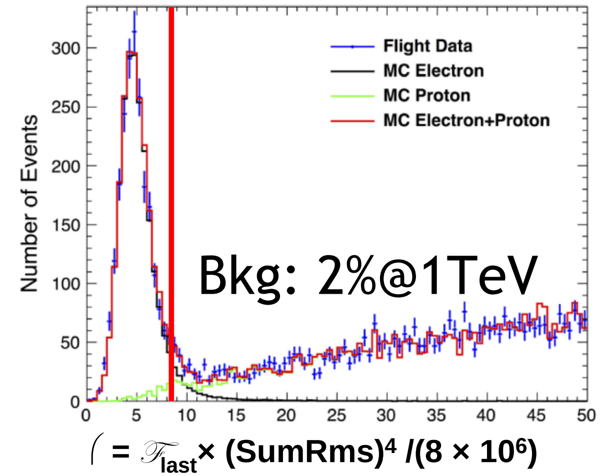
$e^+ + e^-$ spectrum

$e^- + e^+$ spectrum:



DAMPE collab., Nature, 552, (2017)





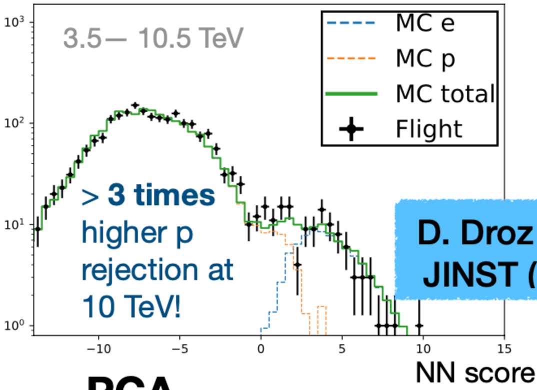
Excellent energy resolution and **powerful e/p identification**

$e^+ + e^-$ spectrum (in process)

Work in process:

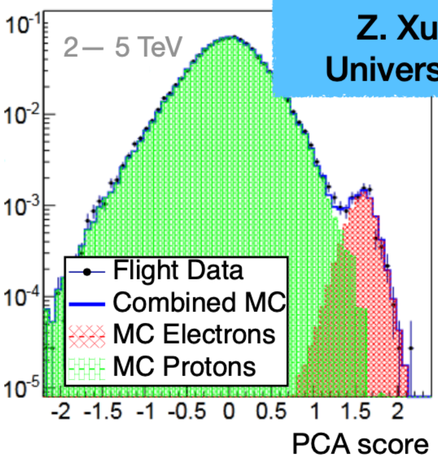
1. Deep and long-term detector calibration.
2. New particle ID for high energies:
   Neural Networks (NN), Principal Component Analysis (PCA), Application of Neutron Detector (NUD)

NN



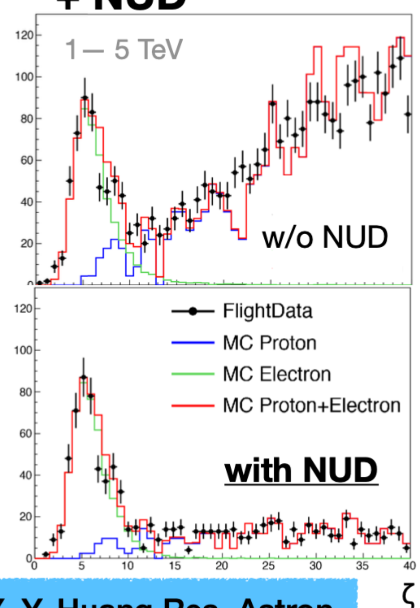
D. Droz et. al. JINST (2021)

PCA



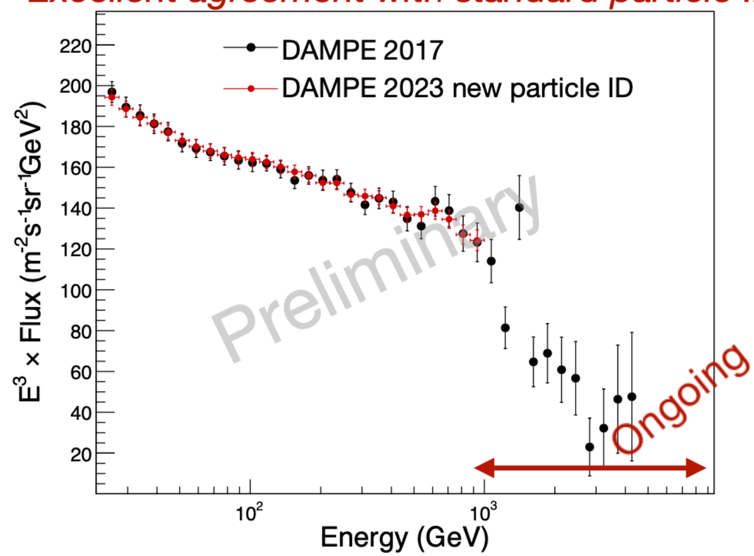
Z. Xu et. al. Universe (2022)

+ NUD



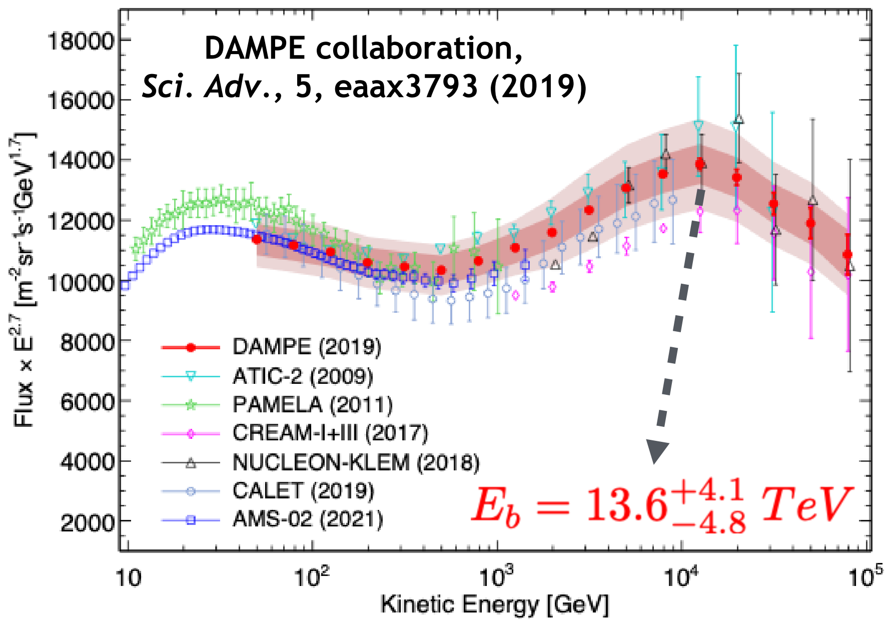
Y.-Y. Huang Res. Astron. Astrophys. (2020)

Excellent agreement with standard particle ID

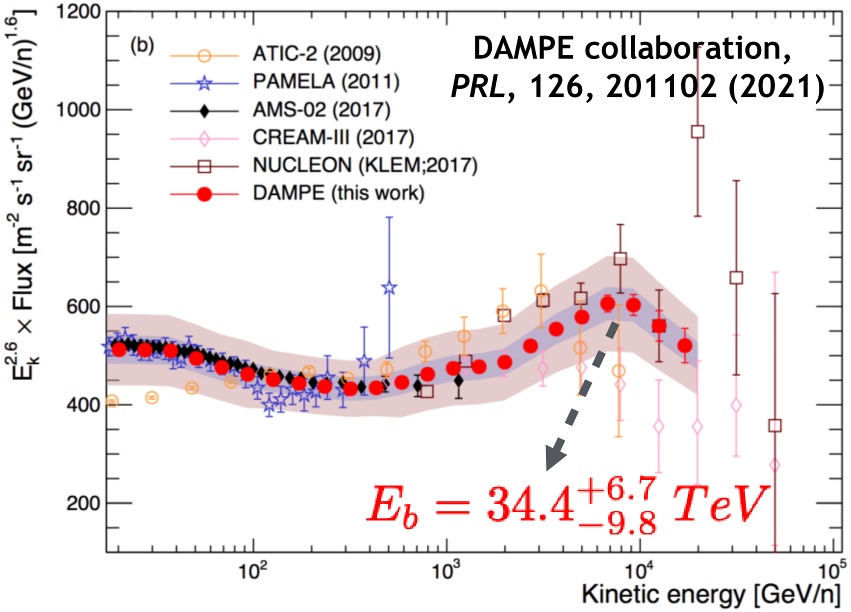


Proton & Helium

CR Proton

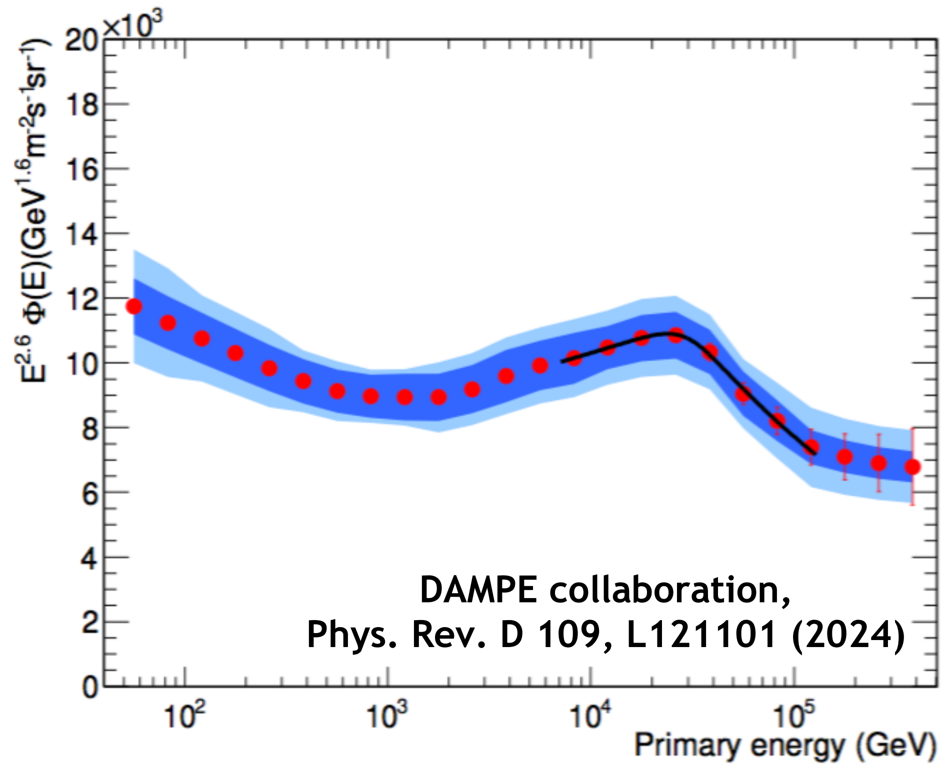


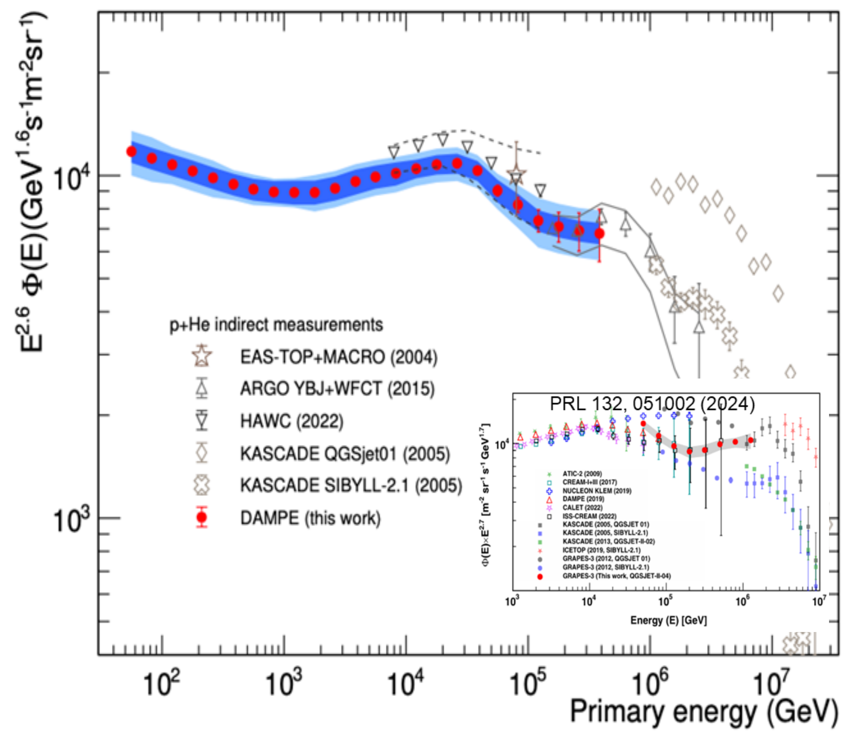
CR Helium



- The spectra of CR proton and helium measured by DAMPE show **a very similar softening feature at tens of TeVs**
- The softening energies are consistent with **being charge dependent (i.e. knee-like)**, although a dependence on particle mass can not be ruled out yet

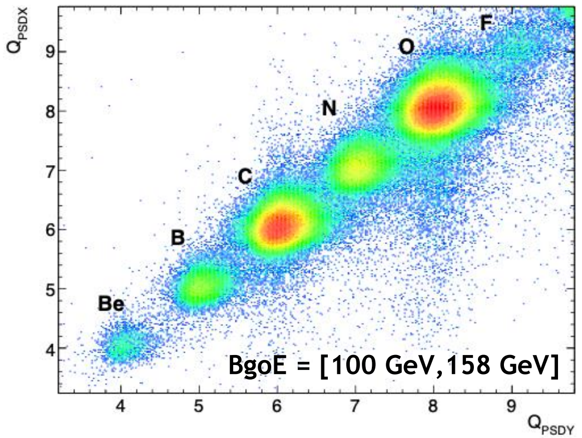
Proton+Helium spectrum



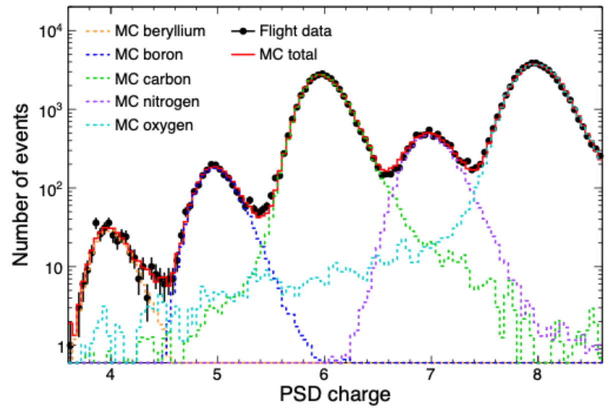


- Very low contamination + Very large statistics => Higher energy range
- Hint of spectral hardening at ~150 TeV, consistent with GRAPES-3 and others

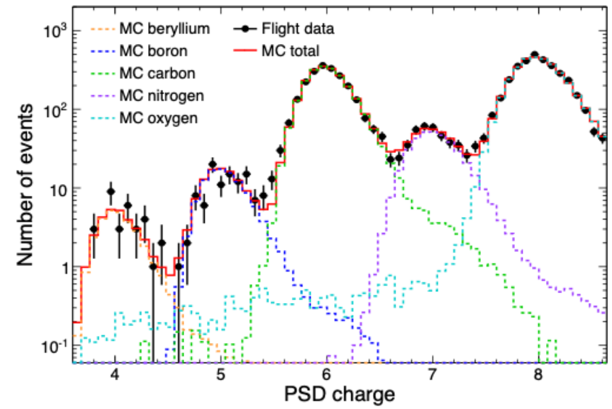
Carbon & Oxygen

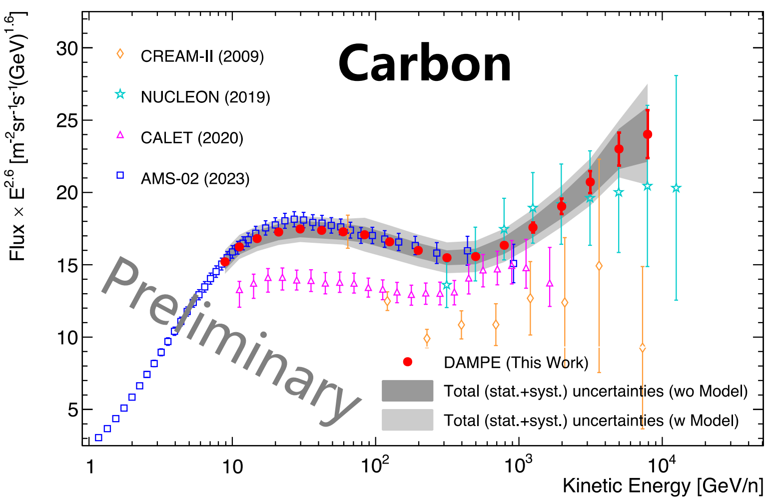


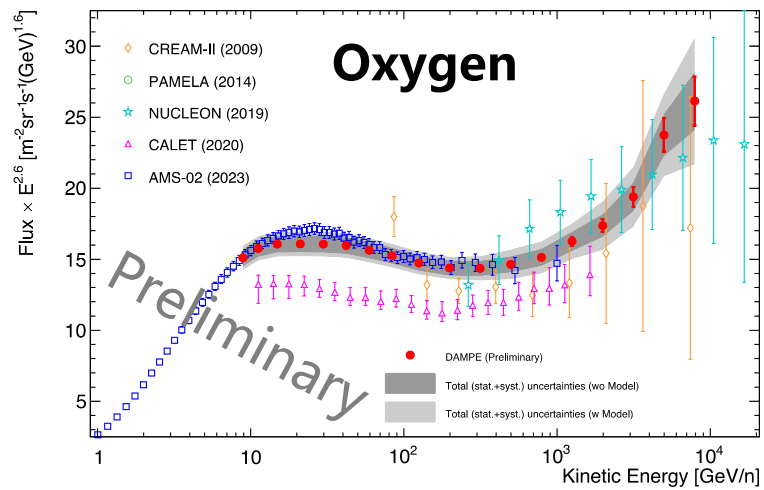
0.63-2 TeV



3.16-10 TeV



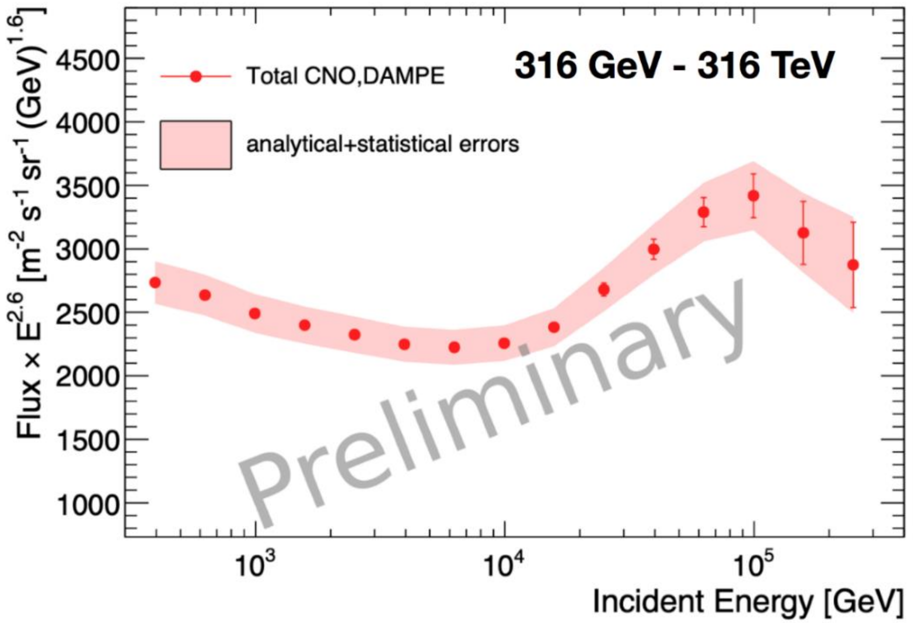


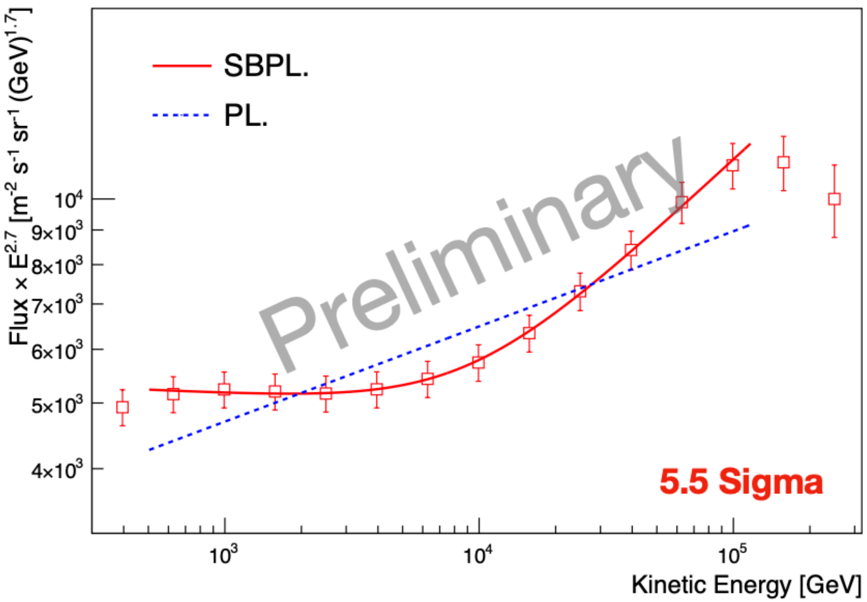


Preliminary DAMPE measurements confirm the hardening structure at several hundreds of GeV/n observed by previous experiments.

CNO group

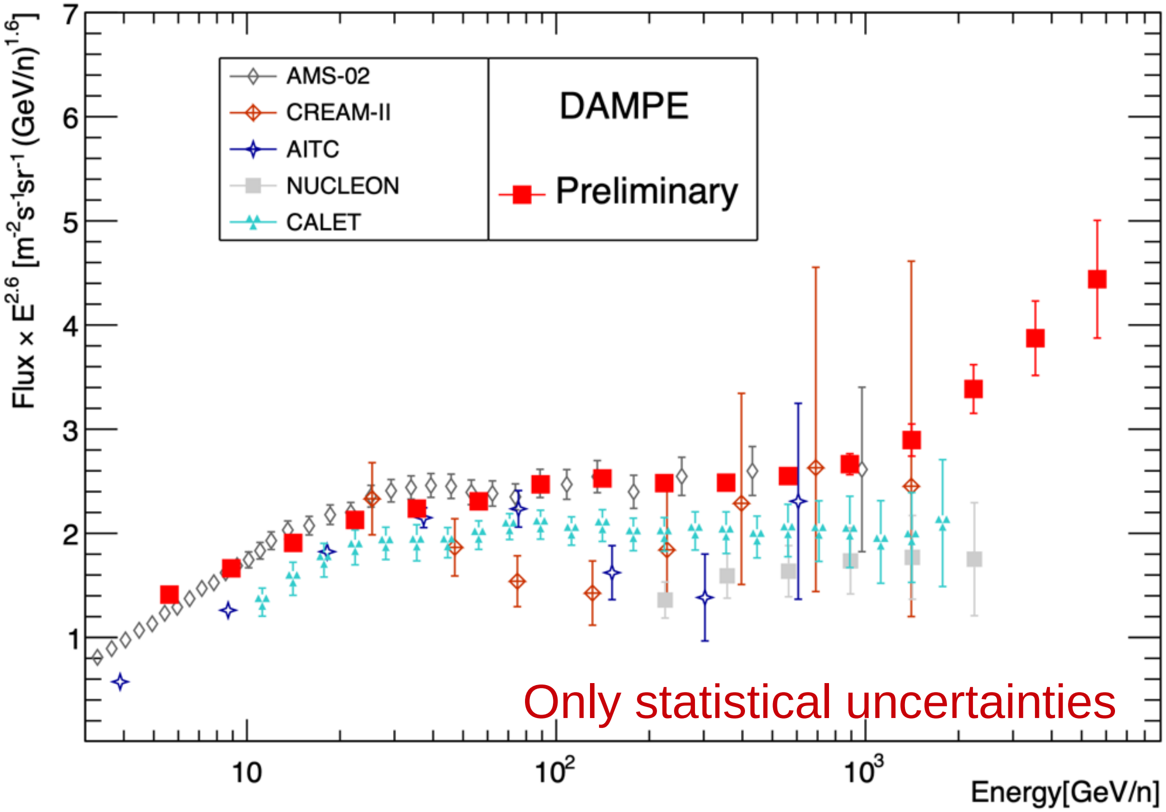
The spectrum of CNO group in cosmic rays





- **The spectrum of CNO group can be measured up to 500 TeV**
- **A spectral hardening at ~9 TeV with 5.5 sigma of CL. is observed**

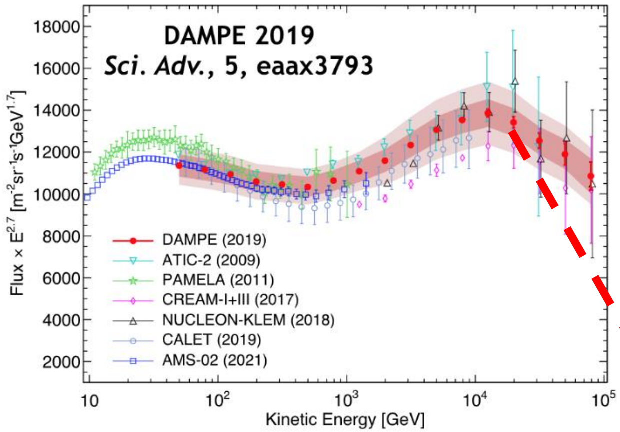
Iron



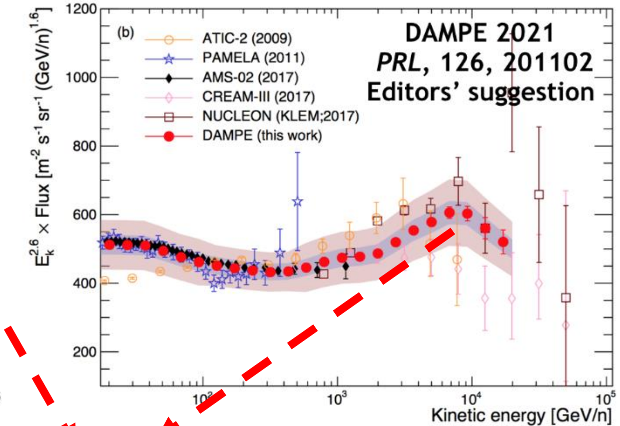
Preliminary iron spectrum up to 10 TeV/n shows a significant hardening around 1 TeV/n. Evaluation of systematics is in progress …

A universal sub-knee feature?

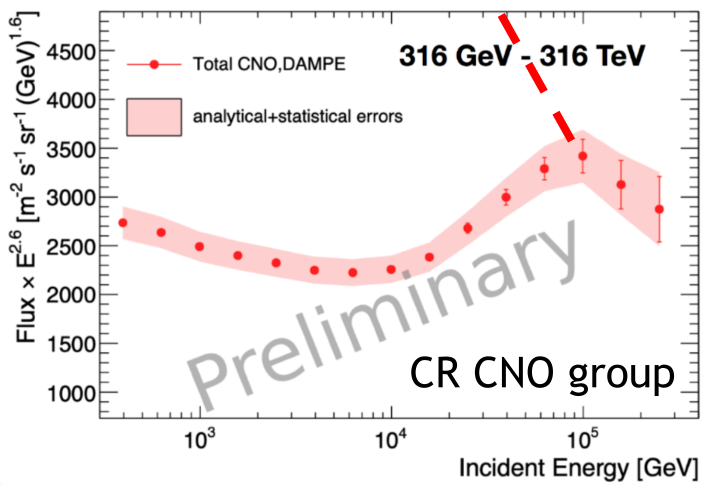
CR Proton

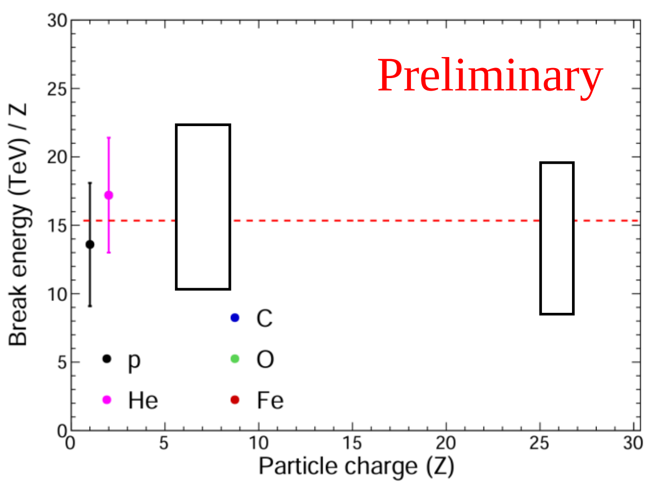


CR Helium

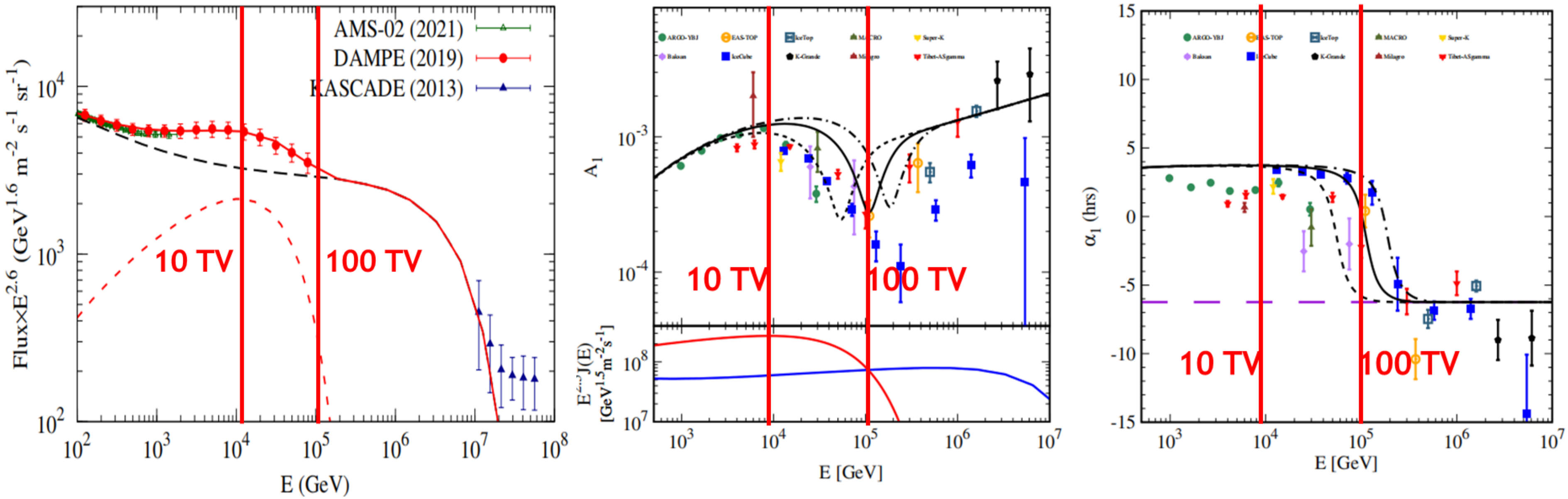


Universal softening





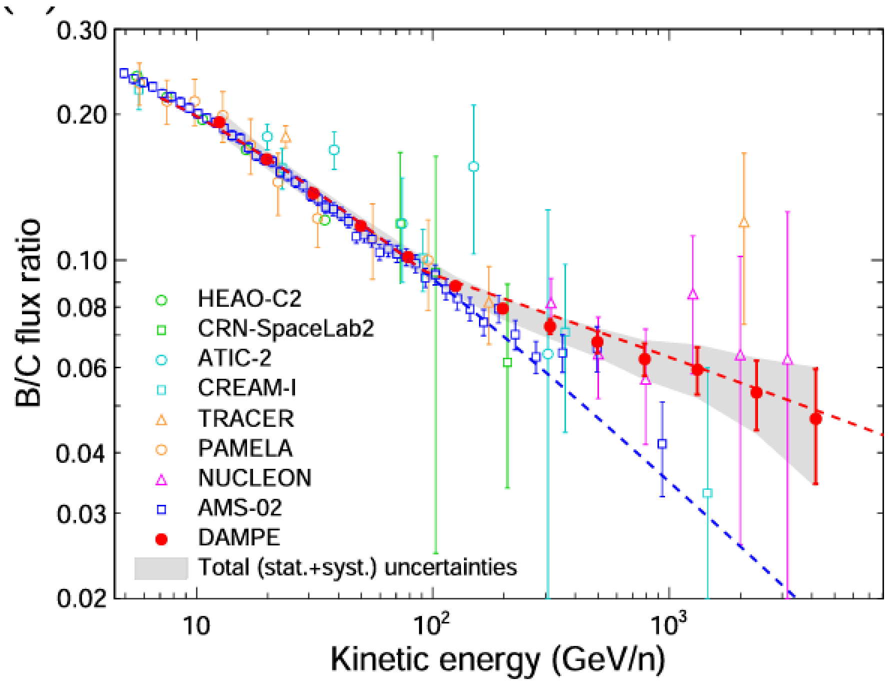
Nearby source model

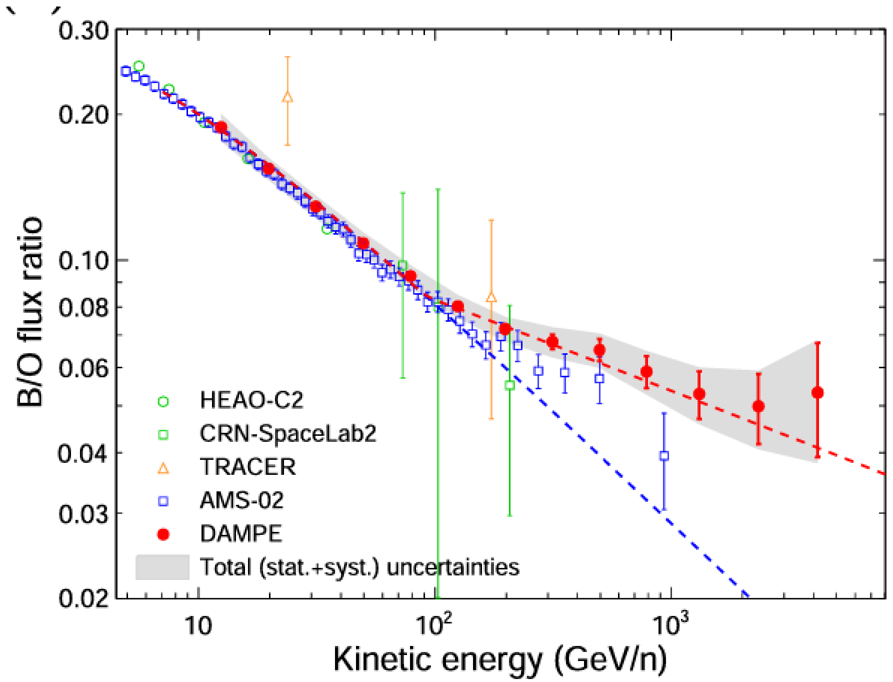


- The spectra and anisotropies show correlated structures: ~10 TV and ~100 TV
- Two component model of bkg + nearby source can naturally account for the data
- Spectra: algebraic sum; anisotropy: vector sum

Liu + JCAP (2019); Yue + Fron. Phys. (2019); Qiao + ApJ (2023)

B/C & B/O (secon.-to-prim.)

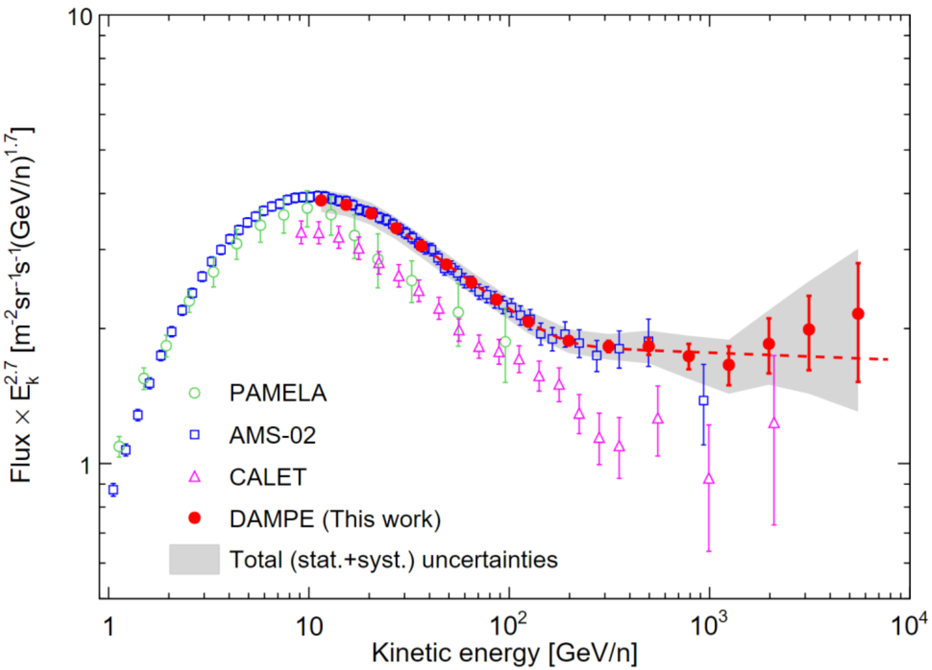


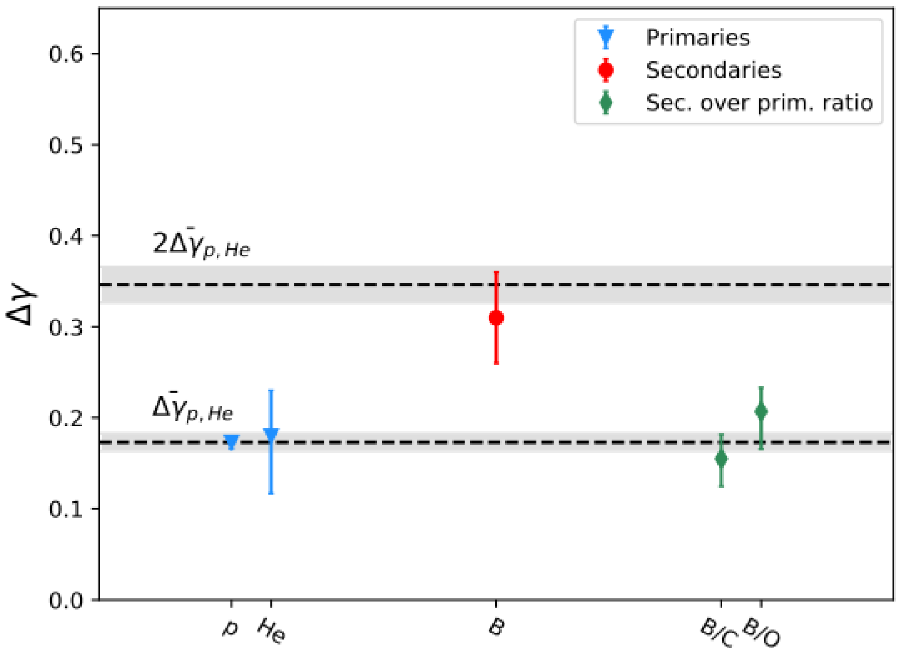


- **Rigidity-dependence of diffusion coefficient: $R^{-1/3}$ (Kolmogorov 1941) or $R^{-1/2}$ (Kraichnan 1965); the secondary-to-primary ratio spectrum is expected to follow it**
- **Observation: significant spectral hardening of B/C, B/O (2022 Sci. Bull.), Li/C, Li/O, Be/C, and Be/O (work in progress)**
- **Cause: spectral break of diffusion coefficient (change of turbulence properties of ISM)?**

Boron (Secondary)

Boron spectrum up to ~8 TeV/n

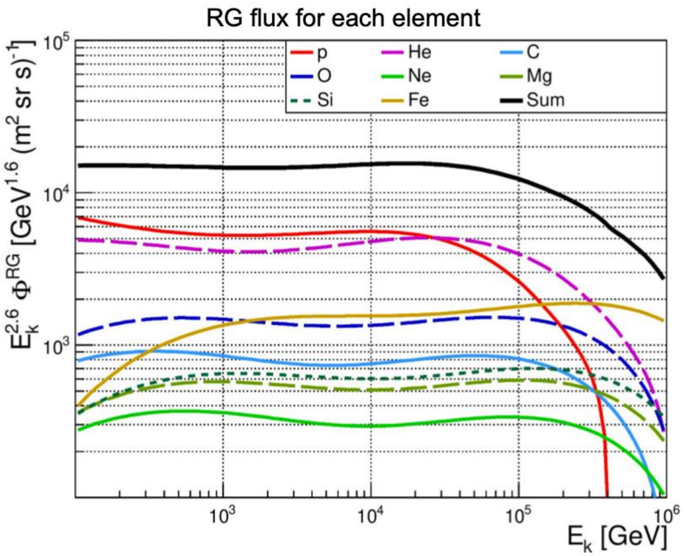




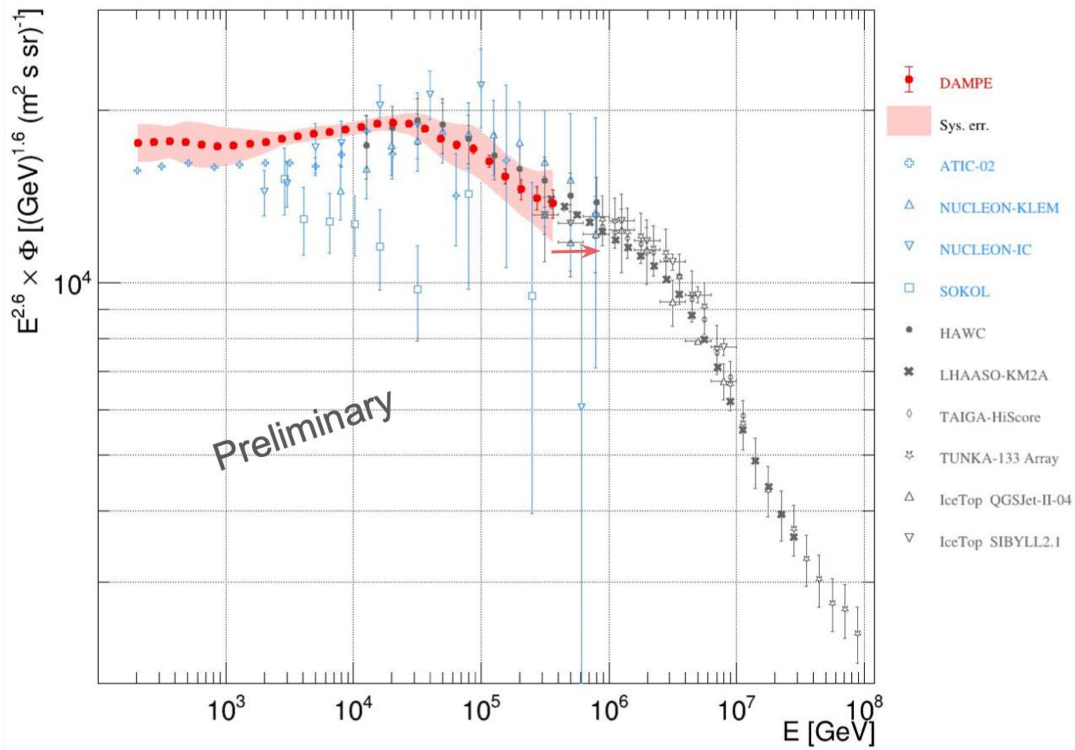
- Spectral index change is about twice of that of the proton and others (arXiv:2412.11460)
- Imprint of propagation since the secondary particles experience one more diffusion (Diffusion coefficient \propto $R^{-\Delta}$)?

All particle spectrum

CR composition model



All-particle spectrum



- **Different composition models are evaluated and applied in the analysis**
- **Preliminary all-particle spectrum shows a “sub-knee” feature at tens of TeV, most probably due to the softening of different components**

Summary

- The cosmic ray spectral hardening at ~200 GeV/n, firstly discovered by ATIC and PAMELA, has been confirmed
- The spectral index change of the secondary Boron cosmic ray at ~200 GeV/n is about twice that of proton and helium CRs
- Significant spectral softening of proton and Helium cosmic rays at ~10 TV has been observed by DAMPE and CALET. Such a sub-knee structure likely presents in the spectra of all of the abundant primary CRs
- About 150 TeV, the proton + Helium spectrum got hardened again
- For the electron + positron cosmic rays, the single power-law spectrum above ~1 TeV found by HESS will be tested by DAMPE soon