中国科学院稳定支持基础研究领域青年团队计划

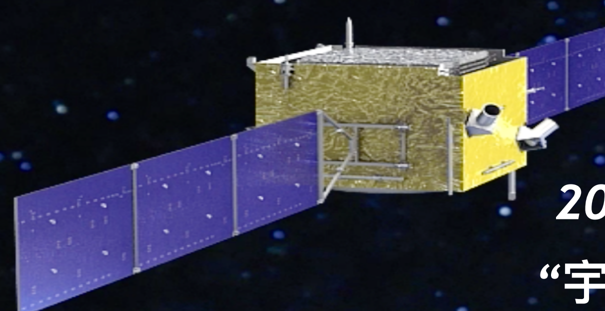
“宇宙线起源”青年团队

“悟空”号暗物质粒子探测卫星
核素宇宙线能谱探测进展

岳 川

中国科学院紫金山天文台

(on behalf of the DAMPE Collaboration)



*2023*弥散伽马射线与宇宙线研讨会

“宇宙线起源”青年团队年度总结会议

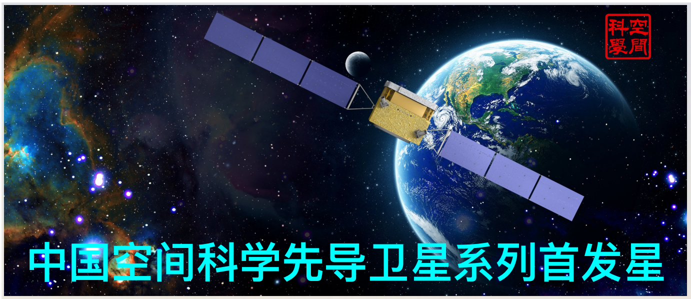
Oct 22, 2023 | 合肥

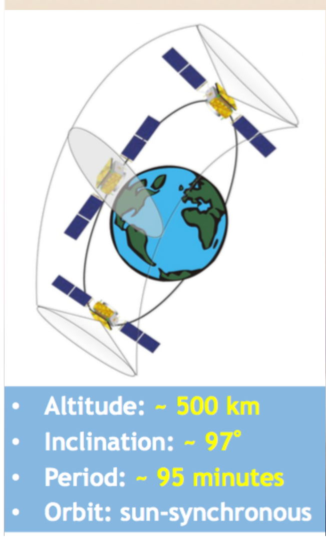
Outline

- DAMPE mission
- Detector performance for nuclei
- Cosmic-Ray nuclei spectral measurements
- Summary

DAMPE mission

The Dark Matter Particle Explorer (DAMPE) 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).



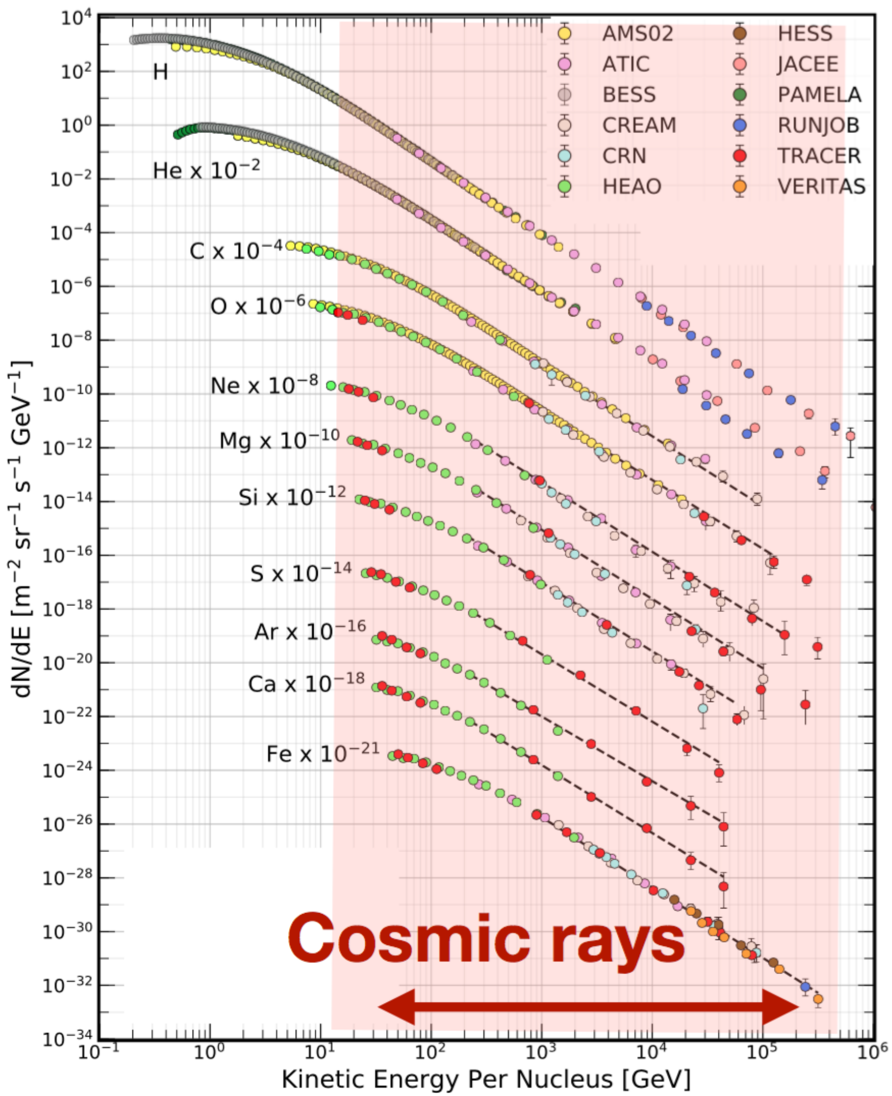


CHINA
- Purple Mountain Observatory, CAS, Nanjing
- Institute of High Energy Physics, CAS, Beijing
- National Space Science Center, CAS, Beijing
- University of Science and Technology of China, Hefei
- Institute of Modern Physics, CAS, Lanzhou

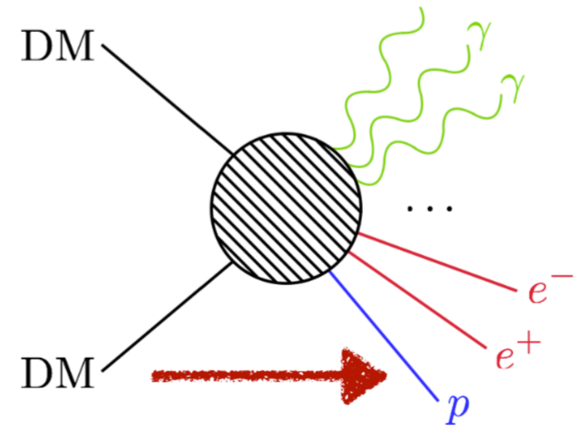
ITALY
- INFN Perugia and University of Perugia
- INFN Bari and University of Bari
- INFN Lecce and University of Salento
- INFN LNGS and Gran Sasso Science Institute

SWITZERLAND
- University of Geneva

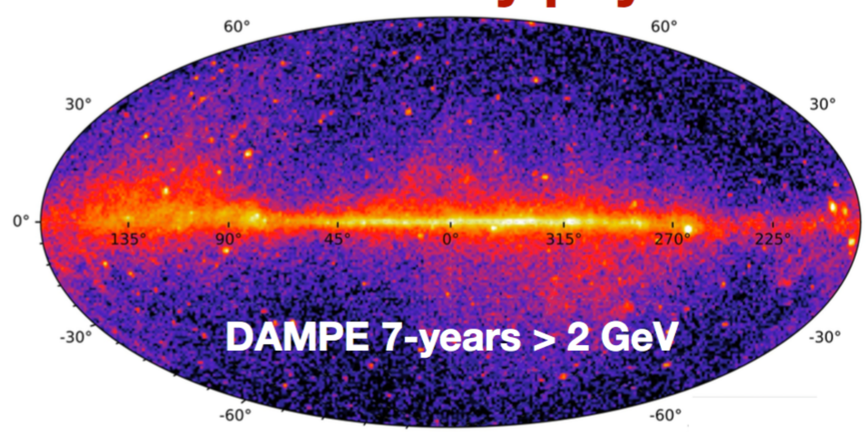
Scientific objects



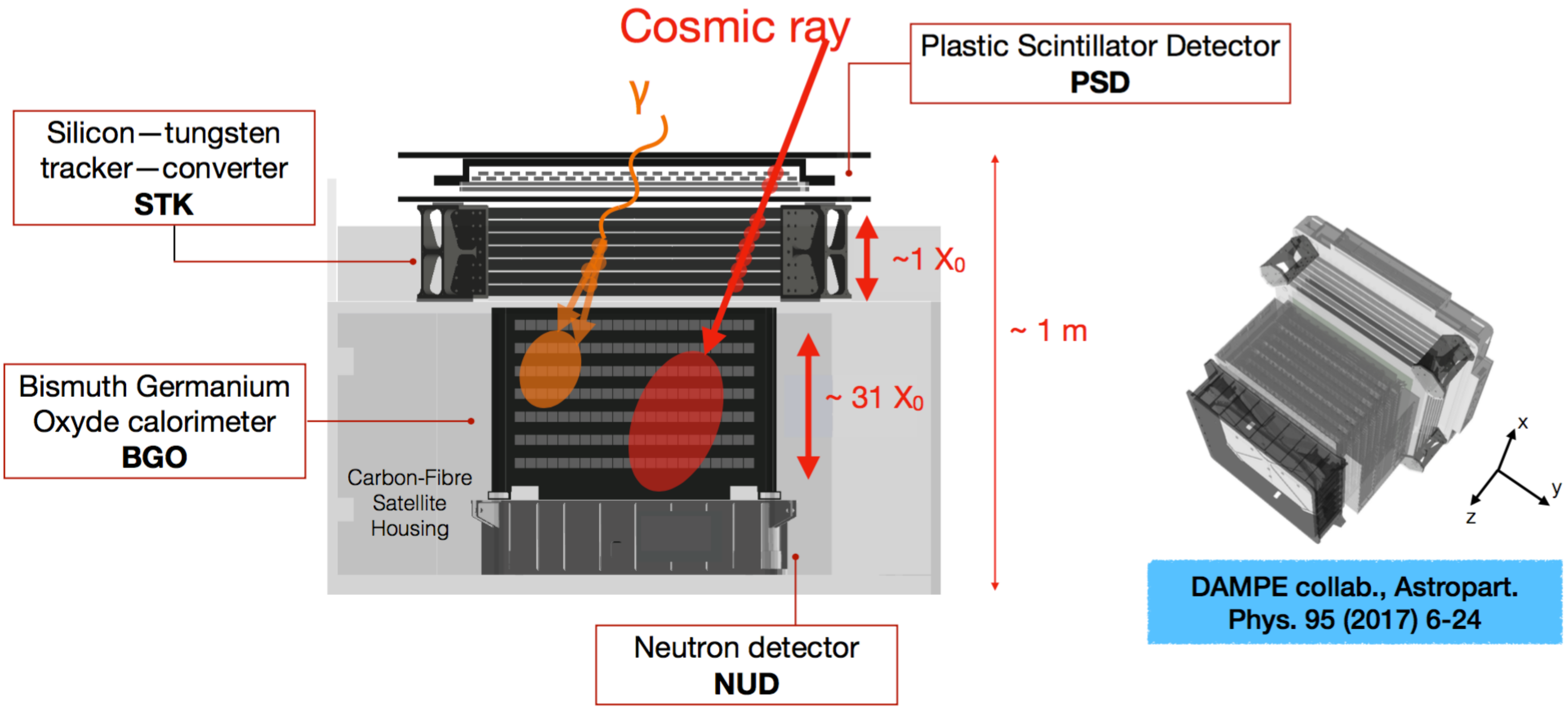
Indirect DM detection



Gamma-ray physics



DAMPE detector

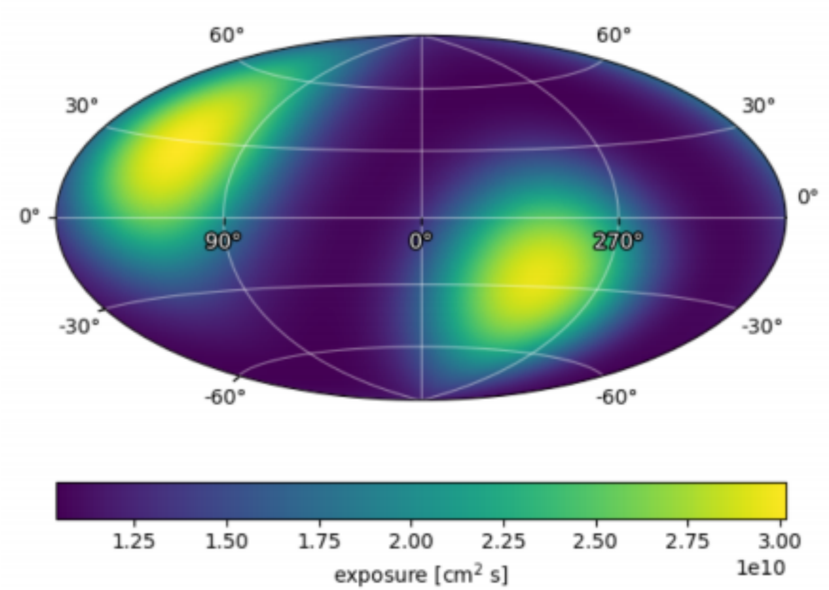


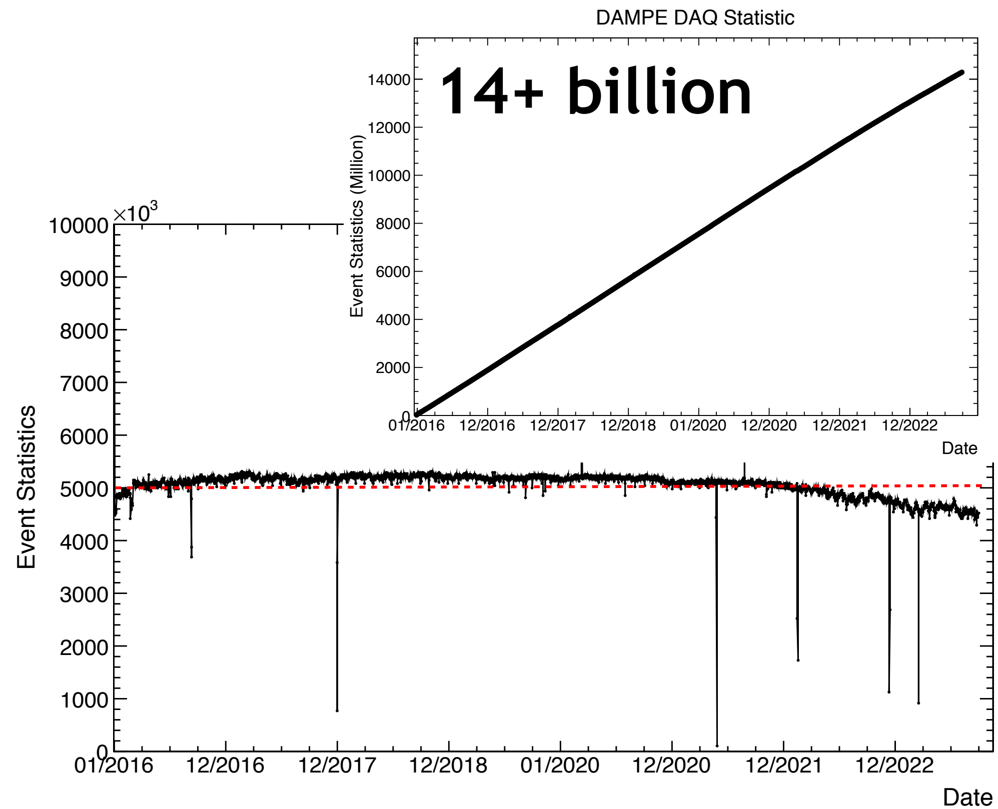
DAMPE collab., Astropart. Phys. 95 (2017) 6-24

- PSD: charge measuresument via dE/dx and ACD for photons
- STK: track, charge, and photon converter
- BGO: energy measurement, particle (e-p) identification
- NUD: Particle identification

On-orbit operation

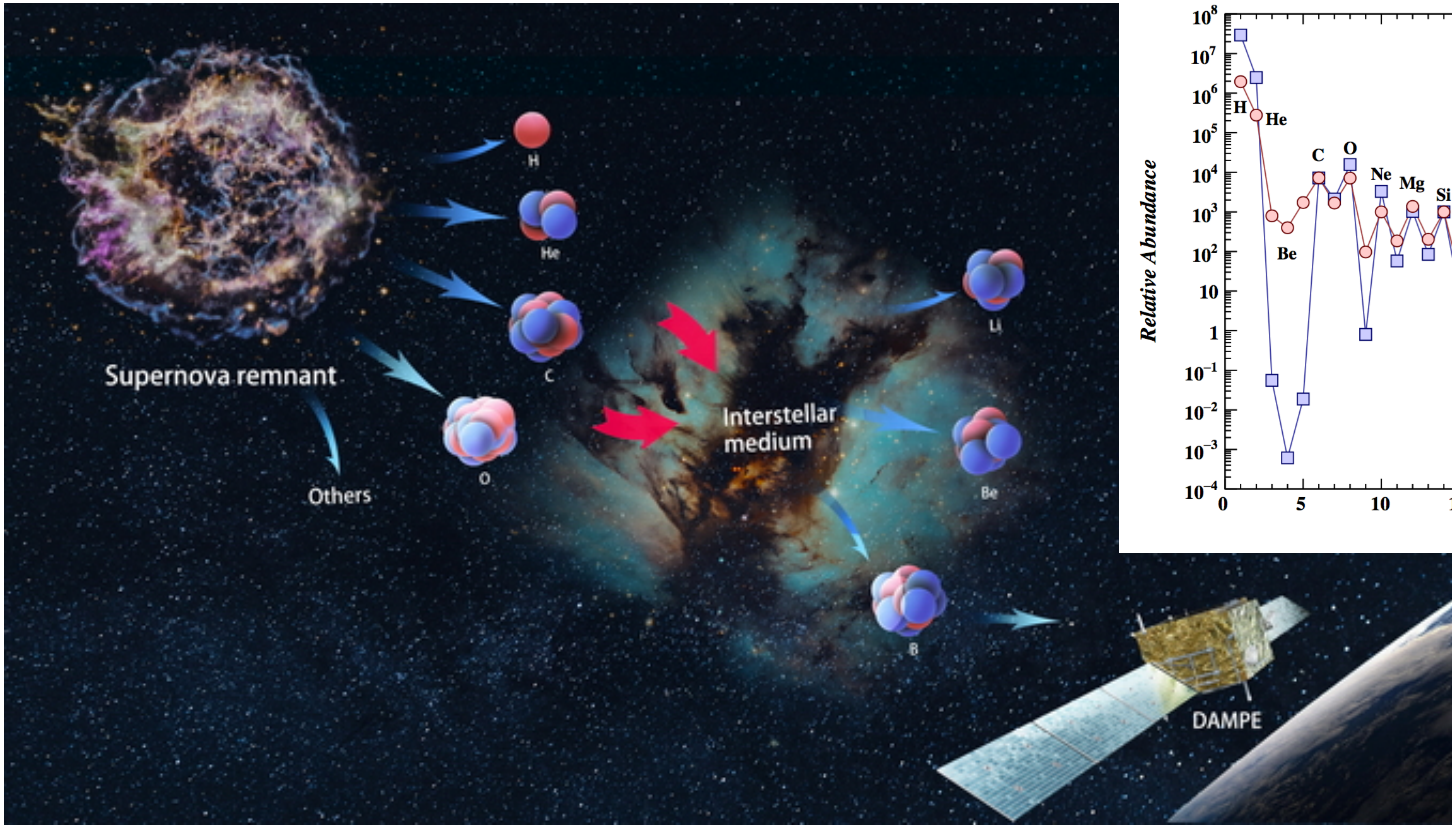
DAMPE 7 year exposure map

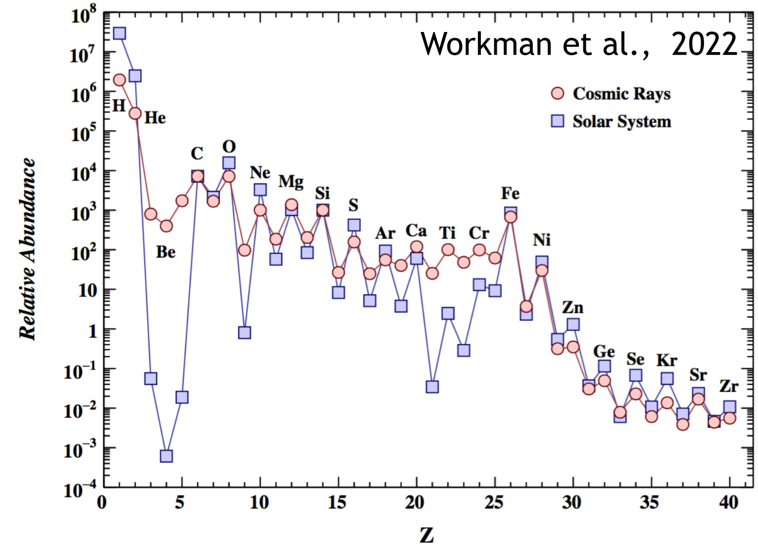




Since the launch on Dec. 17, 2015, DAMPE has operated on-orbit for more than 7.5 years, surveyed the sky for 17 times, and recorded **14+ billion** events (~5 million per day)

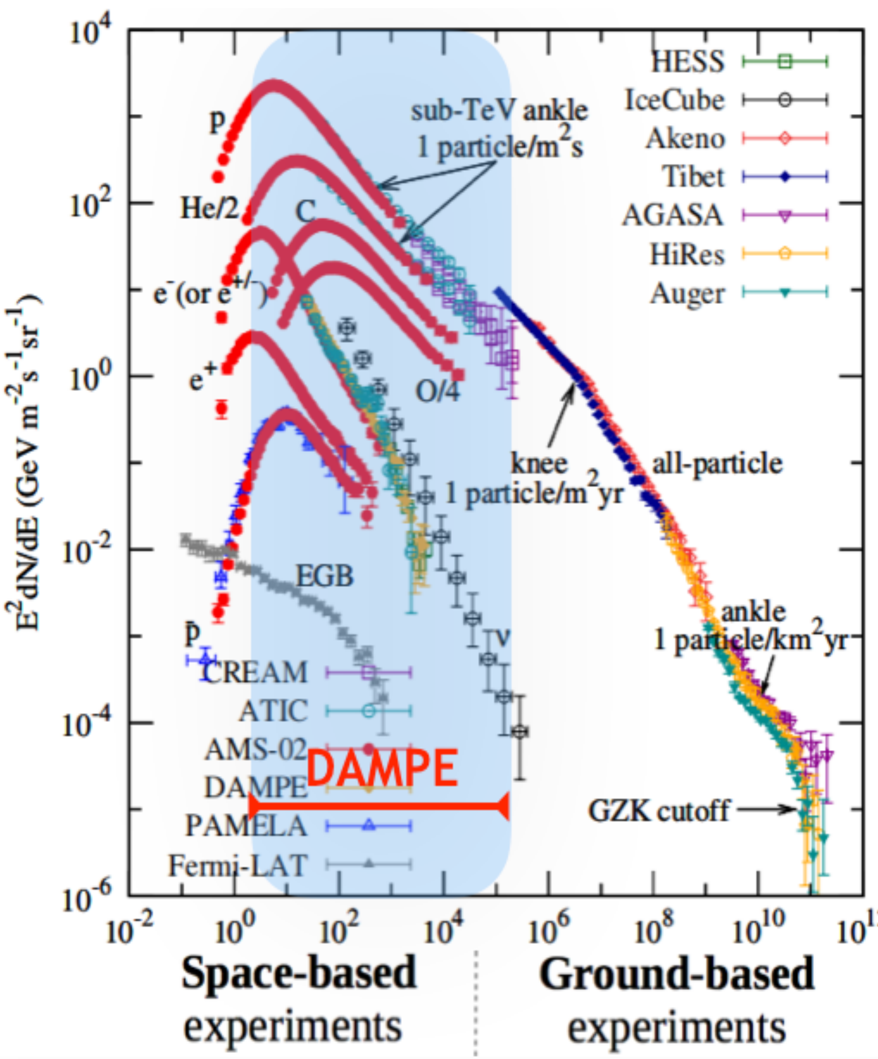
Cosmic-Ray nuclei



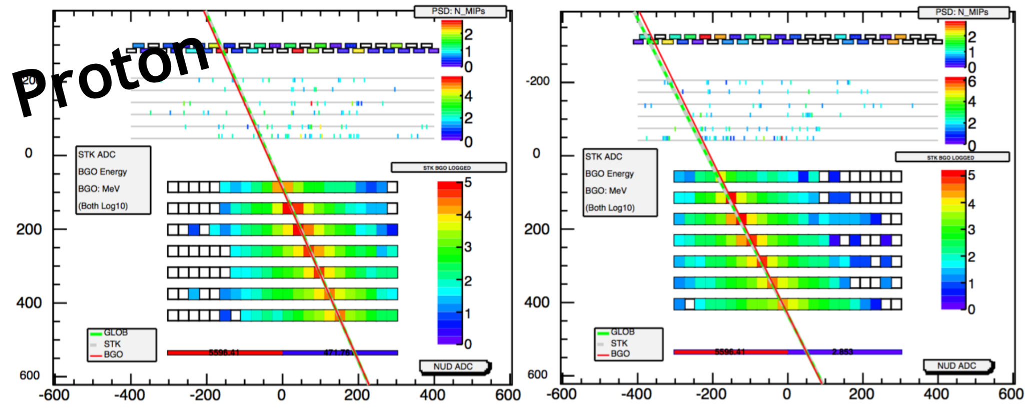


- Primary elements (H, He, C, O, …, Fe) are produced in the stars and accelerated to high energy cosmic-rays by the astronomic explosions
- Secondaries (Li, Be, B, F, sub-Fe) are mainly produced by the collision of the primary cosmic-rays with the interstellar medium

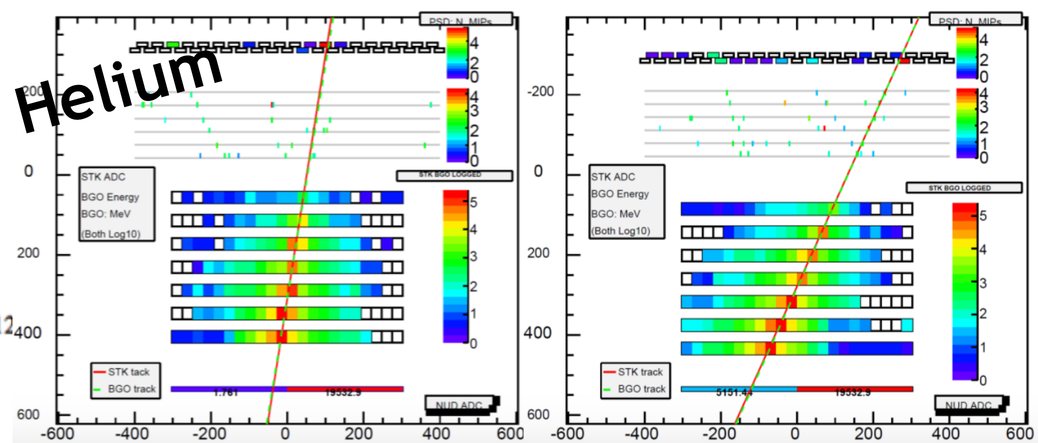
Cosmic-Ray nuclei



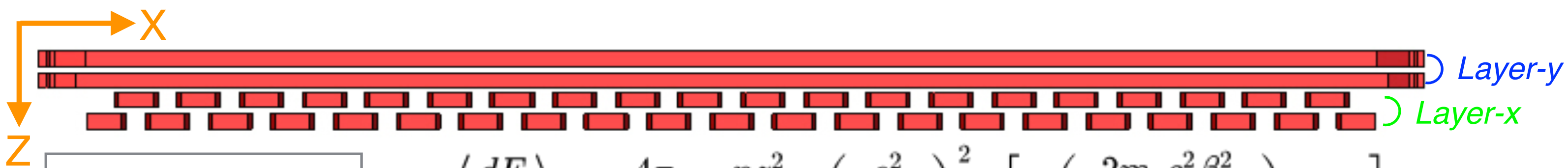
Orbit Proton (BGO-Energy: 1.2 TeV)



Orbit Helium (BGO-Energy: 1.8 TeV)

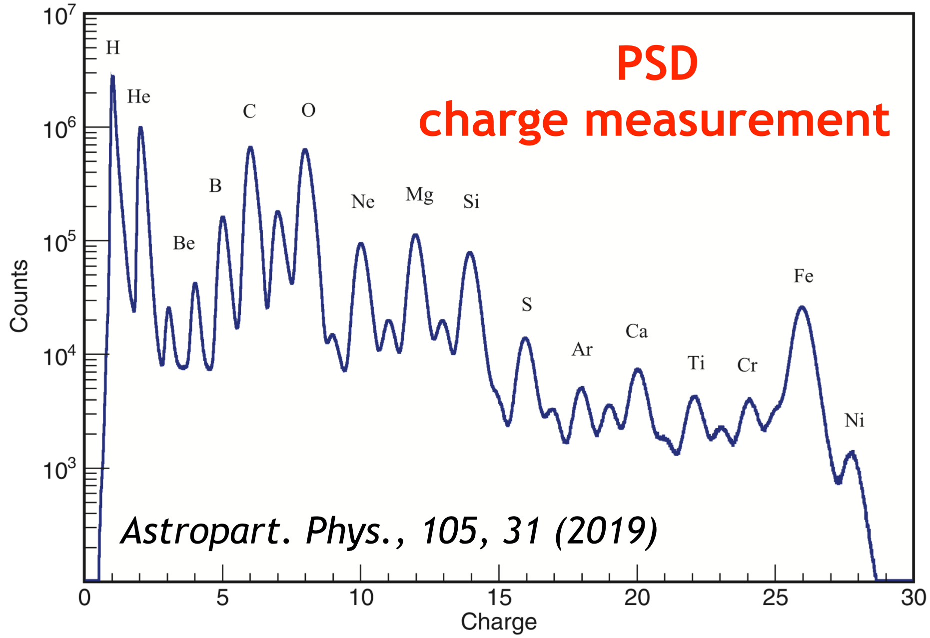


Particle identification



Bethe-Bloch

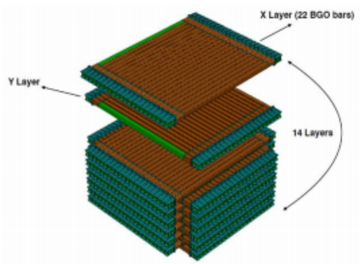
$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$



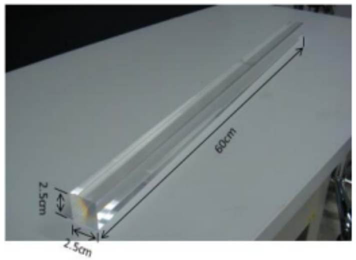
Element	σ_Z	Element	σ_Z	Element	σ_Z	Element	σ_Z
Li	0.14	C	0.18	Ne	0.21	S	0.25
Be	0.21	N	0.21	Mg	0.22	Ca	0.29
B	0.17	O	0.20	Si	0.25	Fe	0.30

Energy measurement

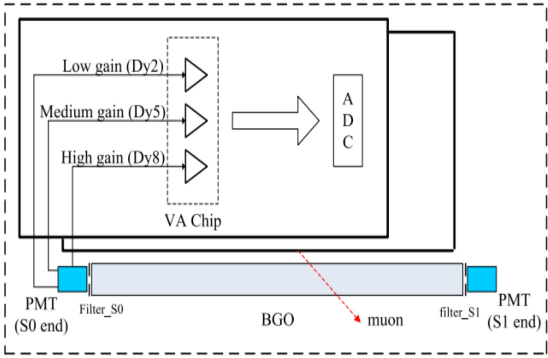
BGO calorimeter



308 BGO bars

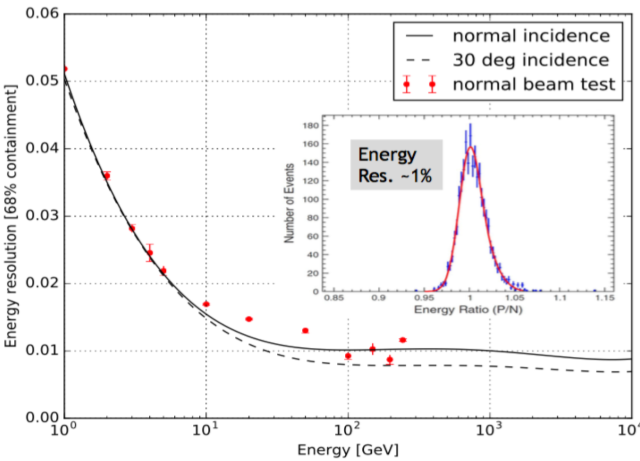


616 PMTs

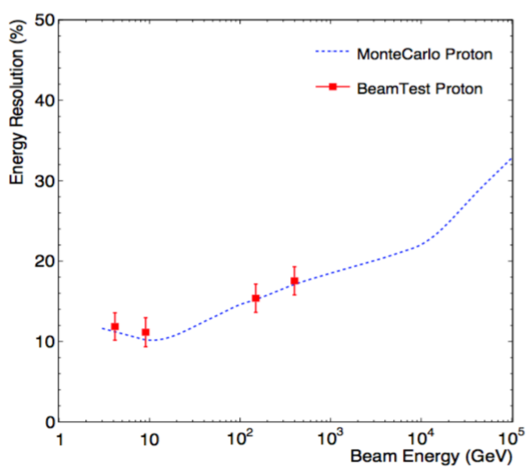


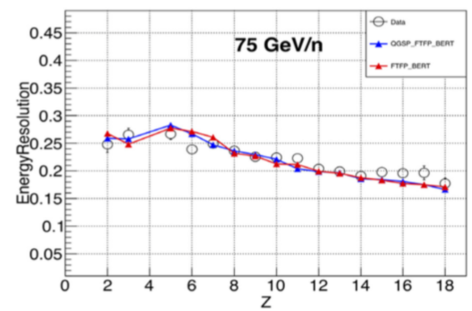
Beam tests at CERN PS & SPS

- 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



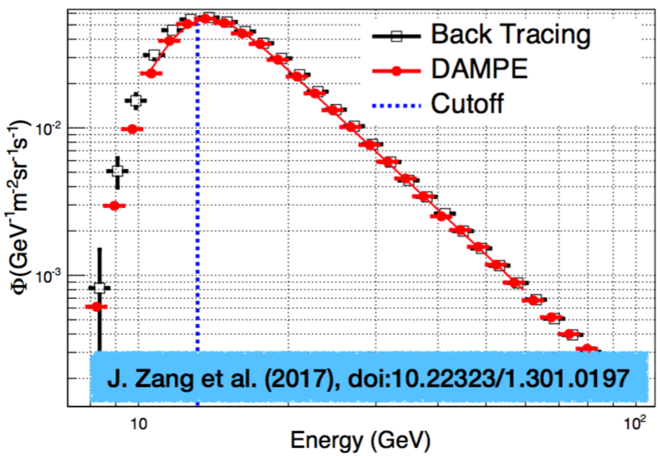


Y. Wei et al. NIMA 922 (2019)

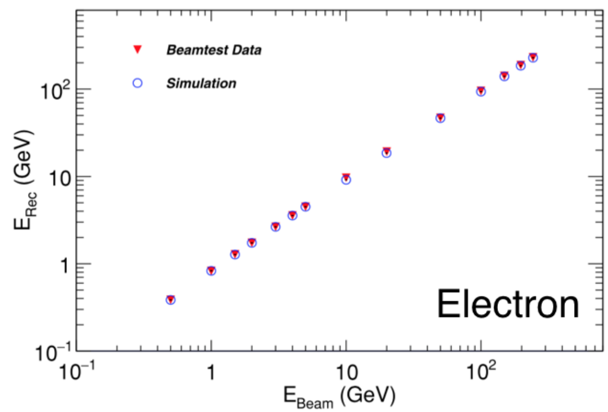
Energy measurement

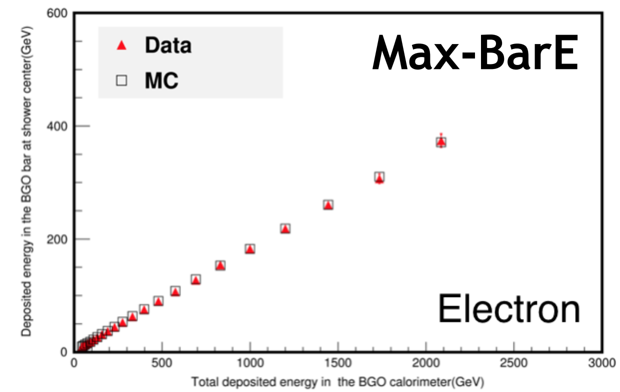
- On-orbit energy scale verified with **geomagnetic cut-off**
- Good linearity to ~2.5 (100) TeV with electron (nuclei) events

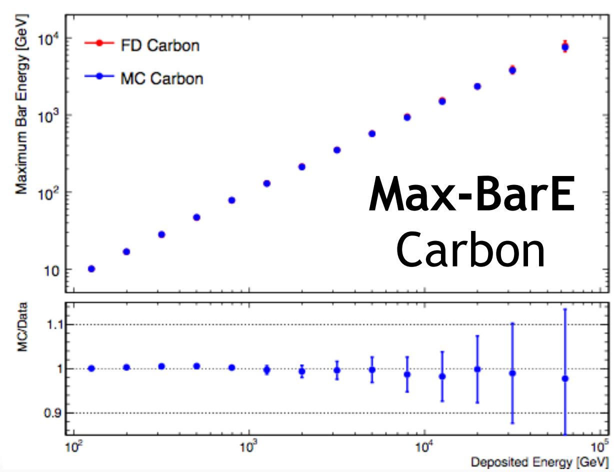
cosmic-ray electron
geomagnetic cut-off

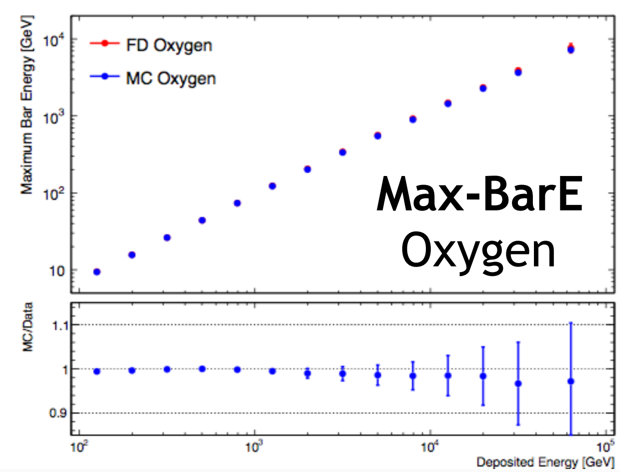


E scale in flight: **+ 1.25%** ± 1.75%(stat) ± 1.34%(sys)









Energy measurement

Bayesian Unfolding Method
[Giulio D'Agostini, NIM A362(1995), 487]

$$N_i = \sum_{j=1}^{n} \alpha_{ij} M_j (1 - \beta_j)$$

$$\alpha_{ij} = \frac{P(E_{d,j}|E_{0,i})\hat{N}_i}{\epsilon_i \sum_{i=1}^{n} P(E_{d,j}|E_{0,i})\hat{N}_i}$$

N_i : **Unfolded event number**

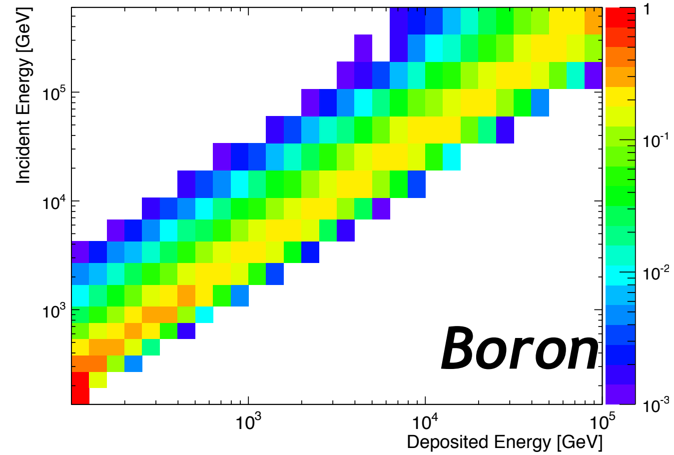
M_j: **Measured event number**

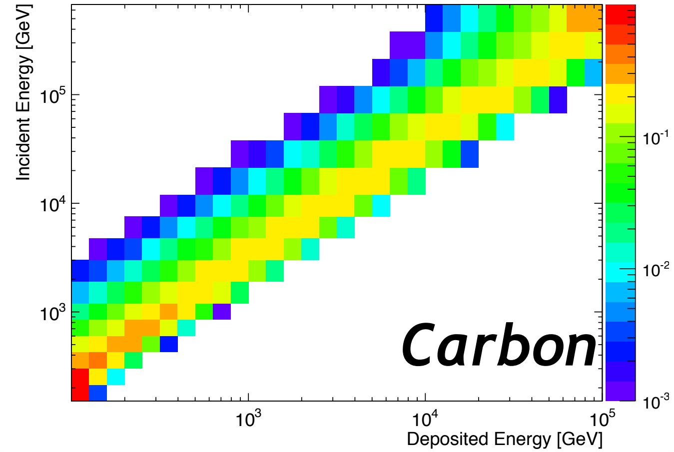
β_j : **Background**

$P(E_{d,j}|E_{0,i})$: **Energy response matrix**

$\hat{N}_i$: **Prior ($E^{-2.7}$)**

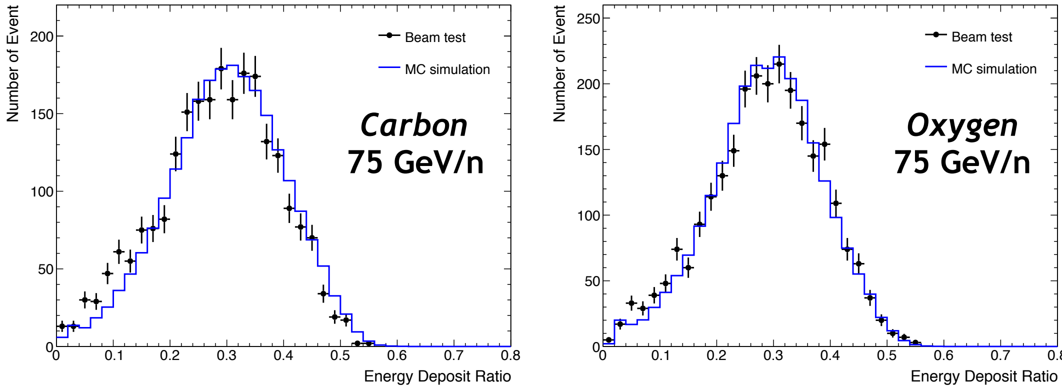
$$V_{kl} = V_{kl}(\mathbf{n}(E)) + V_{kl}(\mathbf{M})$$

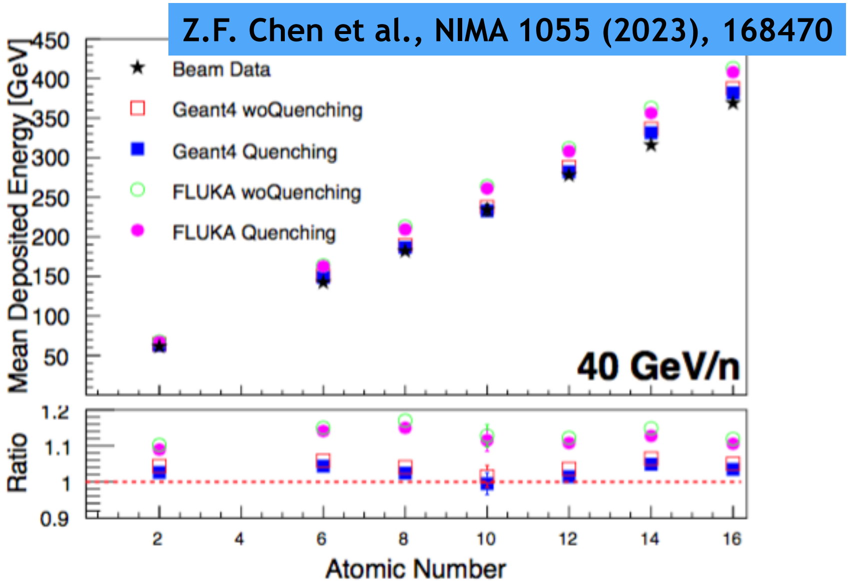


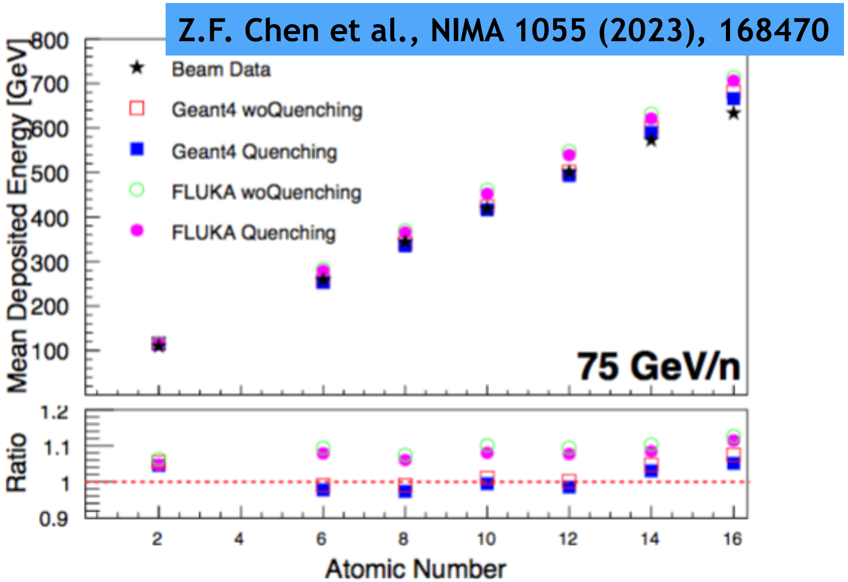


Energy measurement

Ion Beam Test @ CERN

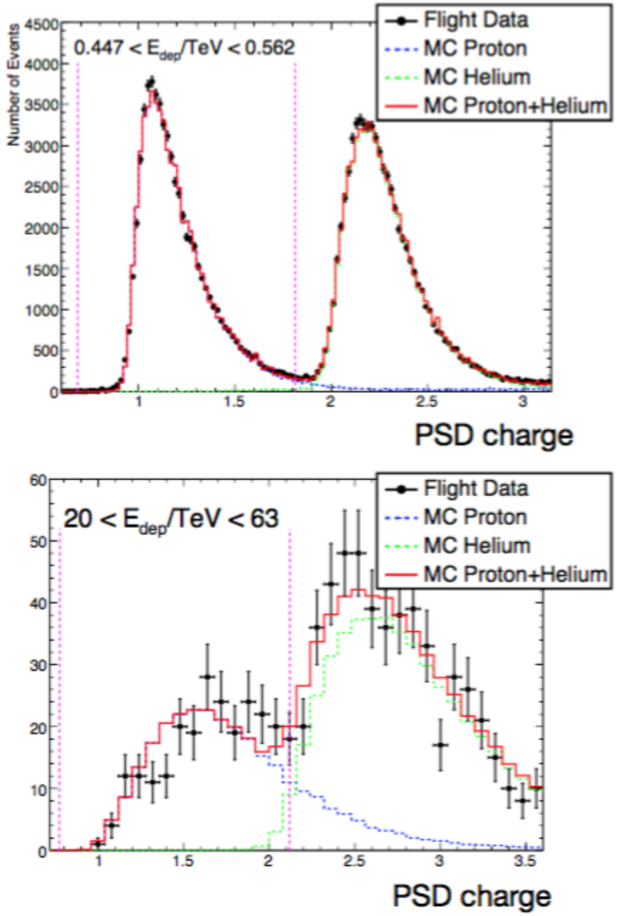


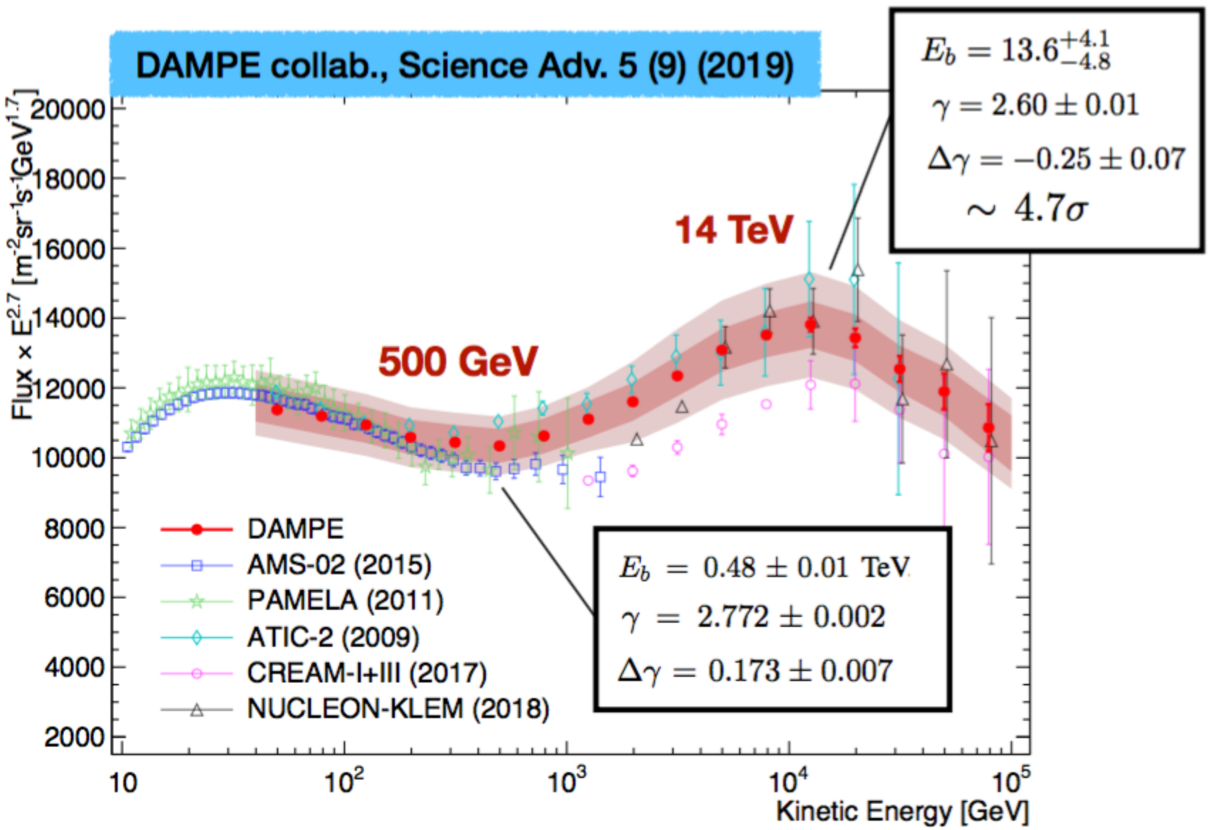




The energy responses of MC simulation (Geant4) show good agreements with BT-data

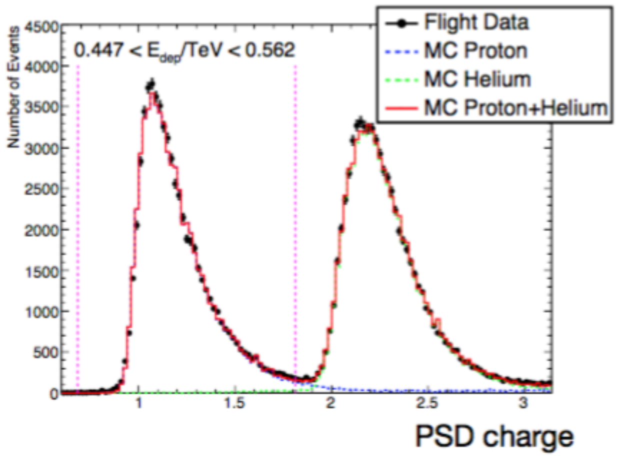
Proton spectrum

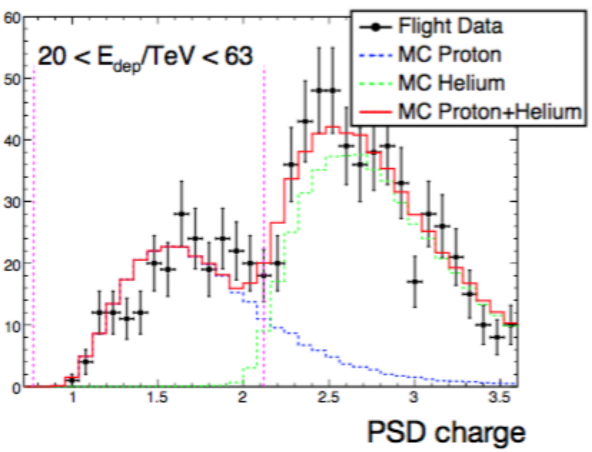


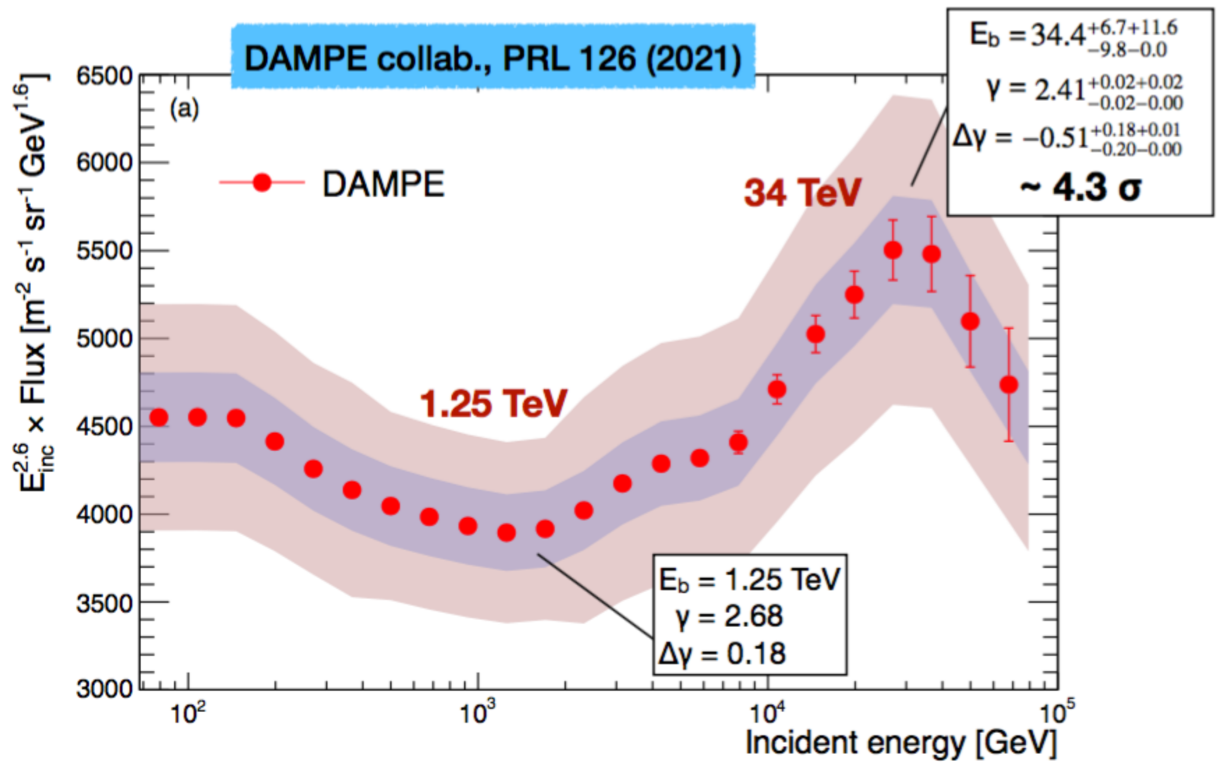


The DAMPE measurement confirms the spectral hardening at a few hundreds of GeVs found by previous experiments, and more importantly, it reveals a spectral softening feature at ~14 TeV.

Helium spectrum



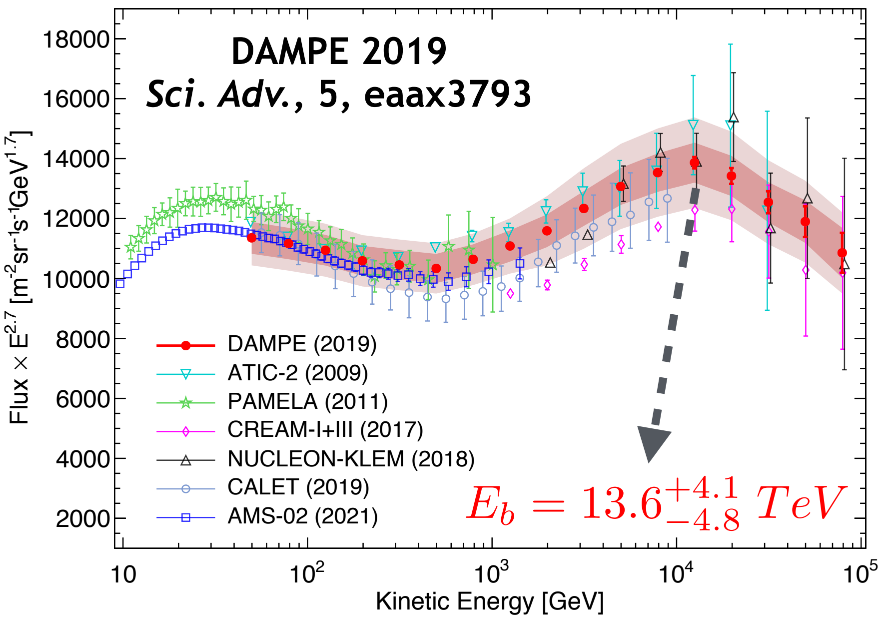




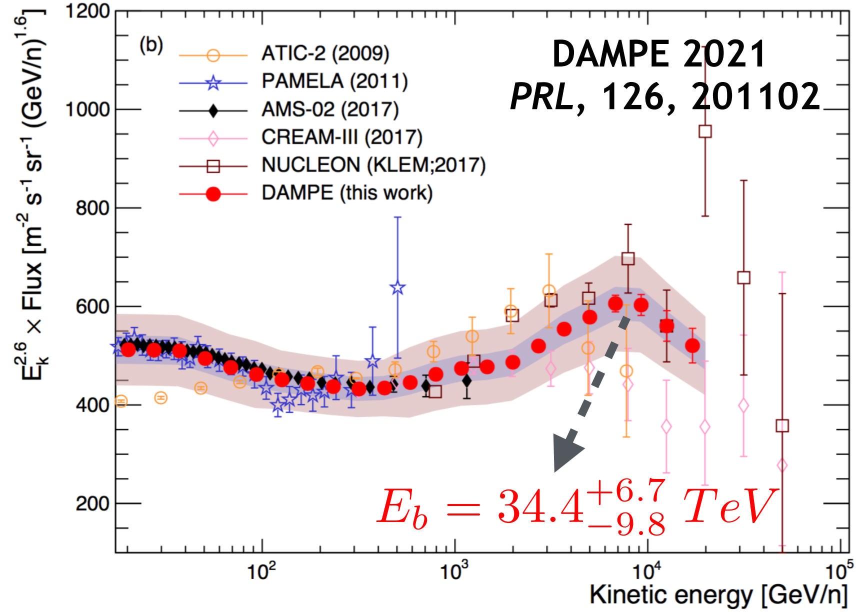
The DAMPE measurement confirms the spectral hardening at TeV-energies found by previous experiments, and more importantly, it reveals a spectral softening feature at a few decades of TeVs.

Proton v.s. Helium

CR Proton



CR Helium

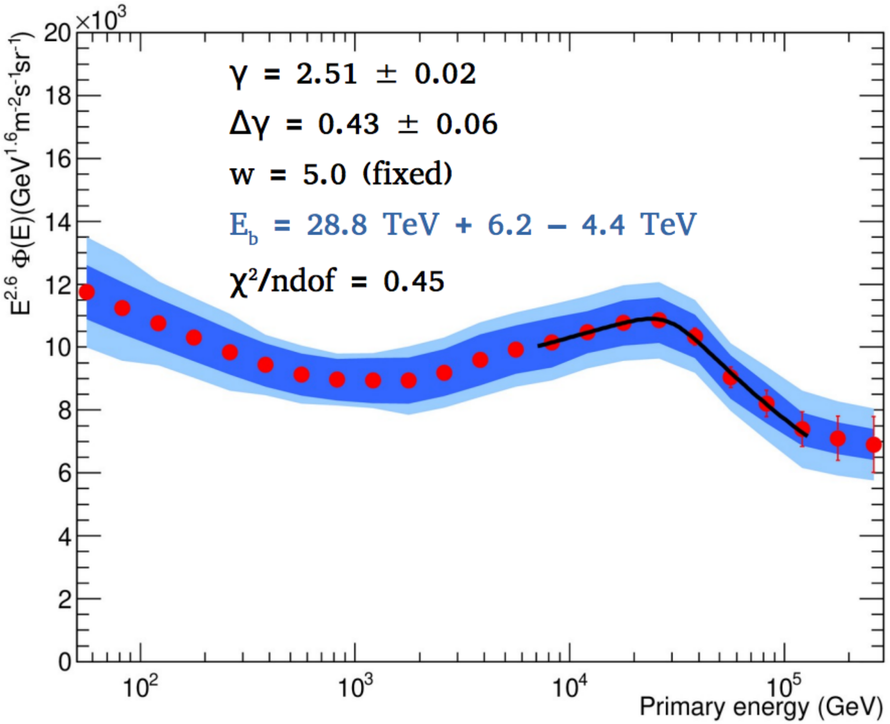


- ✳ The spectra of CR proton and helium measured by DAMPE show a very similar softening feature at tens of TeVs.
- ✳ The softening energies are well consistent with a dependence on particle charge, although a dependence on particle mass can not be ruled out yet.
- ✳ The results implicate a Z-dependent spectral break (e.g. “knee”) in CR nuclei, which is likely an imprint of a nearby cosmic ray source.

p+He spectrum

Independent analysis of p+He spectrum in the collaboration

Very low contamination + Very large statistics => High upper limit of measurement



Smoothly-broken power-law model (SBPL)

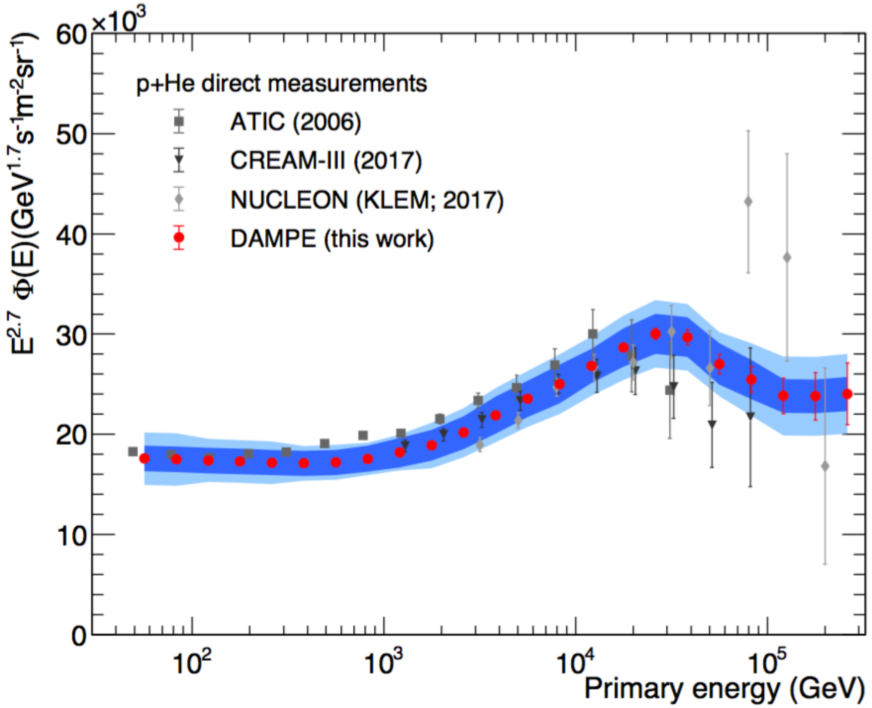
$$\Phi(E) = \Phi_0 \left(\frac{E}{TeV}\right)^{-\gamma} \left[1 + \left(\frac{E}{E_b}\right)^{1/w}\right]^{-\Delta\gamma \cdot w}$$

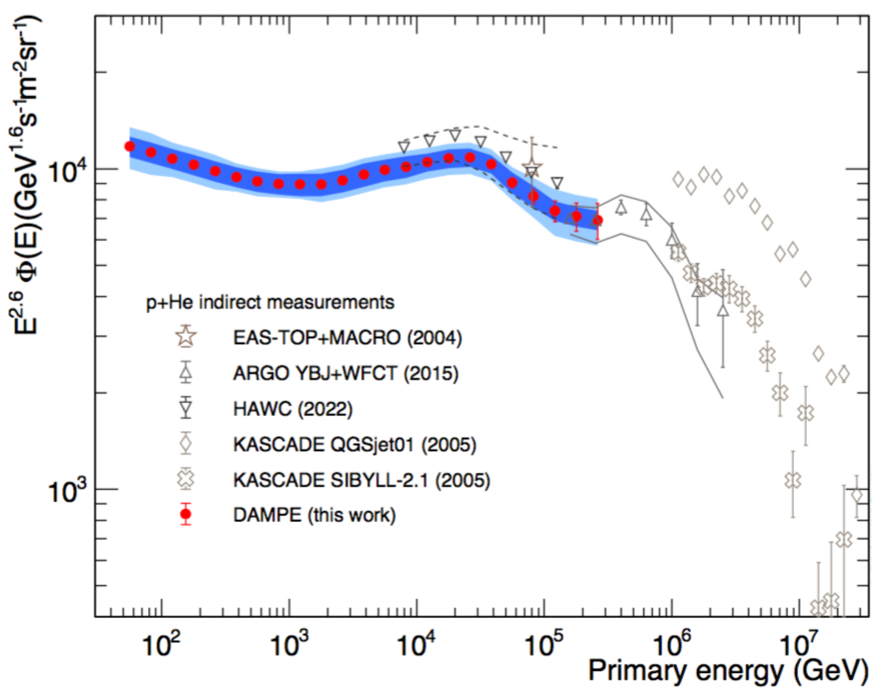
	Proton	Helium	Proton+Helium
E_b (TeV)	$13.6^{+4.1}_{-4.8}$	$34.4^{+6.7+11.6}_{-9.8-0.0}$	$28.8^{+6.2+2.9}_{-4.4-0.0}$
γ	2.60 ± 0.01	$2.41^{+0.02+0.02}_{-0.02-0.00}$	$2.51^{+0.021+0.01}_{-0.024-0.00}$
$\Delta\gamma$	-0.25 ± 0.07	$-0.51^{+0.18+0.01}_{-0.20-0.00}$	$0.43^{+0.066+0.066}_{-0.057-0.00}$

SBPL model favored on the PL model with a significance of 6.6σ

p+He spectrum

Independent analysis of p+He spectrum in the collaboration

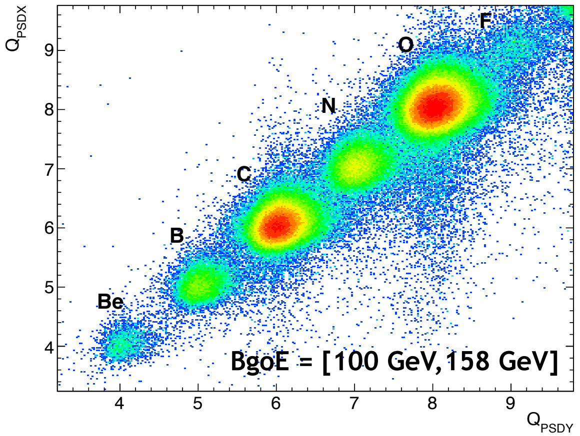


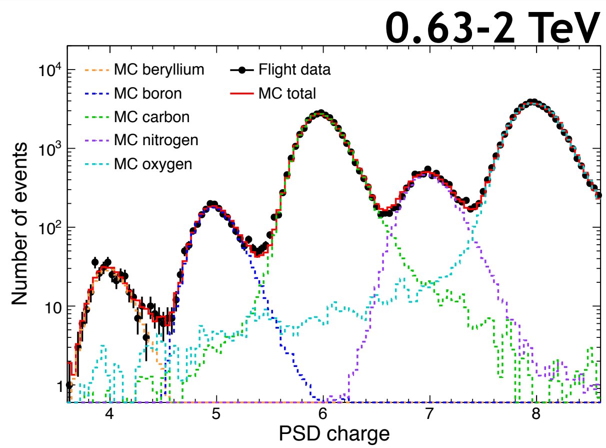


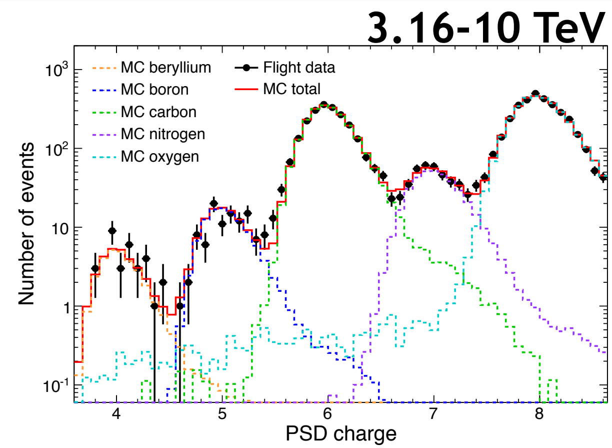
- Link between direct/indirect CR measurements
- **Hint of new spectral hardening at ~150 TeV**

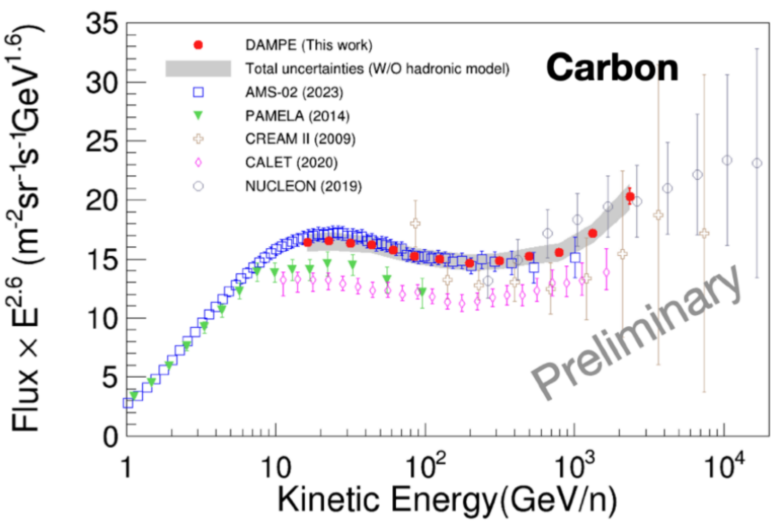
DAMPE collab., arxiv:2304.00137 (2023)

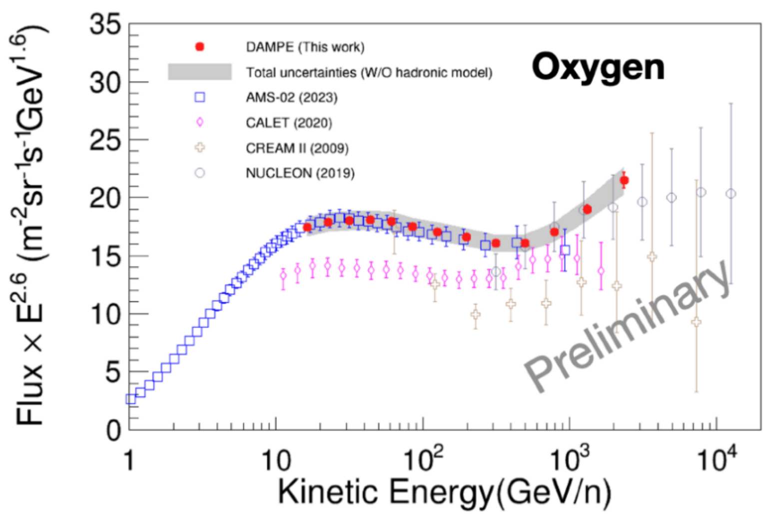
Carbon and Oxygen





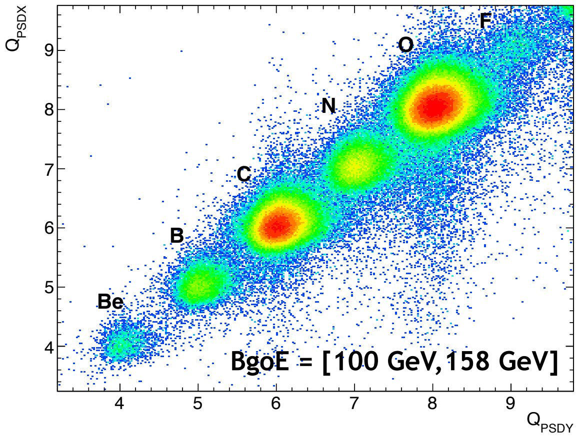


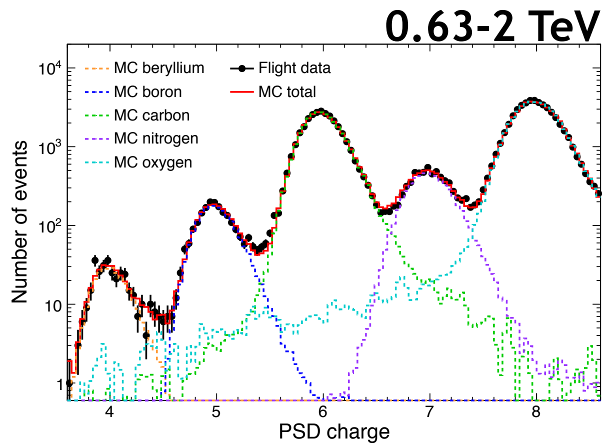


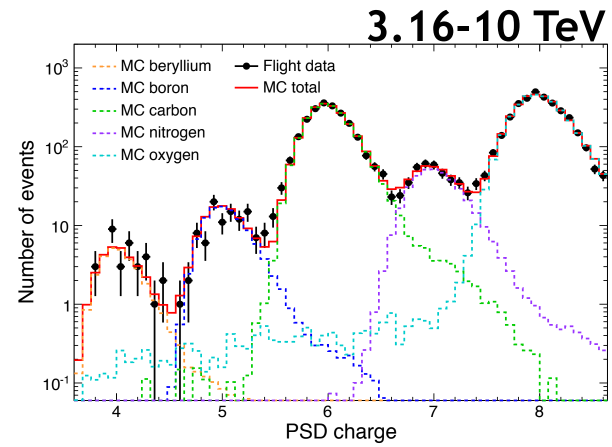


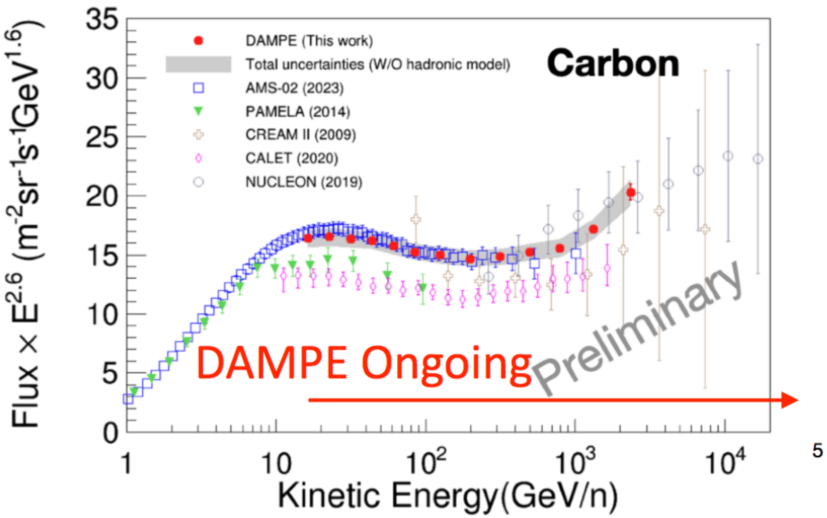
- **Preliminary DAMPE measurements confirm the hardening structure at several hundreds of GeV/n observed by previous experiments.**

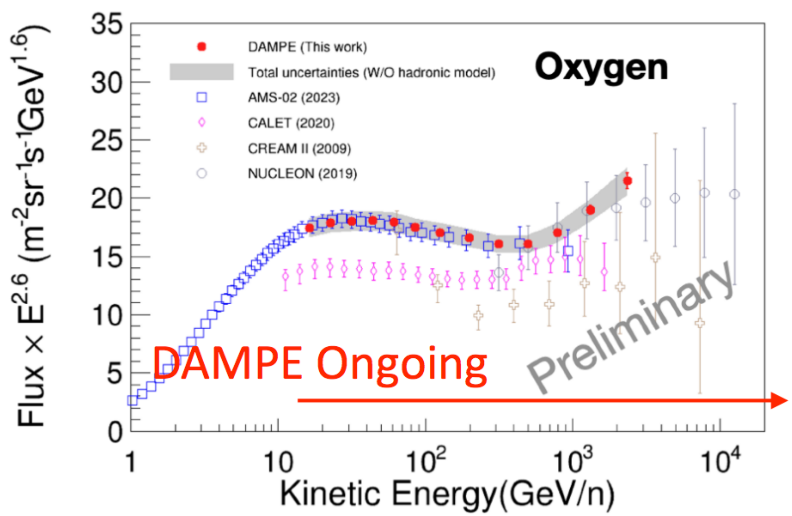
Carbon and Oxygen









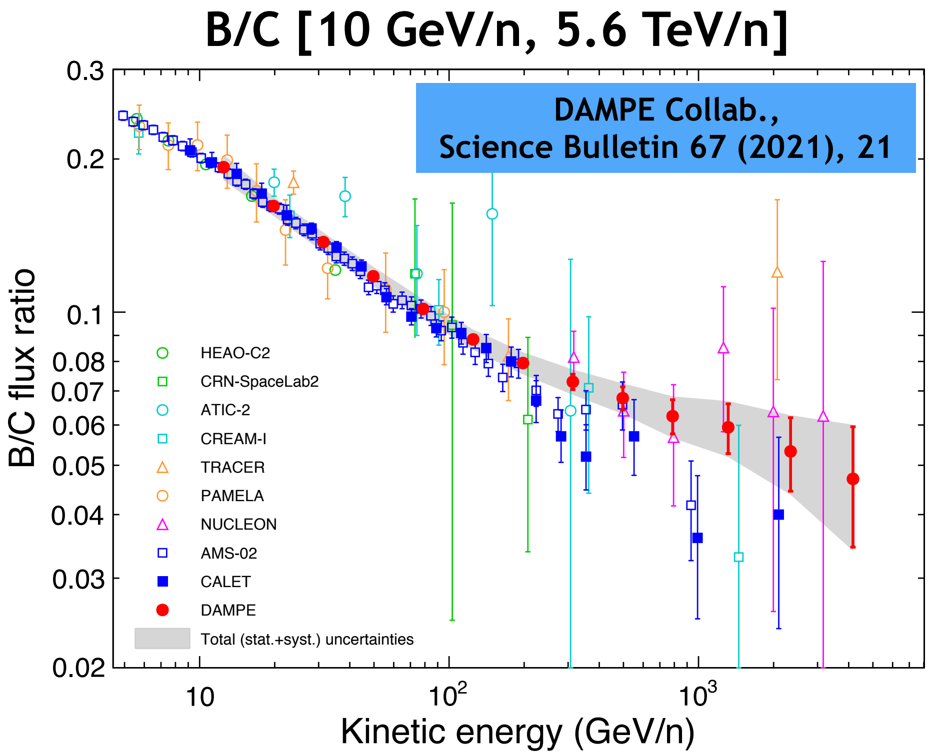


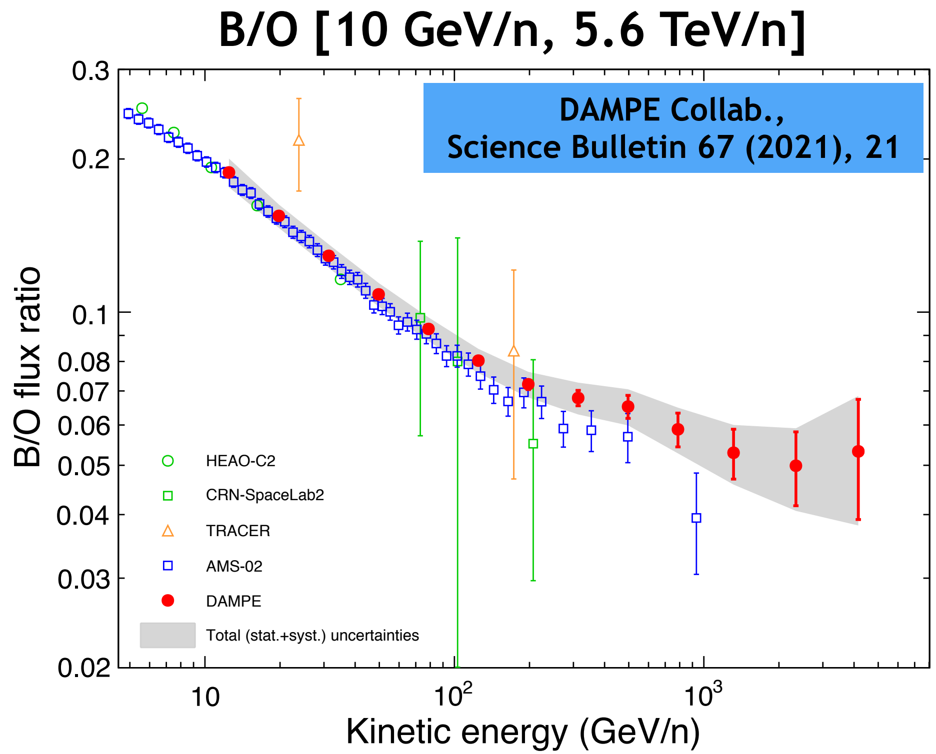
- **DAMPE is expected to extend the CO spectral measurements up to tens of TeV/n.**

B/C and B/O

✦ Boron nuclei are mainly produced by **the fragmentation of heavier nuclei**, e.g. C and O.

✦ Precise measurements of **the B/C(O) flux ratio** are crucial to constrain **the CR propagation.**





- **The DAMPE measurements clearly reveal a significant hardening feature at ~100 GeV/n for both B/C and B/O, which deviates from the predictions of conventional turbulence theories of the interstellar medium.**

B/C and B/O

Nuisance Parameter Method (S. Abdollahi et al., PRD, 2017)

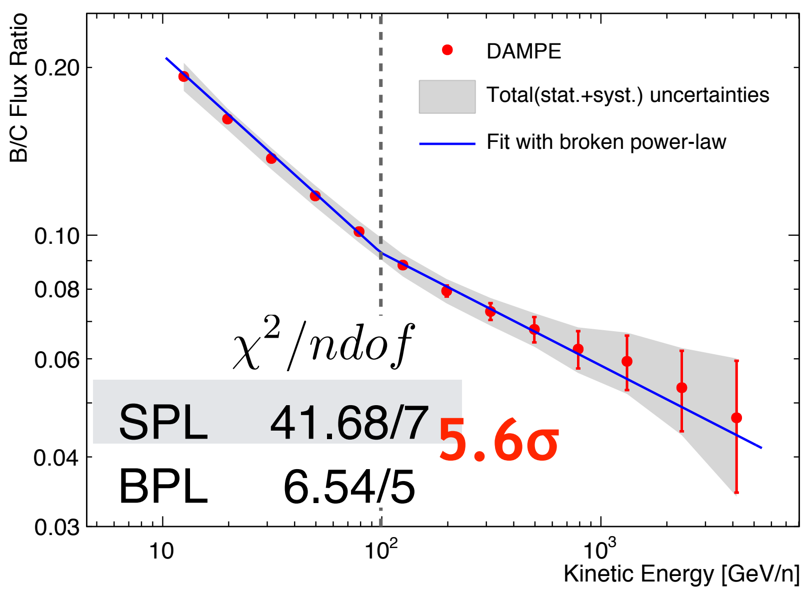
$$\chi^2 = \sum_i \sum_j [R(E_{k,i})S(E_{k,i};\, \boldsymbol{w}) - R_i]\mathcal{C}_{ij}^{-1}[R(E_{k,j})S(E_{k,j};\, \boldsymbol{w}) - R_j] + \sum_{\ell=1}^{m} \left(\frac{1 - w_\ell}{\tilde{\sigma}_{\mathrm{sys},\ell}}\right)^2$$

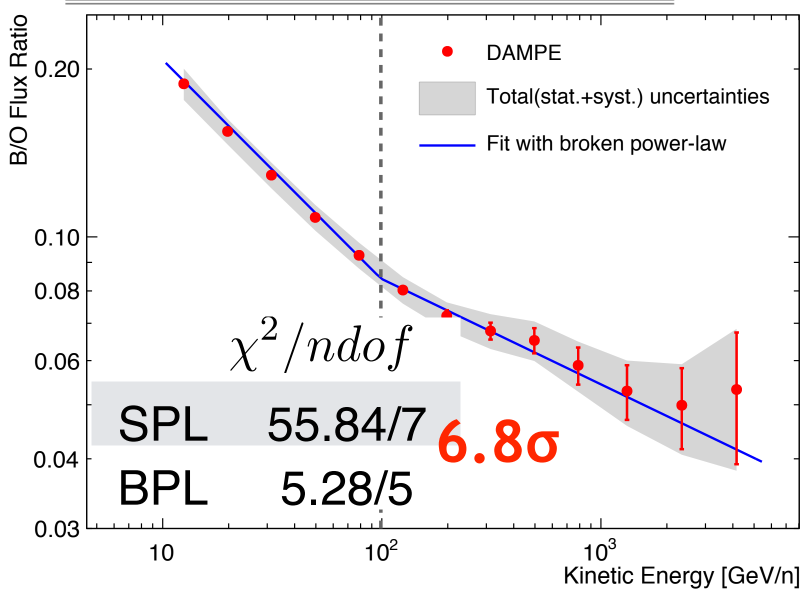
SPL: $R(E_k) = R_0 \left(\frac{E_k}{\mathrm{GeV/n}}\right)^{-\gamma}$

BPL: $R(E_k) = \begin{cases} R_0\,(E_k/E_b)^{-\gamma_1}, & E_k \le E_b \\ R_0\,(E_k/E_b)^{-\gamma_2}, & E_k > E_b \end{cases}$

	B/C	B/O
Nuisance parameters	4	4
R_0	$0.093^{+0.004+0.000}_{-0.004-0.001}$	$0.084^{+0.003+0.000}_{-0.003-0.000}$
γ_1	$0.356^{+0.008+0.000}_{-0.008-0.017}$	$0.394^{+0.010+0.000}_{-0.010-0.026}$
E_b (GeV/n)	$98.9^{+8.9+10.0}_{-8.8-0.0}$	$99.5^{+7.4+7.7}_{-7.1-0.0}$
γ_2	$0.201^{+0.024+0.008}_{-0.024-0.000}$	$0.187^{+0.024+0.000}_{-0.024-0.019}$
χ^2/dof	6.61/5	5.51/5

DAMPE Collab., Science Bulletin 67 (2021), 21





Summary

- The DAMPE detector has operated smoothly for more than 7.5 years, opening a new window to look at the high-energy cosmic-ray nuclei up to hundreds of TeVs
- Precise measurements of proton (helium) spectra reveal **universal softening features at ~14 (34) TeV**
- Precise measurements of B/C and B/O reveal a **unexpected hardening feature at ~100 GeV/n**
- More results about cosmic ray nuclei spectral measurements are forthcoming

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Thank You!