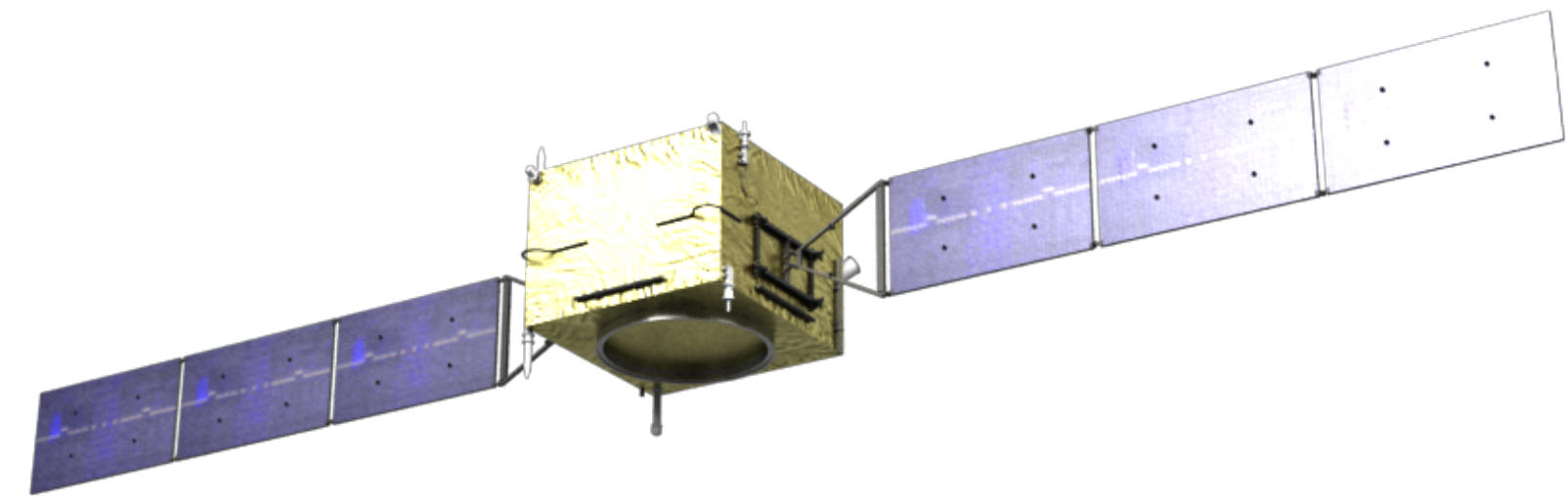




基于“悟空”号卫星的宇宙线探测进展

Direct Cosmic-ray Detection with the DAMPE Space Mission

岳川

中国科学院·紫金山天文台

代表DAMPE国际合作组



中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会

2026, 7/13 - 7/19, 广州

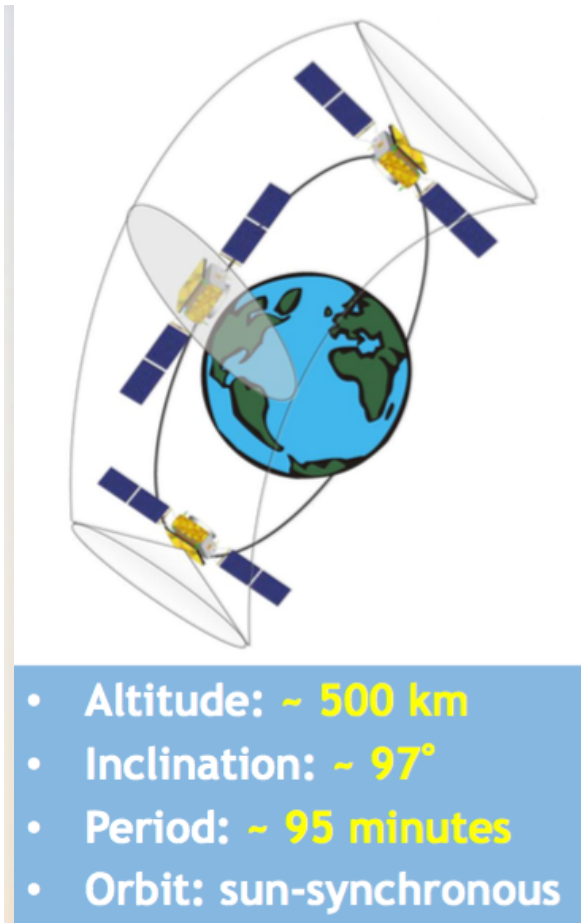
Outline

- 暗物质粒子探测卫星“悟空”号 (DAMPE)
- 基于DAMPE的高能宇宙线探测
- DAMPE宇宙线探测进展
- 总结与展望

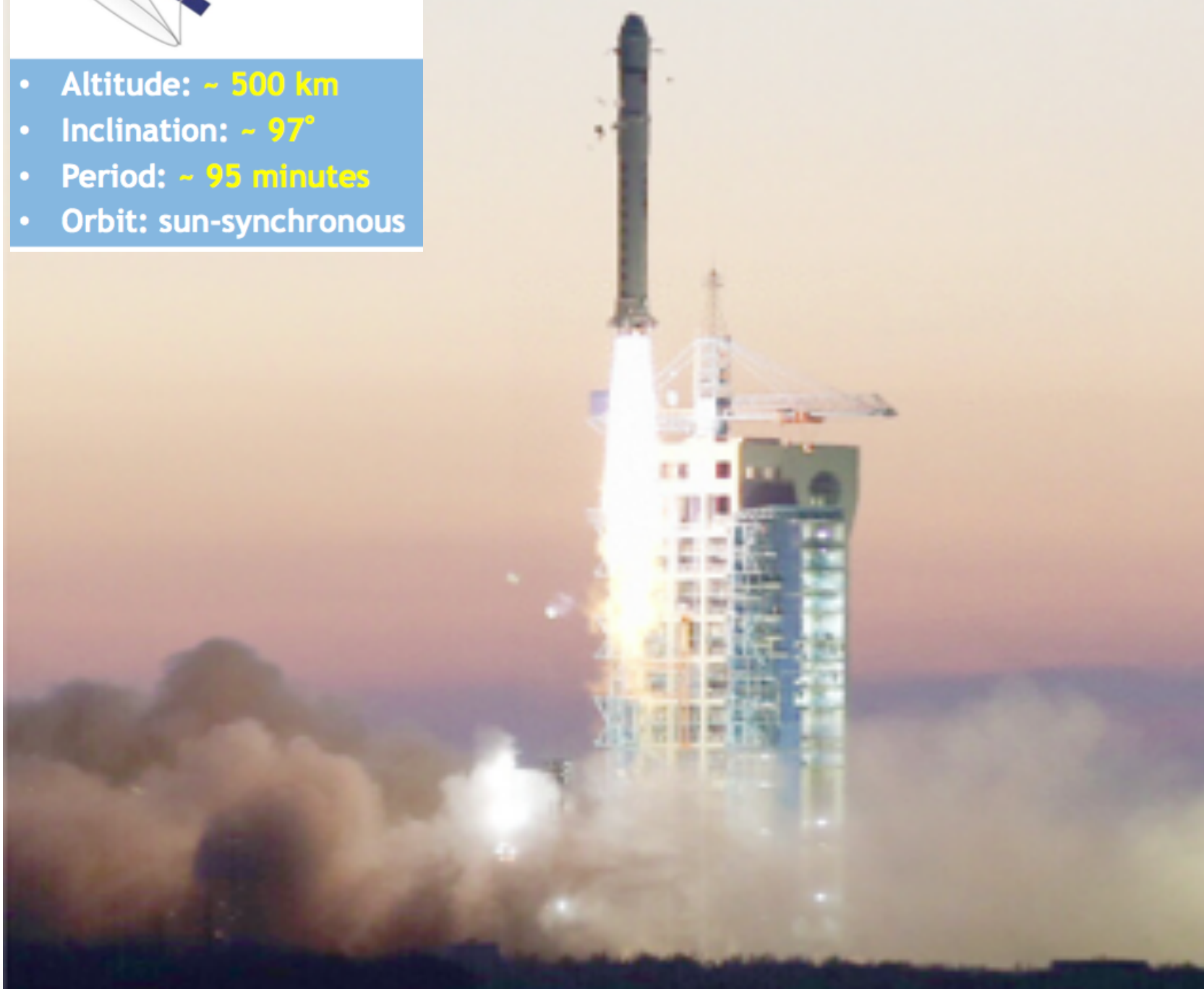


“悟空”号 (DAMPE) 卫星

暗物质粒子探测卫星“悟空”号 (DAMPE) 是中国科学院空间先导专项首发星
2015年12月17日成功发射，实现了中国空间天文卫星“0”的突破，已平稳运行超过十年



2015年12月17日
@酒泉

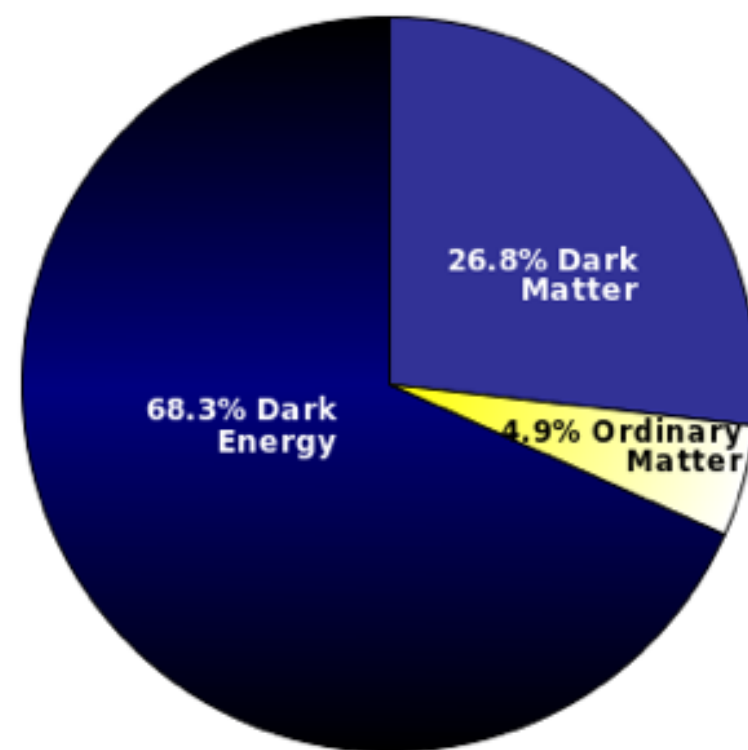
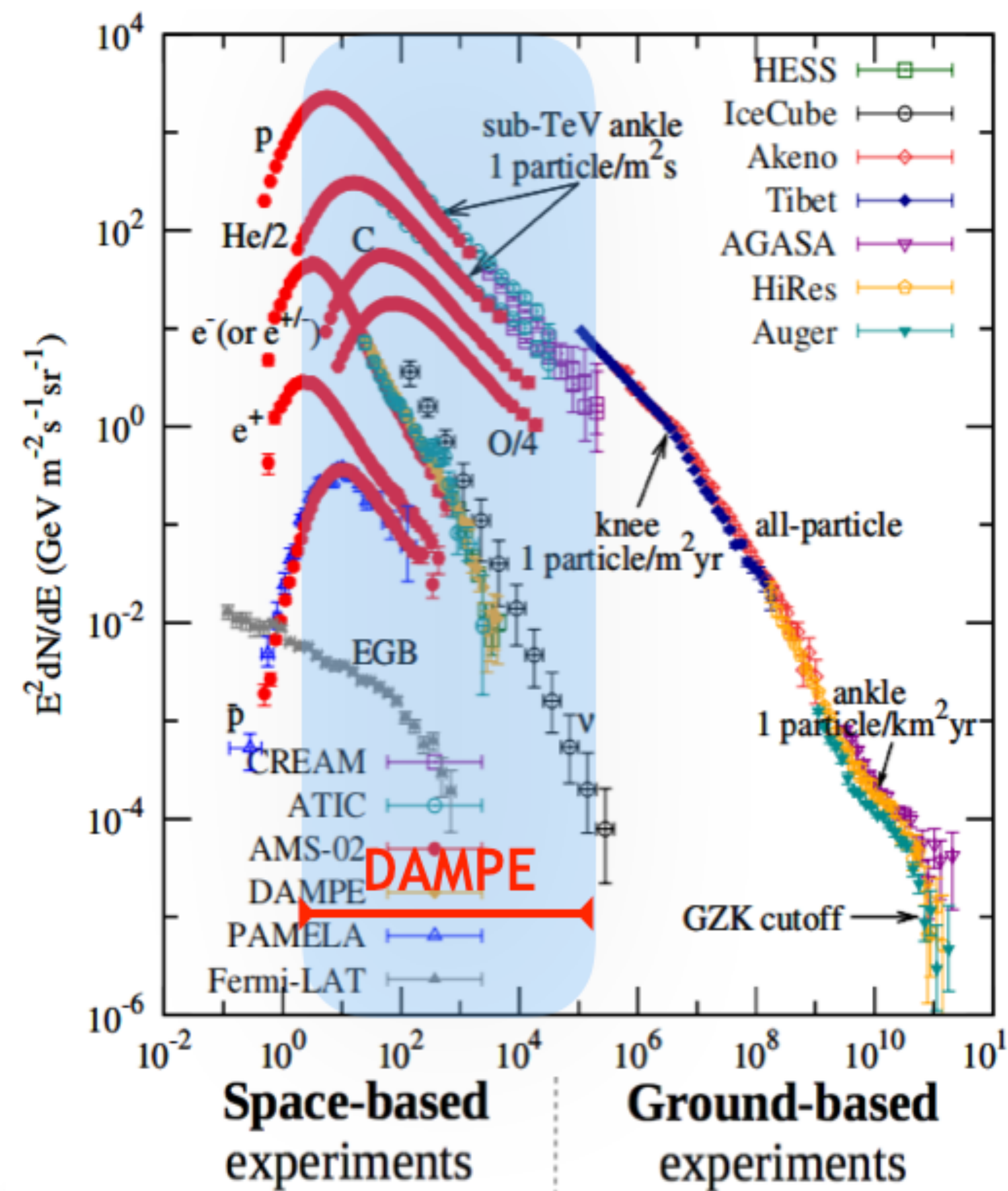


150+
members

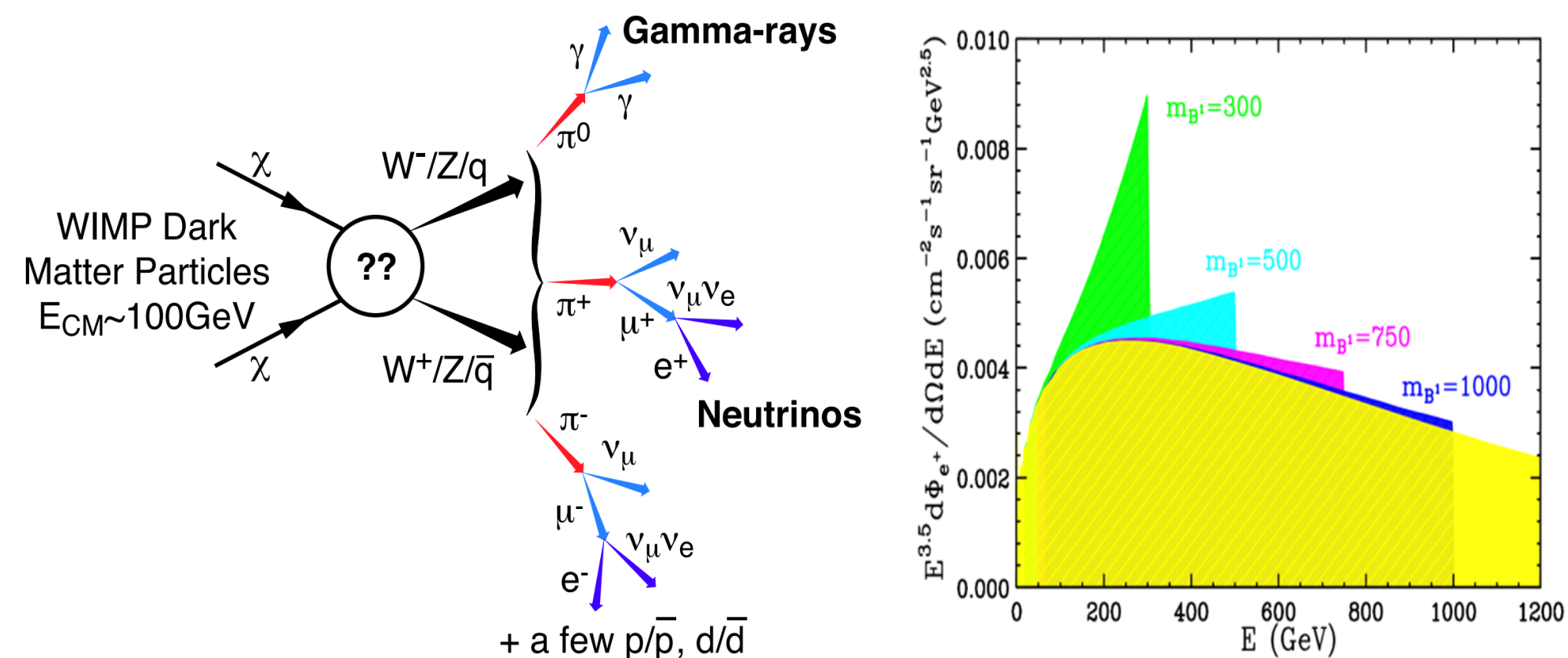
- CHINA
 - Purple Mountain Observatory, CAS, Nanjing
 - Institute of High Energy Physics, CAS, Beijing
 - National Space Science Center, CAS, Beijing
 - University of Science and Technology of China, Hefei
 - Institute of Modern Physics, CAS, Lanzhou
- ITALY
 - INFN Perugia and University of Perugia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



宇宙线物理

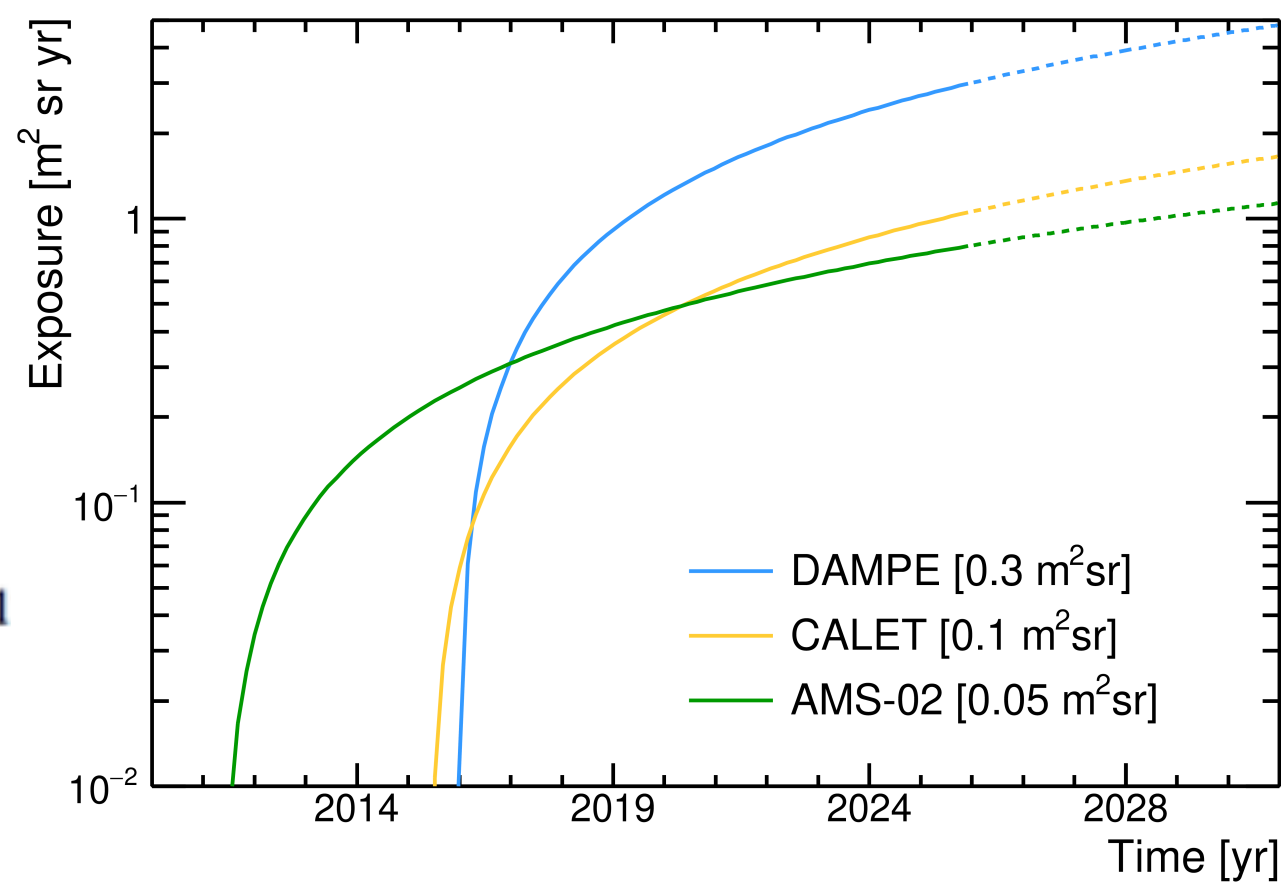
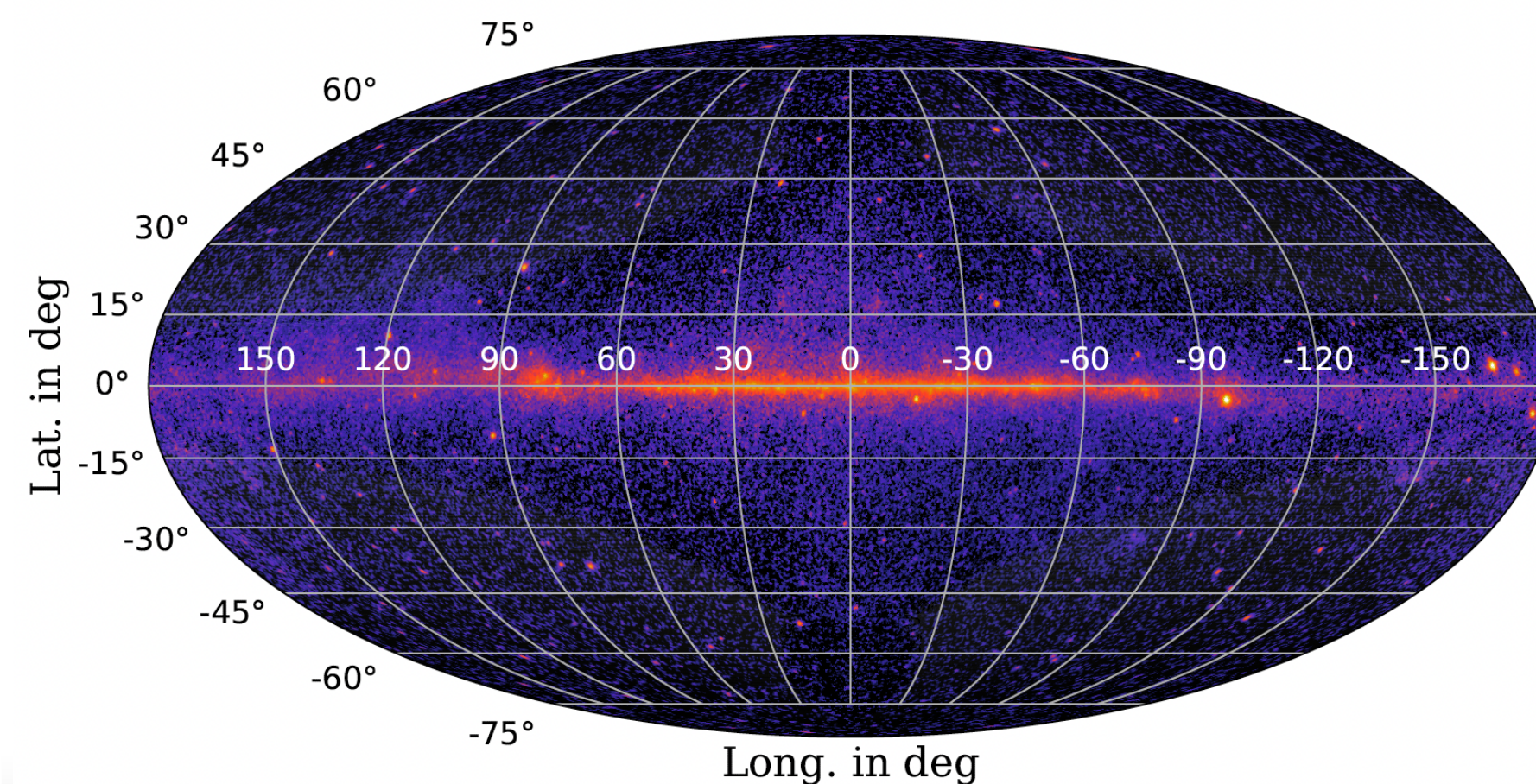


暗物质间接探测



高能伽马射线天文

Flux map with 9 years of DAMPE flight data

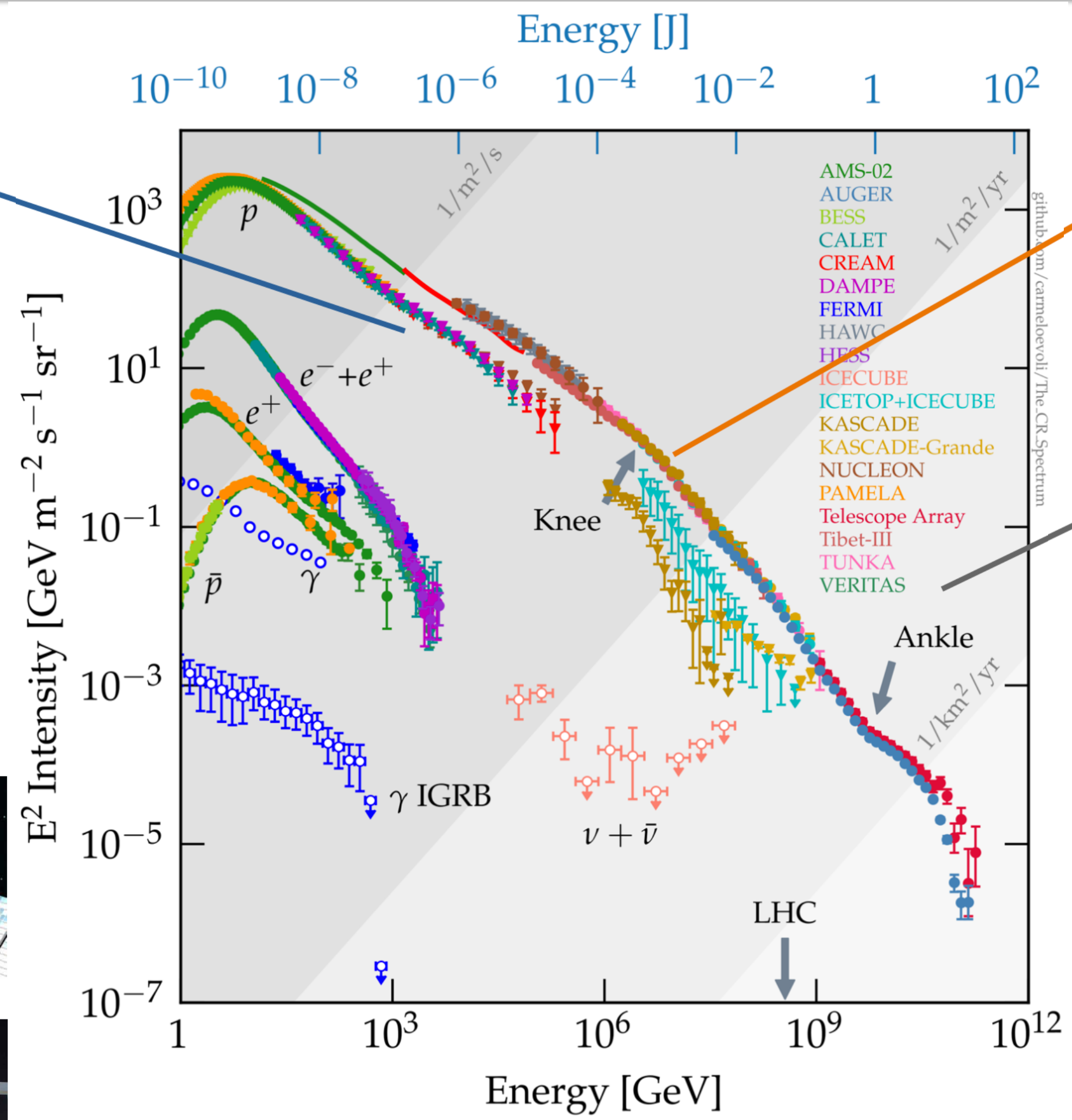
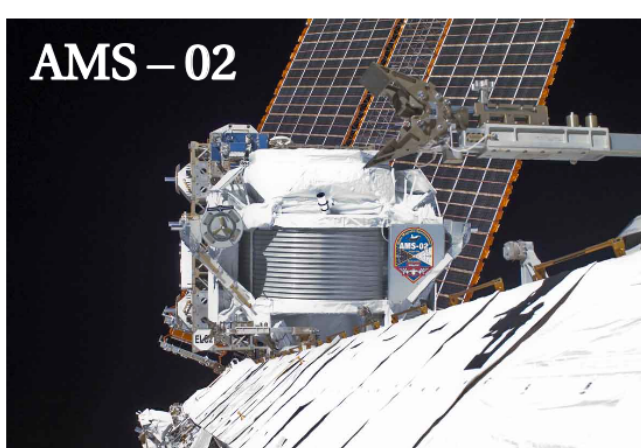
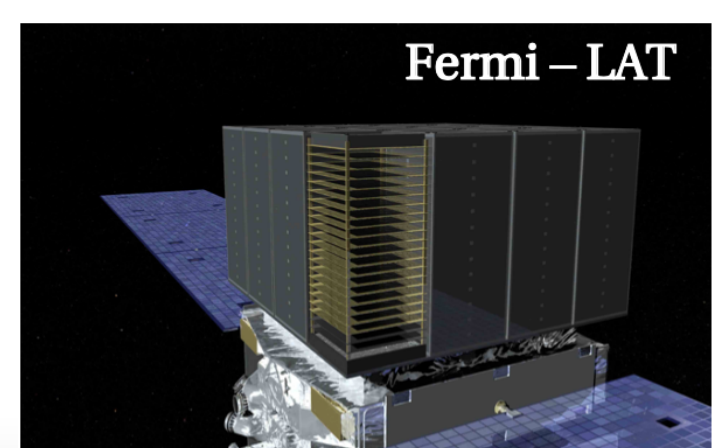
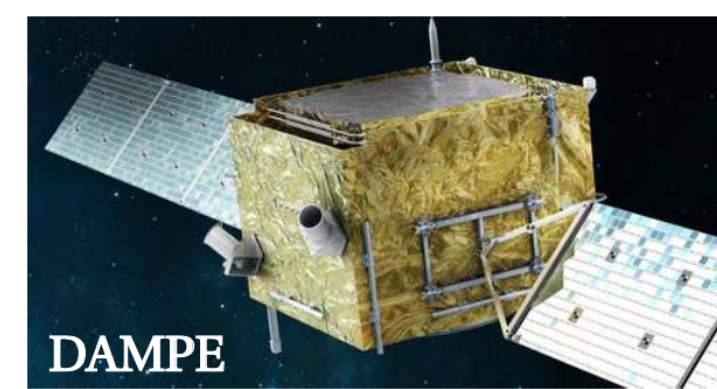
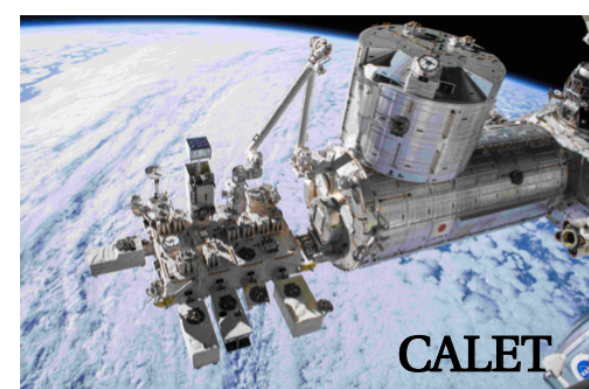


宇宙线探测

Energies achieved with **current space – borne direct CR experiments** (~ hundred TeV)

直接探测实验

- 精确鉴别粒子成分
- 成分能谱精确测量(<PeV)



Maximal energies achieved with direct detection CR experiments (~ PeV)

Region covered by **indirect CR experiments** (~ 10^{20} eV)

间接探测实验

- 超大探测面积/超高能量上限
- 高能区能谱测量(>100 TeV)

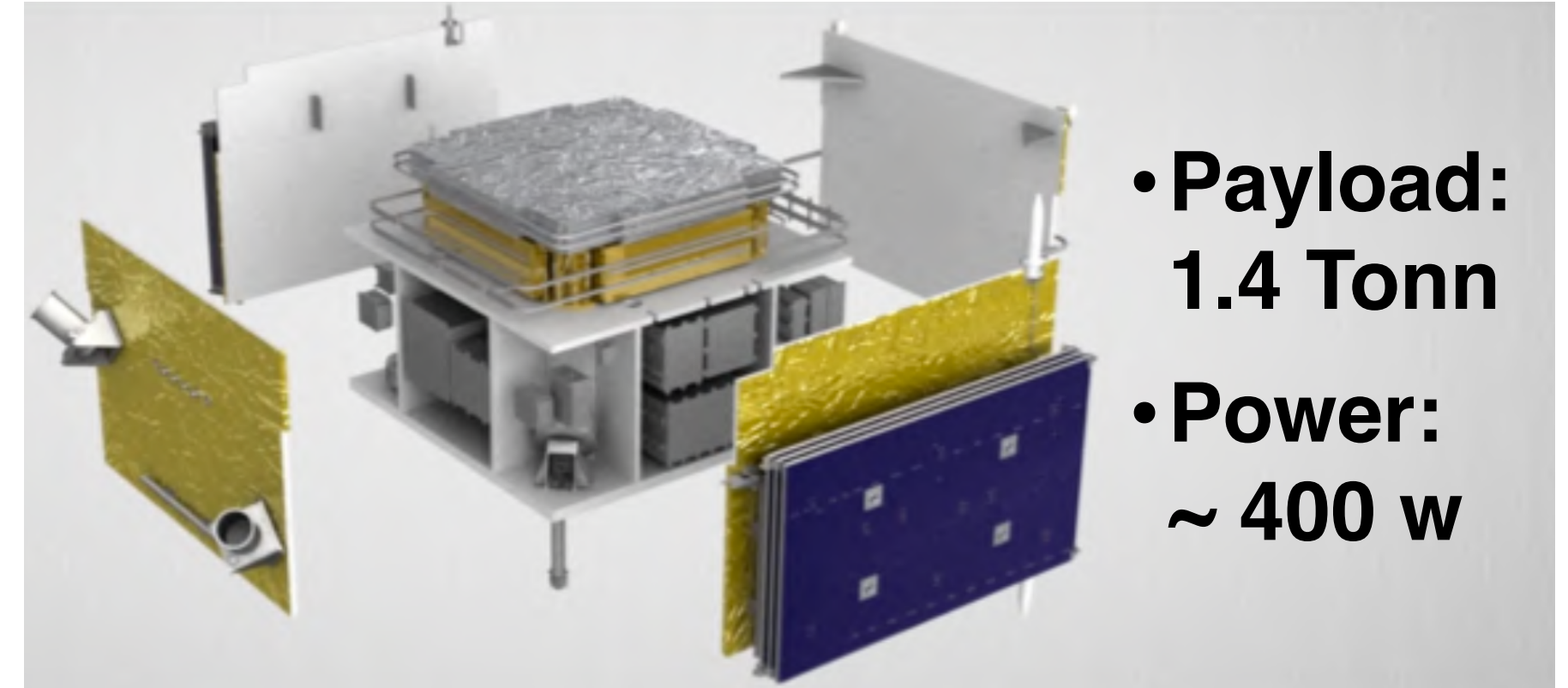
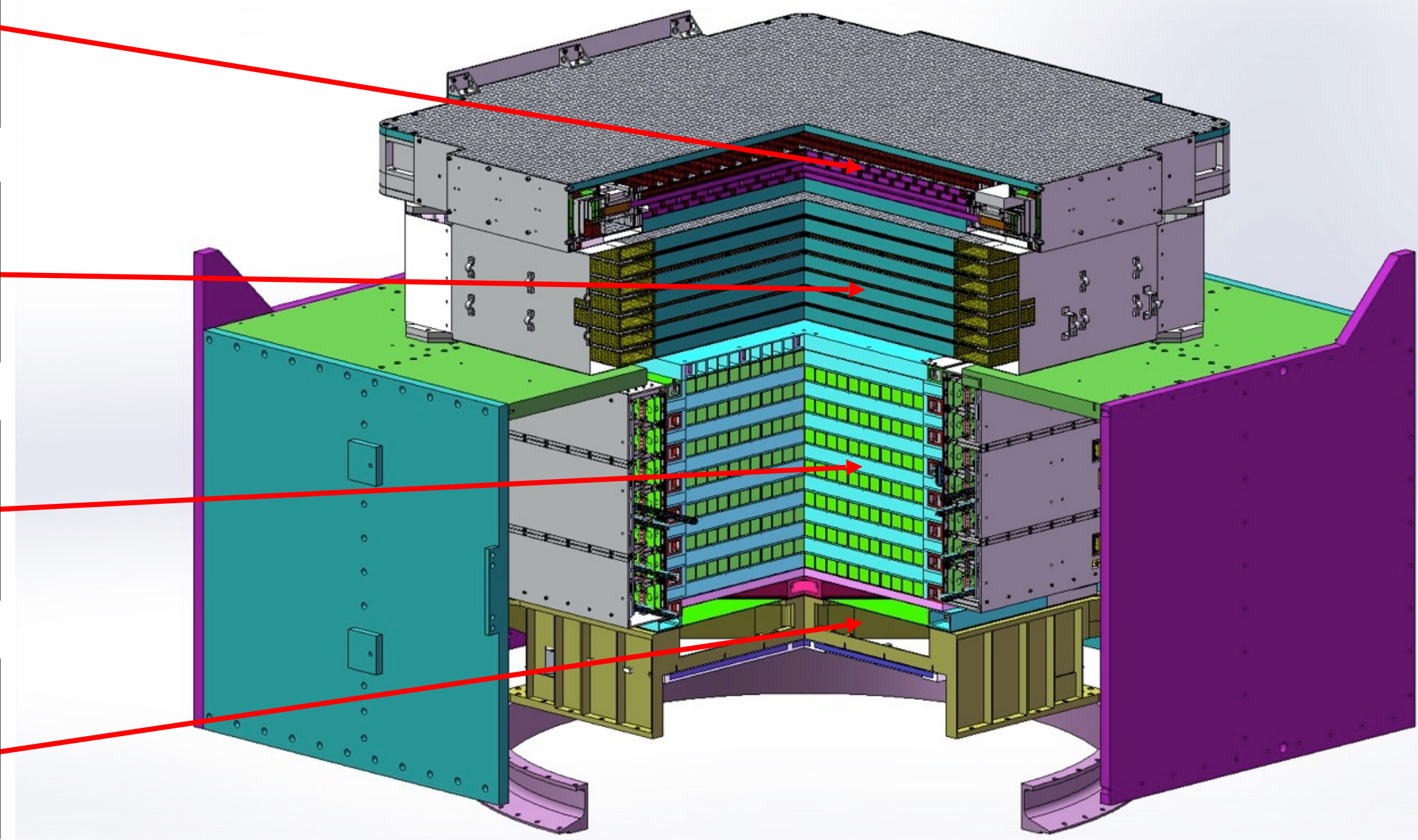


Understanding CR acceleration & propagation mechanisms

DAMPE探测器

J. Chang et al., Astropart. Phys. 95 (2017)

- 塑料闪烁体探测器 (PSD)**
电荷测量、光子反符合
- 硅微条径迹探测器 (STK)**
径迹测量、电荷测量
- BGO量能器 (BGO)**
能量测量、轻子/强子鉴别
- 中子探测器 (NUD)**
高能轻子/强子鉴别

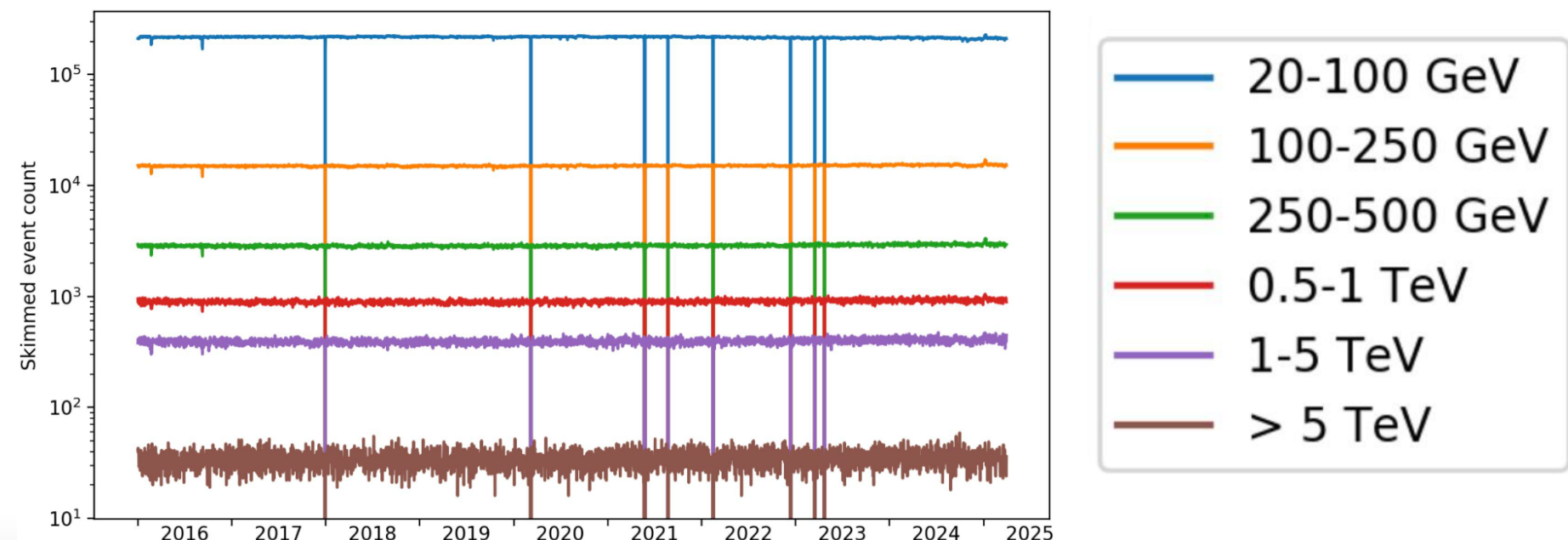
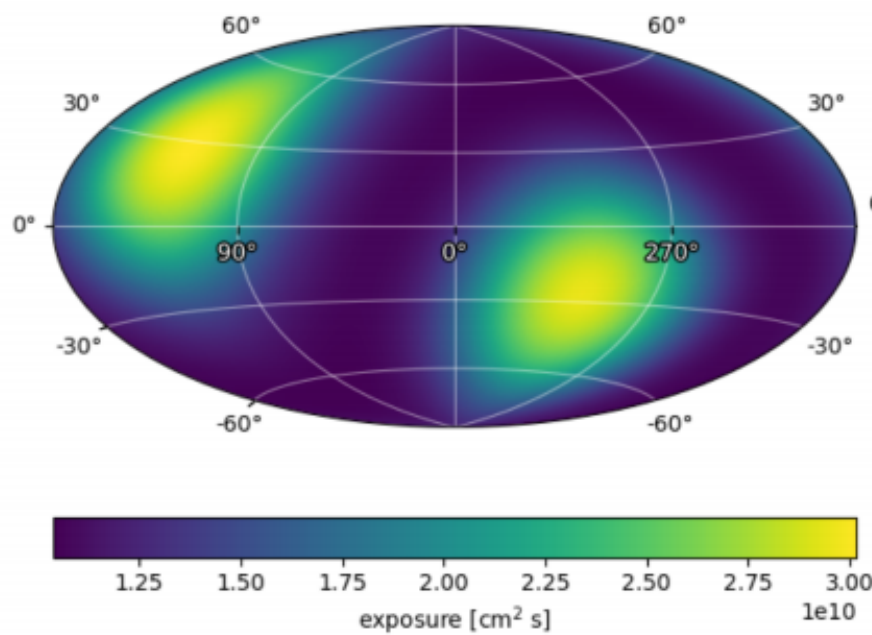
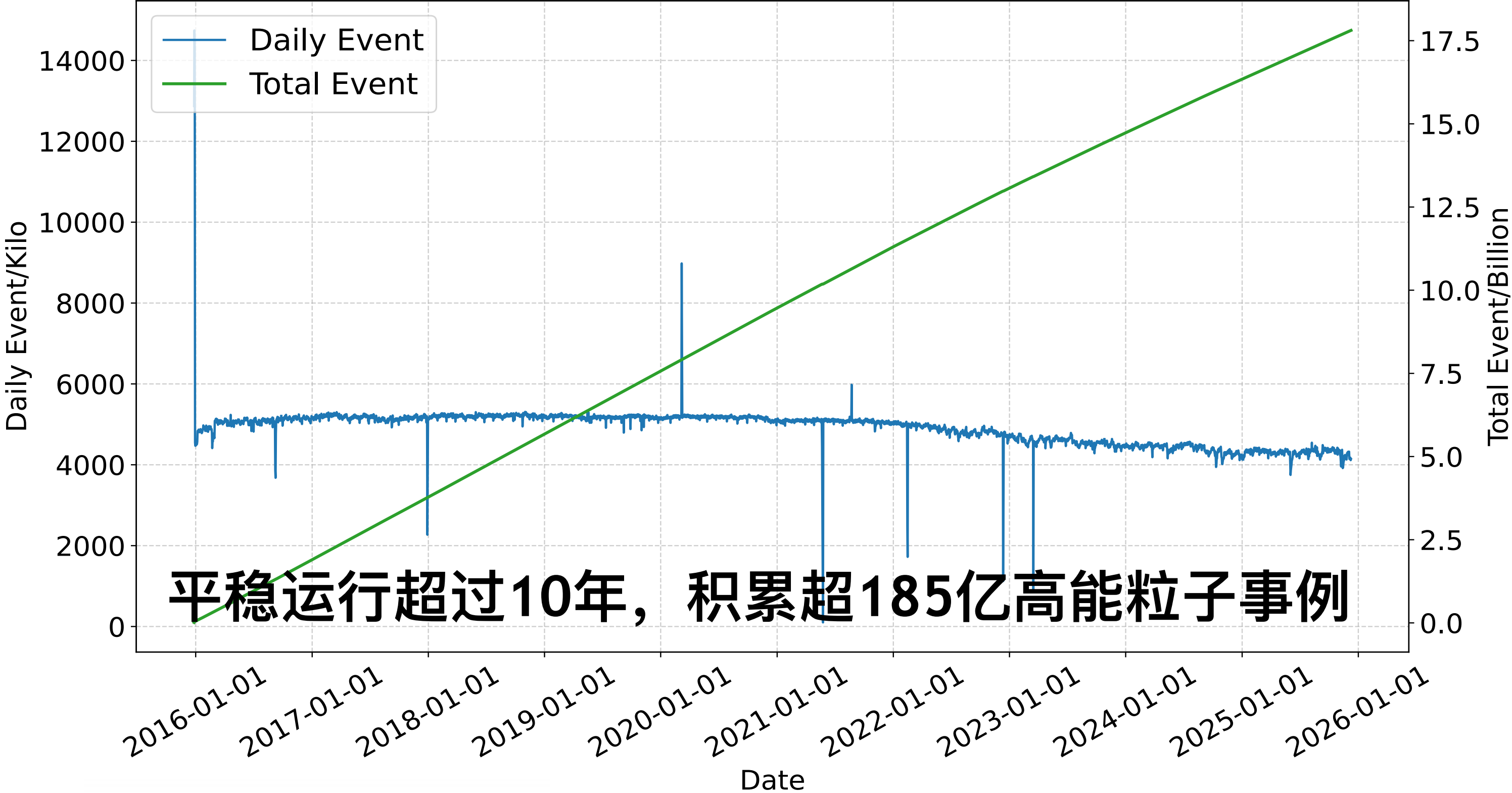


Parameter	Value
Energy range (e/ γ)	5 GeV to 10 TeV
Energy resolution (e/ γ)	1.5% at 800 GeV
Energy range (p/ion)	50 GeV to 500 TeV
Energy resolution (p)	40% at 800 GeV
Geometric factor (e)	0.3 m ² sr above 30 GeV
Angular resolution (γ)	0.1 degree at 100 GeV
Field of view	1.0 sr

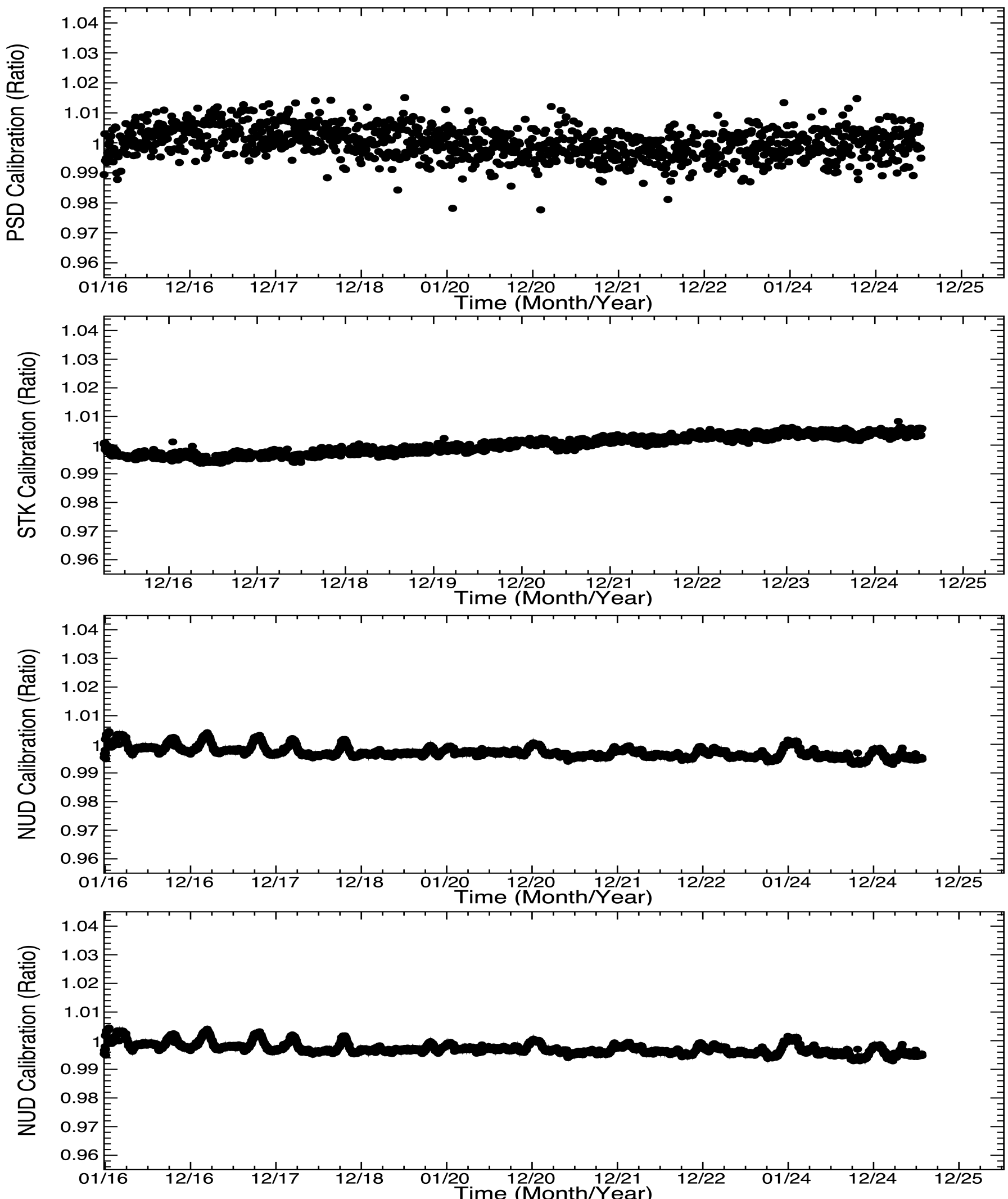
- PSD: Charge measurement via dE/dx , ACD for photons
- STK: Track, charge, and photon converter
- BGO: Energy measurement, particle (e/p) identification
- NUD: Additional e/p identification in high energy range

DAMPE在轨运行

DAMPE Data Statistics (updated 20251209)

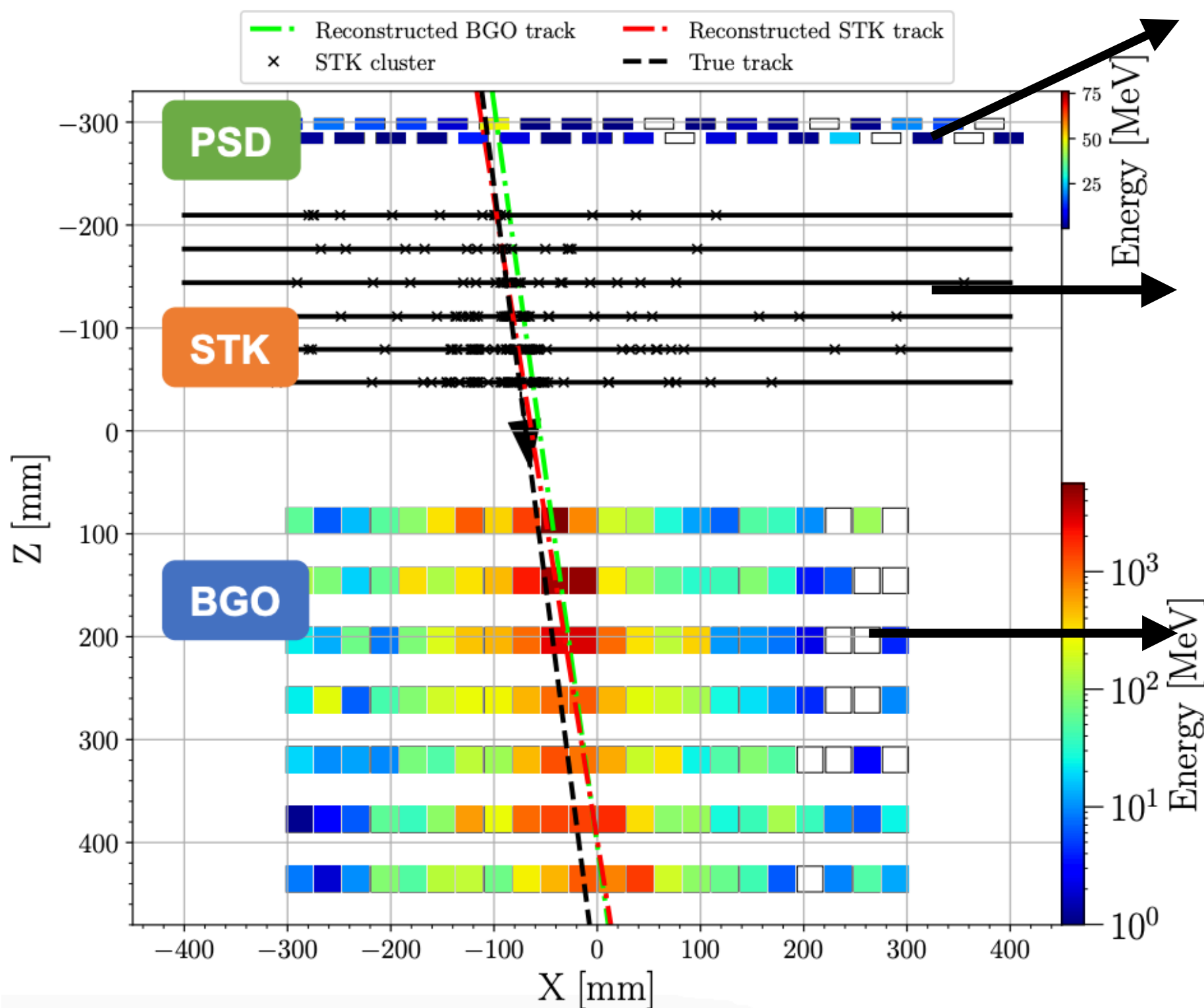


探测器状态保持良好



DAMPE宇宙线探测

典型的宇宙线粒子“簇射”



BGO量能器:

~ 32 X_0 (辐射长度)

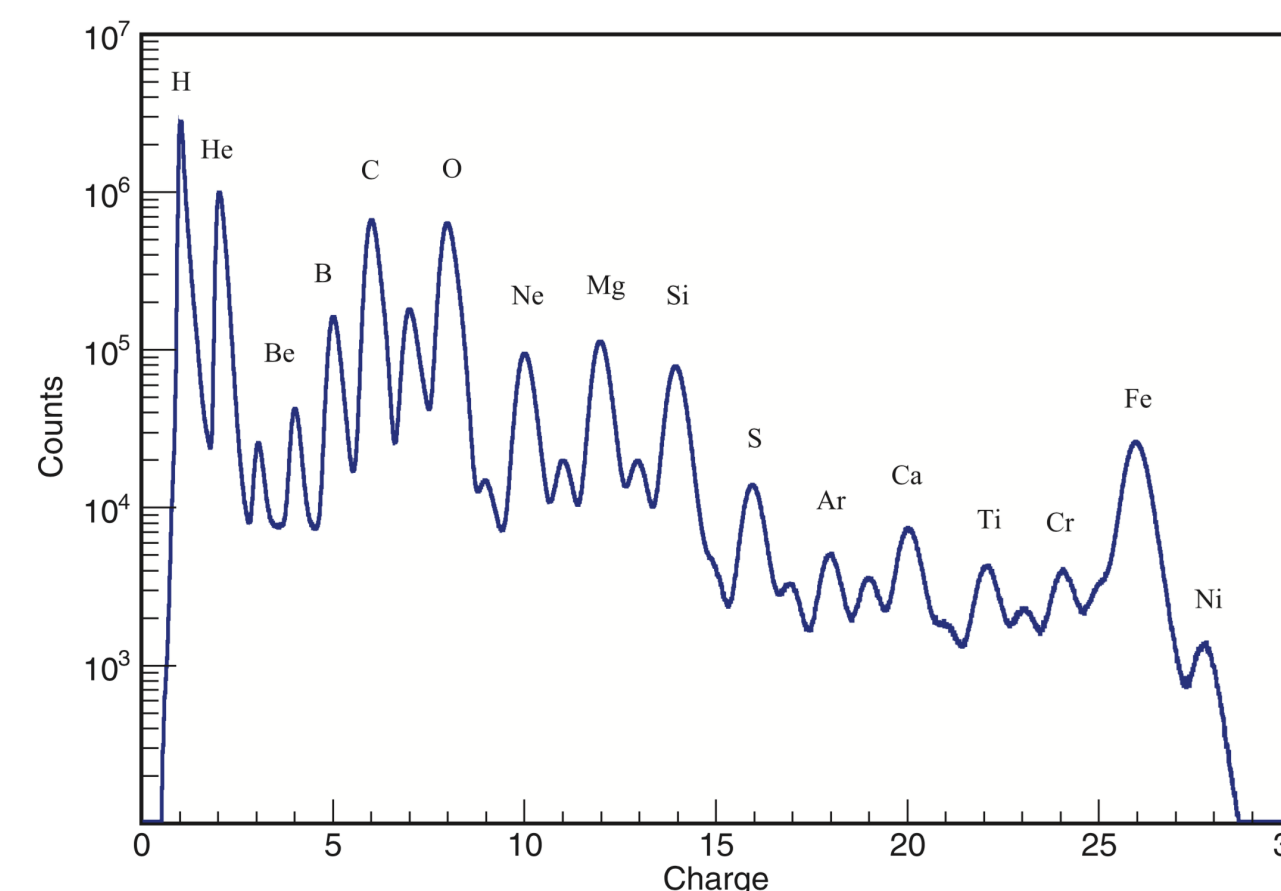
~ 1.6 λ (核相互作用长度)

电荷测量

径迹测量

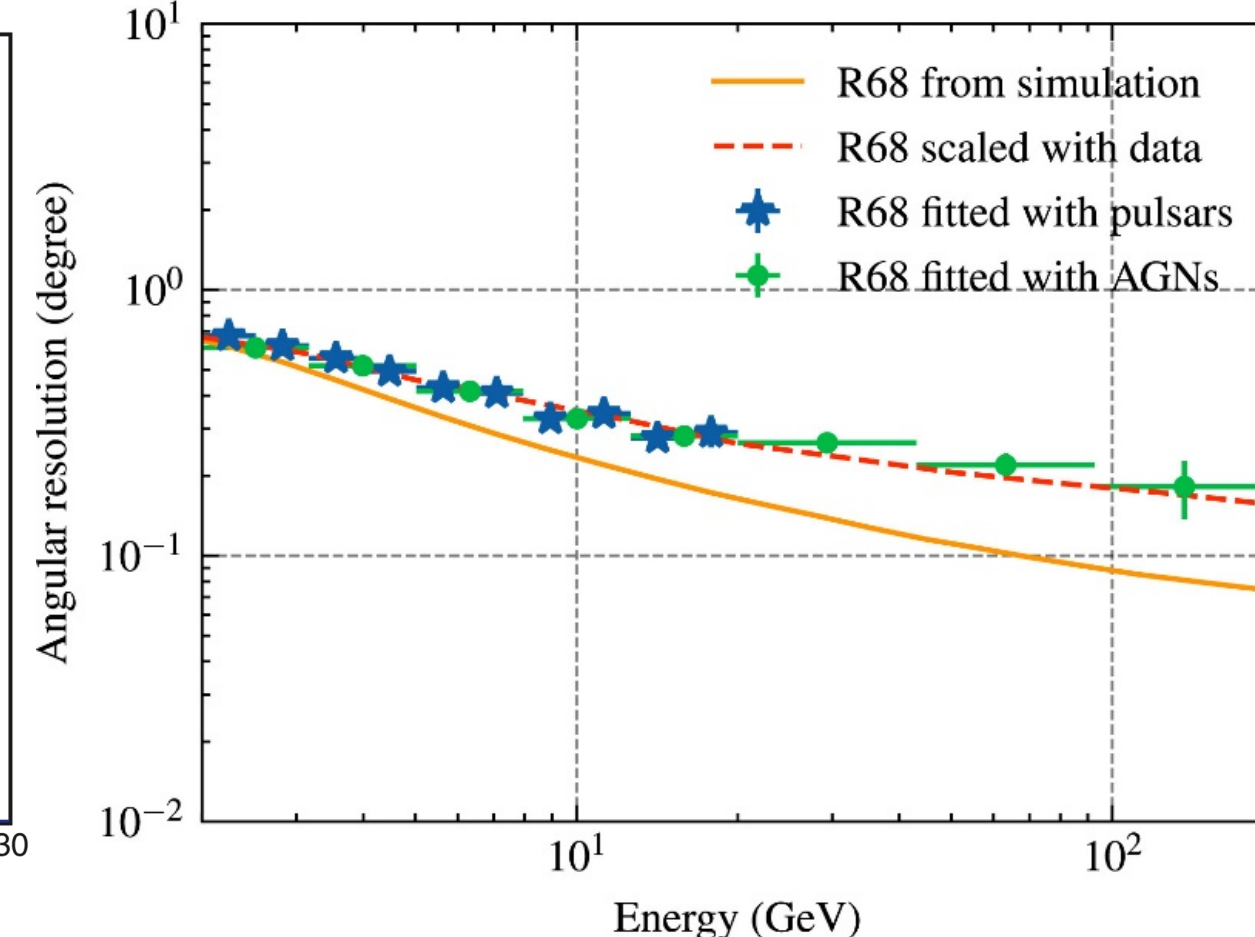
能量测量

PSD电荷分辨



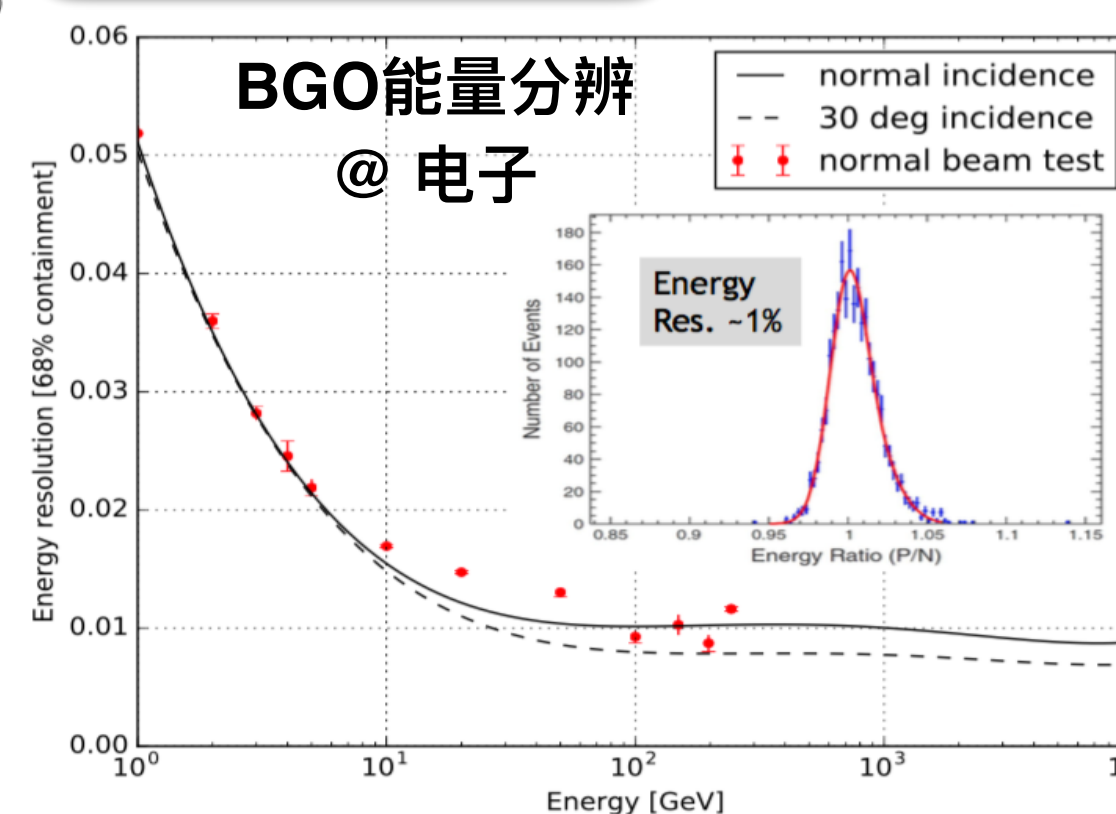
T. Dong et al., Astropart. Phys. 105 (2019)

STK角度分辨



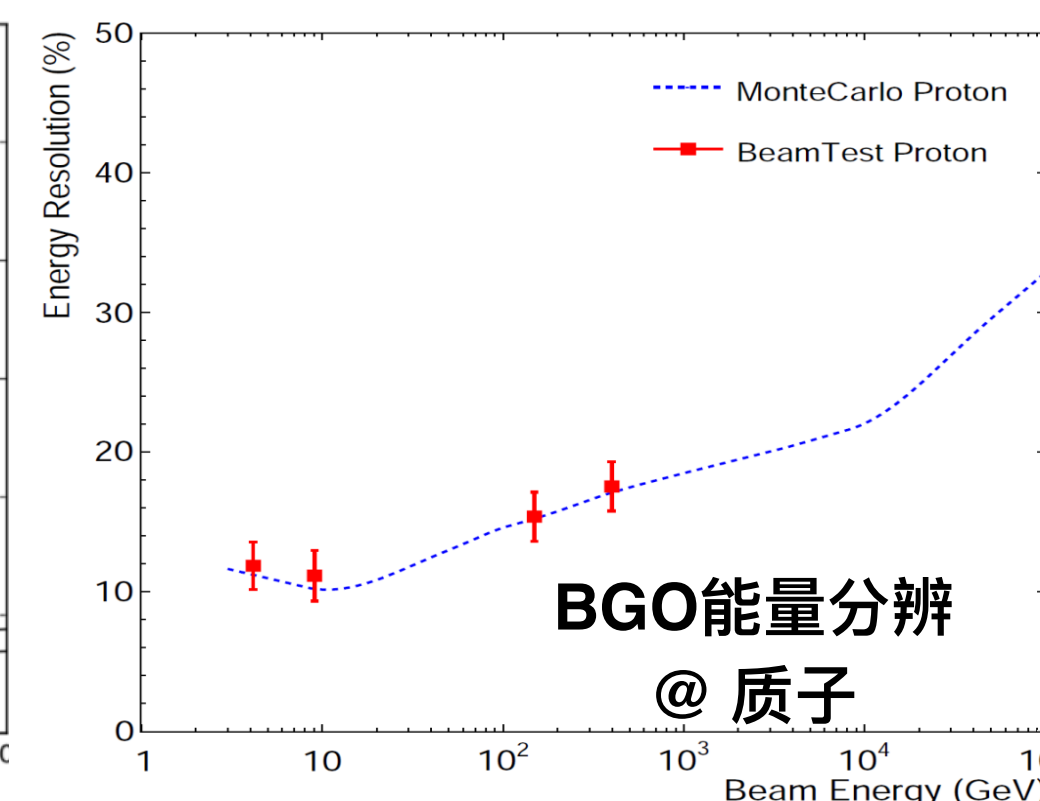
K. Duan et al., Astropart. Phys. 165 (2025)

BGO能量分辨 @ 电子

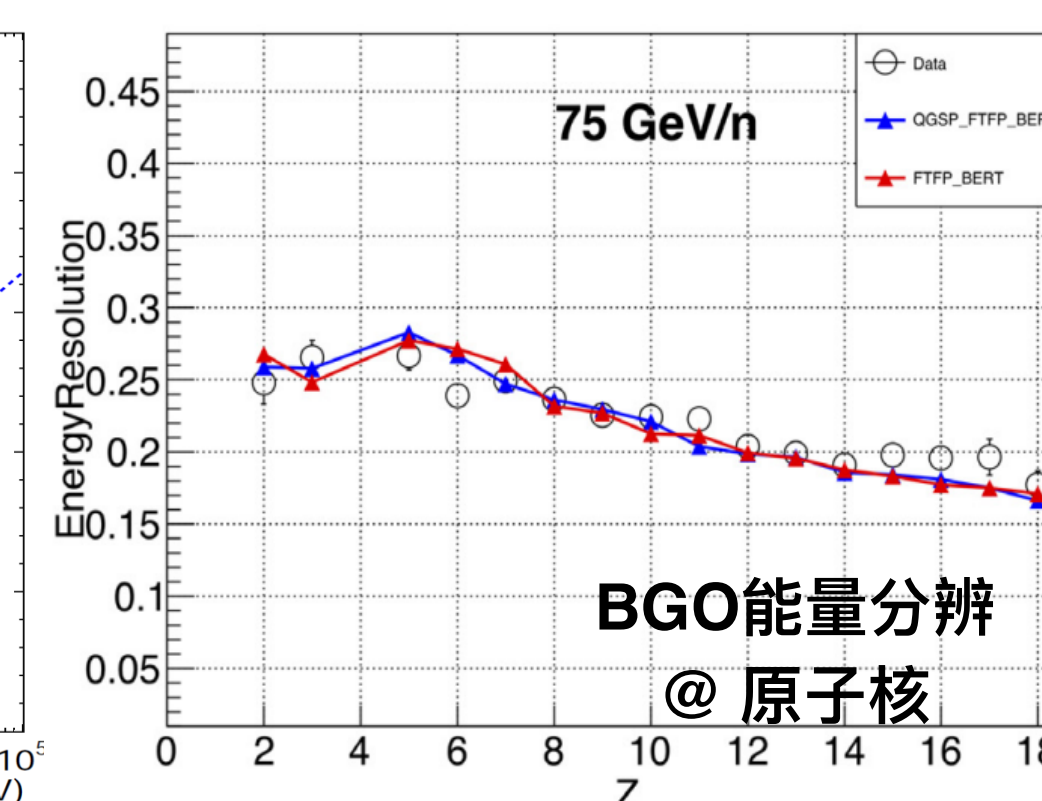


J. Chang et al., Astropart. Phys. 95 (2017)

BGO能量分辨 @ 质子



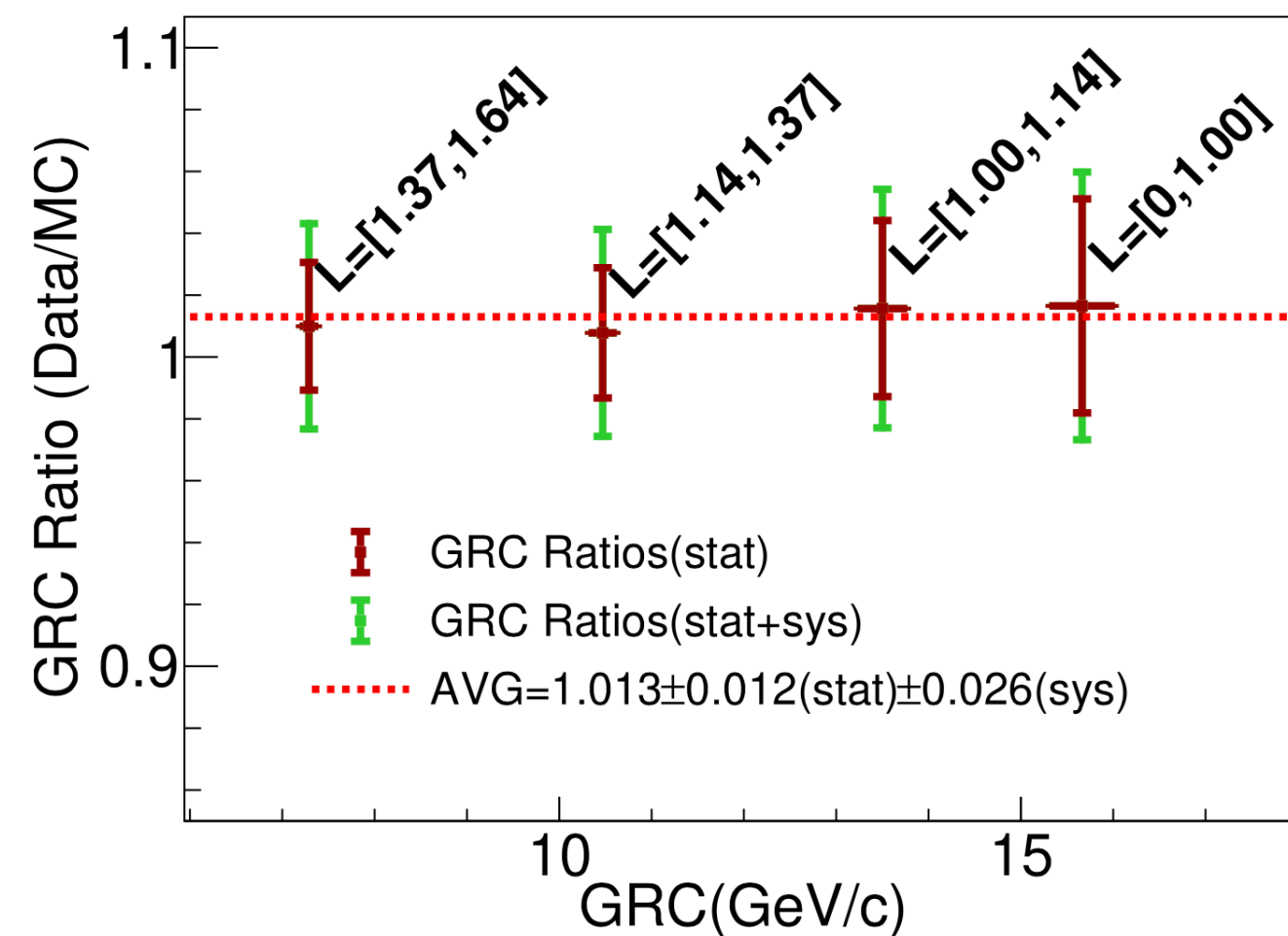
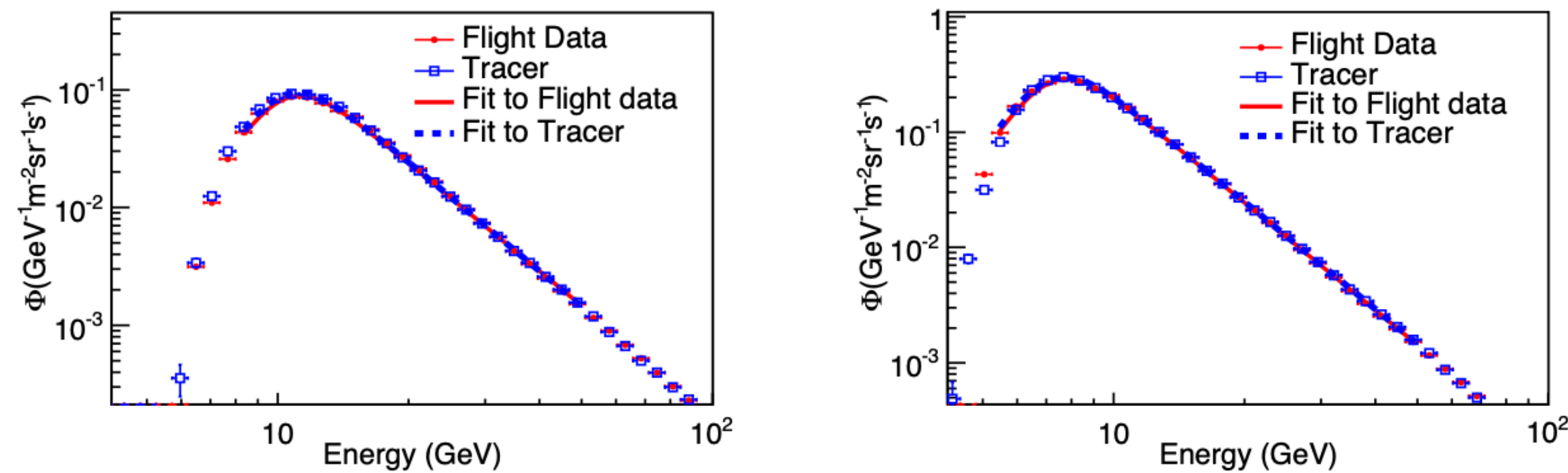
75 GeV/n



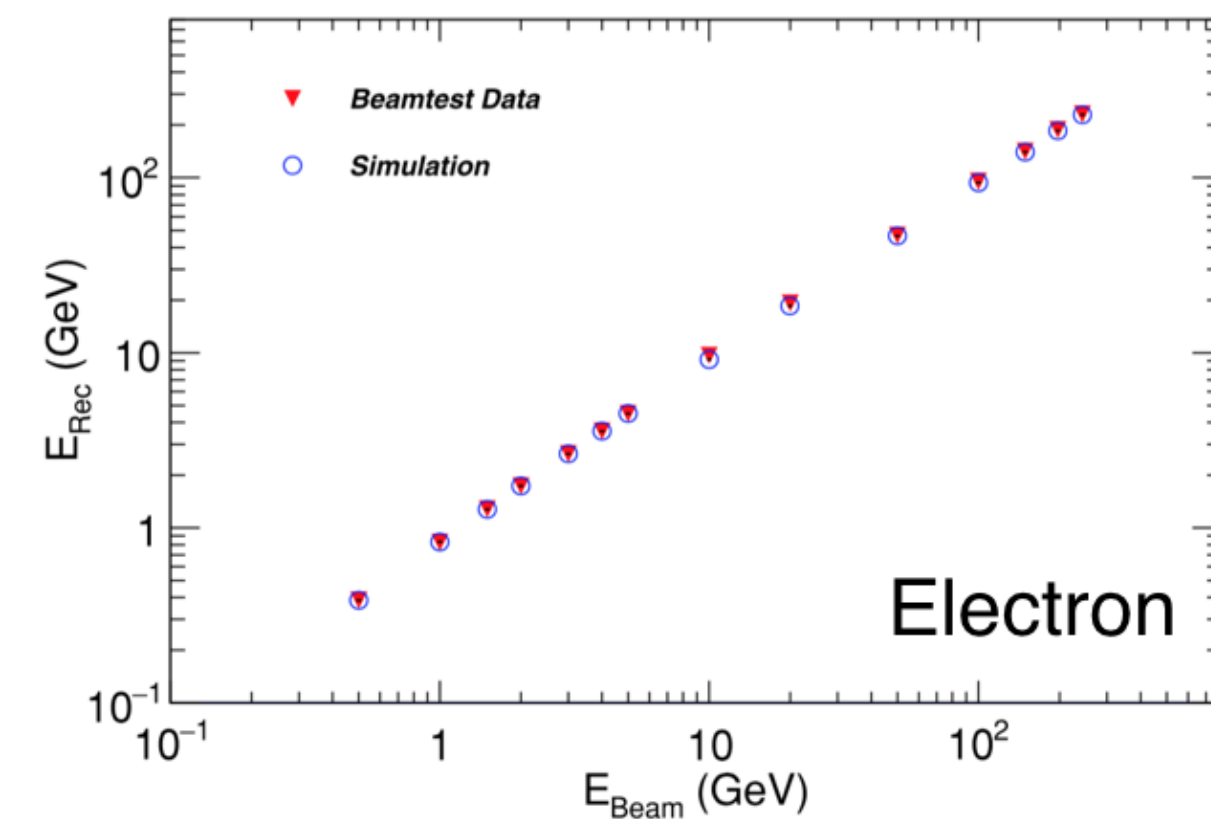
Y. Wei et al. NIMA 922 (2019)

能量刻度与标定

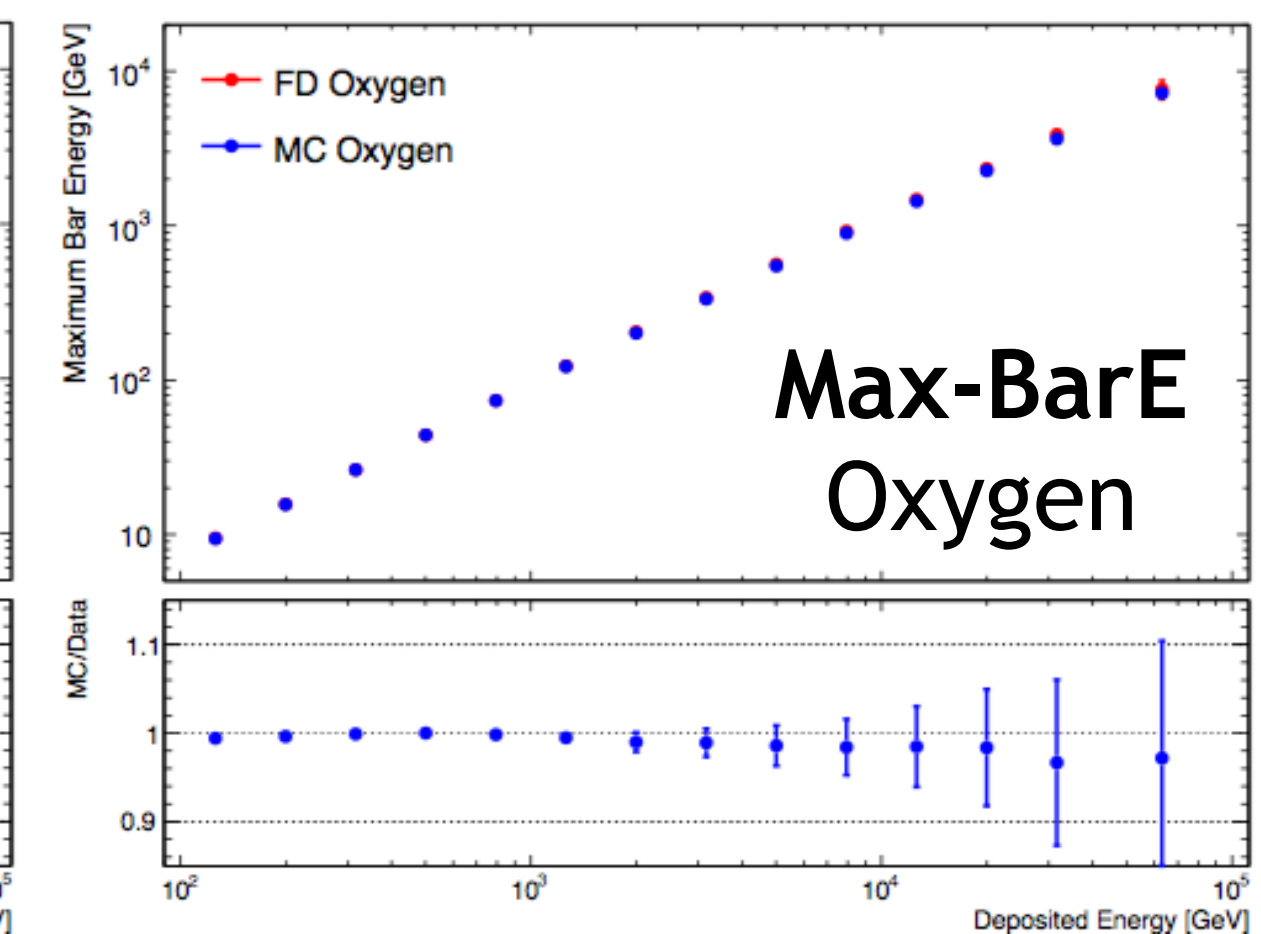
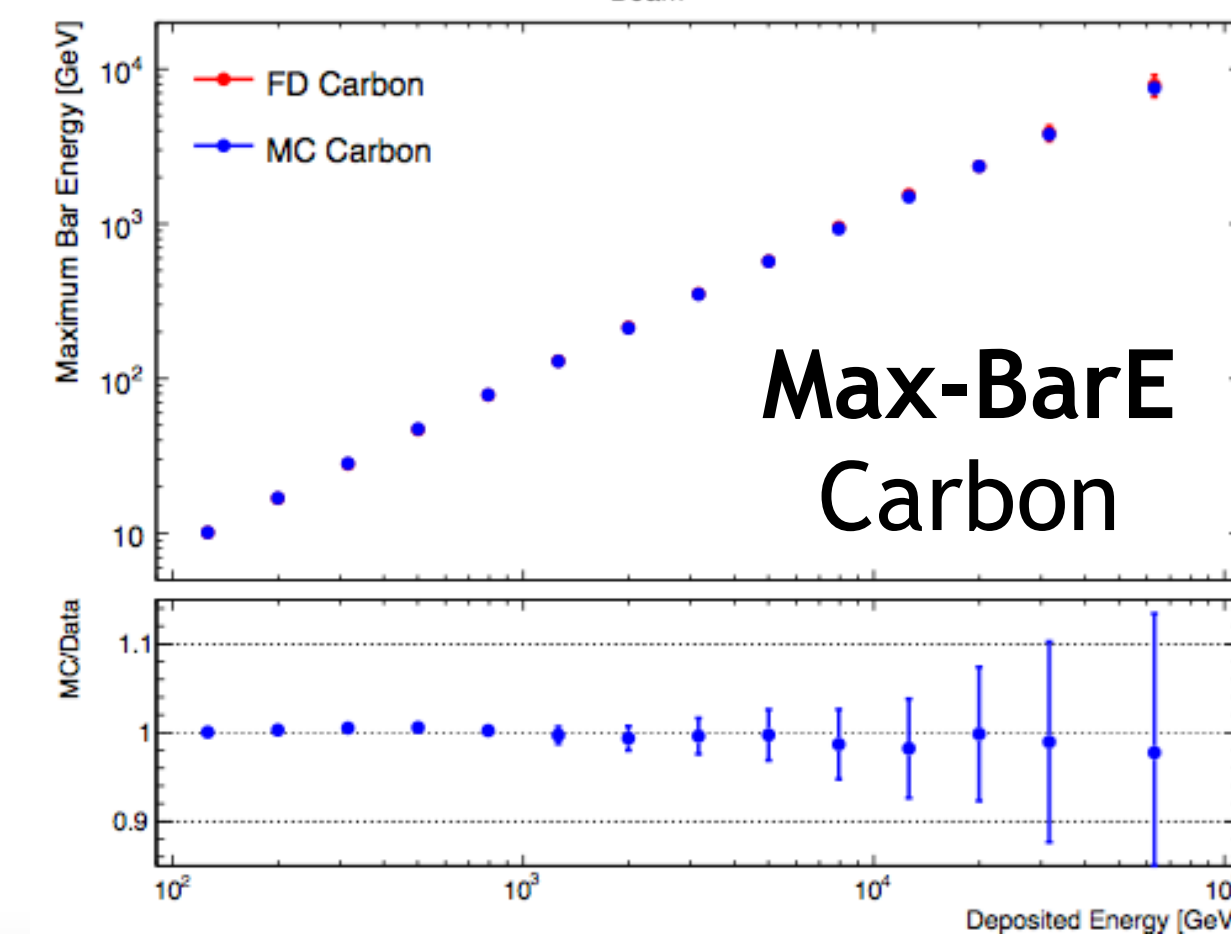
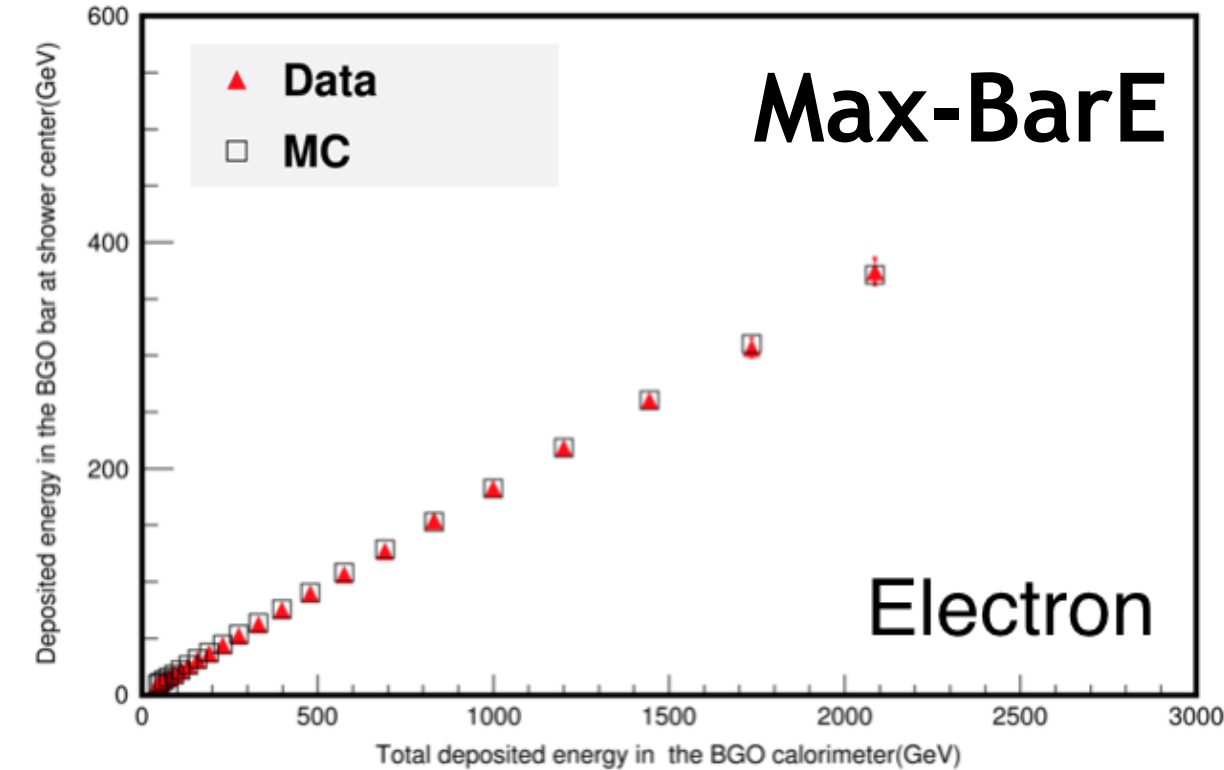
- 基于在轨最小电离质子开展单元能量刻度，利用电子地磁刚度截断开展绝对能标检验
- 多增益通道联合实现跨越6个量级的能量测量，高能区未出现单元能量非线性效应



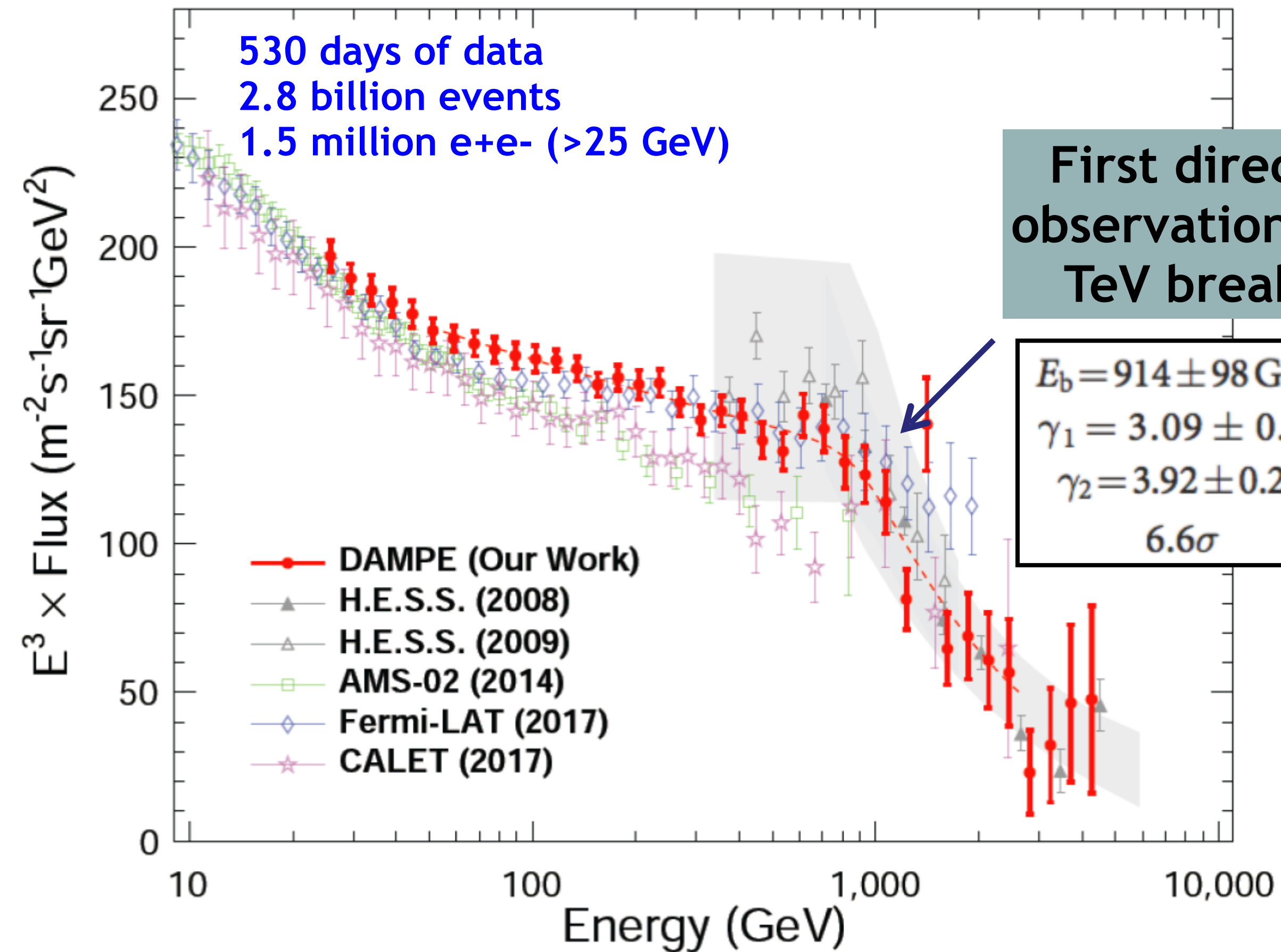
J. Zang et al. *Astropart. Phys.* 173 (2025)



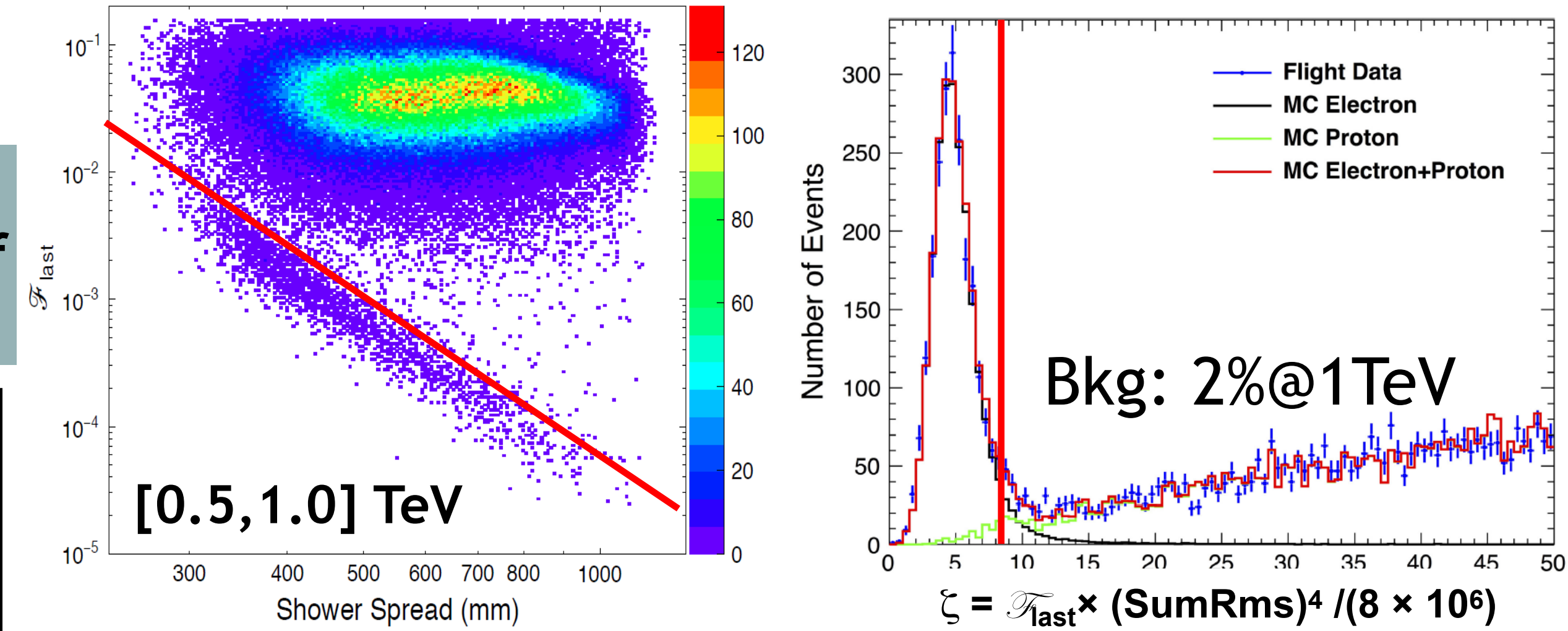
C. Zhao et al. *NIMA* 1092 (2022)



宇宙线总电子能谱



DAMPE collaboration, Nature 552, 63-66 (2017)



Work in process:

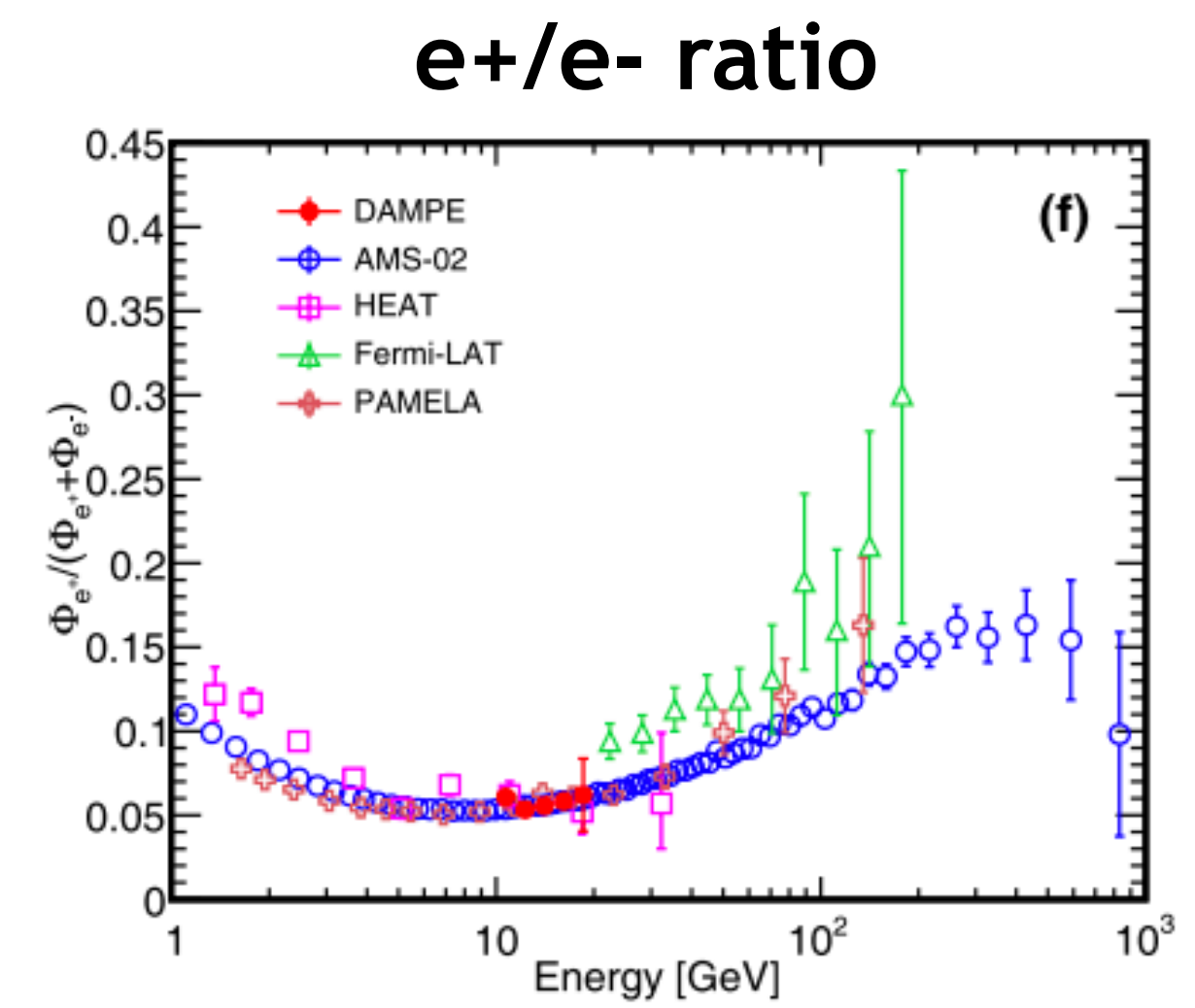
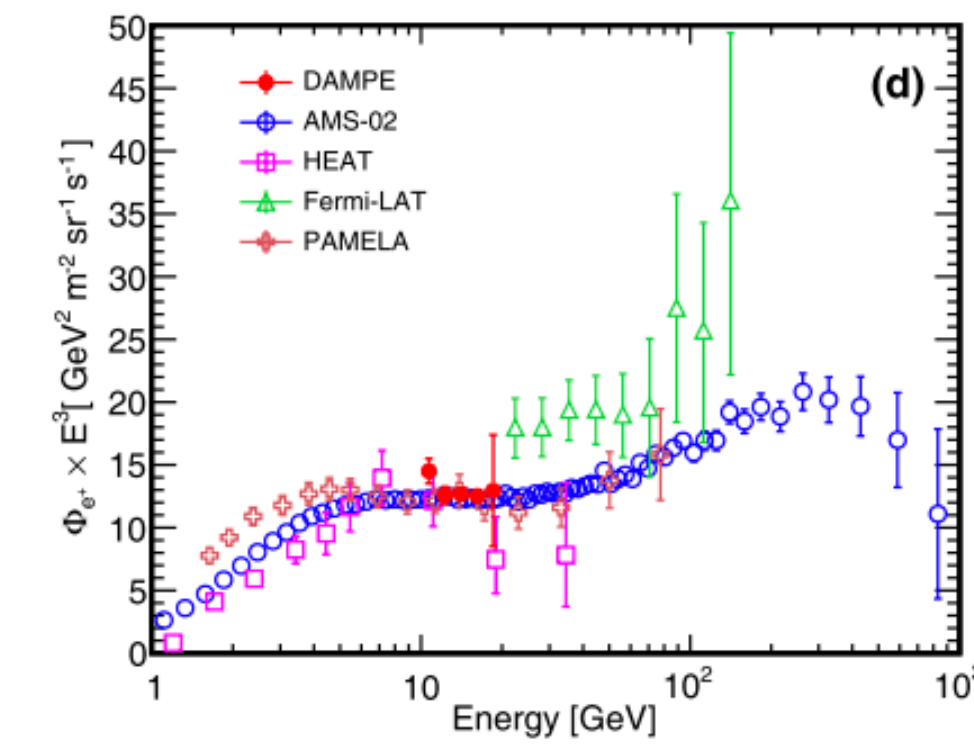
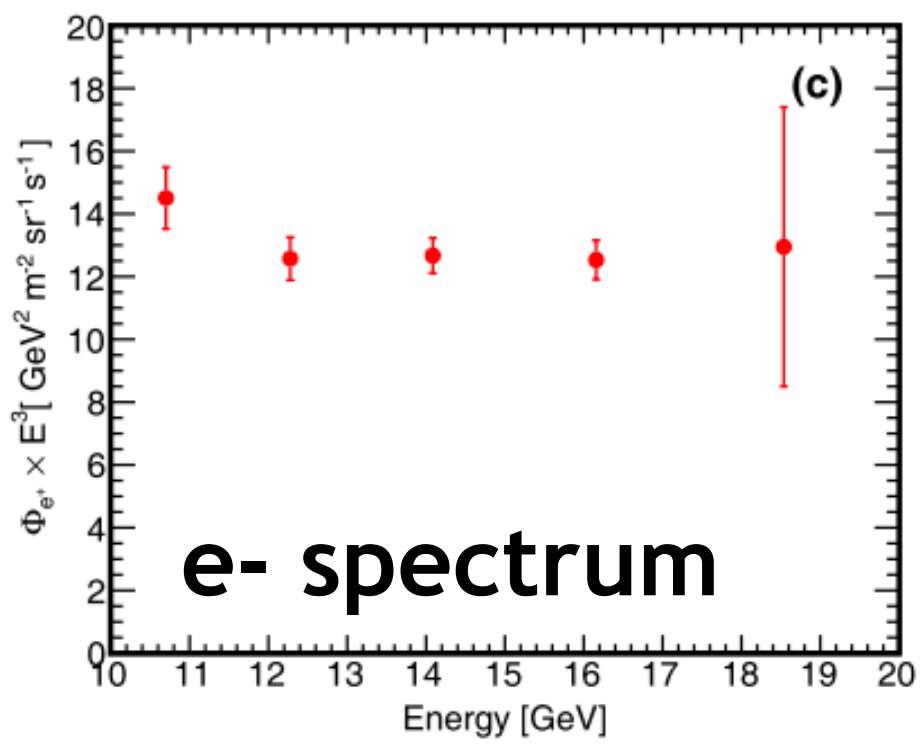
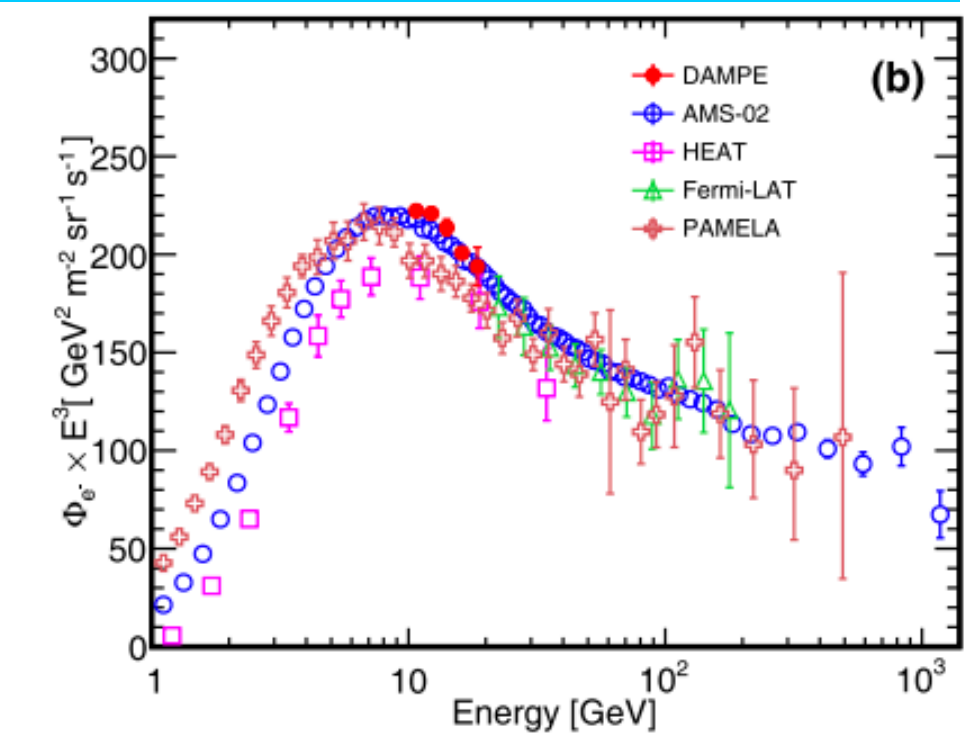
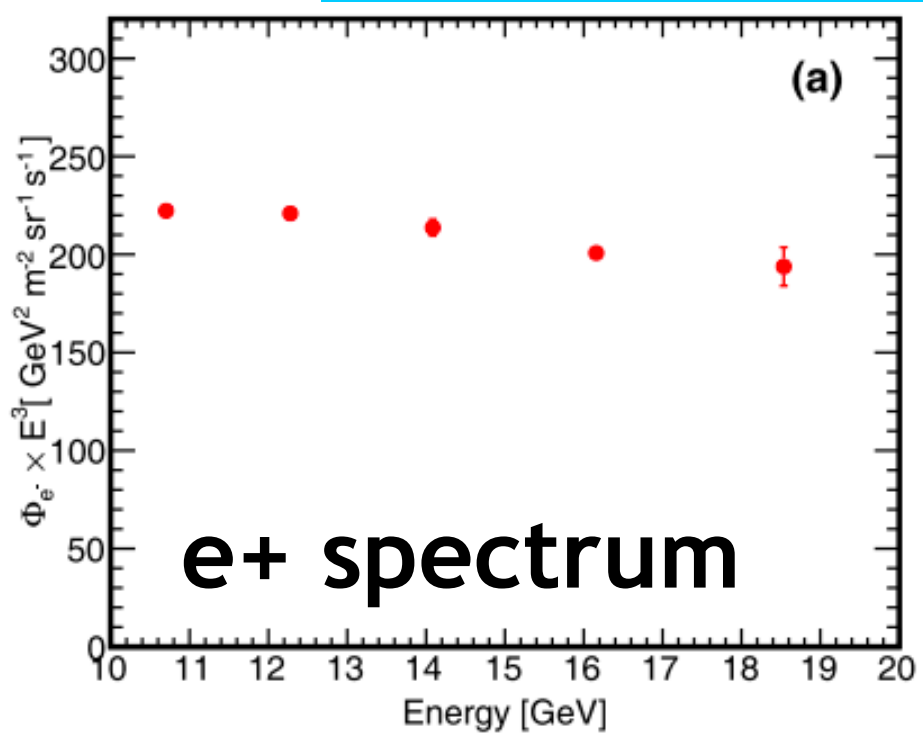
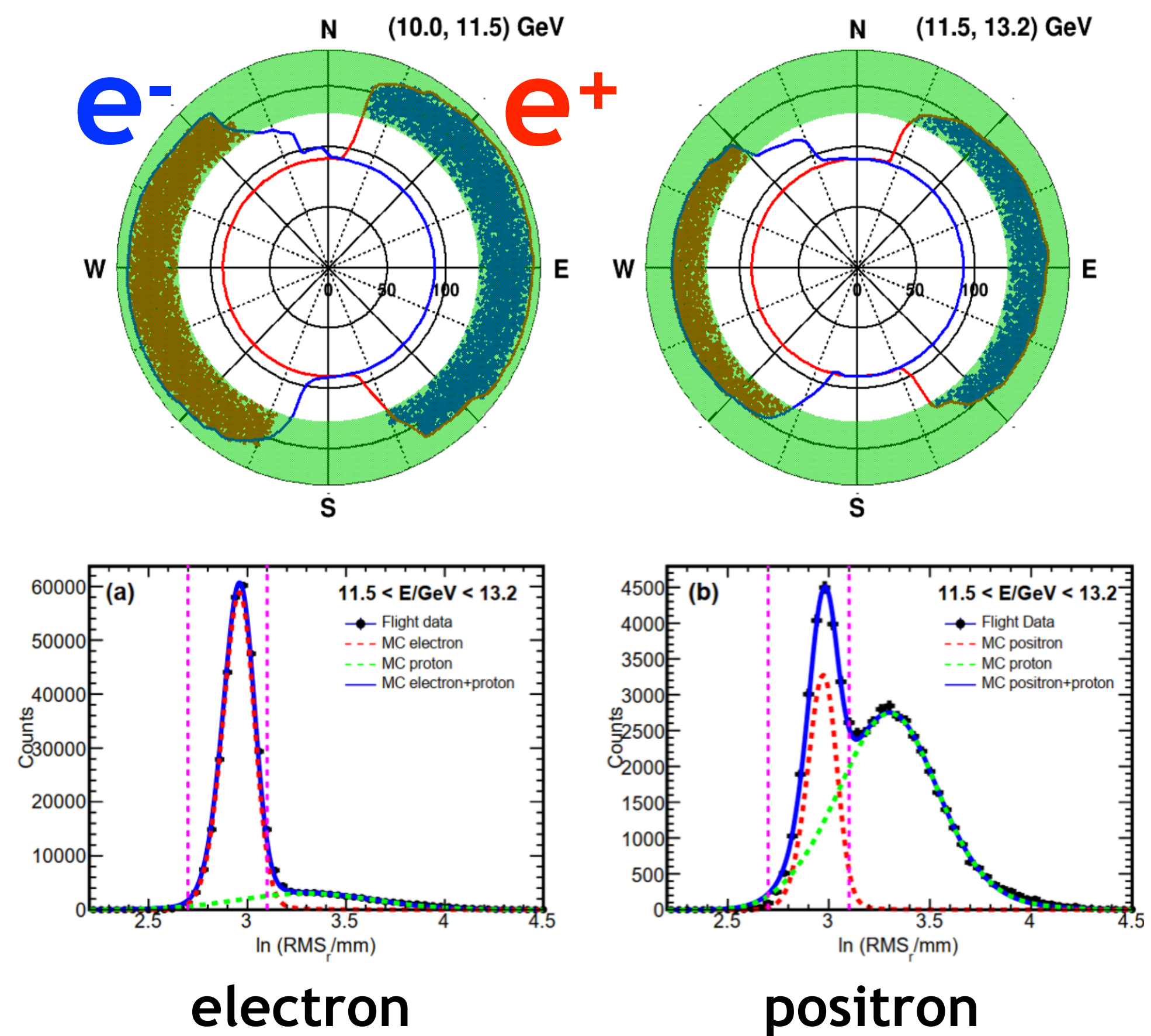
1. Deep and long-term detector calibration.
2. New particle ID for high energies:
Neural Networks (NN), Principal Component Analysis (PCA),
Application of Neutron Detector (NUD)
3. Non-fiducial event selection and reconstruction

◎ DAMPE具备优异的能量分辨和粒子鉴别(e/p)能力, 可将总电子能谱精确测量至**15TeV以上**

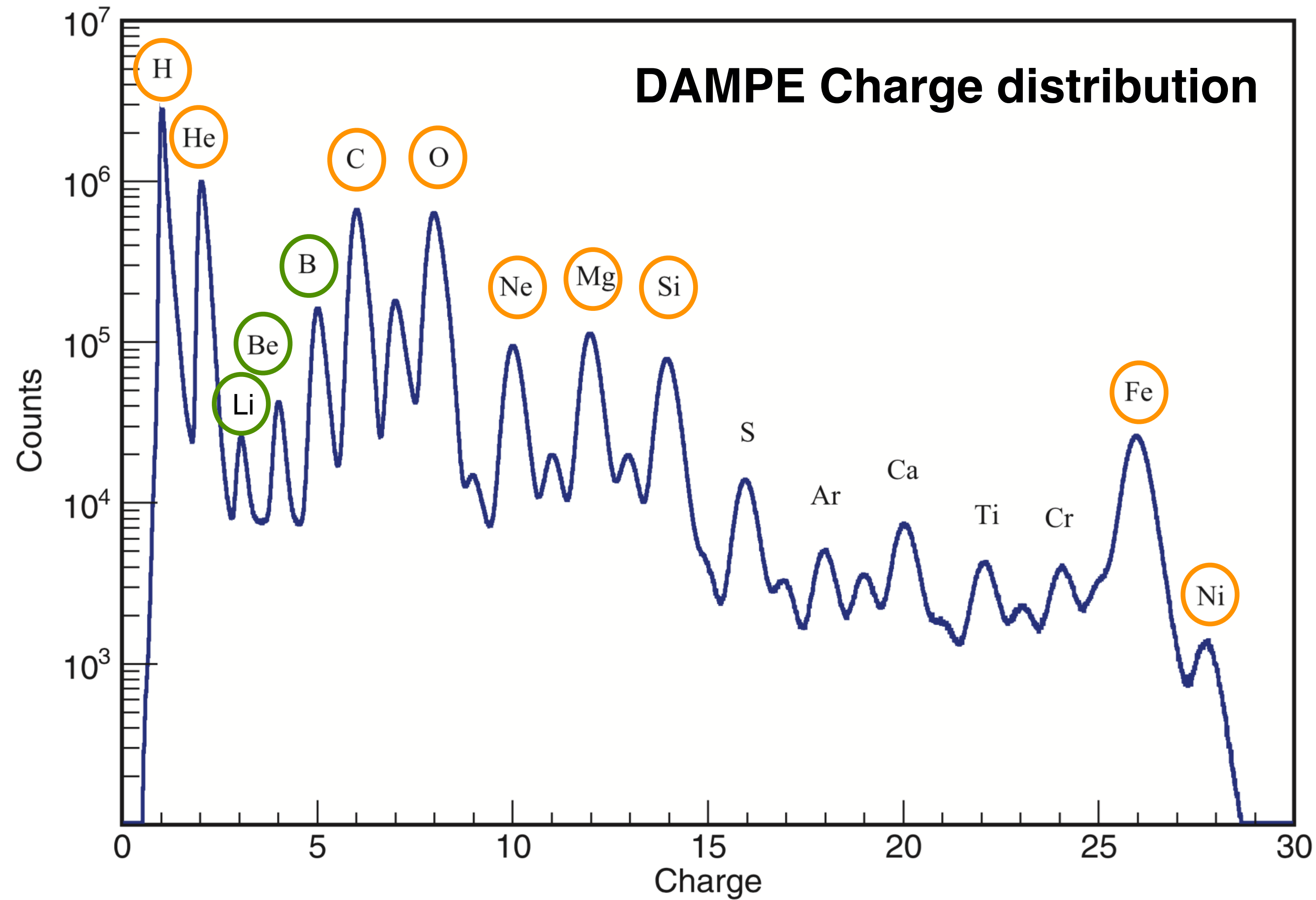
宇宙线正/负电子能谱

◎借助地磁场偏转效应造成的正负电子地球阴影区的差异实现对正负电子的鉴别

DAMPE collab., Chin. Phys. C 49, 115001 (2025)



◎DAMPE借助地磁场开展了对10-20GeV能区正负电子能谱及正电子比例的直接测量，对该能区正负电子能谱行为独立检验



初级粒子:

CR origin / acceleration

- proton, Helium, p+He
- C, O, Ne, Mg, Si, Fe, Ni, ...

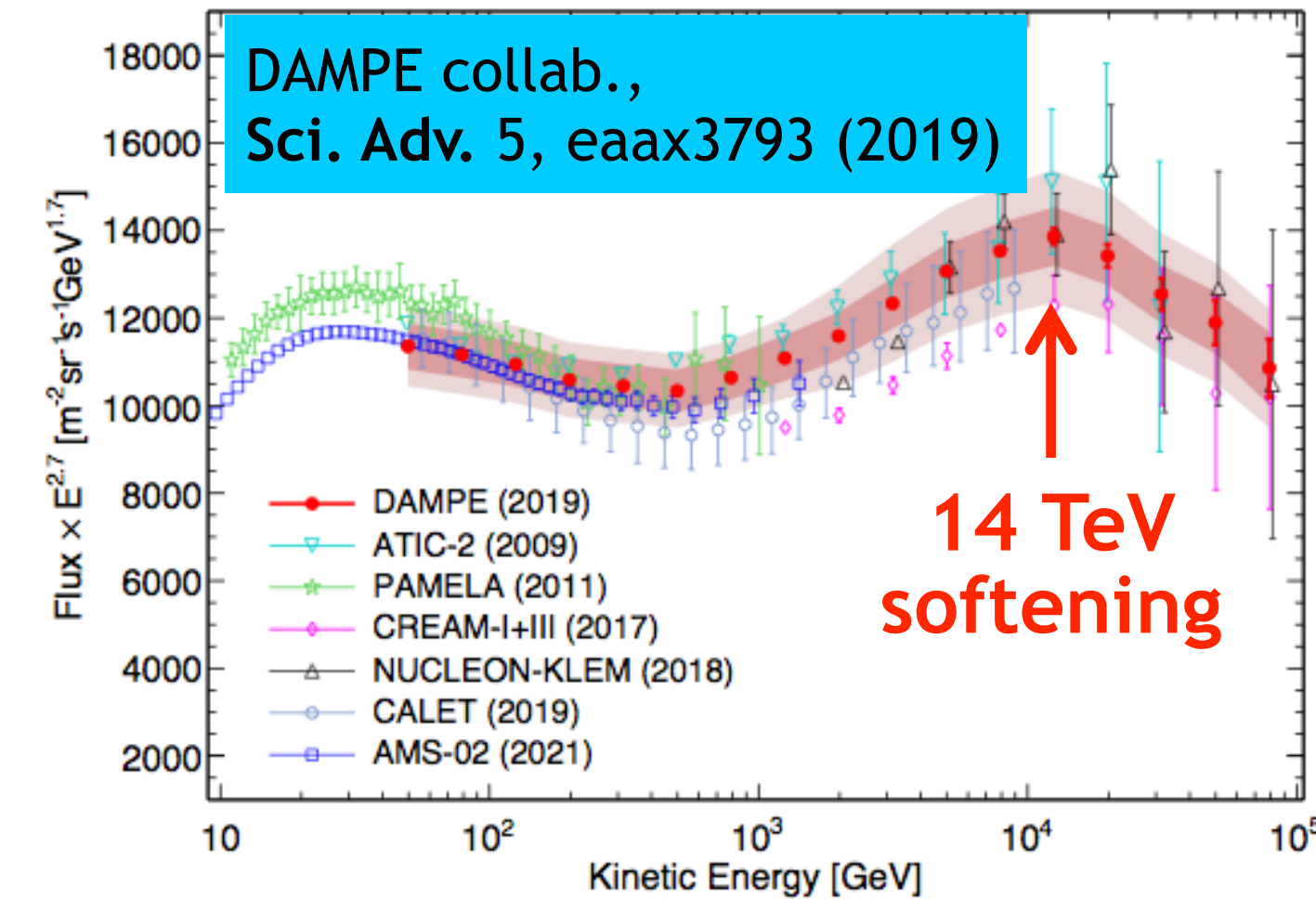
次级粒子:

CR propagation

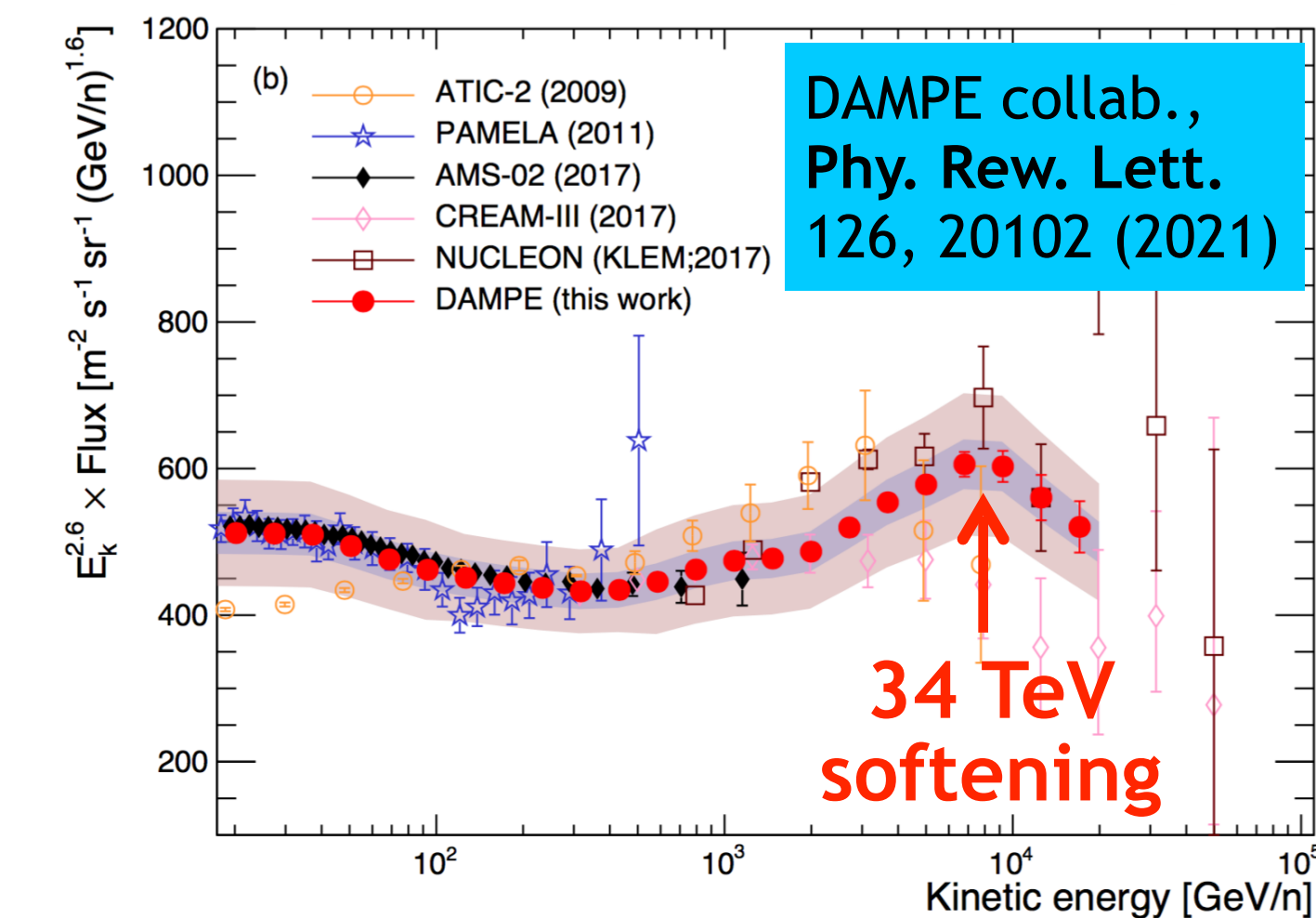
- Li, Be, B, ...
- Sub-Iron

原初宇宙线粒子：质子，氦核

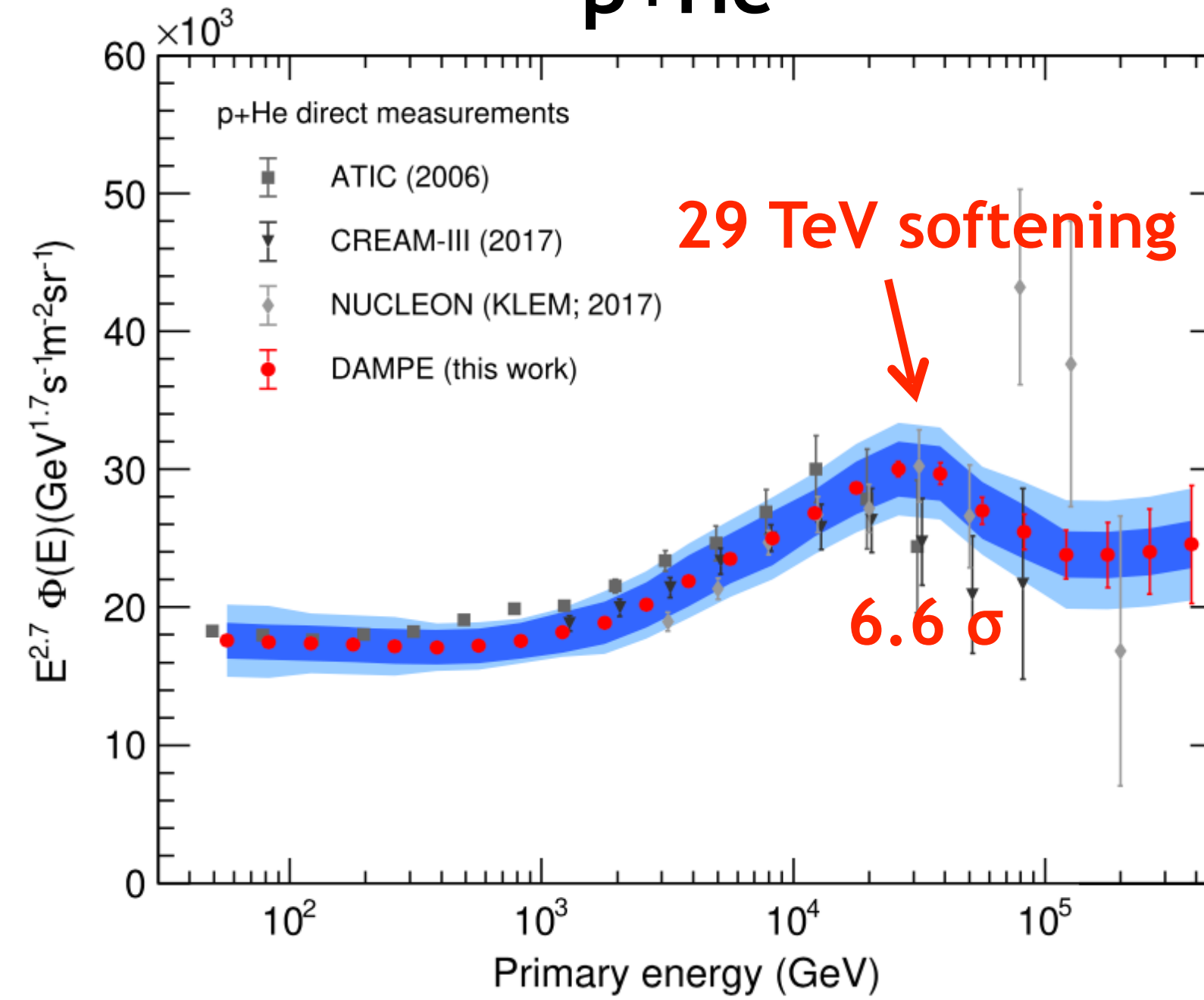
Proton



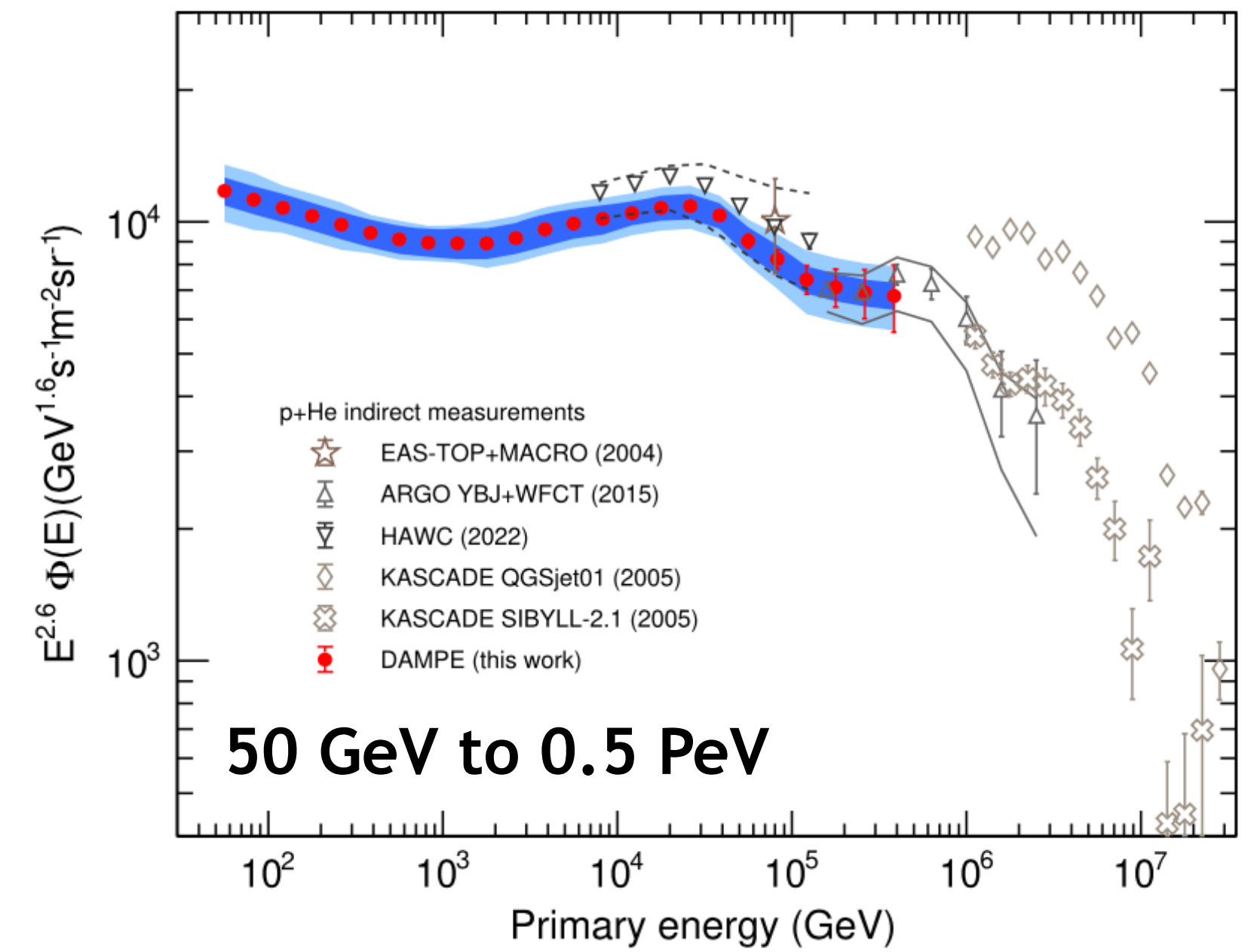
Helium



p+He



DAMPE collab., Phy. Rev.D 109, L121101 (2024)

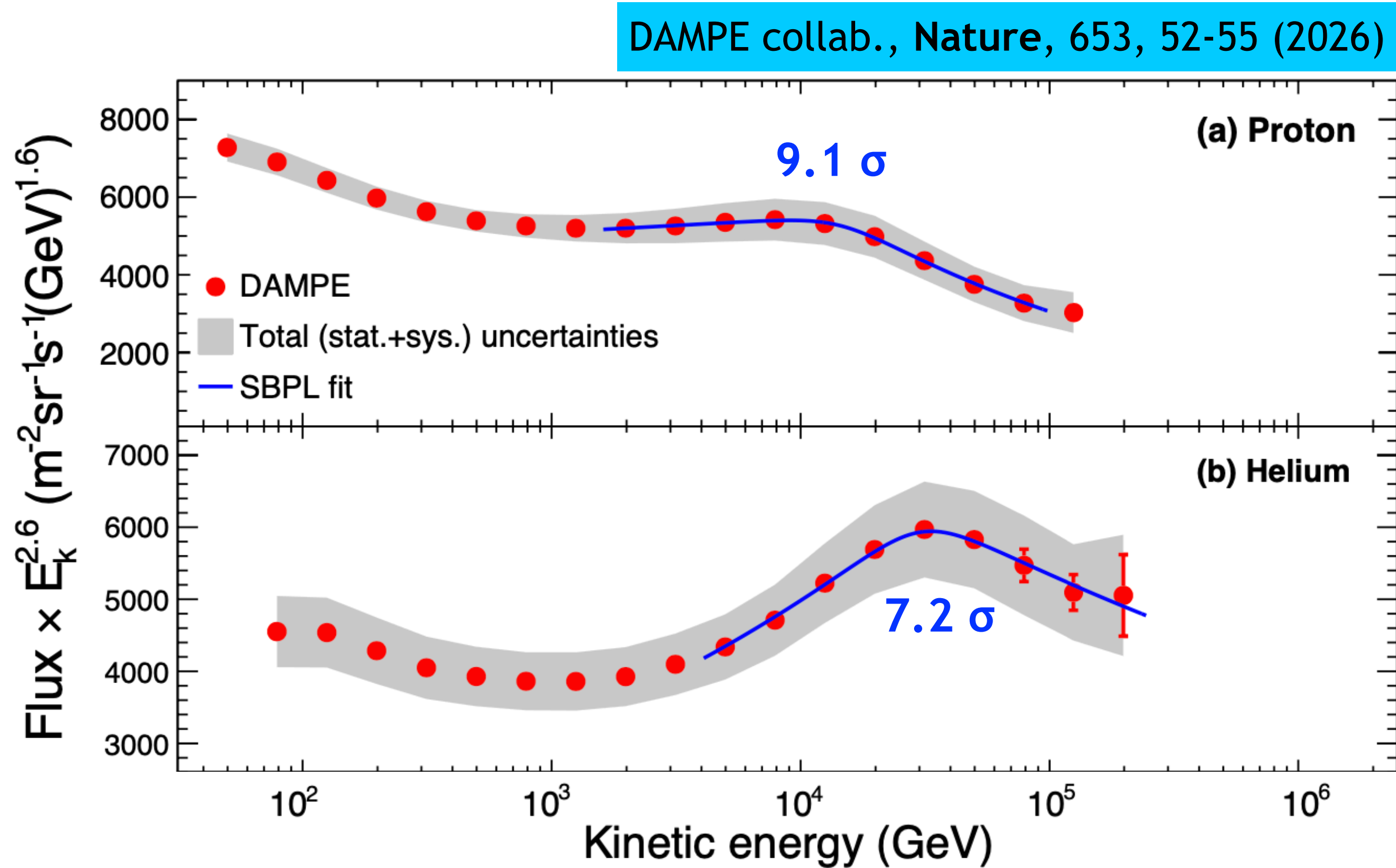
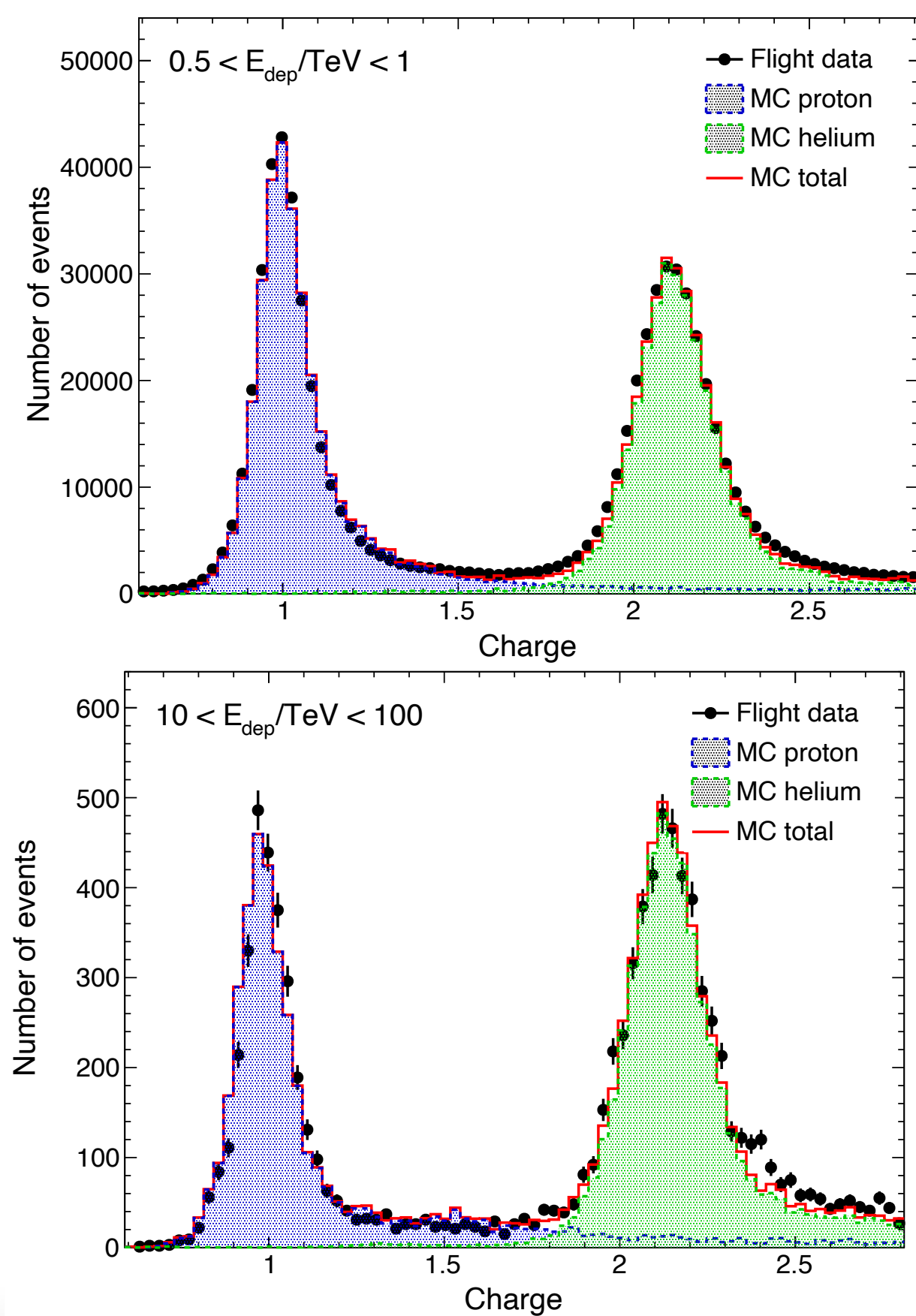


	Proton	Helium	Proton+Helium
E_b (TeV)	$13.6^{+4.1}_{-4.8}$	$34.4^{+6.7+11.6}_{-9.8-0.0}$	$28.8^{+6.2+2.9}_{-4.4-0.0}$
γ	2.60 ± 0.01	$2.41^{+0.02+0.02}_{-0.02-0.00}$	$2.51^{+0.021+0.01}_{-0.024-0.00}$
$\Delta\gamma$	-0.25 ± 0.07	$-0.51^{+0.18+0.01}_{-0.20-0.00}$	$0.43^{+0.066+0.066}_{-0.057-0.00}$

- ◎ DAMPE以高置信度观测到宇宙线质子和氦核具有类似的能谱拐折行为
- ◎ 初步探测到高能能谱变软结构的电荷依赖特征 (p: 14TeV, He: 34 TeV)

Advanced analysis in high energies:

1. New ML track reconstruction & New charge identification : STK + PSD
2. Quenching correction, cross-section correction and new saturation correction up to PeV

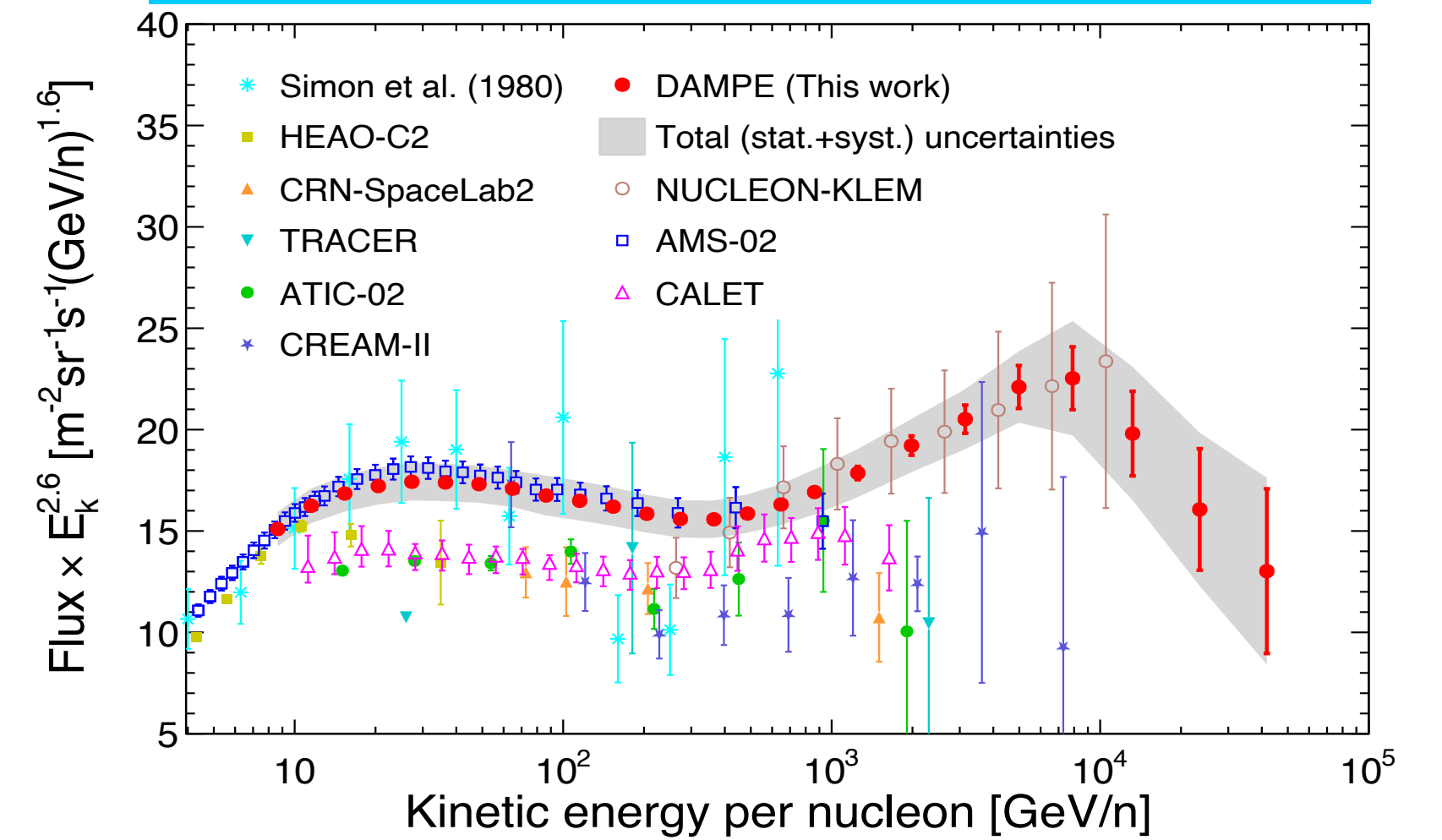
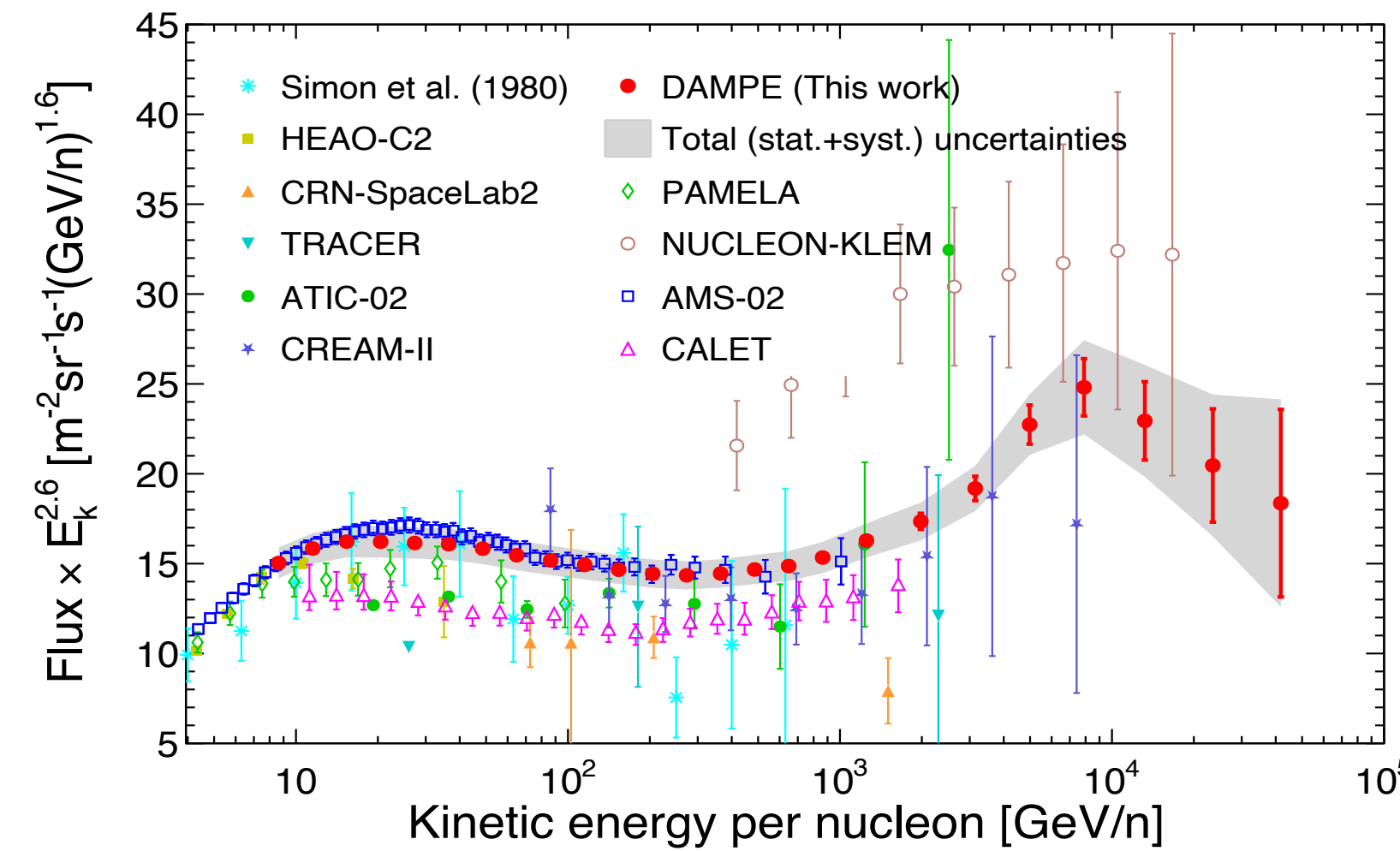
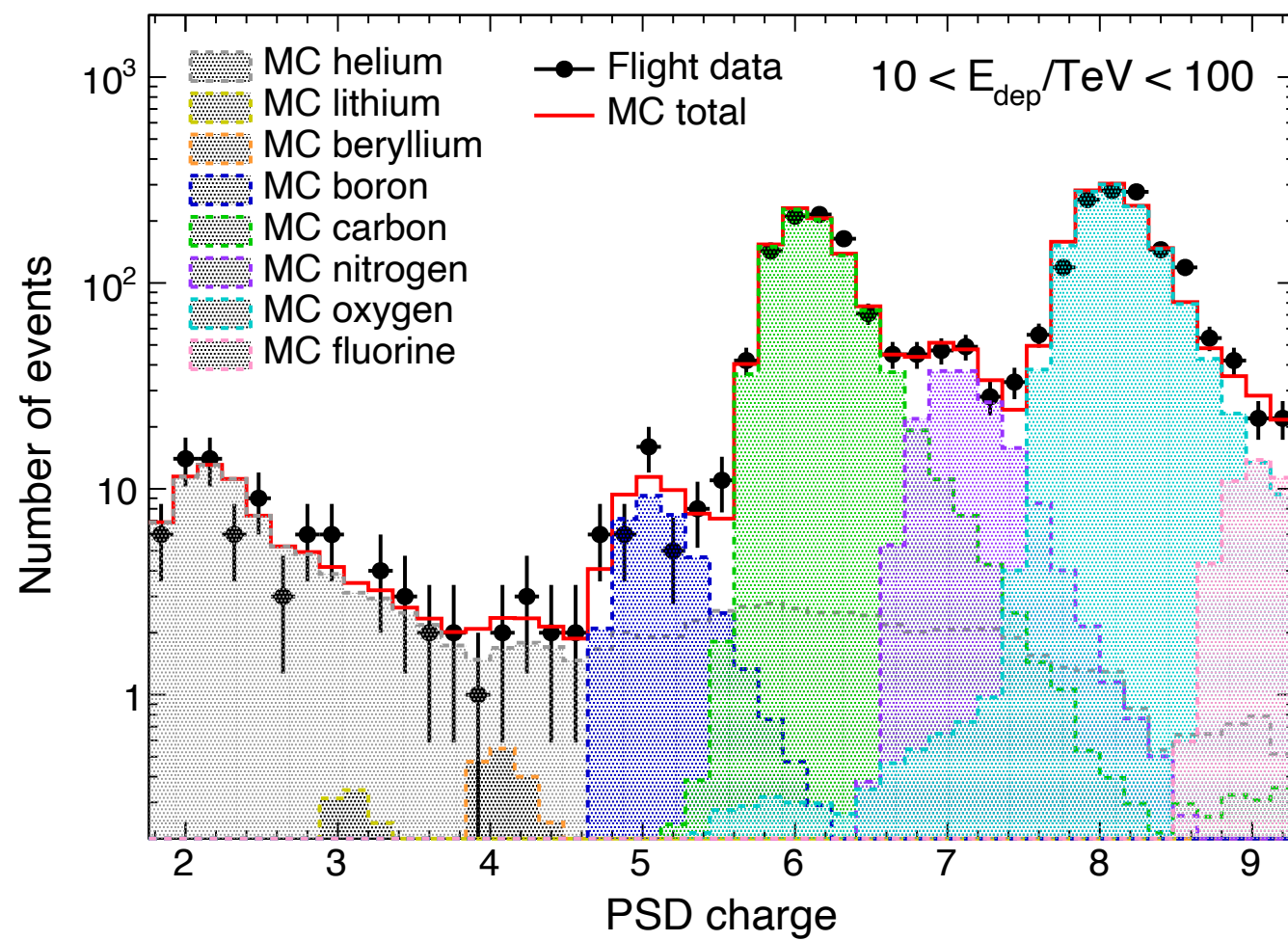
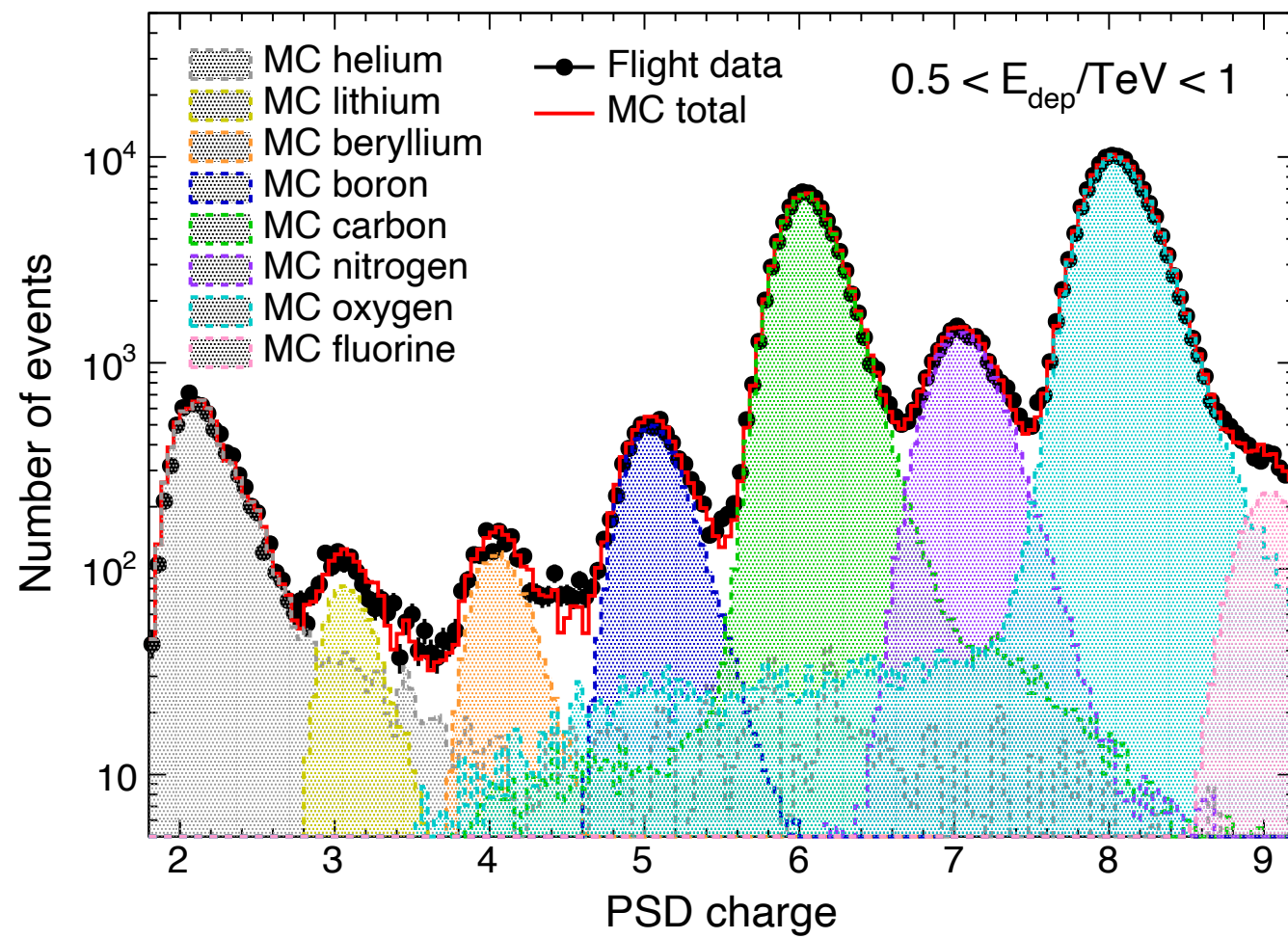


$$\Phi_{\text{SBPL}}(E) = \Phi_0 \cdot \left(\frac{E}{10^3 \text{ GeV}} \right)^{-\gamma} \left[1 + \left(\frac{E}{E_{\text{br}}} \right)^s \right]^{\frac{\Delta\gamma}{s}}$$

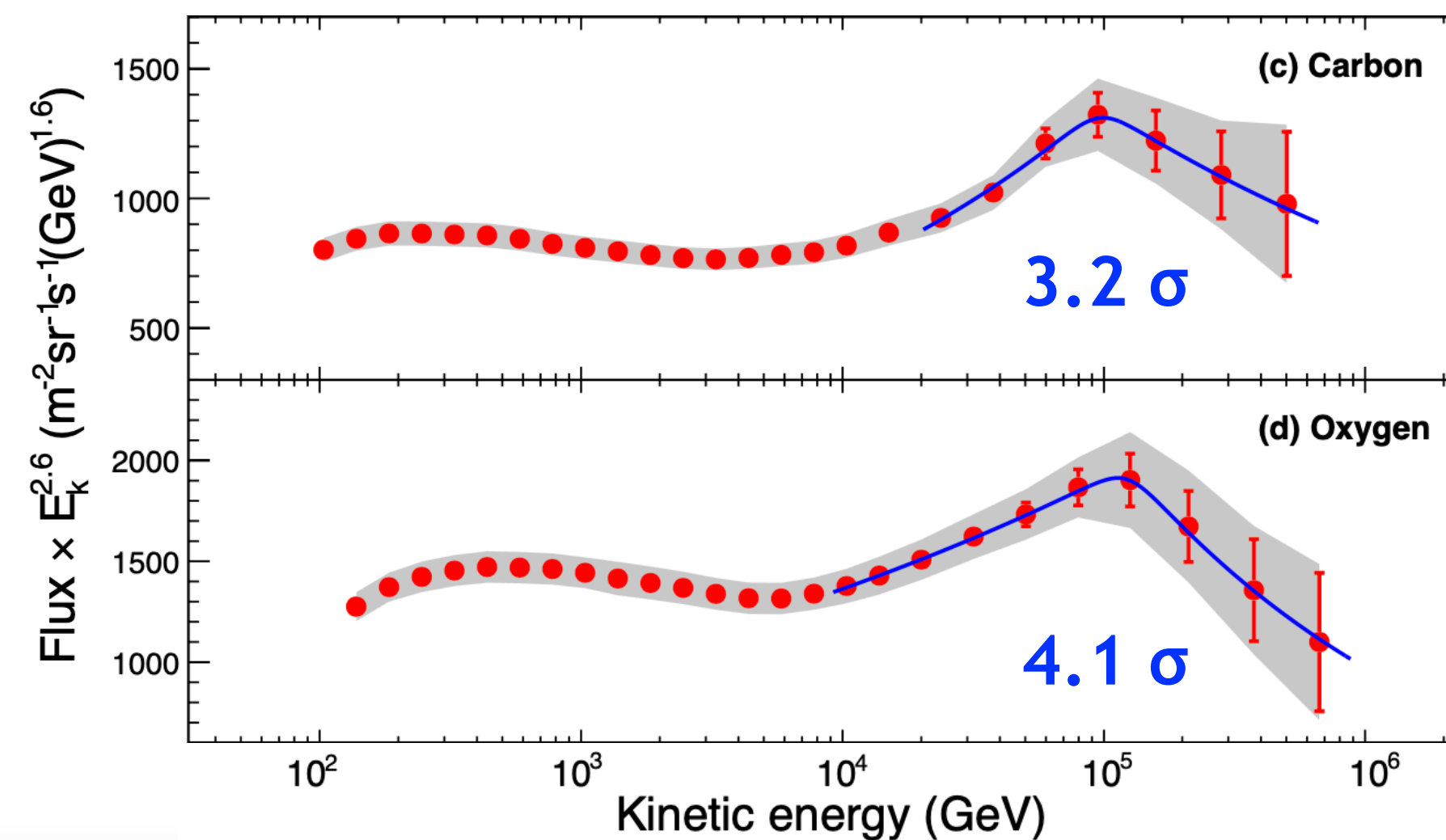
Particle	Proton	Helium
Fit energy range	1.58 - 100 TeV	3.98 - 250 TeV
Nuisance parameters	3	3
Φ_0 ($10^{-5} \text{ GeV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$)	8.08 ± 0.48	5.03 ± 0.35
E_{br} (TeV)	14.6 ± 1.3	30.6 ± 4.4
γ	2.57 ± 0.01	2.40 ± 0.01
$\Delta\gamma$	-0.34 ± 0.05	-0.32 ± 0.07
s	5 (fixed)	5 (fixed)

◎ 基于DAMPE在轨9年观测数据的能谱测量结果

基于DAMPE在轨9年观测数据的能谱测量结果



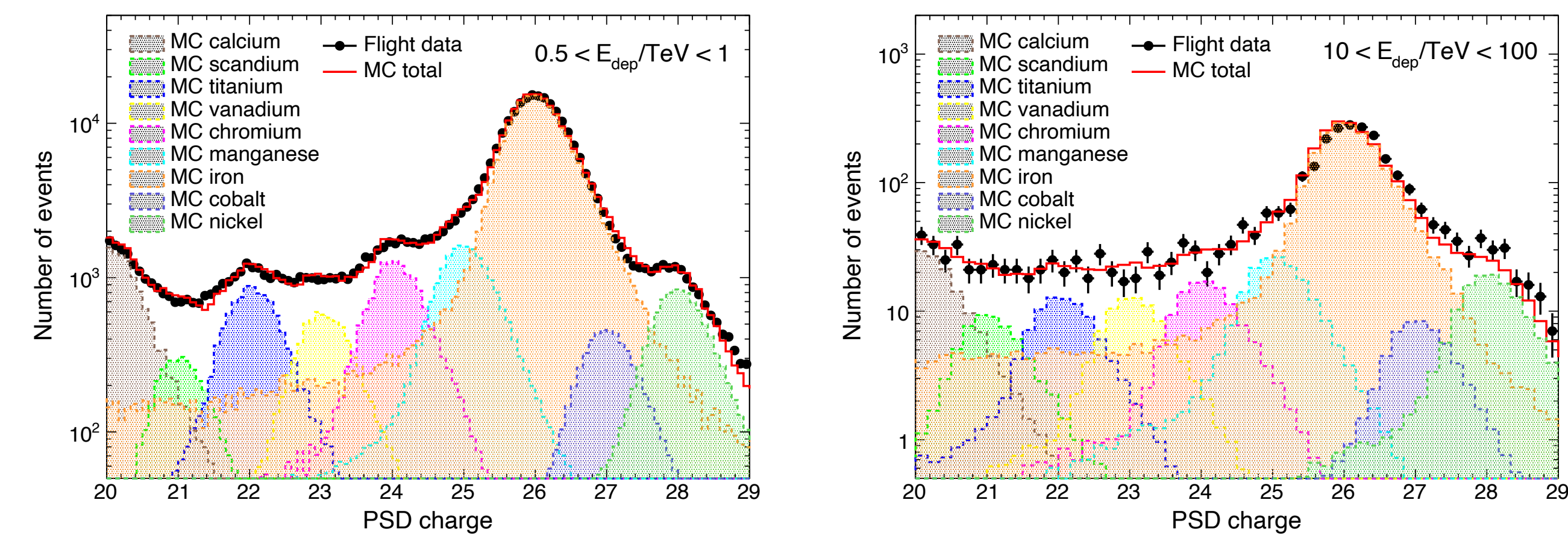
DAMPE collab., Nature, 653, 52-55 (2026)



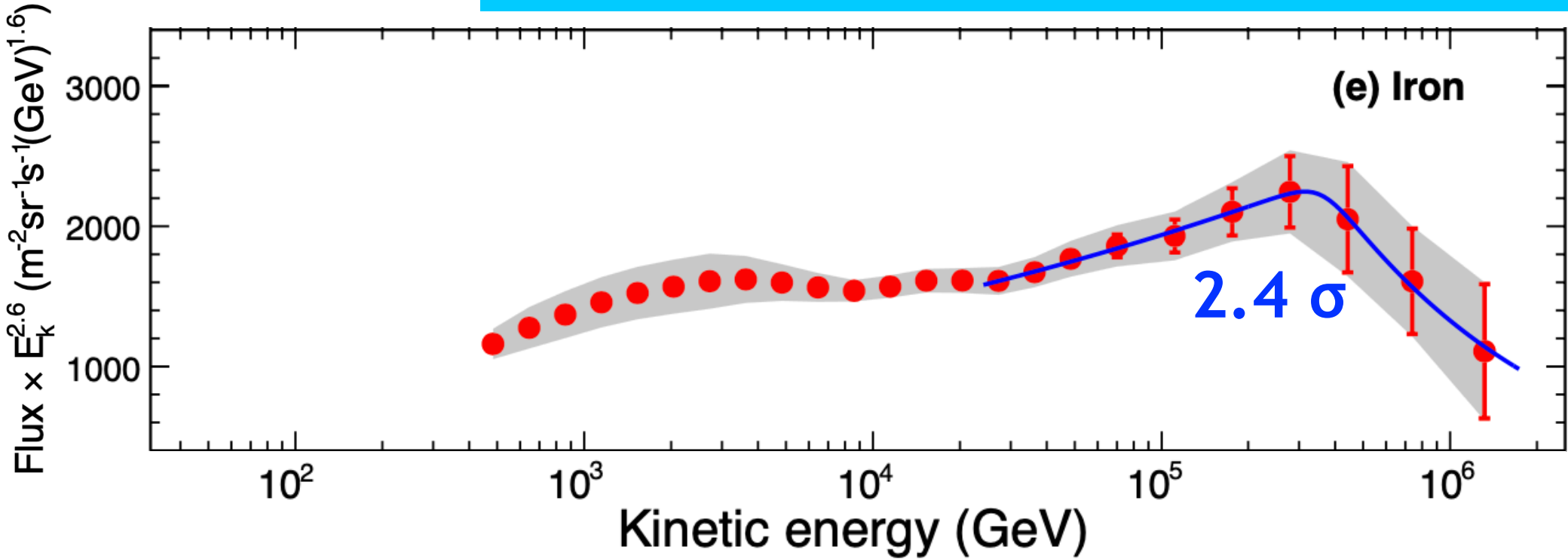
$$\Phi_{\text{SBPL}}(E) = \Phi_0 \cdot \left(\frac{E}{10^3 \text{ GeV}} \right)^{-\gamma} \left[1 + \left(\frac{E}{E_{\text{br}}} \right)^s \right]^{\frac{\Delta\gamma}{s}}$$

Particle	Carbon	Oxygen
Fit energy range	19.0 - 675 TeV	9.0 - 900 TeV
Nuisance parameters	2	3
Φ_0 ($10^{-5} \text{ GeV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$)	0.60 ± 0.12	1.54 ± 0.16
E_{br} (TeV)	96.5 ± 33.5	123 ± 38
γ	2.32 ± 0.06	2.45 ± 0.03
$\Delta\gamma$	-0.49 ± 0.17	-0.48 ± 0.18
s	10 (fixed)	10 (fixed)

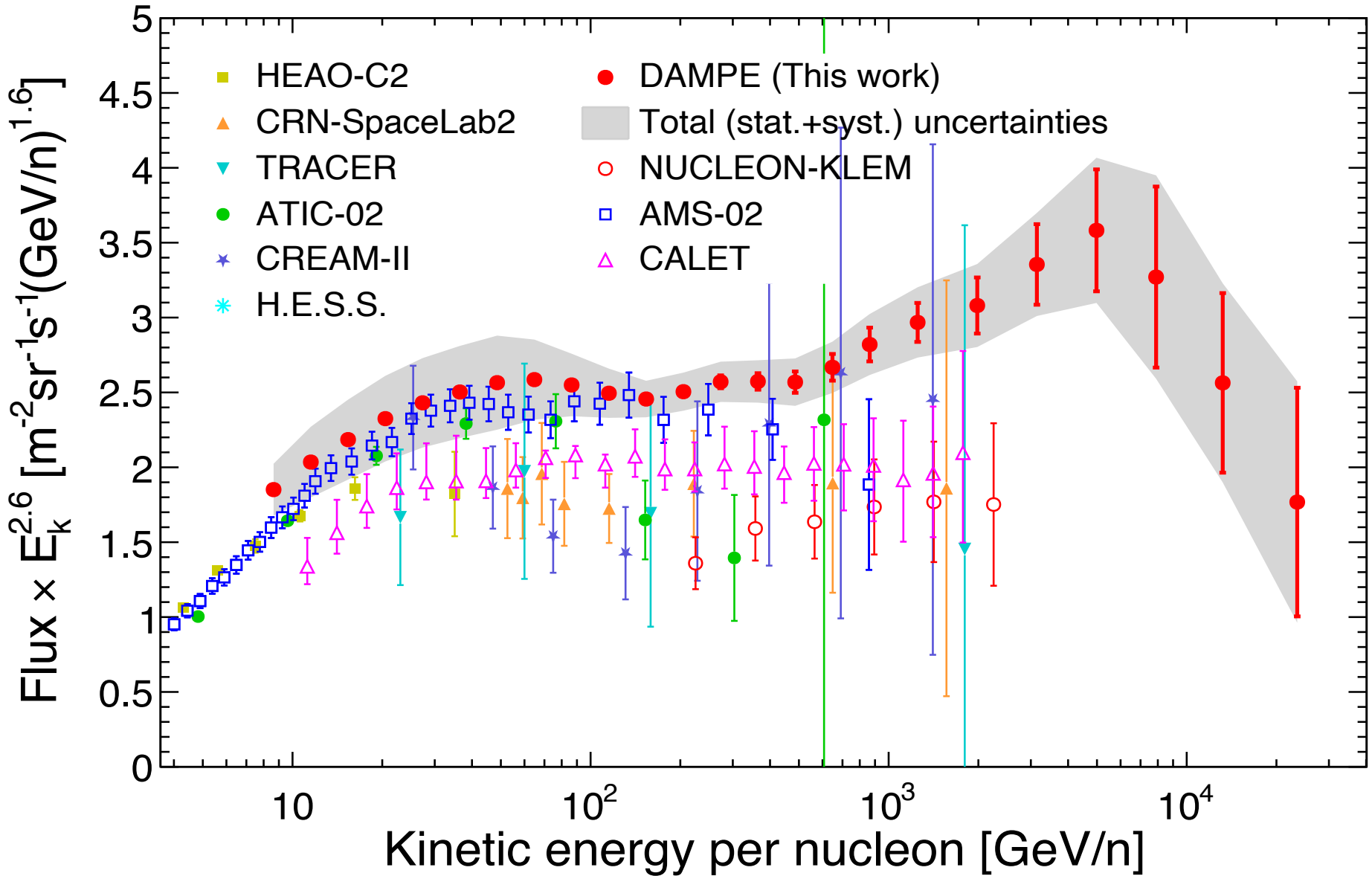
基于DAMPE在轨9年观测数据的能谱测量结果



DAMPE collab., Nature, 653, 52-55 (2026)



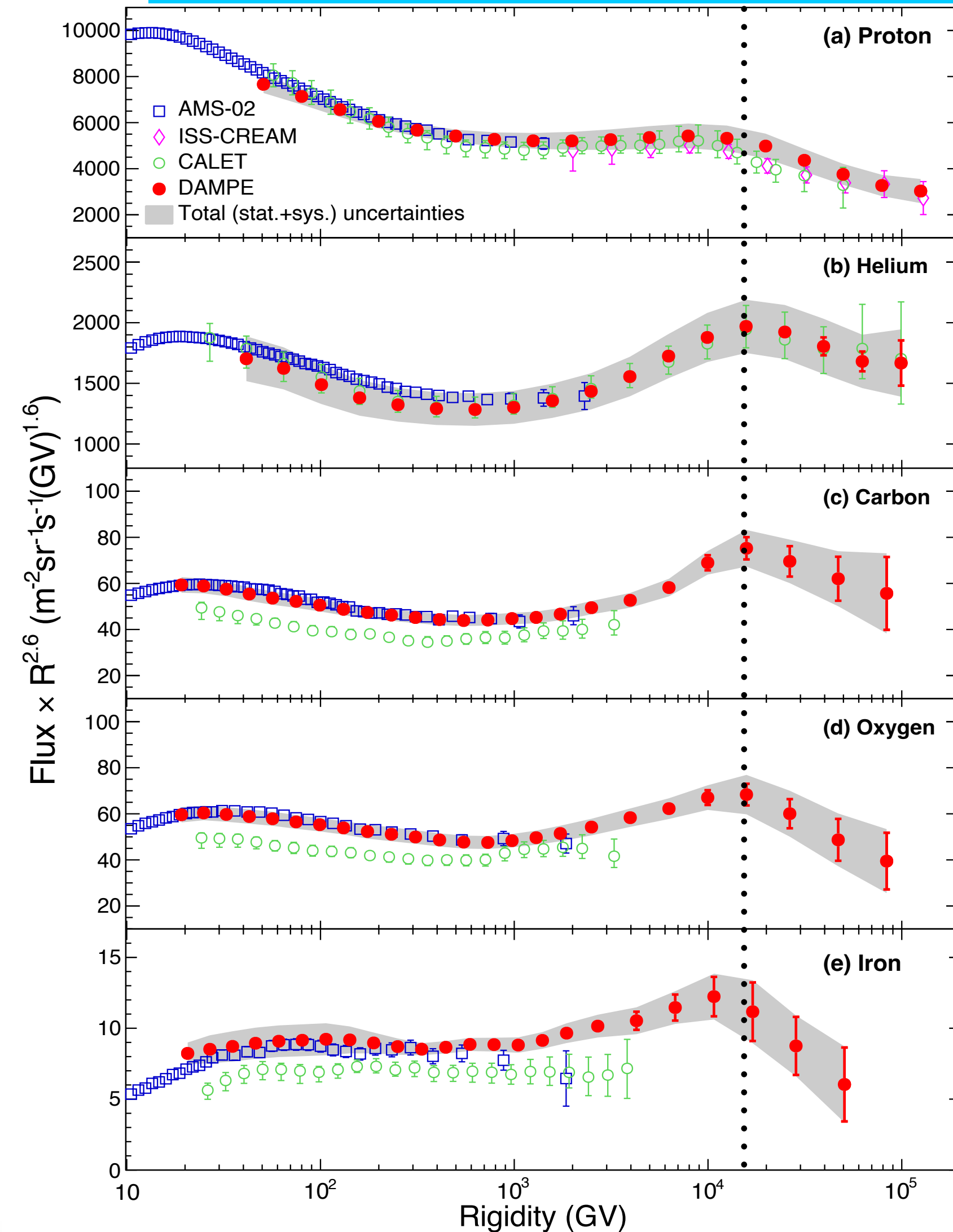
$$\Phi_{\text{SBPL}}(E) = \Phi_0 \cdot \left(\frac{E}{10^3 \text{ GeV}} \right)^{-\gamma} \left[1 + \left(\frac{E}{E_{\text{br}}} \right)^s \right]^{\frac{\Delta\gamma}{s}}$$



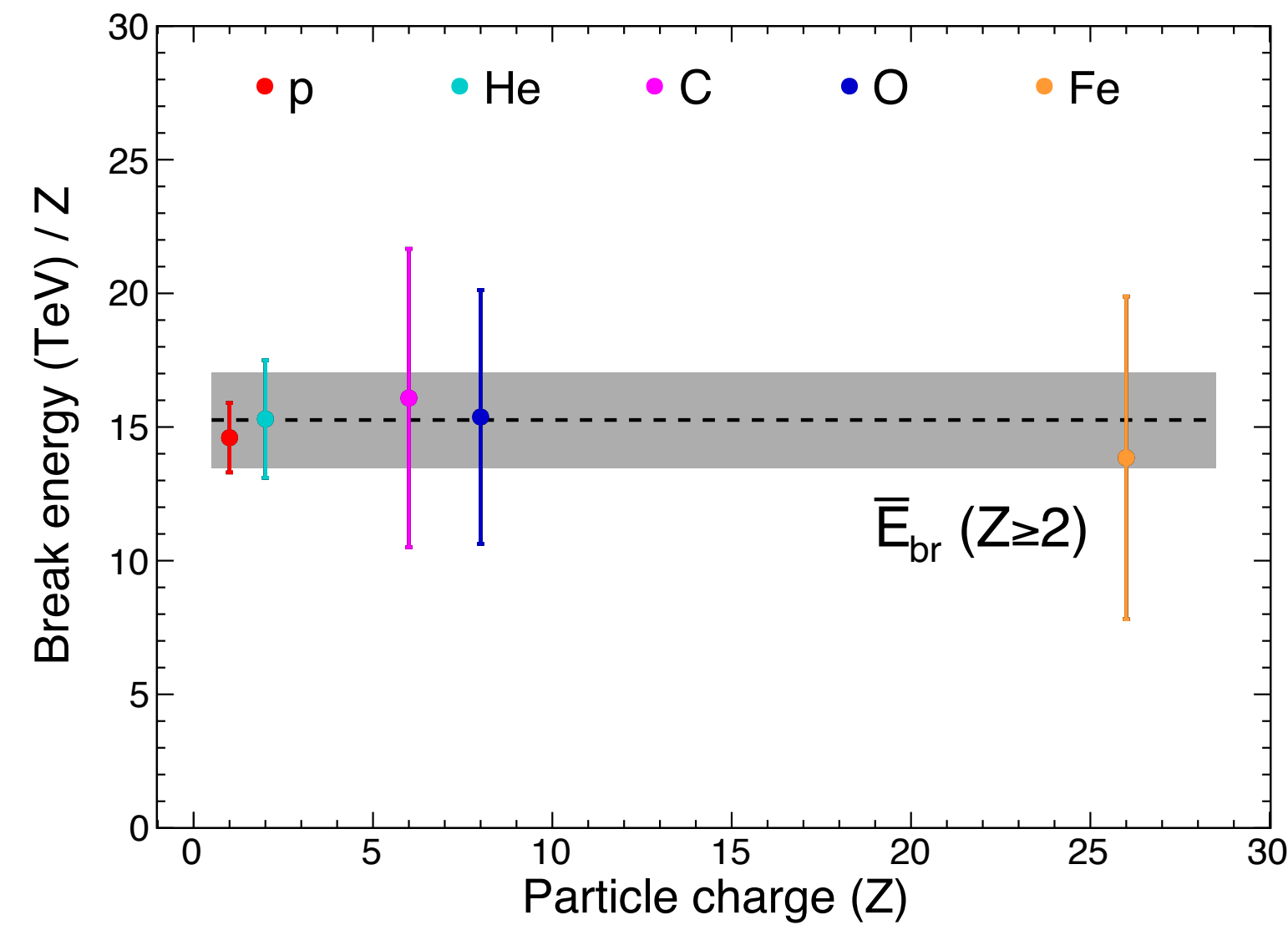
Particle	Carbon	Oxygen	Iron
Fit energy range	19.0 - 675 TeV	9.0 - 900 TeV	236 - 1771 TeV
Nuisance parameters	2	3	3
Φ_0 ($10^{-5} \text{ GeV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$)	0.60 ± 0.12	1.54 ± 0.16	1.50 ± 0.47
E_{br} (TeV)	96.5 ± 33.5	123 ± 38	360 ± 157
γ	2.32 ± 0.06	2.45 ± 0.03	2.46 ± 0.05
$\Delta\gamma$	-0.49 ± 0.17	-0.48 ± 0.18	-0.69 ± 0.41
s	10 (fixed)	10 (fixed)	10 (fixed)

原初宇宙线粒子统一能谱结构

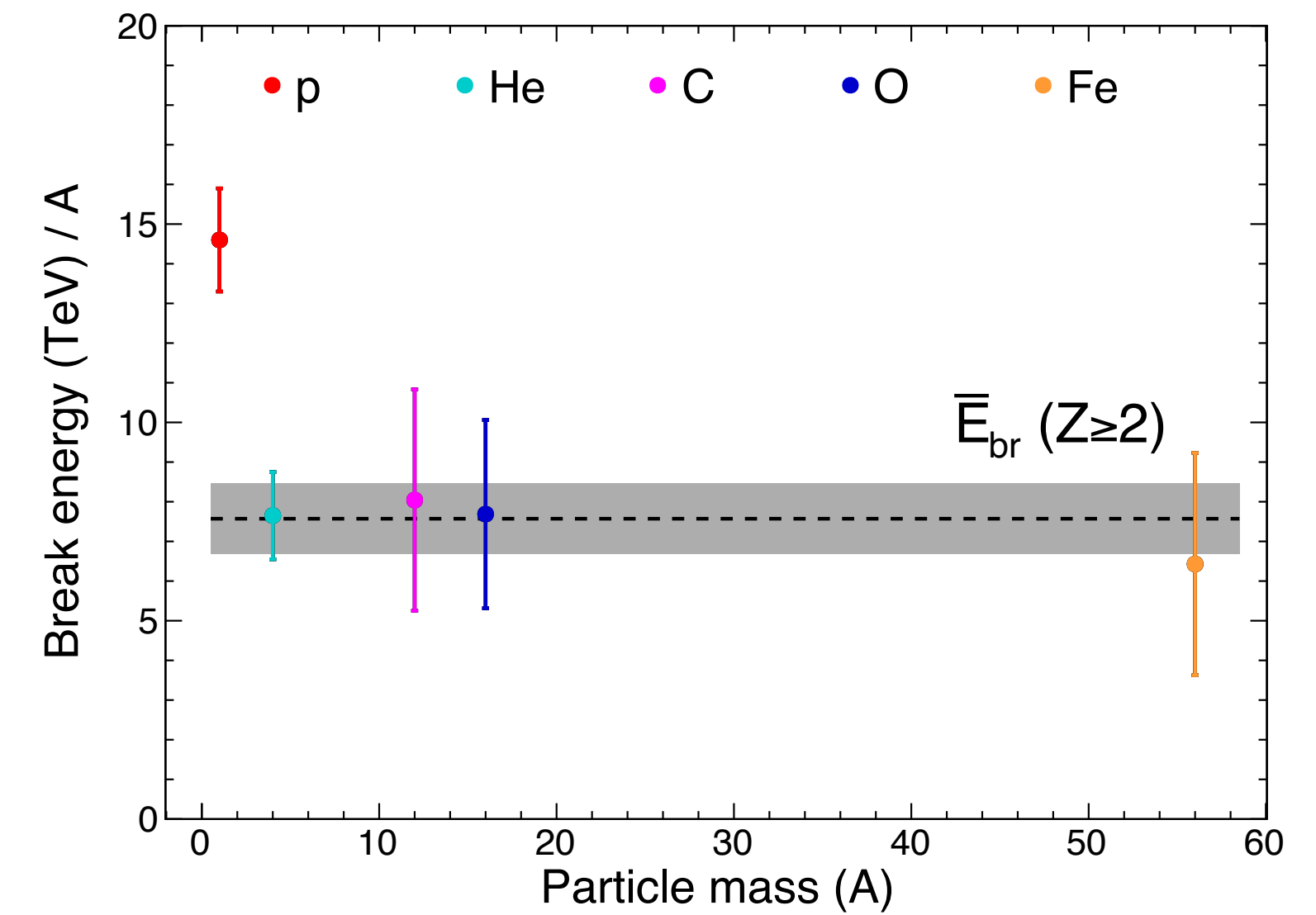
DAMPE collab., Nature, 653, 52-55 (2026)



E_{br} v.s. Z

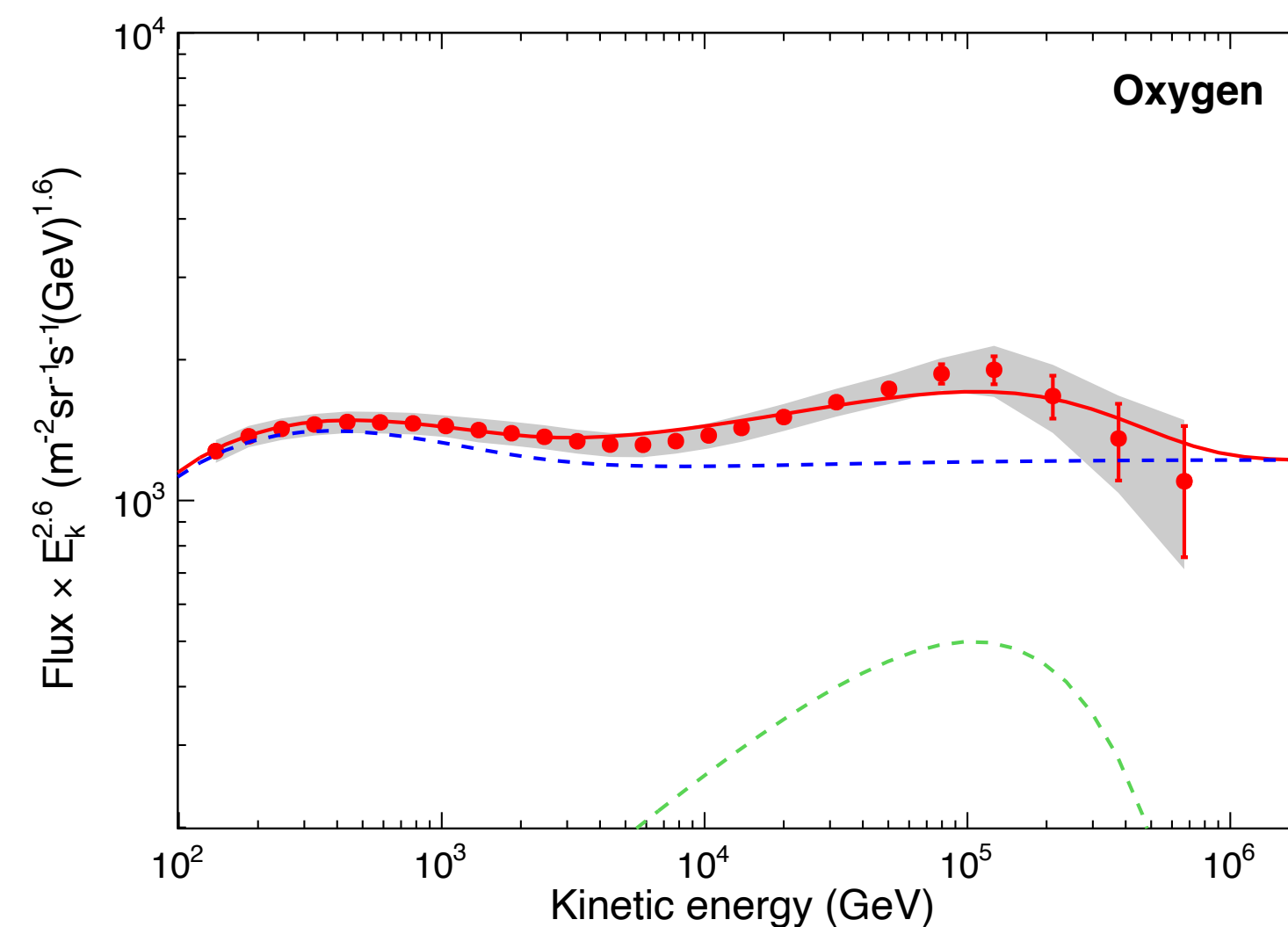
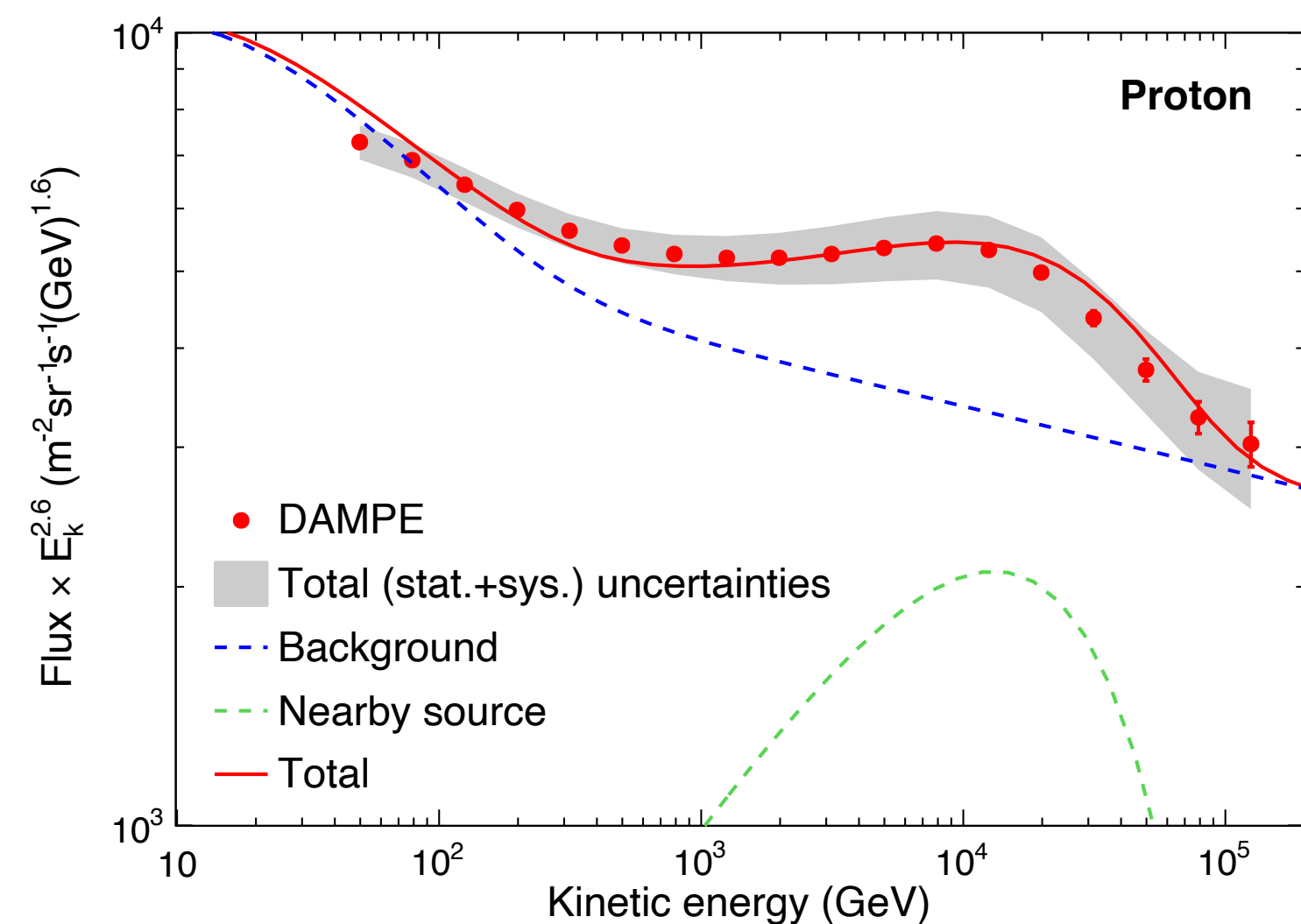


E_{br} v.s. A

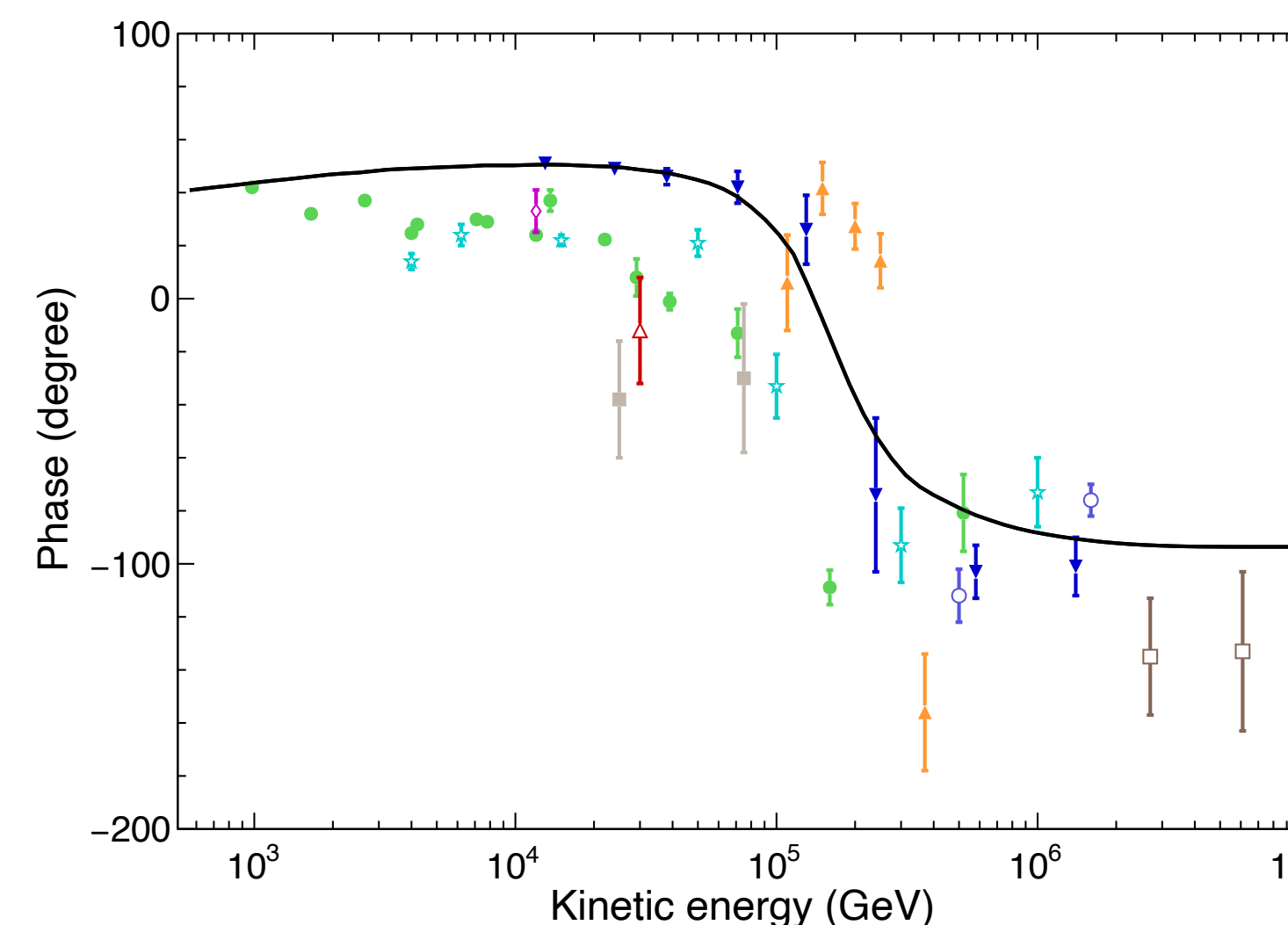
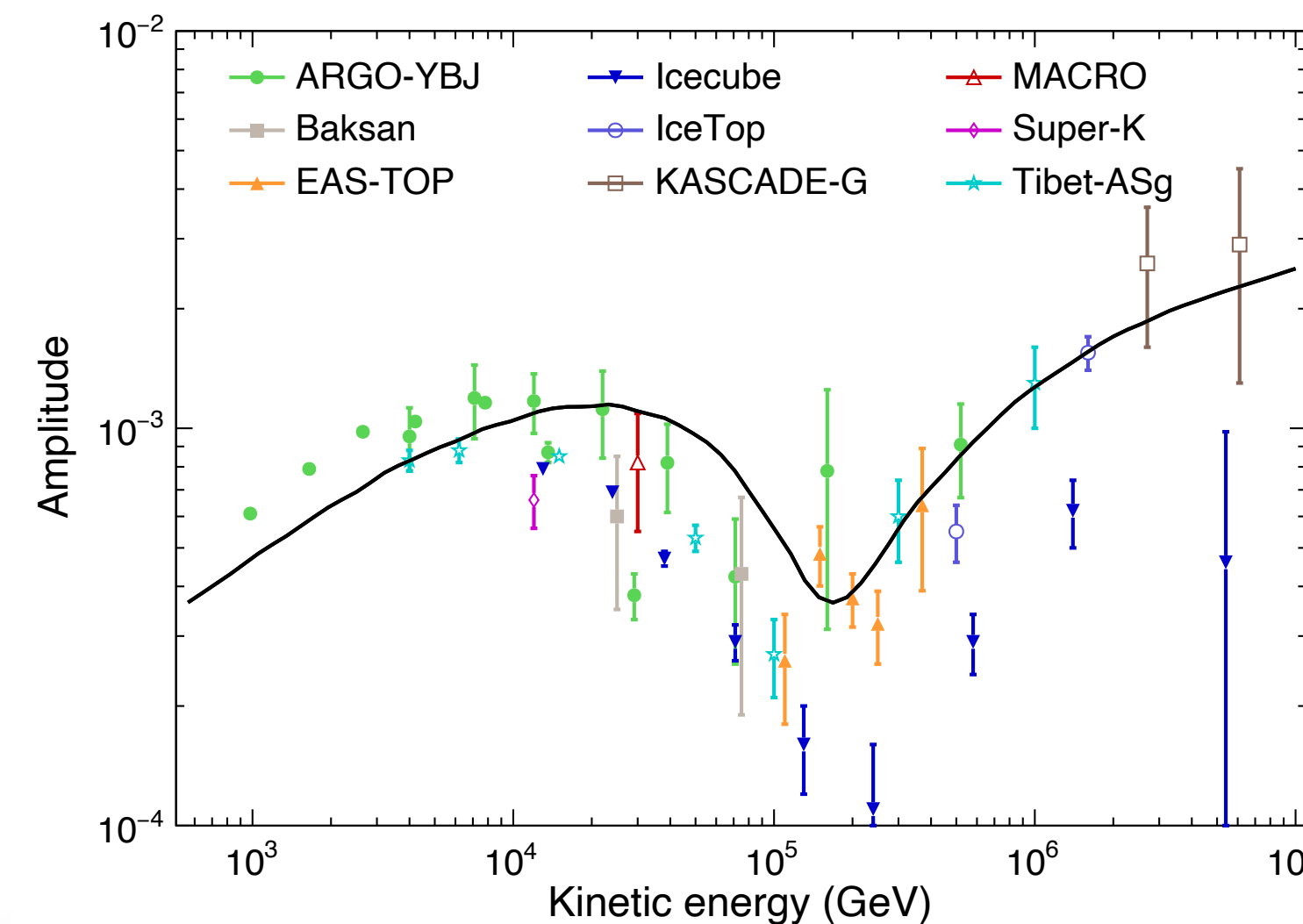


- ◎ DAMPE将5种原初宇宙线粒子能谱直接测量至PeV能区，对C、O、Fe的有效测量上限较之前实验提高近一个量级
- ◎ 揭示出5种粒子能谱存在**统一的鼓包状“超出”结构**，**高能拐折能量正比于 Z** ，对应磁刚度为15TV，在观测上证实了**宇宙线加速的电荷依赖特性**

一种可能的物理图像：背景叠加邻近源模型



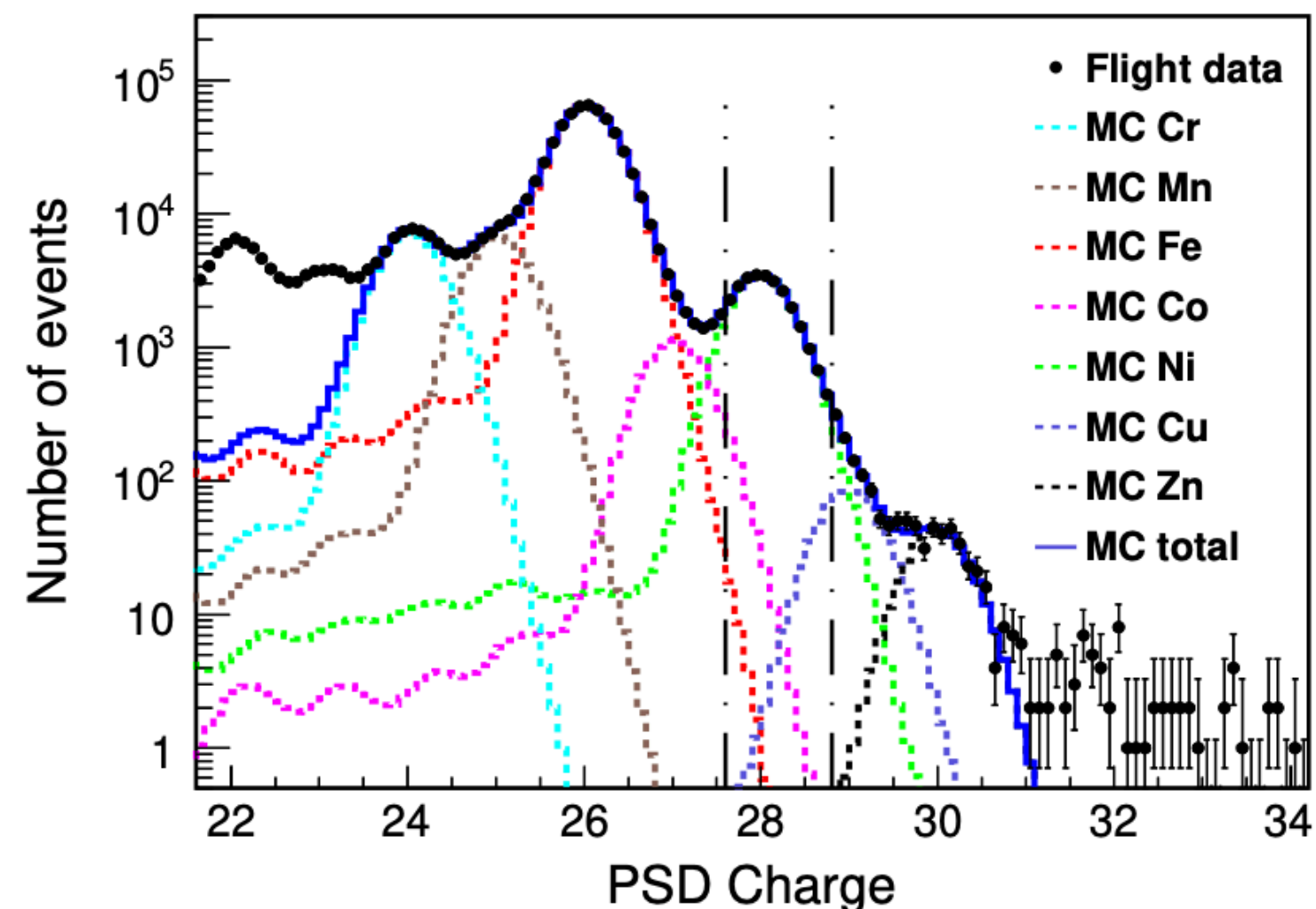
Nearby source:
 Geminga-like
 250 pc, 3.4×10^5 yr
 $q_{\text{src}} \propto (R/\text{GV})^{-\beta} \exp(-R/R_c)$



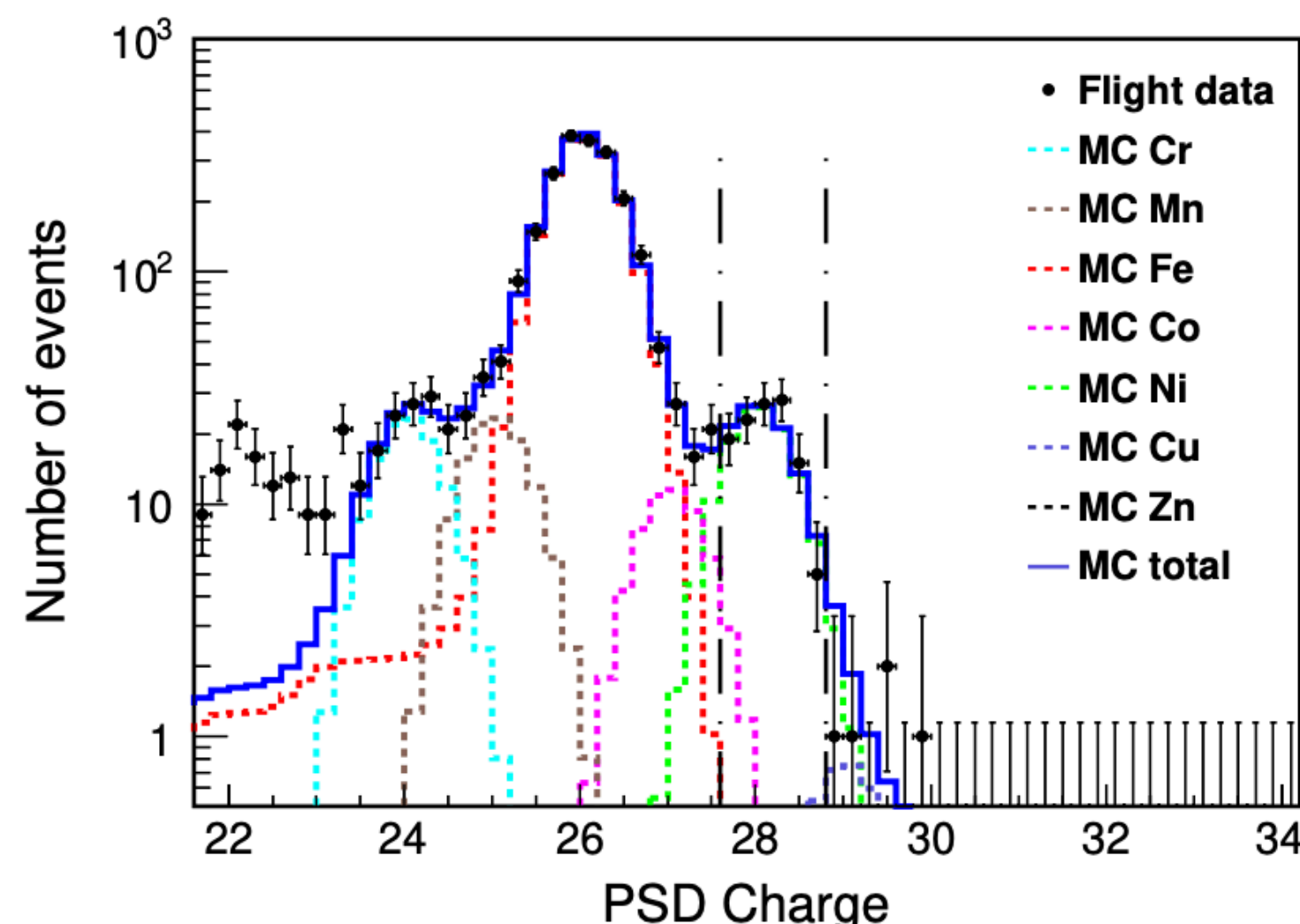
同时解释宇宙线能谱鼓包状
 “超出”结构和大尺度宇宙线
 各向异性随能量的变化

超铁核素：镍核

- 宇宙线中镍是丰度最高的“超铁”核素，一般认为镍和铁一样产生于恒星和合成或超新星爆发过程，因此镍和铁应具有相似的能谱行为。

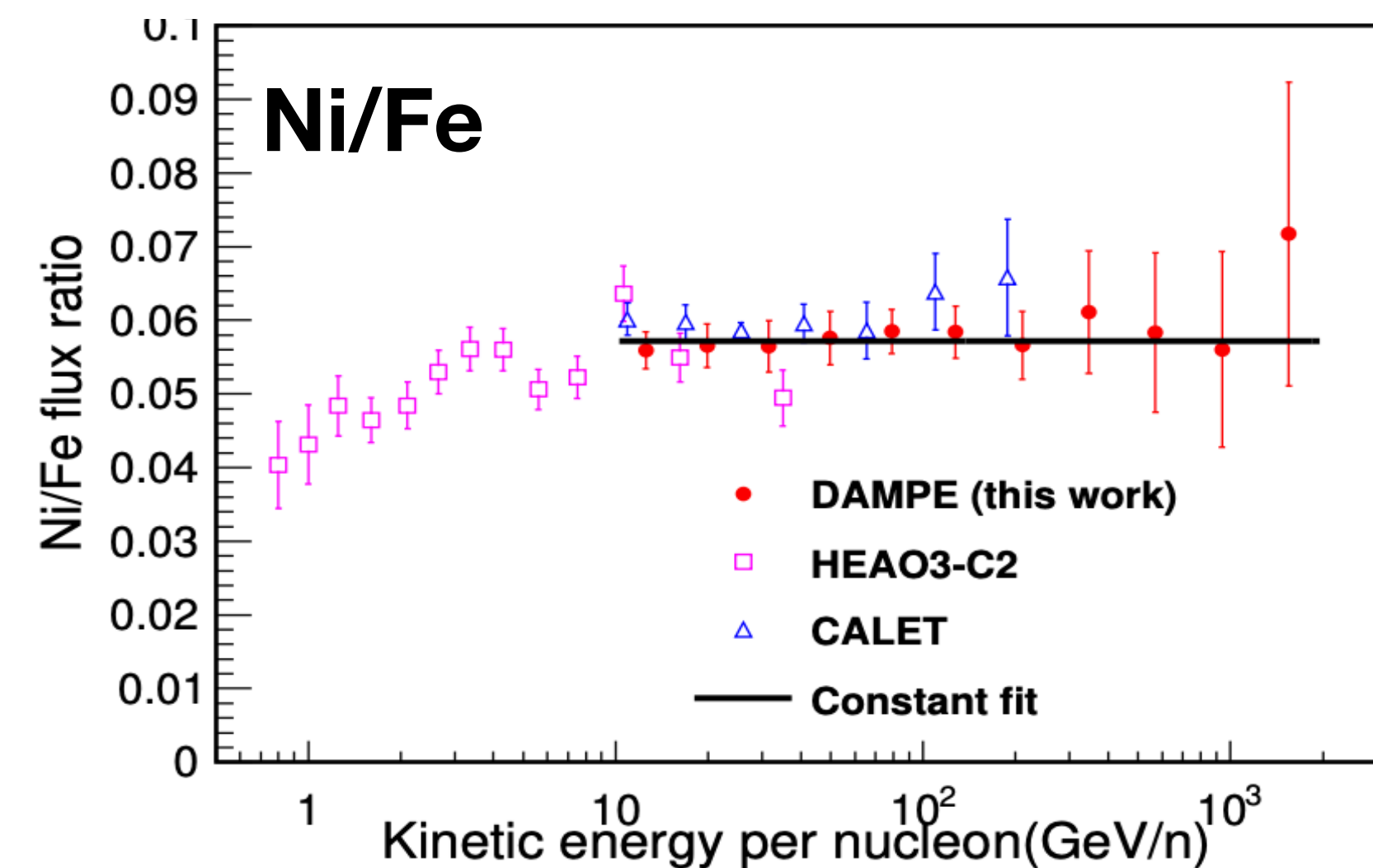
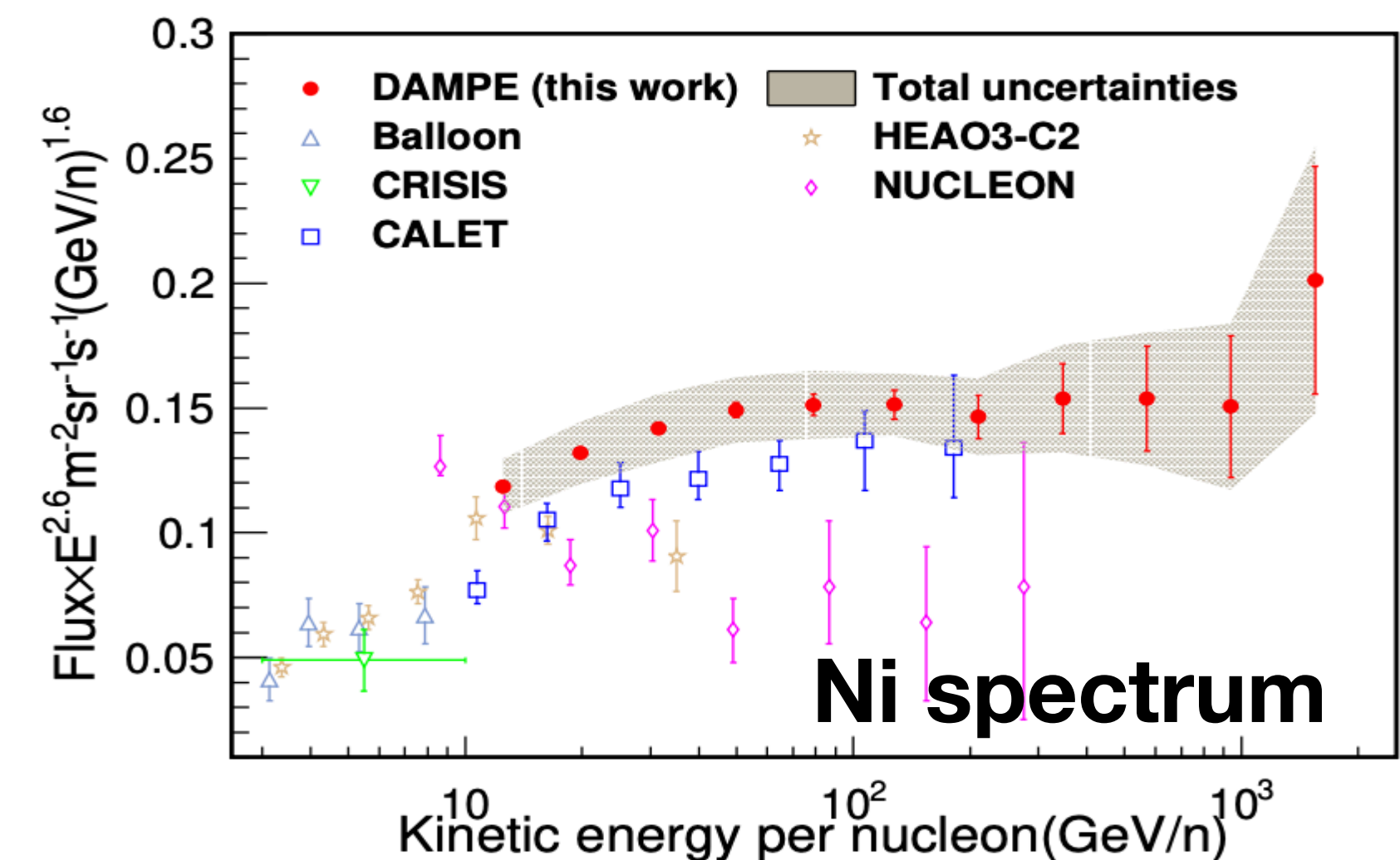


BgoE: [100, 158] GeV



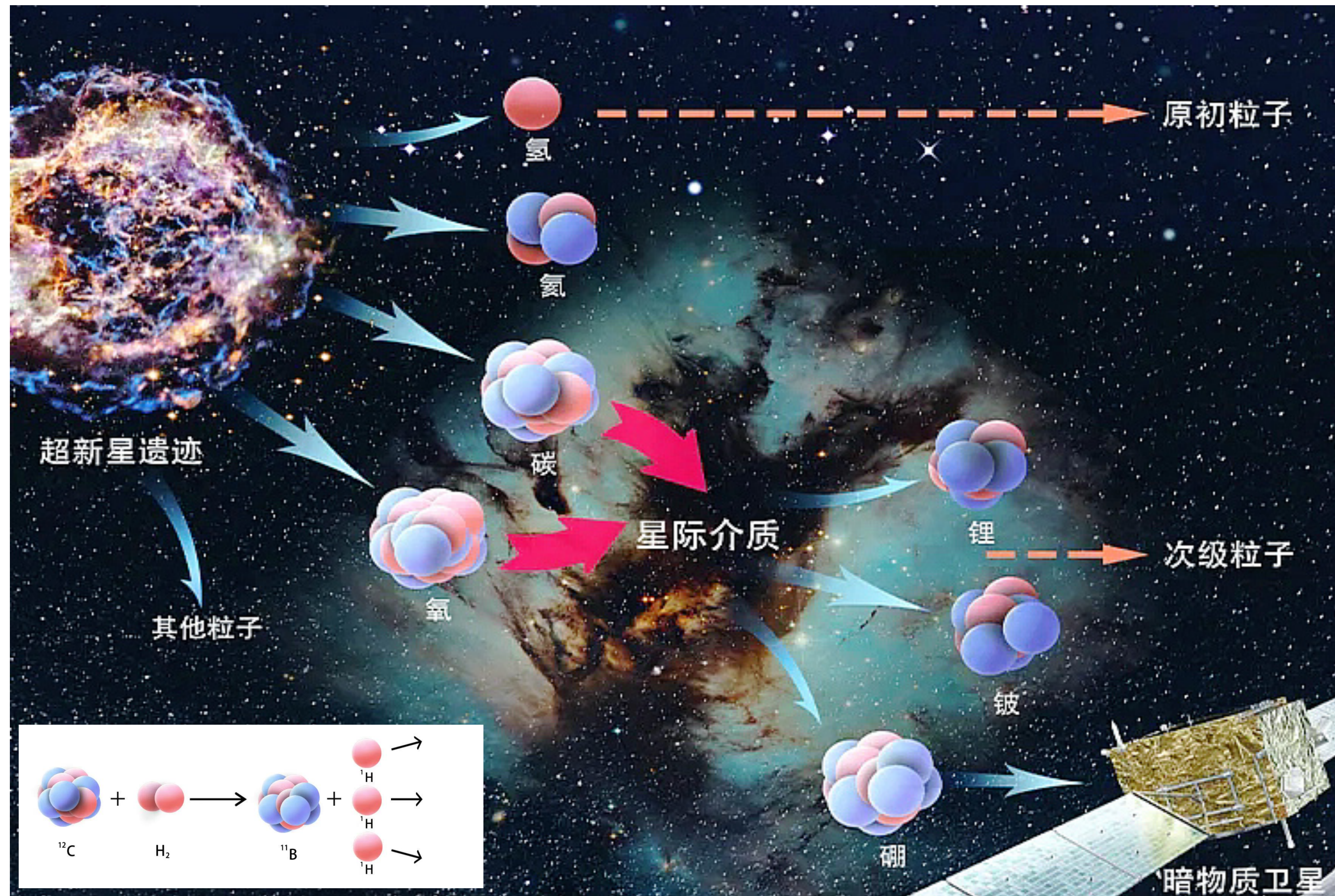
BgoE: [4.6, 10] TeV

- DAMPE获得了10GeV - 2TeV/n的镍核能谱直接测量结果
- 镍/铁流量比随能量呈现出常数特征，表明两者统一起源

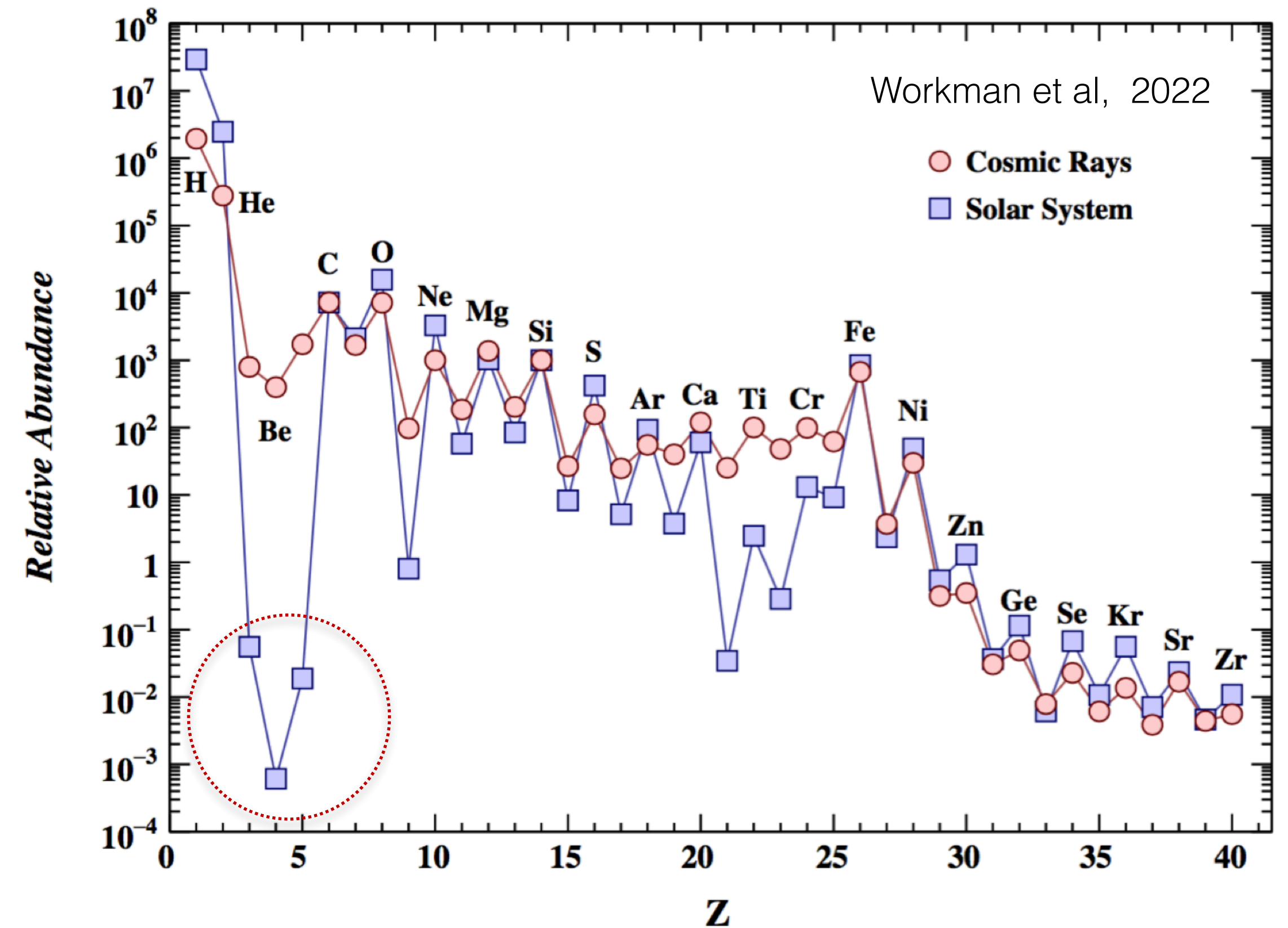


DAMPE collab., Phy. Rew. Lett. in press (2026)

次级宇宙线能谱：硼核

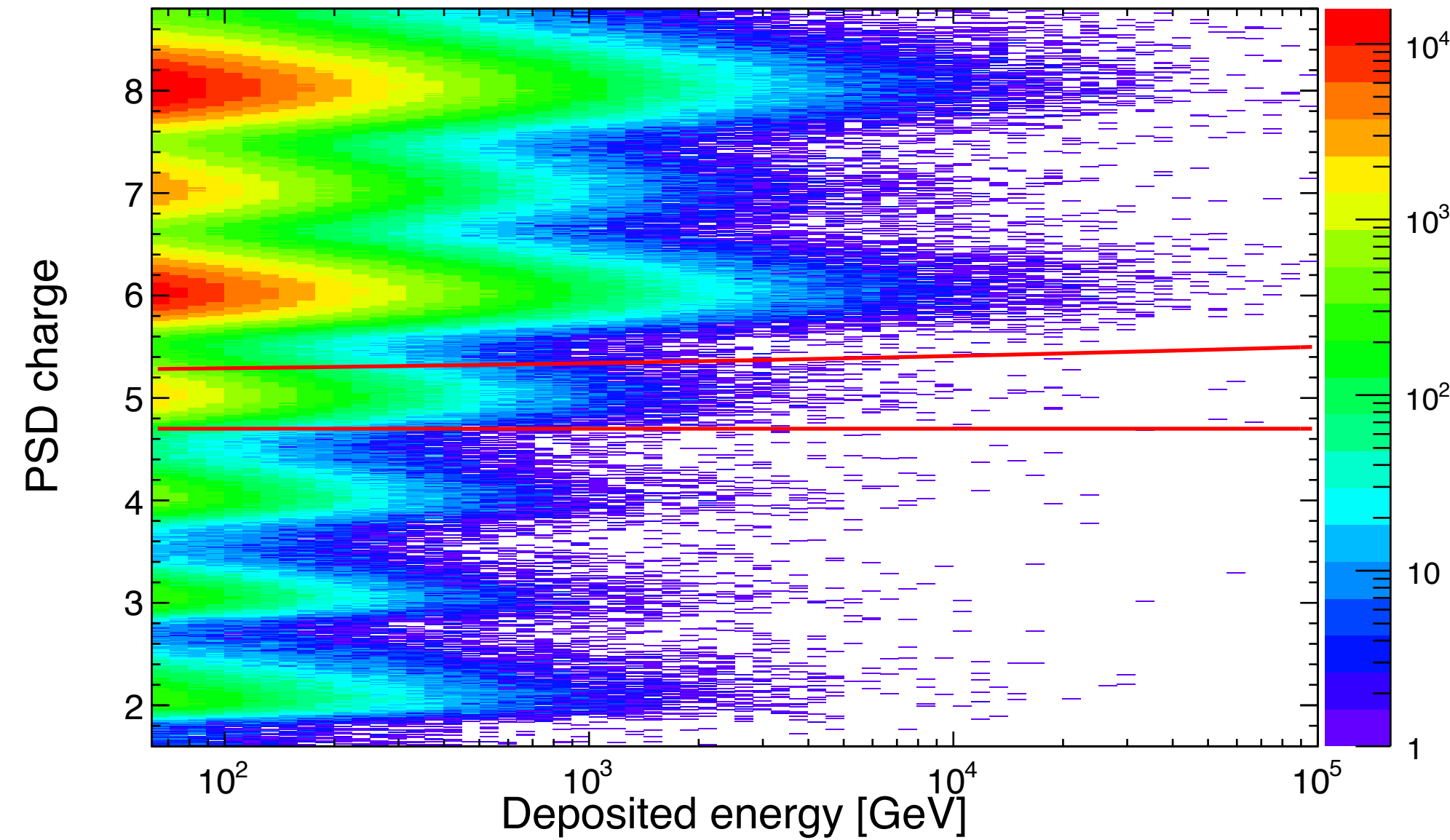


太阳系和宇宙线中元素丰度对比

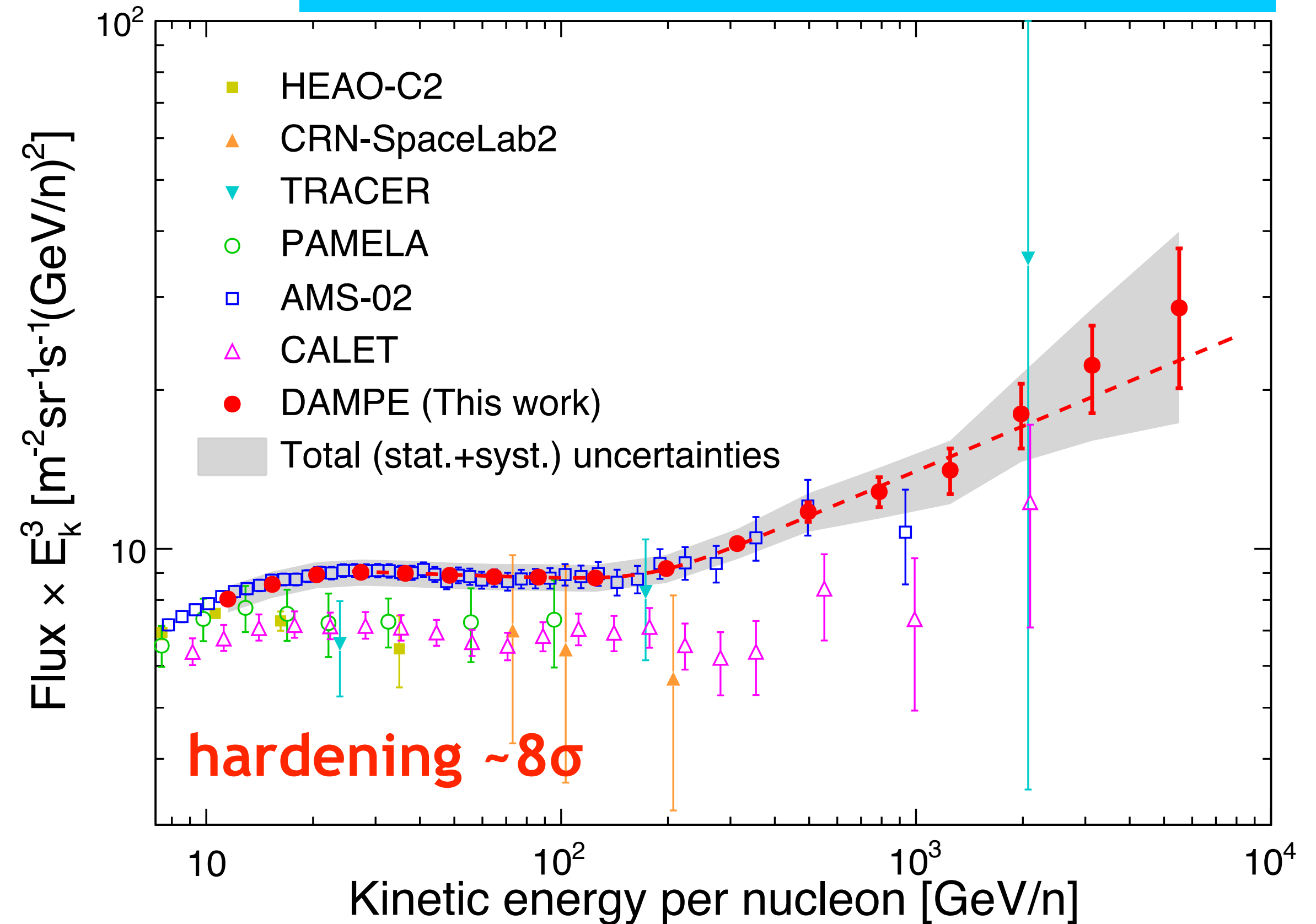


- 宇宙线硼原子核(B)属于**次级粒子**，由碳核(C)、氧核(O)等**原初粒子**与星际介质发生碰撞碎裂后产生
- 其能谱行为是反映**宇宙线在银河系传播特征的关键信使**，也是**构建宇宙线传播模型**的重要观测依据

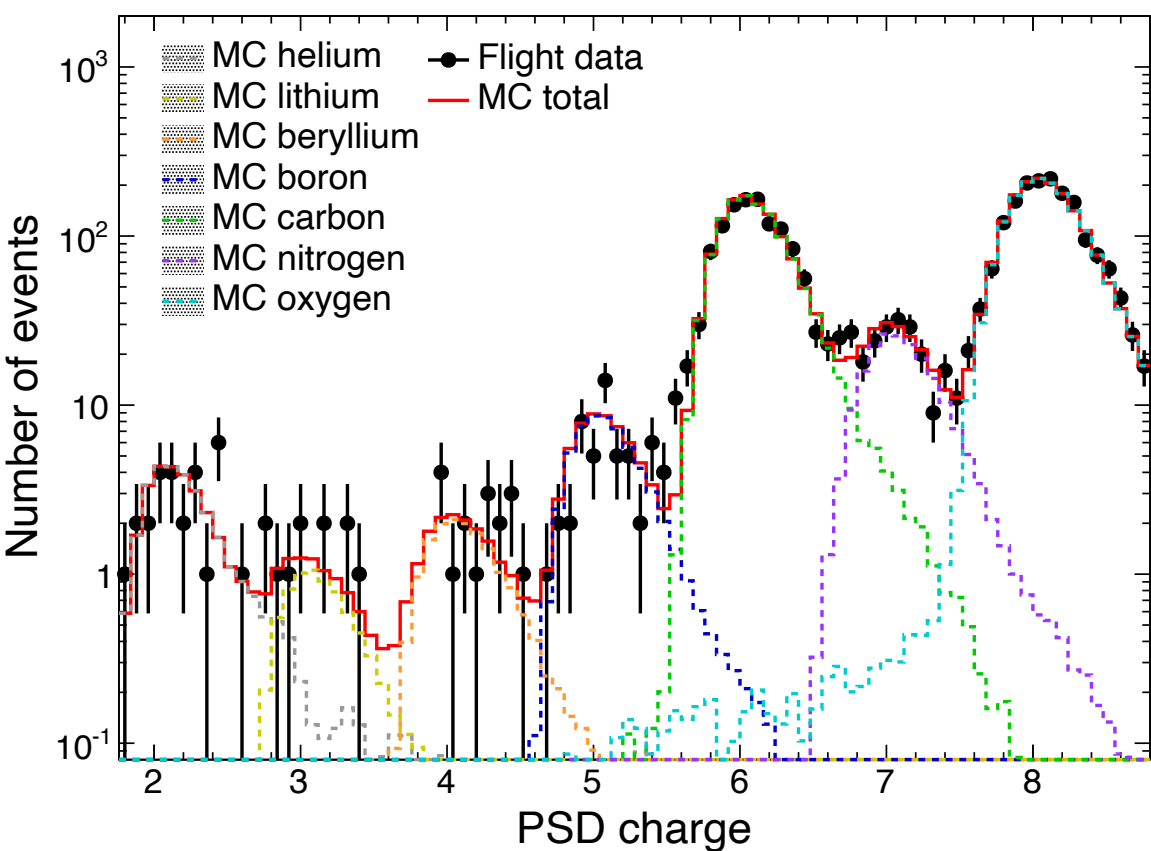
PsdQ vs. BgoE



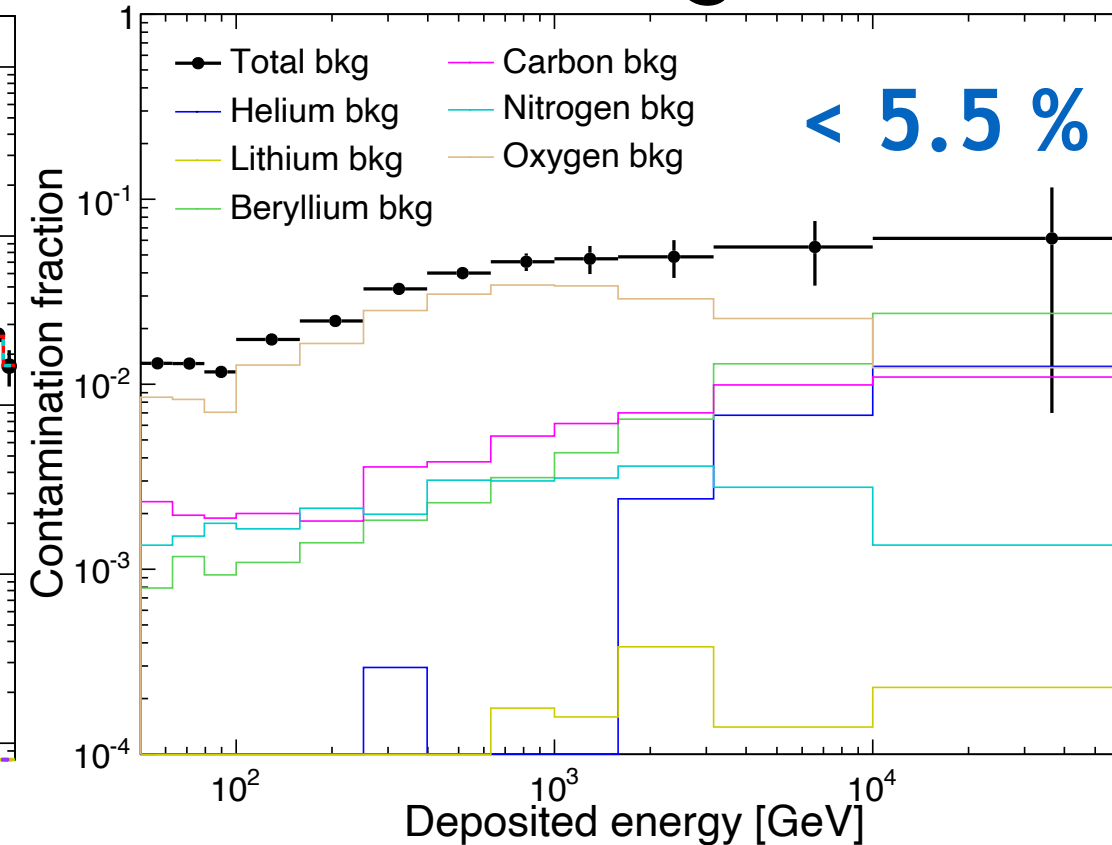
DAMPE collab., Phy. Rev. Lett. 134, 191001 (2025)



BgoE: [6.3, 20] TeV



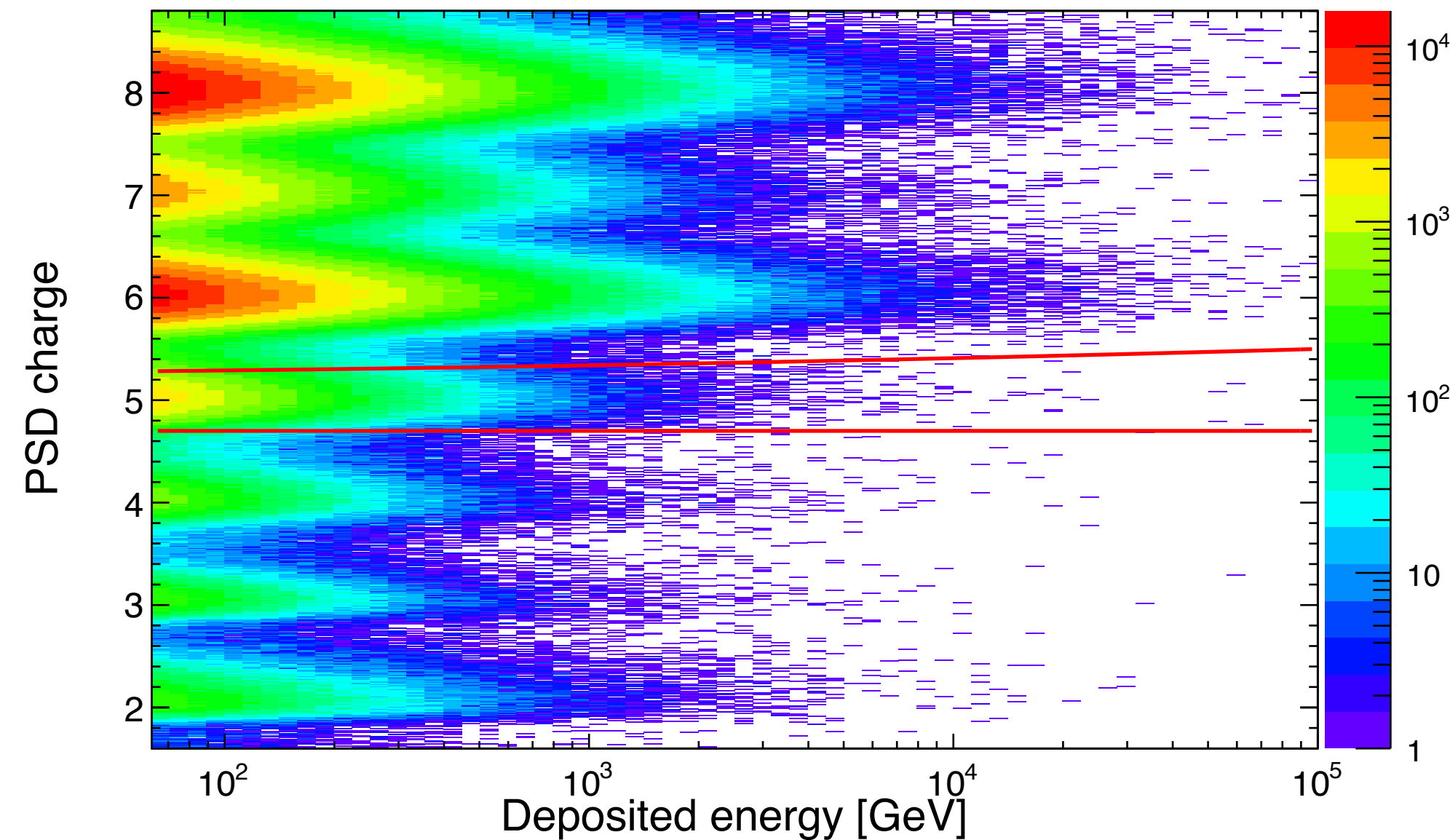
Boron background



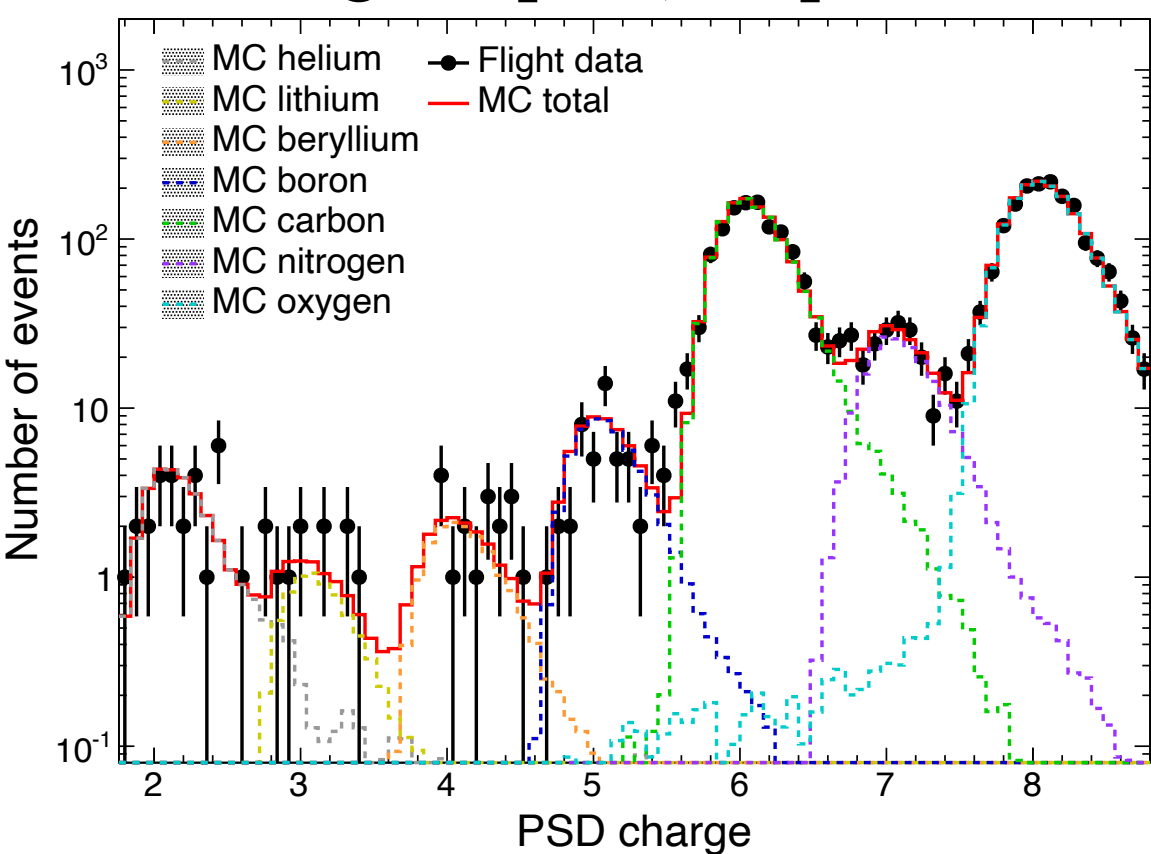
◎ DAMPE实现TeV/n能区硼核能谱精确测量，发现约200GeV/n处的能谱拐折结构(置信度 $\sim 8\sigma$)

次级宇宙线能谱：硼核

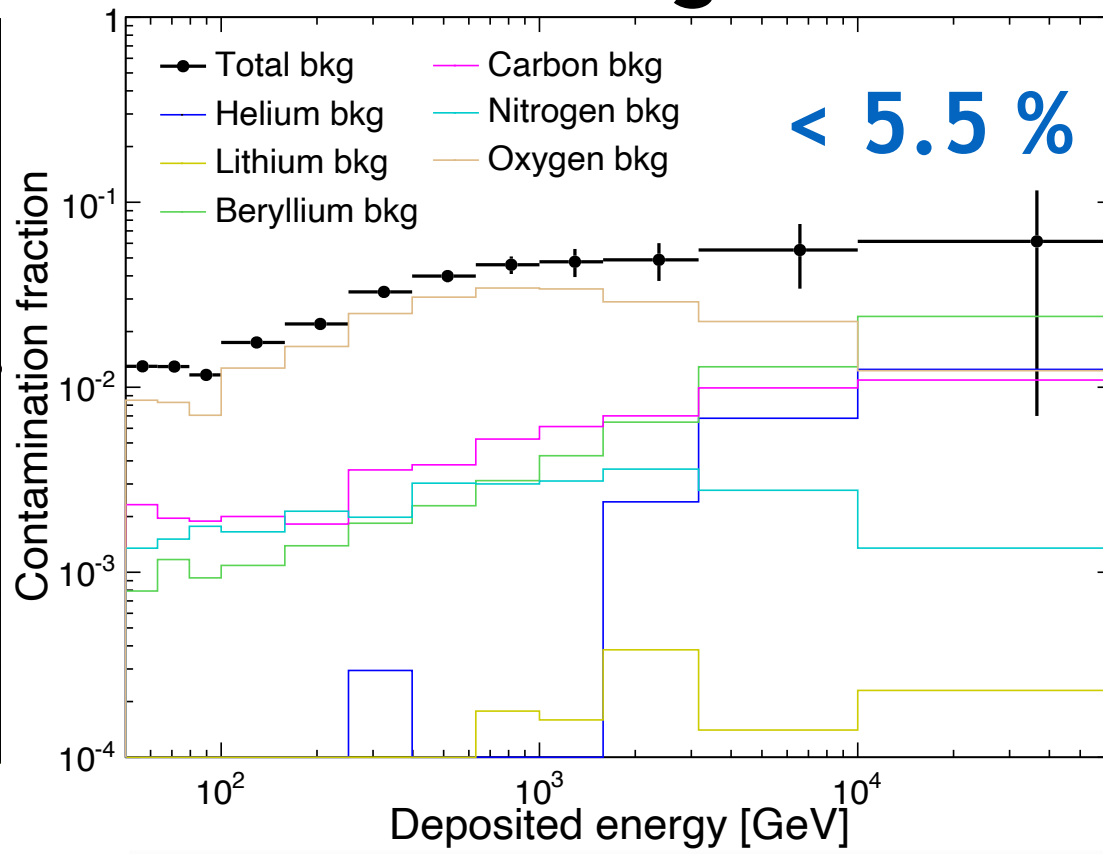
PsdQ vs. BgoE



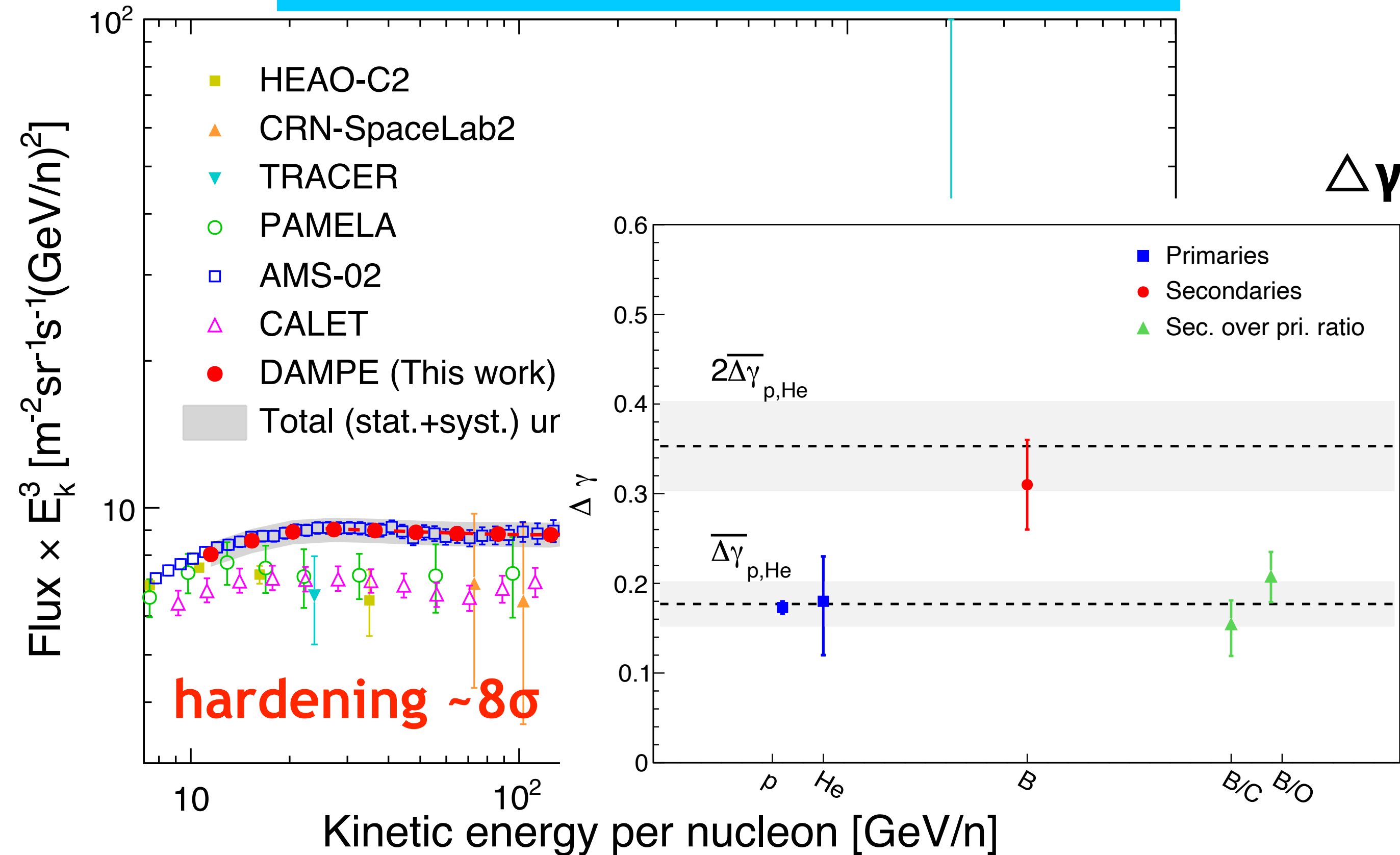
BgoE: [6.3, 20] TeV



Boron background



DAMPE collab., Phy. Rev. Lett. 134, 191001 (2025)

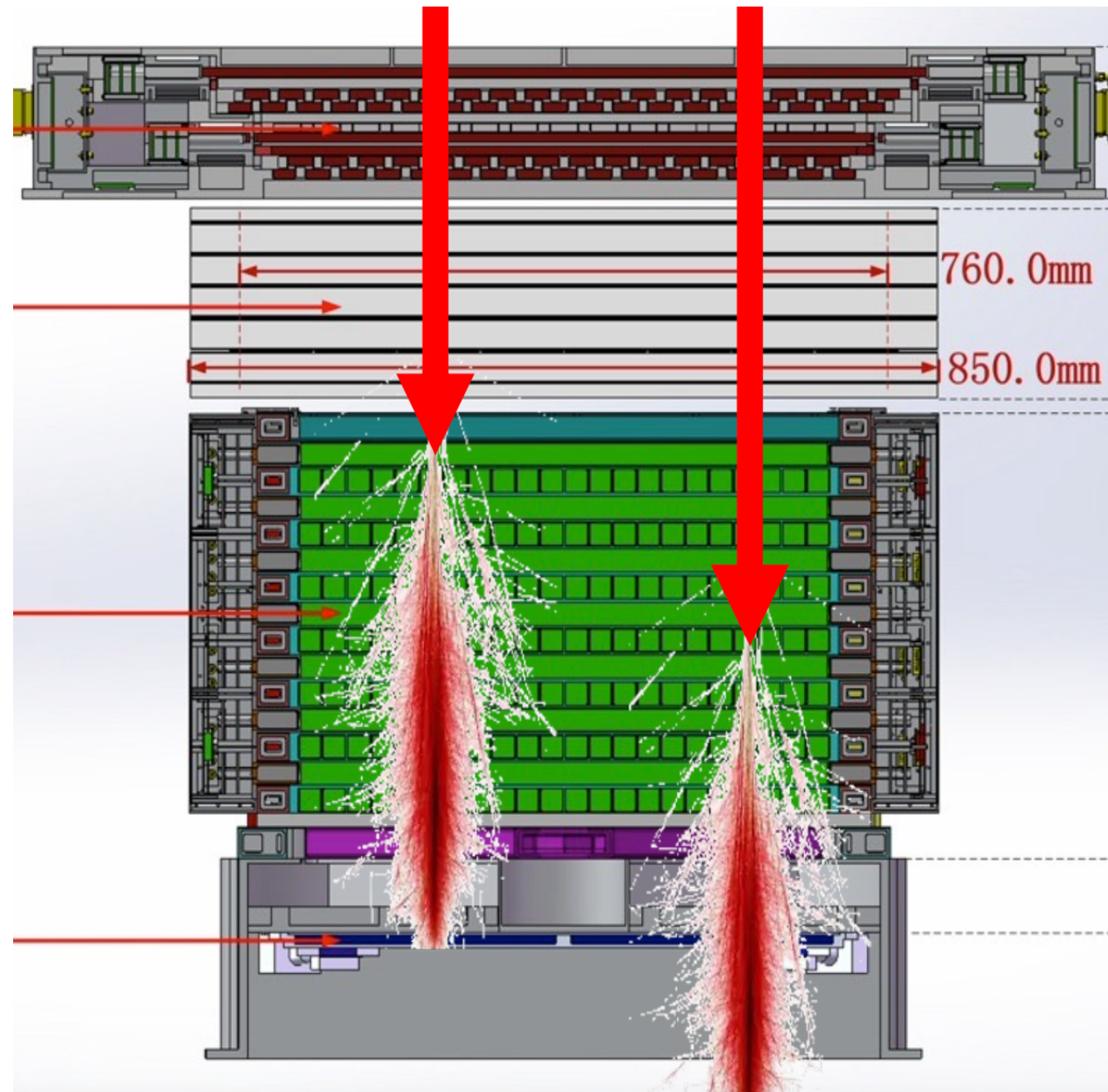


◎ DAMPE实现TeV/n能区硼核能谱精确测量，发现约200GeV/n处的能谱拐折结构(置信度 $\sim 8\sigma$)

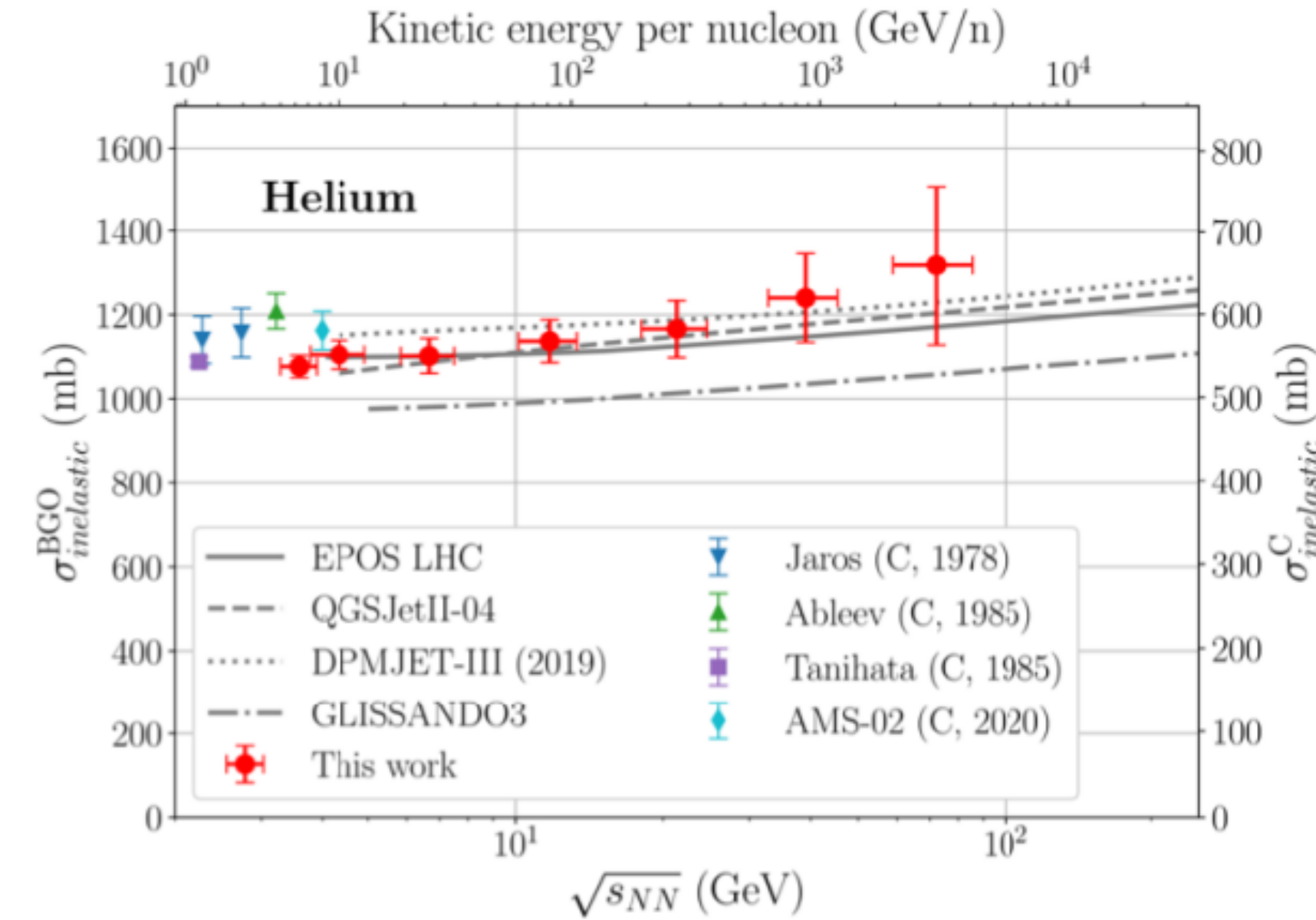
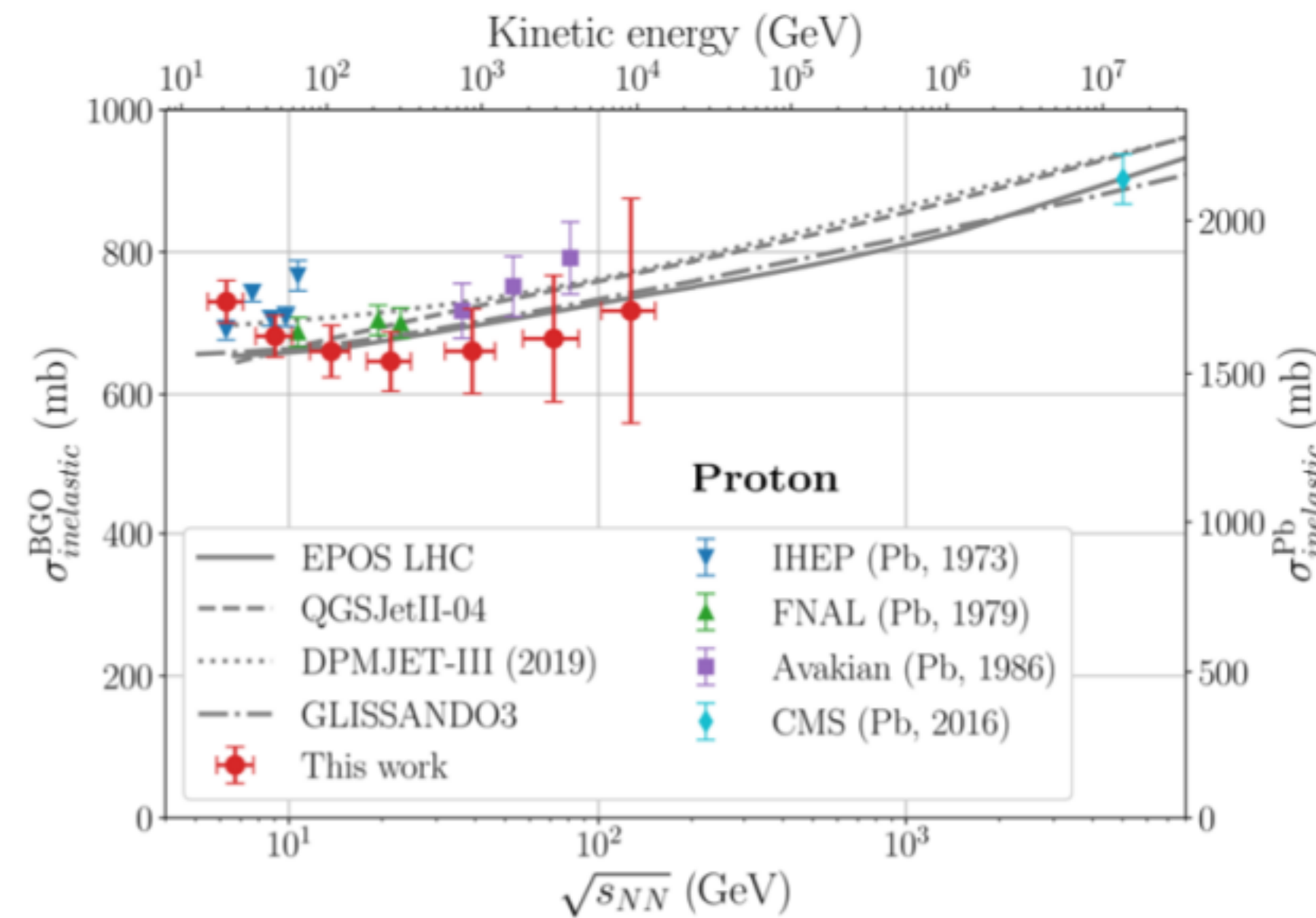
◎ 能谱变硬幅度为质子、氦核约两倍，与宇宙线传播相关

强相互作用截面测量

基于DAMPE的 粒子打靶实验(CR-->BGO)



DAMPE collab., *Phys. Rev. D* 111, 012002 (2025)



碎裂概率 $\longrightarrow$ 强作用截面

$$\alpha_i = \frac{N_i}{\sum_{j=2}^{10} N_j}$$

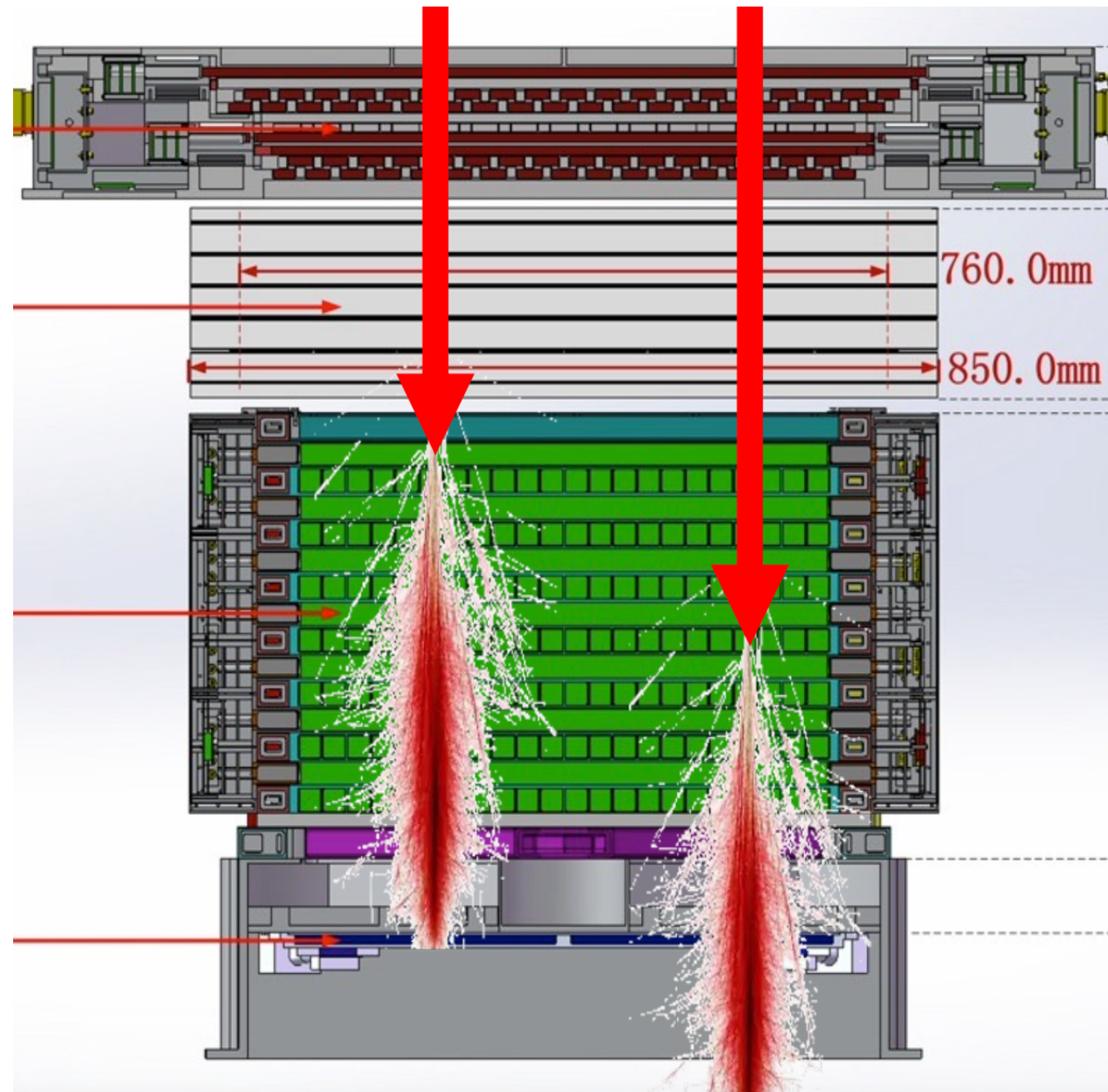
$$\sigma_{true}(E) = (1 + \kappa) \cdot \sigma_{MC}(E)$$

◎ 将质子(p)、氦核(He)与BGO的强作用截面测量扩展至10 TeV

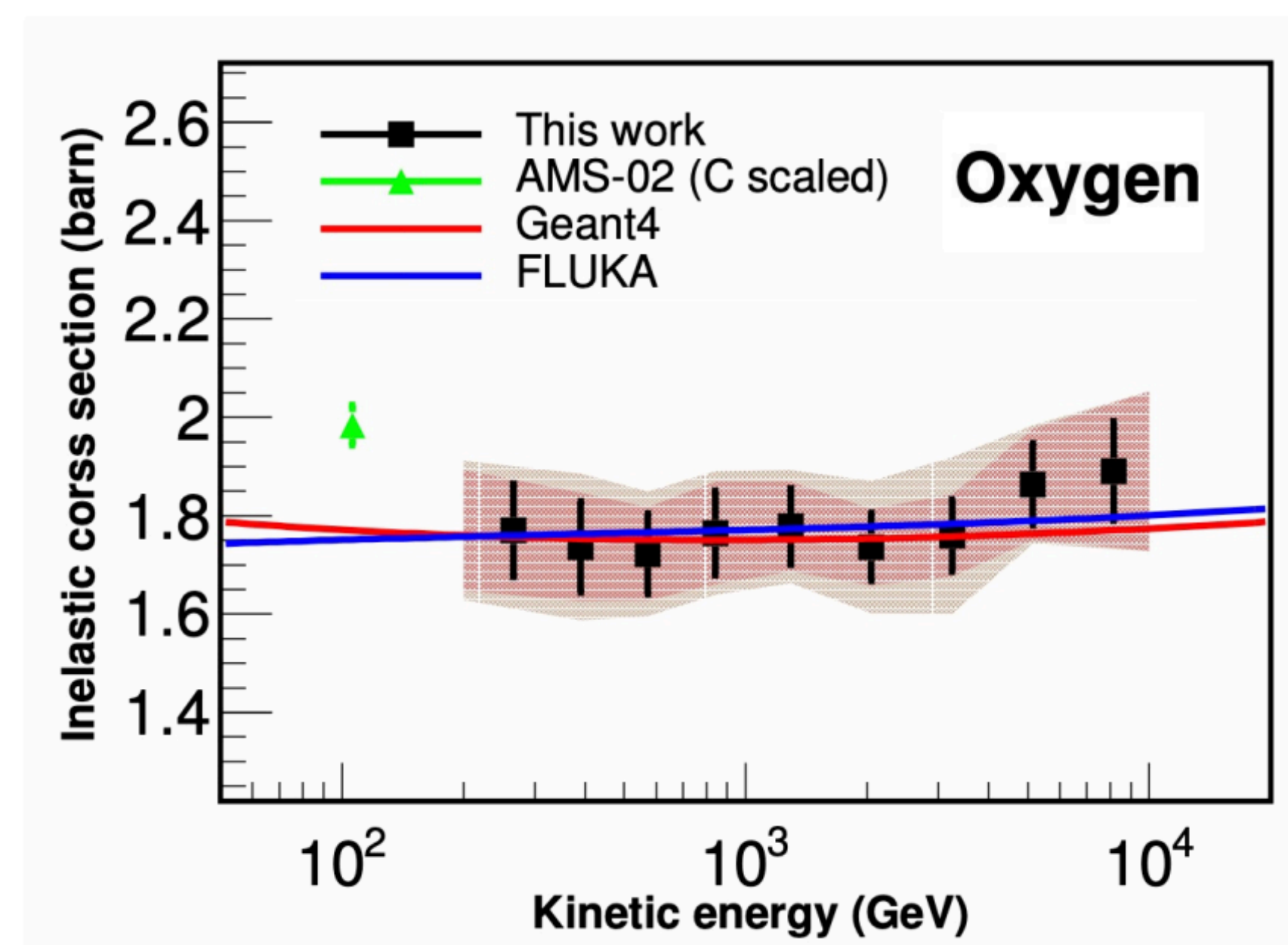
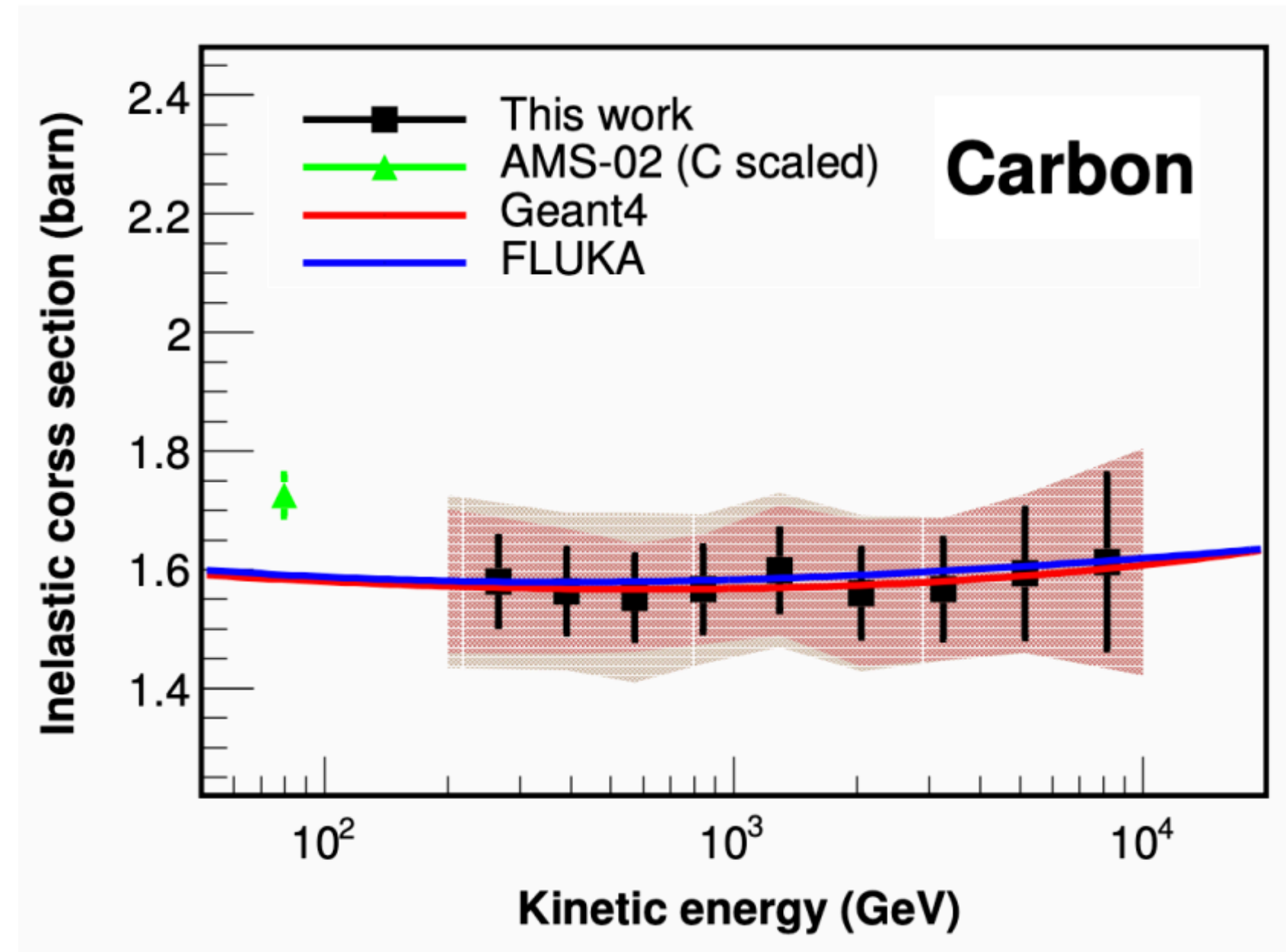
◎ 首次对TeV以上能区氦核的强相互作用截面进行直接测量

强相互作用截面测量

基于DAMPE的 粒子打靶实验(CR-->BGO)



DAMPE collab., *Phy. Rev. D* 112, 022004 (2025)



碎裂概率 $\longrightarrow$ 强作用截面

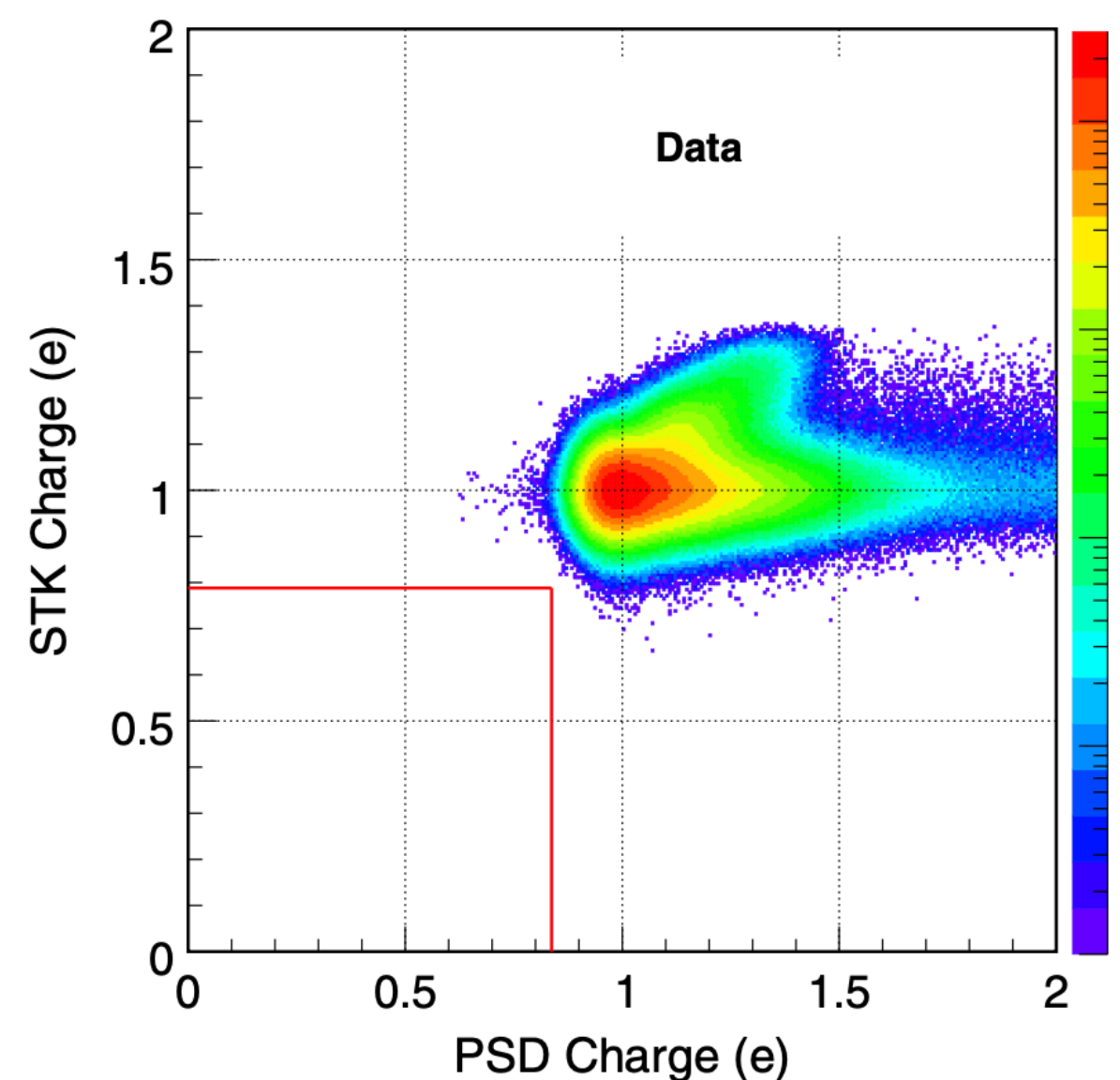
$$\alpha_i = \frac{N_i}{\sum_{j=2}^{10} N_j}$$

$$\sigma_{true}(E) = (1 + \kappa) \cdot \sigma_{MC}(E)$$

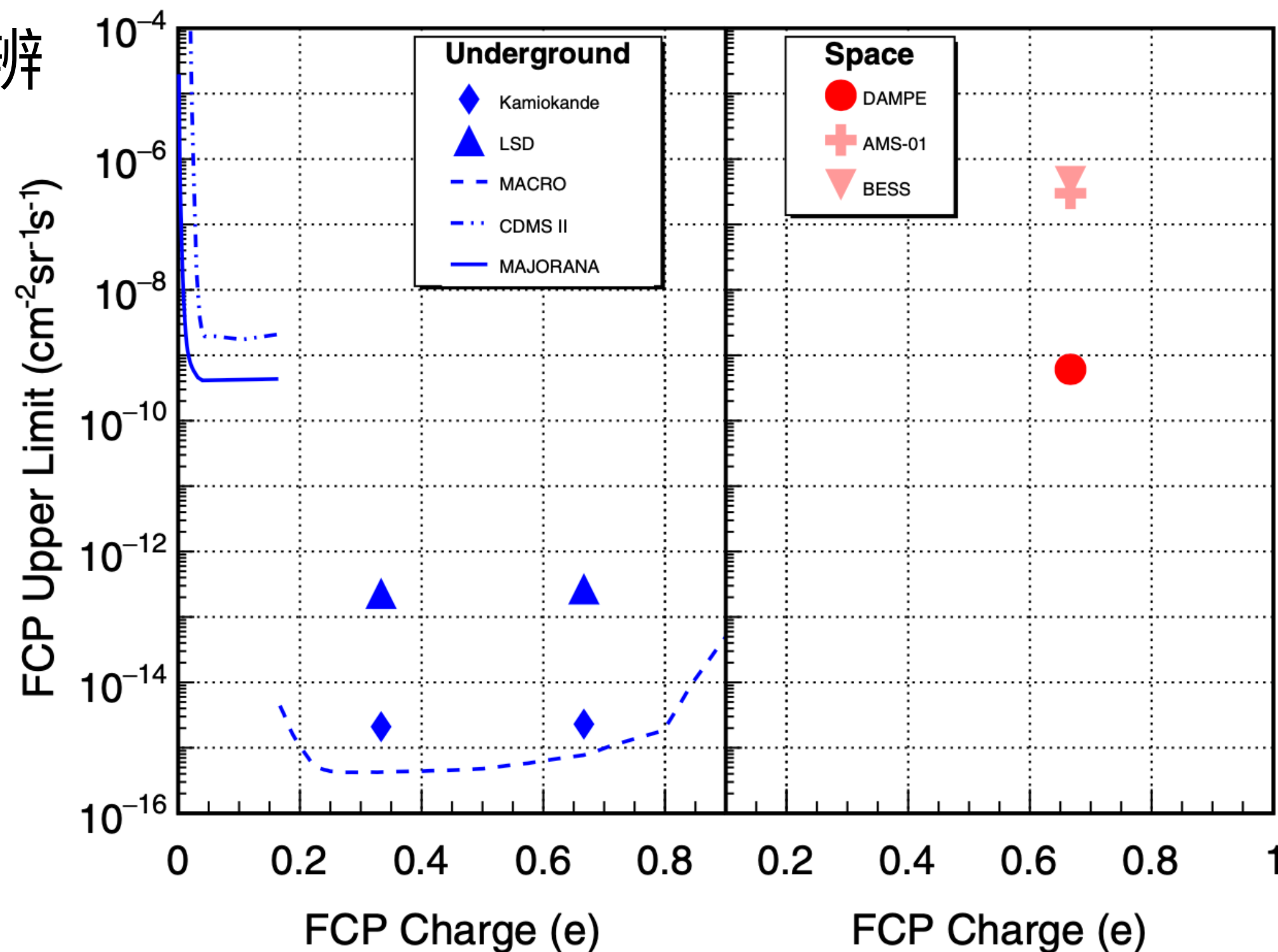
- ◎ 将碳核(C)、氧核(O)与BGO的强作用截面测量扩展至10 TeV
- ◎ 首次对TeV以上能区碳、氧的强相互作用截面进行直接测量

◎ 空间分数电荷(FCP)粒子搜寻

- 超出标准模型的新物理
- DAMPE具备优异电荷分辨

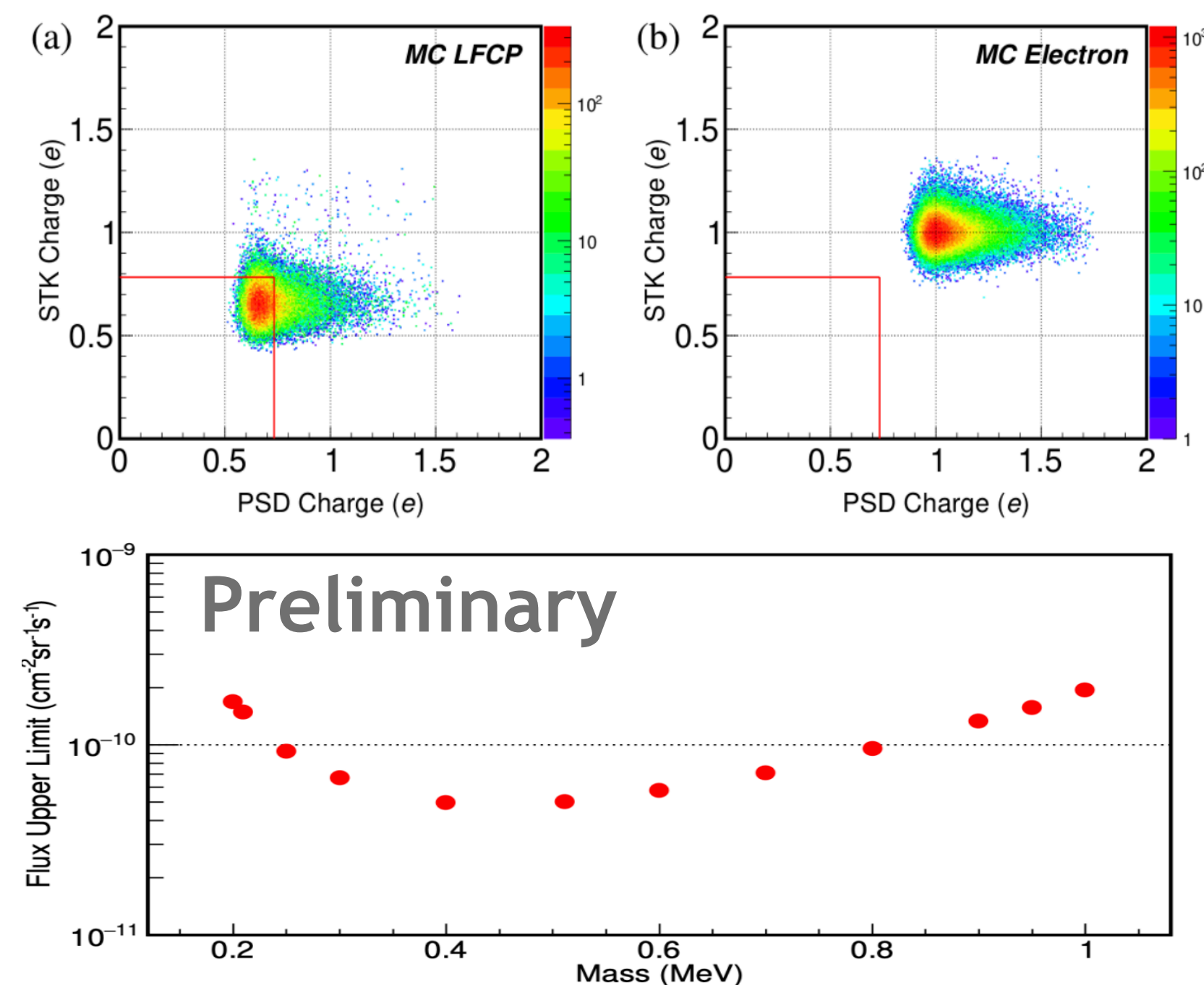


DAMPE collaboration, PRD 106, 063026 (2022)



◎ 轻质量FCP(MeV)搜寻

- 可以产生韧致辐射
- 无法在地面开展探测

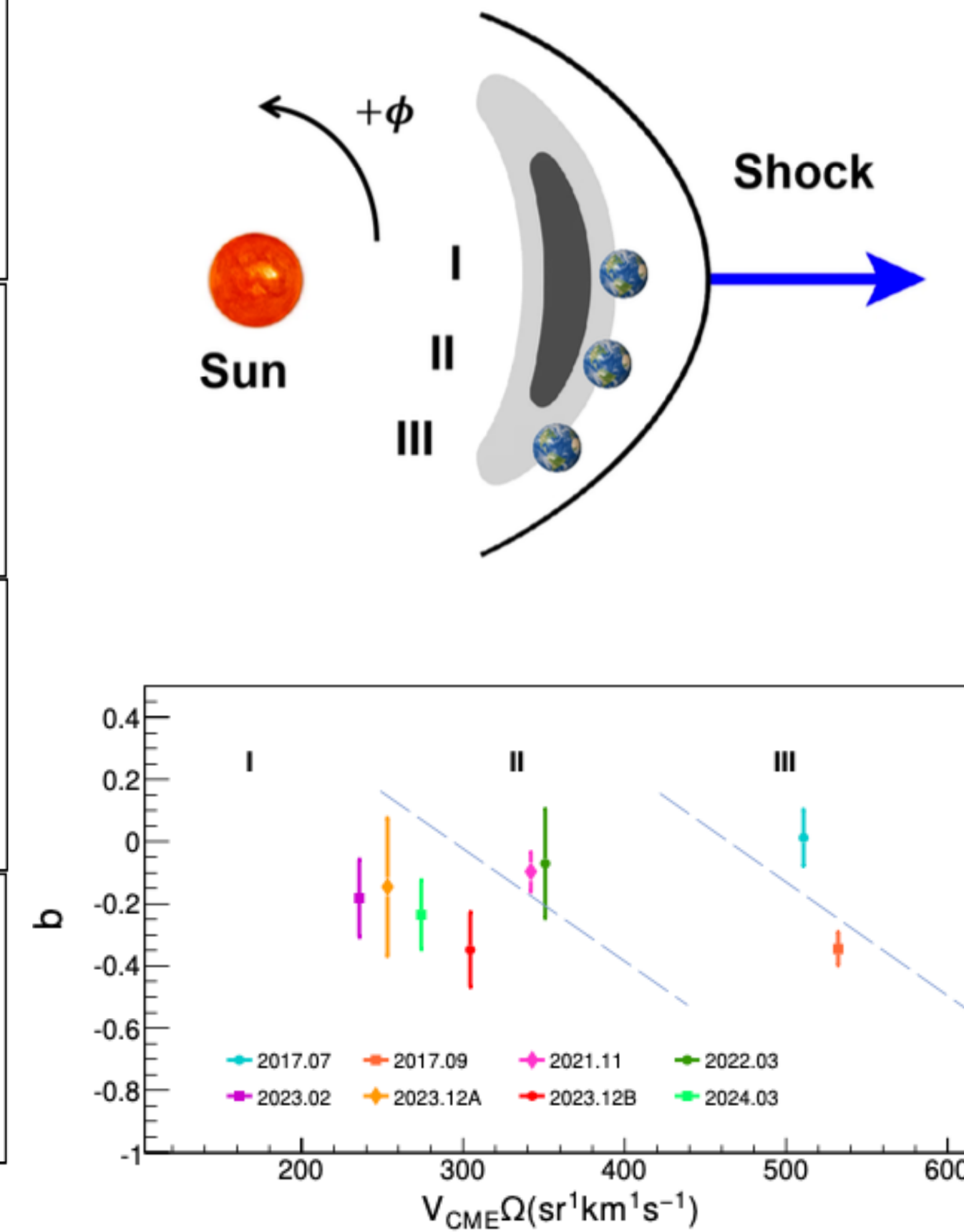
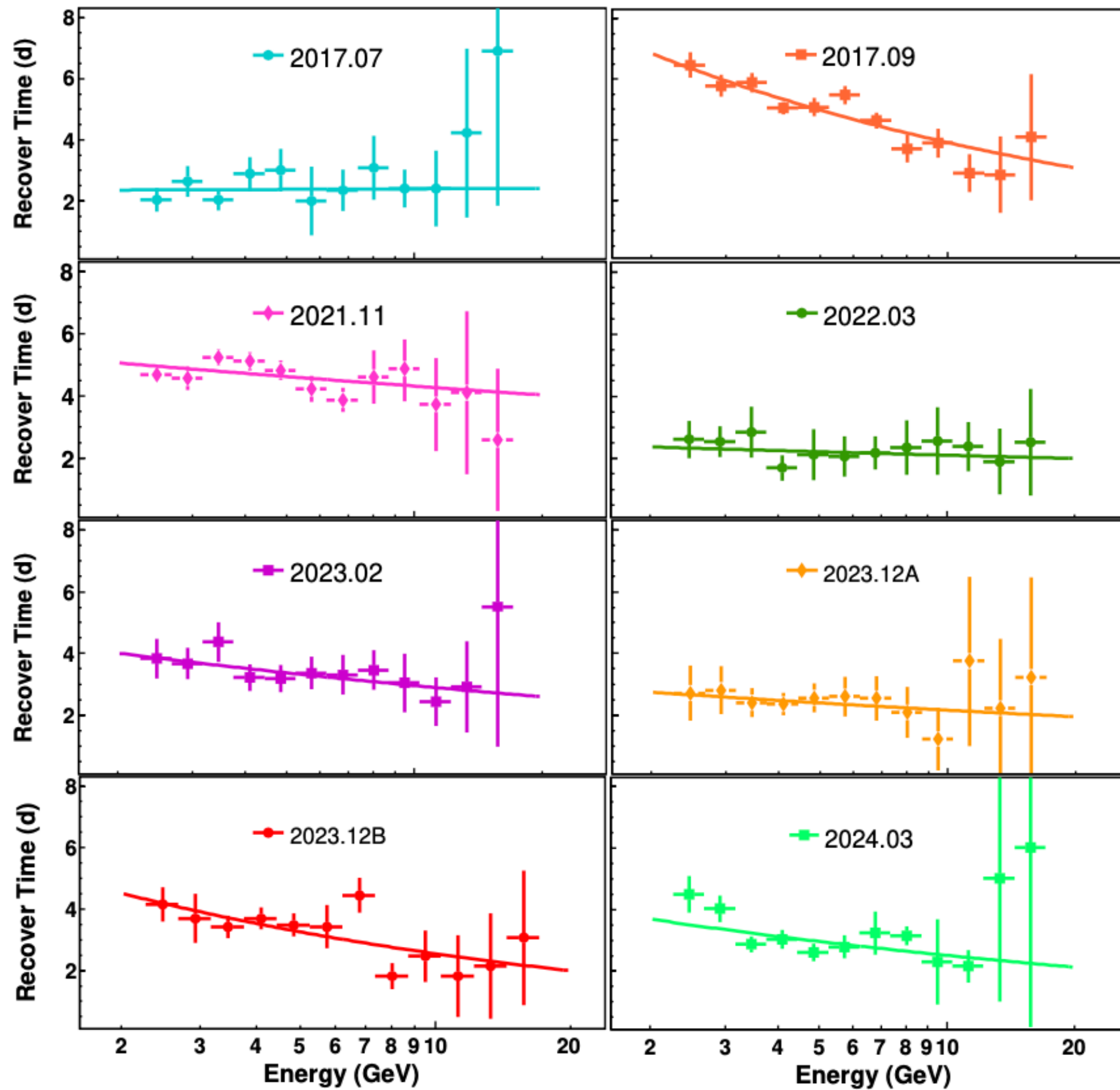
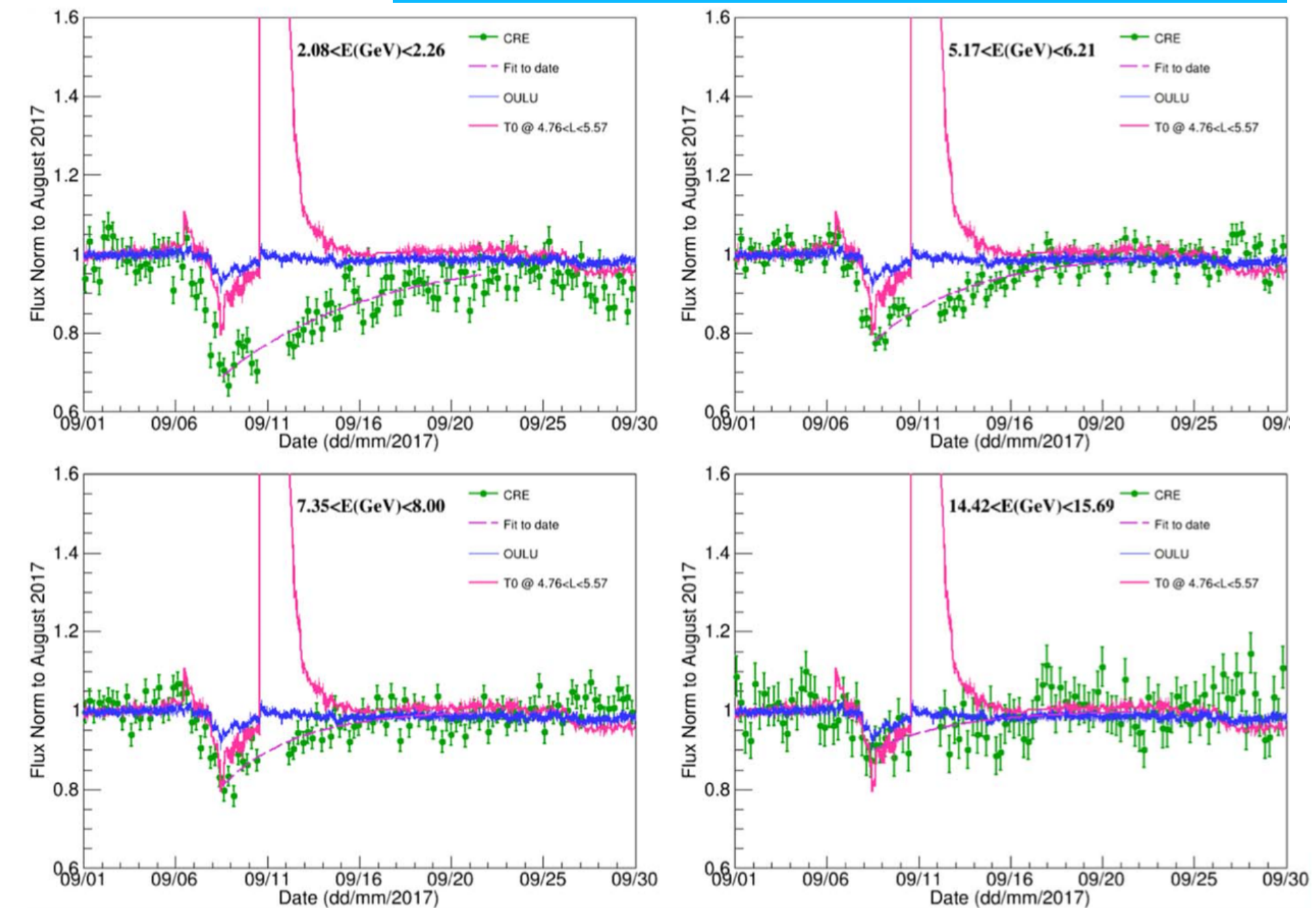


◎ DAMPE获得了空间分数电荷粒子(质量GeV)最严格流量上限探测结果, 轻分数电荷粒子搜寻获得初步结果

note: 地面实验搜寻的质量空间在百GeV

- 福布斯下降(Forbuse Decrease, FD):
伴随太阳爆发活动(如CME)的宇宙线流量快速下降和缓慢恢复过程

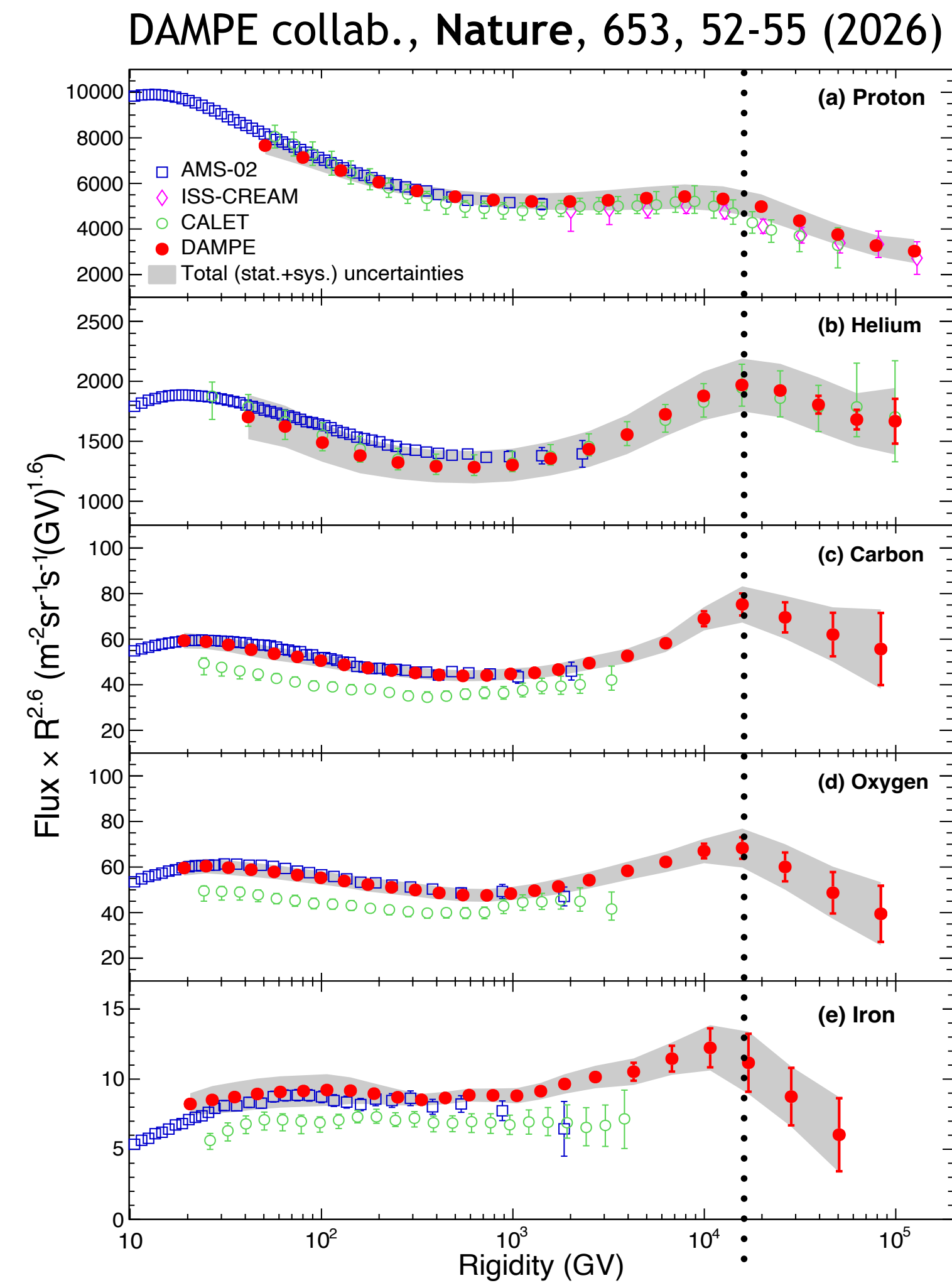
DAMPE collab., *ApJL* 920, L43 (2021)



DAMPE collab., *Phy. Rev. Lett.* 136, 101004 (2026)

- DAMPE对多例CME关联电子FD事件的观测结果表明FD特征多样性与地球相对CME的位型密切相关

- “悟空”号暗物质粒子探测卫星(DAMPE)是我国空间科学系列卫星首发星, 至今已平稳运行超过10年, 目前探测器工作状态正常
- DAMPE有效探测能区领先于同类探测实验, 具备优异的粒子鉴别能力和能量分辨(电子), 为空间高能宇宙线观测打开了新的窗口
- DAMPE将5种原初宇宙线粒子(质子、氦、碳、氧和铁)的能谱直接测量至PeV能区, 揭示出5种粒子能谱存在统一的鼓包状“超出”结构, 高能拐折能量正比于 Z , 对应磁刚度为15TV, 在观测上证实了宇宙线加速的电荷依赖特性
- DAMPE发现次级宇宙线硼核在百GeV/n处的能谱变硬结构, 且变硬程度约为原初粒子质子、氦核的两倍, 表明能谱变硬与宇宙线传播效应相关
- DAMPE将继续开展宇宙线成分能谱测量分析, 尤其是在TeV-PeV能区发挥重要作用, 帮助解答宇宙线起源、加速和传播问题



感谢聆听!