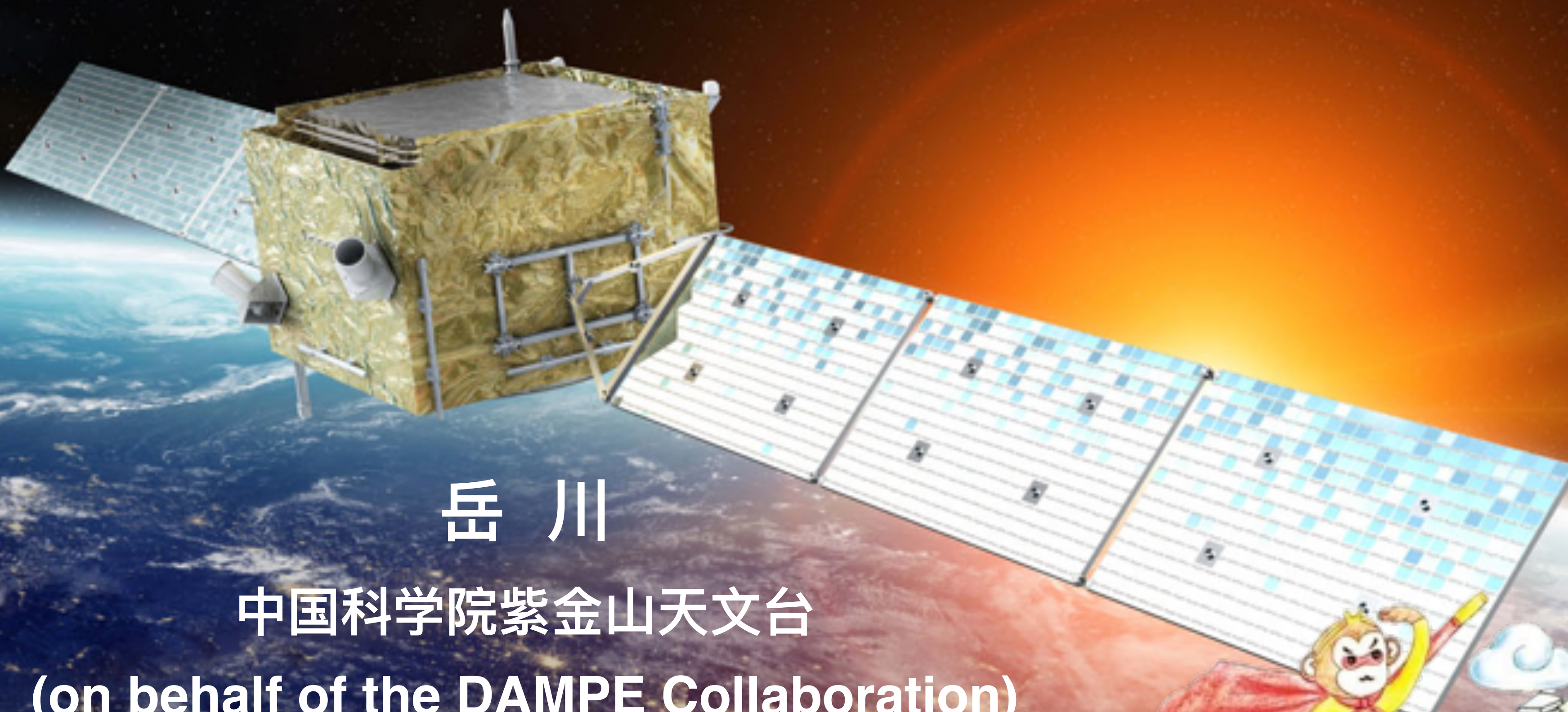
Recent progresses of the Dark Matter Particle Explorer (“WuKong”)



岳 川

中国科学院紫金山天文台

(on behalf of the DAMPE Collaboration)

第三届粒子物理前沿研讨会

2022/07/23

The DAMPE collaboration

- 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

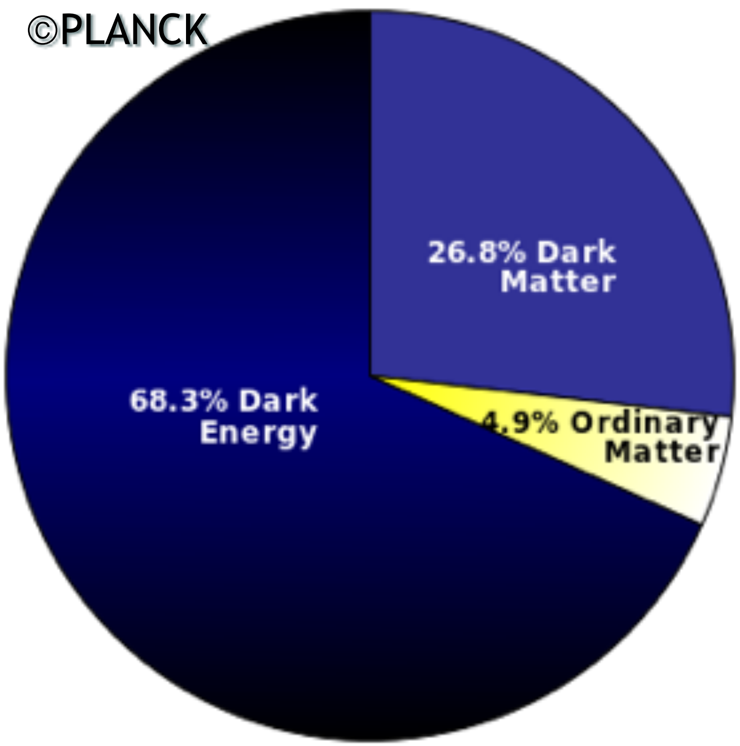
- ITALY
  - INFN Perugia and University of Perugia
  - INFN Bari and University of Bari
  - INFN Lecce and University of Salento
  - INFN LNGS and Gran Sasso Science Institute

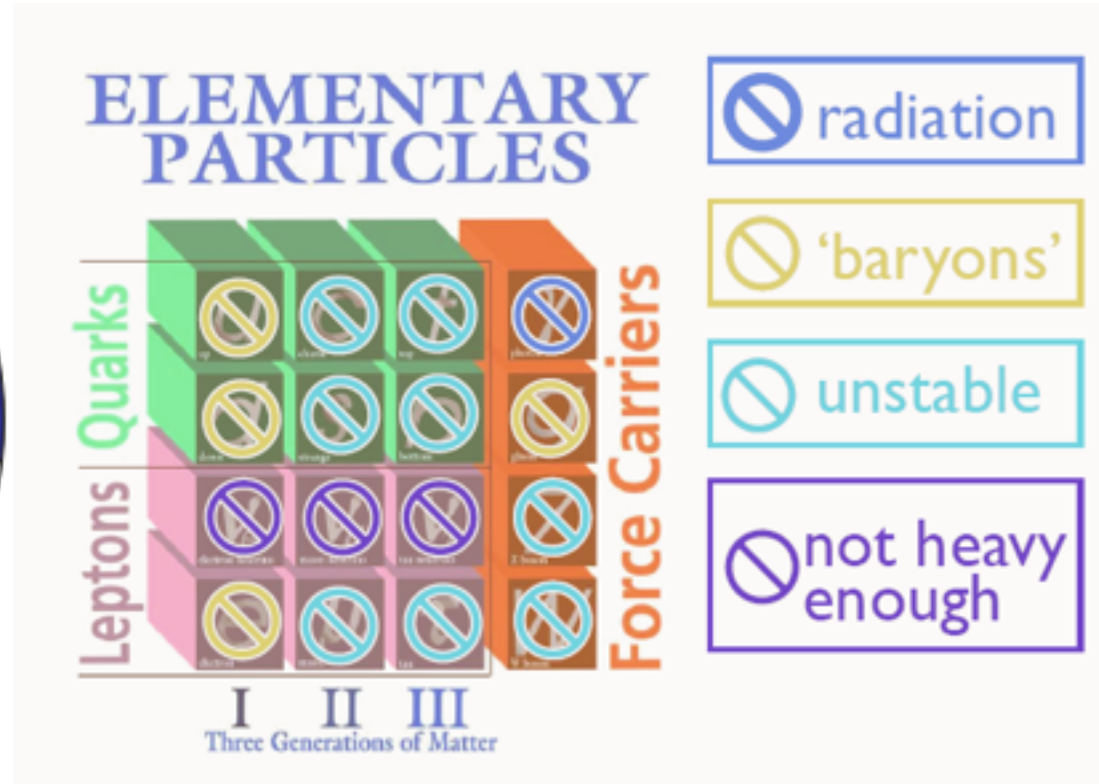
- SWITZERLAND
  - University of Geneva

Outline

- Scientific background
- DAMPE mission
- On-orbit performance
- Physical Results
- Summary

Dark matter problem



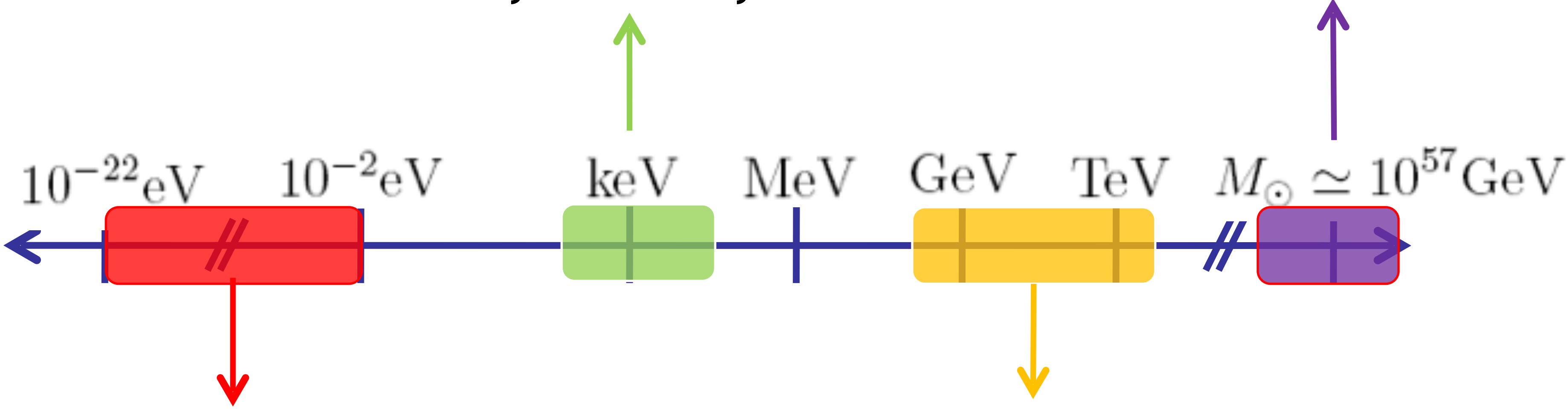


Large amount of the Universe is "dark". The nature of dark matter and dark energy challenges severely the modern physics.

Dark matter candidates

Sterile neutrinos:
neutrino oscillation,
X-ray astronomy

MACHOs: lensing,
gravitational waves

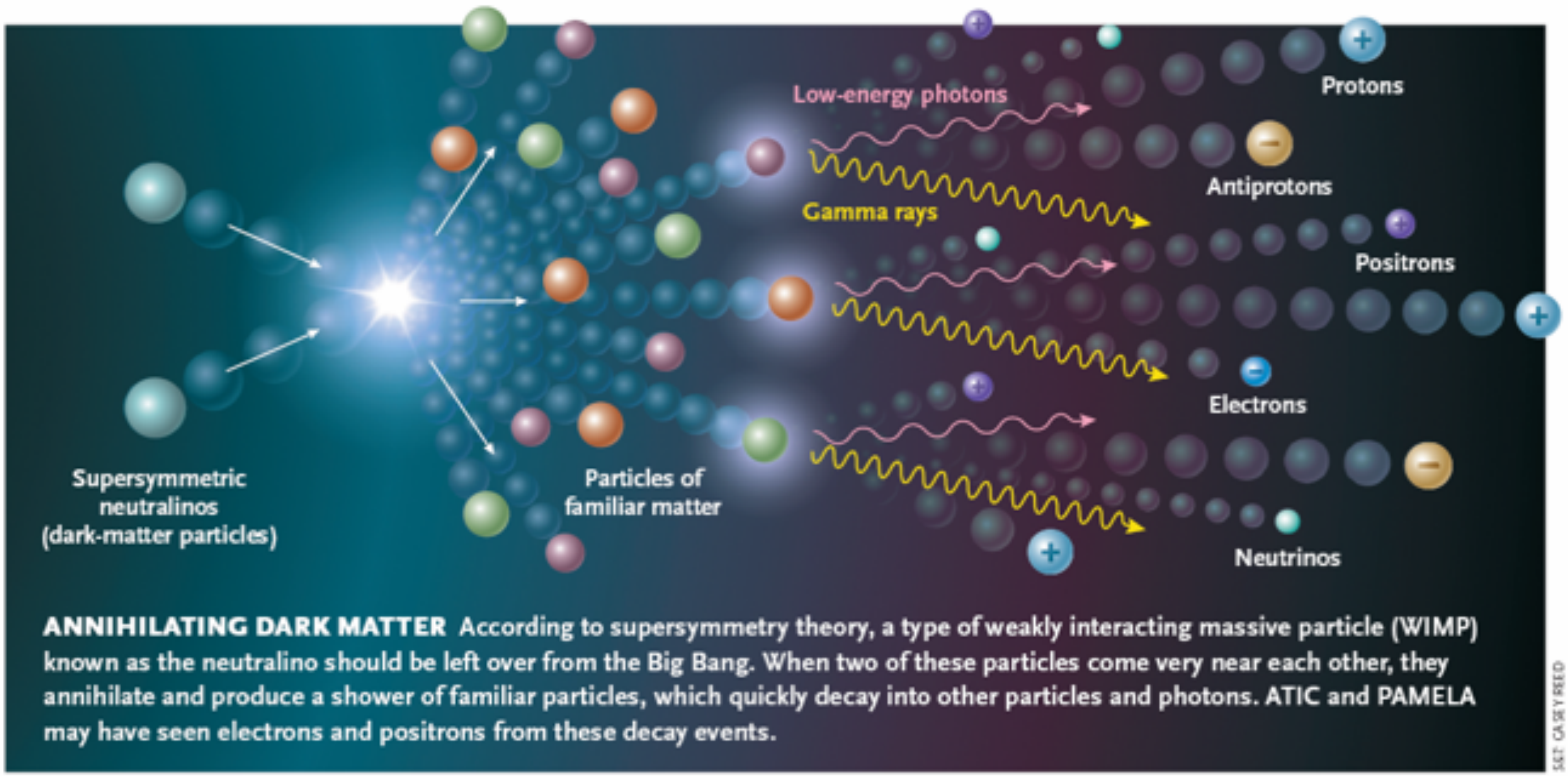


Ultralight DM (axion-like
particle, dark
photon, ...):
cavity experiments, radio
astronomy

WIMPs: direct detection,
indirect detection,
collider detection

Many dark matter candidates span nearly 100 orders of magnitude in mass (and interaction strength)

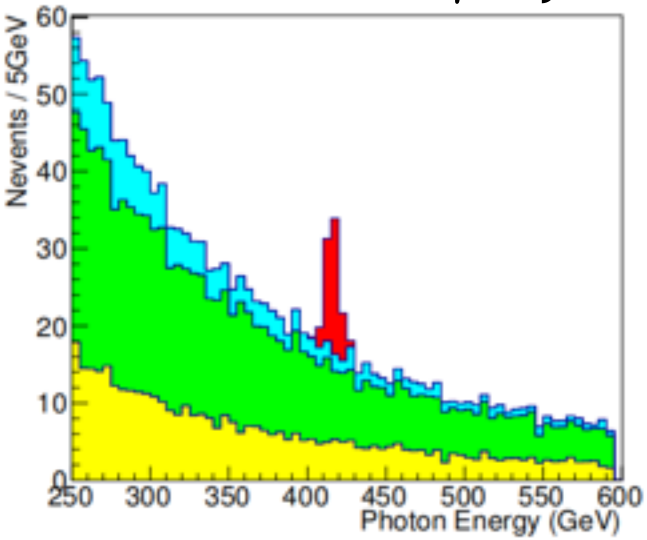
Dark matter detection



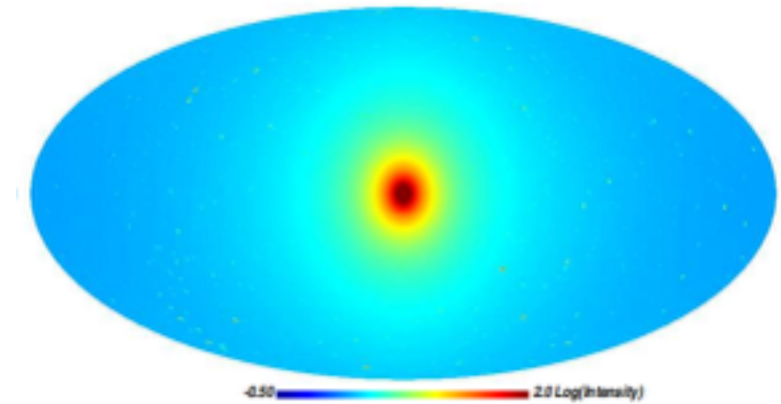
- Among many candidates of dark matter, the weakly interacting massive particles (WIMP) are still one of the most promising candidates
- The indirect detection of its annihilation or decay products in cosmic rays and gamma rays is one of the leading ways

Characteristic signals

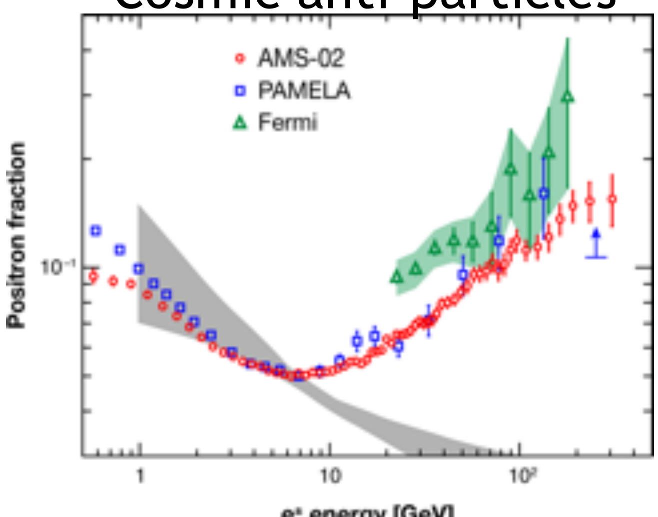
Monochromatic γ-ray



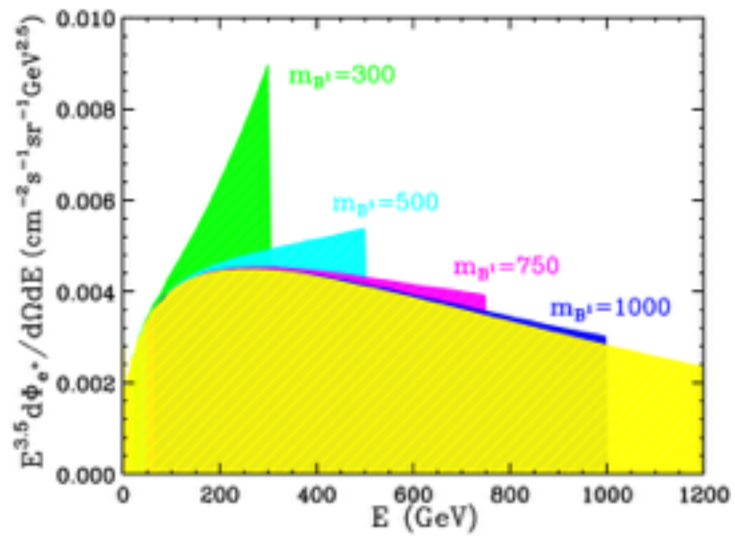
Spherical γ-ray morphology



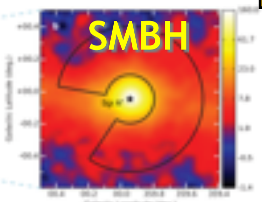
Cosmic anti-particles

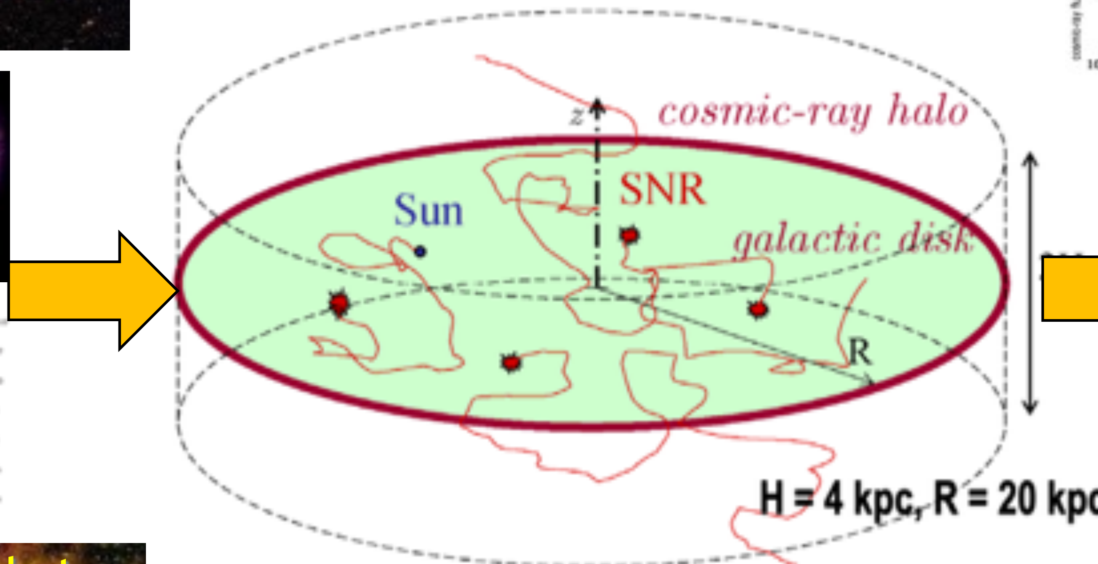


Special features of e+e- spectrum

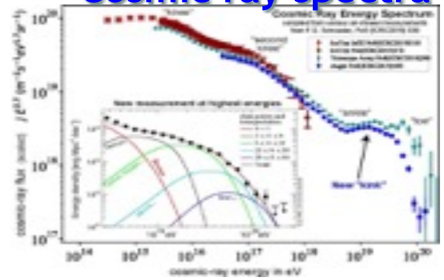


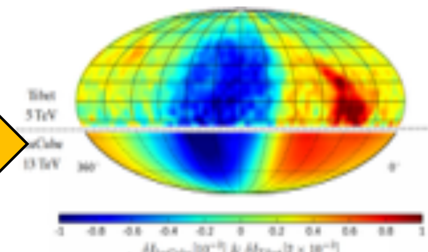
Cosmic ray physics



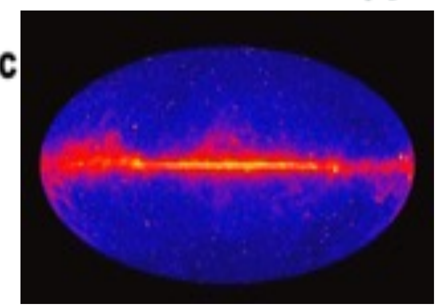


Cosmic ray spectra





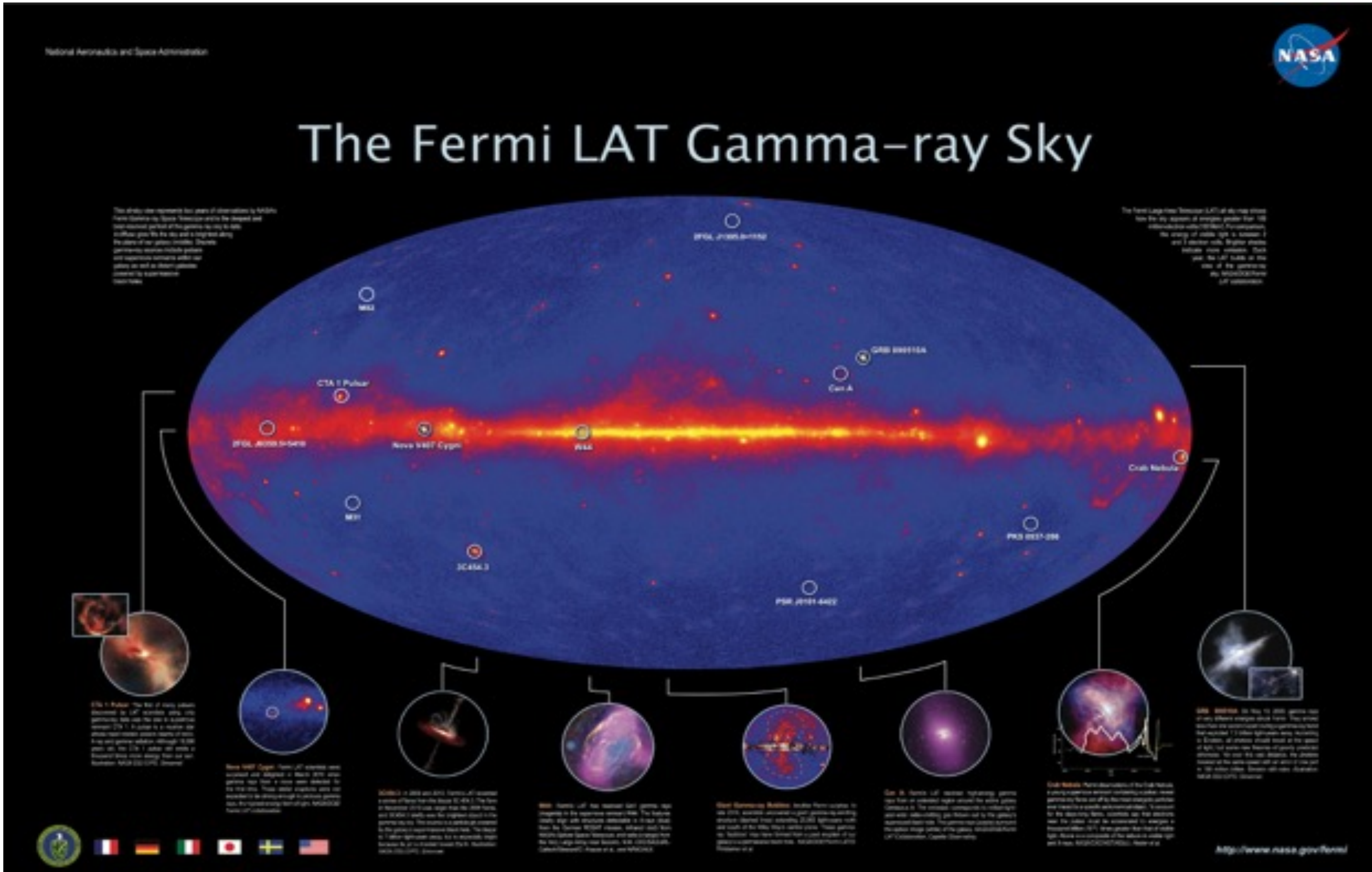
Anisotropy



Gamma-ray emission

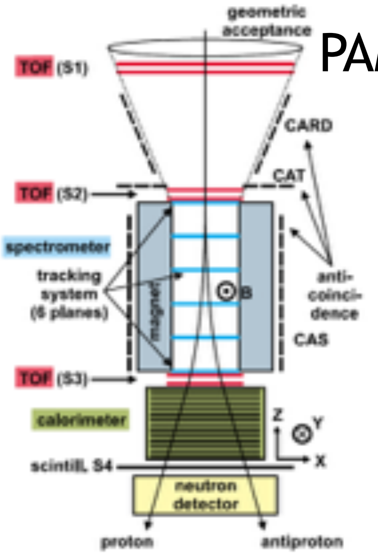
Acceleration Propagation Detection

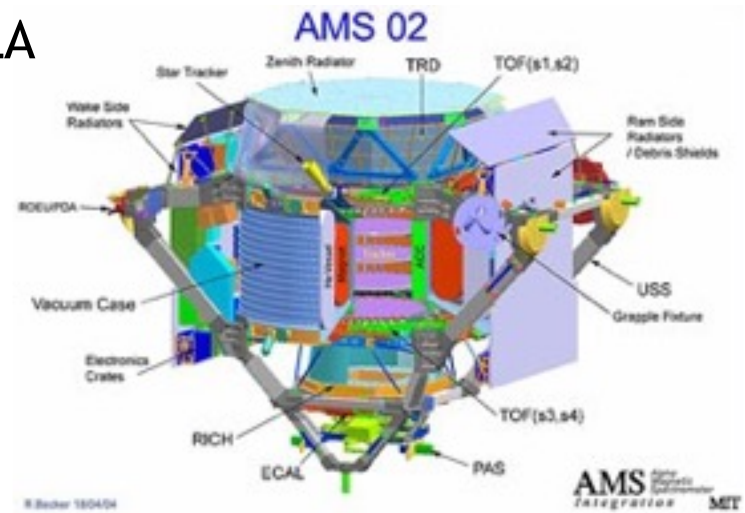
Gamma-ray astronomy



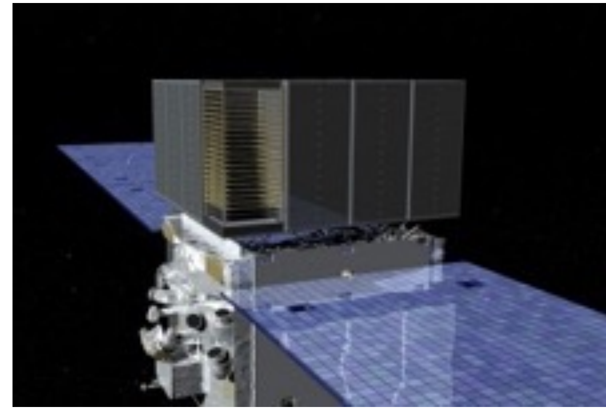
Recent space particle/γ detectors

PAMELA



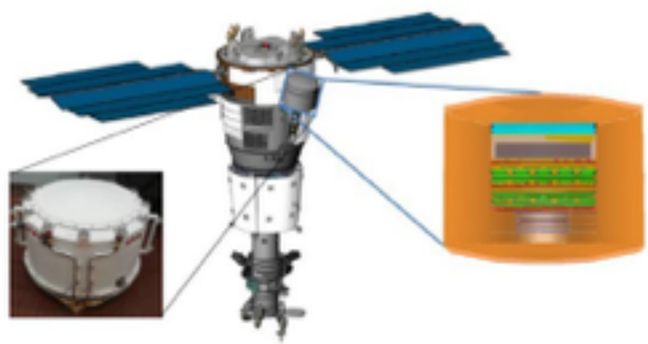


Fermi

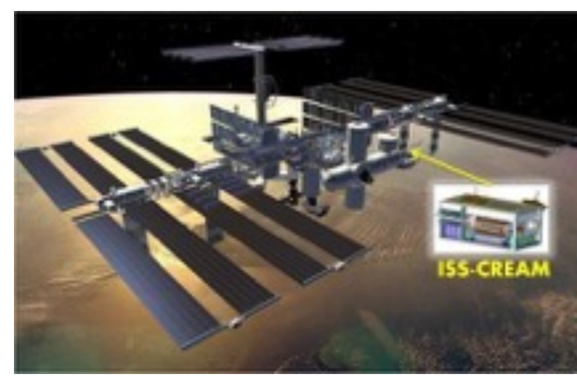


CALET

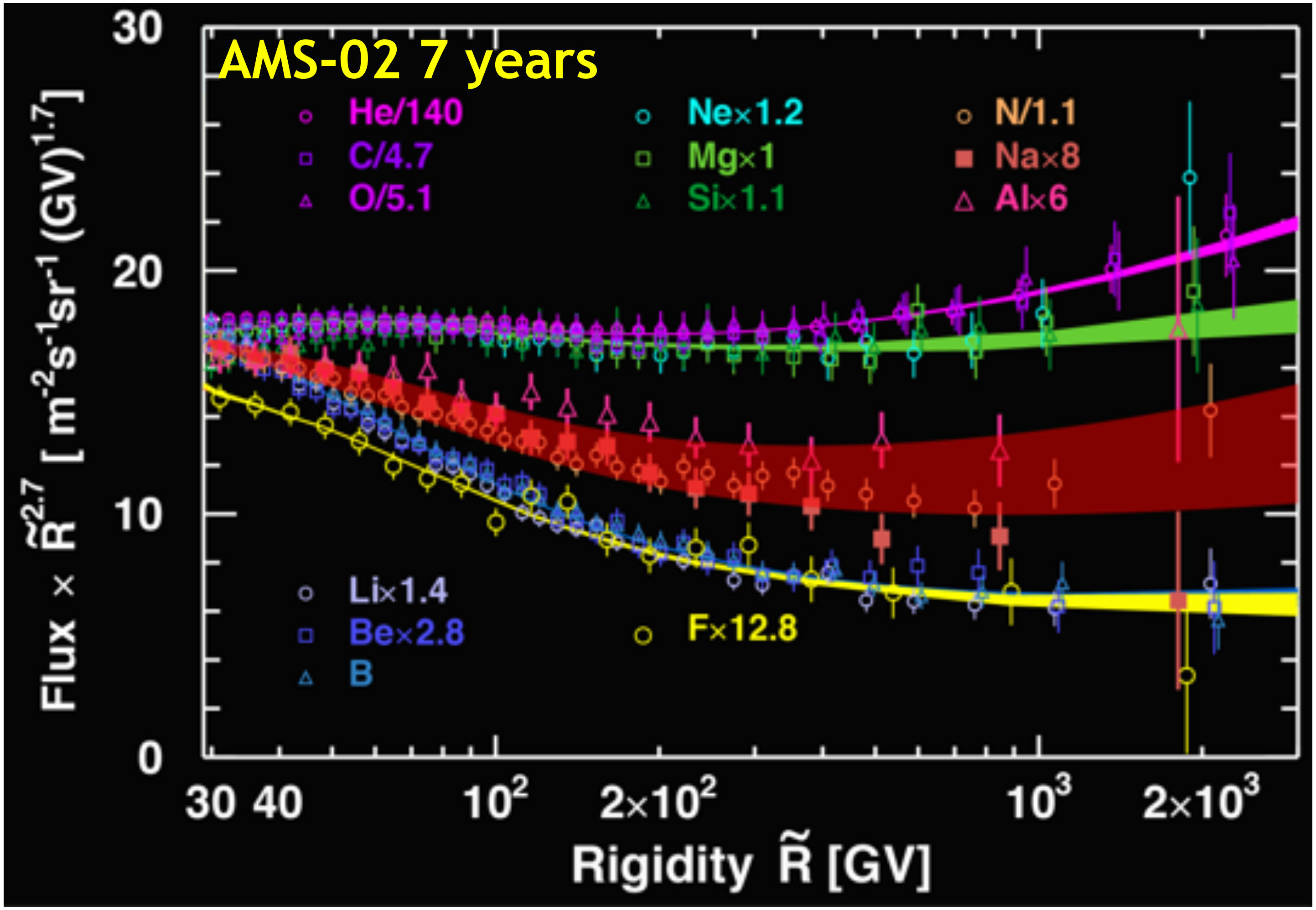
NUCLEON



ISS-CREAM



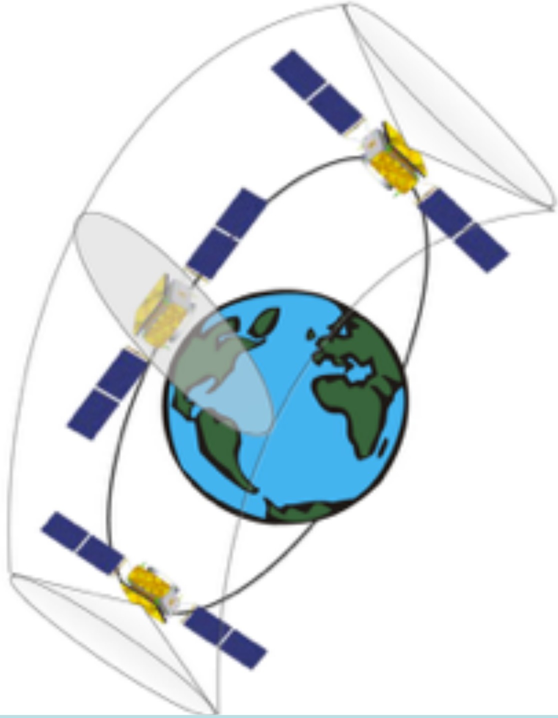
CR direct measurements



Maximum rigidity of AMS-02: ~ few TV

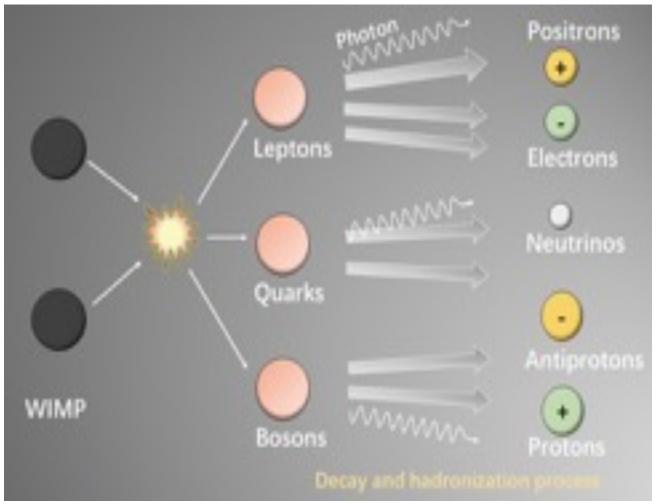
DAMPE mission

DAMPE (“Wukong”) lanuched on Dec. 17, 2015



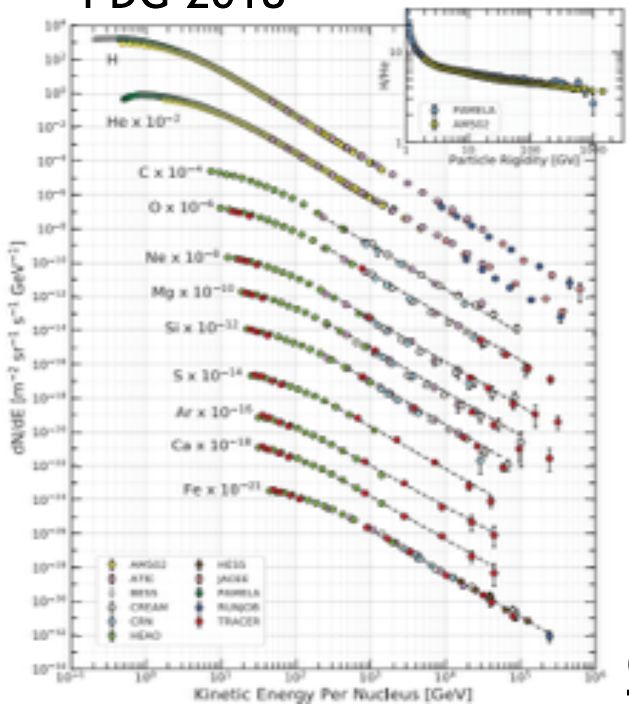
- Altitude: 500 km
- Inclination: 97.4°
- Period: 95 minutes
- Orbit: Sun-synchronous

Scientific objectives

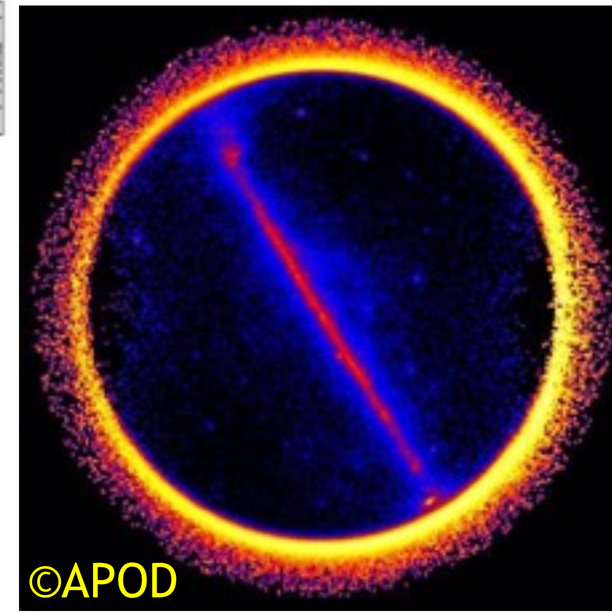


<u>Indirect detection of dark matter</u> (high-precision measurements of e+e- and γ)

PDG 2018



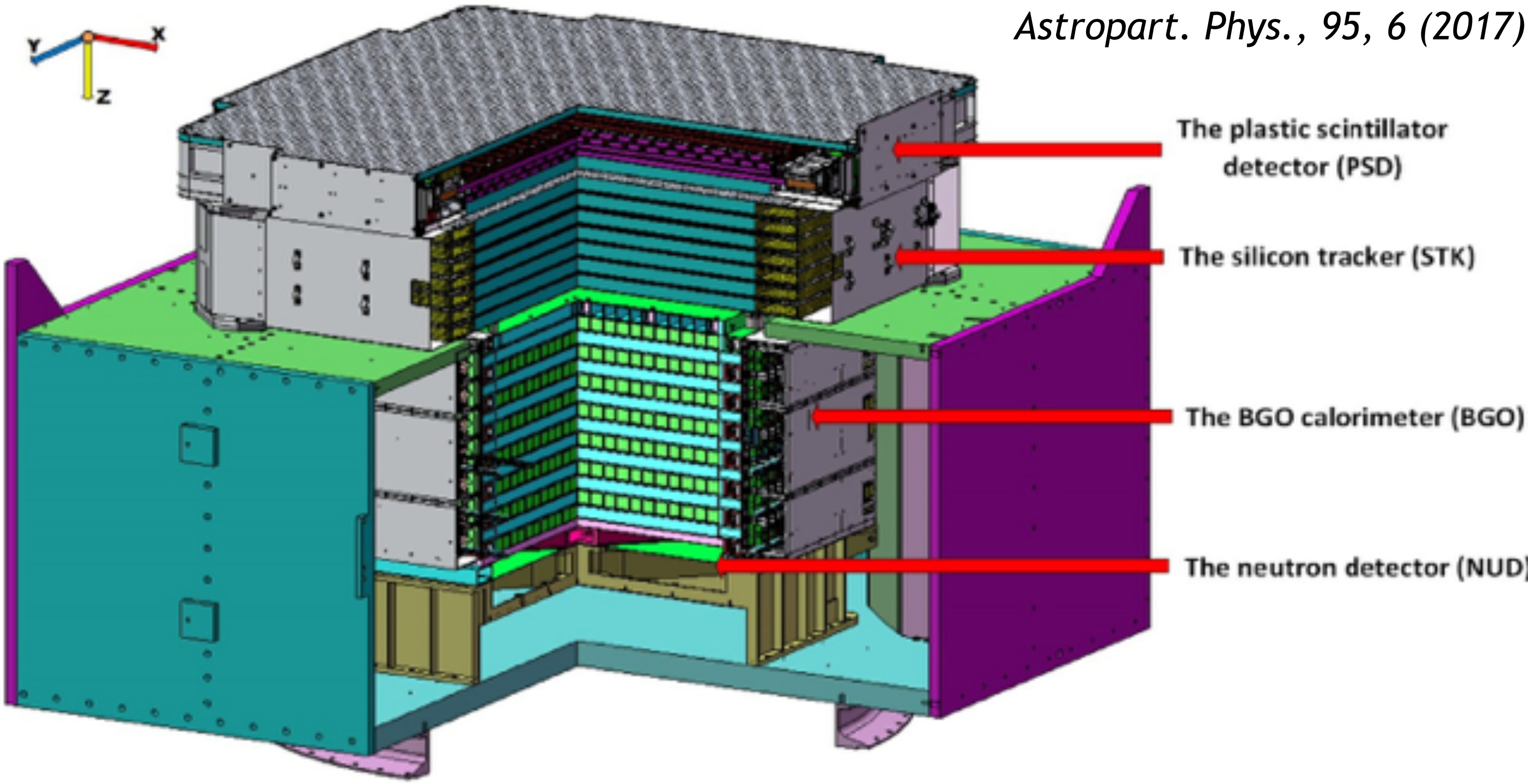
<u>Cosmic ray physics</u> (measurements of nuclei spectra up to 100 TeV)



<u>Gamma-ray astronomy</u> (measurements of spectra, morphologies, and variations of γ-ray sources)

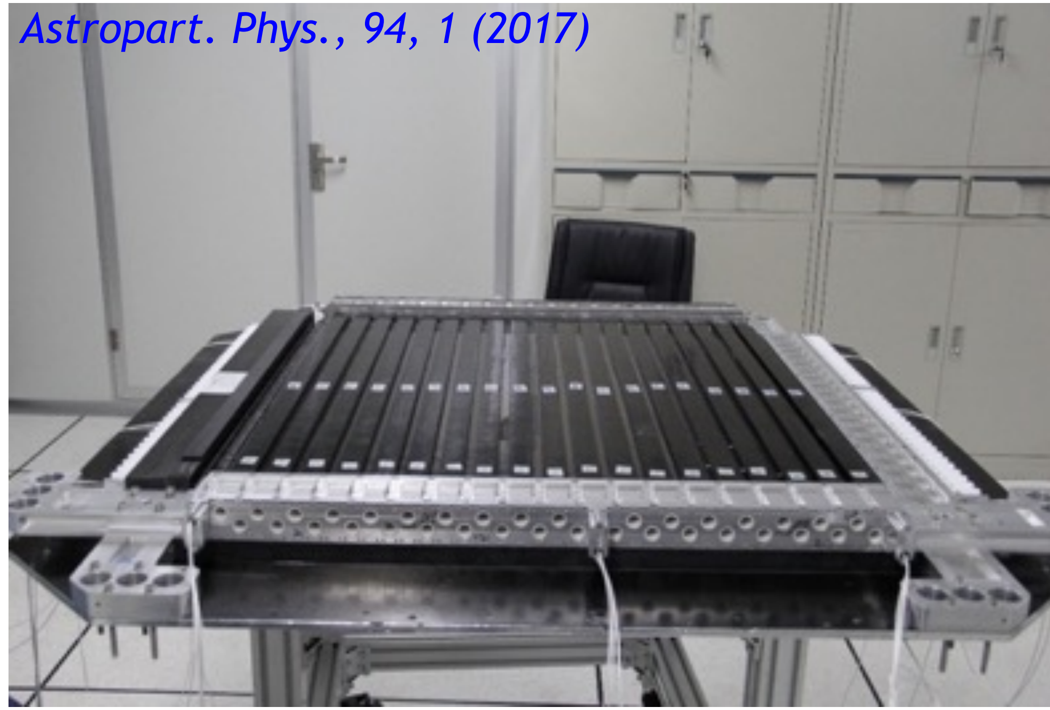
DAMPE instrument

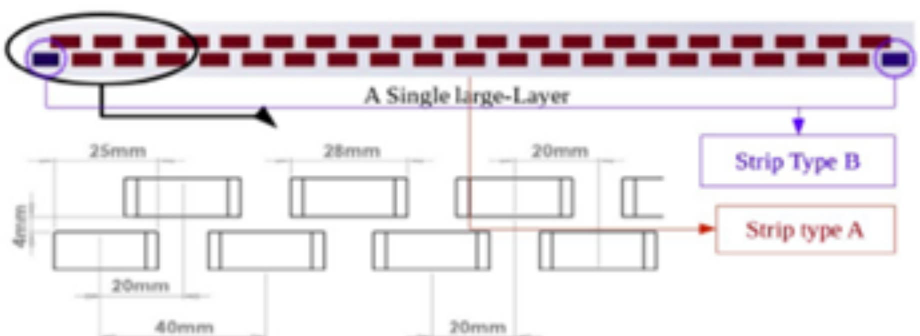
Astropart. Phys., 95, 6 (2017)



- 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

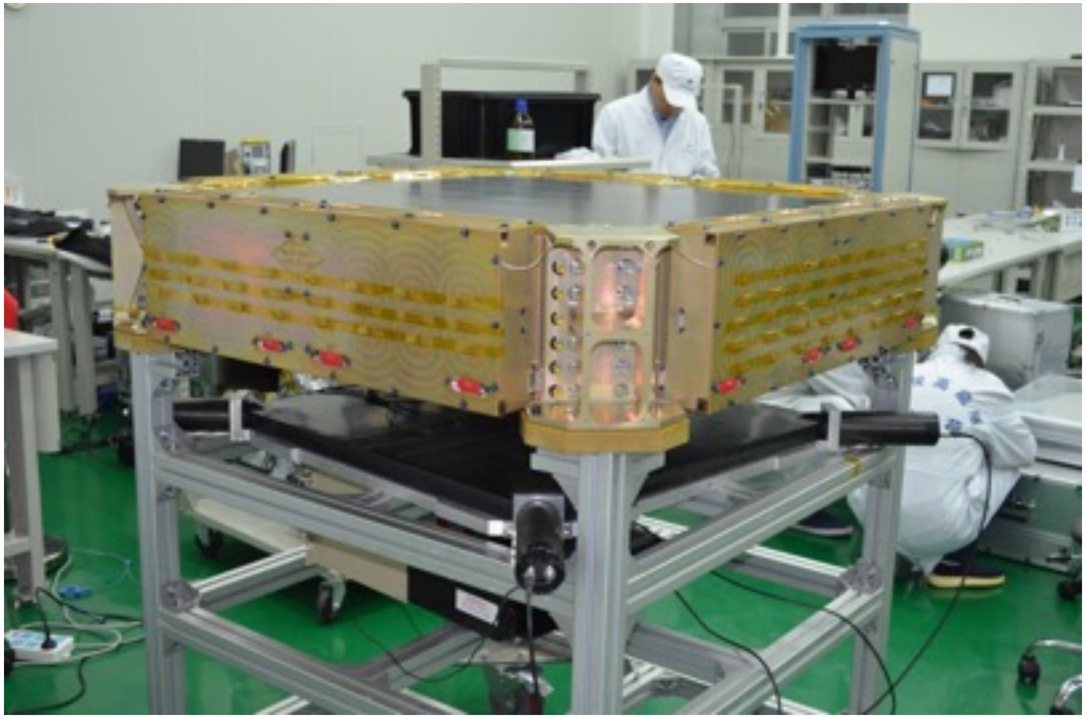
PSD charge detector





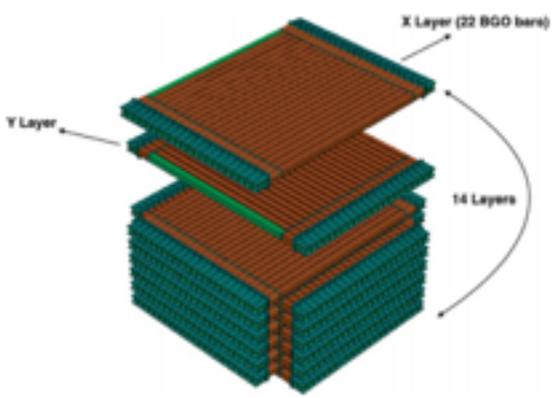
- 2 layers (x,y) of 88.4 cm × 2.8 cm × 1 cm
- Active area: 82 cm × 82 cm
- Weight : ~103 kg
- Power: ~ 8.5 W

Silicon tracker (STK)



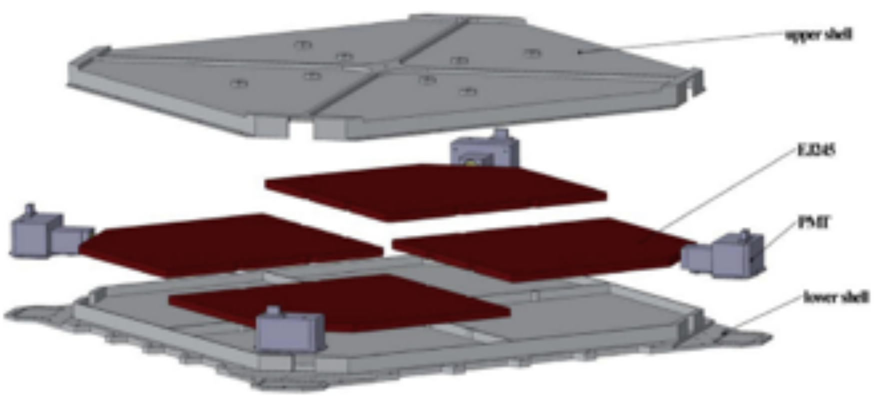
- Detection area: 76 cm × 76 cm
- Weight : ~154 kg
- Power: ~ 82 W
- Three 1 mm tungsten plates for enhanced photon conversion (0.86 X_0)

BGO calorimeter



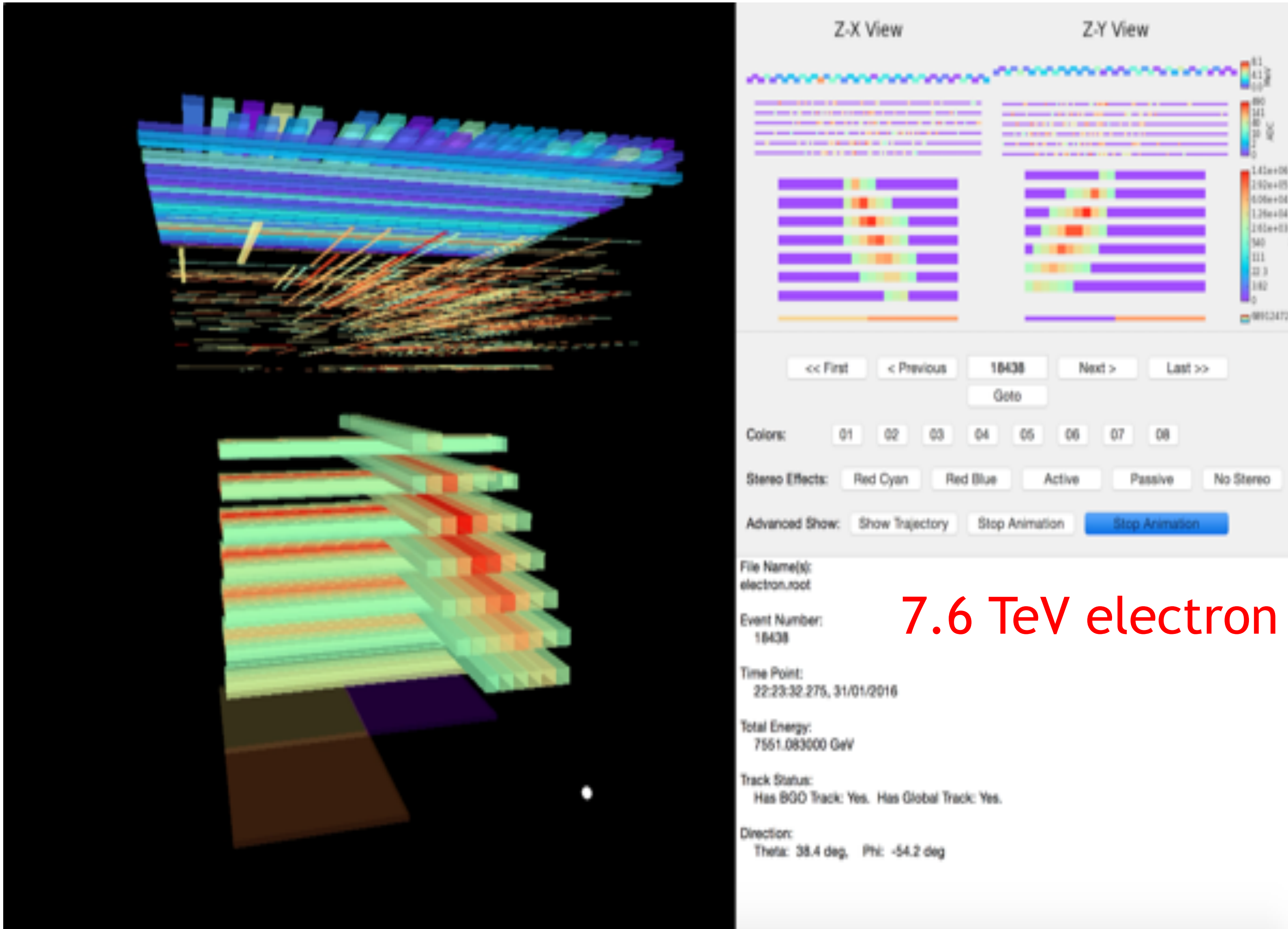
- ➢ Outer envelop: 100 cm x 100 cm x 50 cm
- ➢ Detection area: 60 cm x 60 cm
- ➢ Total weight: ~1052 kg
- ➢ Total power consumption: ~ 41.6 W

NUD neutron detector



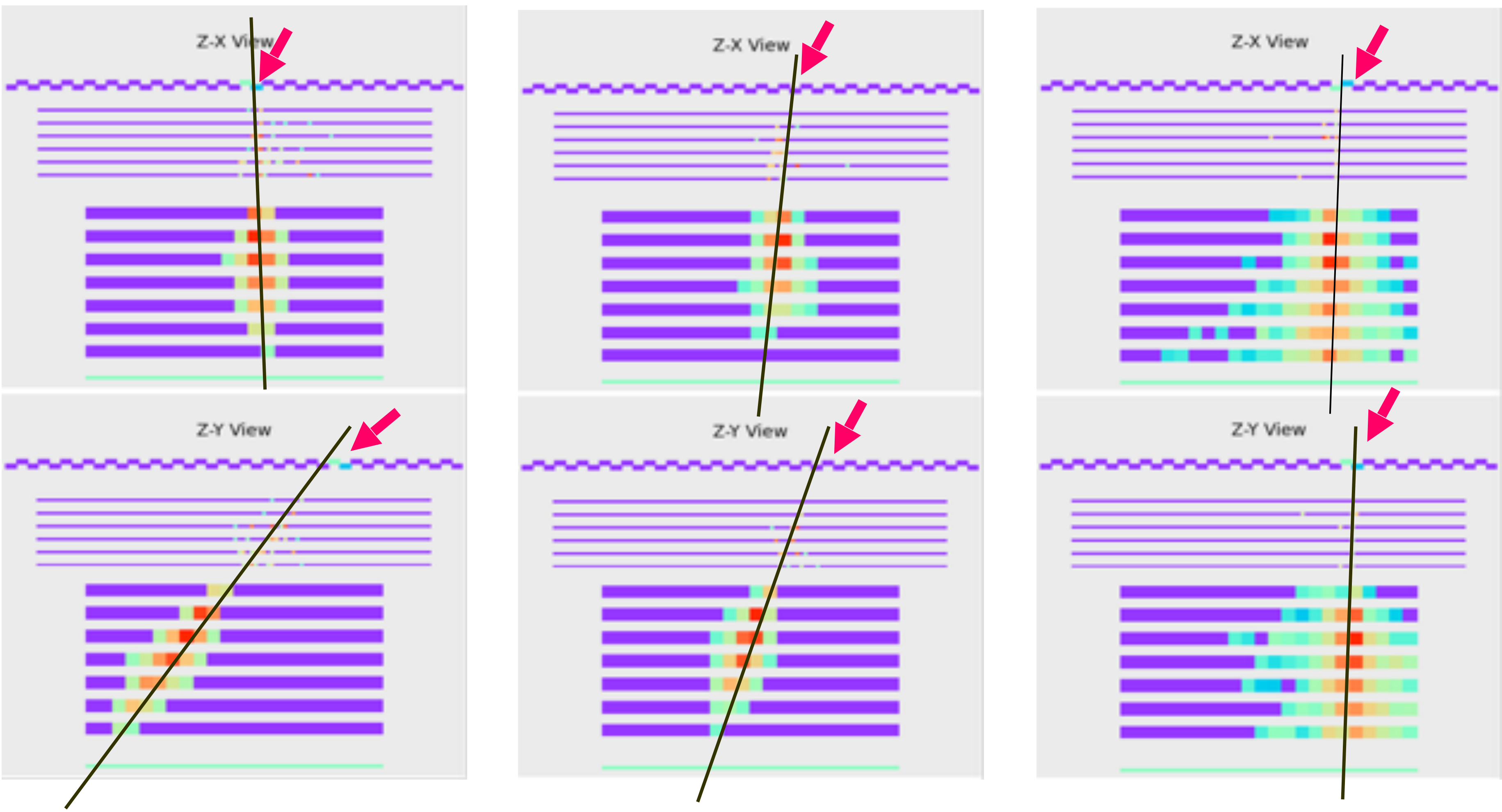
- $n + {}^{10}B \rightarrow \alpha + {}^{7}Li + \gamma$
- 4 plastic scintillators
- Active area: 60 cm x 60 cm
- Total weight: ~12 kg
- Total power: ~ 0.5 W

A typical event



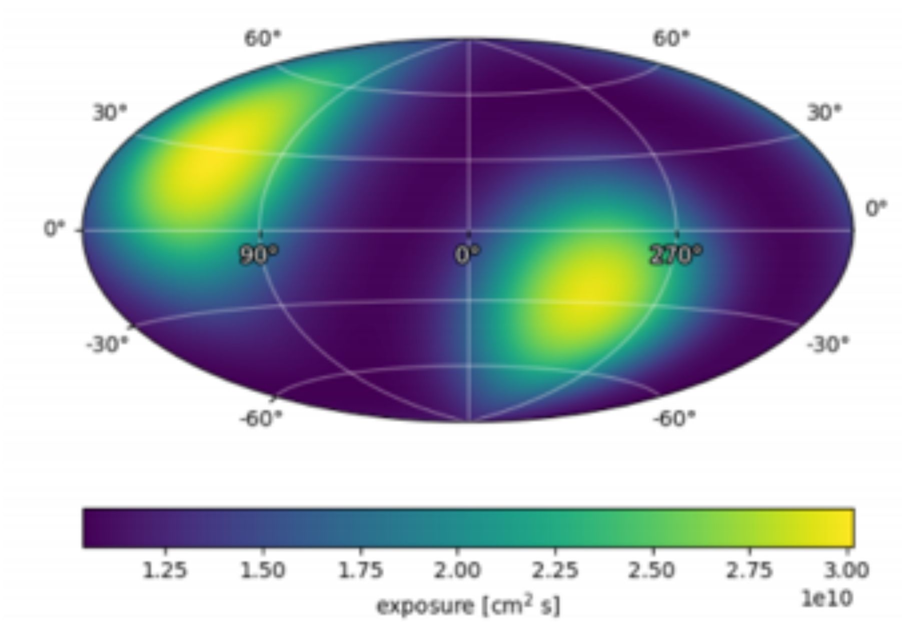
Particle identification

electron gamma proton

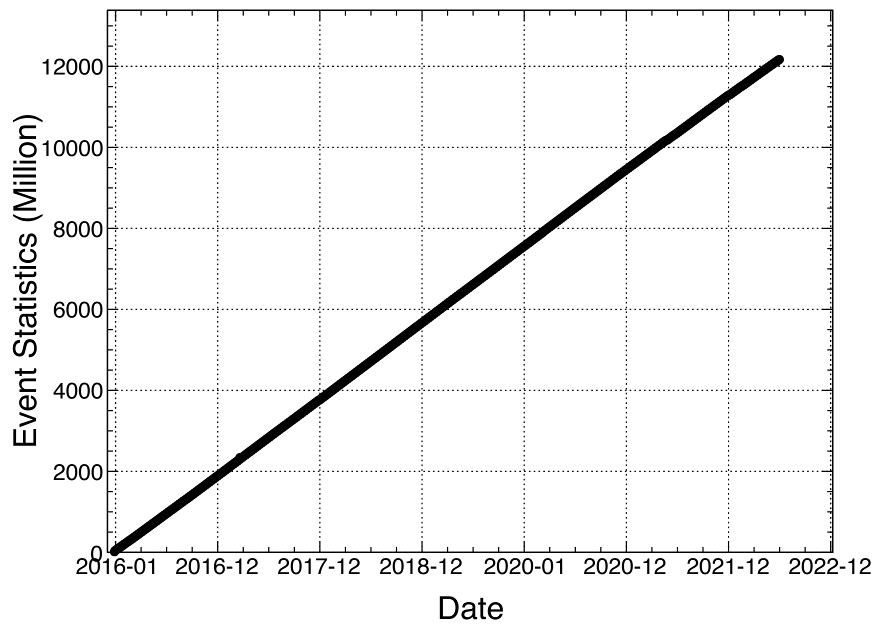


Performance

DAMPE 6 year exposure map

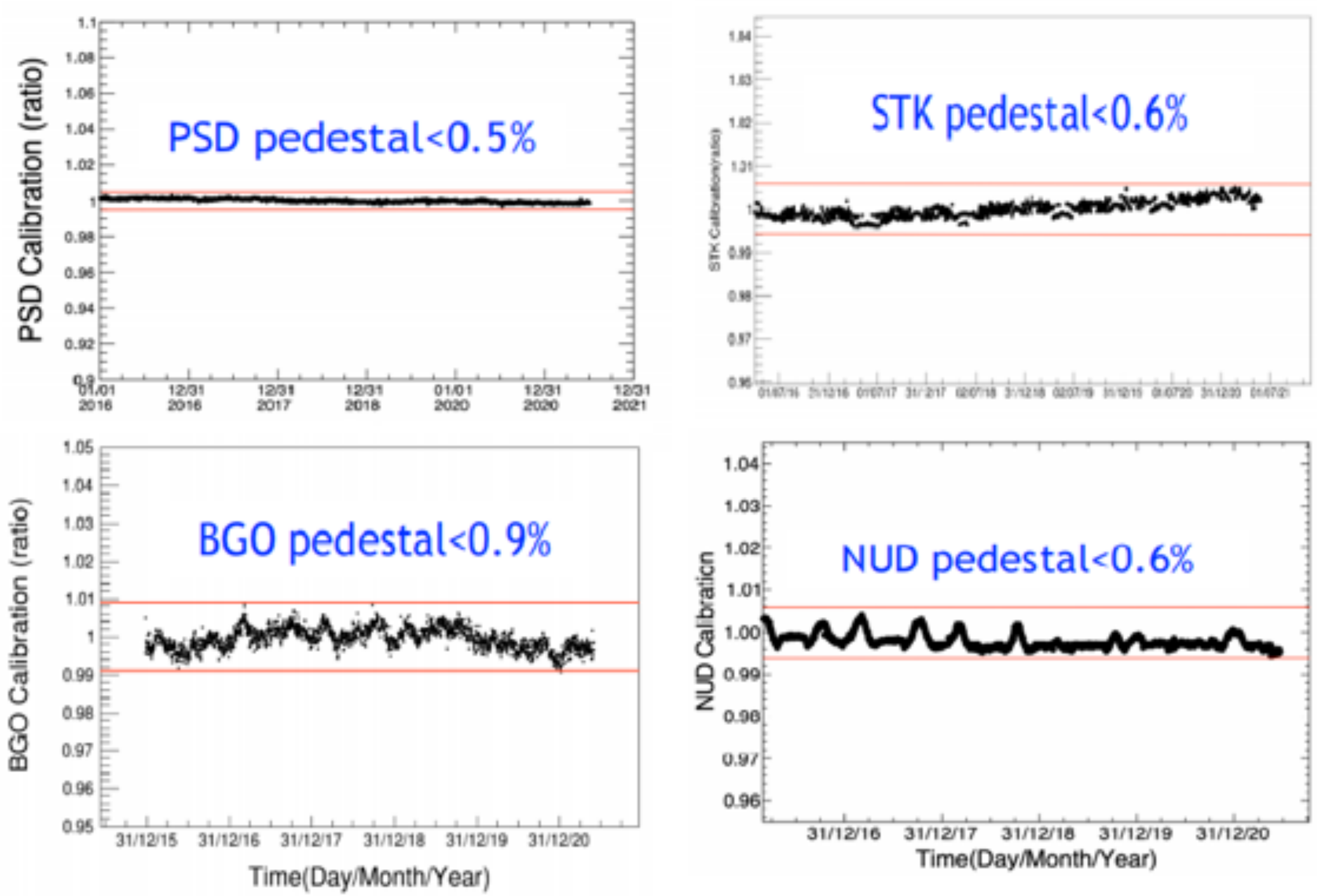


12+ billion events



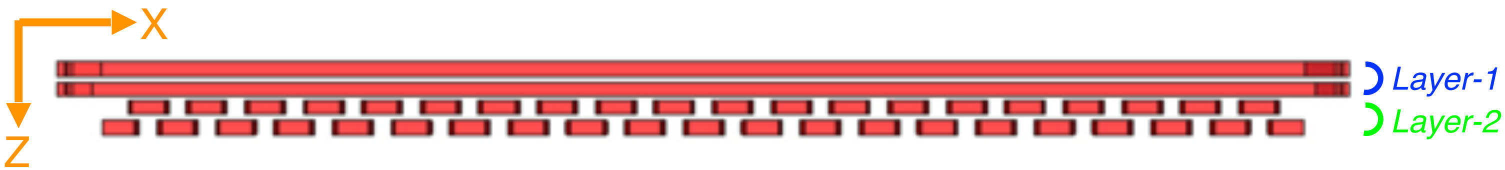
Since the launch on Dec. 17, 2015, DAMPE has operated on-orbit for 6.5+ years, surveyed the sky for 14 times, and recorded more than 12 billion events

Performance



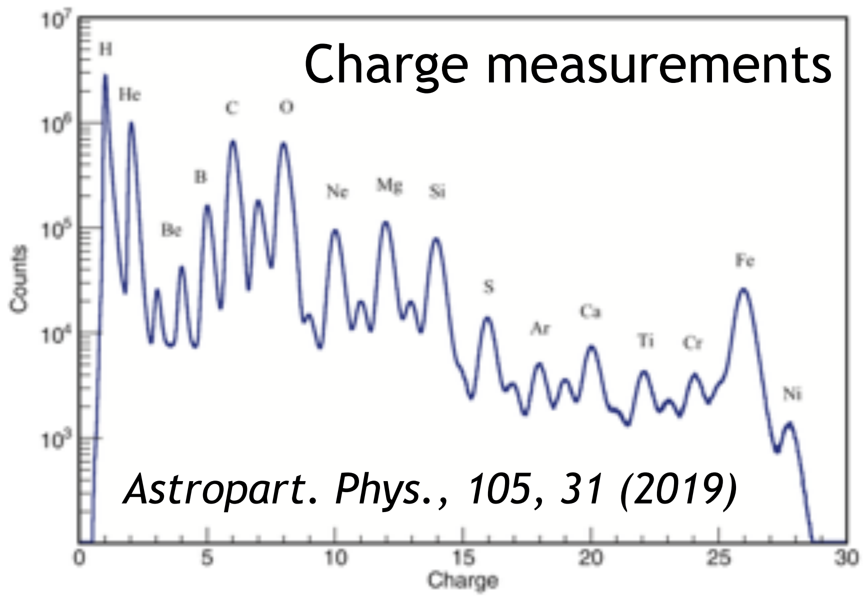
All sub-detectors work in very stable condition

PSD charge measurement



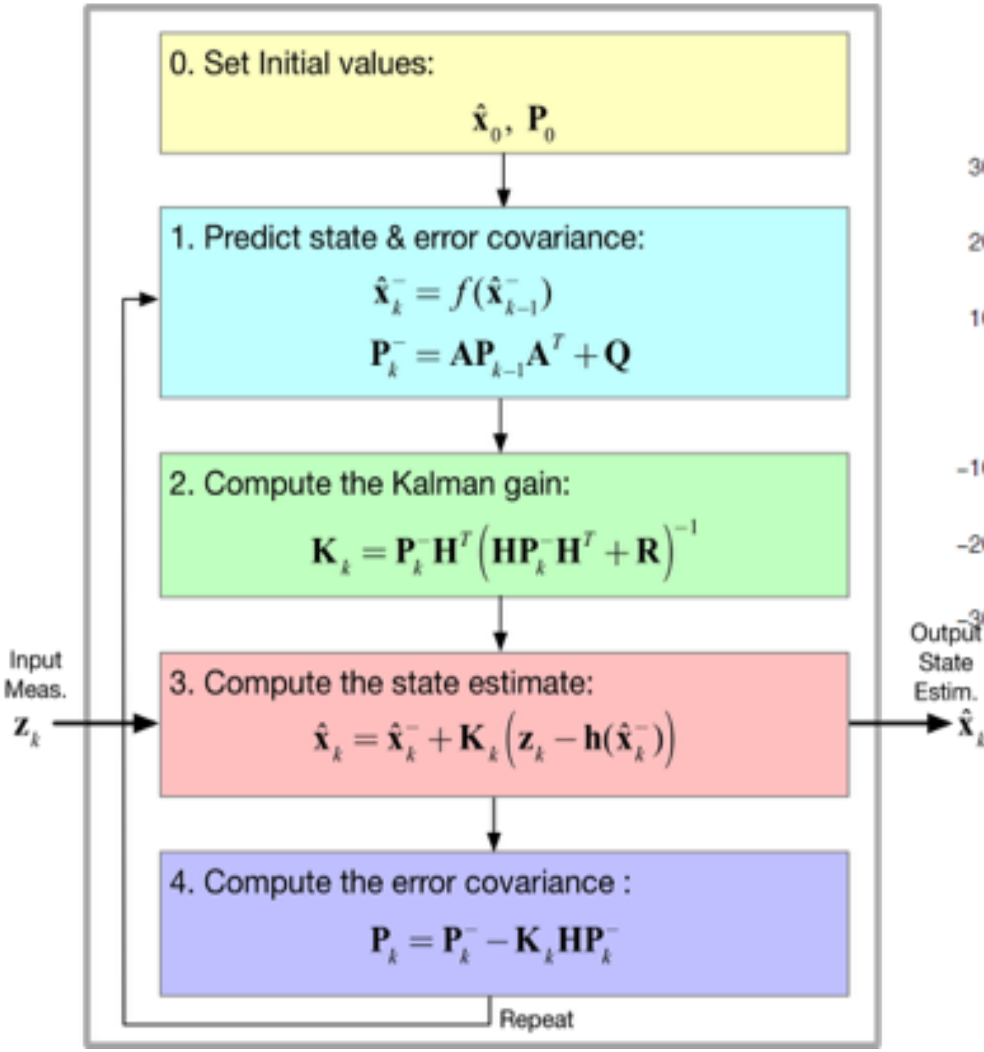
Bethe-Bloch formula

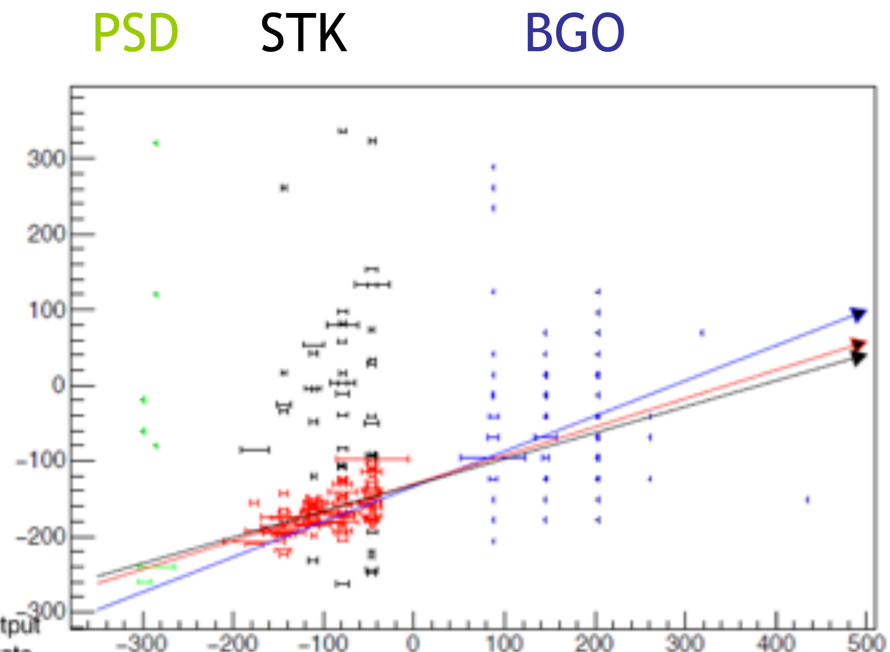
$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$



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

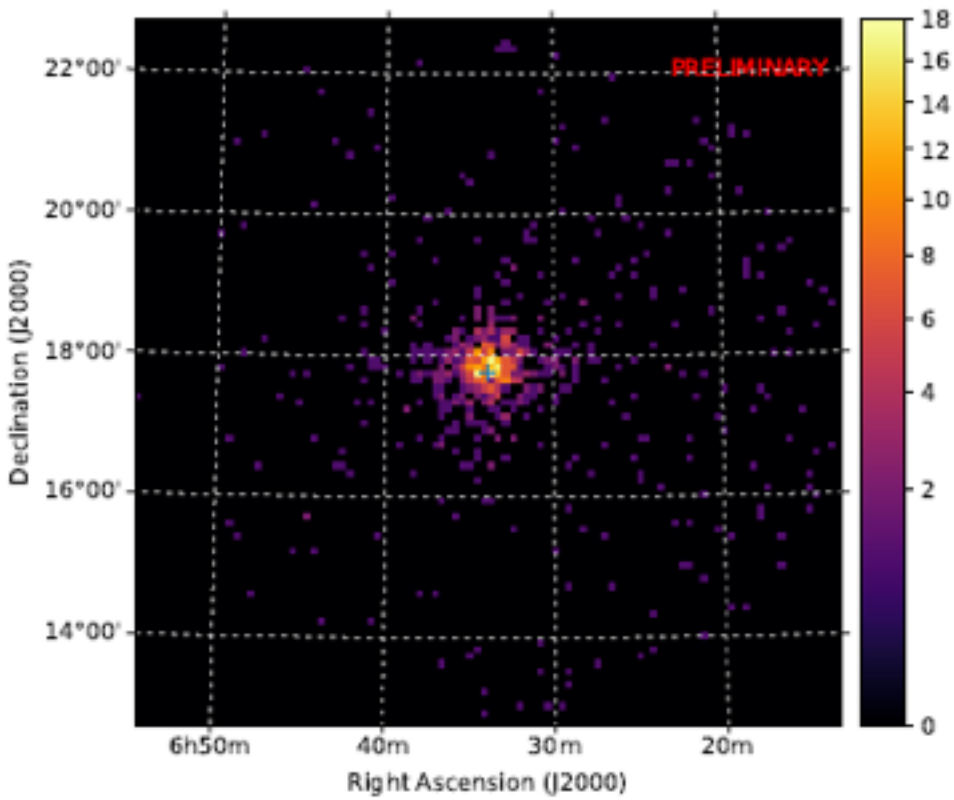
STK direction measurement

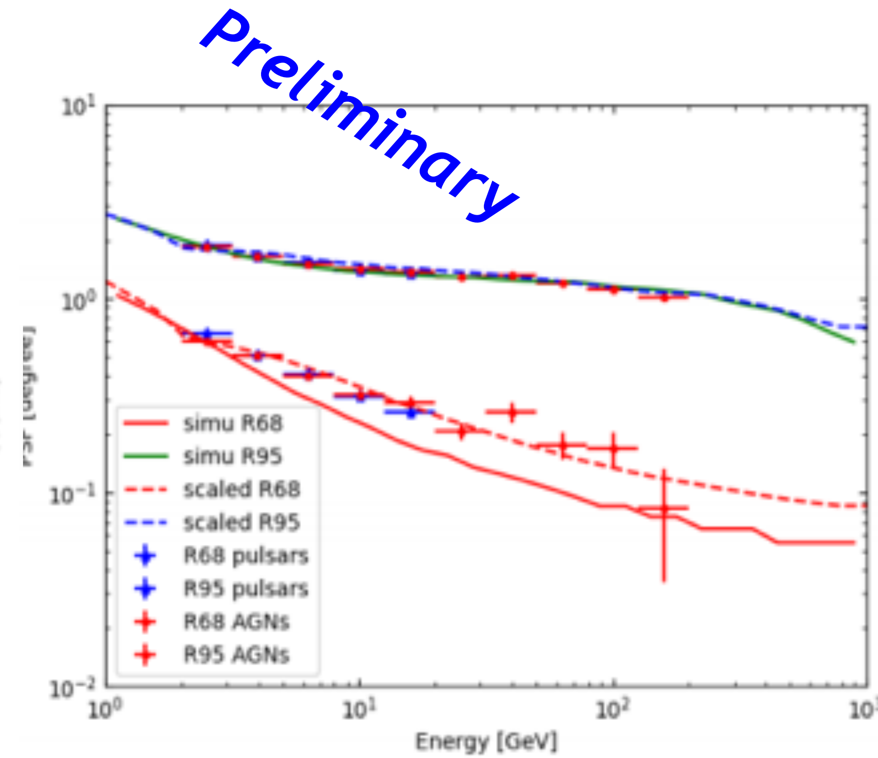




Kalman filter for track reconstruction

STK direction measurement

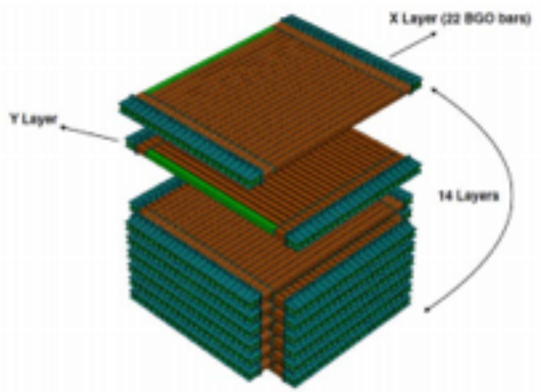




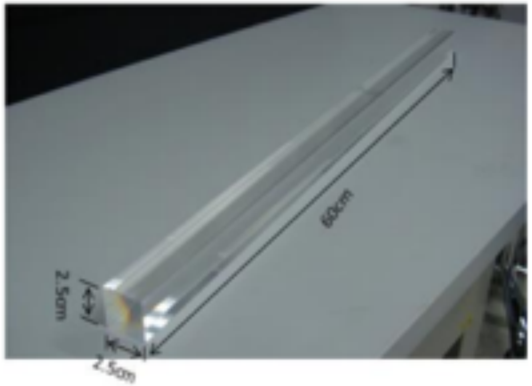
Angular resolution calibrated with photons from pulsars and stacked AGNs gives ~0.4 degrees @ 10 GeV

BGO energy measurement

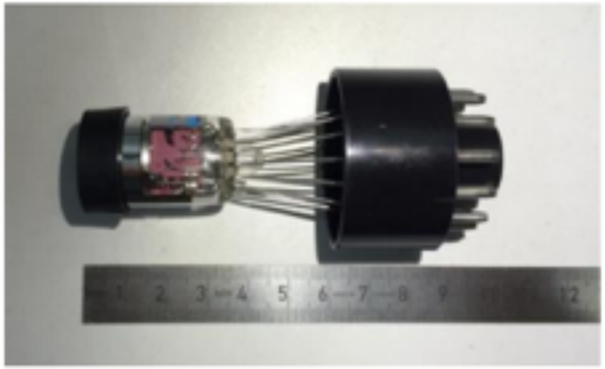
BGO calorimeter

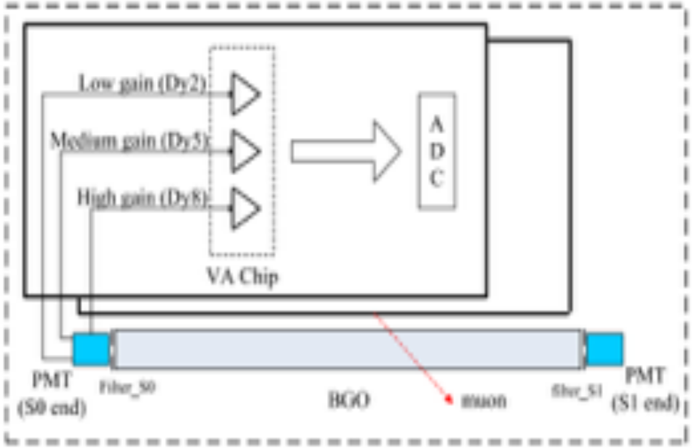


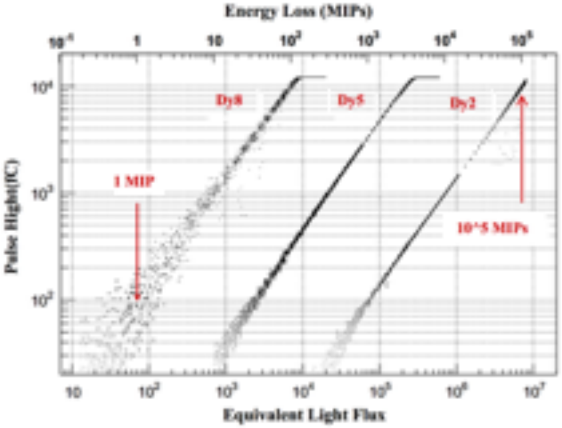
308 BGO bars



616 PMTs

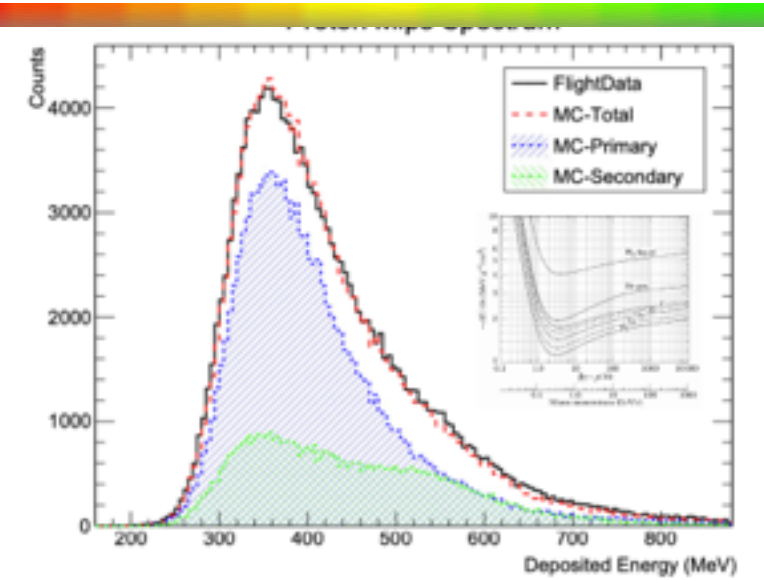




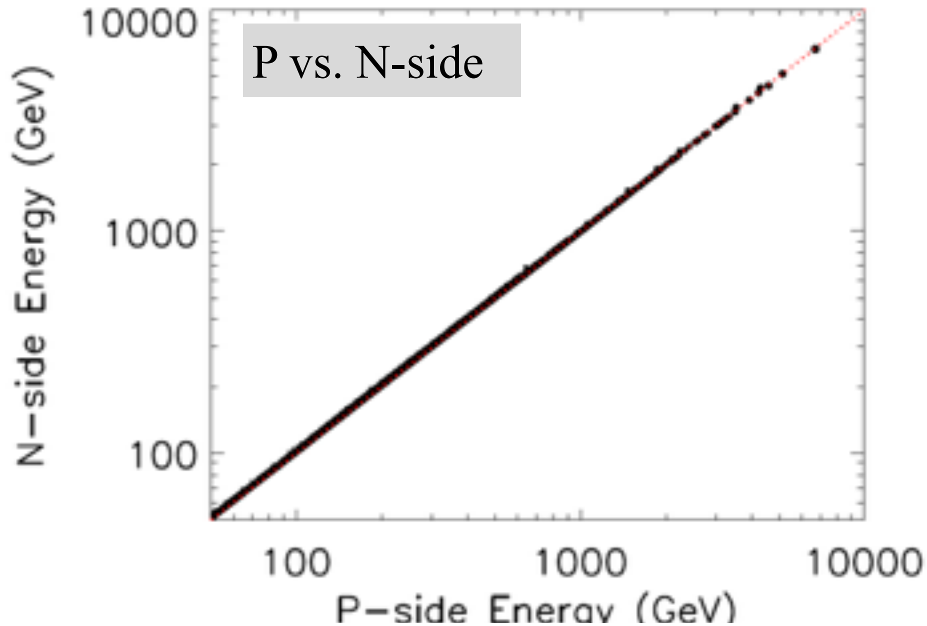


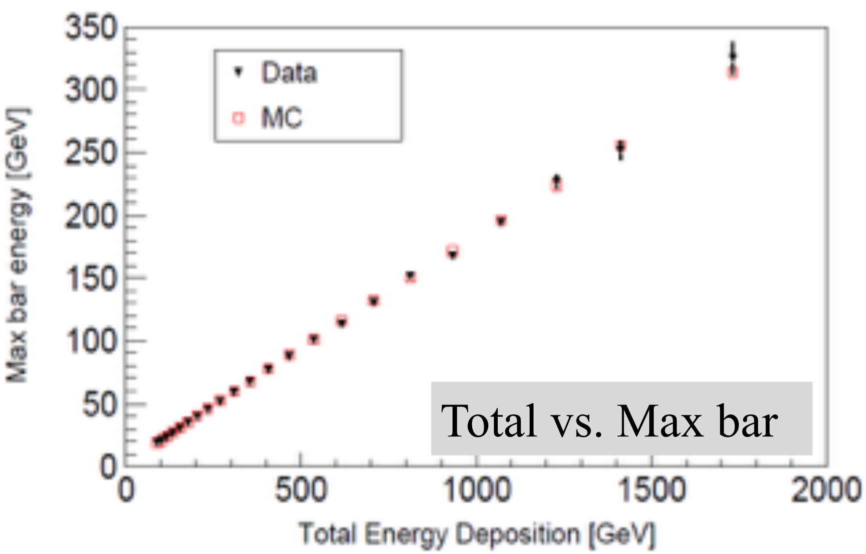
- Thick calorimeter (32 X_0): high-resolution
- Two-side readouts
- Three dynode outputs enable a $>10^6$ dynamic range

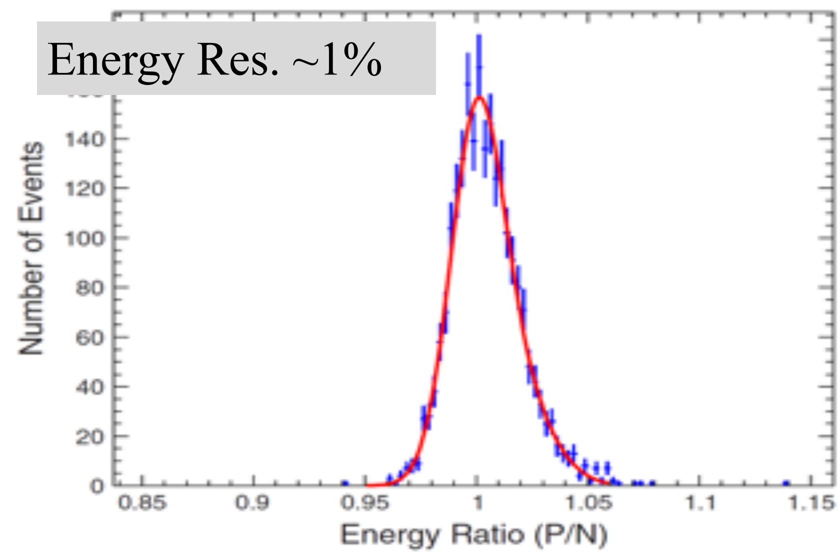
BGO energy measurement



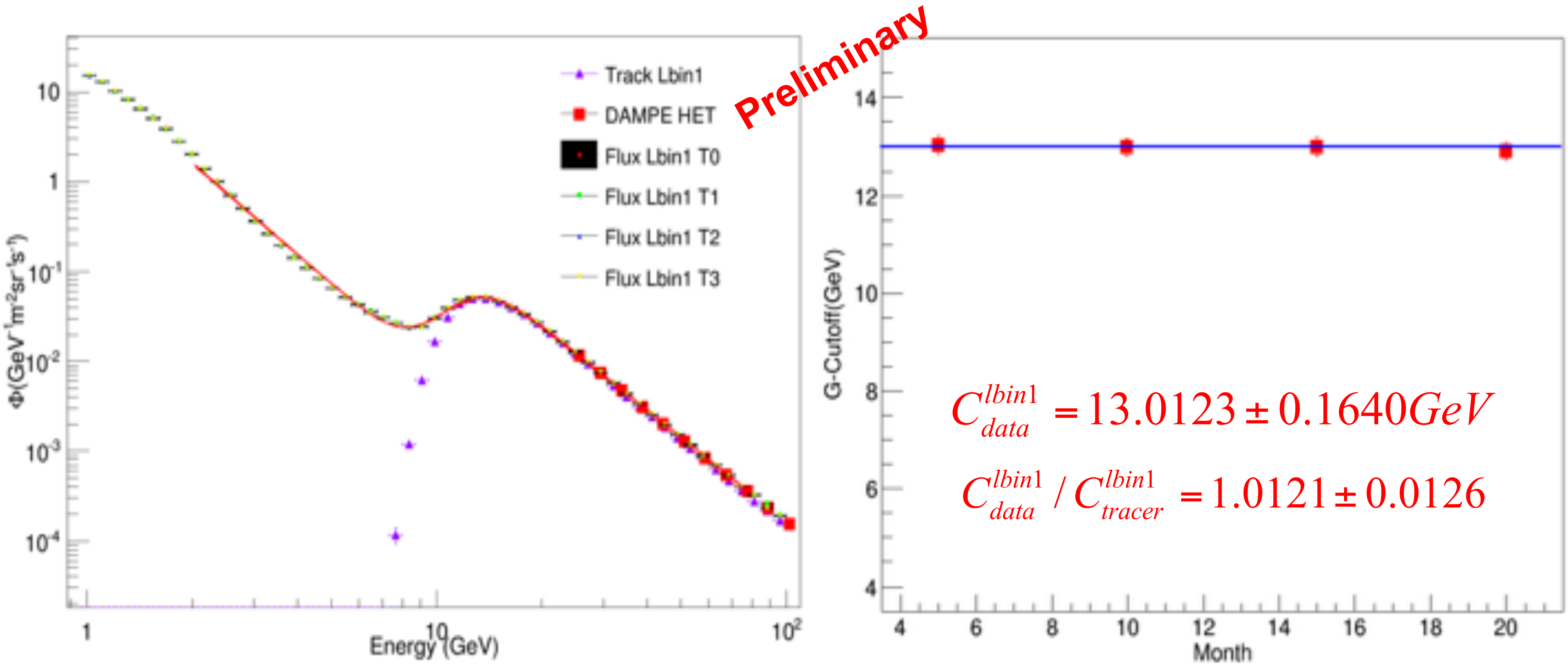
NIMA, 856, 11 (2017)





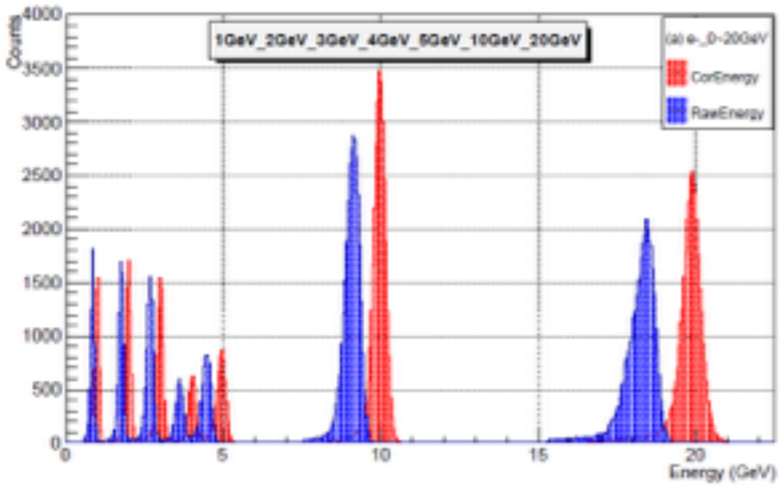


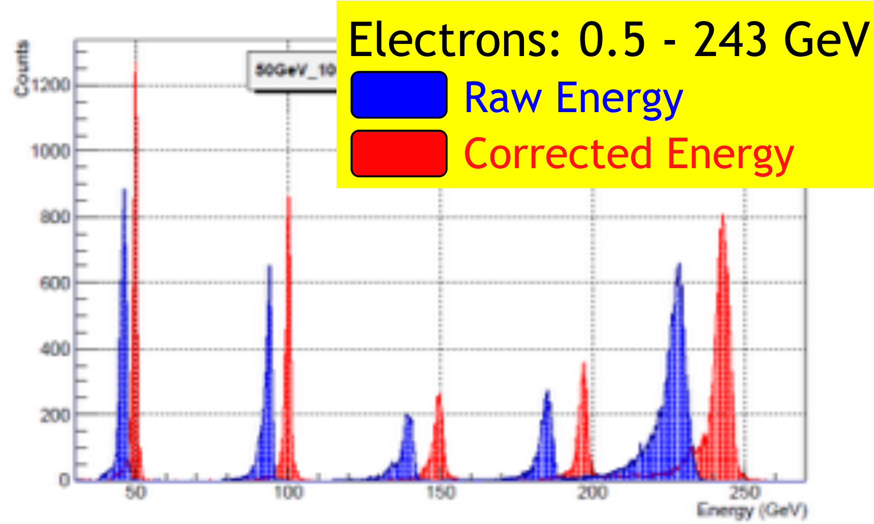
Absolute energy scale (e+e-)

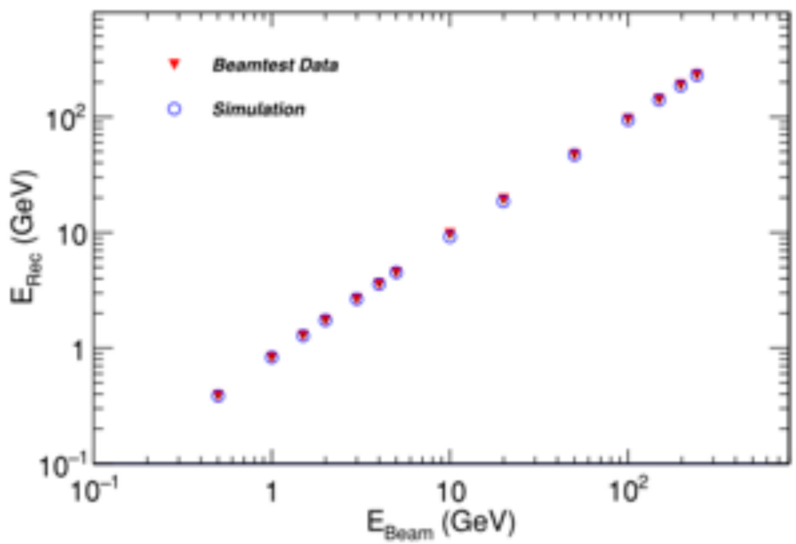


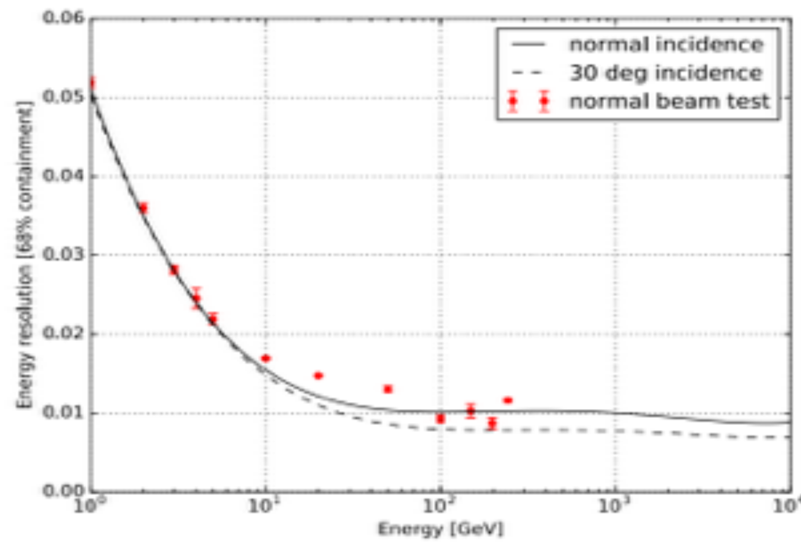
- An energy scale higher by (1.2+/-1.3)% from the geomagnetic cutoff
- Cutoff energy is stable with time (a slight decrease due to solar modulation)

Test beam validation of energy measurement









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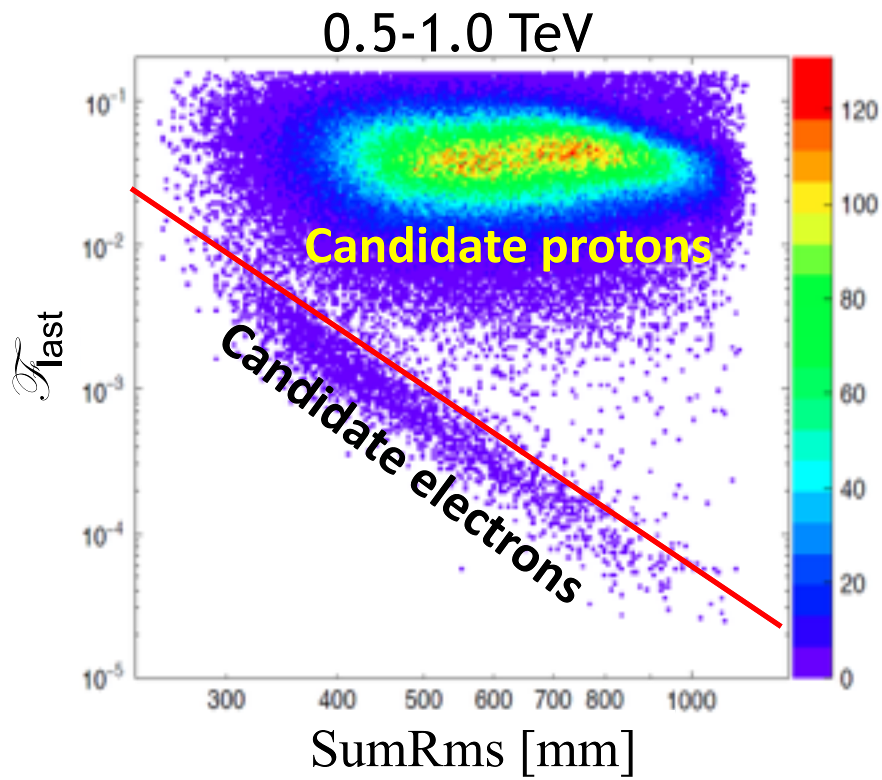
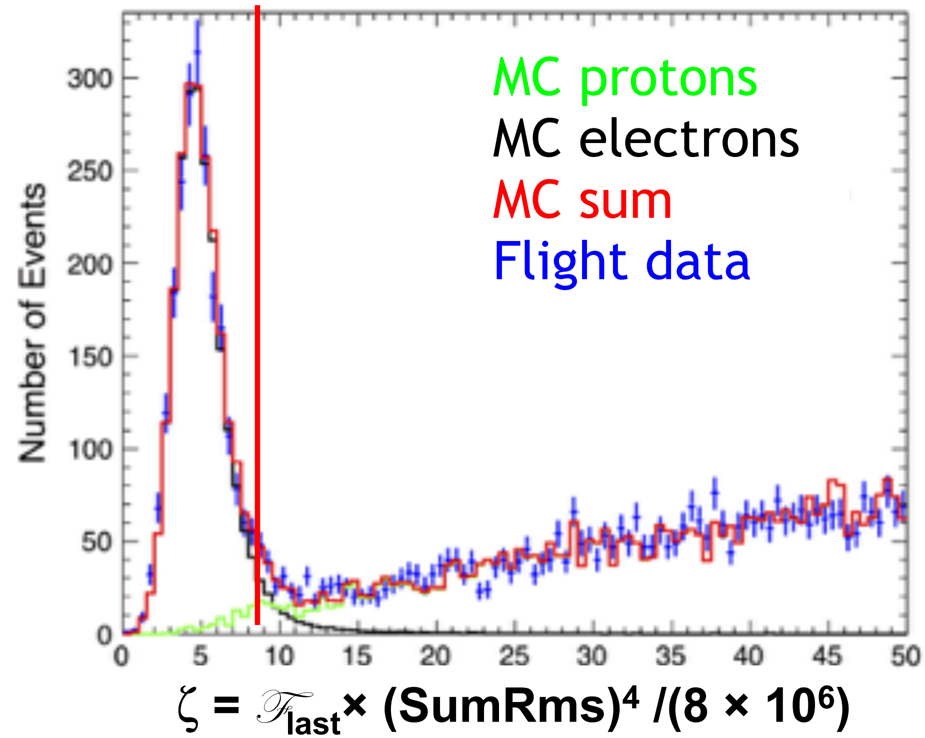
Particle (e-p) identification

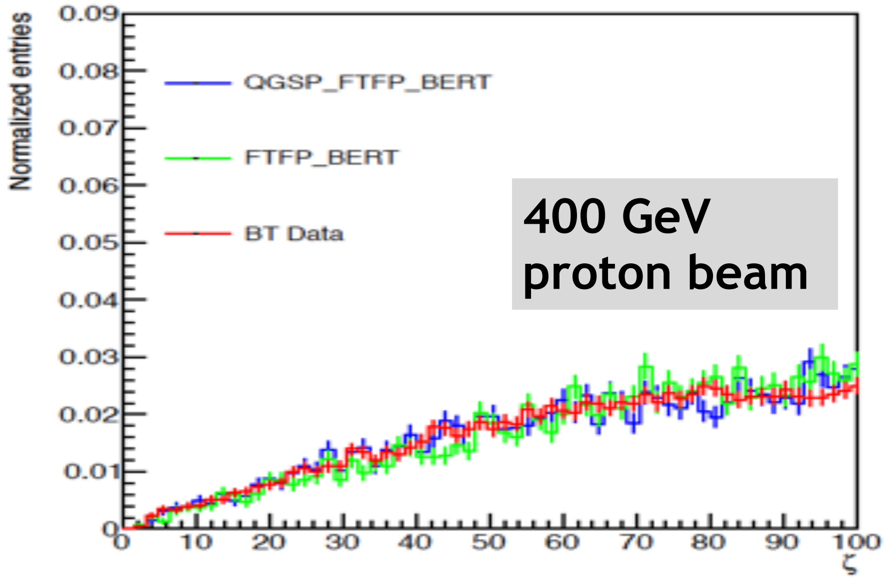


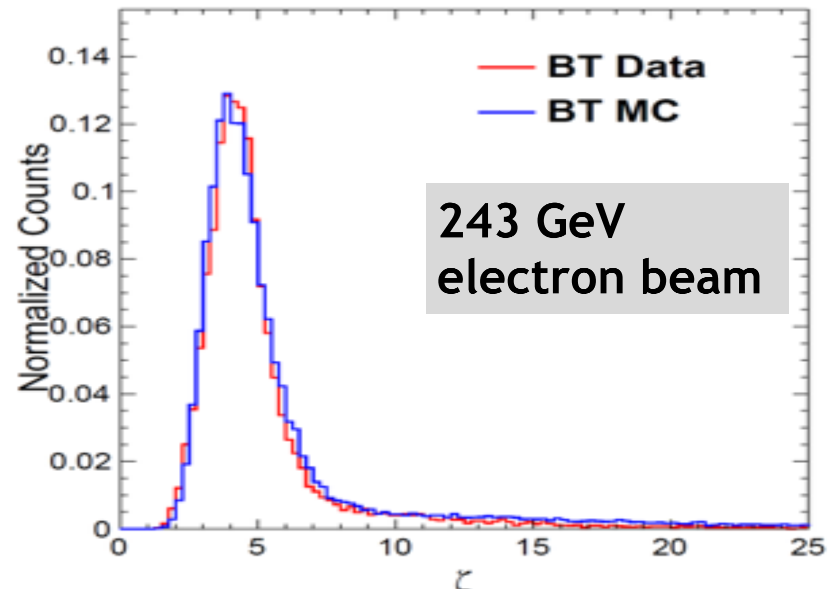


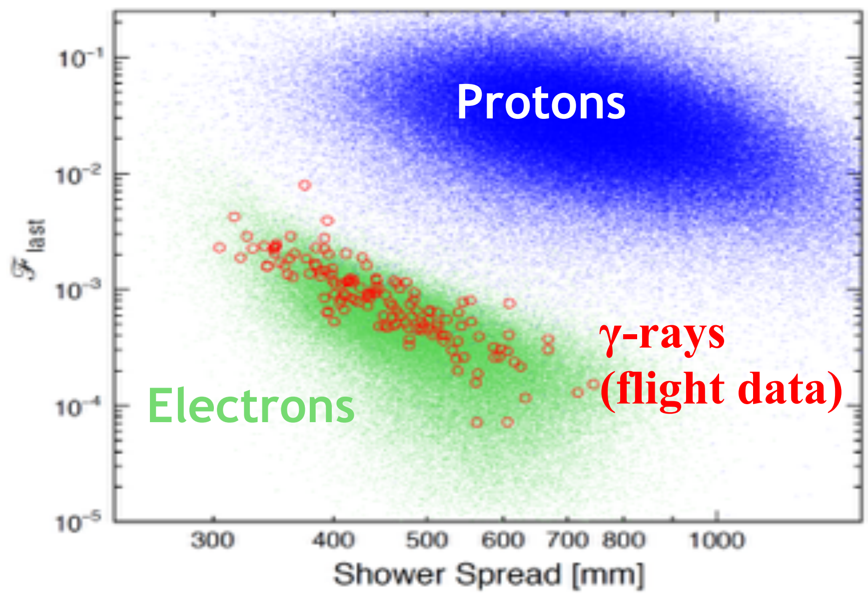
- DAMPE uses lateral (SumRMS) and longitudinal (energy ratio in last layer) developments of showers to discriminate electrons from protons
- For 90% electron efficiency, proton background is ~2% @ TeV, ~5% @ 2 TeV, ~10% @ 5 TeV

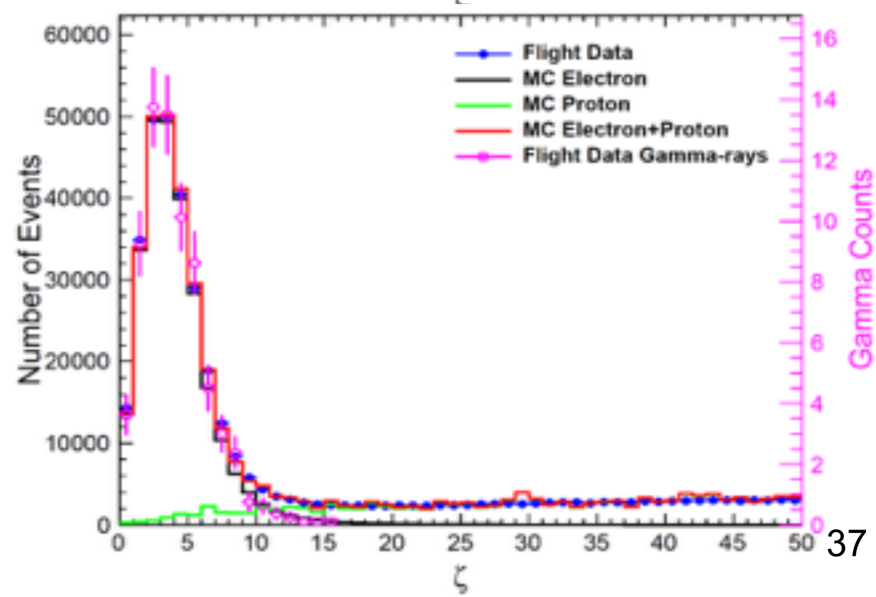
Nature, 552, 63 (2017)

Validation of particle ID

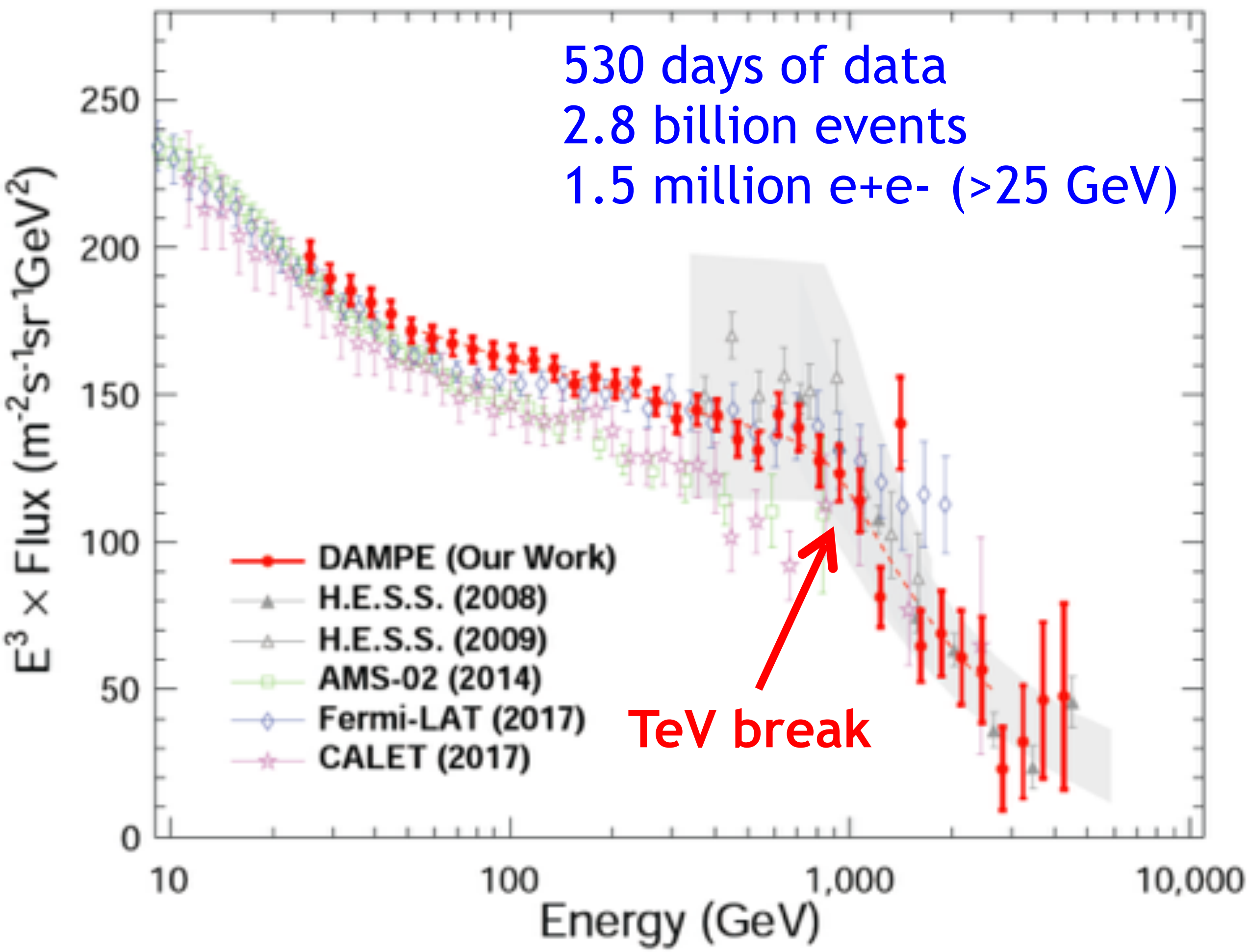








Results: $e^+ + e^-$ spectrum

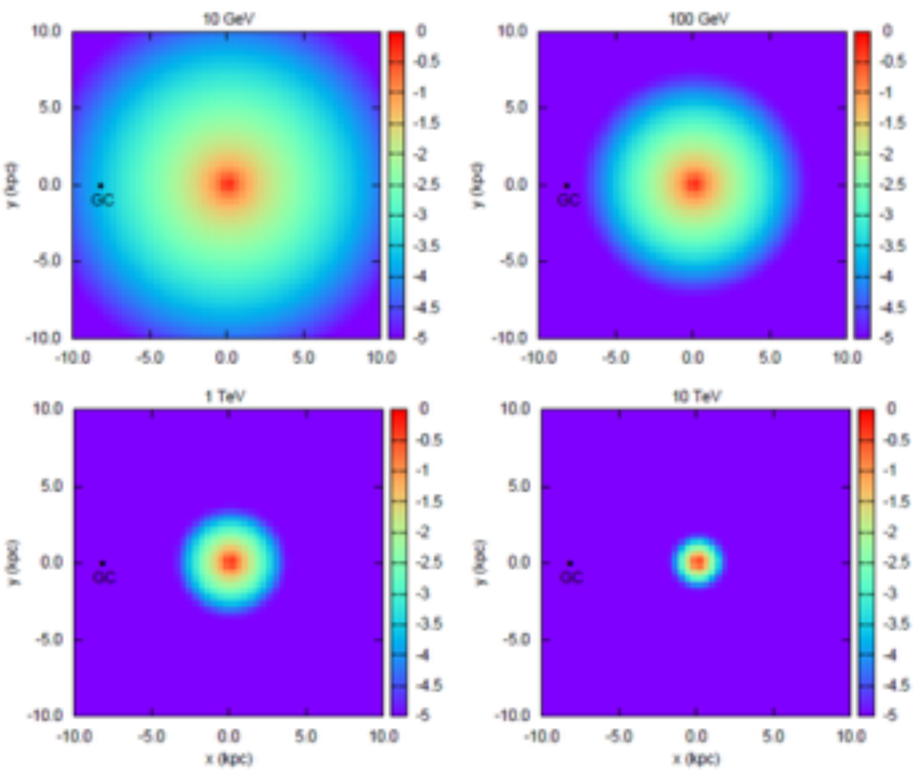


Nature, 552, 63 (2017)

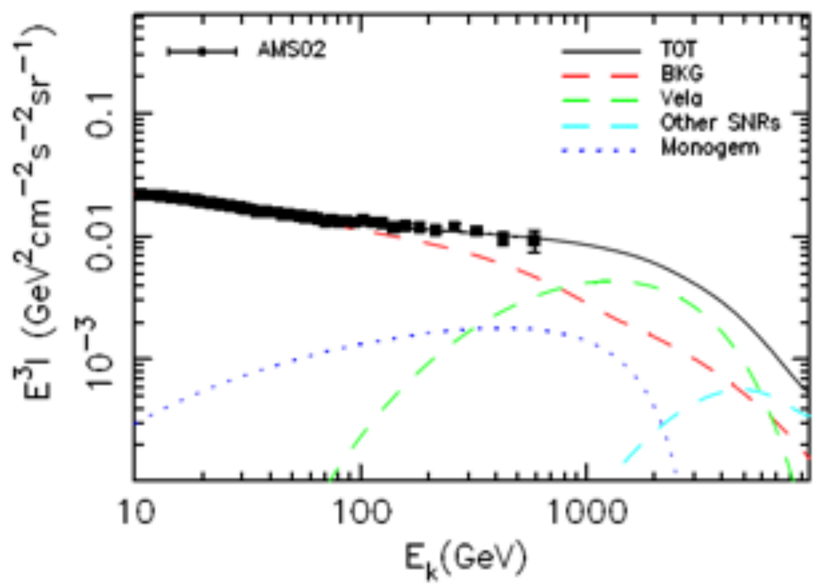
- Three different PID methods give very consistent results on event-by-event level
- Direct detection of a spectral break at ~1 TeV with 6.6σ confidence level
- Analysis with new data is on-going

Implication of e+e- softening

- Cooling time of TeV electrons ~ Myr, effective propagation range ~ kpc
- Assuming a total SN rate of 0.01 per year, the total number of SNRs within the effective volume and cooling time is O(10)

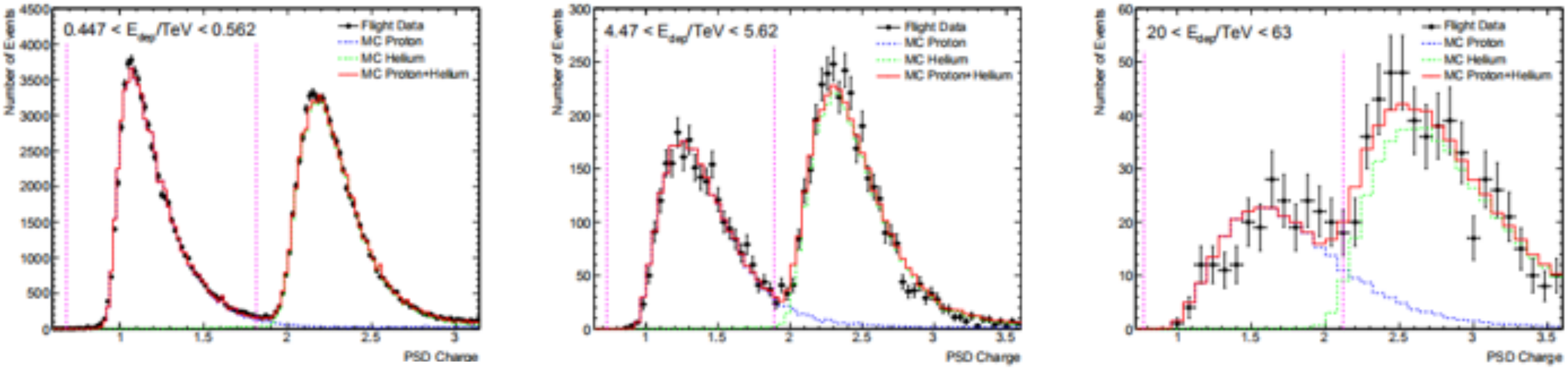


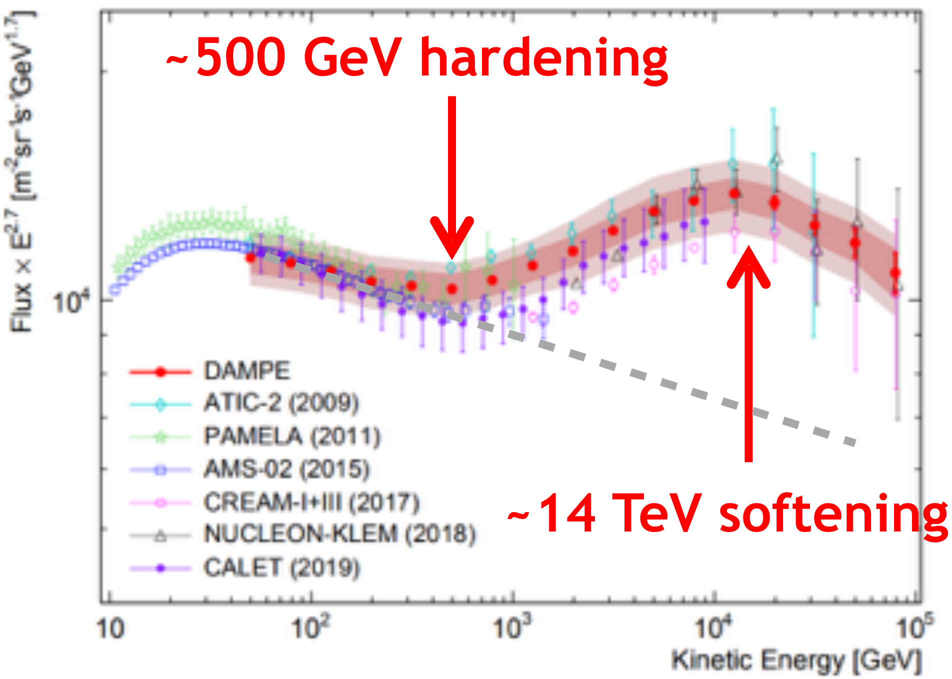
Astrophys. J., 836, 172 (2017)



Fang et al. (2017),
Di Mauro et al. (2017),
Manconi et al. (2019)...

Results: proton spectrum

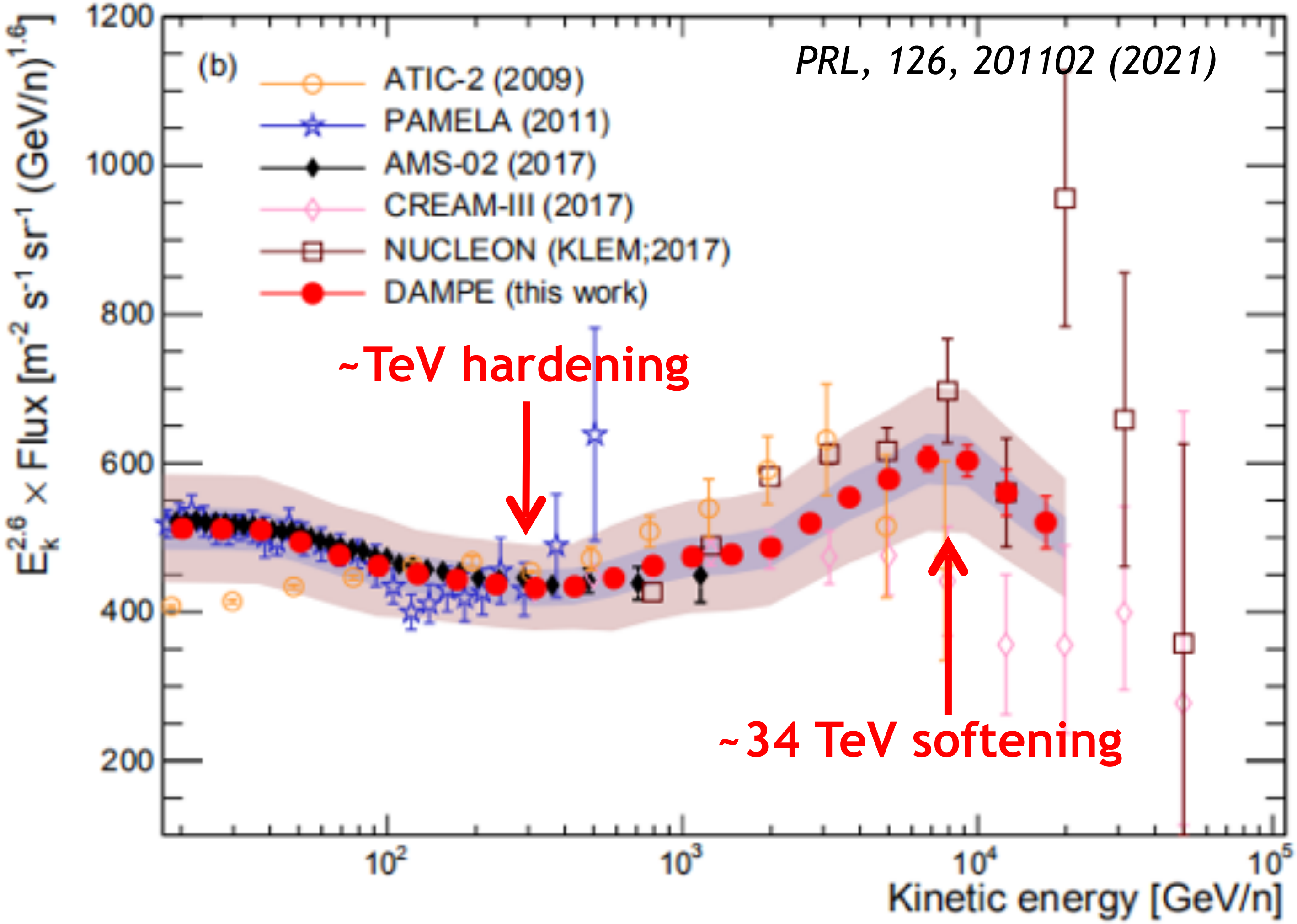




- Hundreds of GeV hardening consistent with previous measurements
- Newly detecting a softening at ~14 TeV with a high significance (4.7 σ)

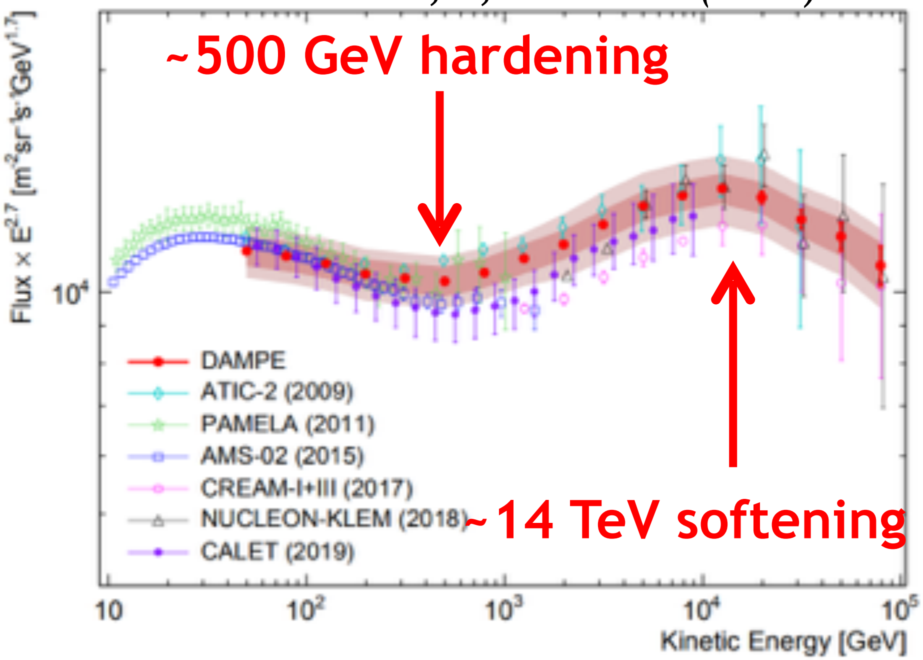
Science Advances, 5, eaax3793 (2019)

Results: helium spectrum

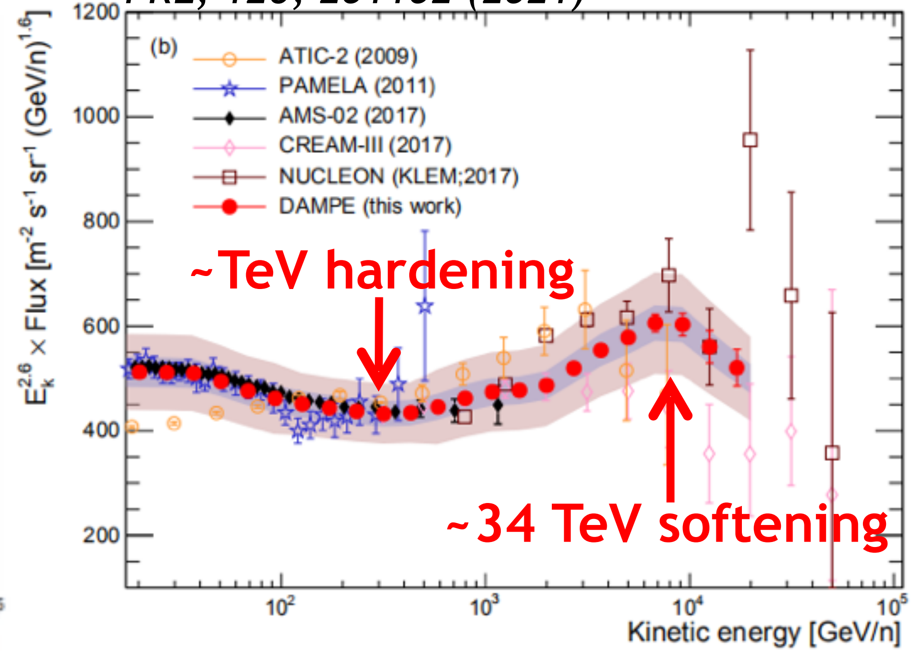


Results: proton vs. helium

Science Advances, 5, eaax3793 (2019)



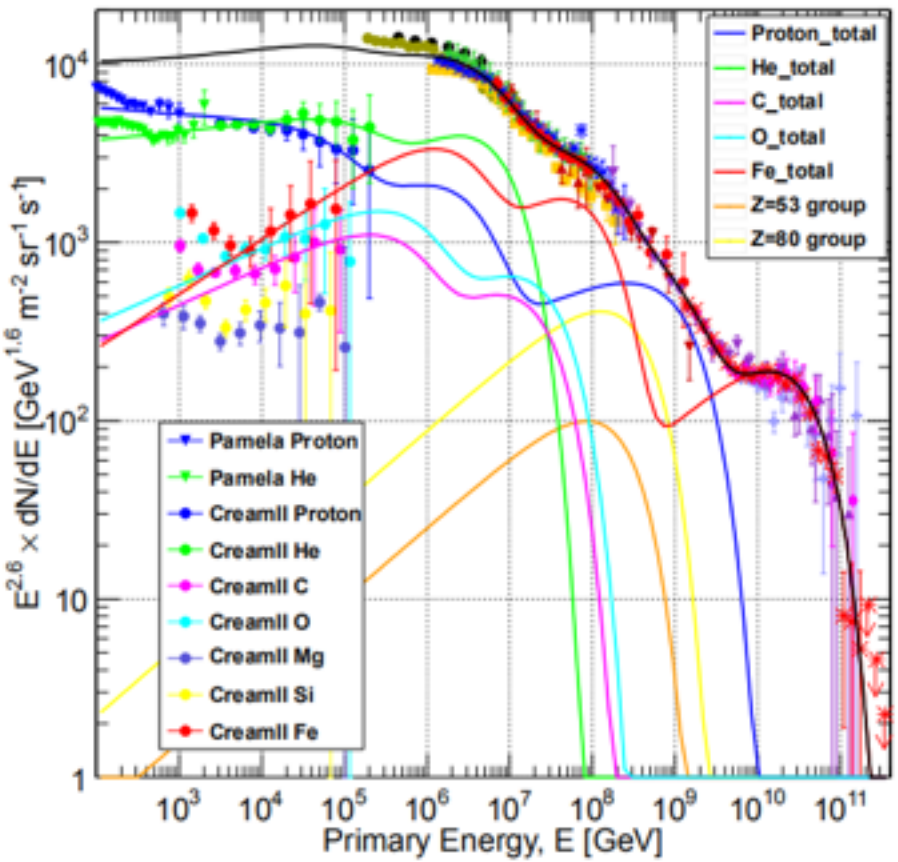
PRL, 126, 201102 (2021)



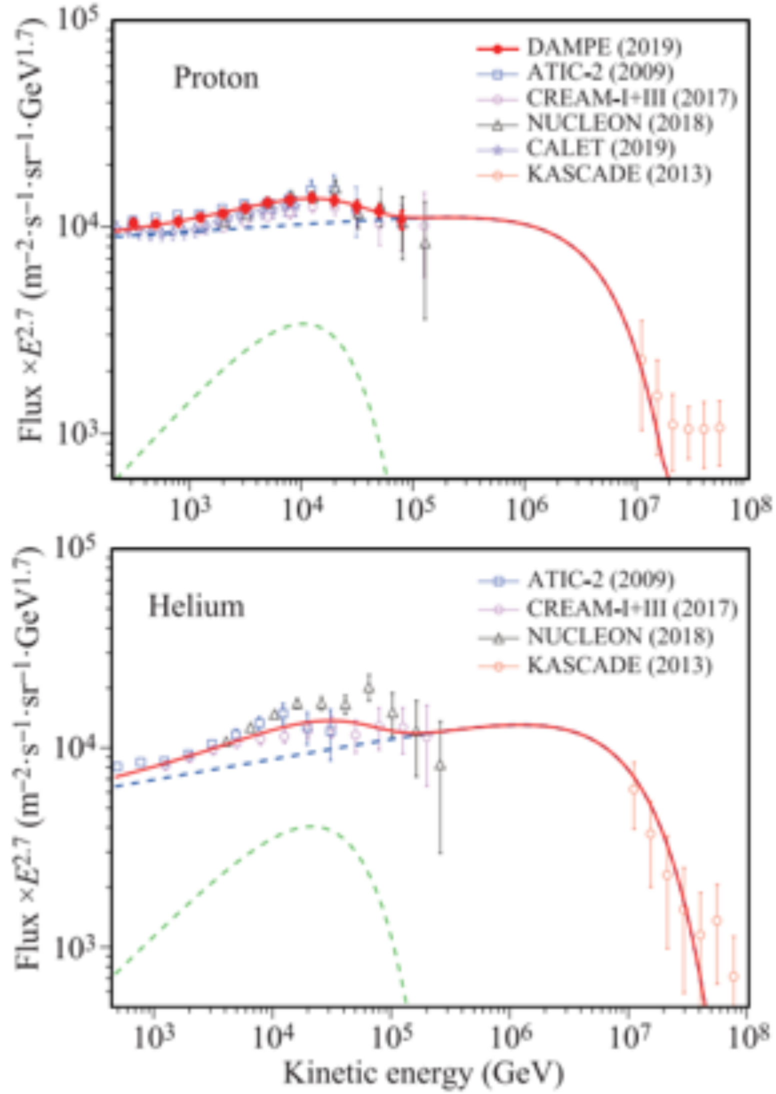
- ➢ Proton: softening at $14^{+4.1}_{-4.8}$ TeV
- ➢ Helium: softening at $34^{+6.7}_{-9.8}$ TeV
- ➢ A nearly Z-dependent softening

Implication of p, He spectrum

Gaisser et al. (2013)



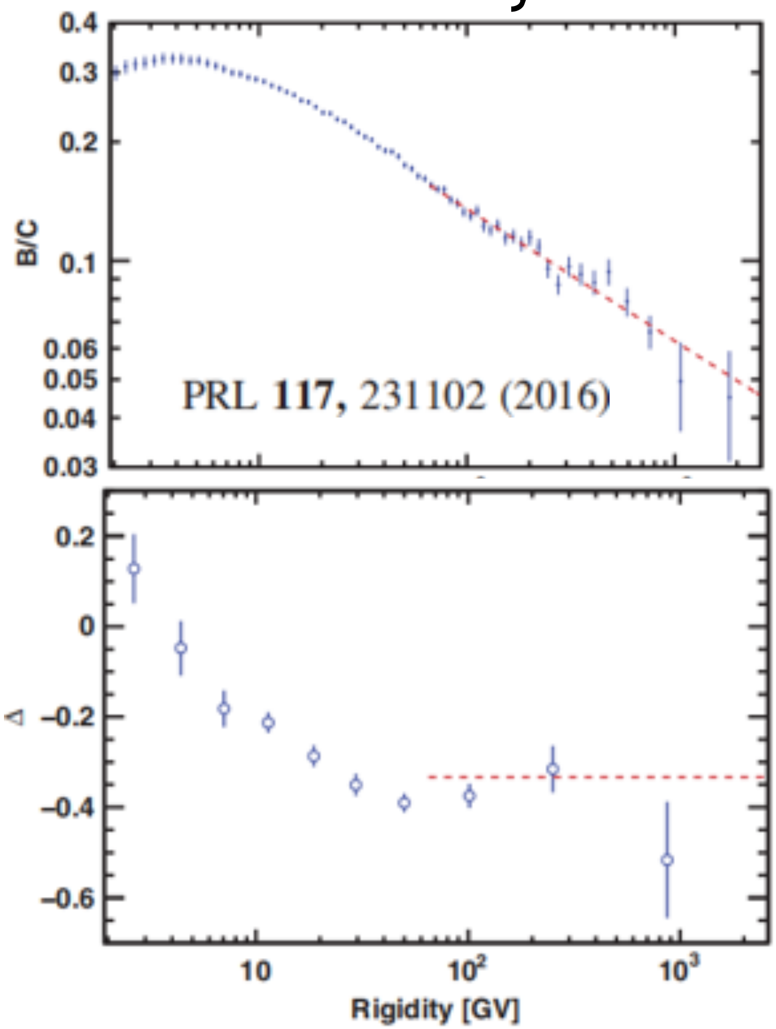
Yue et al., Front. Phys., 15, 24601 (2020)



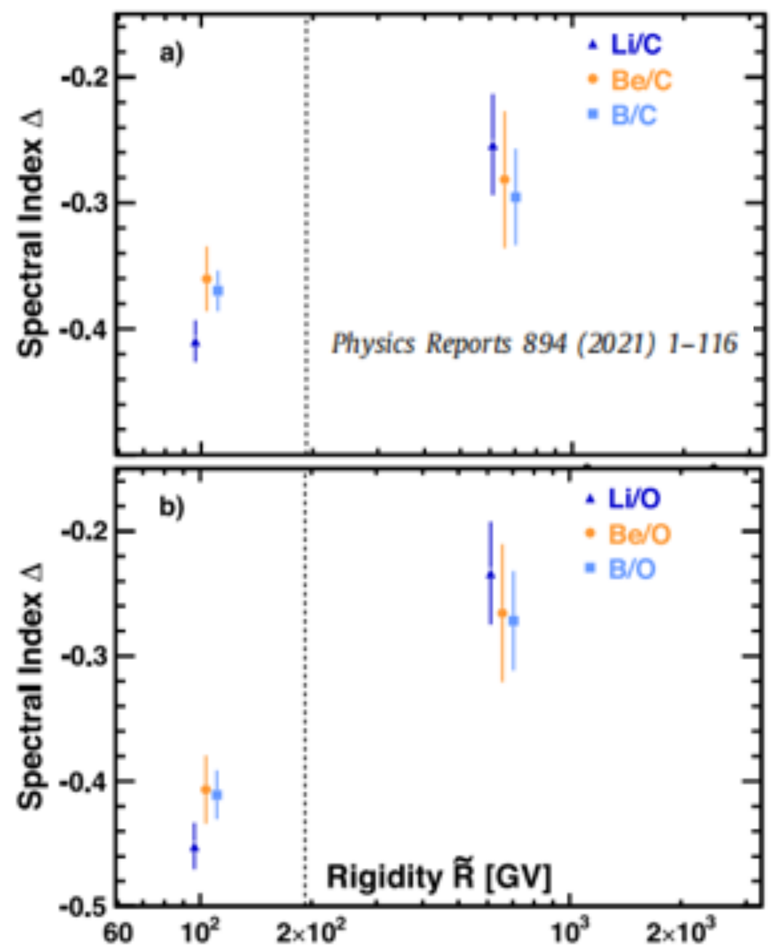
Liu et al., 1812.09673
Malkov et al., 2105.04630
...

Results: B/C ratio

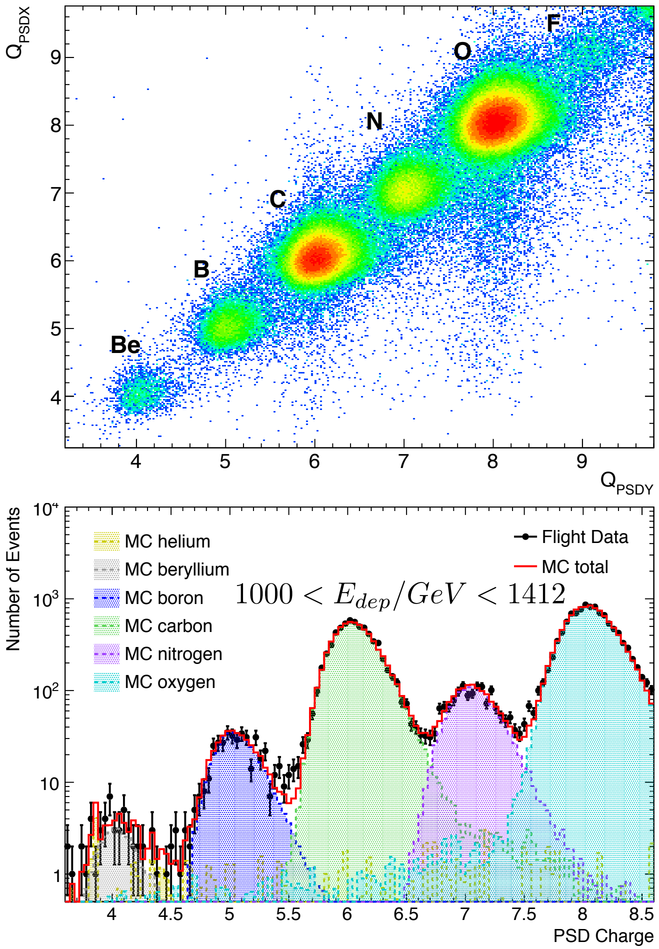
AMS-02 5 years

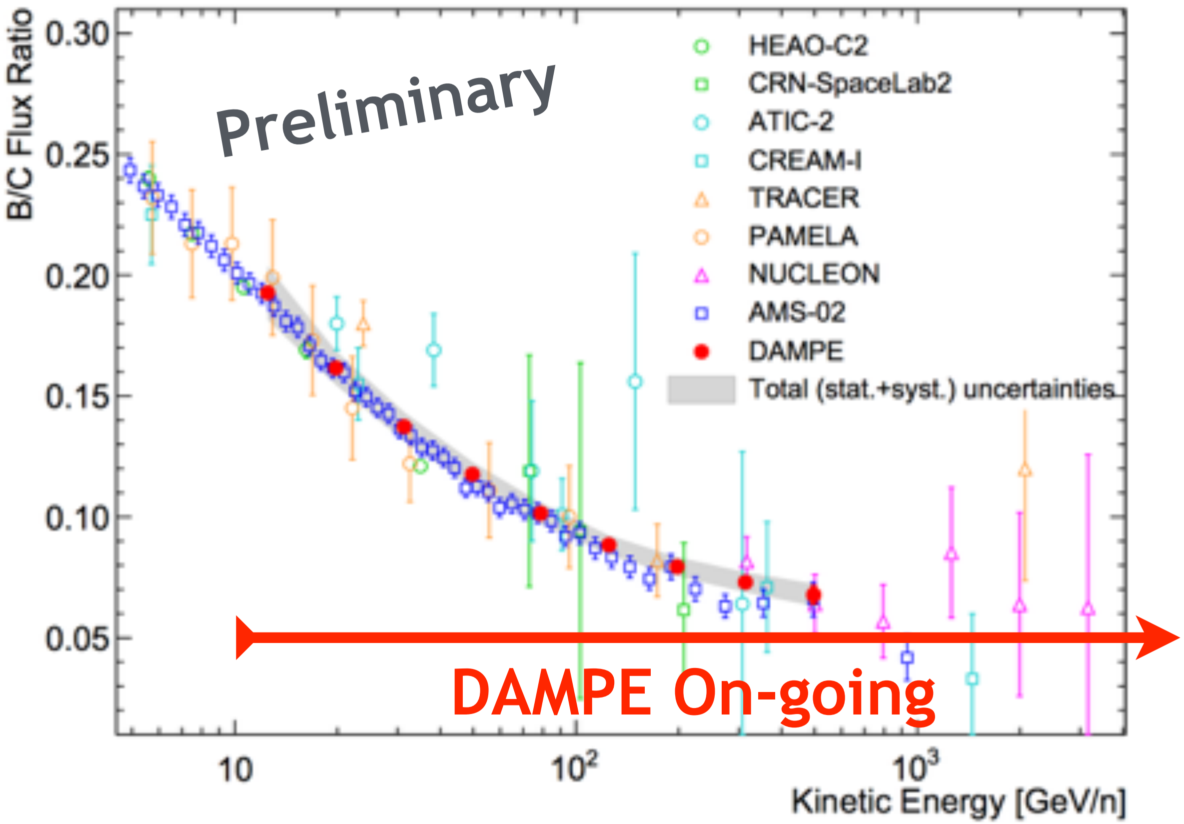


AMS-02 7 years



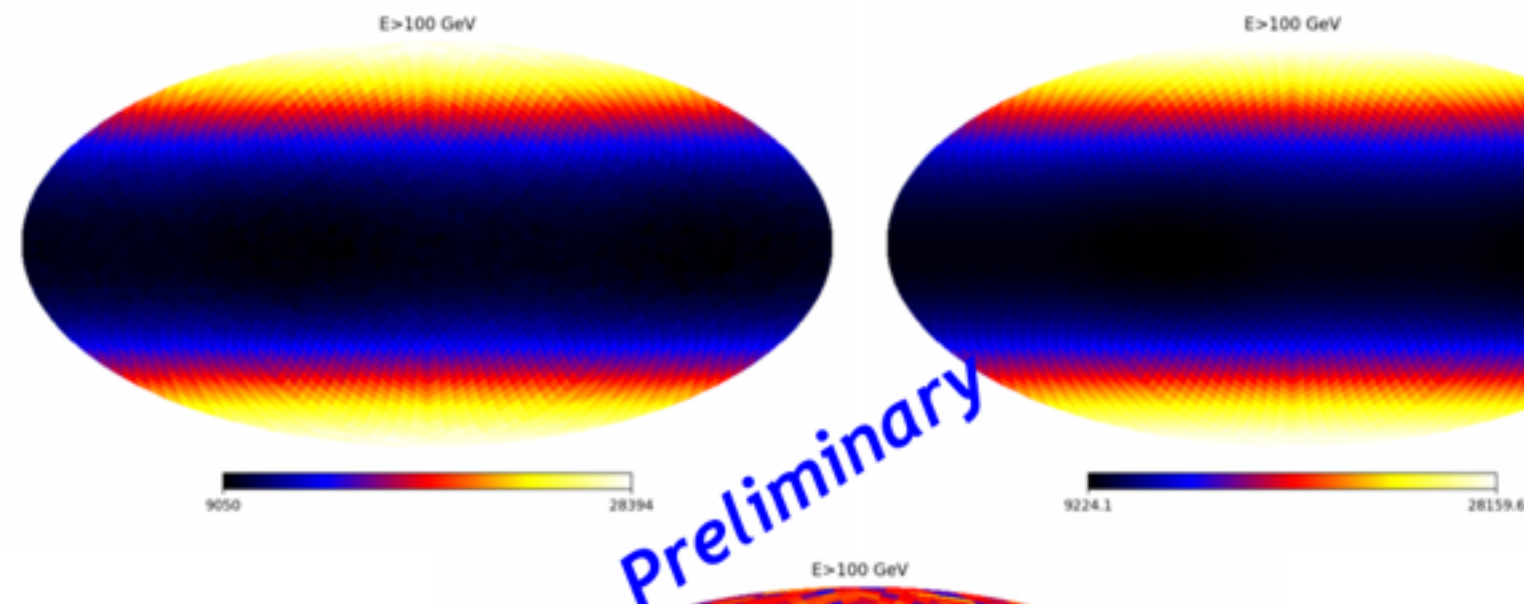
Results: B/C ratio

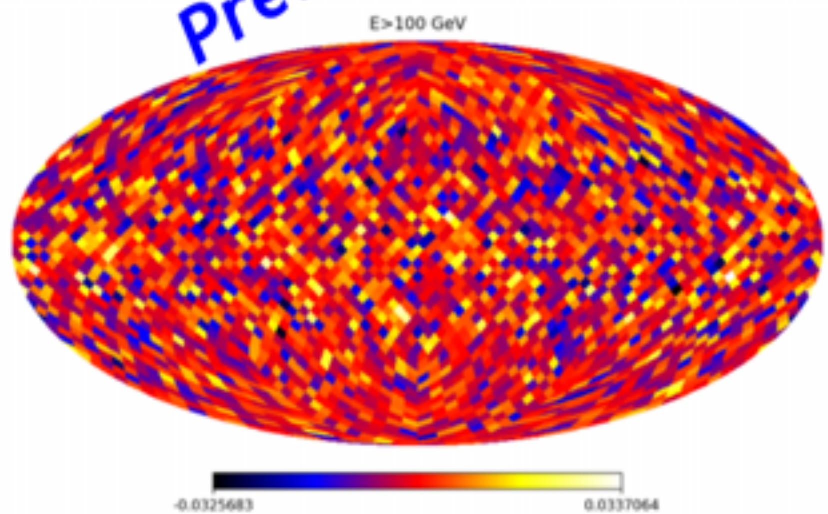




DAMPE can precisely measure B/C to much higher energies and critically test whether there is a high-energy break of B/C

Results: cosmic ray anisotropy

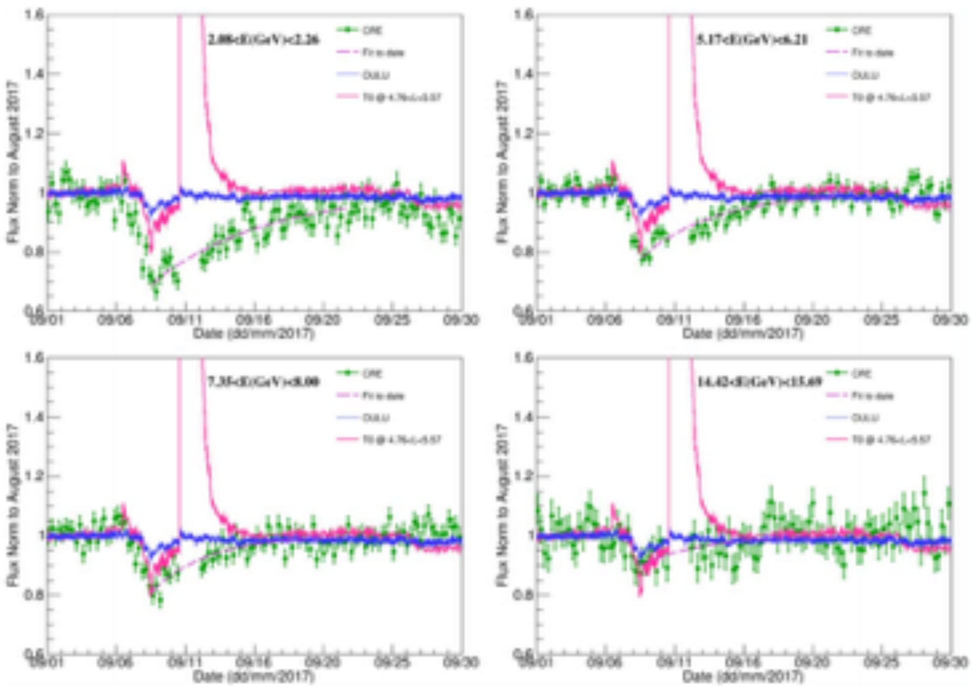


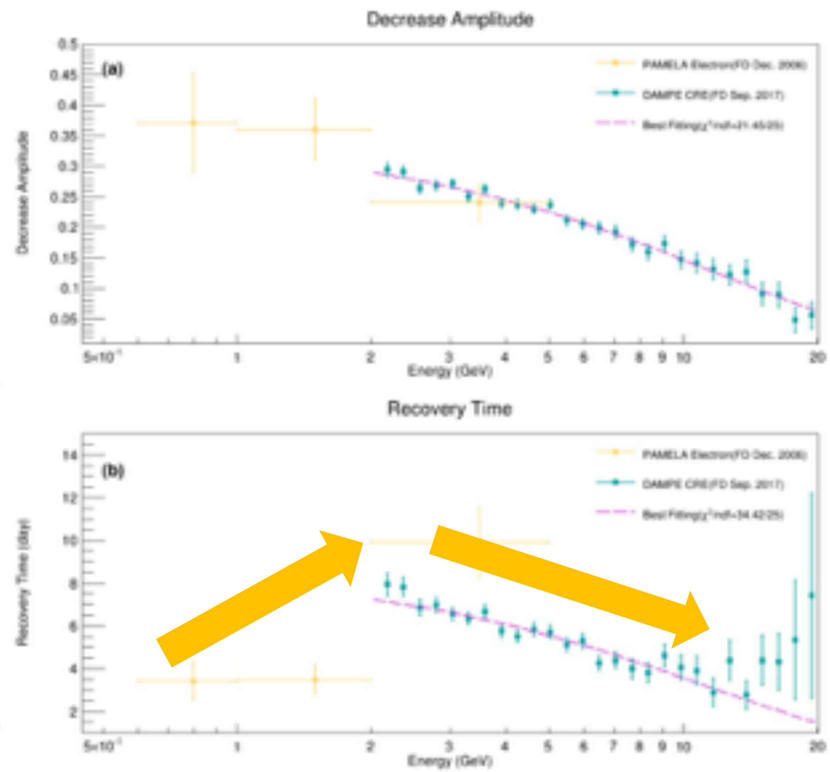


95% UL of dipole amplitude for 5-yr data (>~100 GeV): 1.2×10^{-3}

Results: Forbush decrease

ApJL, 920, L43 (2021)

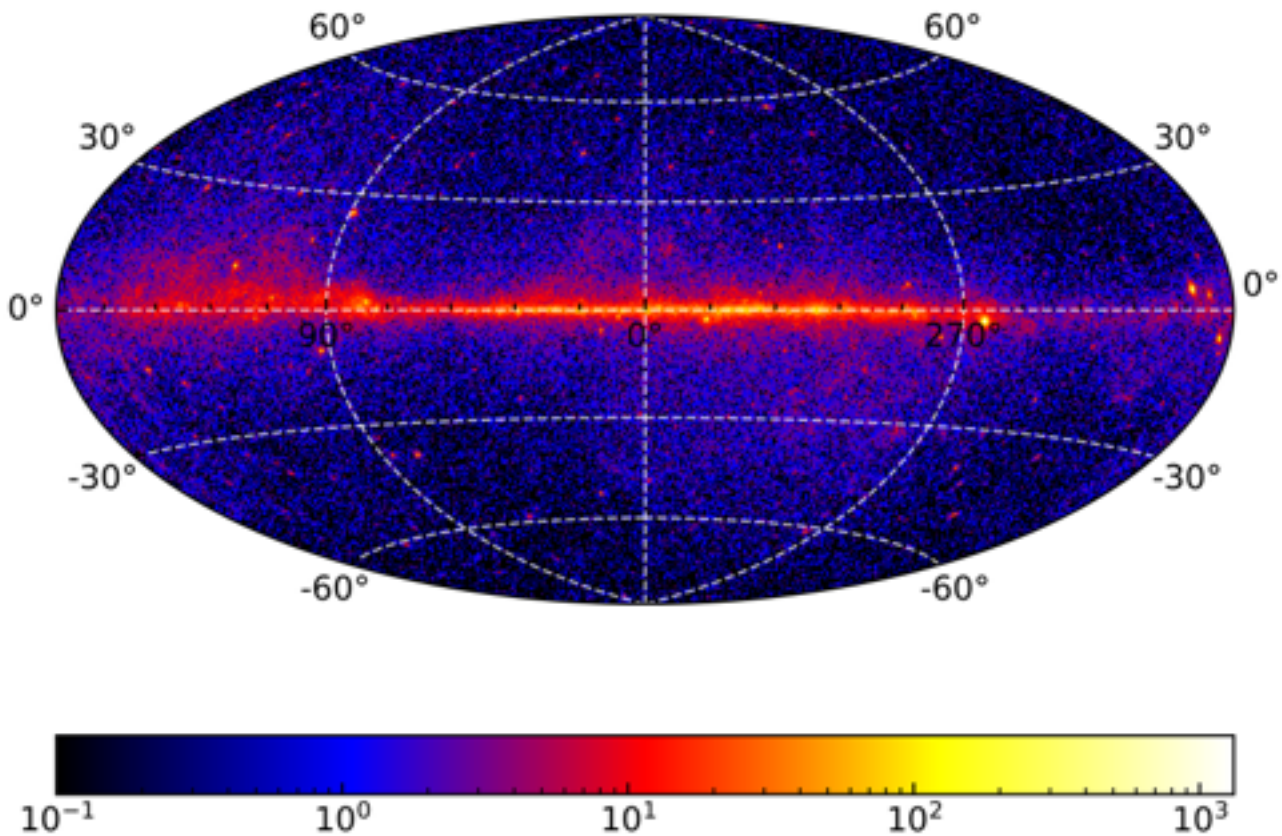




- ➢ DAMPE observed the Forbush decrease of cosmic ray e+e- with high precision
- ➢ Reveal new features of the recovery time

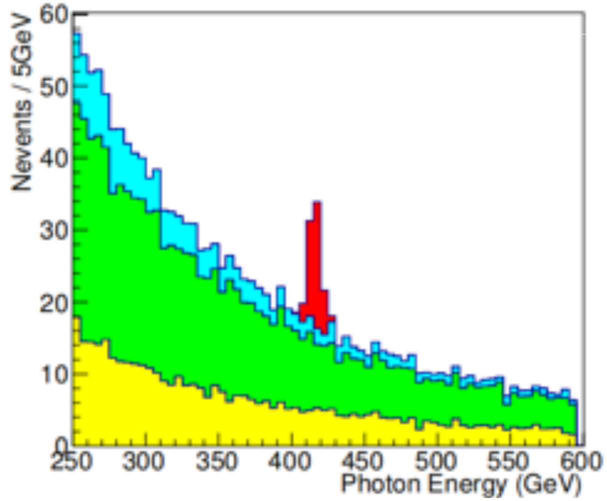
Results: γ-ray skymap

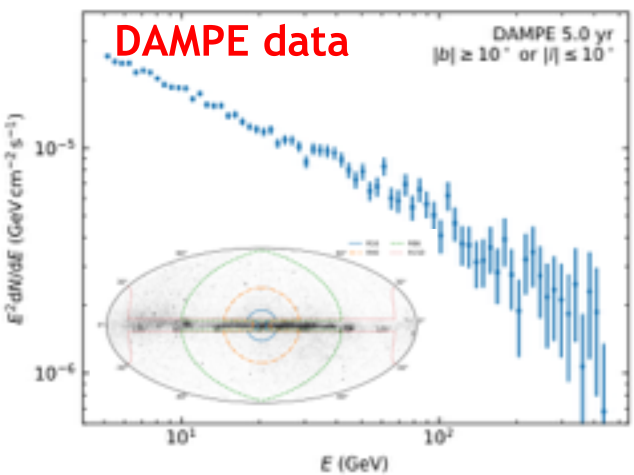
E>2 GeV, 6 years



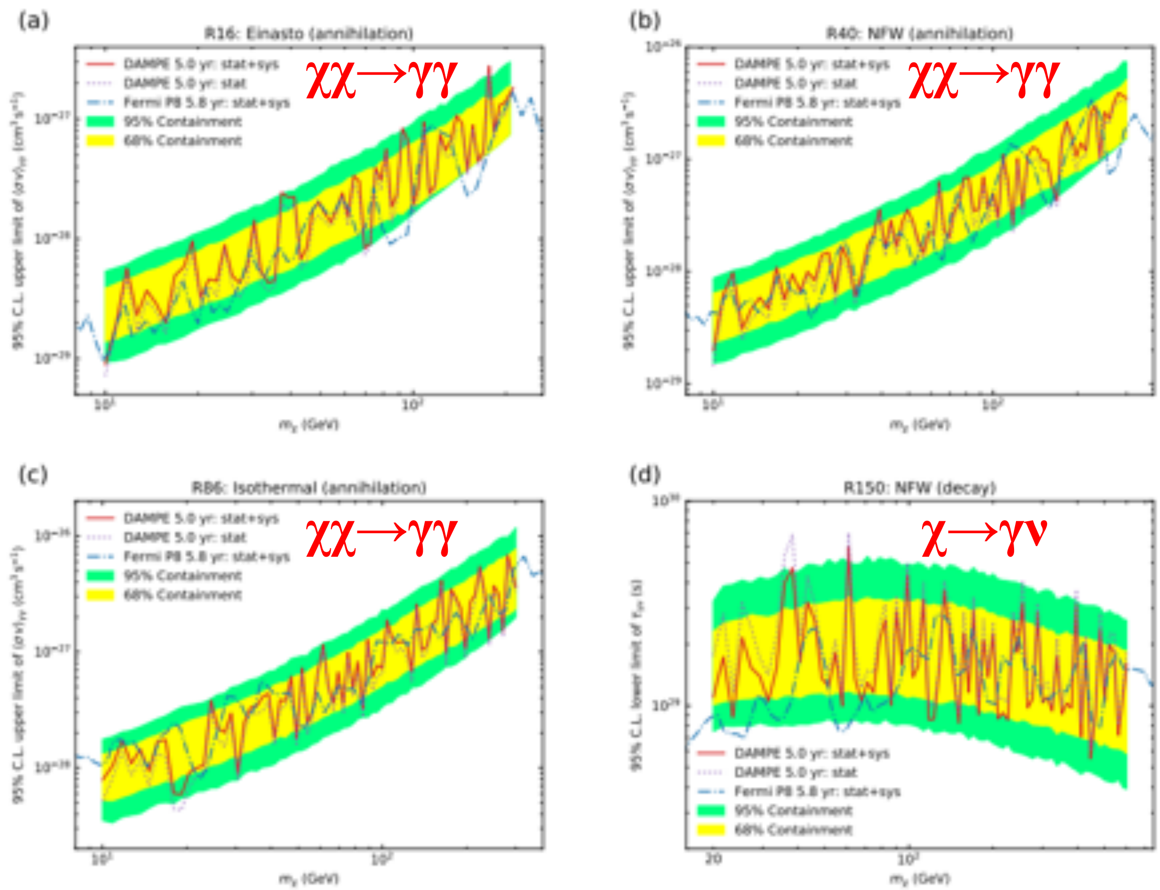
Data available at http://dgdb.pmo.ac.cn/dampe/

Results: γ-ray line searches



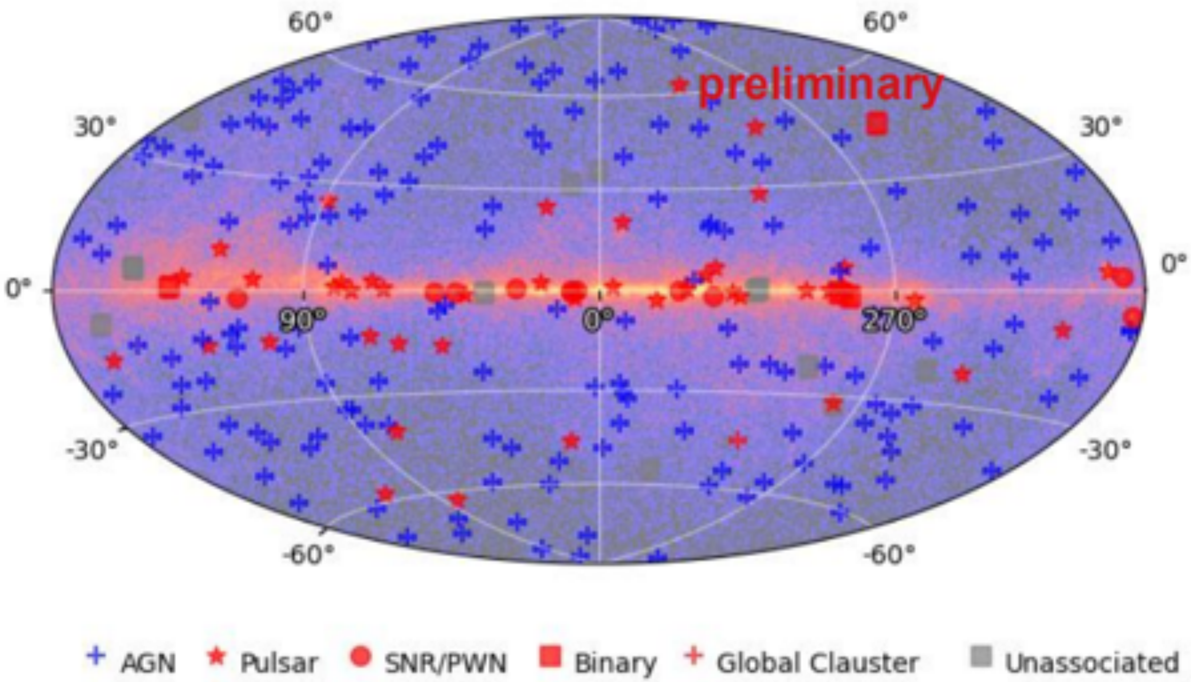


Science Bulletin, 67, 679 (2022)



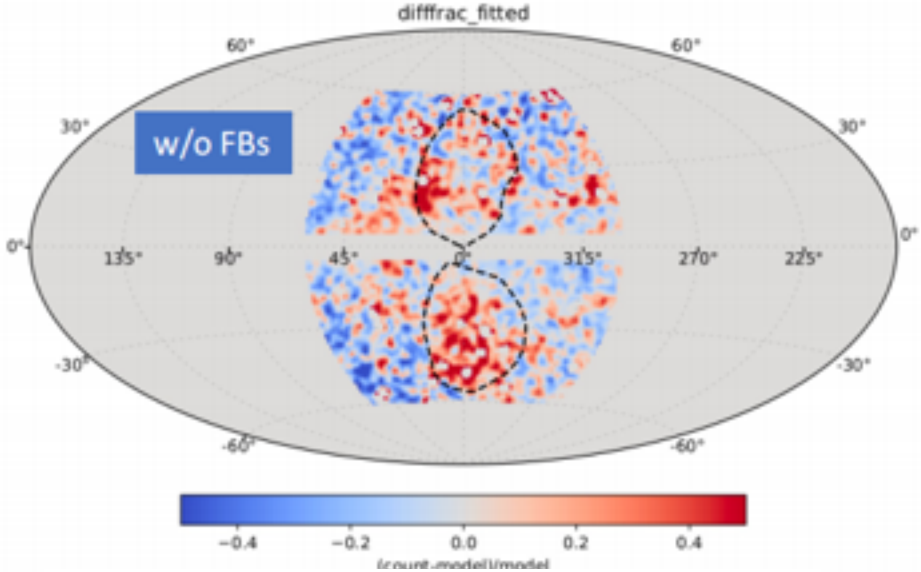
Obtain the most stringent constraints on dark matter annihilation cross section or decay lifetime

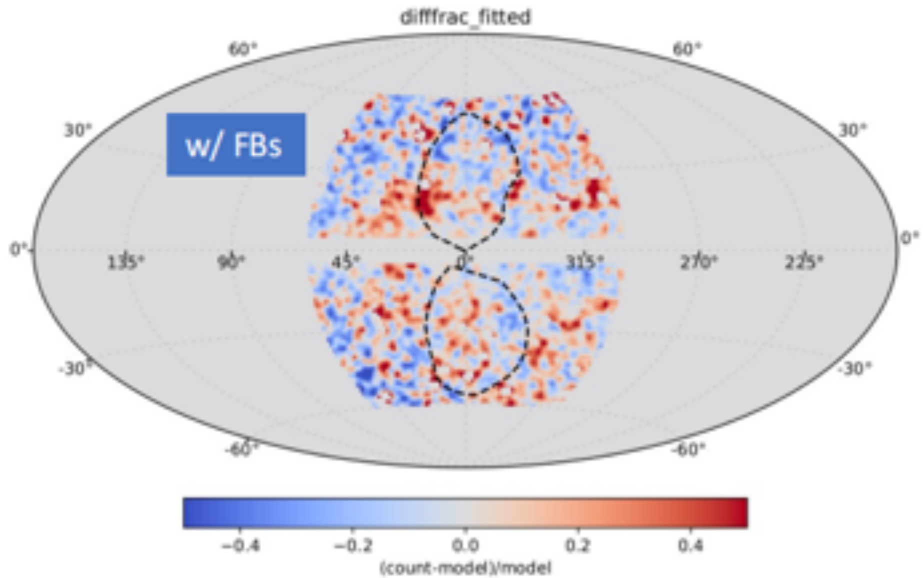
Results: γ-ray catalog

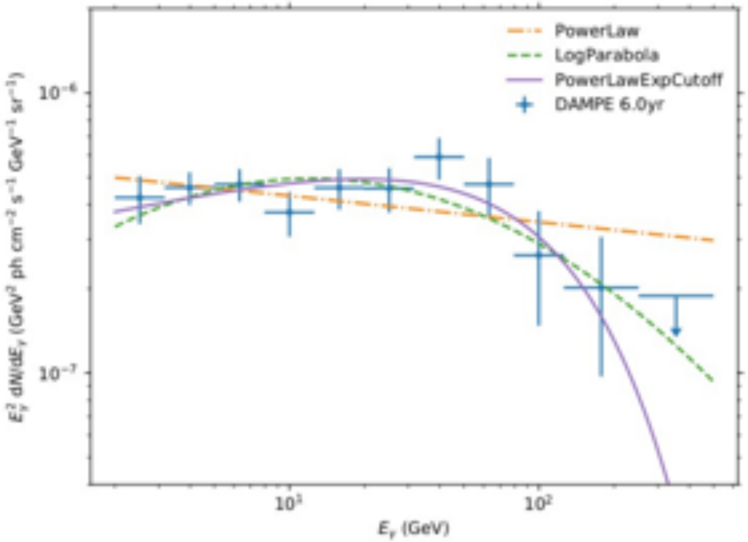


Source Type	Number
AGN	175
Pulsar	45
SNR/PWN	11
Binary	4
Globular cluster	1
Unassociated	13
Total	249

Results: Fermi bubbles

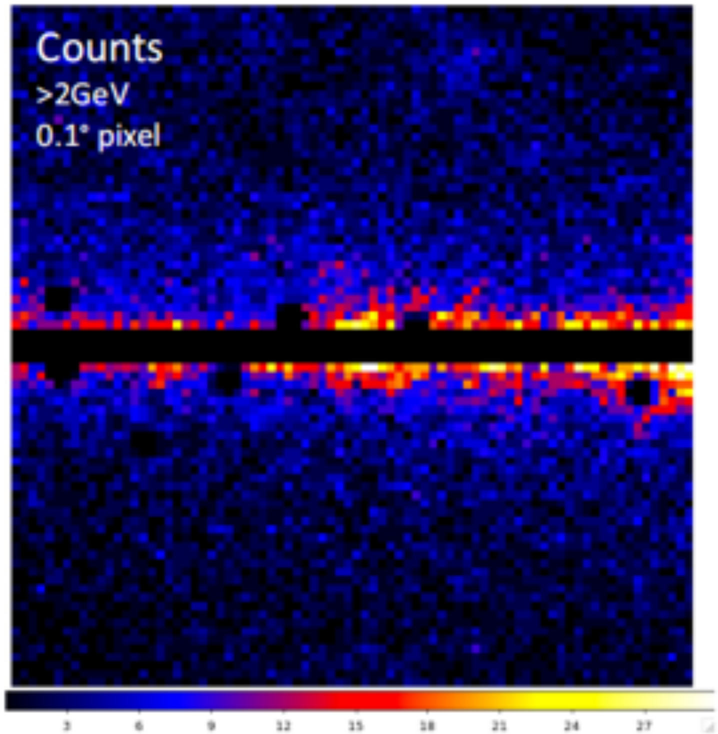


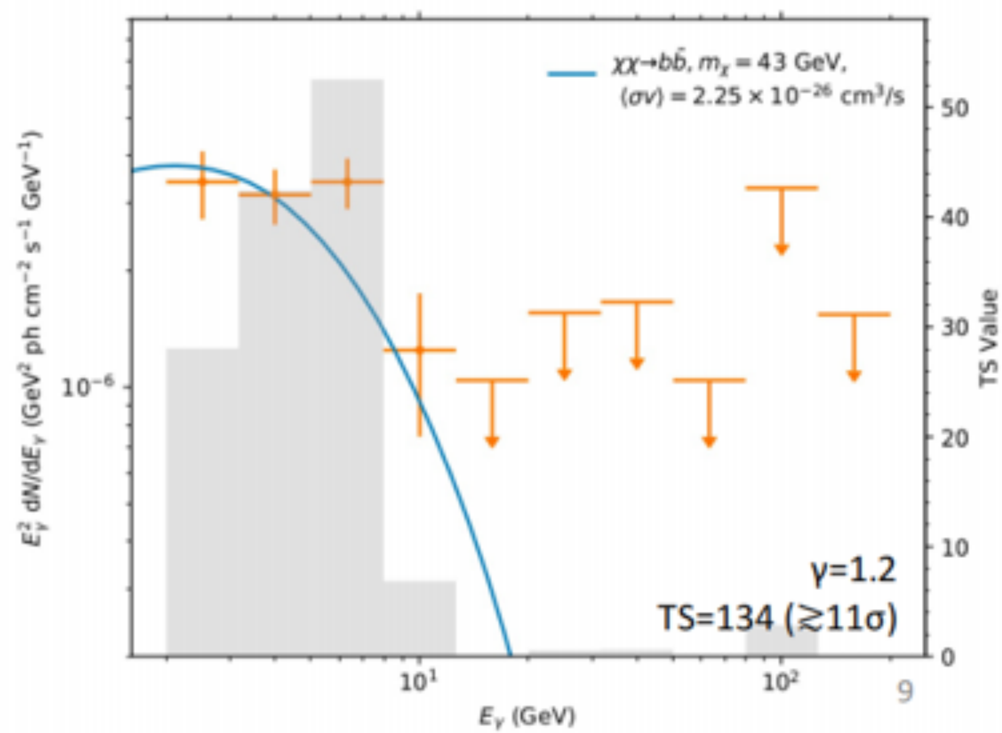




- ➢ Fermi bubbles are detected with ~18σ significance
- ➢ Spectral cutoff is favored at ~3.7σ

Results: GC γ-ray excess





The Galactic center γ-ray excess was detected with ~11σ significance. The spectrum is consistent with a dark matter annihilation model with m~43 GeV and <σv>~2e-26 cm^3/s

Summary

- DAMPE detector works smoothly for 6+ years, opening a new window to look at the high-energy Universe above TeV
- Precise measurements of the $e^{+}+e^{-}$ spectrum show a break at ~TeV energies
- Precise measurements of proton (helium) spectra reveal interesting softening features at ~14 (34) TeV
- Stringent upper limits on dark matter annihilation/decay into monochromatic γ-rays have been obtained
- More than 250 γ-ray sources are detected, including Fermi bubbles and Galactic center excess
- More results about cosmic ray nuclei and γ-rays are coming

Thank You!