Probing the origin and propagation of cosmic rays with DAMPE and LHAASO

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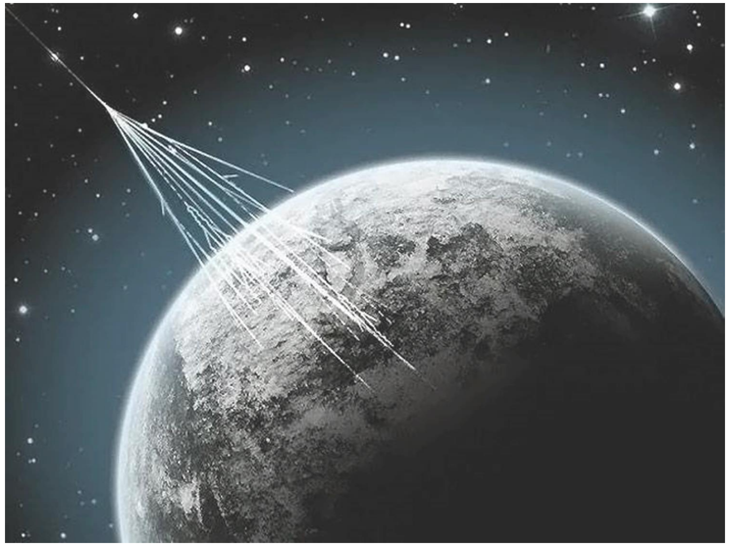
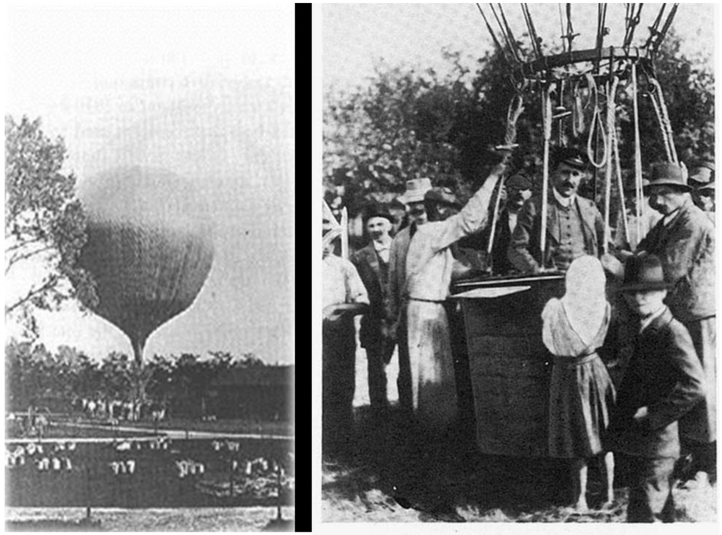
2023.4.6 @ Interdisciplinary Center for Theoretical Study, USTC

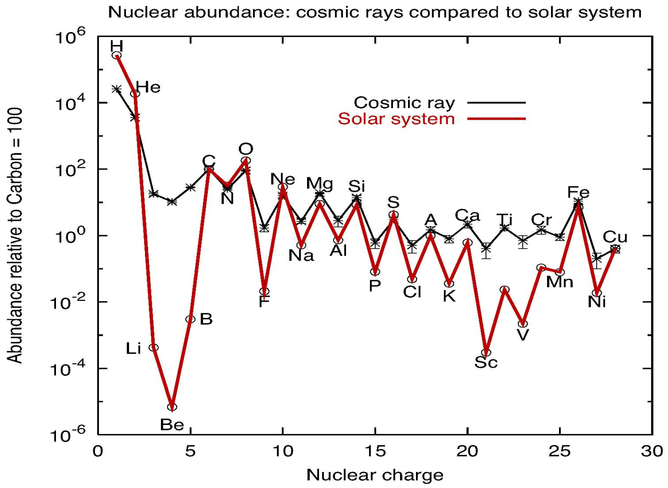
Cosmic rays: overview



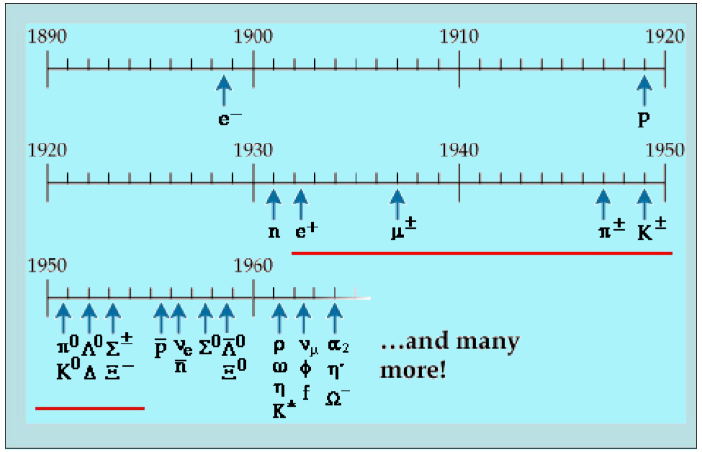
Discovered by V. Hess etc. in 1910s



Hess bei Ballonlandung (1912).



Including almost all elements observed on the Earth



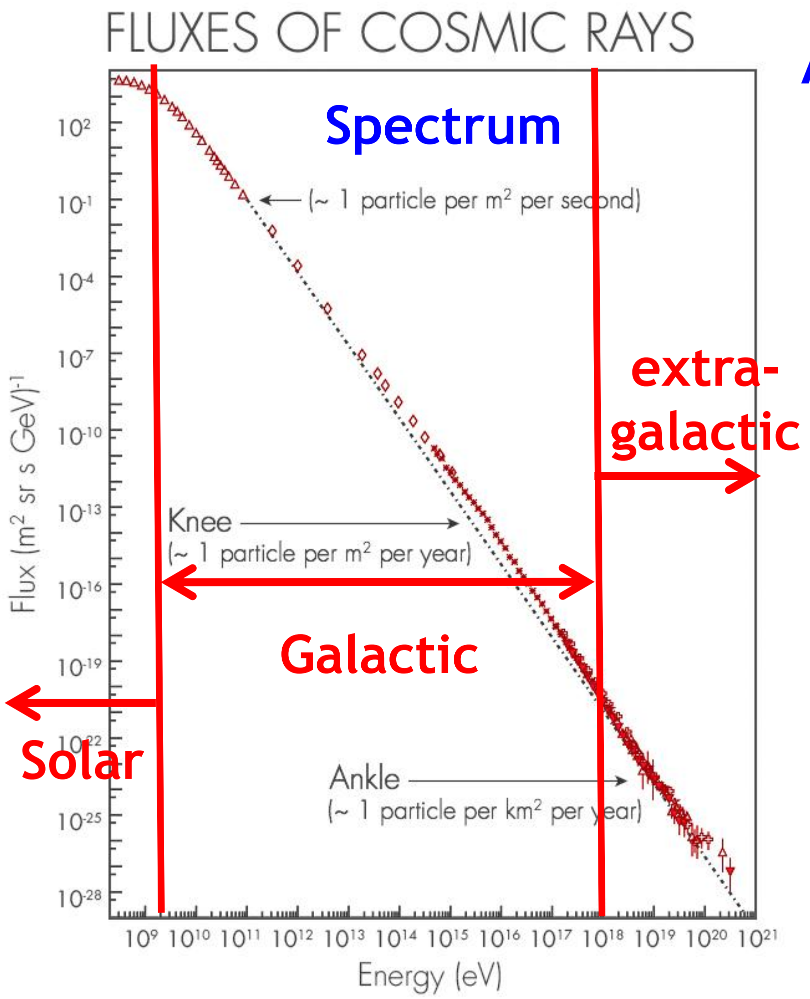
Leading particle physics from 1930s to 1950s

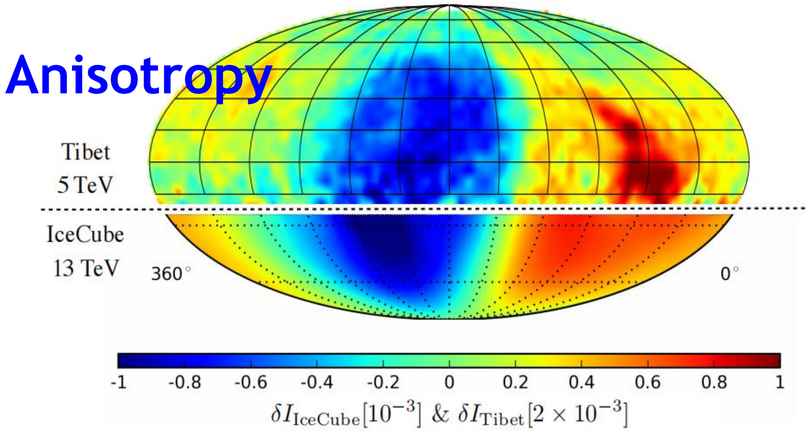
Four astronomical messengers: electromagnetic waves, gravitational waves, cosmic rays, neutrinos

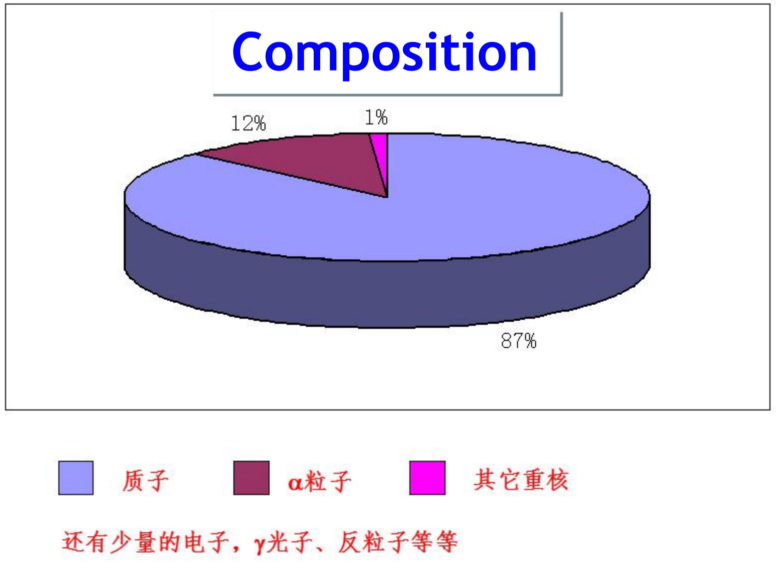
New Physics
- Dark matter
- Acceleration at ultra-high energies
- Lorentz invariance violation

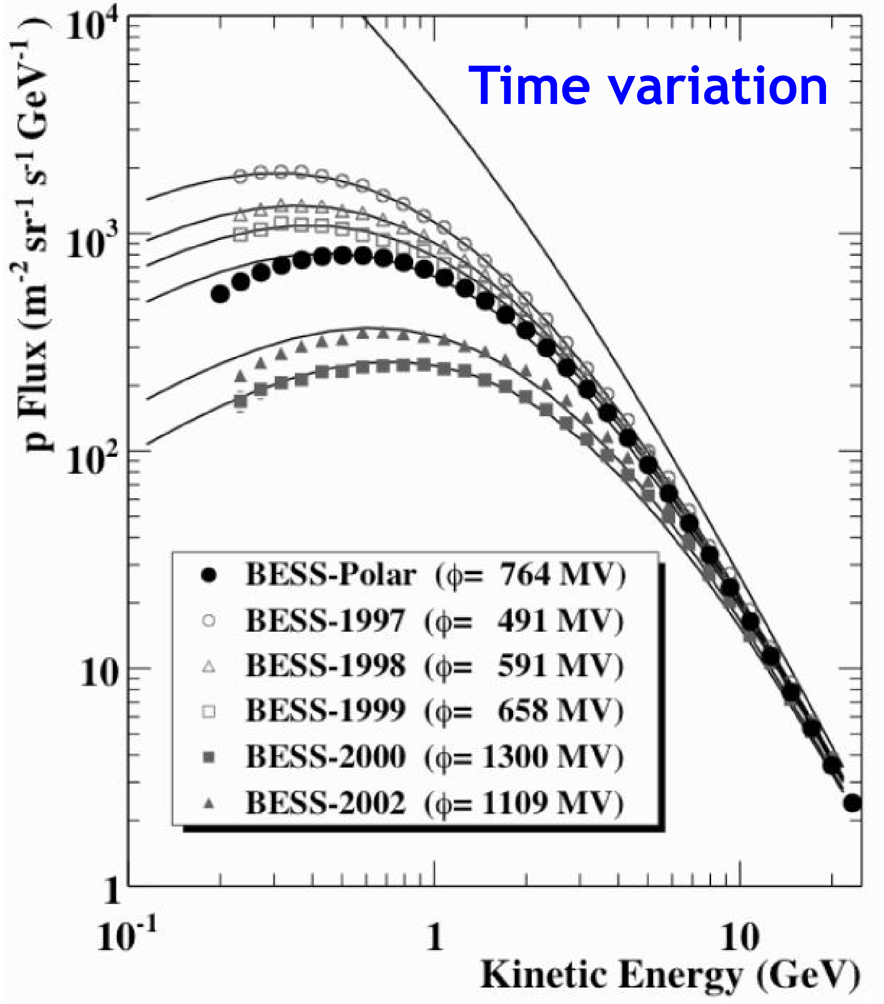
New Astronomy
- Cosmic ray sources
- Objects at extreme conditions (energy, density, gravity etc.)

Cosmic rays: overview



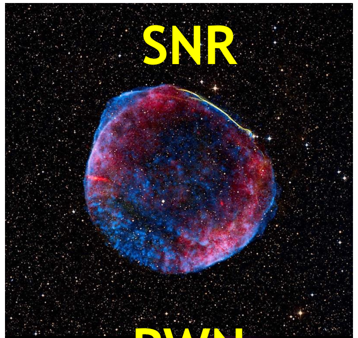


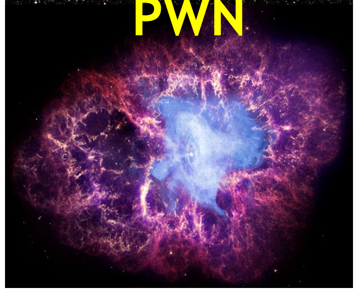


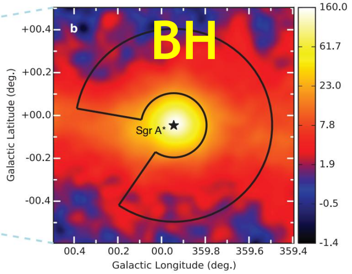


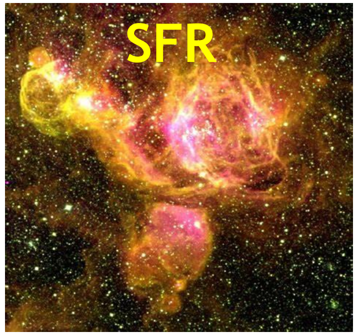
Spectrum: non-thermal power-law, structures; **Anisotropy:** <10^{-3} dipole + small-scale anisotropy; **Composition:** mostly nuclei, a tiny fraction of electrons, positrons, anti-particles; **Time variation:** anti-correlation with solar activities at low energies

Production, propagation, and interaction of CRs

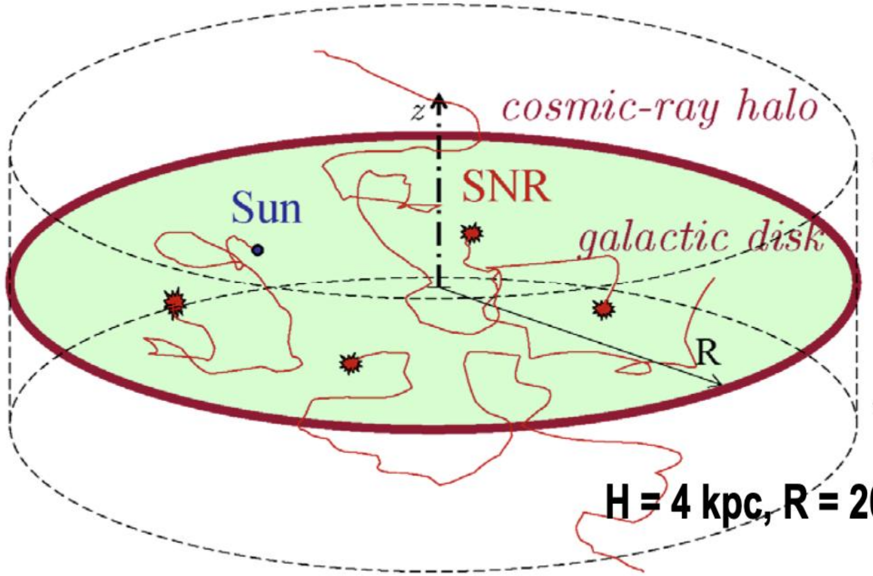






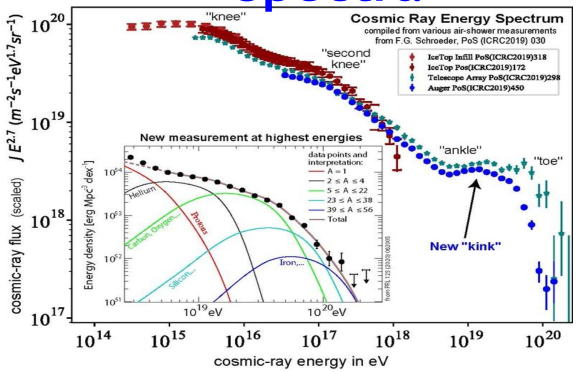


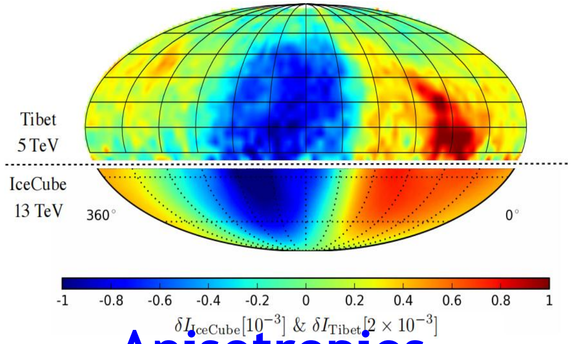
Interstellar propagation



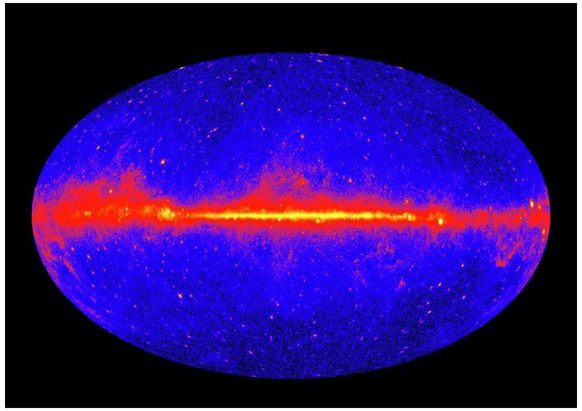
H = 4 kpc, R = 20 kpc

Spectra





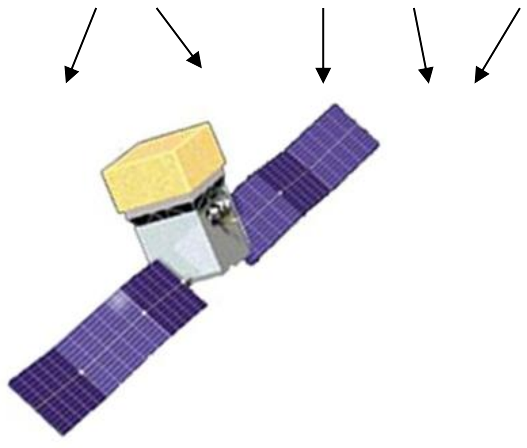
Anisotropies



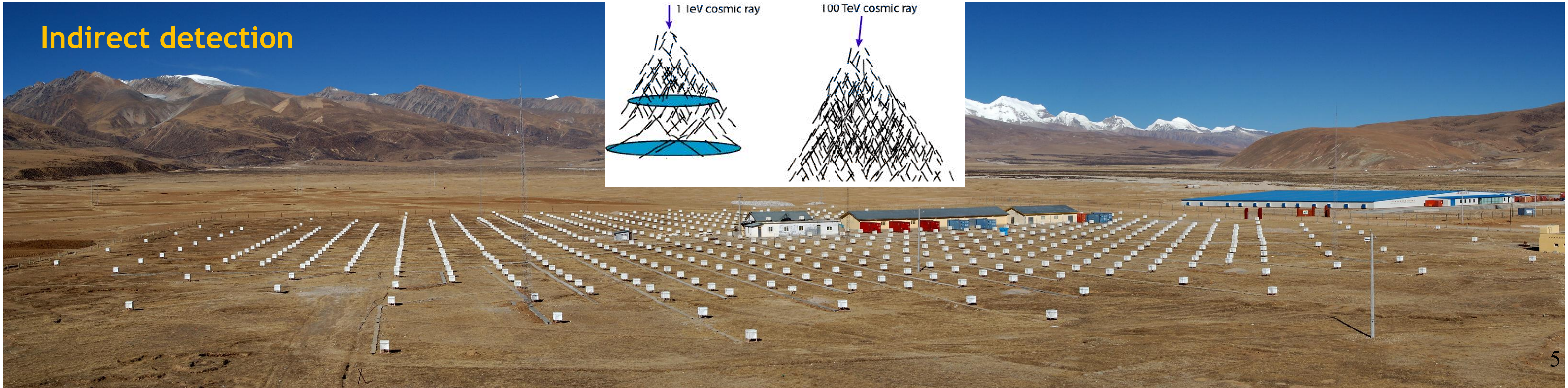
Multi-wavelength emission

Detection of cosmic rays

Direct detection

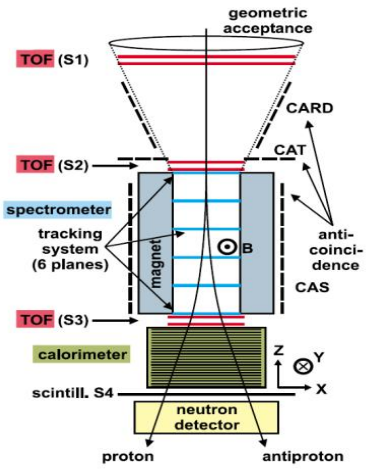


- Low-energy CRs get blocked by the atmosphere, and direct detection in high atmosphere or space is required: small detector, high cost, good particle identity
- High-energy CRs cannot be detected by space detectors due to their low fluxes; the indirect detection of their cascade particles in the atmosphere is required: large-scale detector, economic, poor particle identity

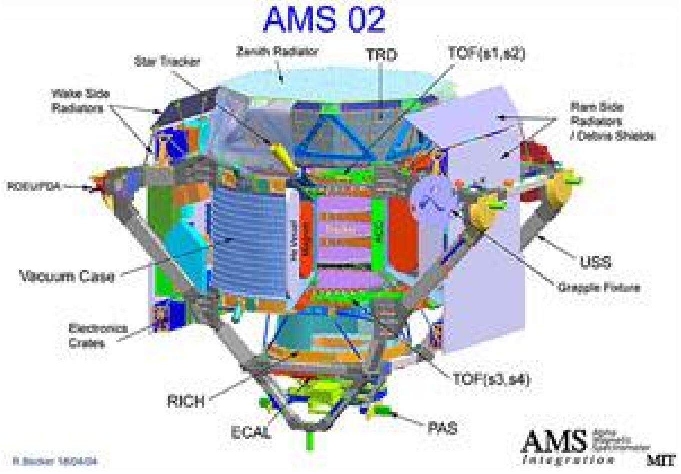


Recent/ongoing experiments

PAMELA

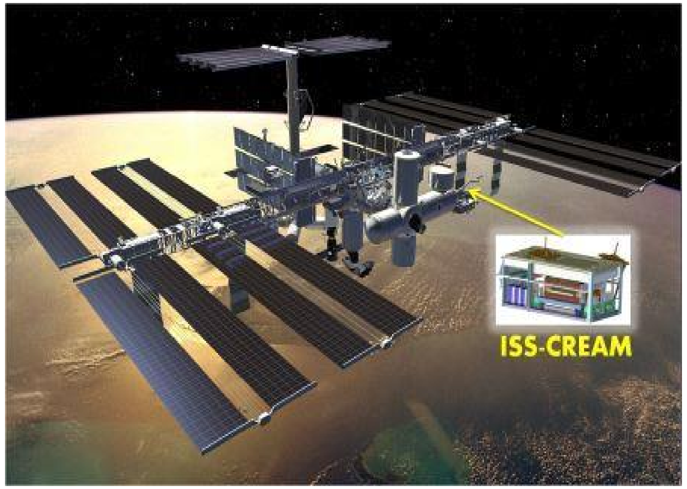


AMS-02



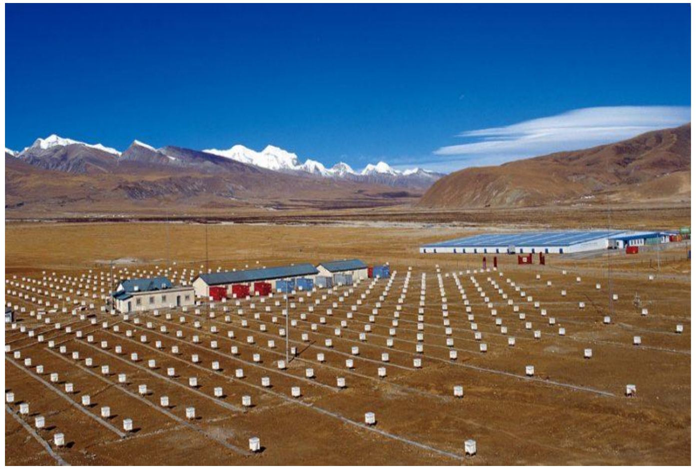
CALET

ISS-CREAM



KSACADE

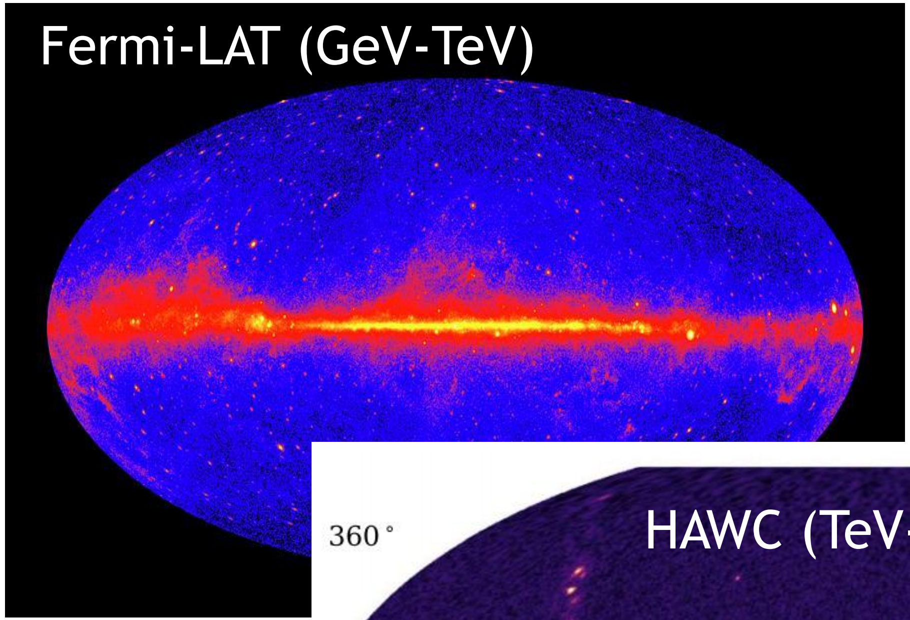
羊八井

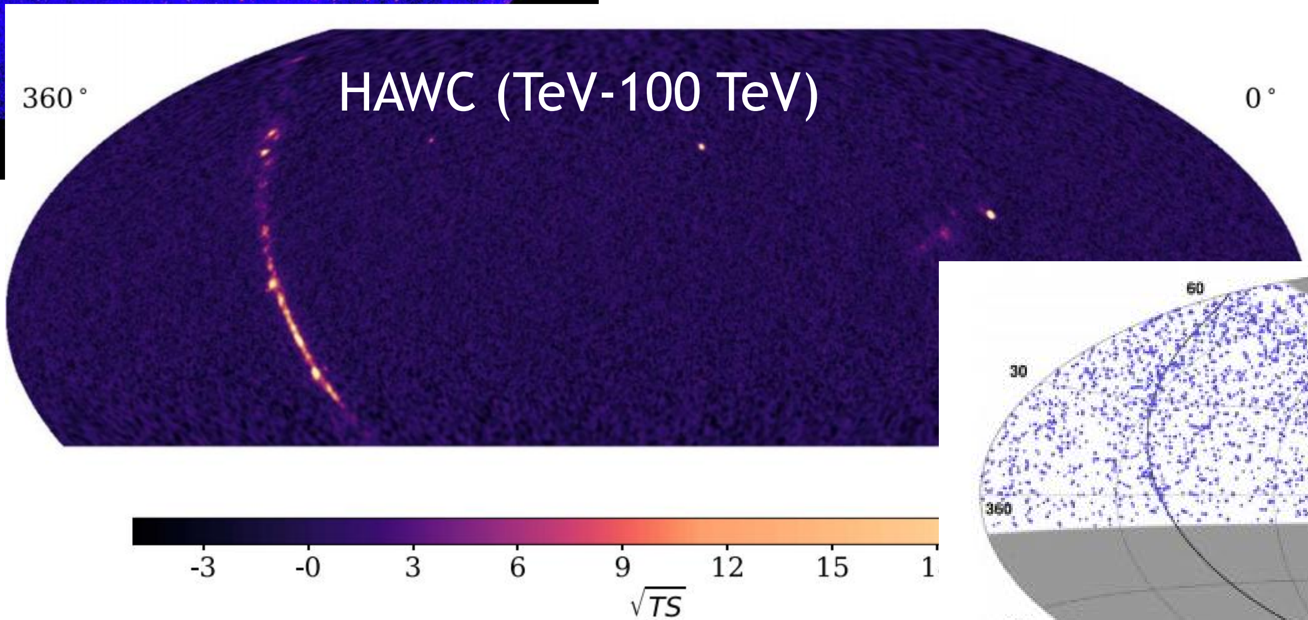


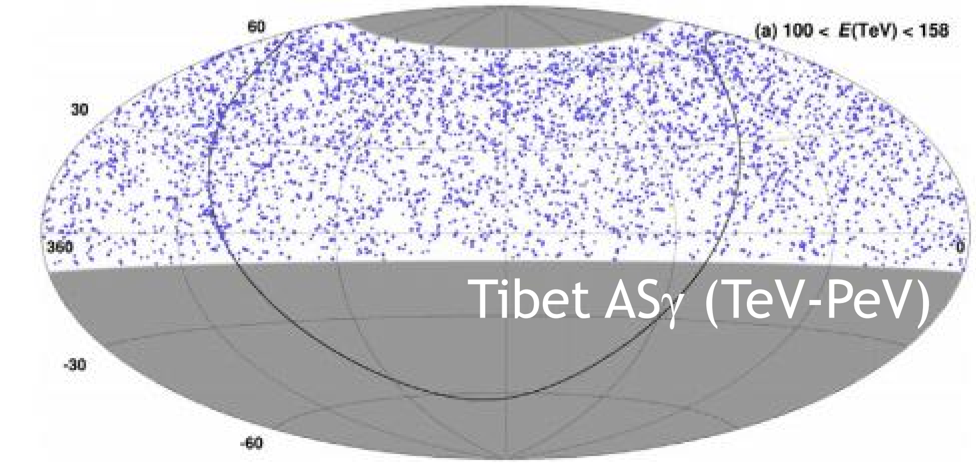
HESS/MAGIC/VERITAS/CTA

HAWC

Gamma-rays from GeV to PeV







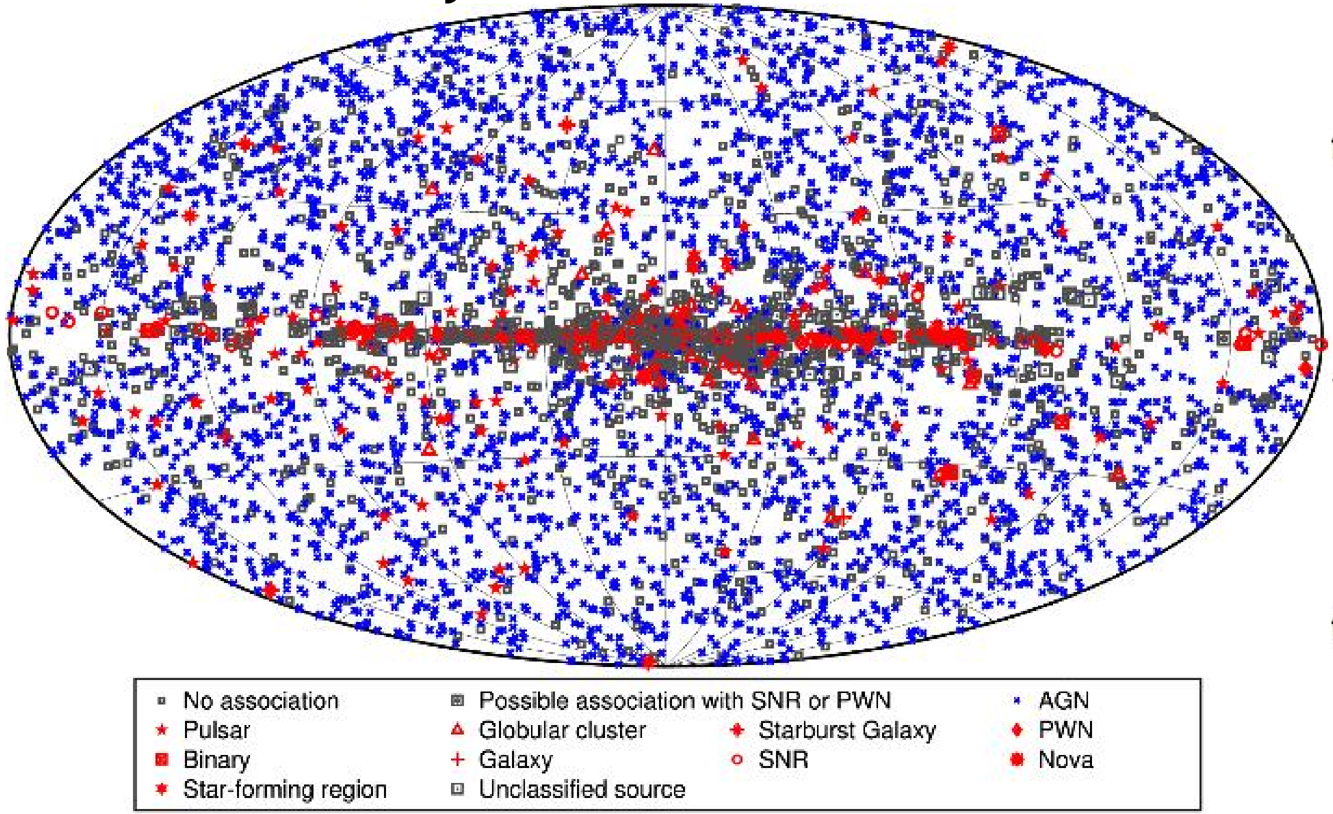
p, α + gas $\rightarrow \pi^0 \rightarrow 2\gamma$

$e^{+/-}$ + gas $\rightarrow \gamma$ (bremsstrahlung)

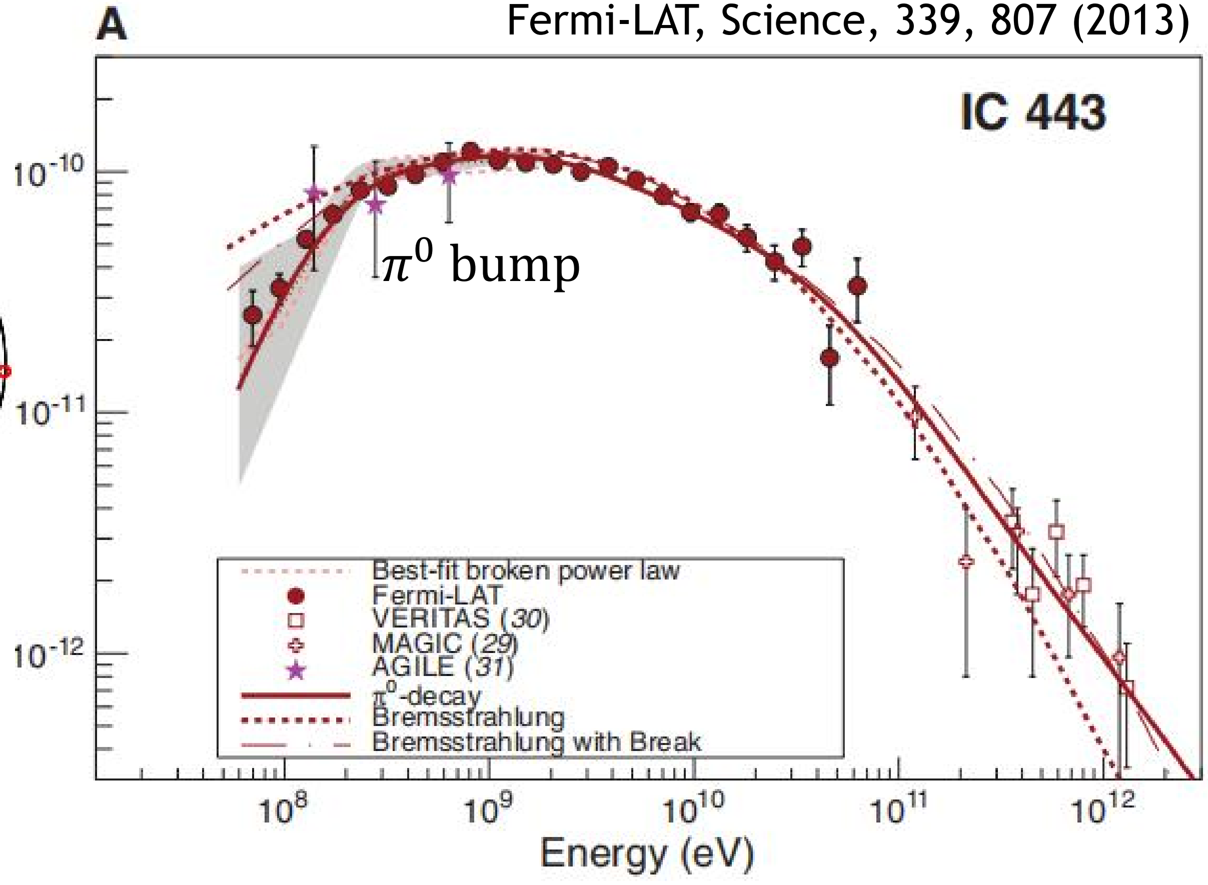
$e^{+/-}$ + ISRF $\rightarrow \gamma$ (inverse Compton scattering)

GeV Gamma-ray observations

>5000 sources by Fermi-LAT

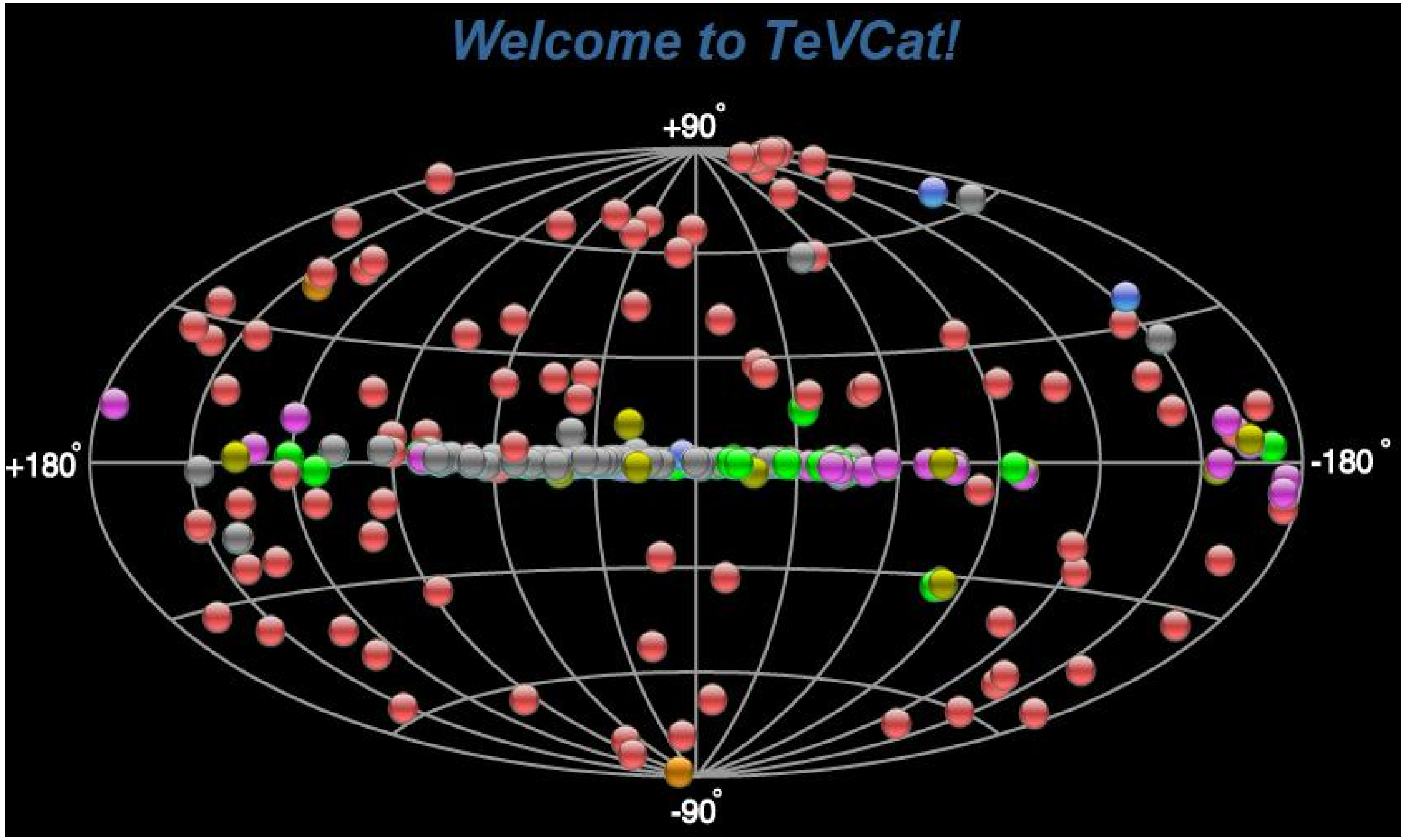


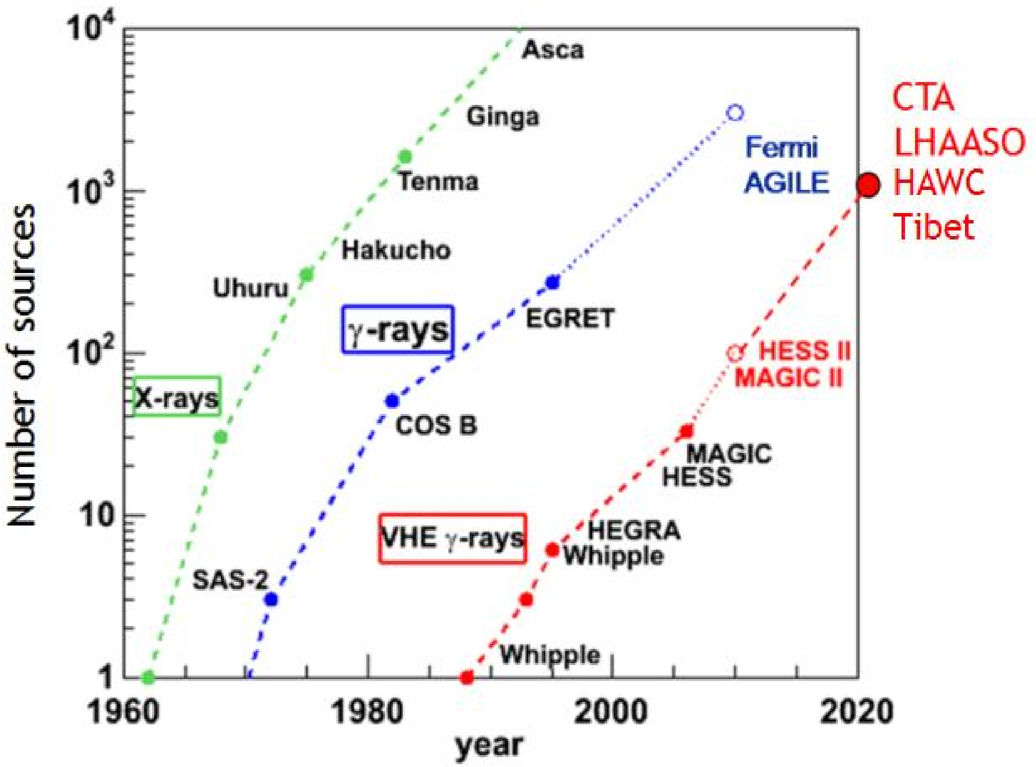
Fermi-LAT, Science, 339, 807 (2013)



Evidence of hadronic CR acceleration at supernova remnants was shown by Fermi-LAT via the characteristic pion-bump; subject to large systematic uncertainties at low energies

TeV Gamma-ray observations



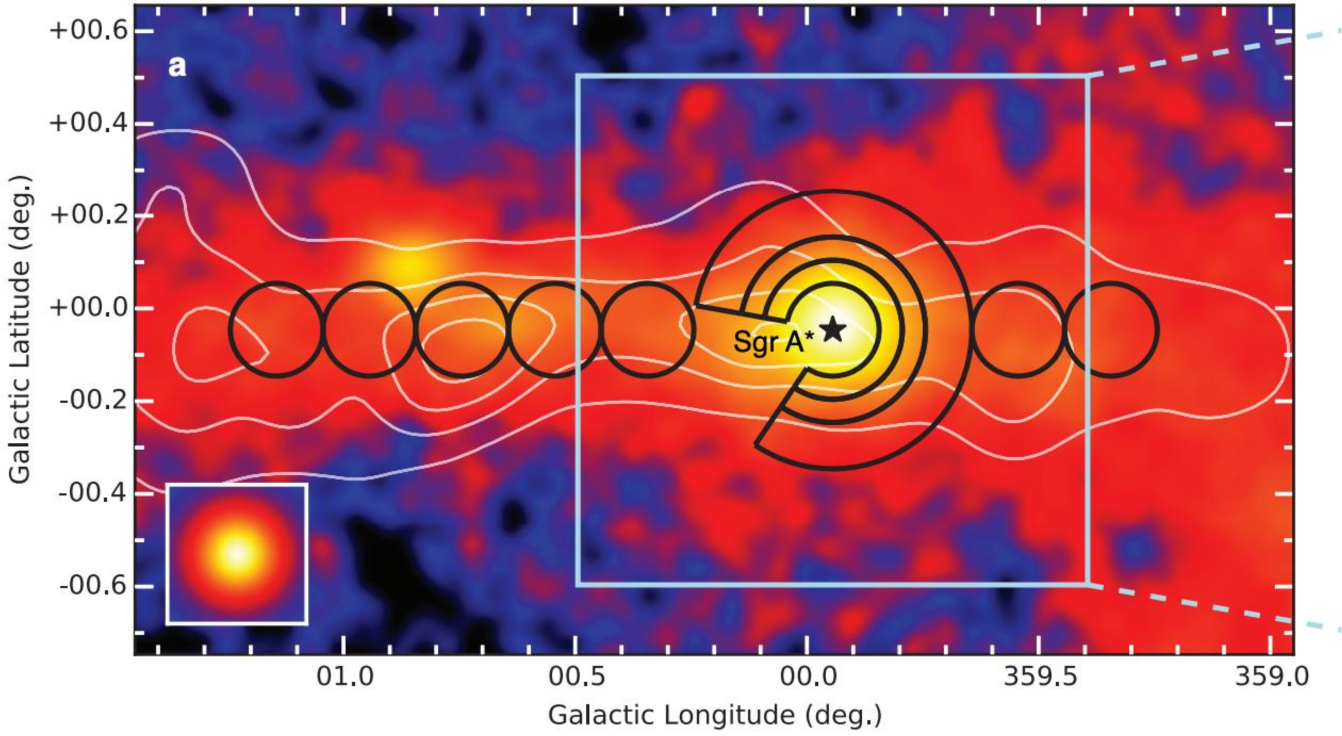


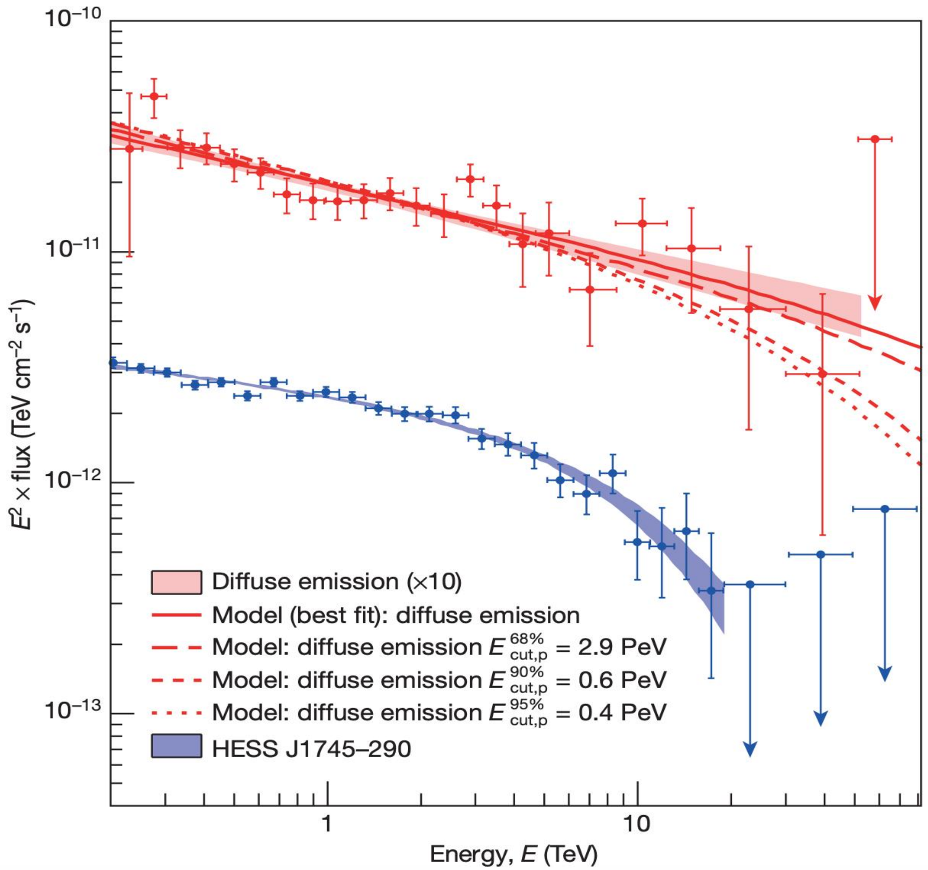
http://tevcat.uchicago.edu/

TeV Gamma-ray observations

Sgr A* as a PeVatron candidate

HESS. Nature. 531. 476 (2016)

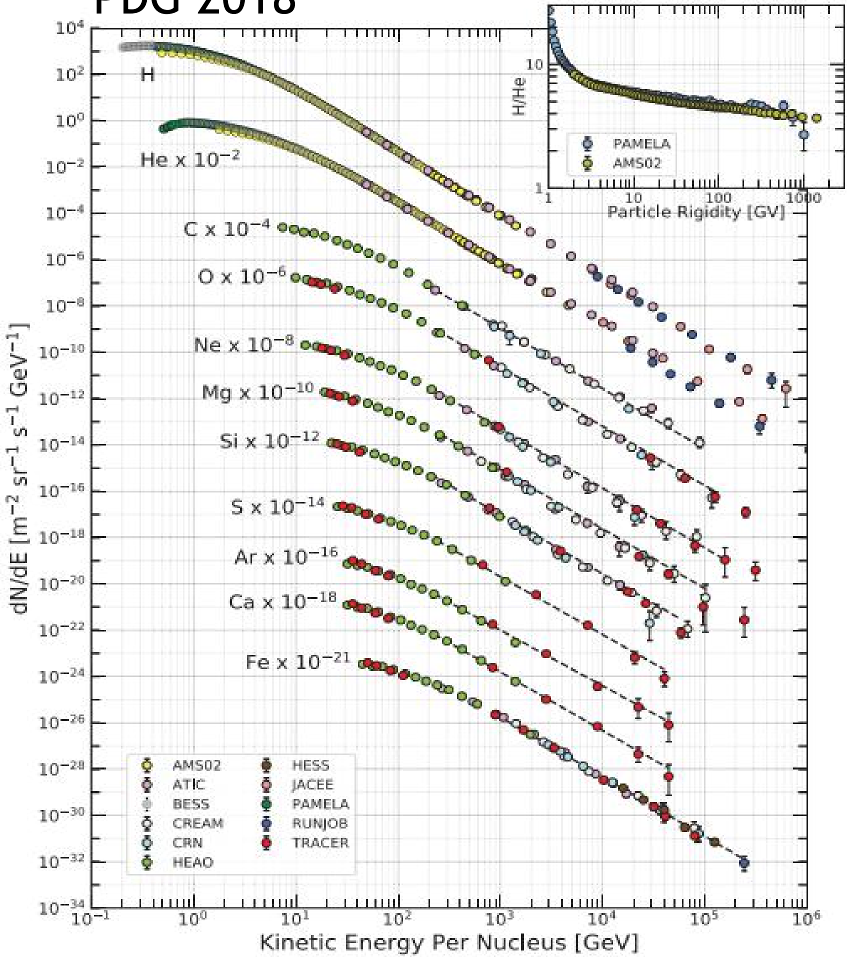


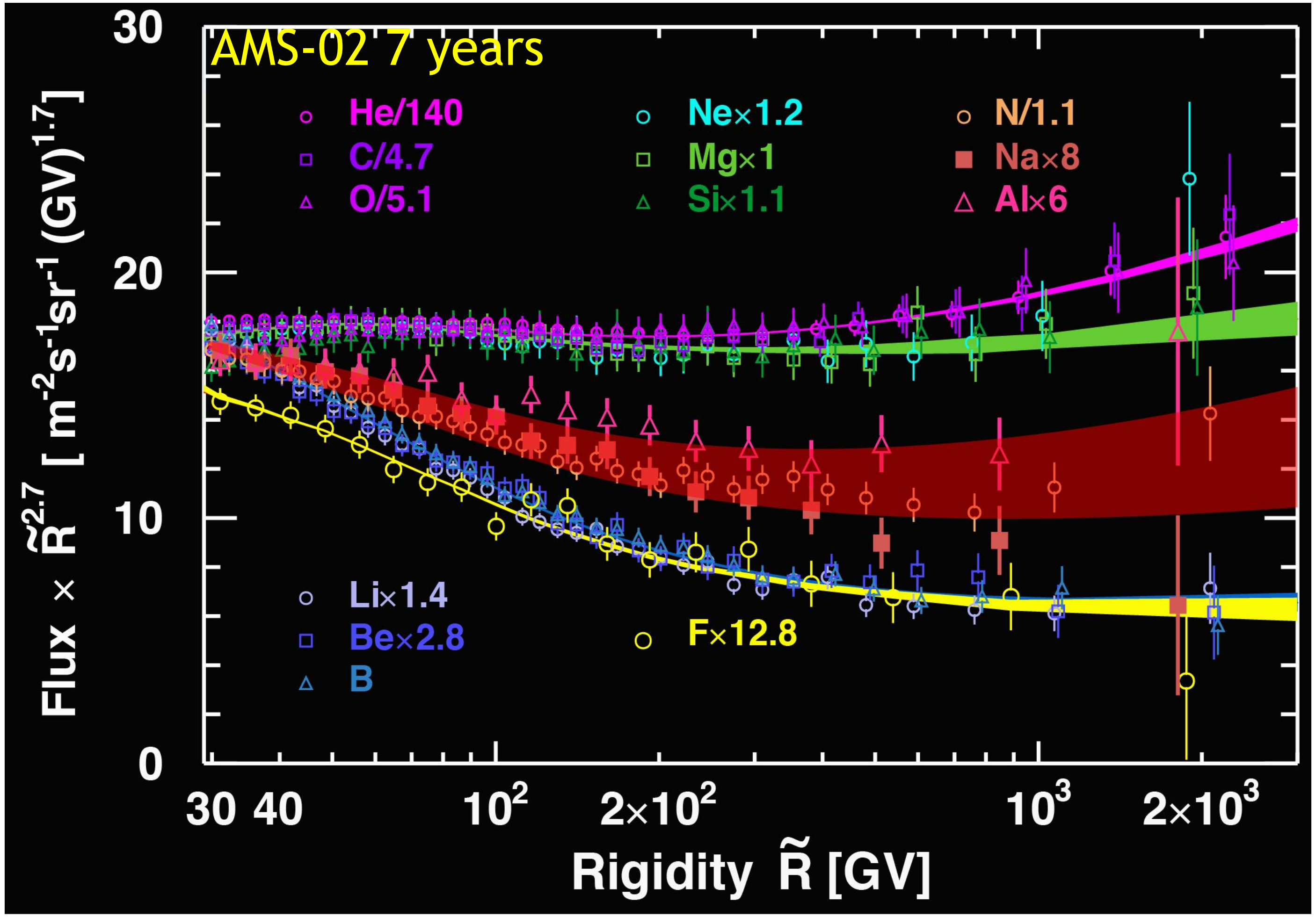


HESS observations of the Galactic center region reveal extended emission up to 50 TeV, could be explained with ISM interaction with CR protons up to PeV

Measurements of CR spectra

PDG 2018

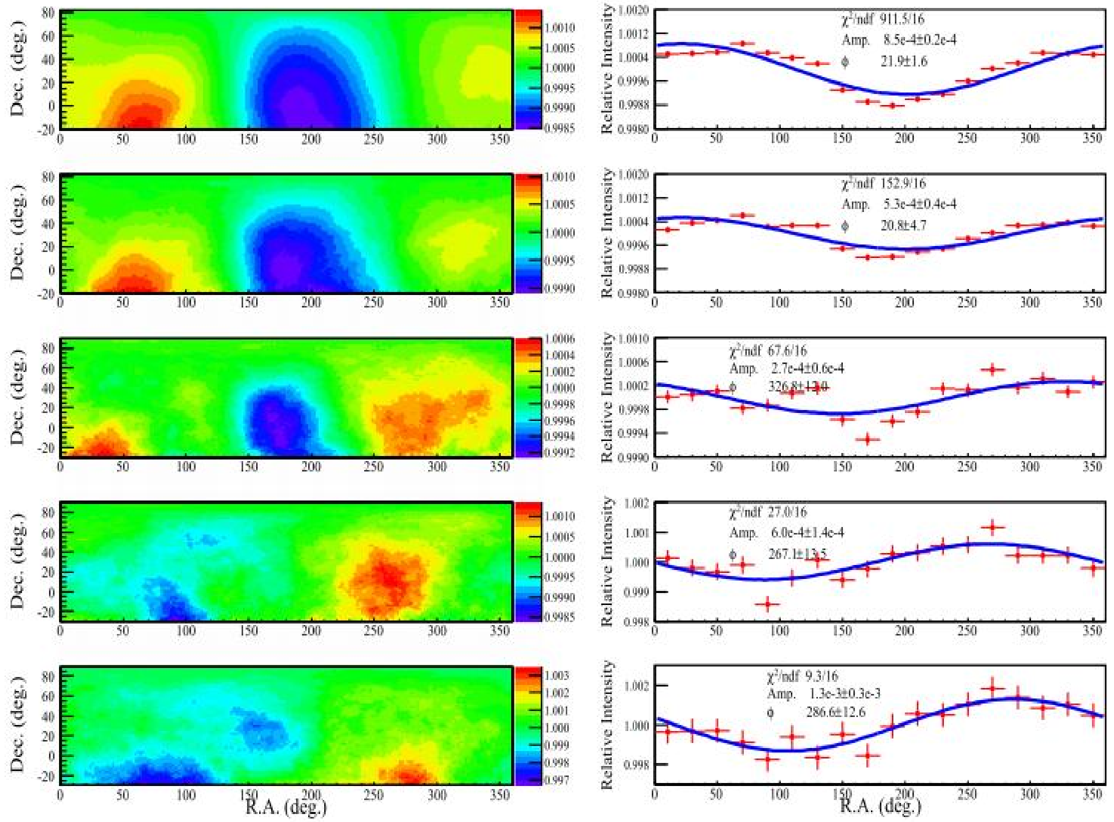




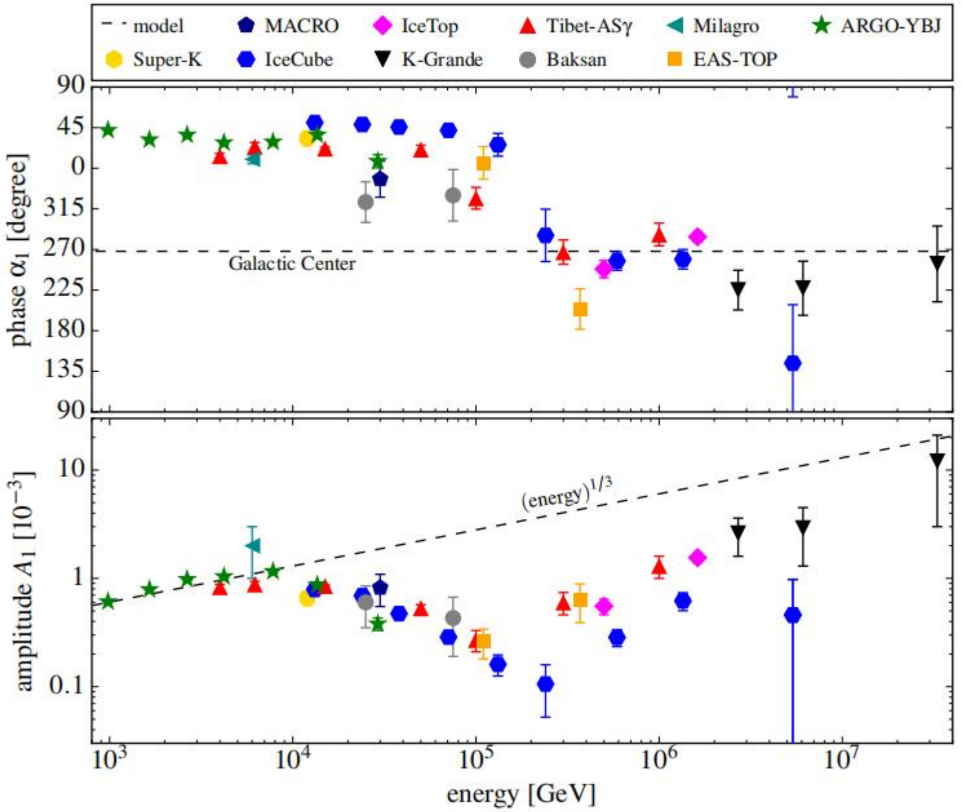
Spectra of many nuclei species have been precisely measured up to TV rigidity, showing hardening features around O(100) GV

Measurements of CR anisotropies

Tibet-ASγ, ApJ, 836, 153 (2017)



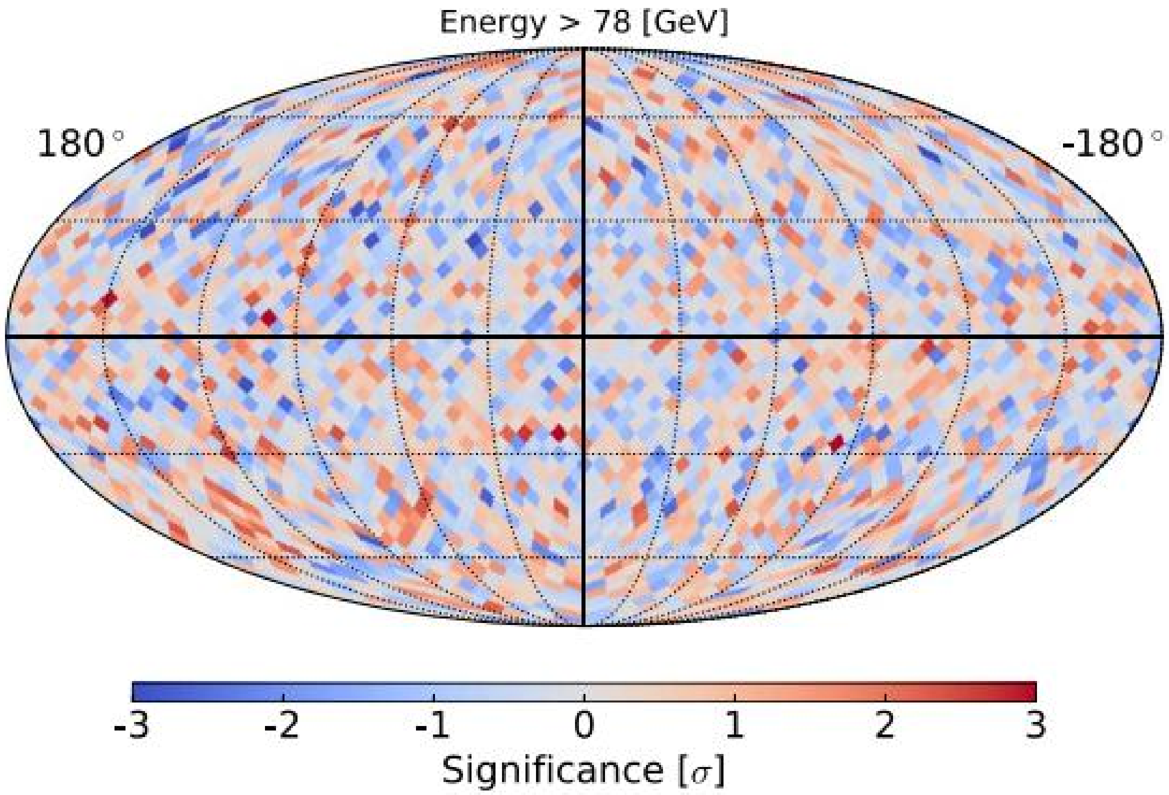
Ahlers & Mertsch, PPNP, 94, 184 (2017)

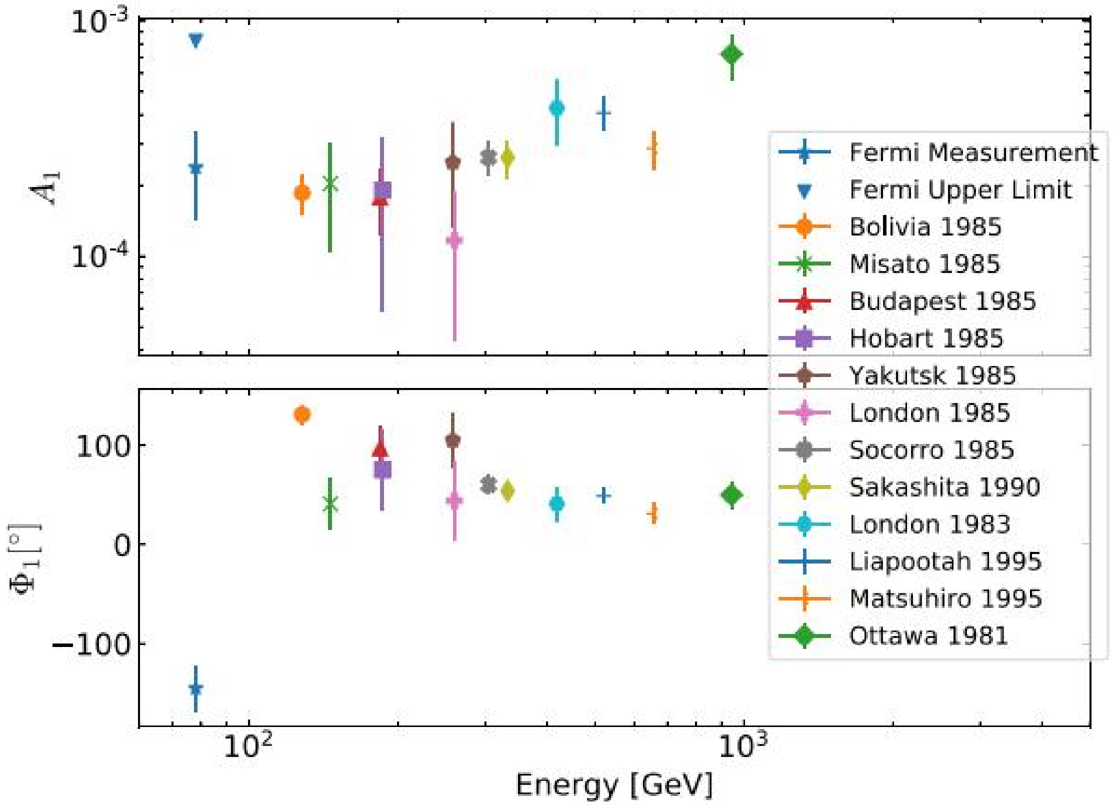


- ➢ **CR particles lose their directions due to the random scatterings in interstellar magnetic field, resulting in very tiny anisotropies (10^{-4}~10^{-3})**
- ➢ **To measure the anisotropies require high statistics, and can only be achieved by groundbased experiments without measurements for individual species**

Measurements of CR anisotropies

Fermi-LAT, ApJ, 883, 33 (2019)

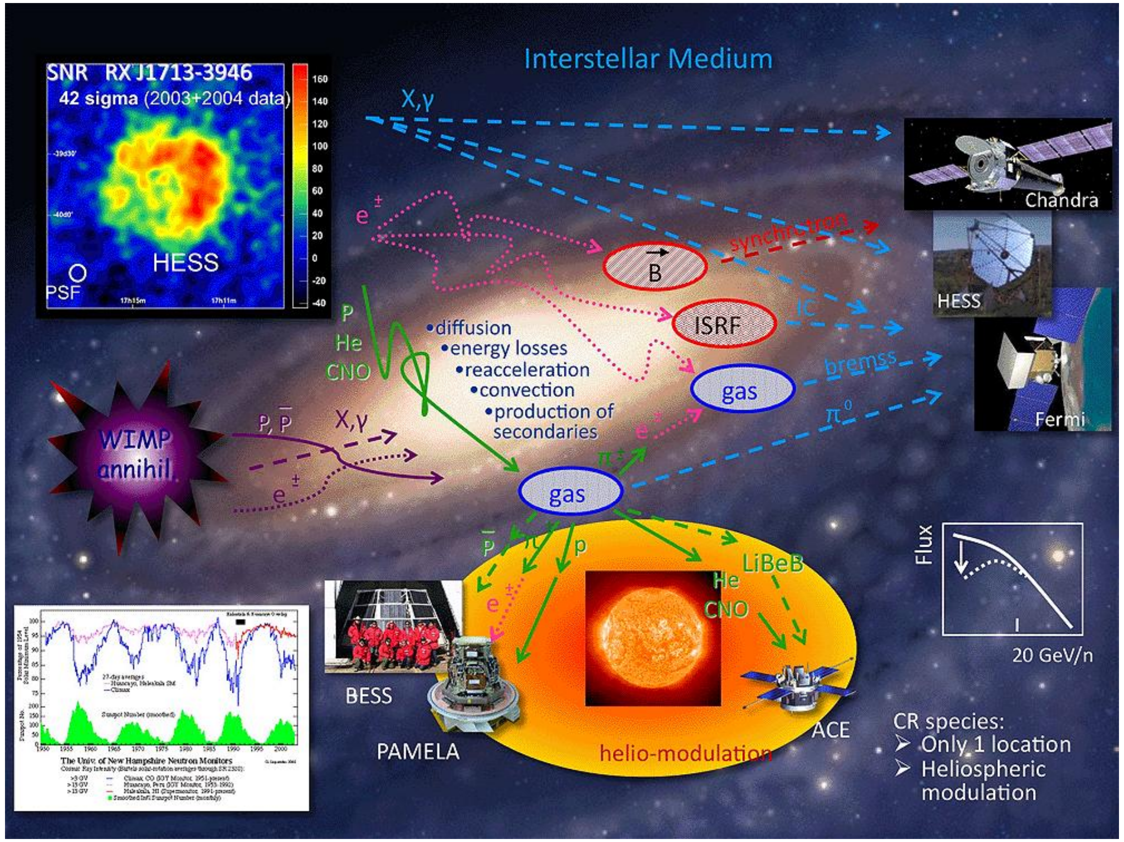


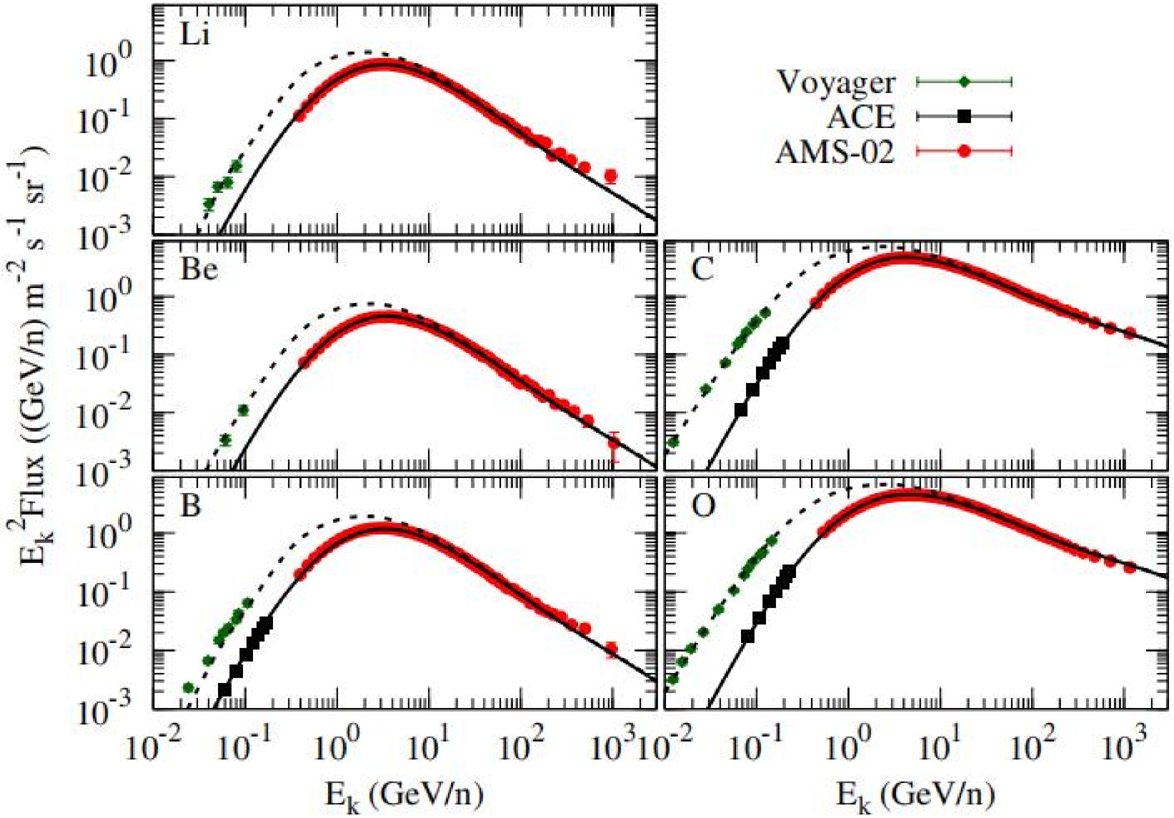


Fermi tried to measure for the first time anisotropies of protons in space, showing a marginal detection (2×10^{-4}) with a low significance (~2.5σ)

Galactic CR propagation model

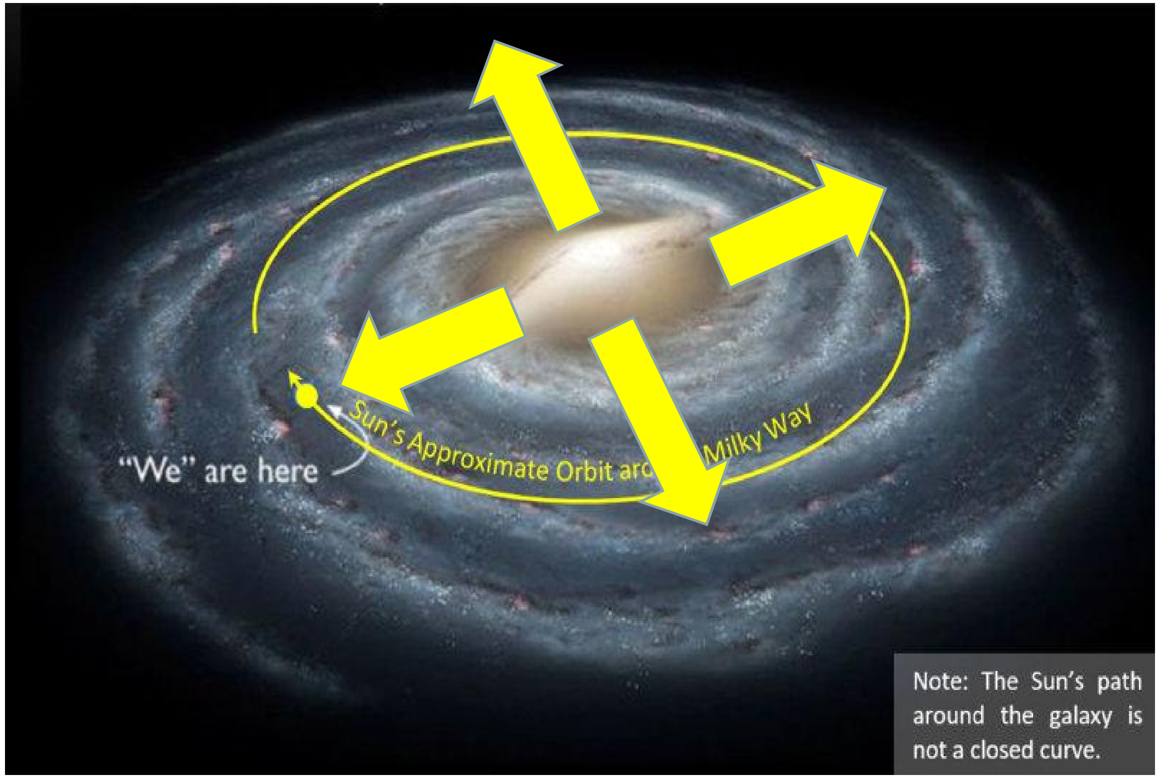
Yuan et al., JCAP, 11, 027 (2020)

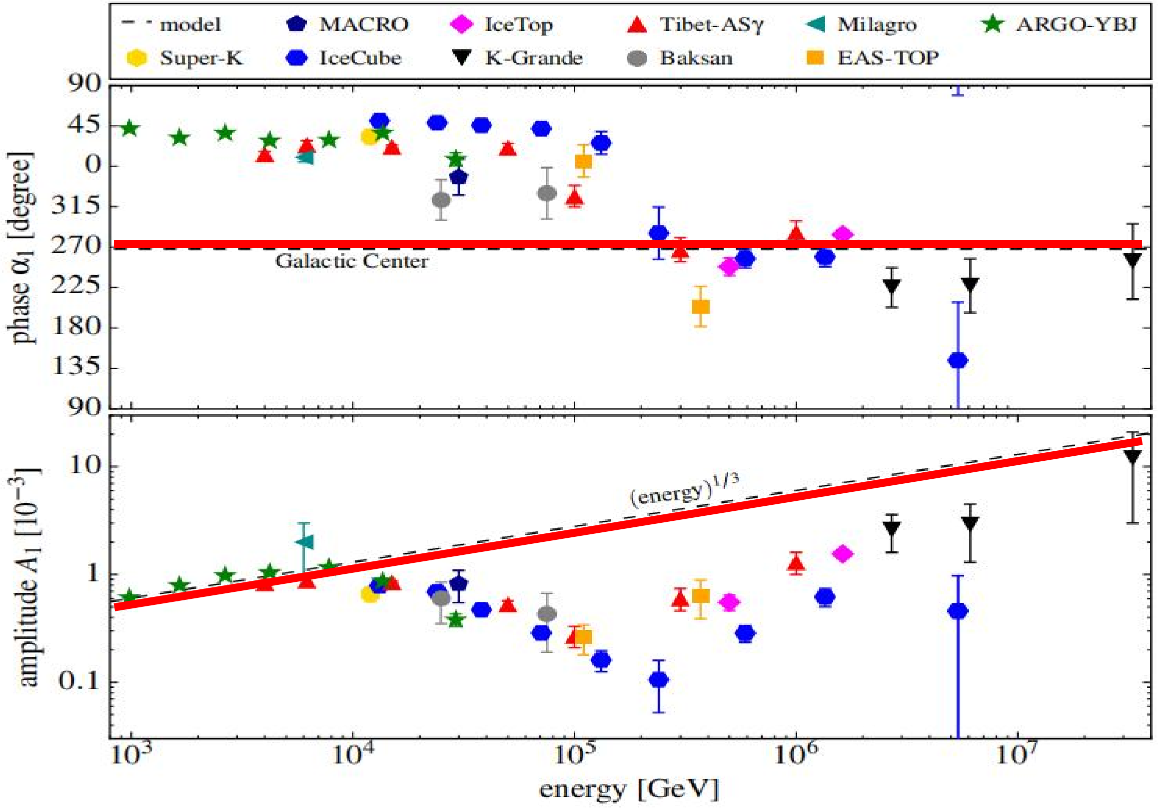




- ➢ Conventional picture: sources locate in a thin disk, particles diffuse in a thicker halo and interact with matter and fields
- ➢ Cannot explain energy evolution of anisotropies (amplitude and phase)
- ➢ Need to be revised to account for many new precise measurements

Galactic CR propagation model





- Conventional picture: sources locate in a thin disk, particles diffuse in a thicker halo and interact with matter and fields
- Cannot explain energy evolution of anisotropies (amplitude and phase)
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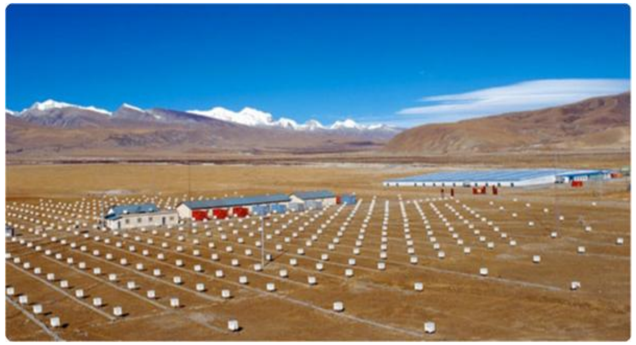
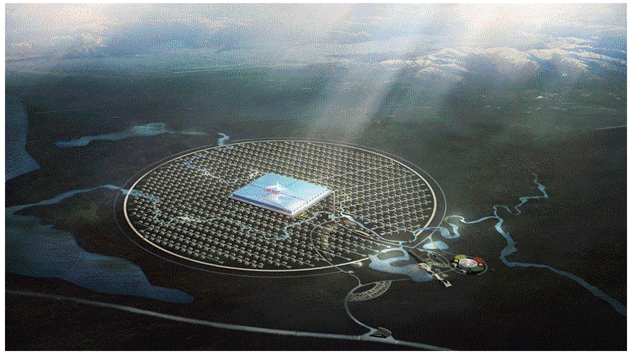
CR studies in China

Yunnan (1950s)

Tibet (1970s)



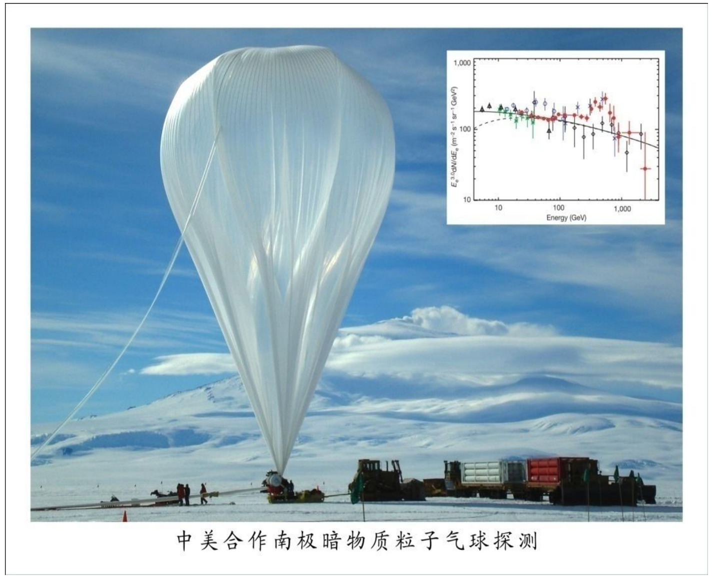
Tibet (1990s)



Sichuan (2010s)

Balloon (1970s)

921 (1990s)



Balloon (2000s)

DAMPE (2010s)

Dark Matter Particle Explorer——DAMPE

NEWS IN FOCUS

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2015年12月17日发射

The Monkey King spacecraft, which took to the skies on 17 December, is designed to detect the high-energy particles produced by annihilating dark matter.

COSMOLOGY

Dark-matter probe launches era of Chinese space science

Monkey King is first in a line of Chinese space missions focused on scientific discovery.

BY ELIZABETH GIBNEY, CELESTE BIEVER & DAVIDE CASTELVECCHI

Against a purple morning sky, in a cloud of brown smoke, the Monkey King took off. China's first space-based dark-matter detector — nicknamed Wukong (or Monkey King) after a warrior in a sixteenth-century Chinese novel — rocketed into the air on 17 December, marking the start of a new direction in the country's space strategy.

From Earth's orbit, the craft aims to detect high-energy particles and γ-rays. Physicists think that dark matter — a substance thought to make up 85% of the Universe's matter but so far observed only through its gravitational effects — could reveal itself by producing such cosmic rays as its constituent particles annihilate.

Wukong, officially called the Dark Matter Particle Explorer (DAMPE), is also notable for being the first in a series of five space-science missions to emerge from the Chinese Academy of Sciences' Strategic Priority Program on Space Science, which kicked off in 2011.

China is already one of the world's major space powers, but so far has focused on human and robotic exploration, with little investment in space science. (A notable exception is the Double Star probe launched in collaboration with the European Space Agency in 2003 to study magnetic storms on Earth.)

The DAMPE lift-off from the Jiuquan Satellite Launch Center in northern China will be followed next year by a further two missions: the world's first quantum-communications satellite and an X-ray telescope observing in ▶

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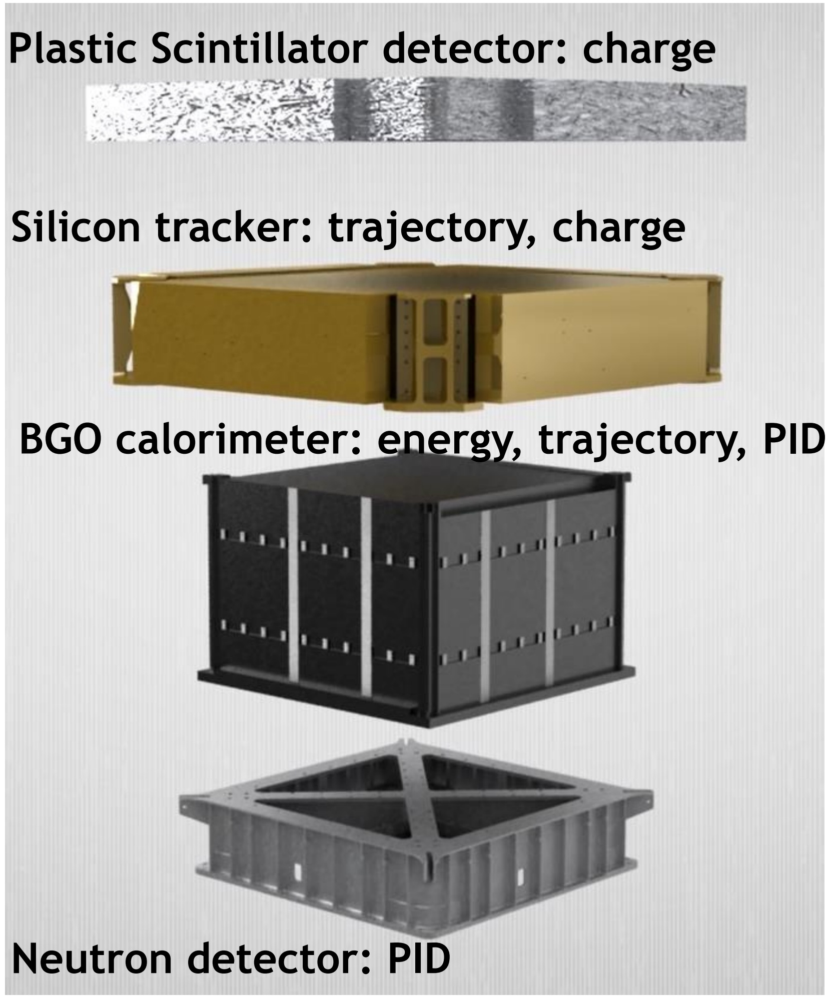
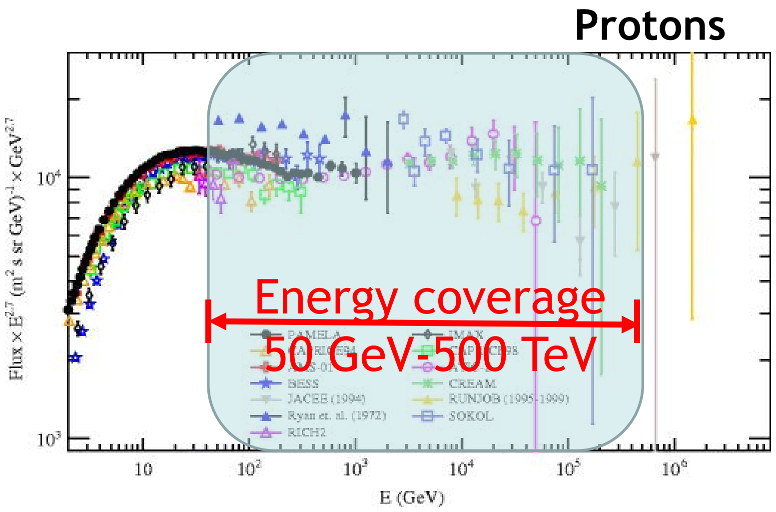
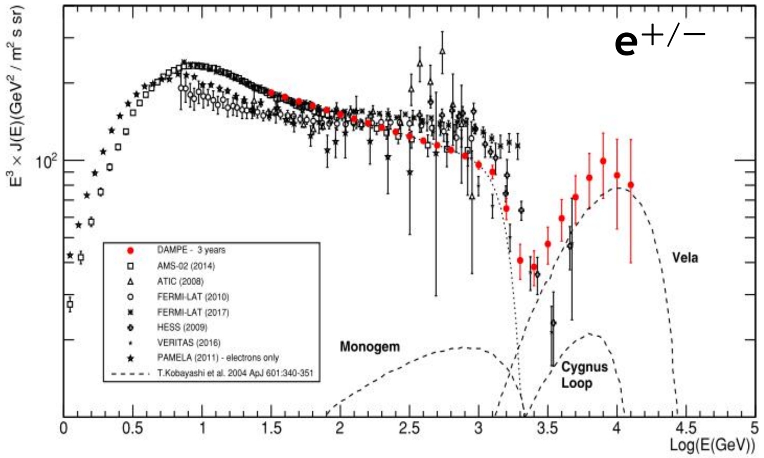
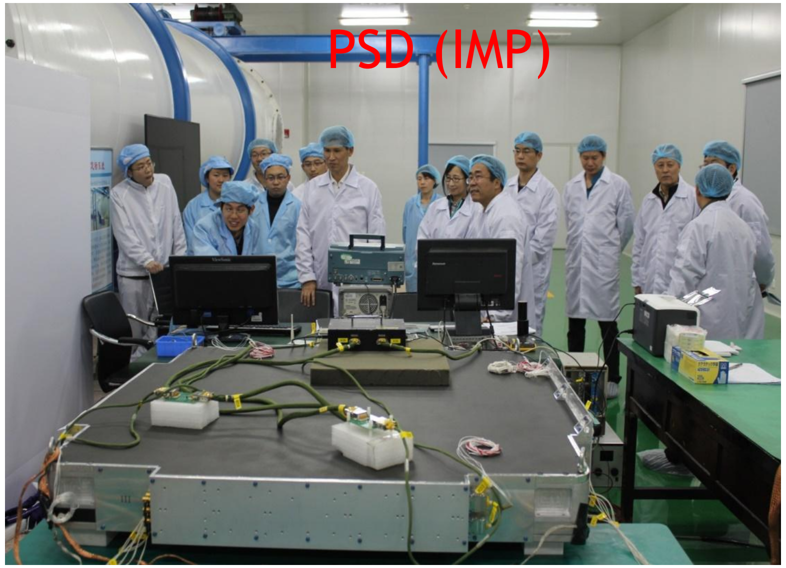


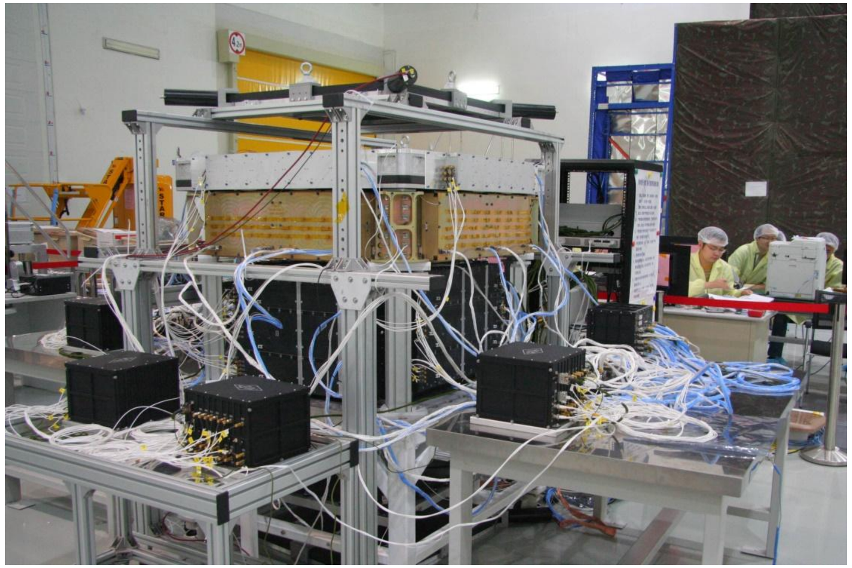




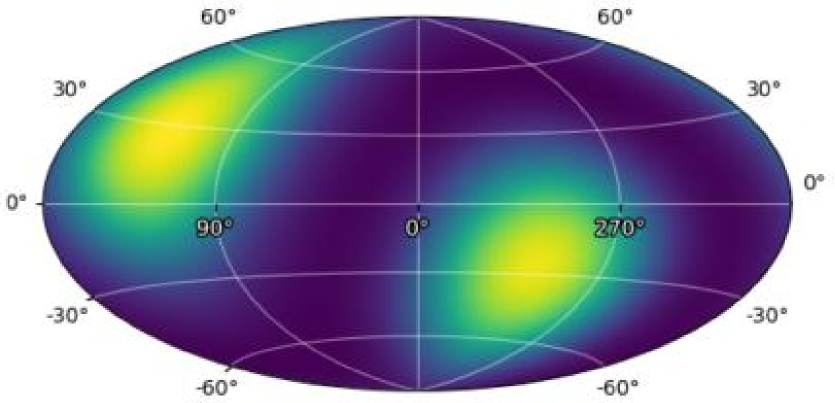
China launched DAMPE in the end of 2015, which provides a unique opportunitity to probe the fundamental questions of CRs

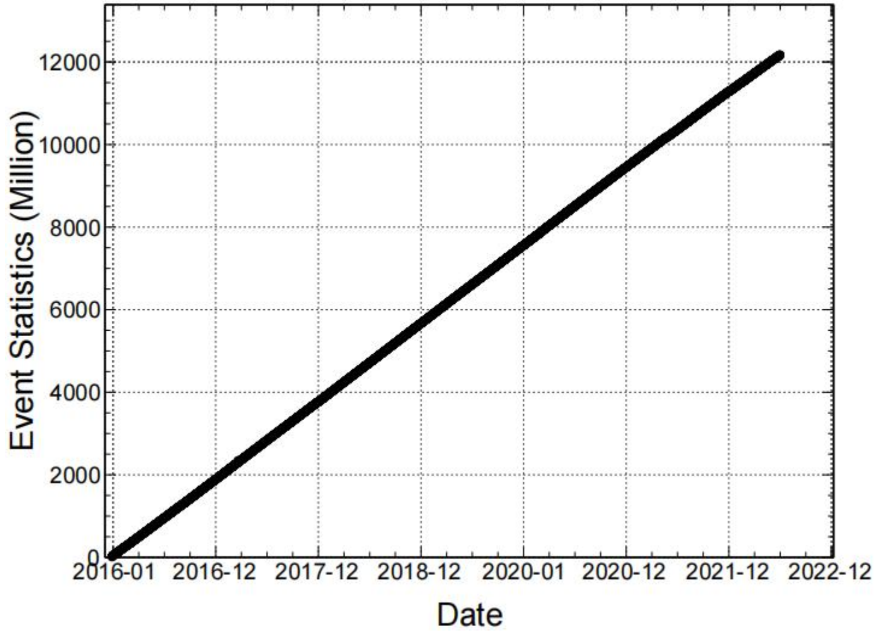
DAMPE detector

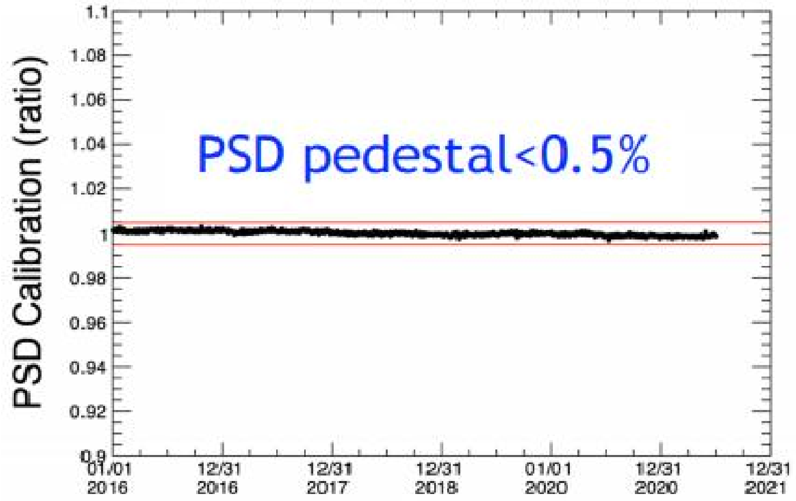


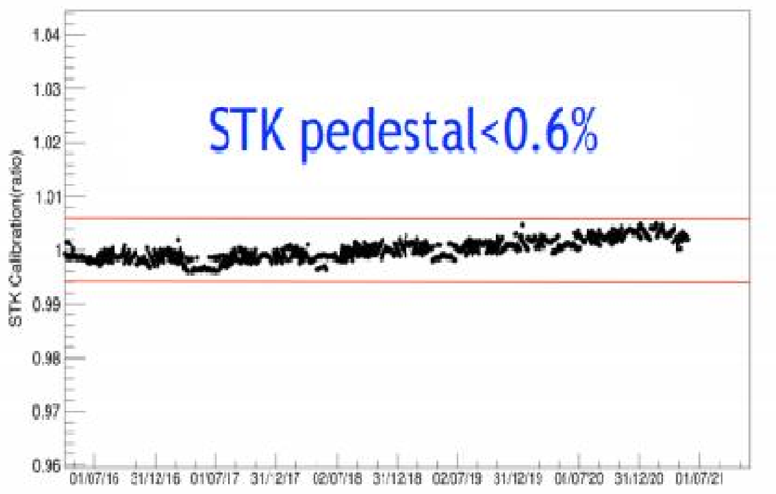


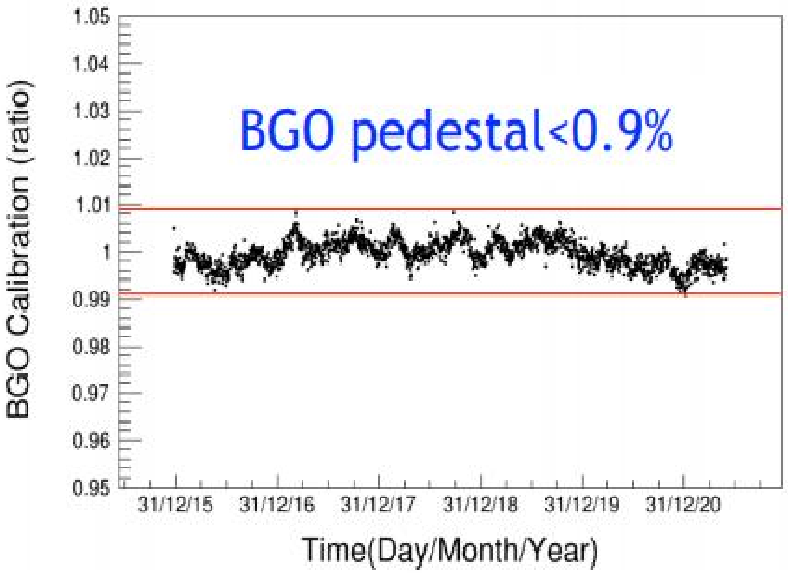
On-orbit performance of DAMPE

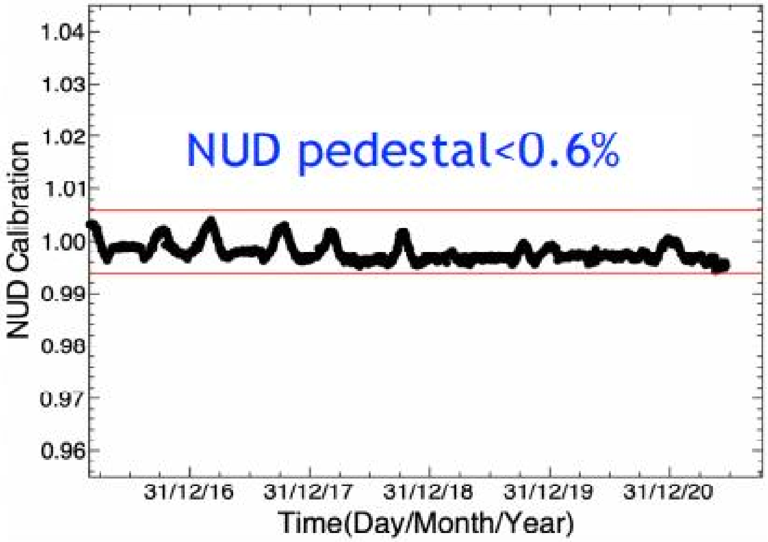




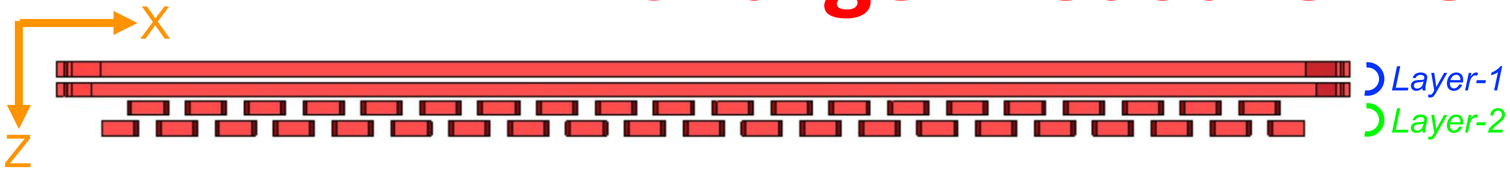








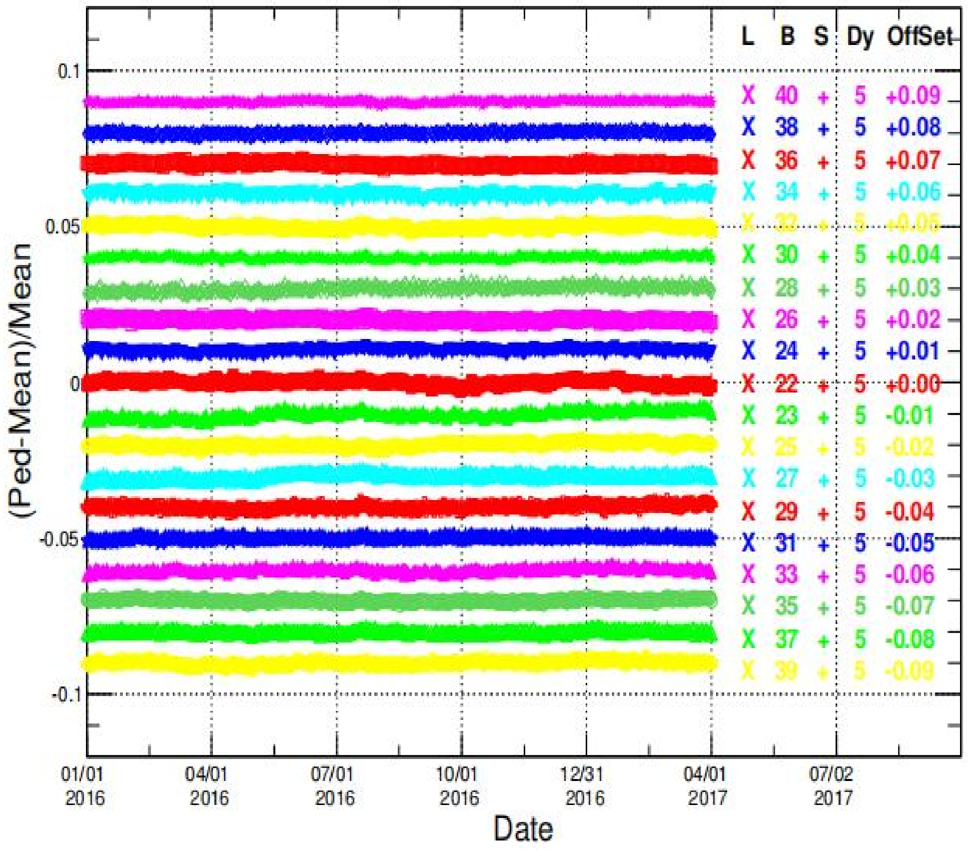
Charge measurement



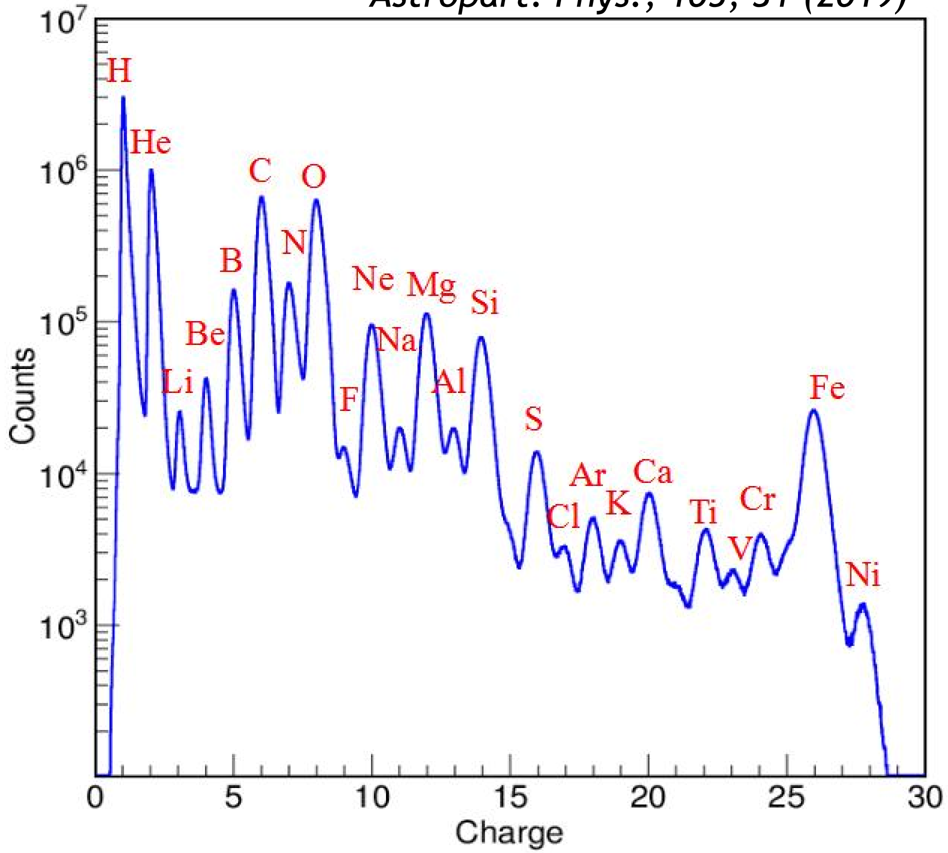
Bethe-Bloch formula

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

Res. Astron. Astrophys., 19, 47 (2019)



Astropart. Phys., 105, 31 (2019)



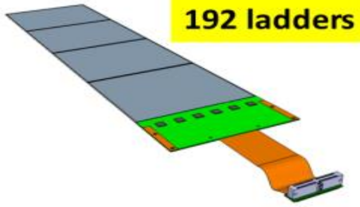
Direction measurement

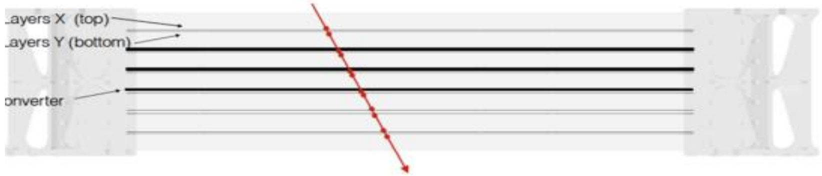
768 silicon sensors
95 x 95 x 0.32 mm³

1,152 ASICs

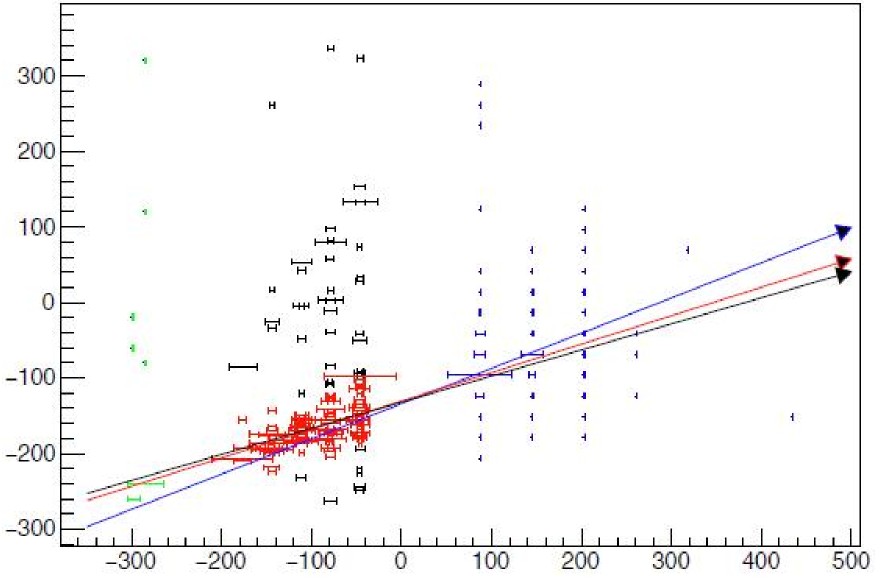
73,728 channels

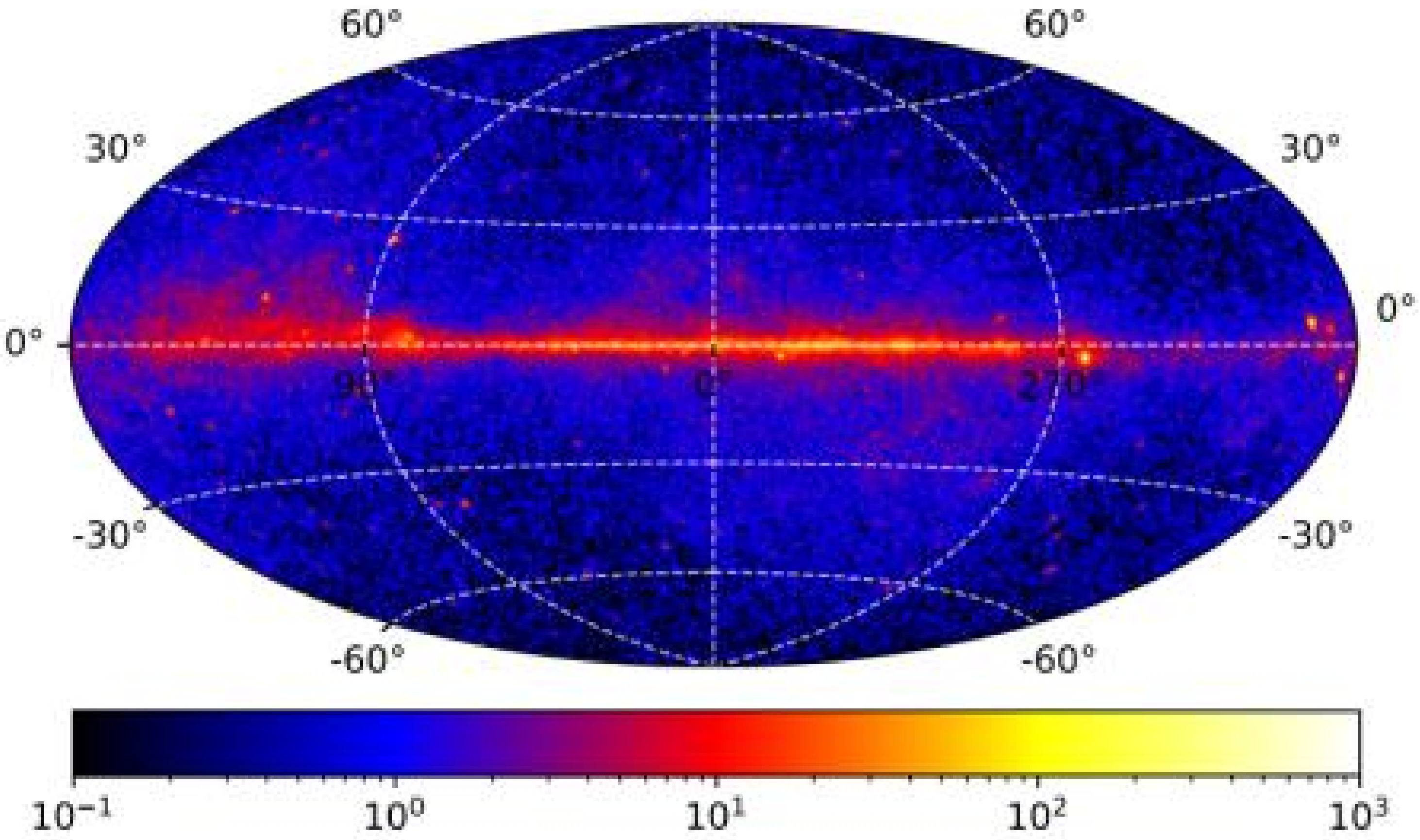
192 ladders





PSD STK BGO

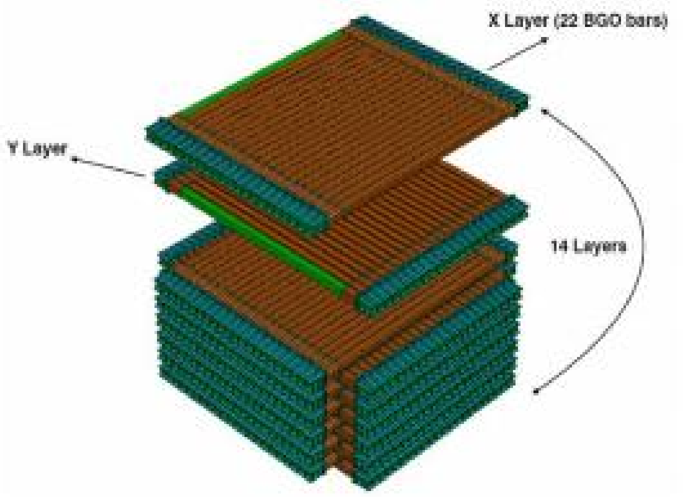




Angular resolution is ~0.4 degrees @ 10 GeV as calibrated by γ-ray point sources

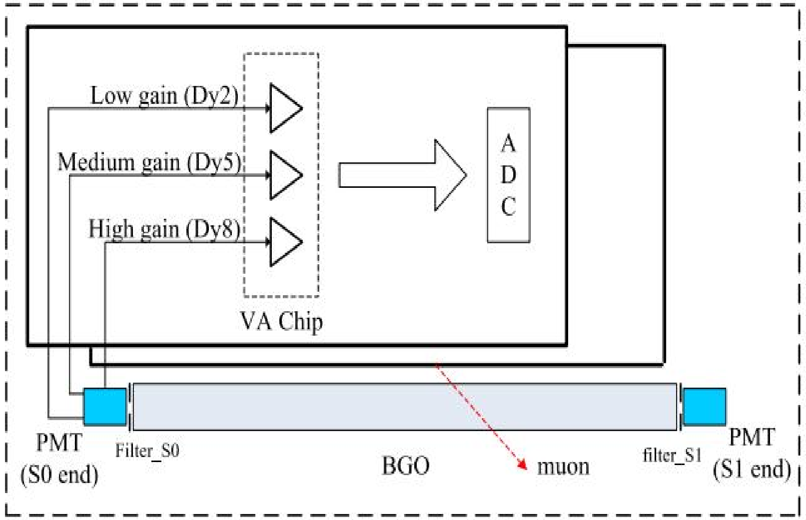
Energy measurement

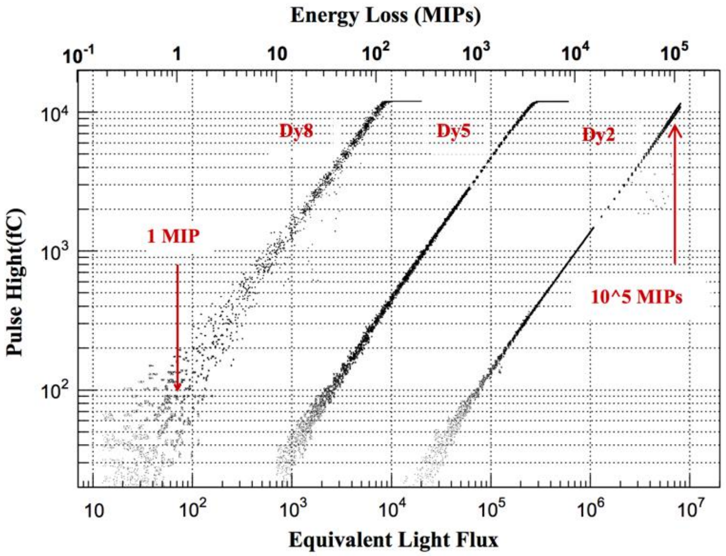
BGO calorimeter



308 BGO bars

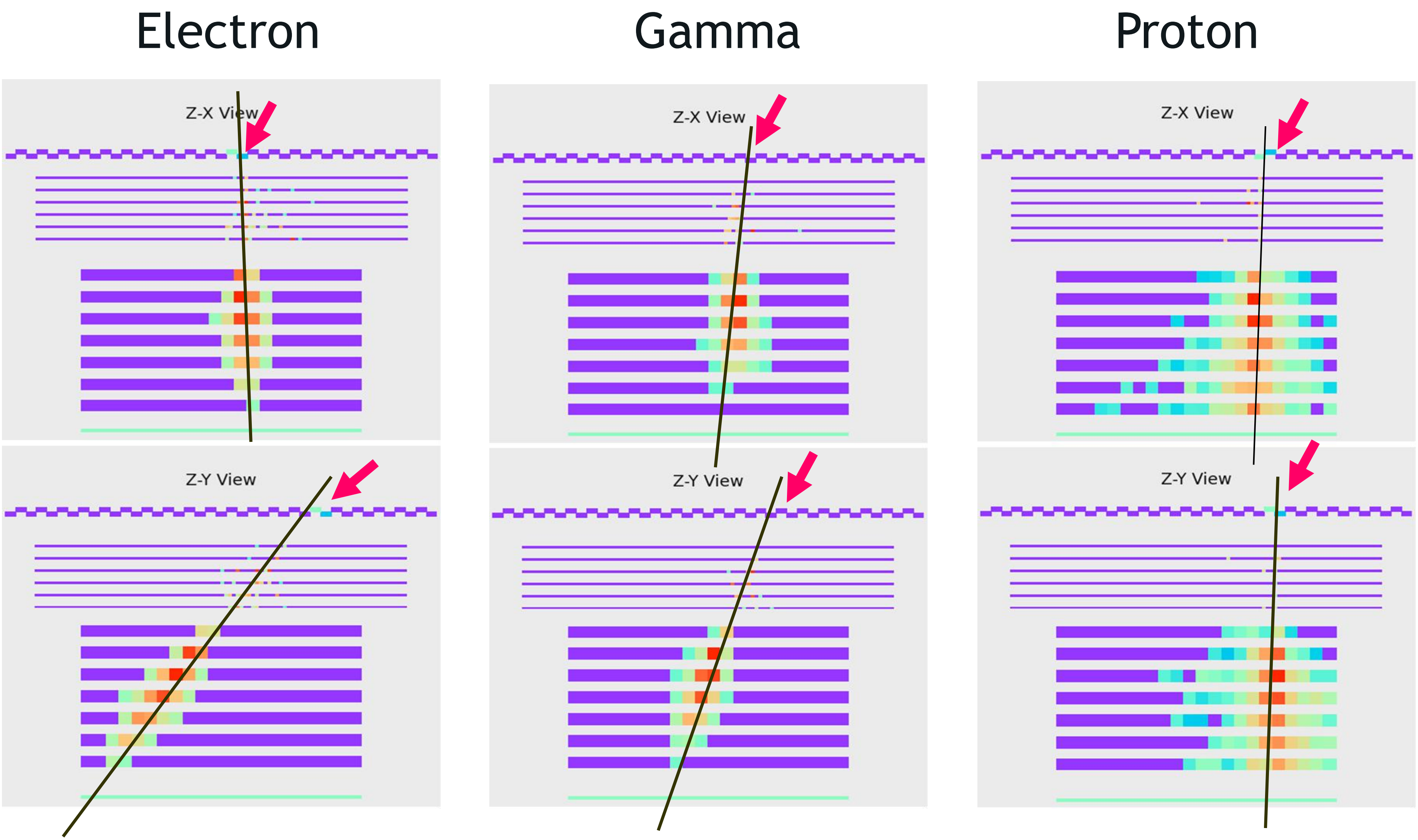
616 PMTs

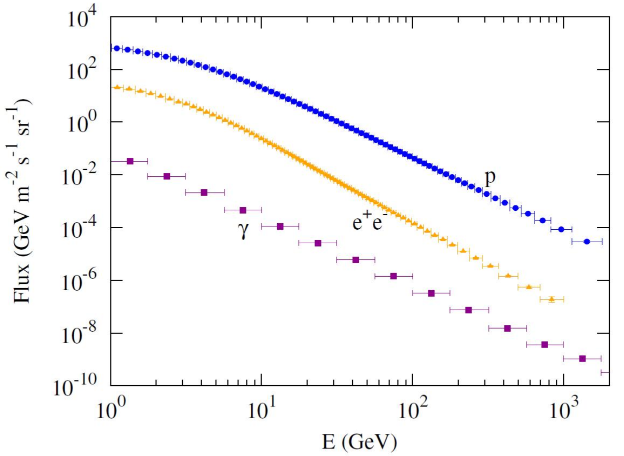




- Thick calorimeter (32 X_0): high-resolution
- Two-side readouts
- Three dynode outputs enable a $>10^6$ dynamic range

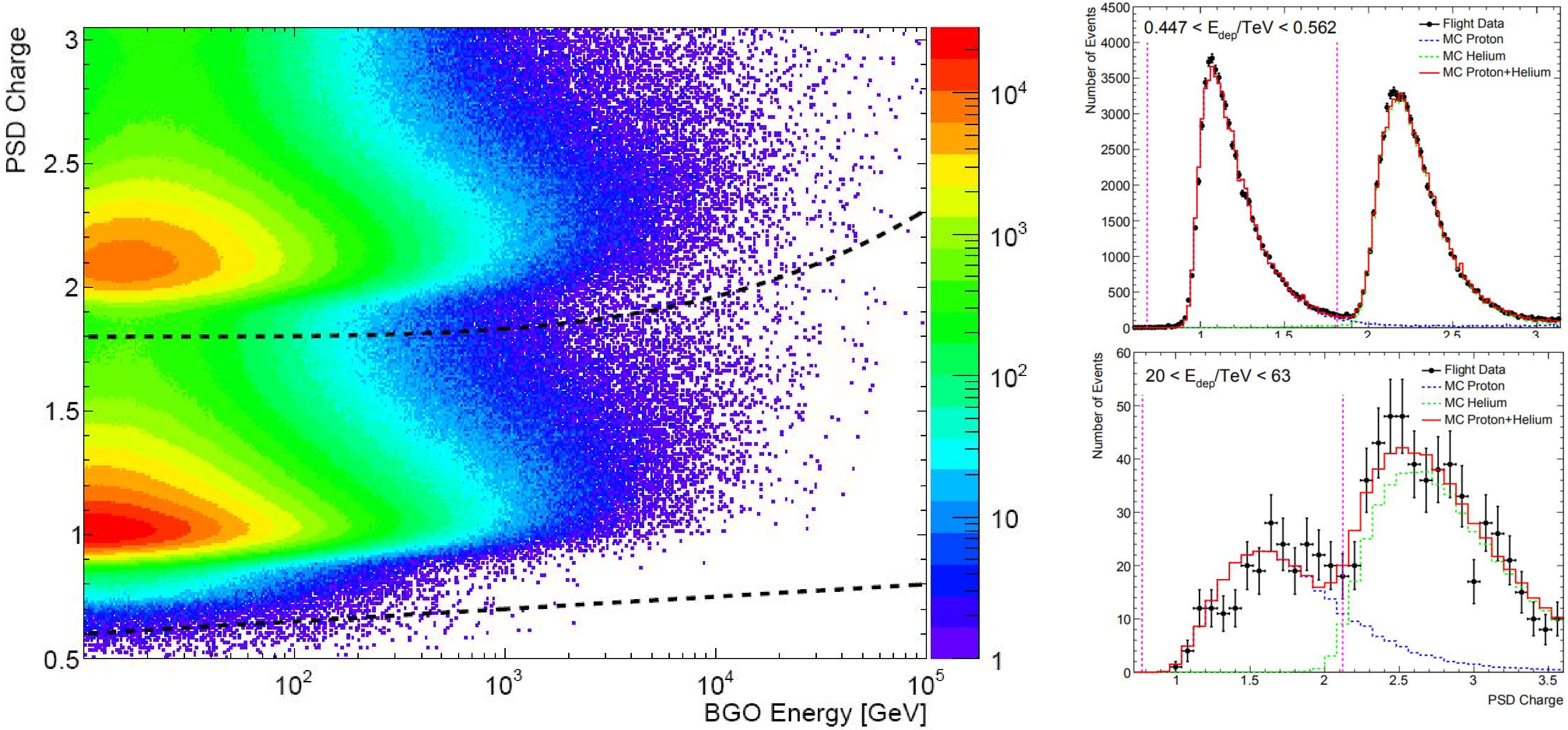
Particle discrimination



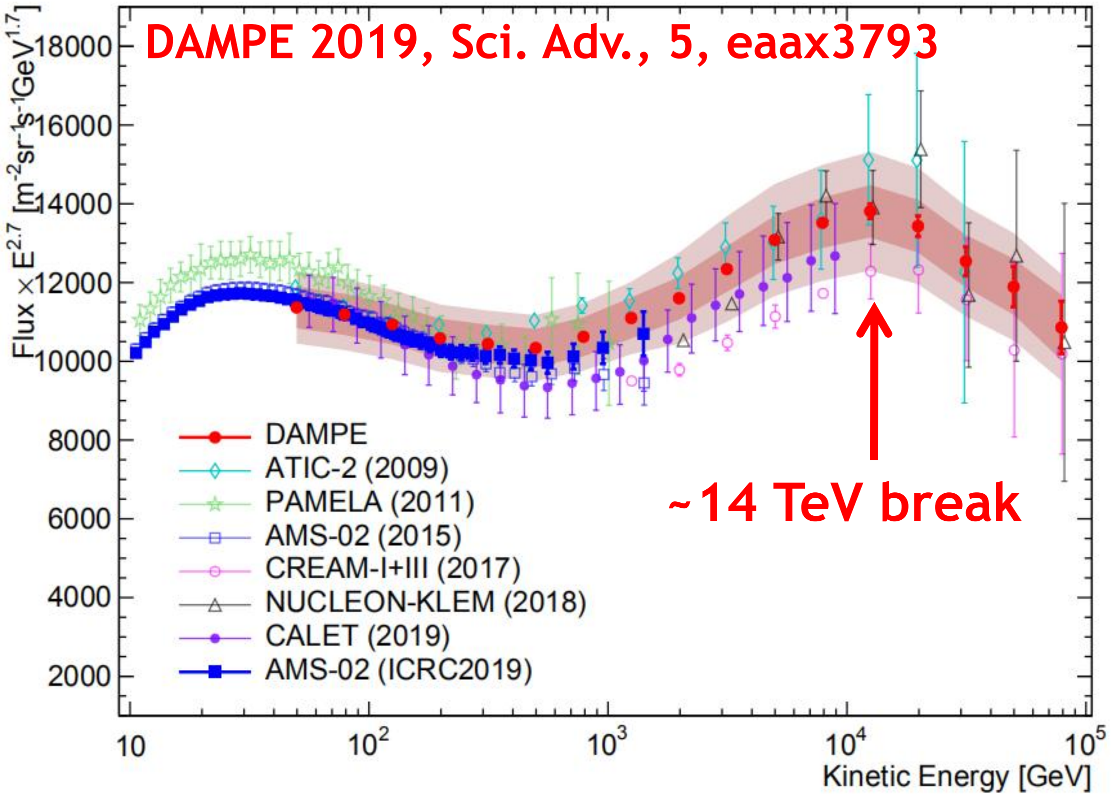


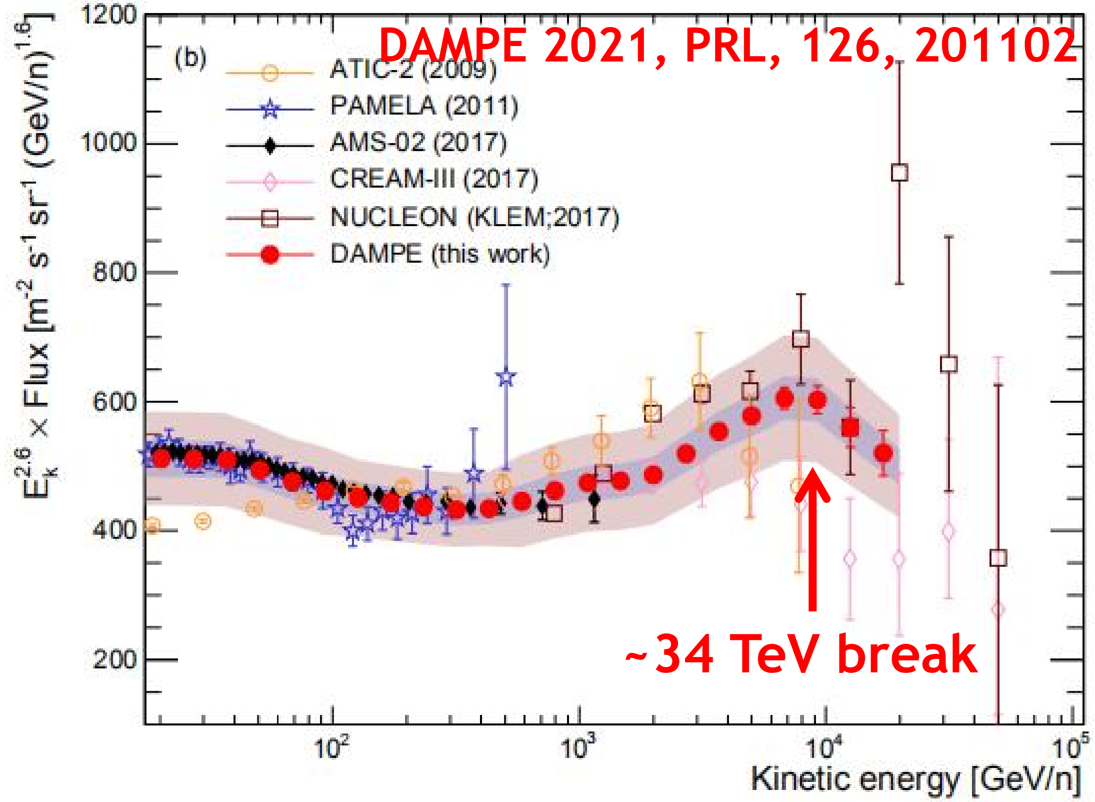
- Gamma, $e^{+/-}$/p, ions are identified by charge
- $e^{+/-}$ and protons are distinguished by shower morphology

Proton and helium spectra



Proton and helium spectra

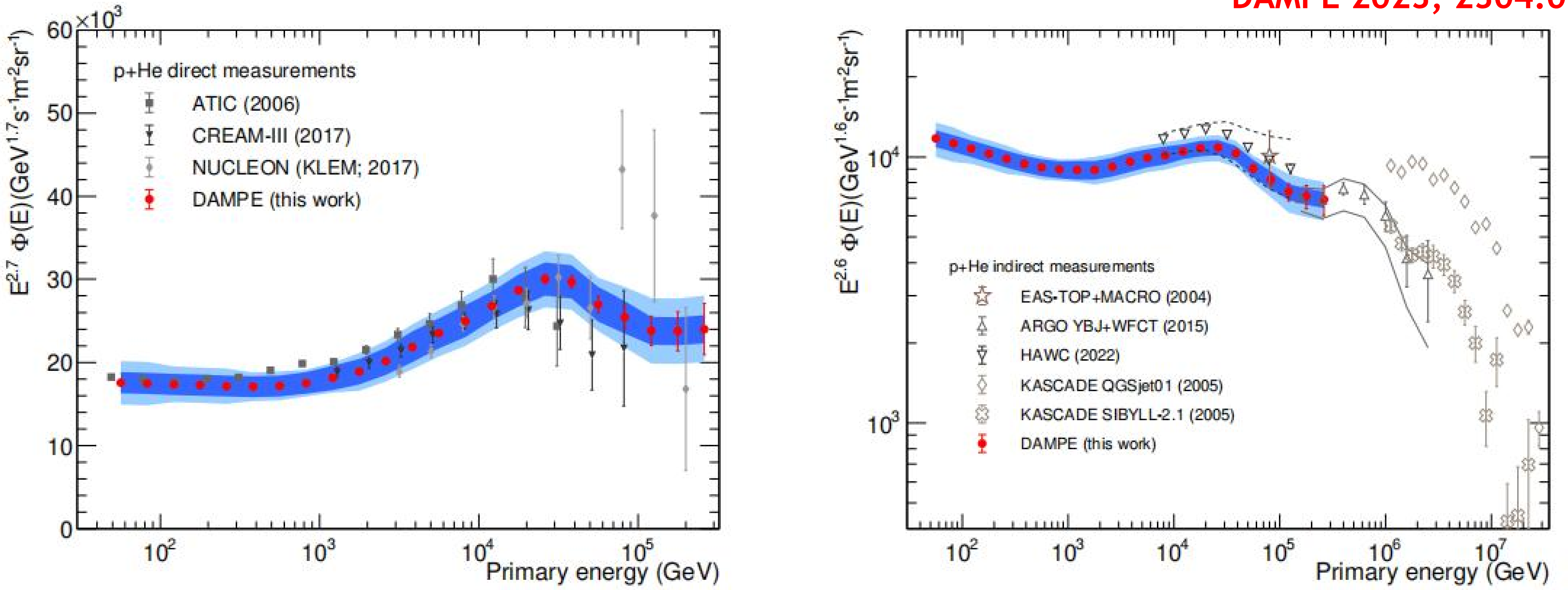




- ➢ Very similar hardening + softening structures of protons and helium
- ➢ The softening energies are ∝ Z

Proton + helium spectrum

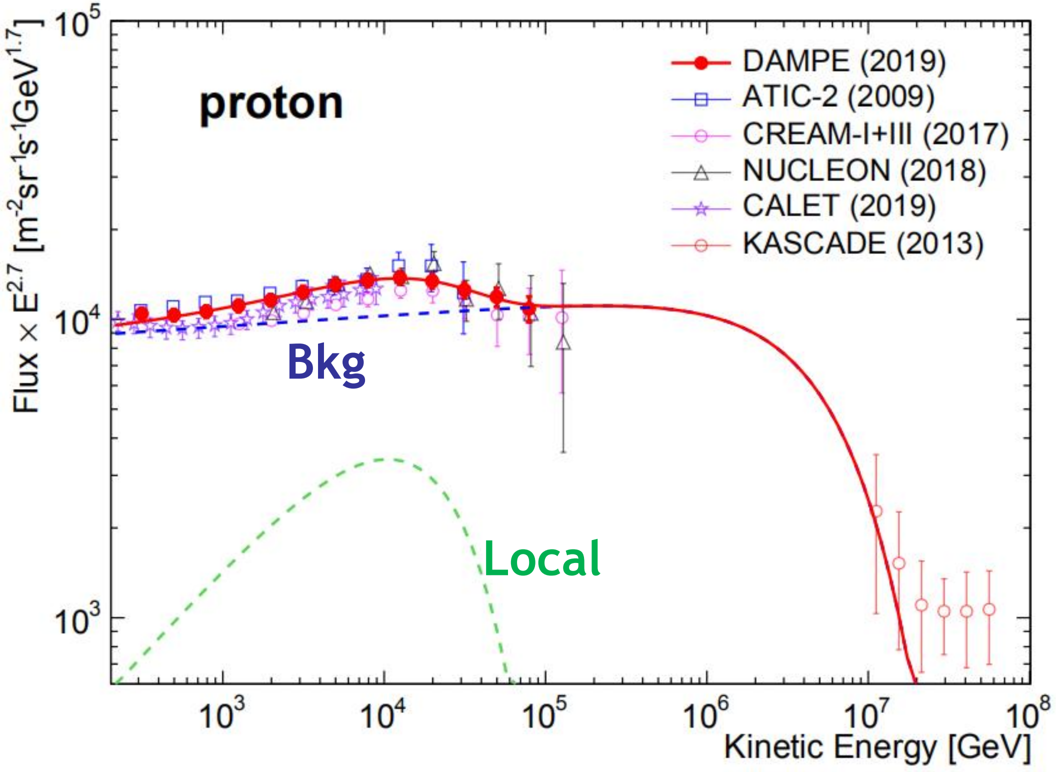
DAMPE 2023, 2304.00137

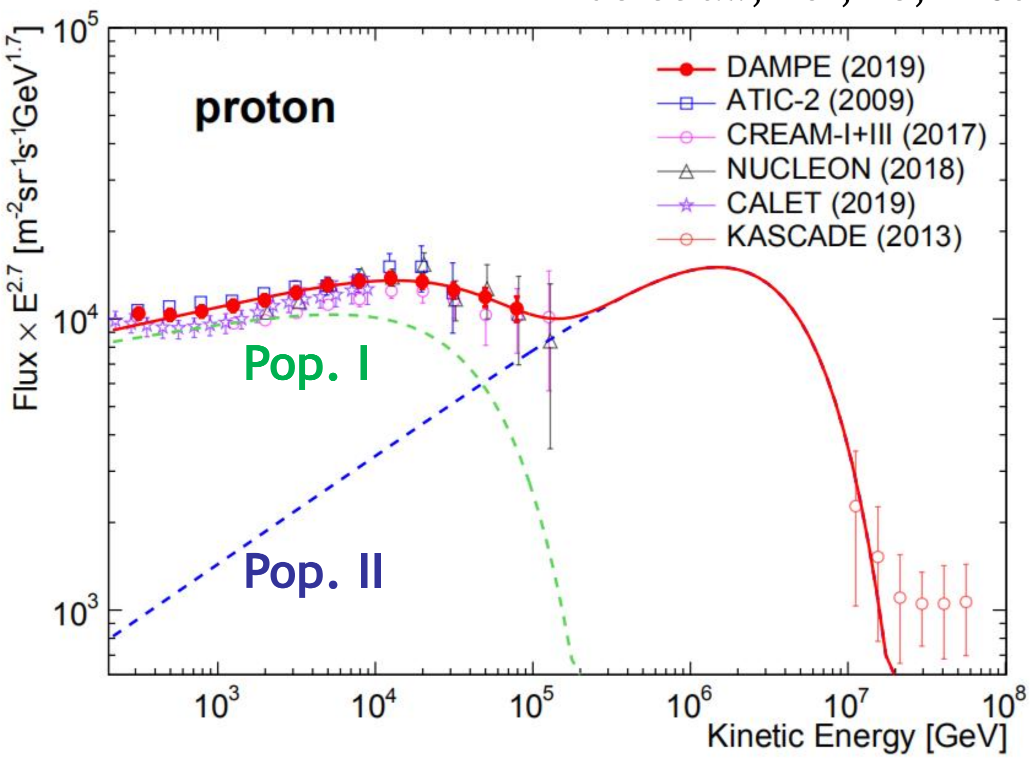


- Nicely connect with groundbased measurements
- Revealing possible flatteing above 100 TeV

Possible interpretations

Yue et al., FoP, 15, 24601 (2020)

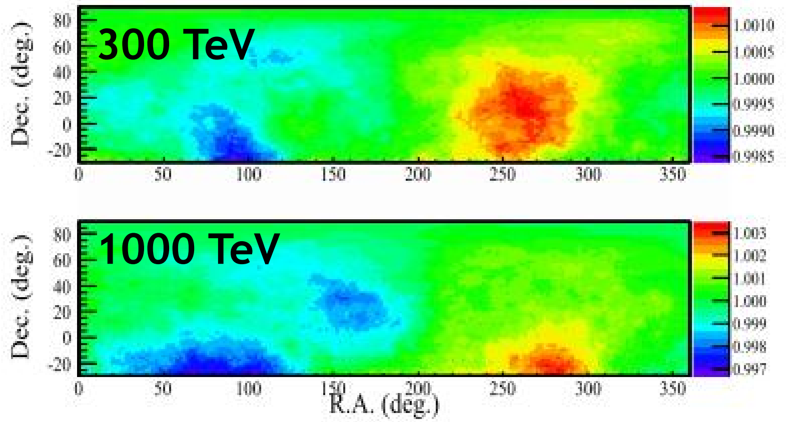


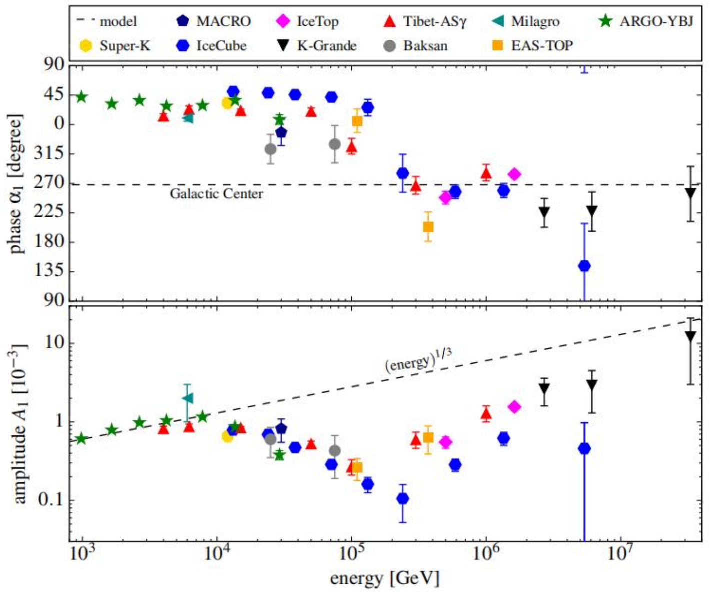


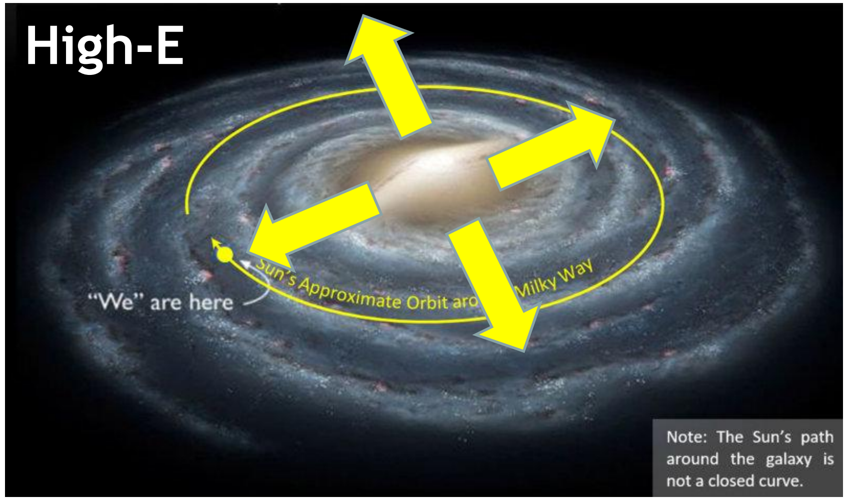
- The structure may be imprint of a local source on top of a smooth background
- Alternatively, from different source populations

Anisotropies: local source(s)?

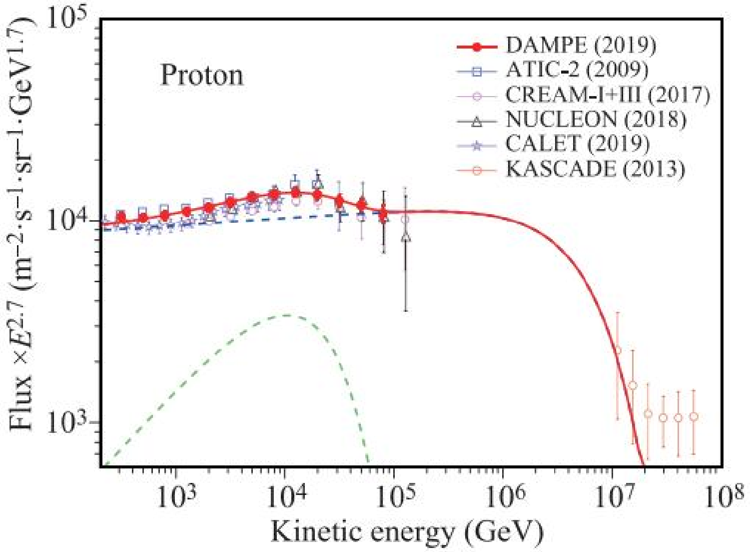
Tibet-ASγ, ApJ, 836, 153 (2017)

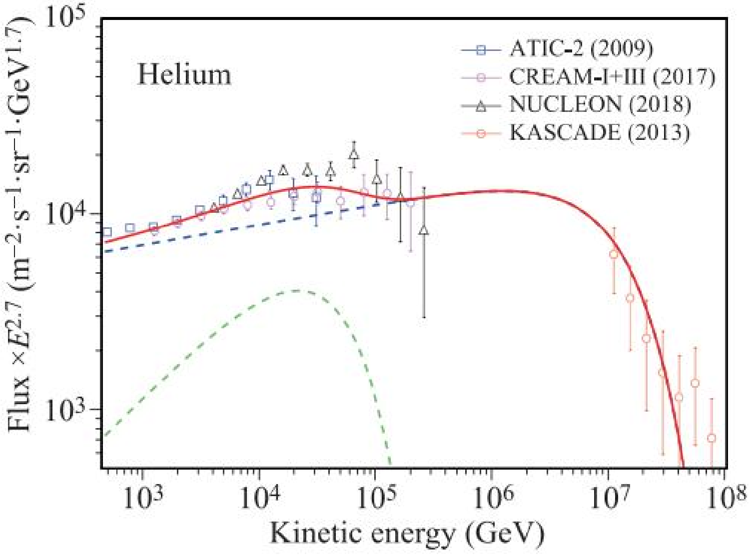






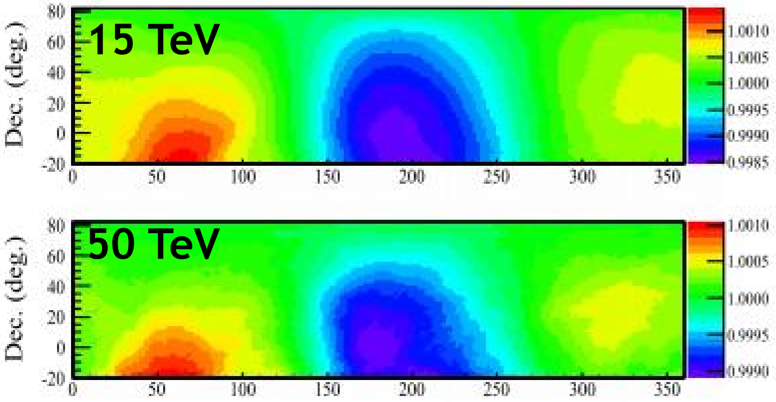
Liu et al. (2019, JCAP)
Qiao et al. (2019 JCAP)

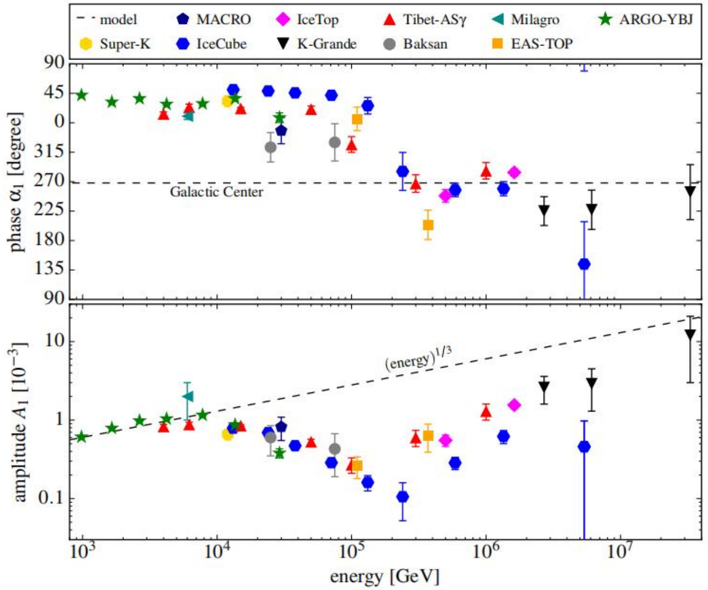


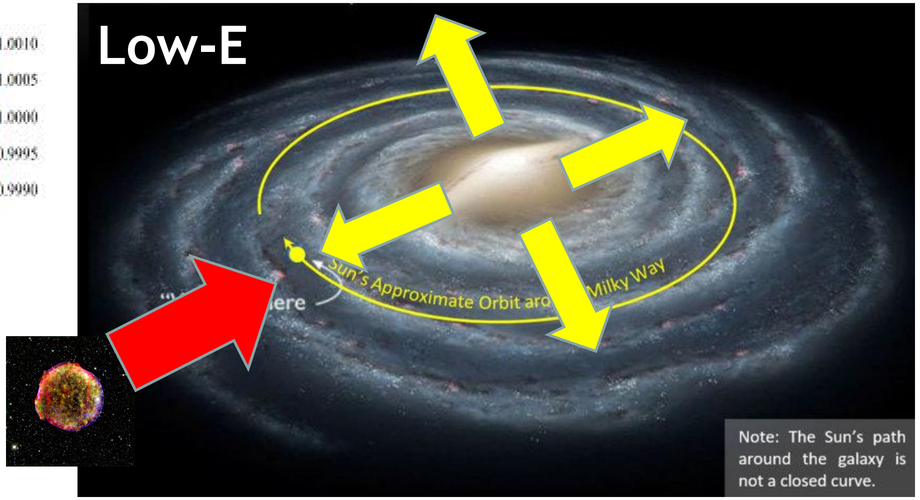


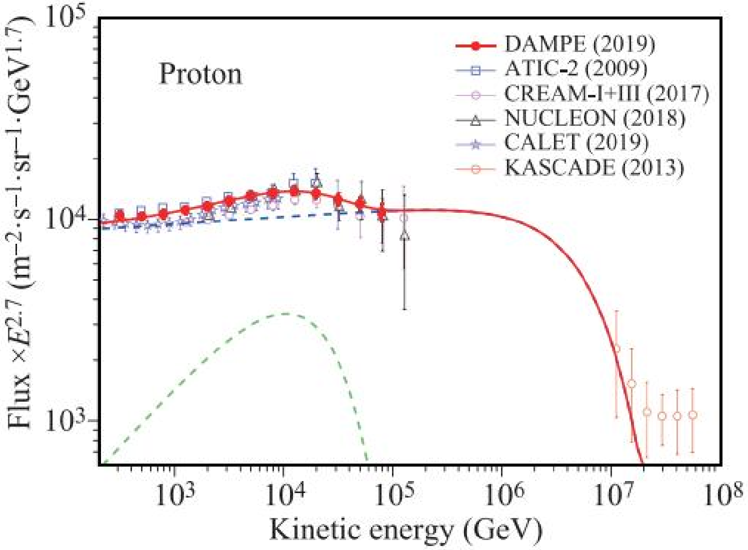
Anisotropies: local source(s)?

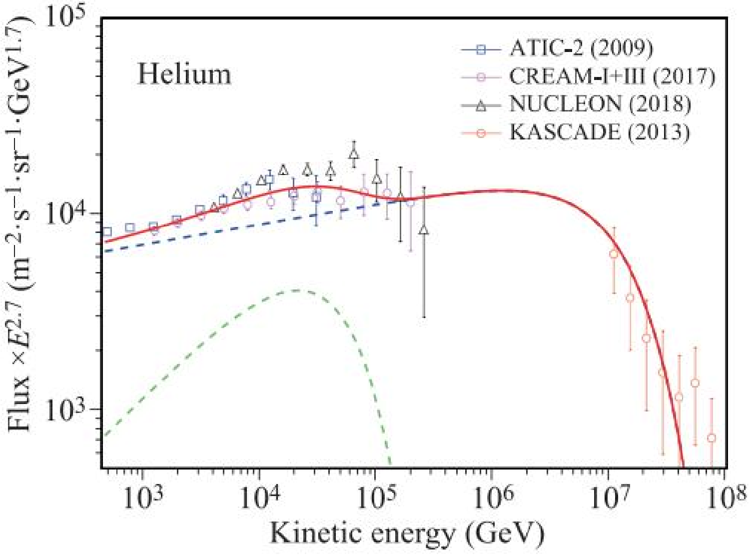
Tibet-ASγ, ApJ, 836, 153 (2017)





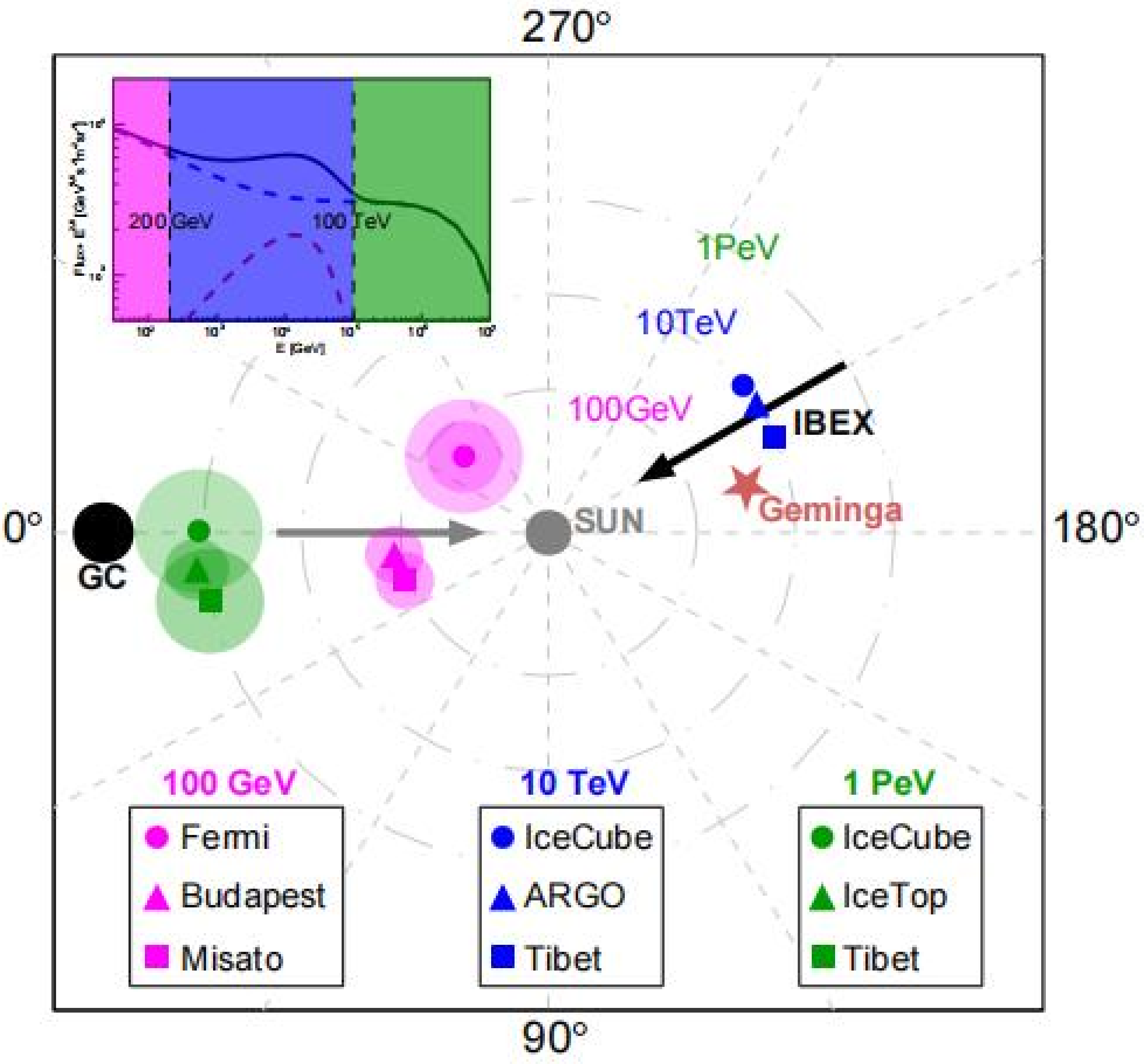


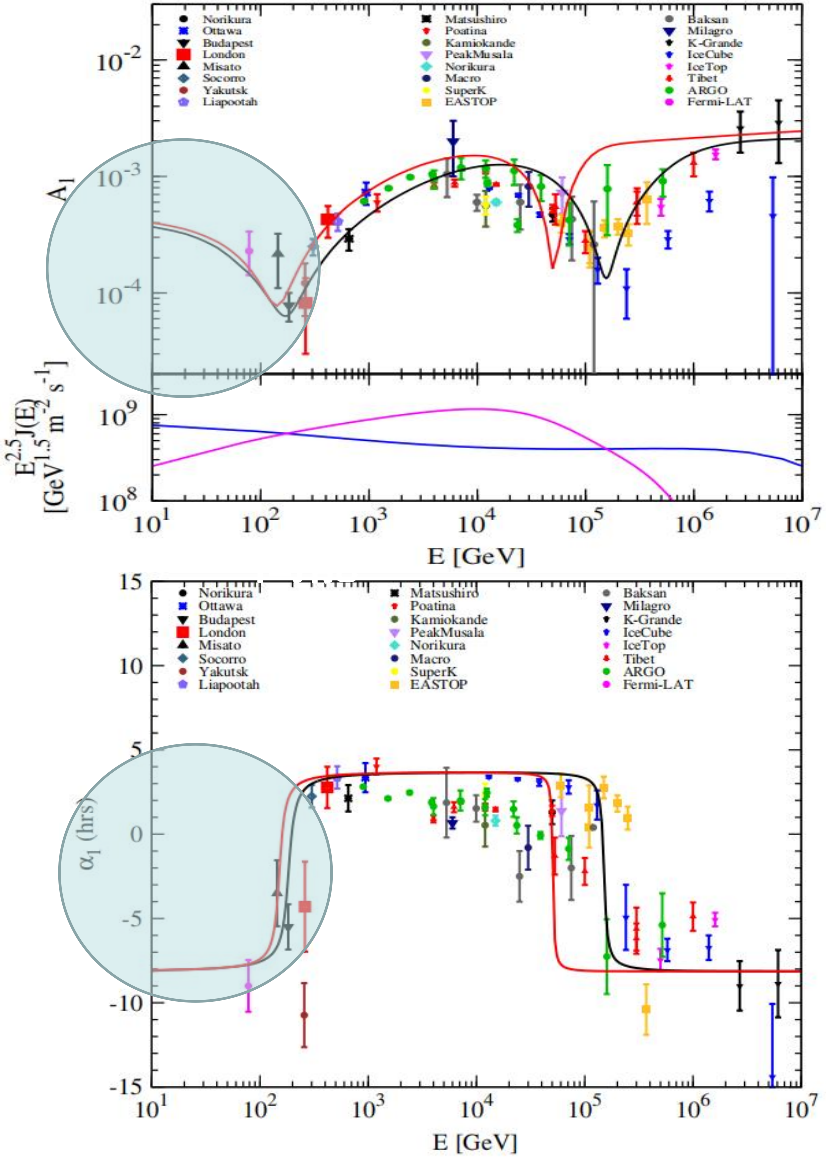




Liu et al. (2019, JCAP)
Qiao et al. (2019 JCAP)

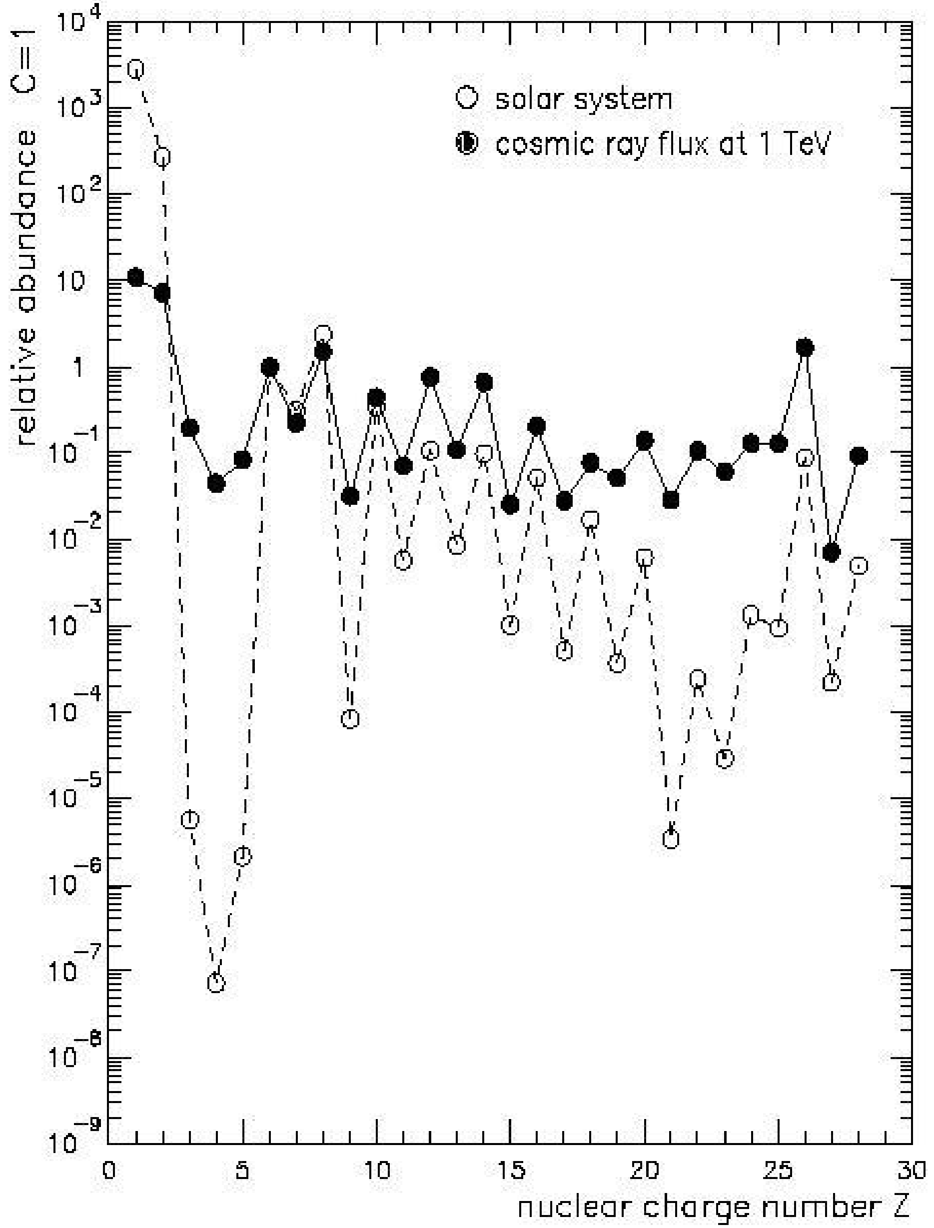
Anisotropies: local source(s)?

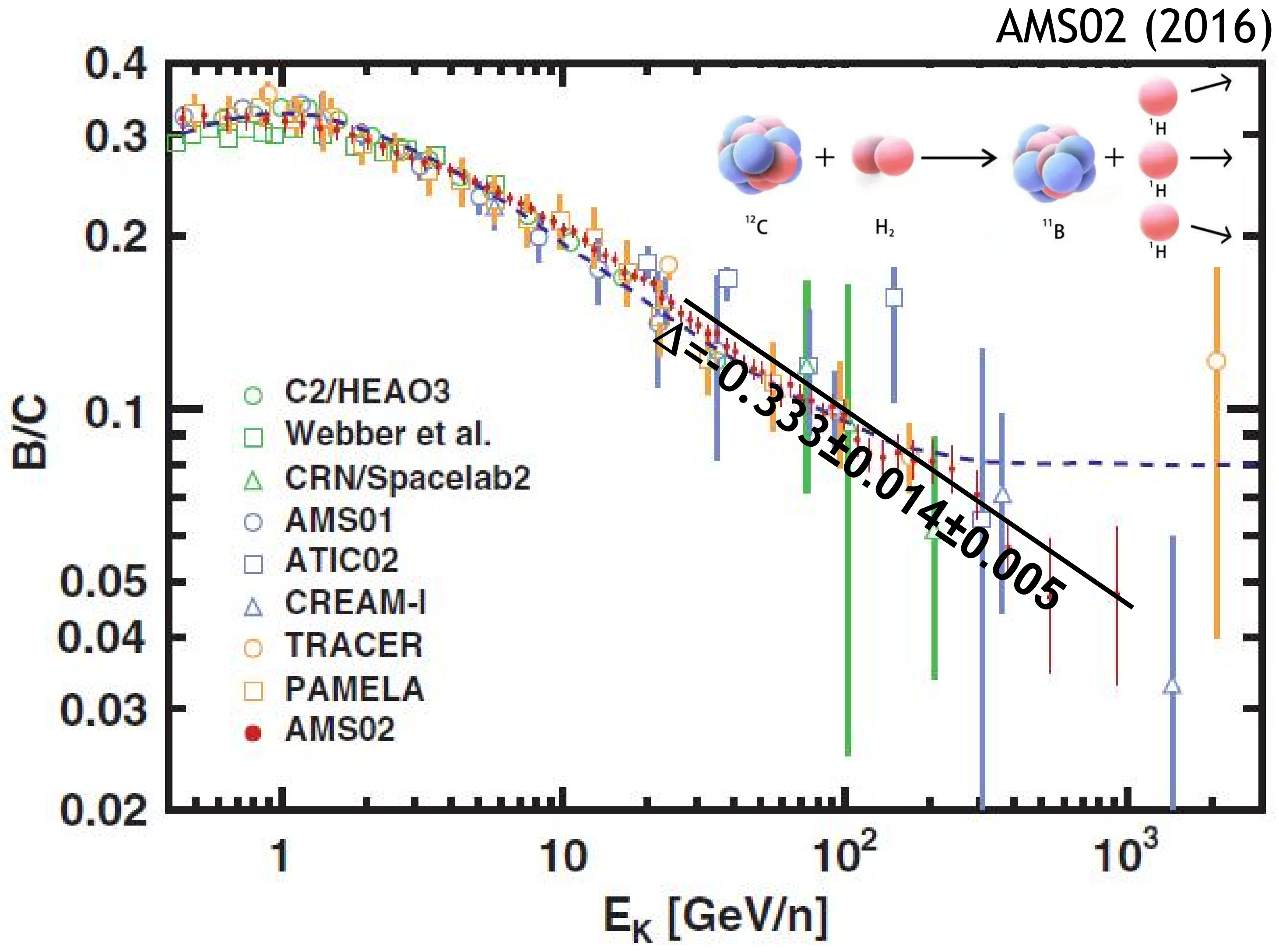




Qiao et al. (2023, ApJ)

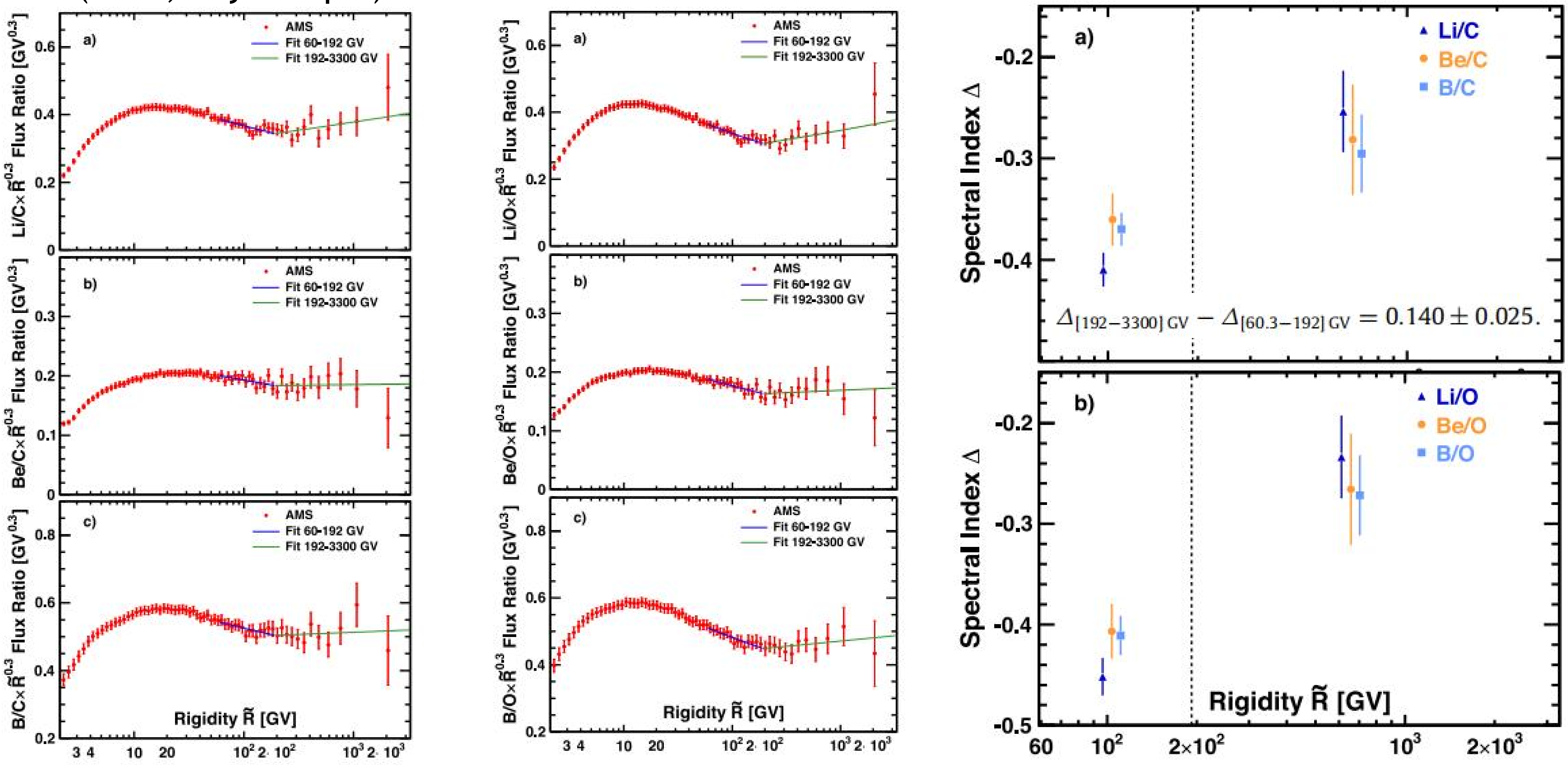
Secondary nuclei: probe of propagation





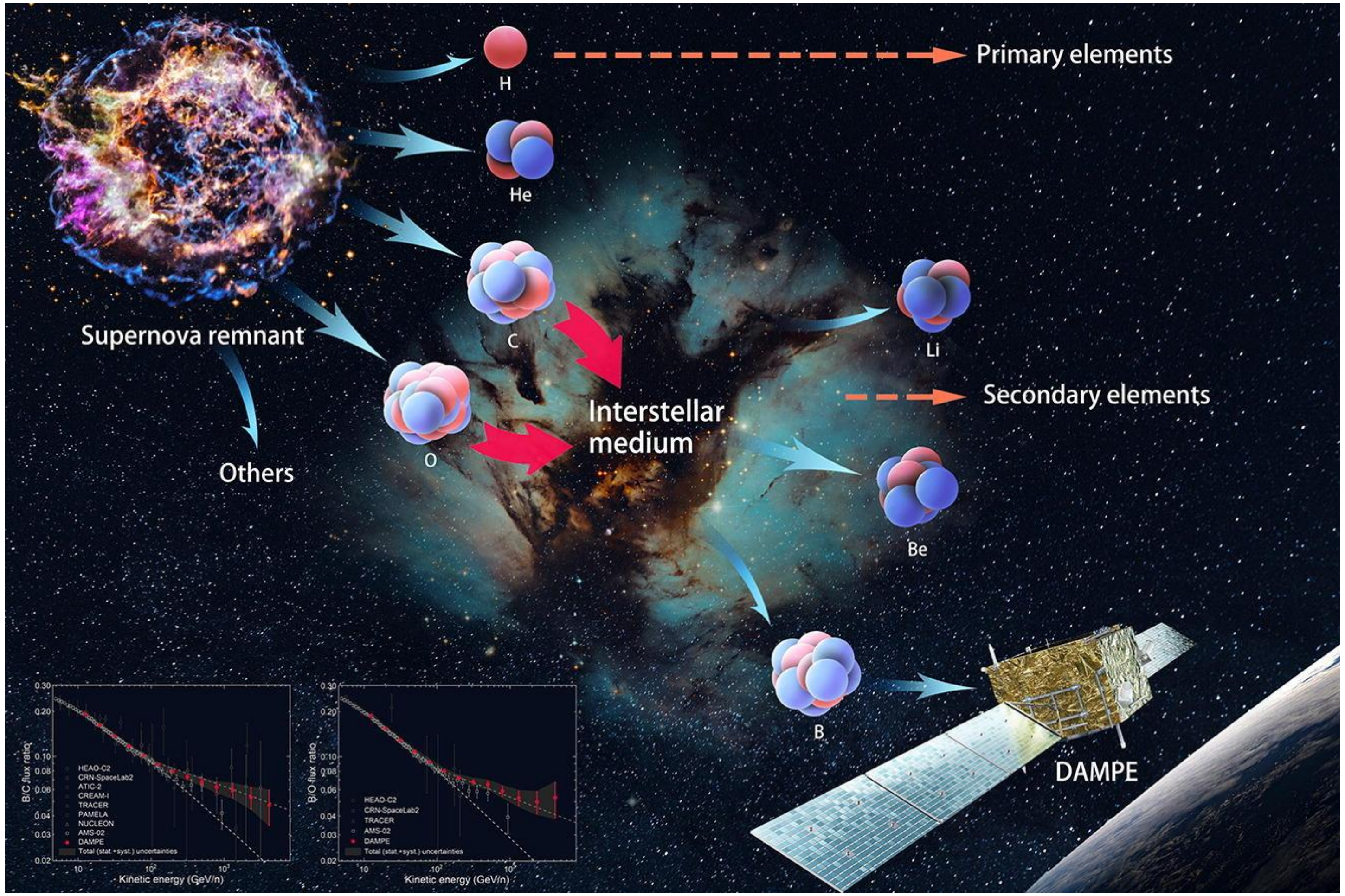
Secondary nuclei: probe of propagation

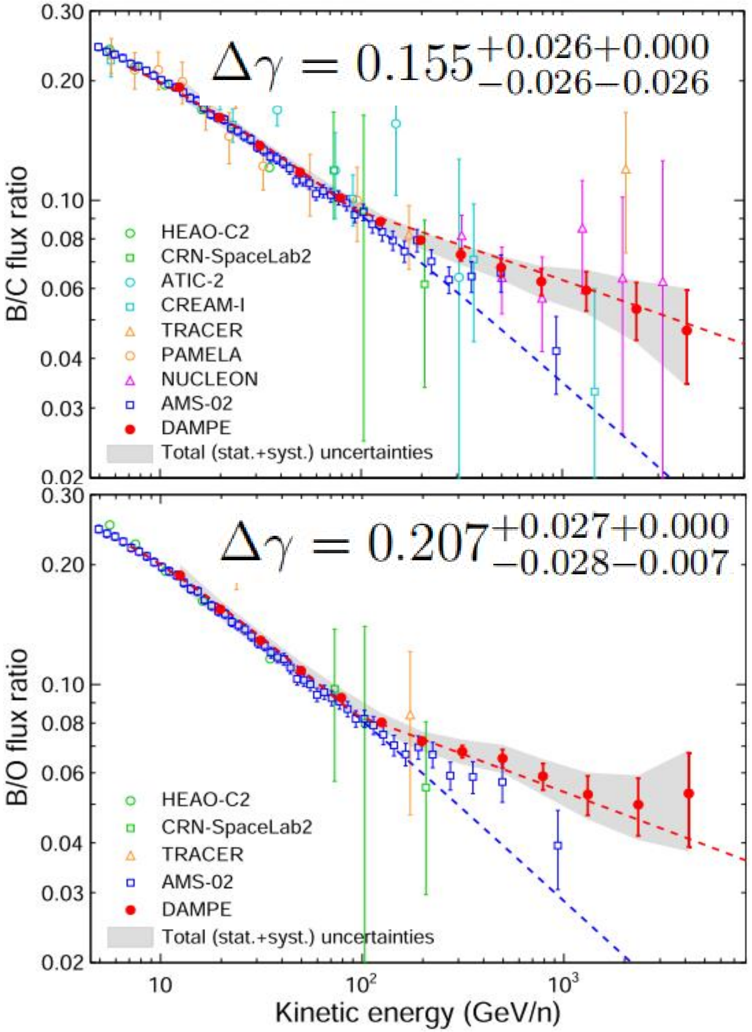
AMS02 (2021, Phys. Rept.)



DAMPE measurement of B/C、B/O

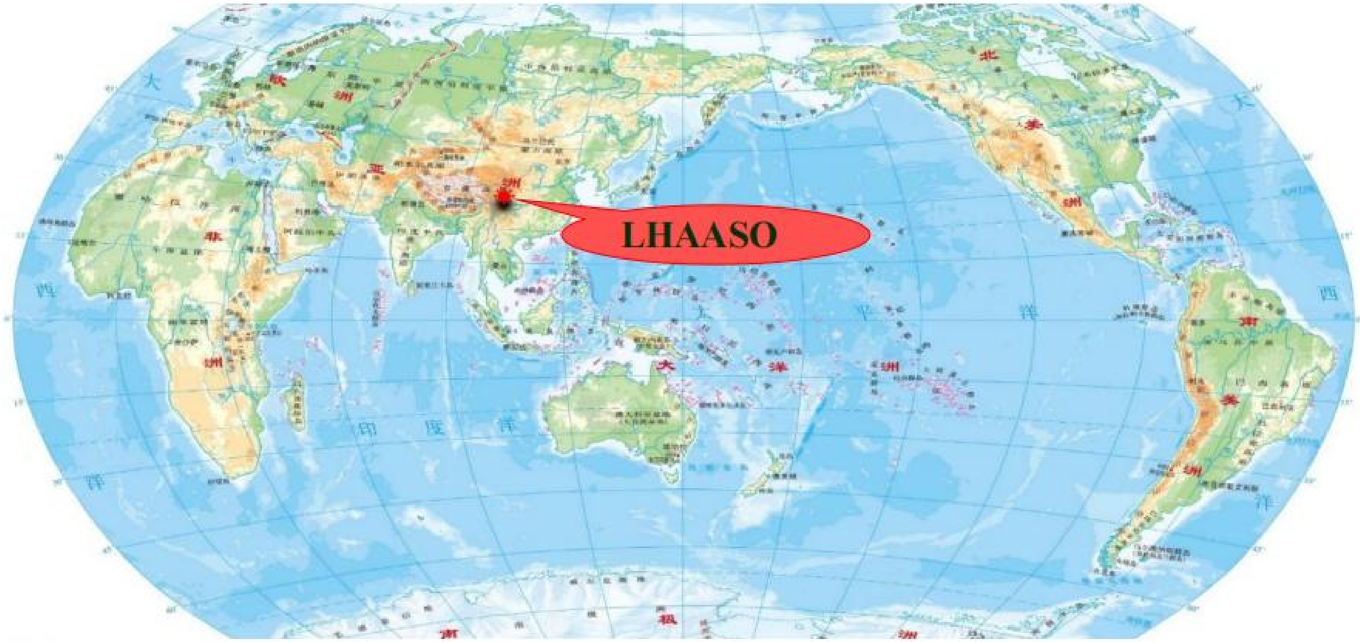
2022, Sci. Bull., 67, 2162

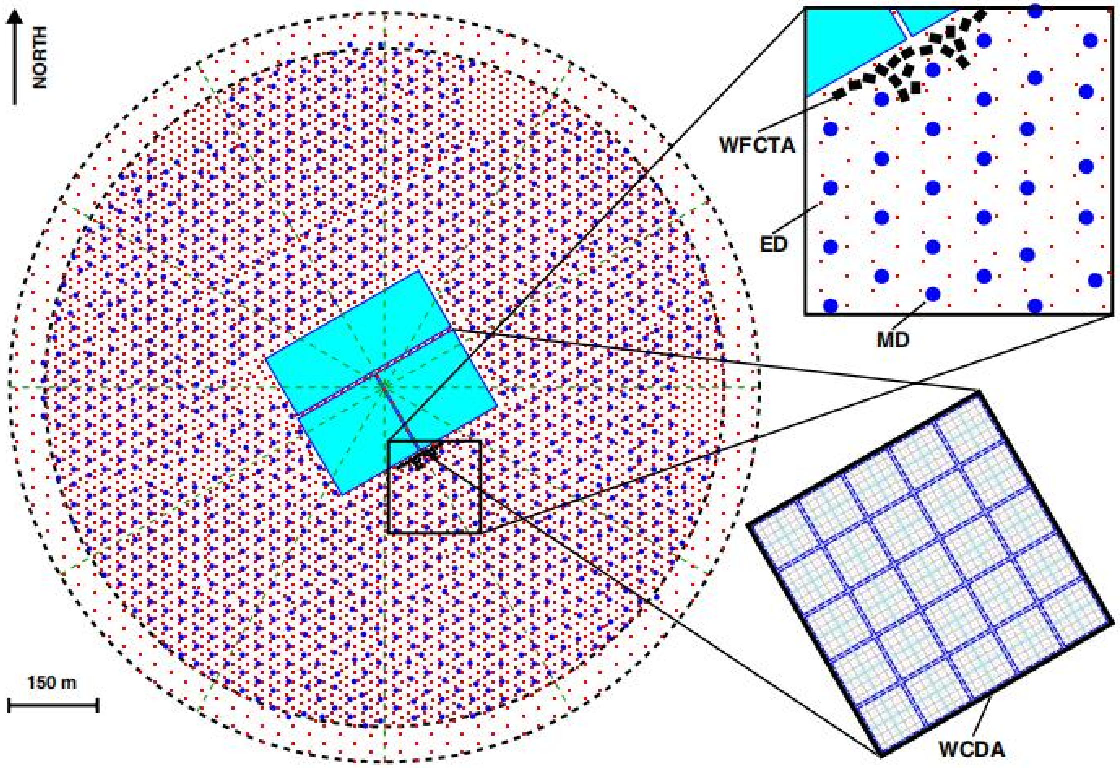




- DAMPE measured B/C, B/O with high precision, revealing breaks at ~100 GeV/n
- Changes of energy-dependence of the diffusion coefficient (properties of the turbulence power spectrum of ISM)

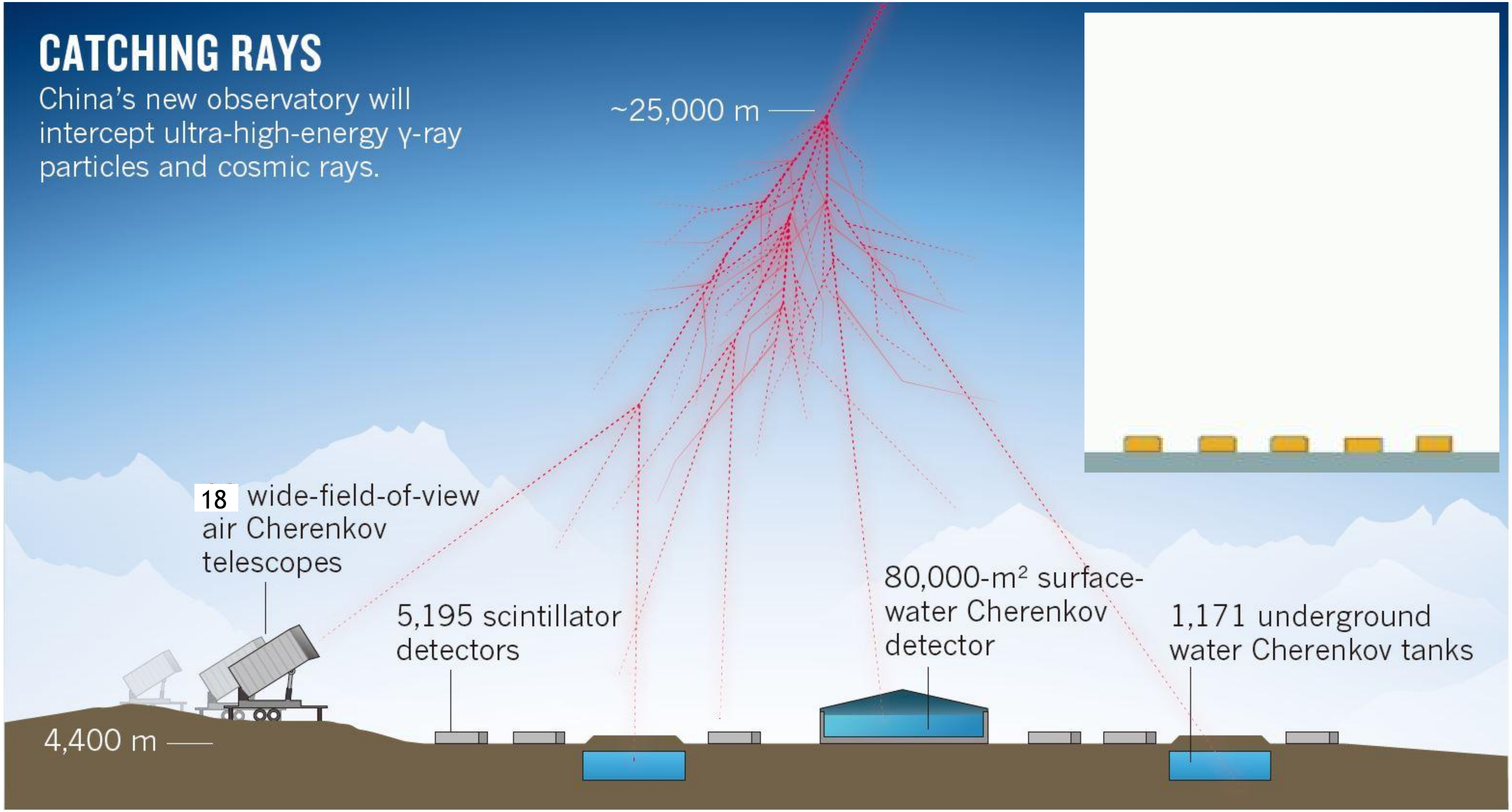
Large High Altitude Air Shower Observatory——LHAASO





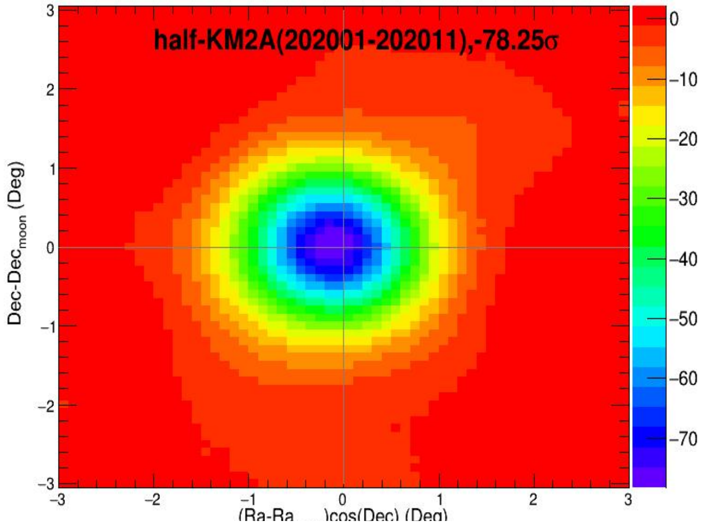
- Haizi mountain, Sichuan, China, 4410 m above the sea level
- LHAASO uses hybrid detector arrays: the square kilometer array (KM2A), the water Cherenkov detector array (WCDA), and the wide field-of-view Cherenkov telescope array (WFCTA)
- Full operation since July 2021

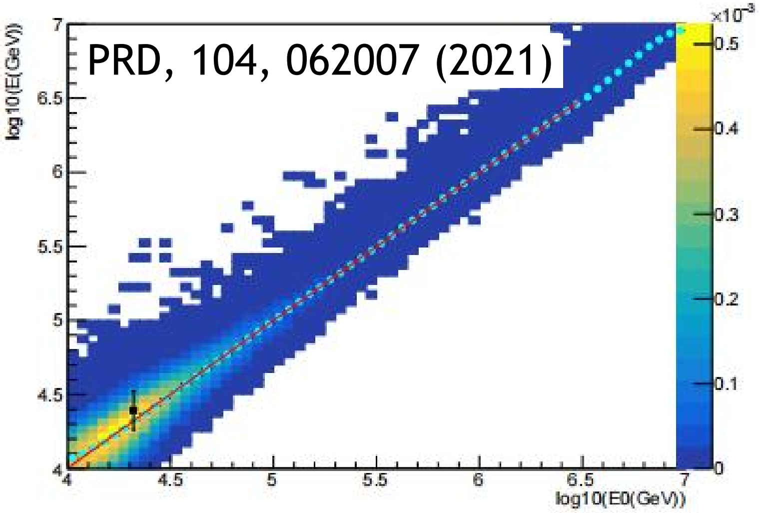
Air shower detection of cosmic rays



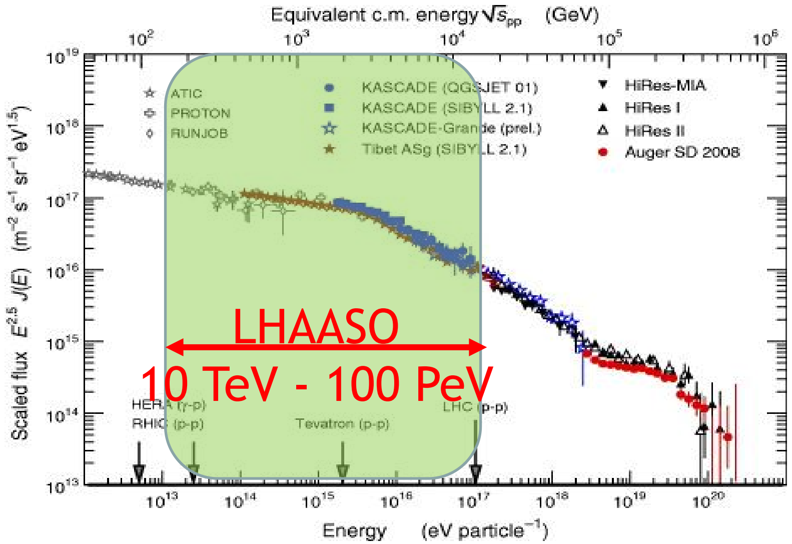
LHAASO performance

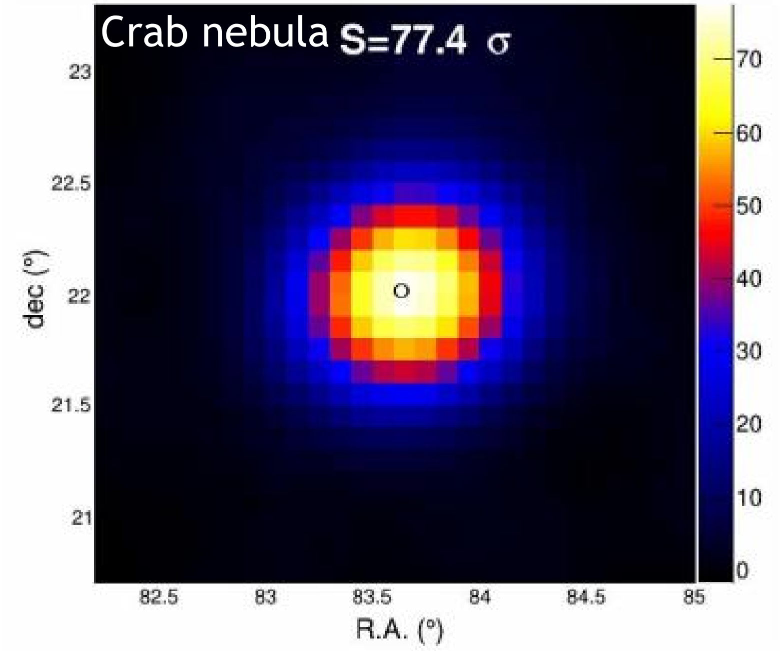
Moon shadow

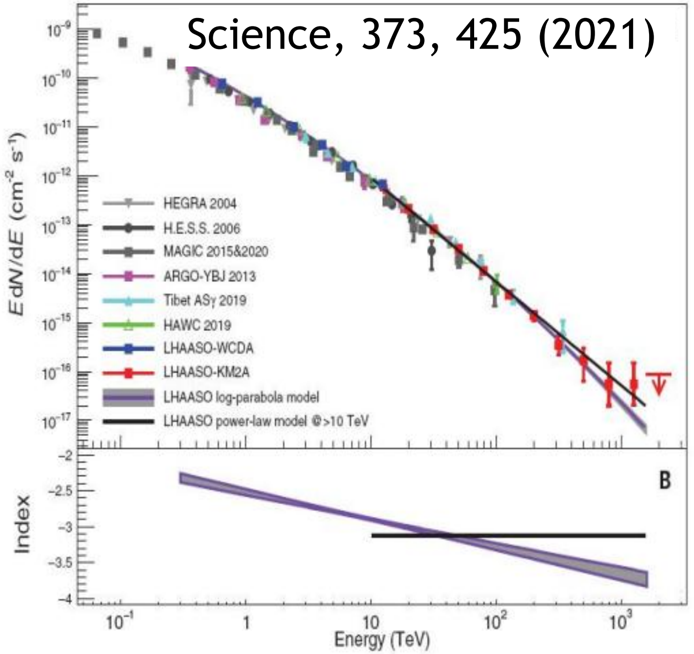


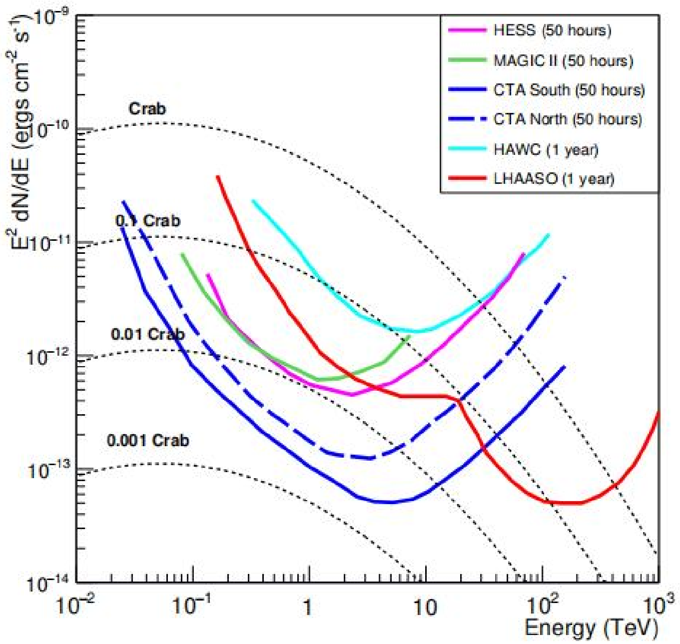


Chin. Phys. C, 46, 035002 (2022)





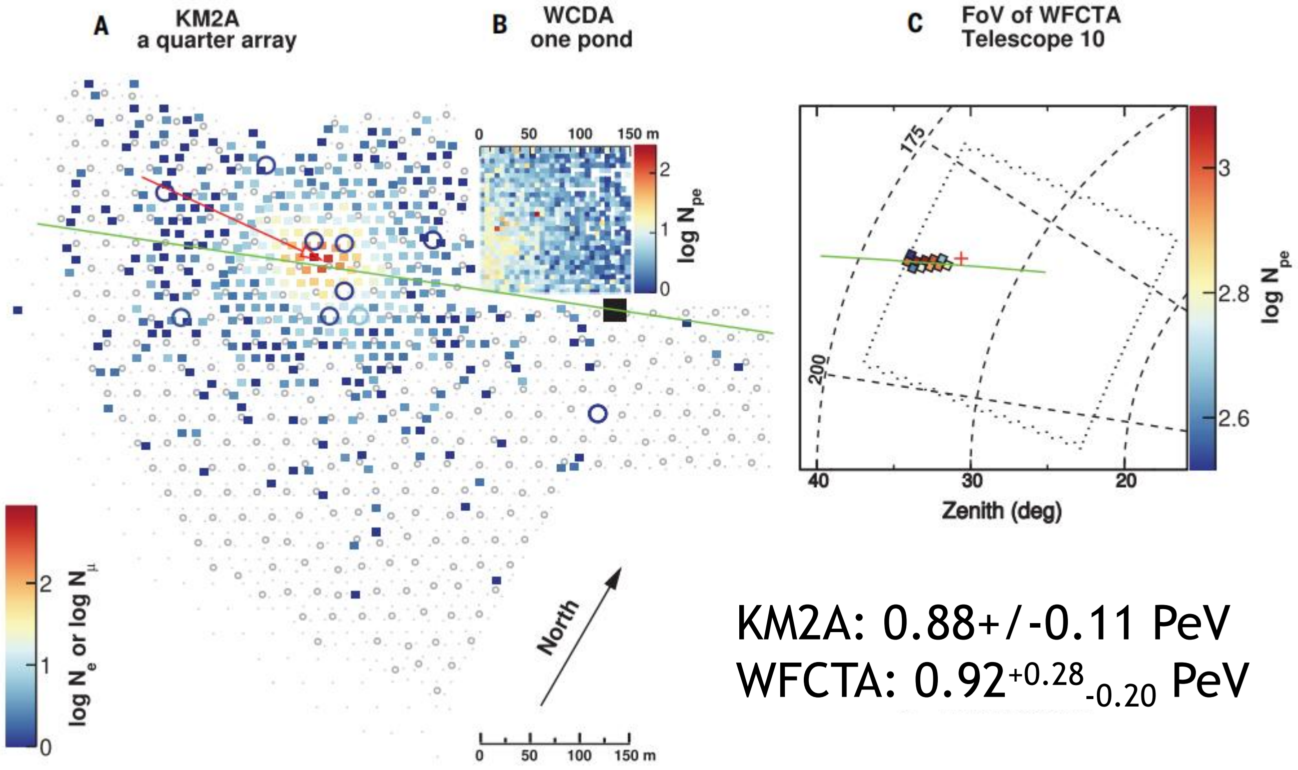




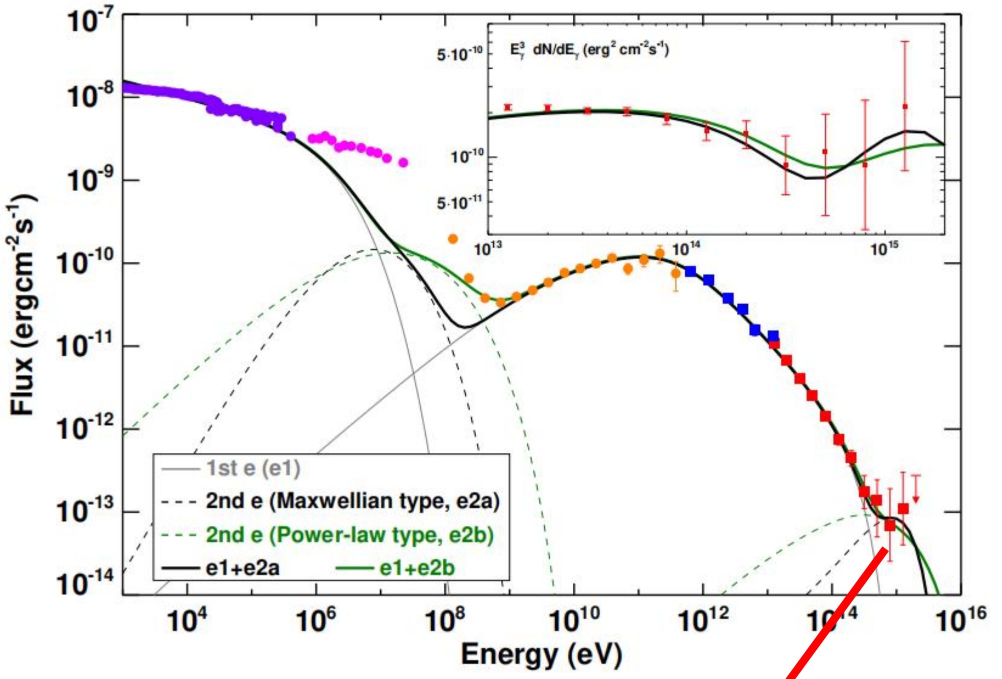
LHAASO observation of crab nebula

Acceleration of PeV electrons by Crab nebula

LHAASO, Science, 373, 425 (2021)



KM2A: 0.88+/-0.11 PeV
WFCTA: $0.92^{+0.28}_{-0.20}$ PeV

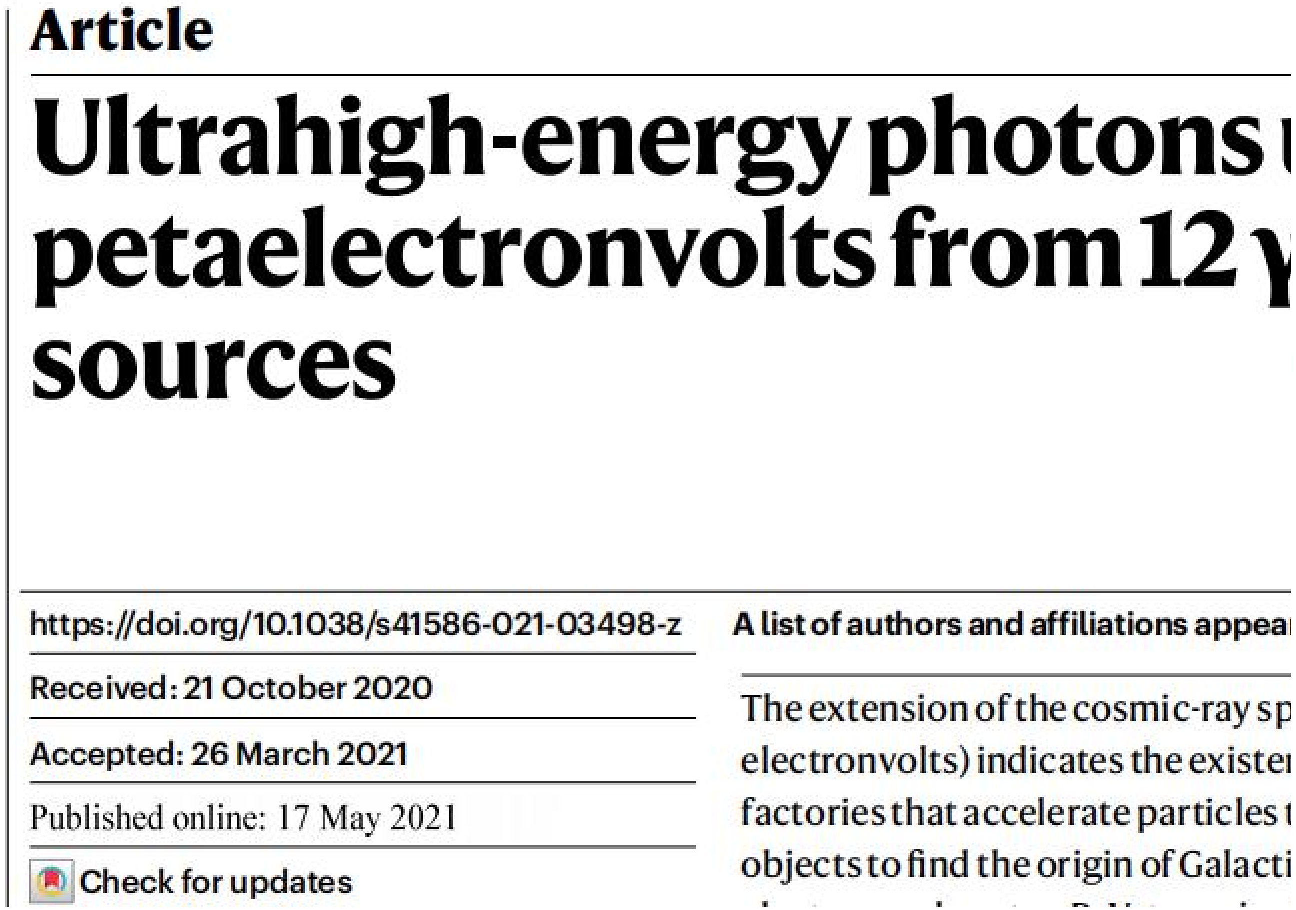


Possible new feature?

LHAASO measurement of the Crab nebula spectrum extends to PeV, revealing PWNe as PeV electron accelerator

LHAASO opens PeV window

LHAASO, Nature, 594, 33 (2021)



Article

Ultrahigh-energy photons u petaelectronvolts from 12 y sources

https://doi.org/10.1038/s41586-021-03498-z

Received: 21 October 2020

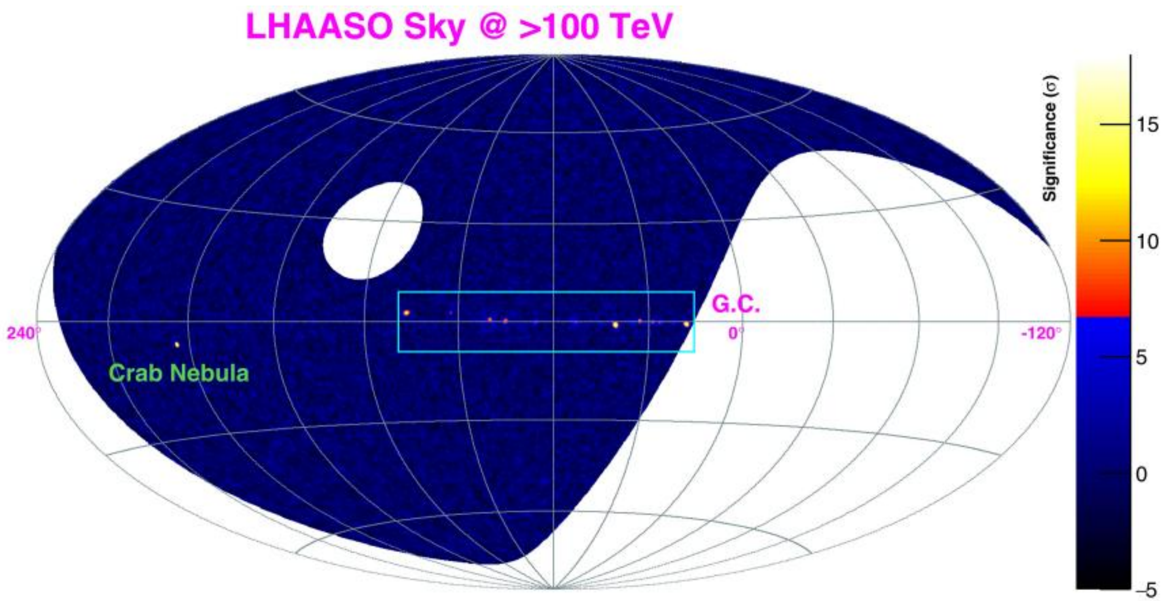
Accepted: 26 March 2021

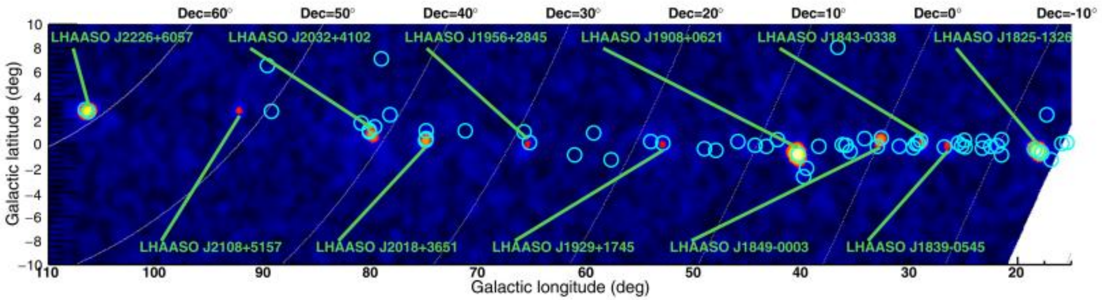
Published online: 17 May 2021

Check for updates

A list of authors and affiliations appea

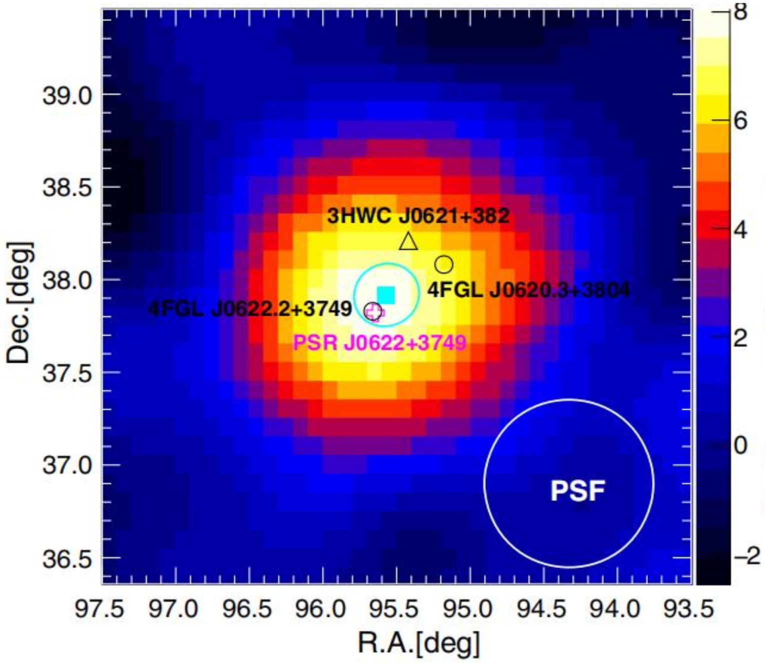
The extension of the cosmic-ray sp electronvolts) indicates the exister factories that accelerate particles t objects to find the origin of Galacti

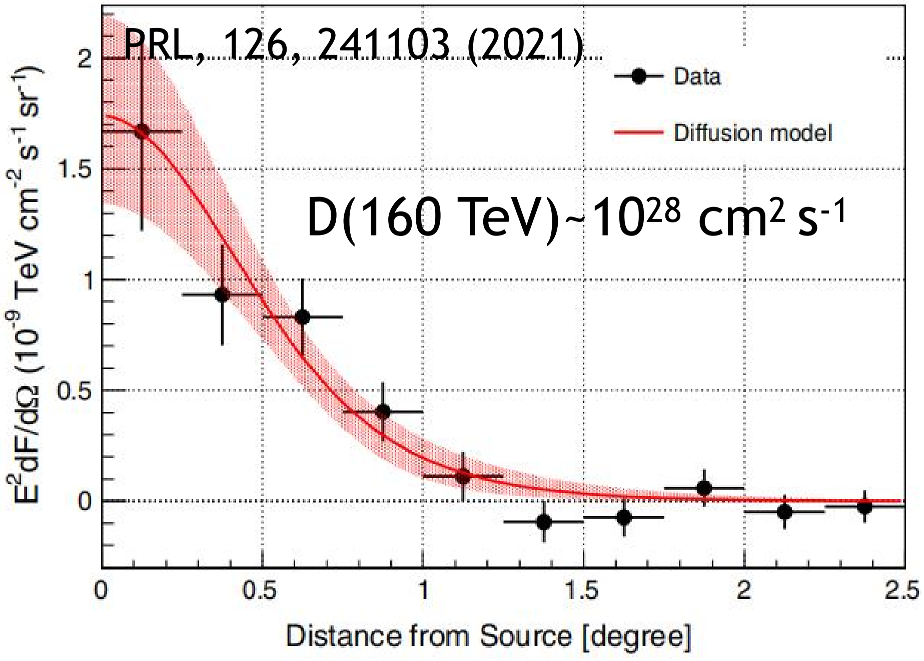




LHAASO discovered a number of PeVatrons, successfully opens the PeV window

LHAASO reveals slow diffusion around pulsars





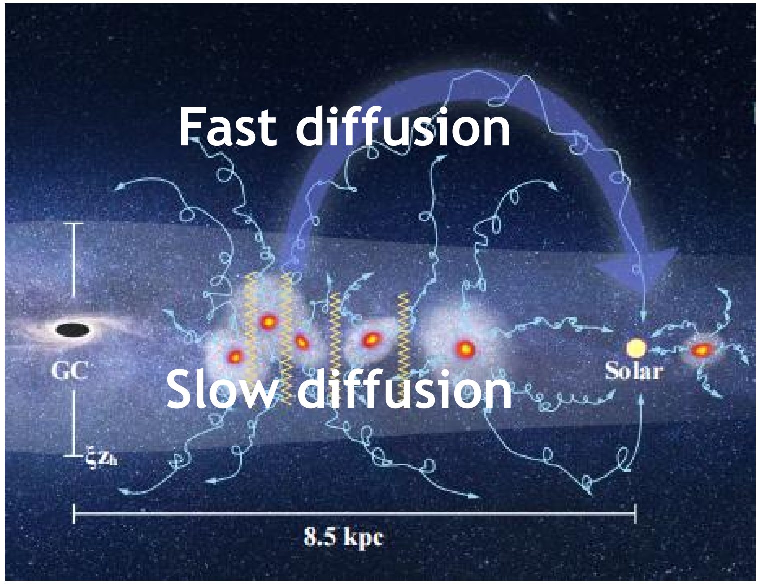
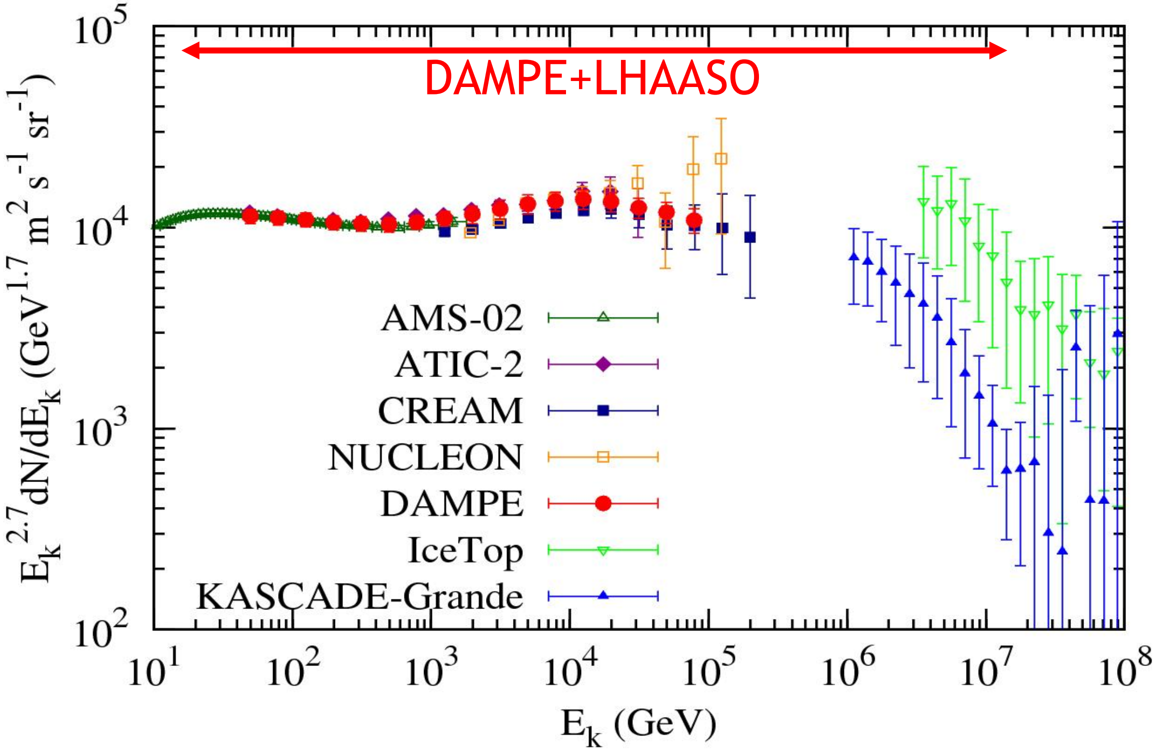


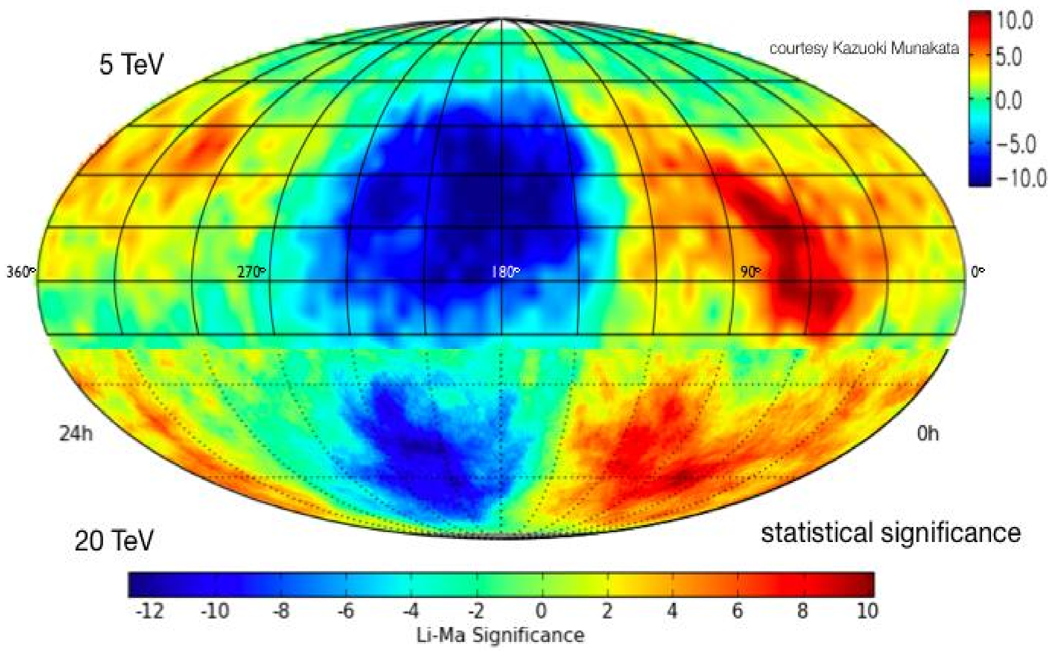
TABLE II. Comparison of the properties of pulsars J0622 + 3749, Geminga, and Monogem.

Name	P (s)	$\dot{P}$ (10^{-14} s s^{-1})	L_{sd} (10^{34} erg s^{-1})	τ (kyr)	d (kpc)	Ref.
J0622 + 3749	0.333	2.542	2.7	207.8	1.60	[25]
Geminga	0.237	1.098	3.3	342.0	0.25	[59]
Monogem	0.385	5.499	3.8	110.0	0.29	[59]

LHAASO discovered extended emission from a pulsar, indicating a very slow diffusion (slower by ~100 times) compared with that inferred from B/C

Joint DAMPE-LHAASO observations

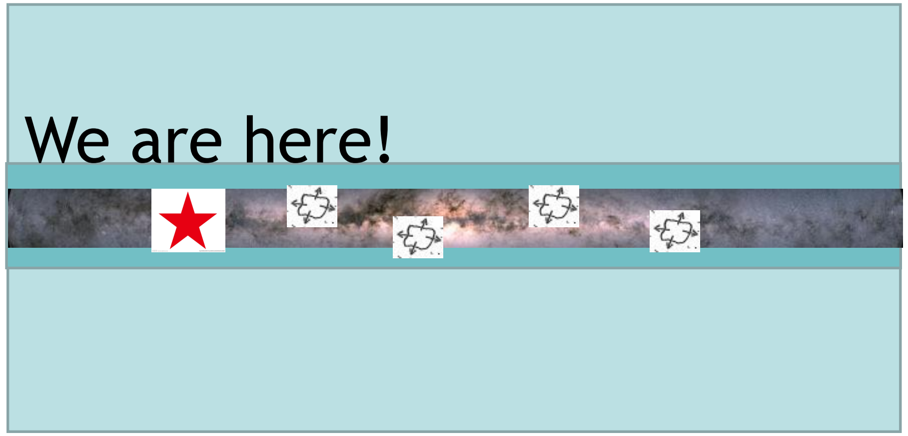




- **Very wide energy coverage (6 orgers of magnitude) measurements of cosmic ray spectra of individual mass component**
- **High-precision measurements of anisotropies of individual mass component**

New paradigm of CR source and propagation

Conventional paradigm

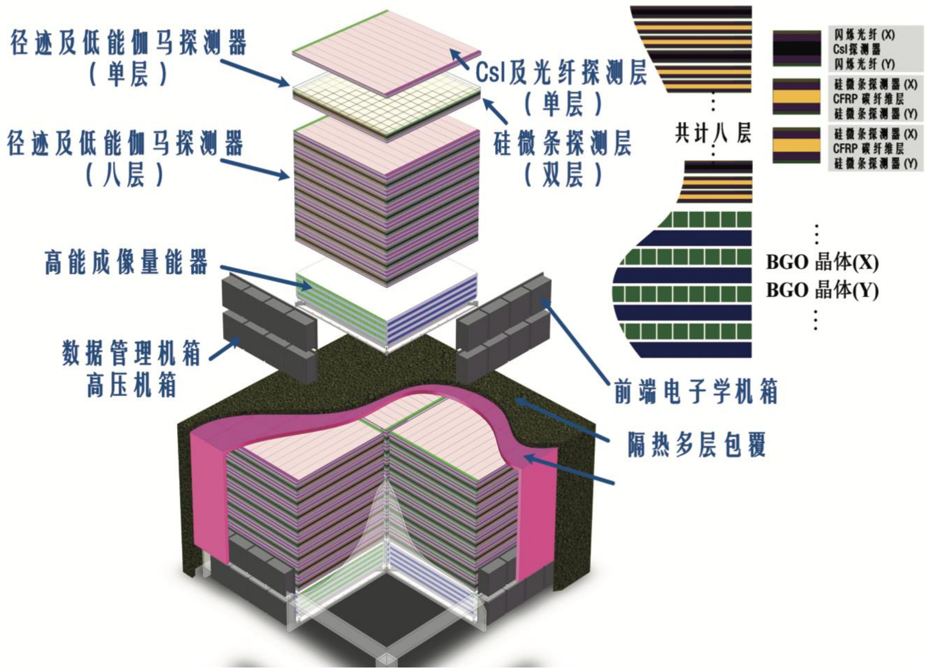


New paradigm

- Continuous source
- Homogeneous, isotropic diffusion
- Can explain roughly low energy data of CRs and diffuse gamma rays

- Continuous source + discrete local source(s)
- Inhomogeneous, anisotropic diffusion
- Reproduce precise measurements of CR spectra, diffuse gamma rays, anisotropies

Very Large Area gamma-ray Space Telescope (VLAST)



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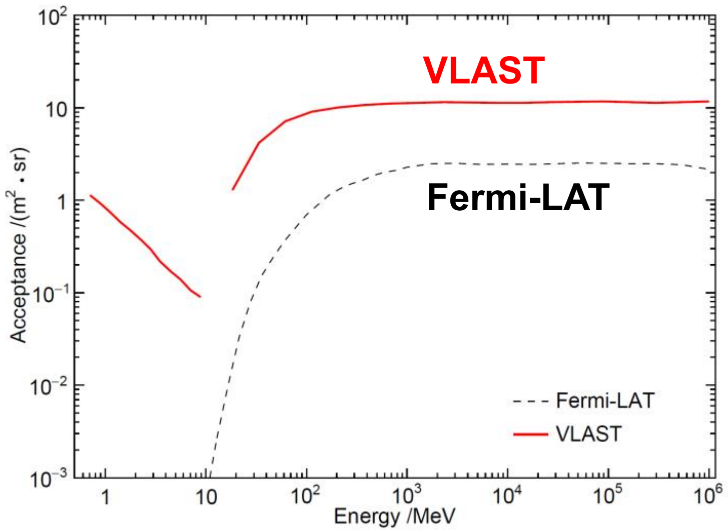
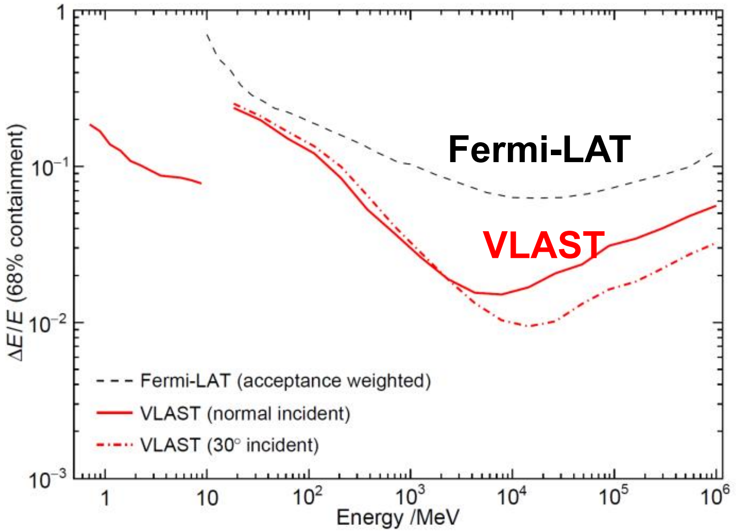
doi: 10.15940/j.cnki.0001-5245.2022.03.002

甚大面积伽马射线空间望远镜计划*

范一中[1,2,3†] 常 进[1,2,3,8‡] 郭建华[1,2,3] 袁 强[1,2,3] 胡一鸣[1,2] 李 翔[1,2,3]
岳 川[1,2] 黄光顺[4,5] 刘树彬[4,5] 封常青[4,5] 张云龙[4,5] 魏逸丰[4,5]

Improve by a factor of ~10 than Fermi-LAT



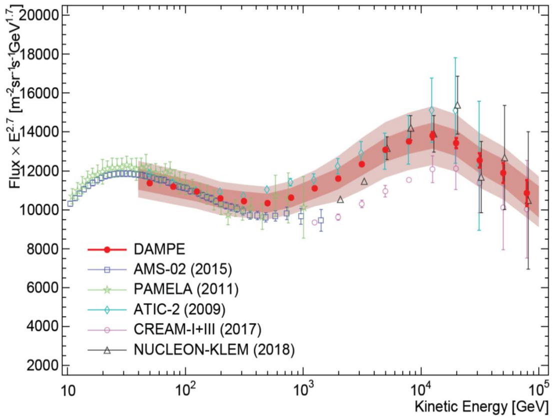


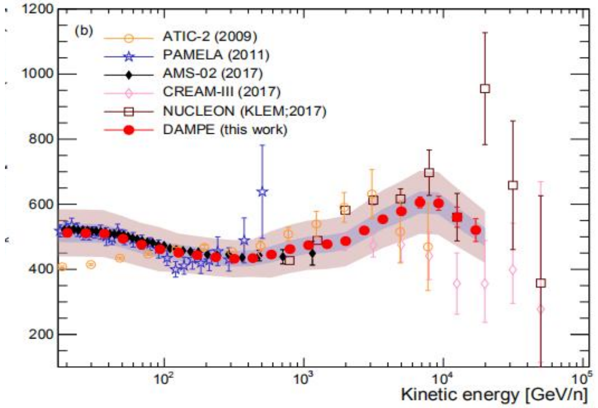
国内外正在运行或提议的一些相关空间探测项目

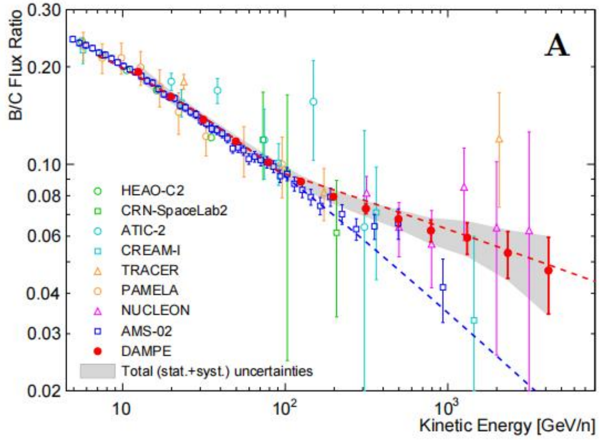
探测设施	主要探测对象	峰值接受度 (m^2 sr)	目前阶段	备注
Fermi-LAT	伽马射线	~ 2	在轨	量能器
悟空号	宇宙线、伽马	~ 0.3	在轨	
AMS-100	宇宙线、伽马	~100	初步概念	磁谱仪
先进粒子天文望远镜APT	伽马射线、宇宙线	~20	关键技术攻关	量能器
HERD	宇宙线	~4	关键技术攻关	
VLAST	伽马射线	~10	关键技术攻关	

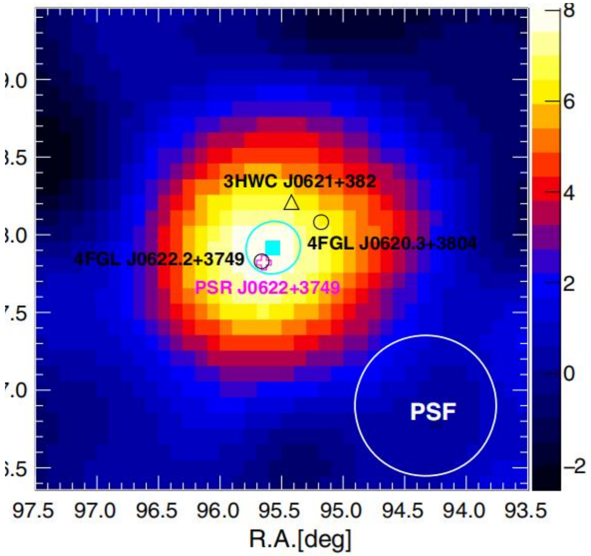
Summary

- DAMPE and LHAASO are among the best experiments in CR/γ detection, offering important opportunity to understand CR origin and propagation
- Precise measurements of p, He spectra show new structures, which may be imprints of local sources
- Detection of breaks of B/C and B/O, and exended emission from pulsar implies new properties of propagation
- New observations of the spectra and anisotropies by joint efforts of DAMPE and LHAASO may eventually uncover the mystery of CRs









Thank you!