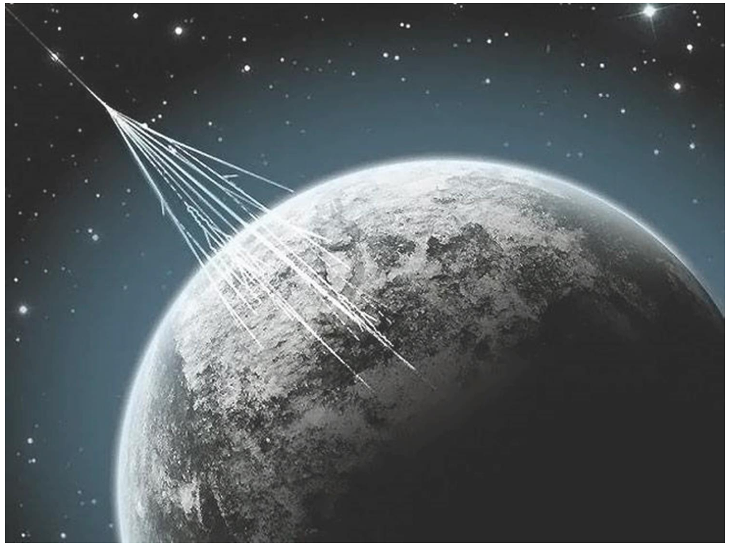
A mini-review on Galactic cosmic rays

Qiang Yuan

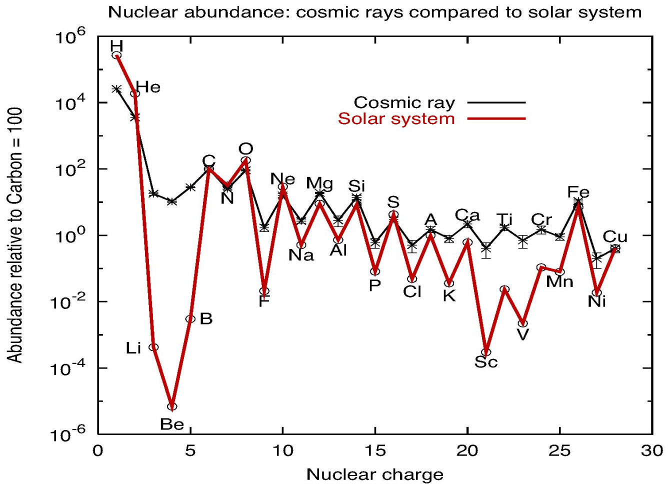
Purple Mountain Observatory, CAS

Workshop on High Energy Cosmic Ray Physics and Next Generation Space Detector,
Urumqi, Xinjiang, 2025-07-31

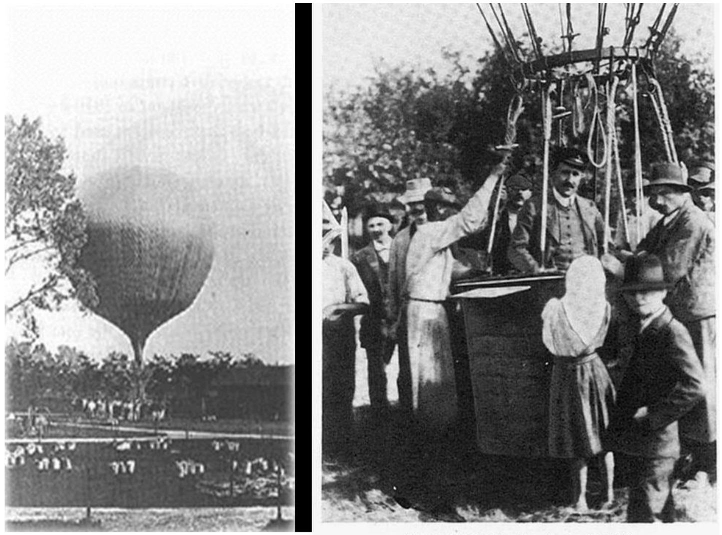
Cosmic rays: overview



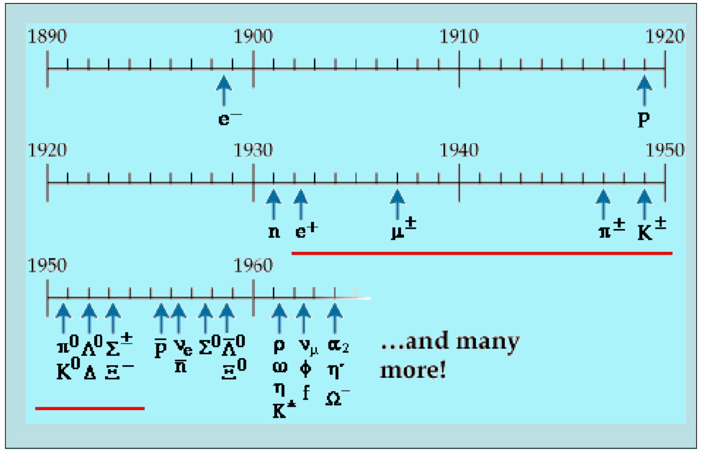
Discovered by V. Hess etc. in 1910s



Including almost all elements observed on the Earth



Hess bei Ballonlandung (1912).



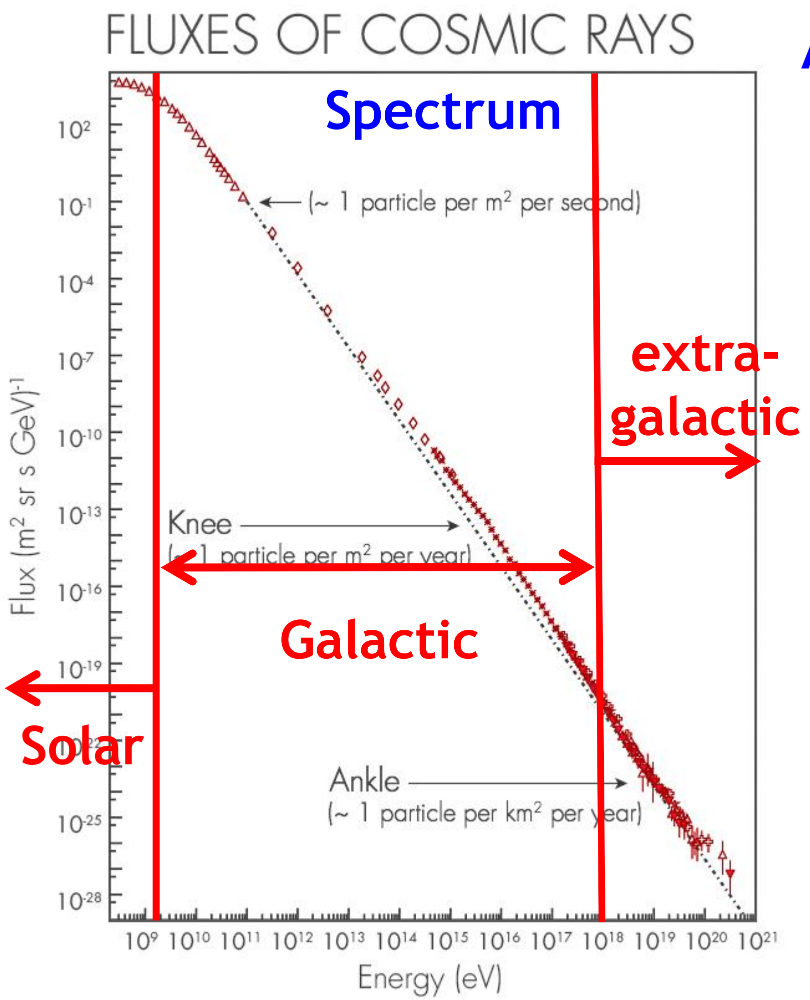
Leading particle physics from 1930s to 1950s

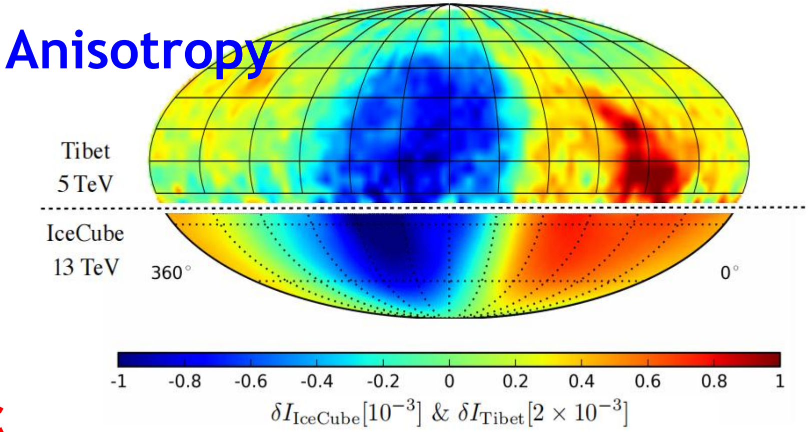
Four astronomical messengers: electromagnetic waves, gravitational waves, cosmic rays, neutrinos

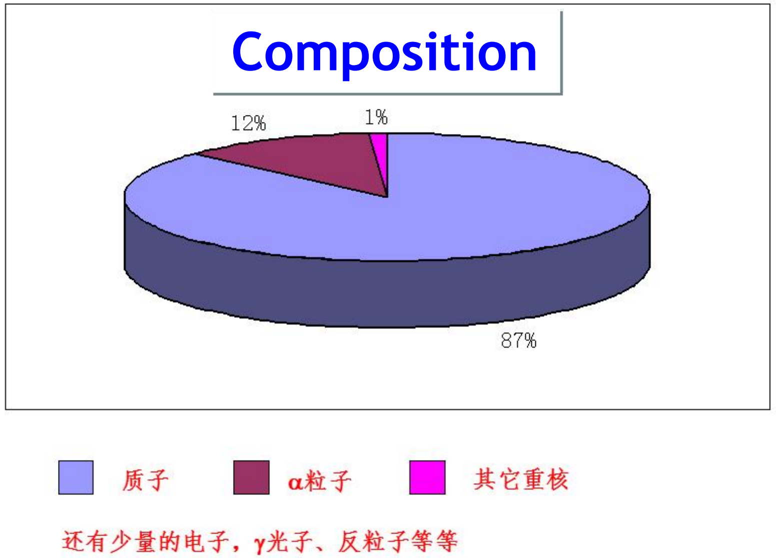
New Physics
- Dark matter
- Acceleration at ultra-high energies
- Lorentz invariance violation

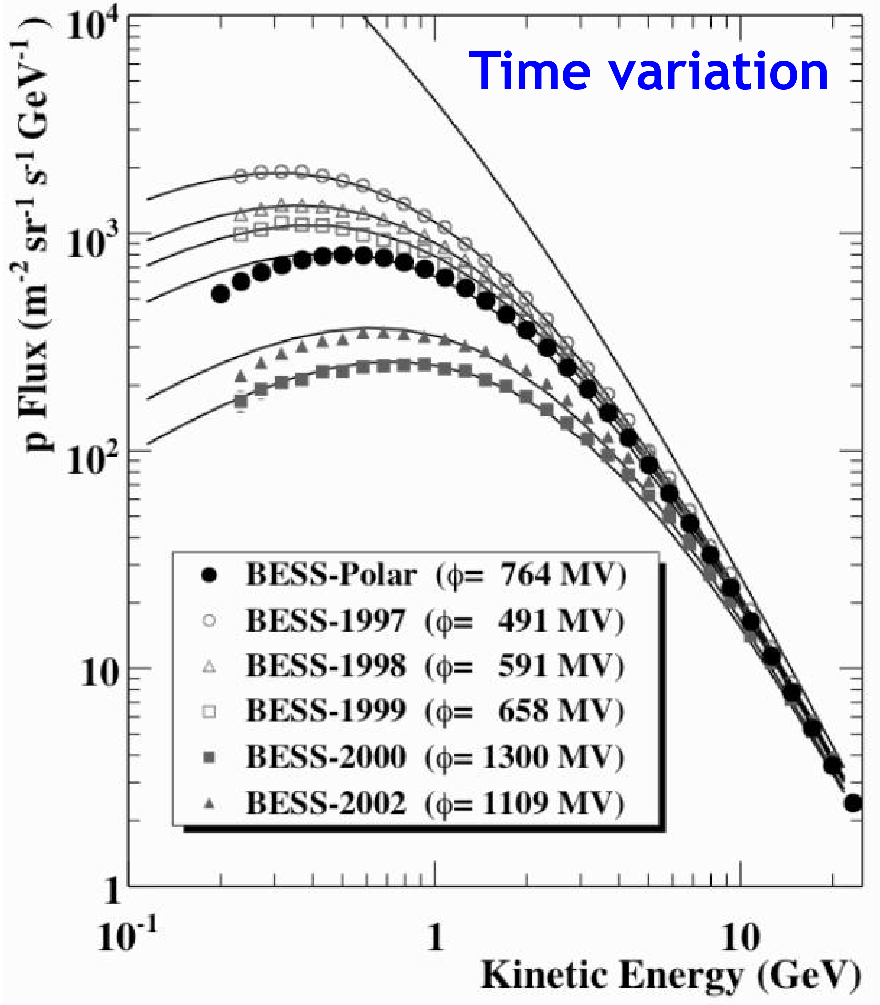
Extreme Astronomy
- Multi-messenger sources
- Objects at extreme conditions (energy, density, gravity etc.)

Cosmic rays: overview





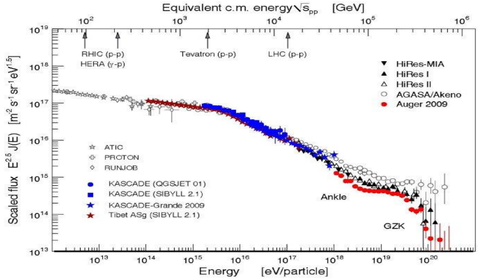




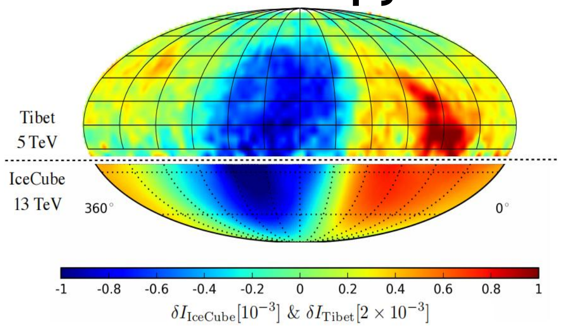
Spectrum: non-thermal power-law, structures; **Anisotropy:** $<10^{-3}$ dipole + small-scale anisotropy; **Composition:** mostly nuclei, a tiny fraction of electrons, positrons, anti-particles; **Time variation:** anti-correlation with solar activities at low energies

General picture about GCRs

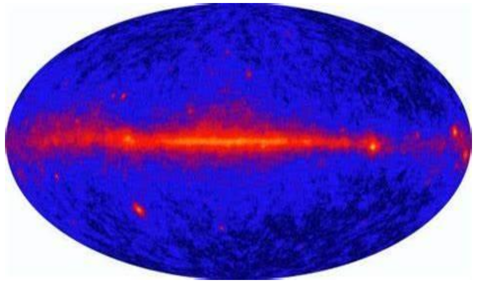
Spectra

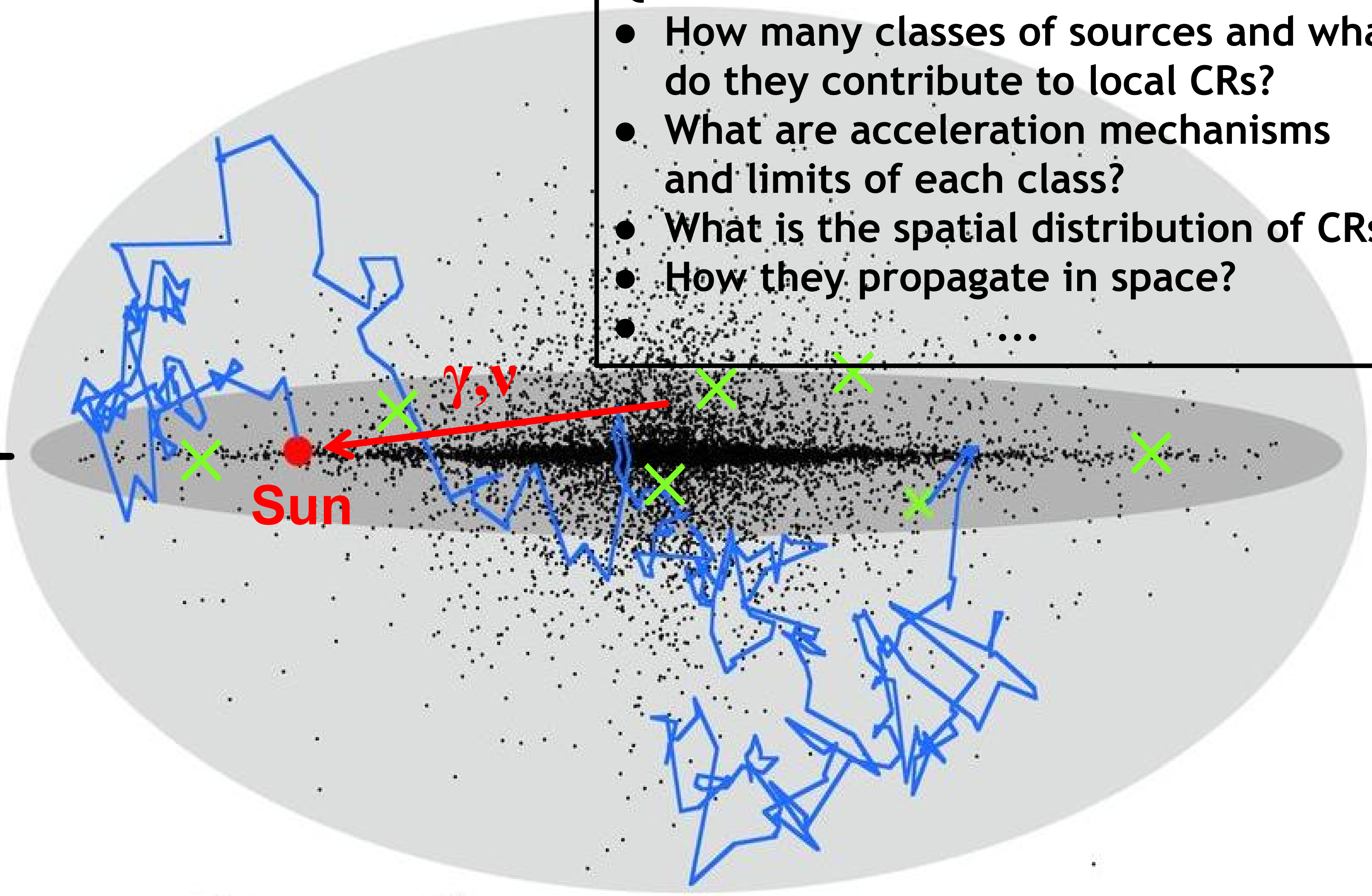


Anisotropy



MW radiation

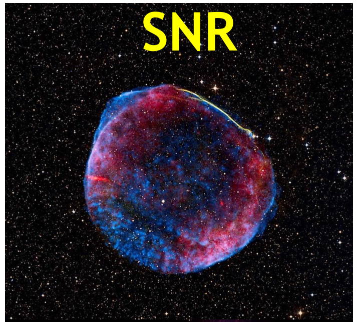


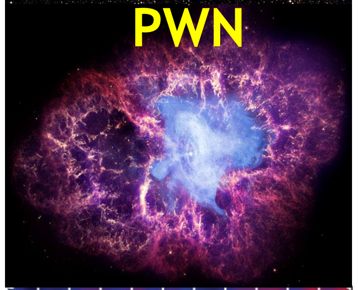


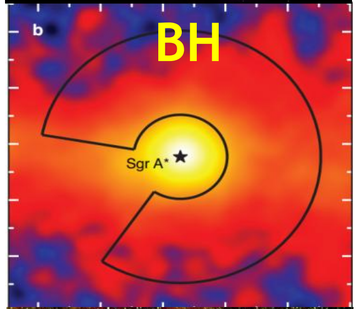
Questions:

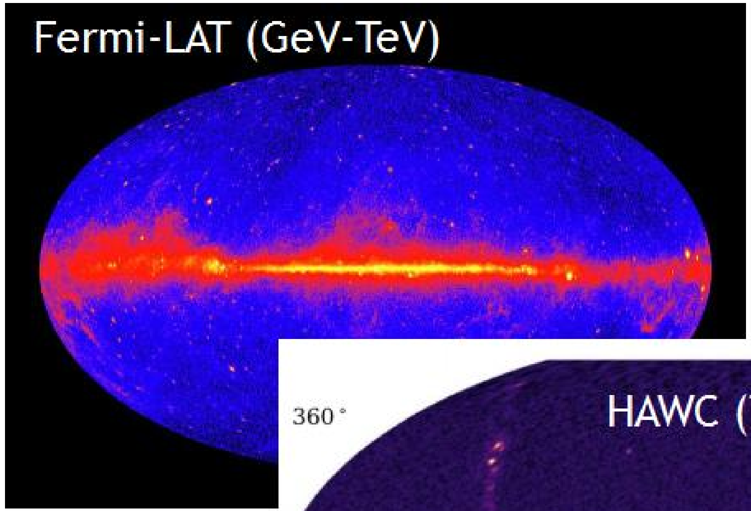
- How many classes of sources and what do they contribute to local CRs?
- What are acceleration mechanisms and limits of each class?
- What is the spatial distribution of CRs?
- How they propagate in space?
- ...

Sources can accelerate CRs





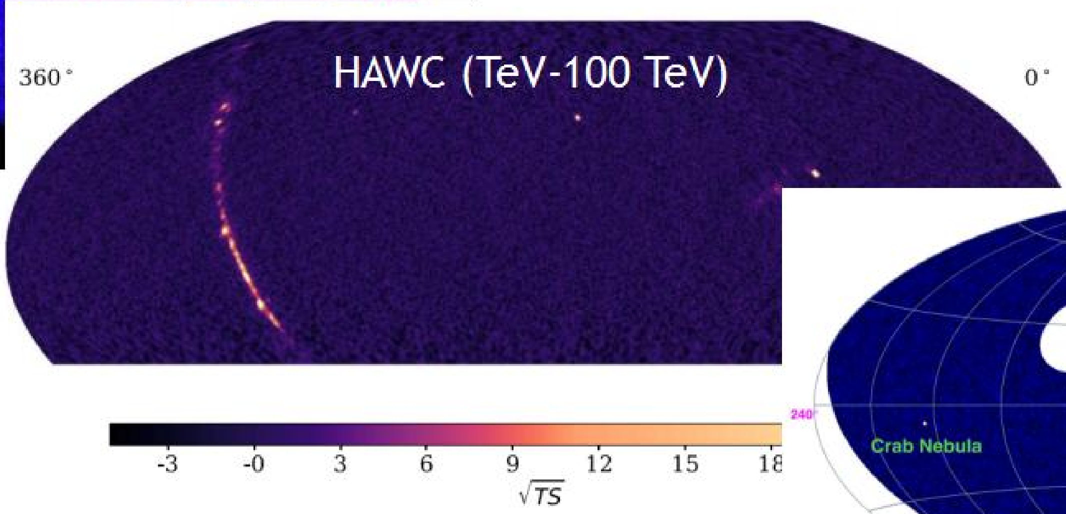


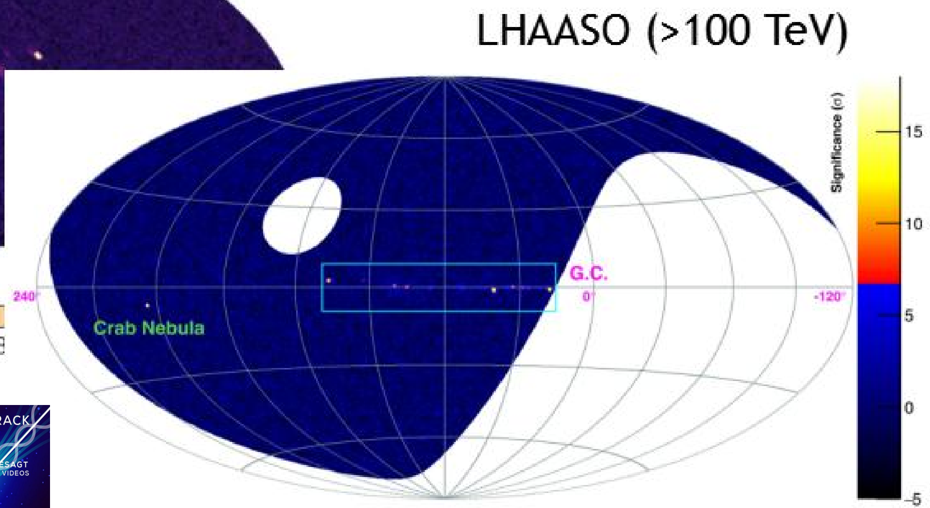


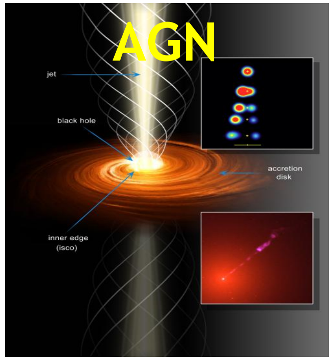
$p, \alpha + \text{gas} \rightarrow \pi^0 \rightarrow 2\gamma$

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

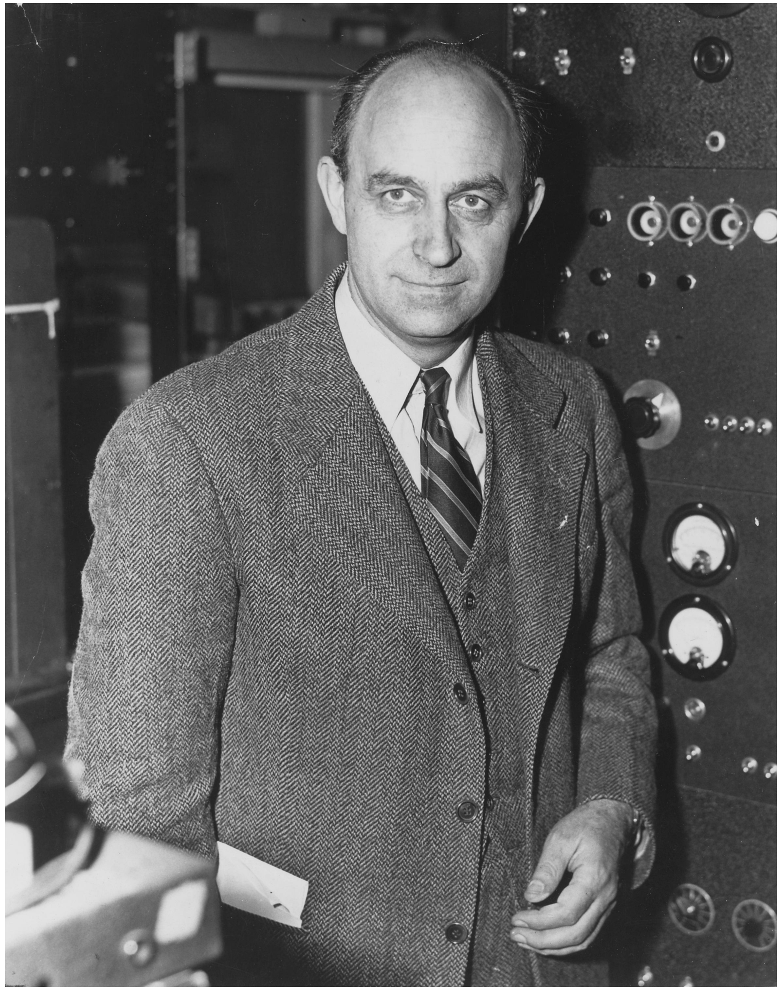
$e^{+/-} + \text{ISRF} \rightarrow \gamma$ (inverse Compton scattering)







Fermi statistical acceleration



Enrico Fermi

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

Assuming: every "collision" results in energy gain $\Delta E = \xi E$, particle has an escape probability P_{esc}

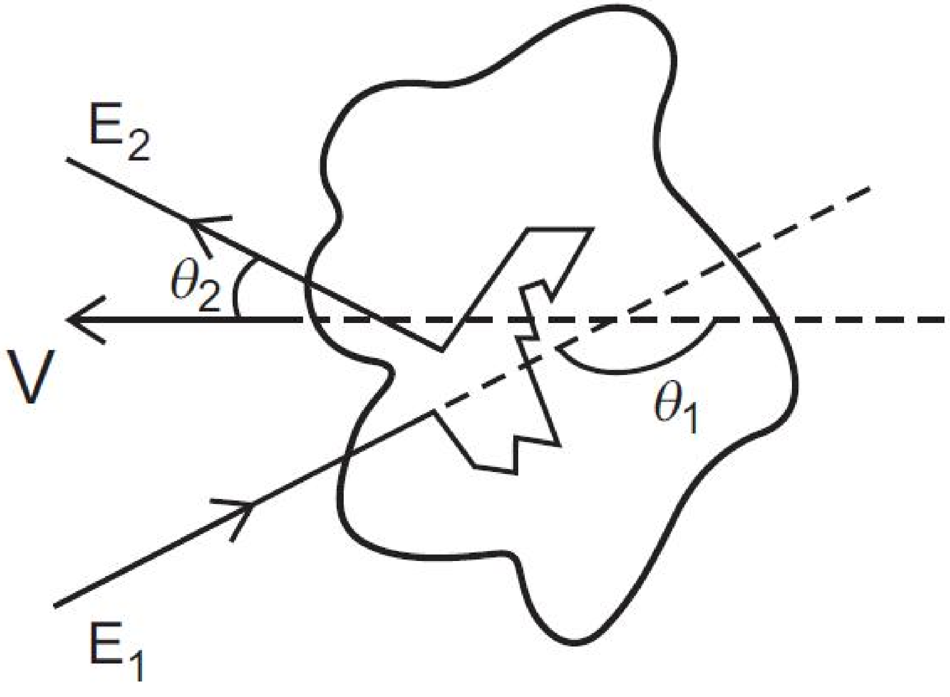
$$N(\geq E) \propto \sum_{m=n}^{\infty} (1-P_{\rm esc})^m = \frac{(1-P_{\rm esc})^n}{P_{\rm esc}},$$

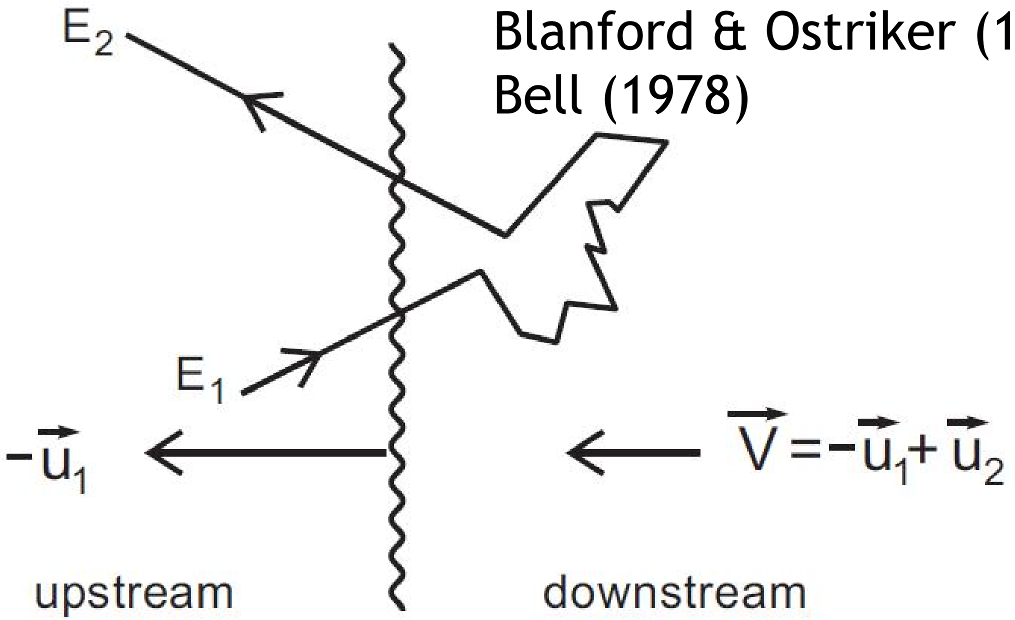
$$= \frac{1}{P_{\rm esc}} \left(\frac{E}{E_0}\right)^{-\gamma}$$

$$\gamma = \ln\left(\frac{1}{1-P_{\rm esc}}\right) / \ln(1+\xi) \approx \frac{P_{\rm esc}}{\xi} = \frac{1}{\xi} \times \frac{T_{\rm cycle}}{T_{\rm esc}}$$

2^{nd} and 1^{st} order Fermi acceleration

Krymskii (1977)
Axford et al. (1978)
Blanford & Ostriker (1978)
Bell (1978)



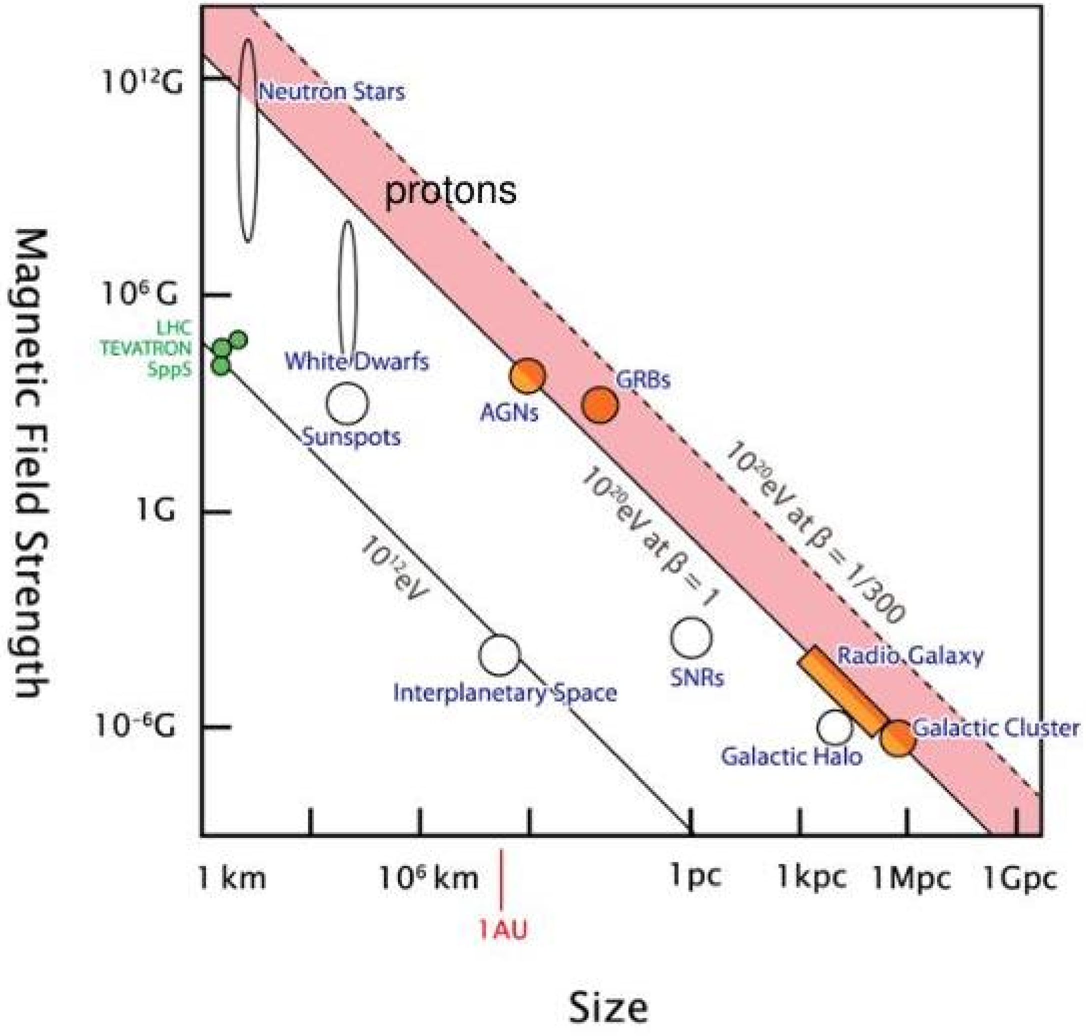


$$\frac{\triangle E}{E_1} = \frac{1+\frac{1}{3}\beta^2}{1-\beta^2} - 1 \sim \frac{4}{3}\beta^2$$

$$\frac{\Delta E}{E_1} = \frac{1+\frac{4}{3}\beta+\frac{4}{9}\beta^2}{1-\beta^2} - 1 \sim \frac{4}{3}\beta$$

Gaisser (1990)

Maximum energy: Hillas criterion



$$\mathbf{E} = -\mathbf{u} \times \mathbf{B}$$

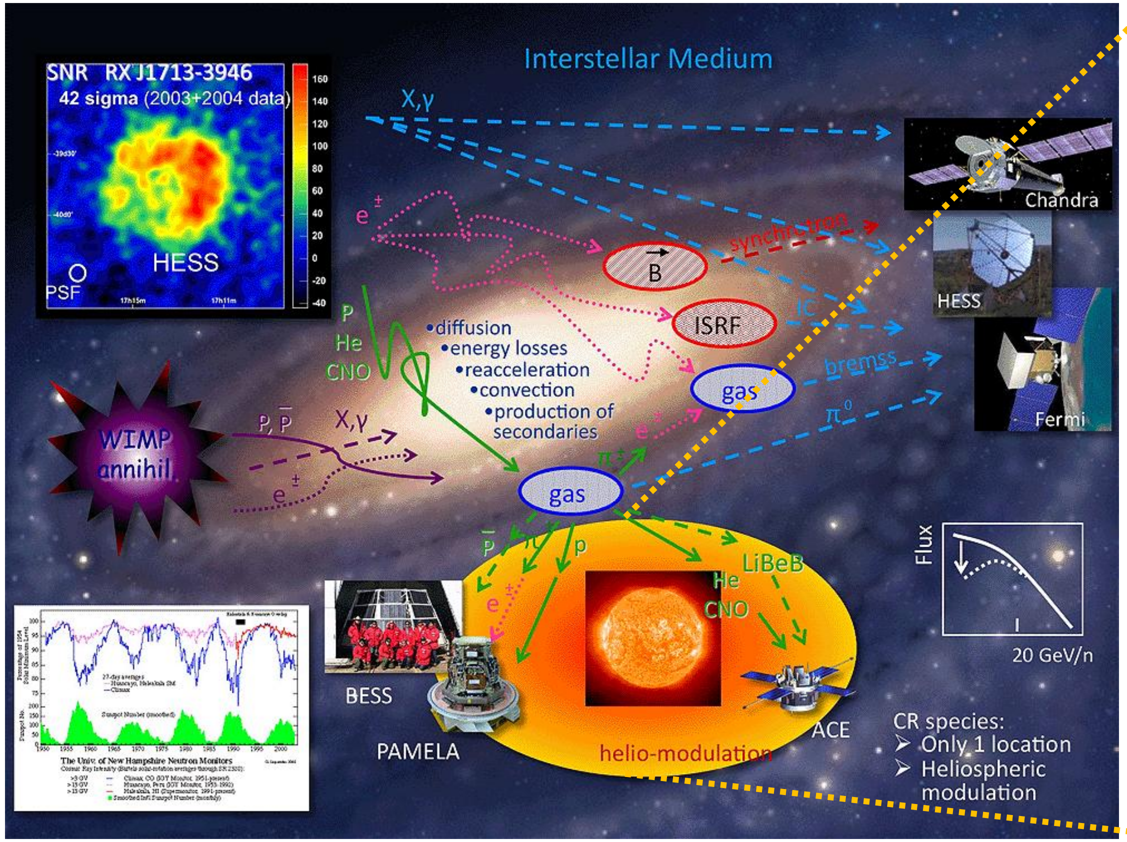
$$E_{max} = uZBL$$

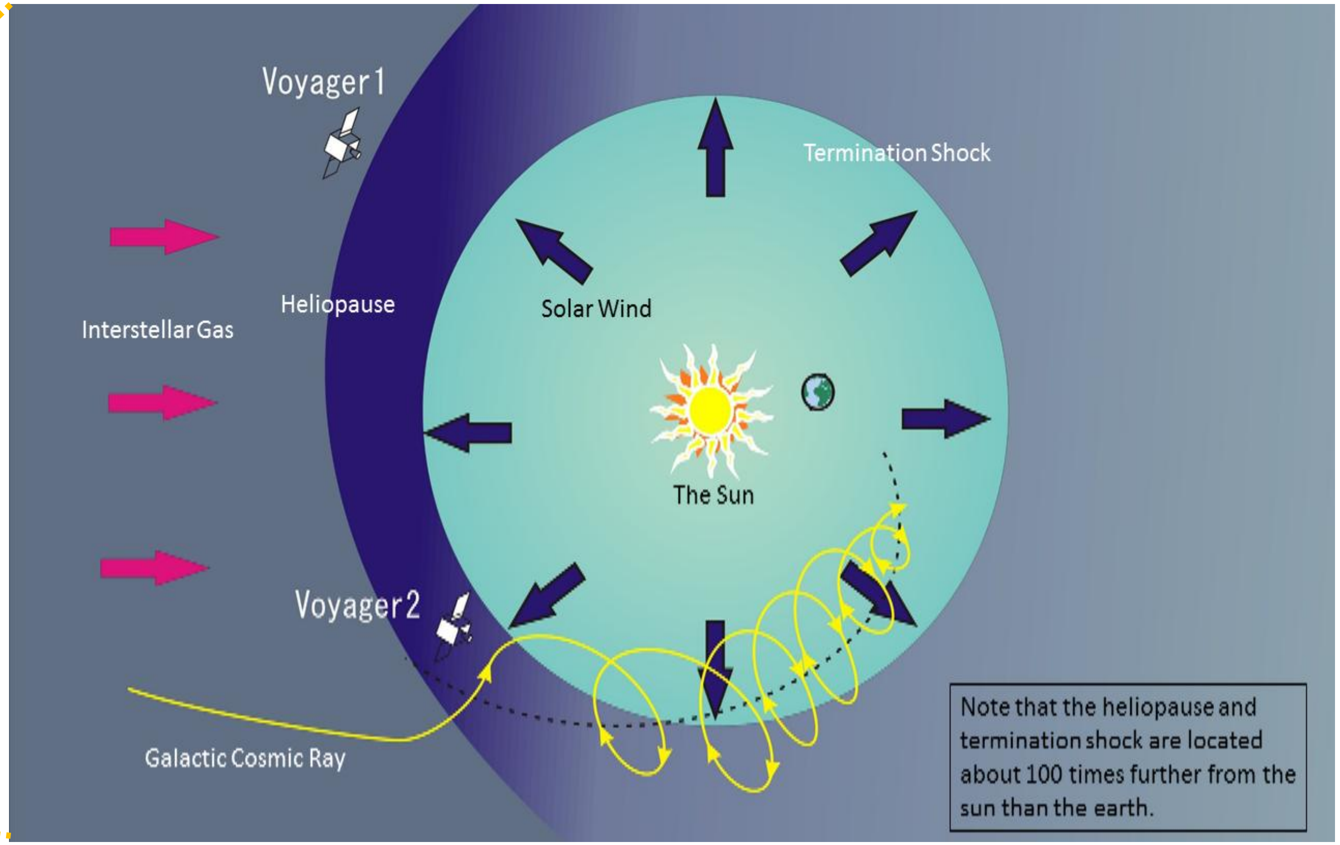
The maximum energy a particle with charge Z can get through moving a distance L in electric field uB

Hillas (1984, ARA&A, 22, 425)

Propagation in the Milky Way and heliosphere

I. V. Moskalenko

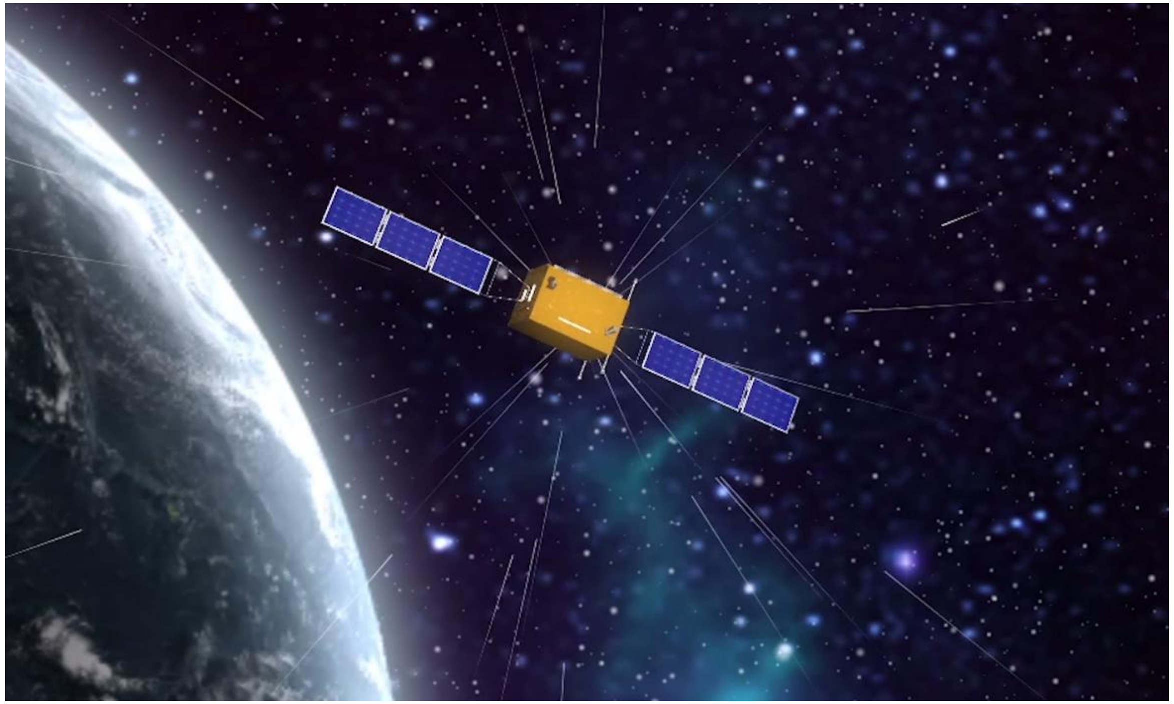


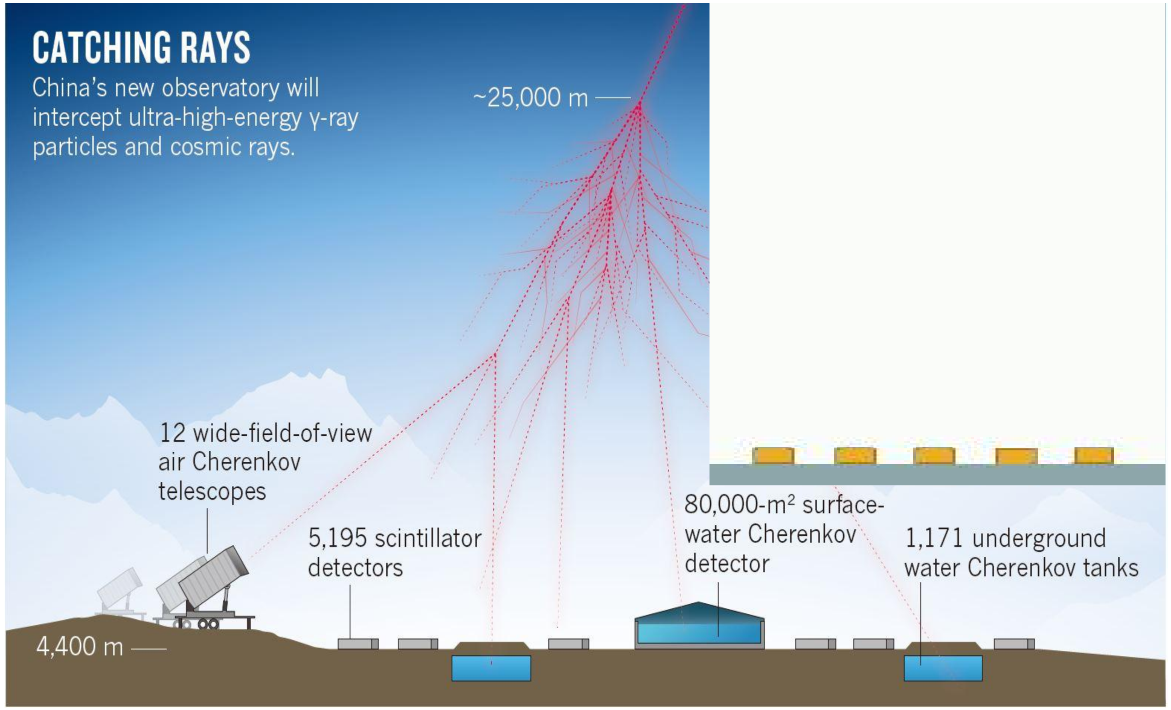


$$\frac{\partial \psi(\vec{r}, p, t)}{\partial t} = q(\vec{r}, p, t) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi)$$

$$+ \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

Detection of CRs





Space direct detection:

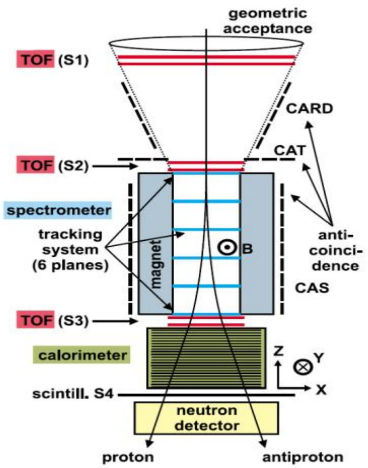
- No atmosphere impact, good particle identification
- Small scale, low energy

Ground indirect detection:

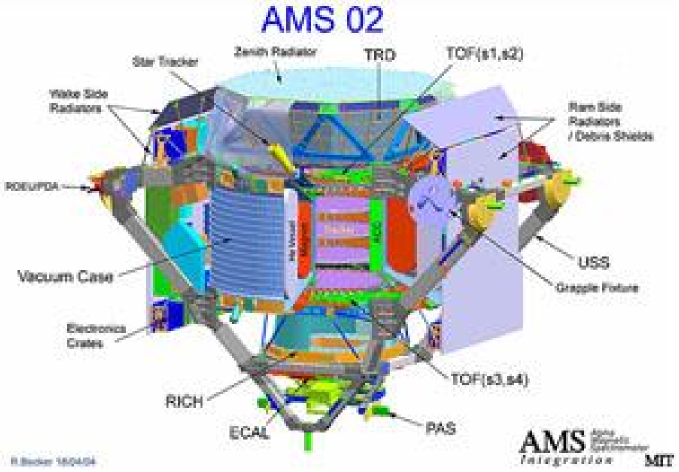
- Relatively poor particle identification
- Large scale, high energy

Recent/ongoing experiments

PAMELA

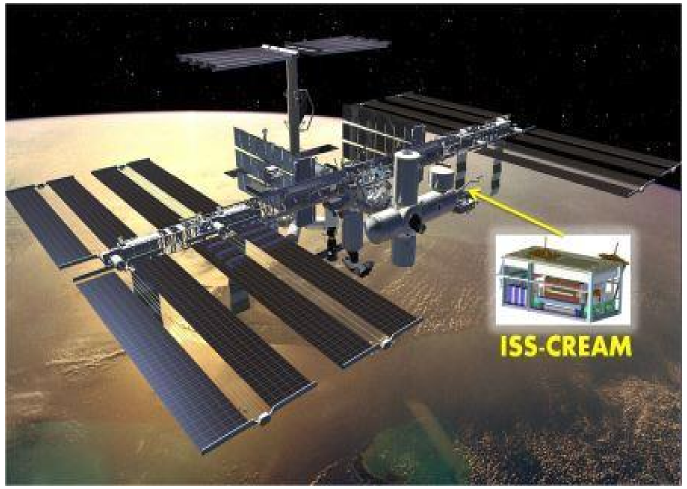


AMS-02



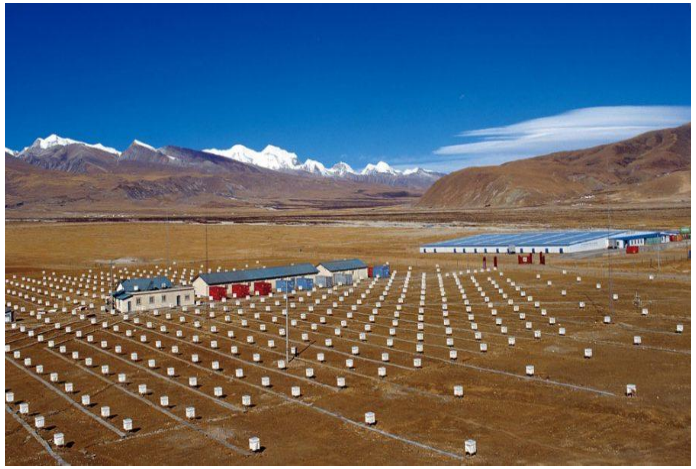
CALET

ISS-CREAM



KSACADE

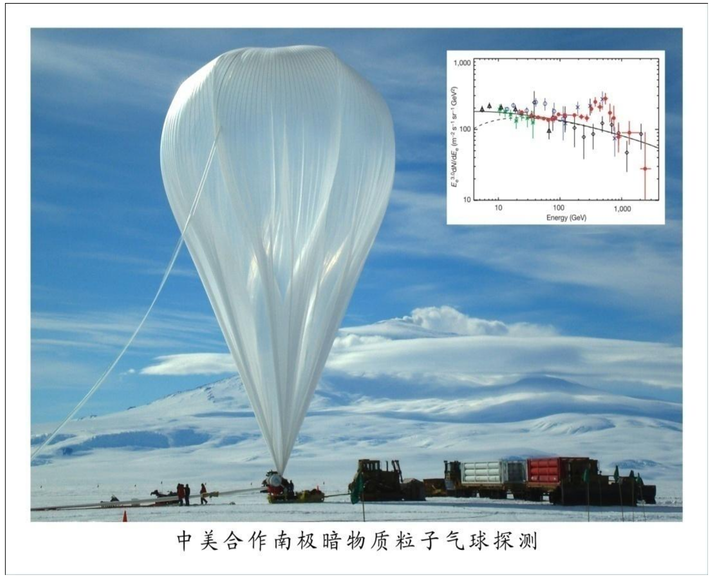
Tibet



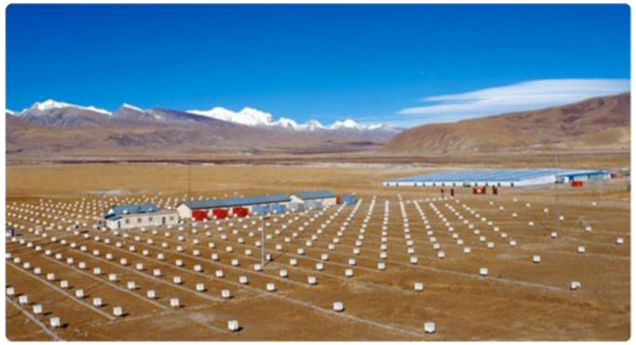
HESS/MAGIC/VERITAS/CTA

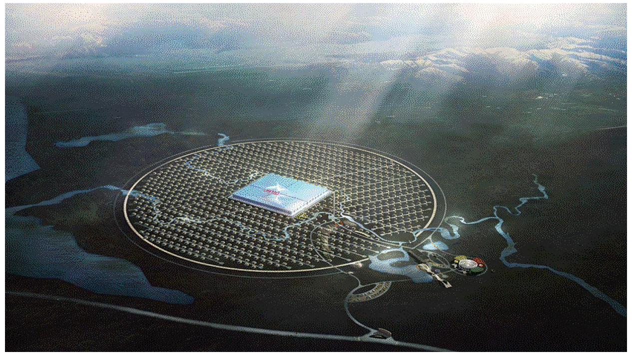
HAWC

CR studies in China



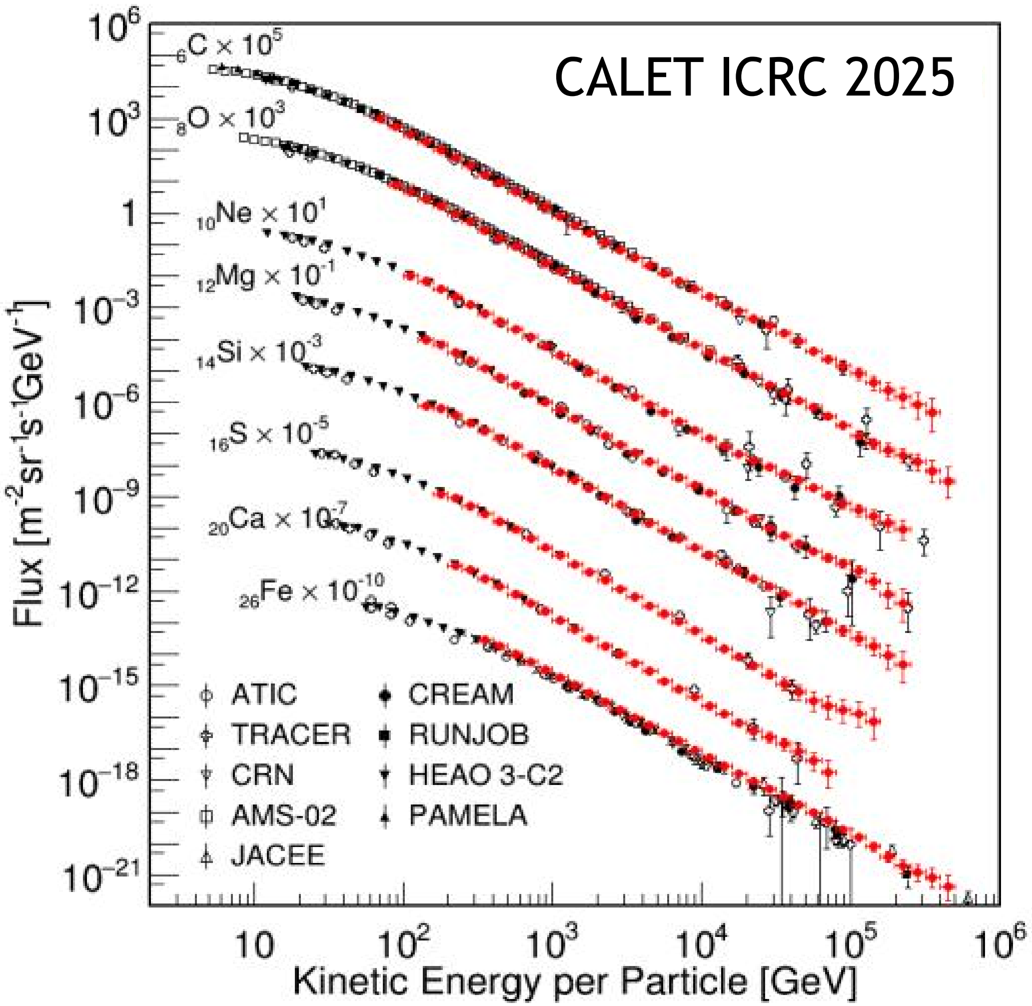
Balloon (1970s) | Manned space (1990s) | Balloon (2000s) | DAMPE (2010s)

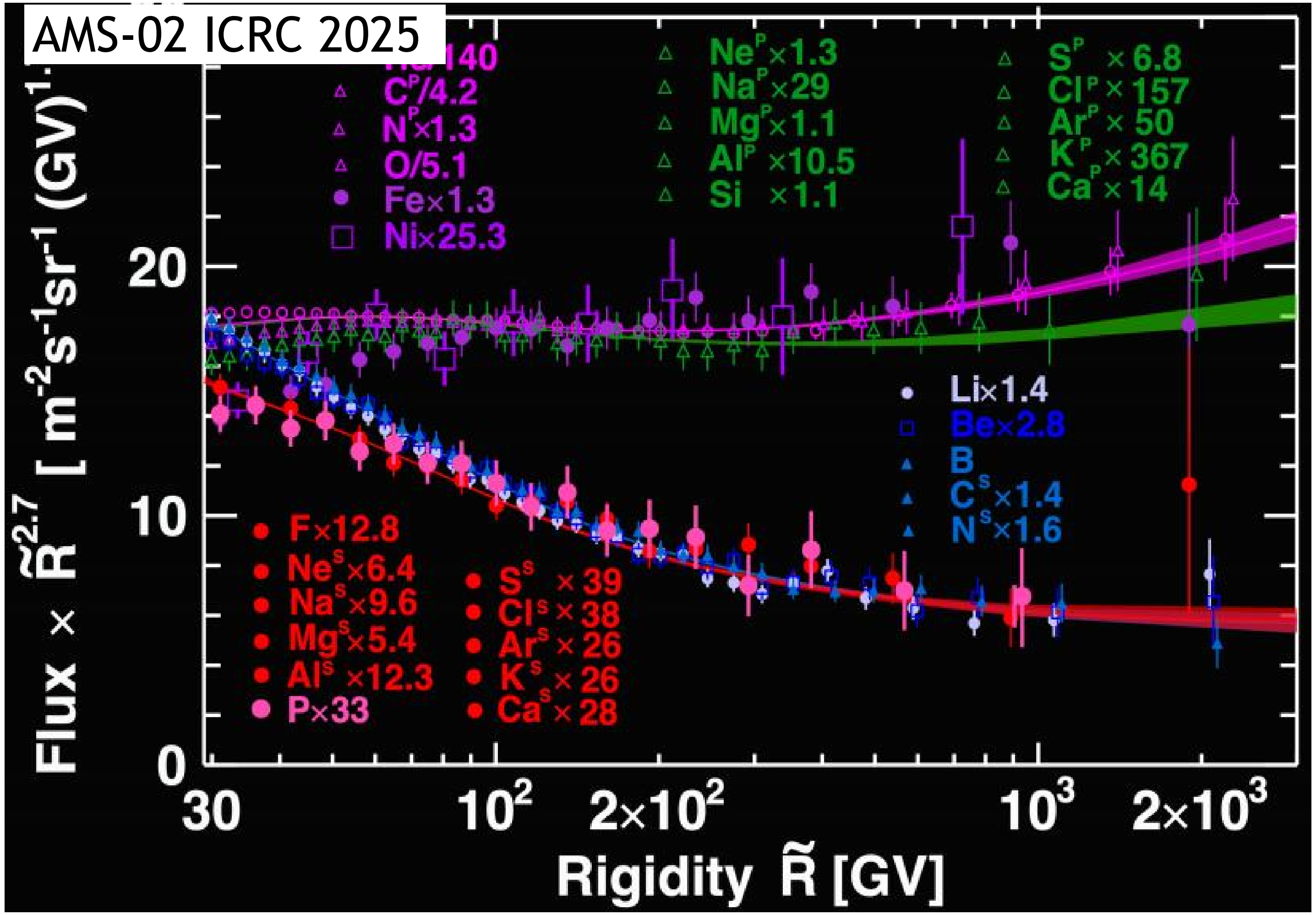




Yunnan (1950s) | Tibet (1970s) | Tibet (1990s) | Sichuan (2010s)

Measurements of CR spectra

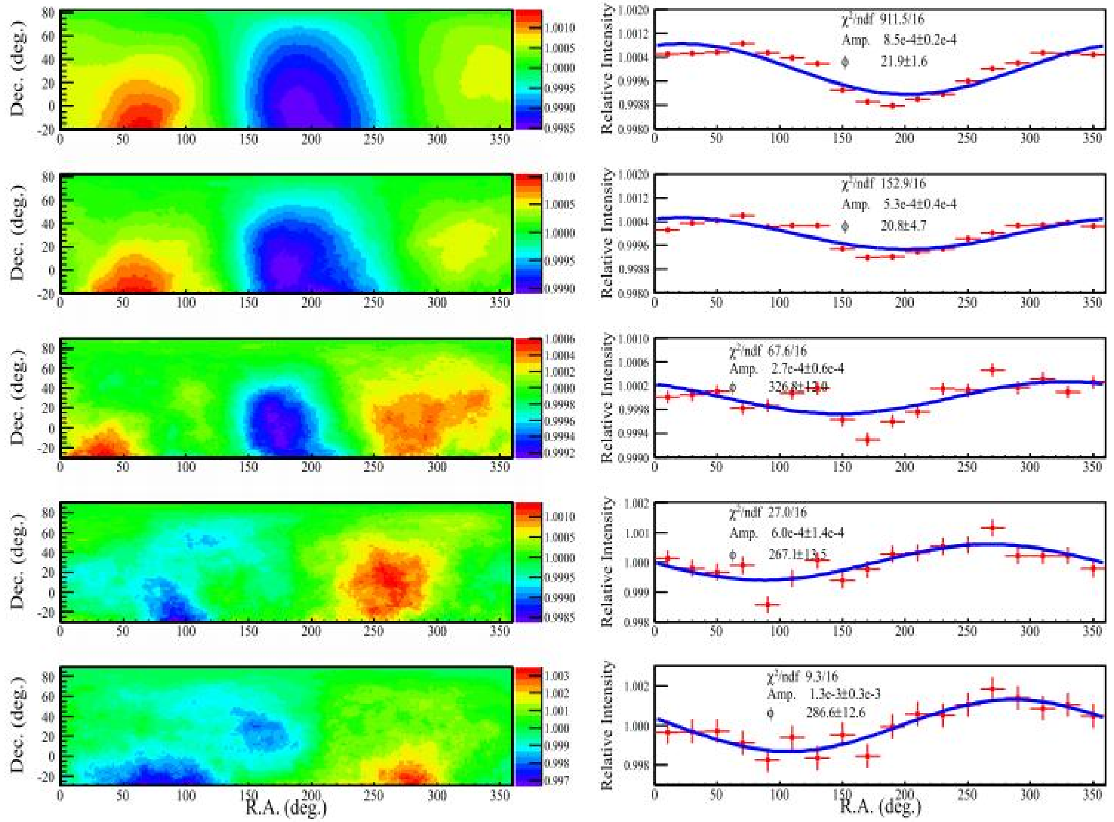




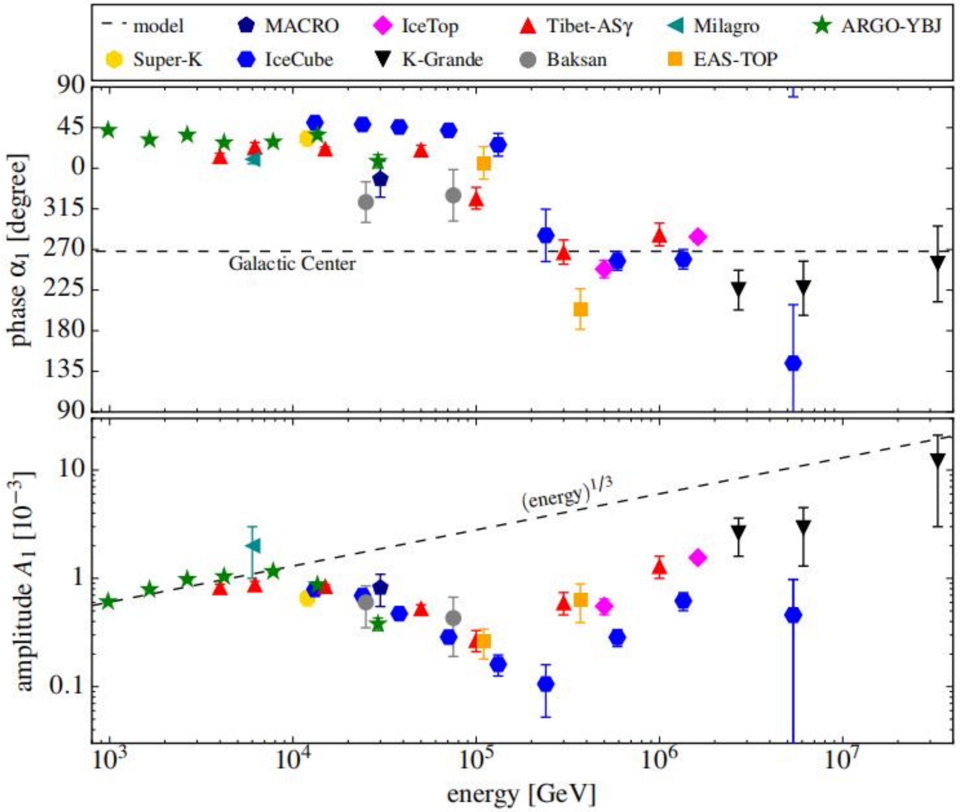
Spectra of many nuclei species have been precisely measured up to TV rigidity, showing hardening features around O(100) GV

Measurements of CR anisotropies

Tibet-ASγ, ApJ, 836, 153 (2017)



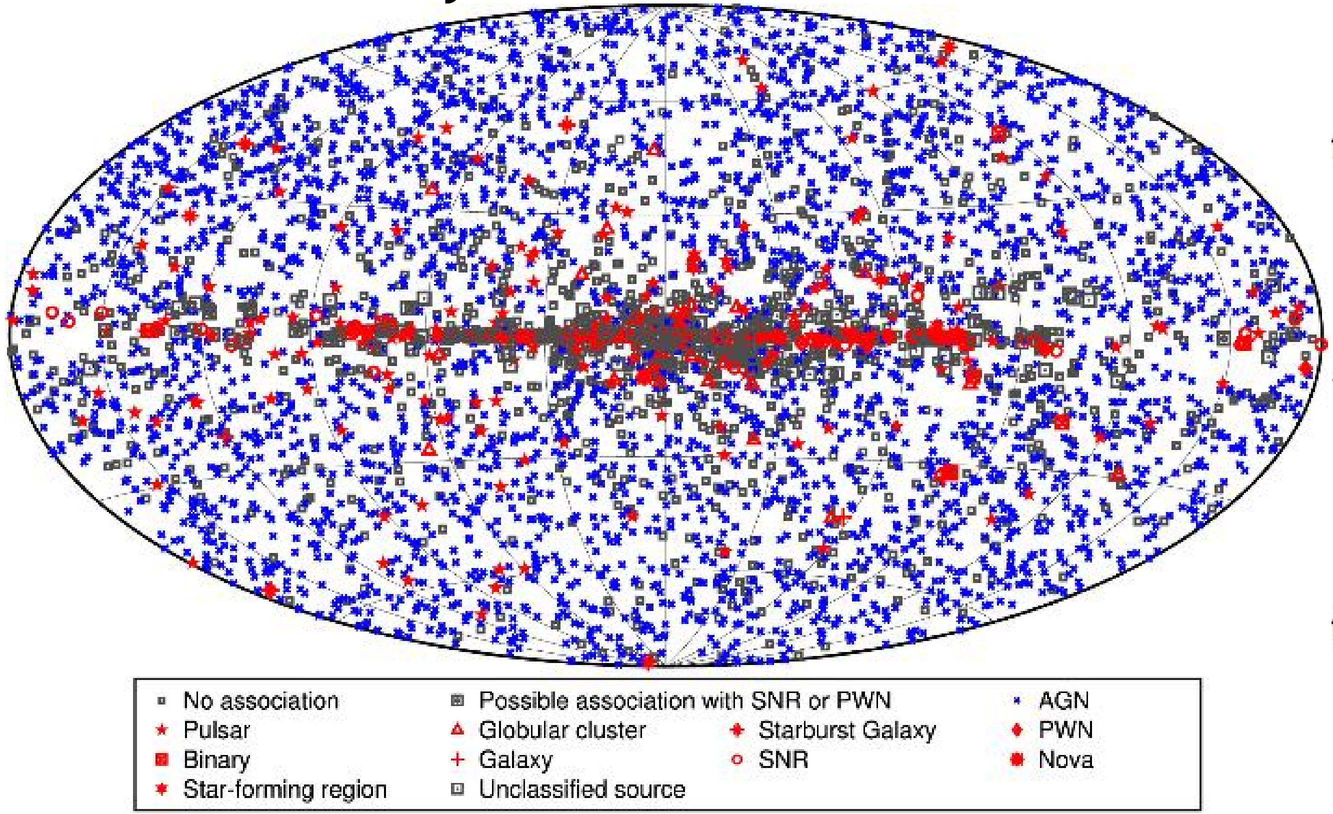
Ahlers & Mertsch, PPNP, 94, 184 (2017)



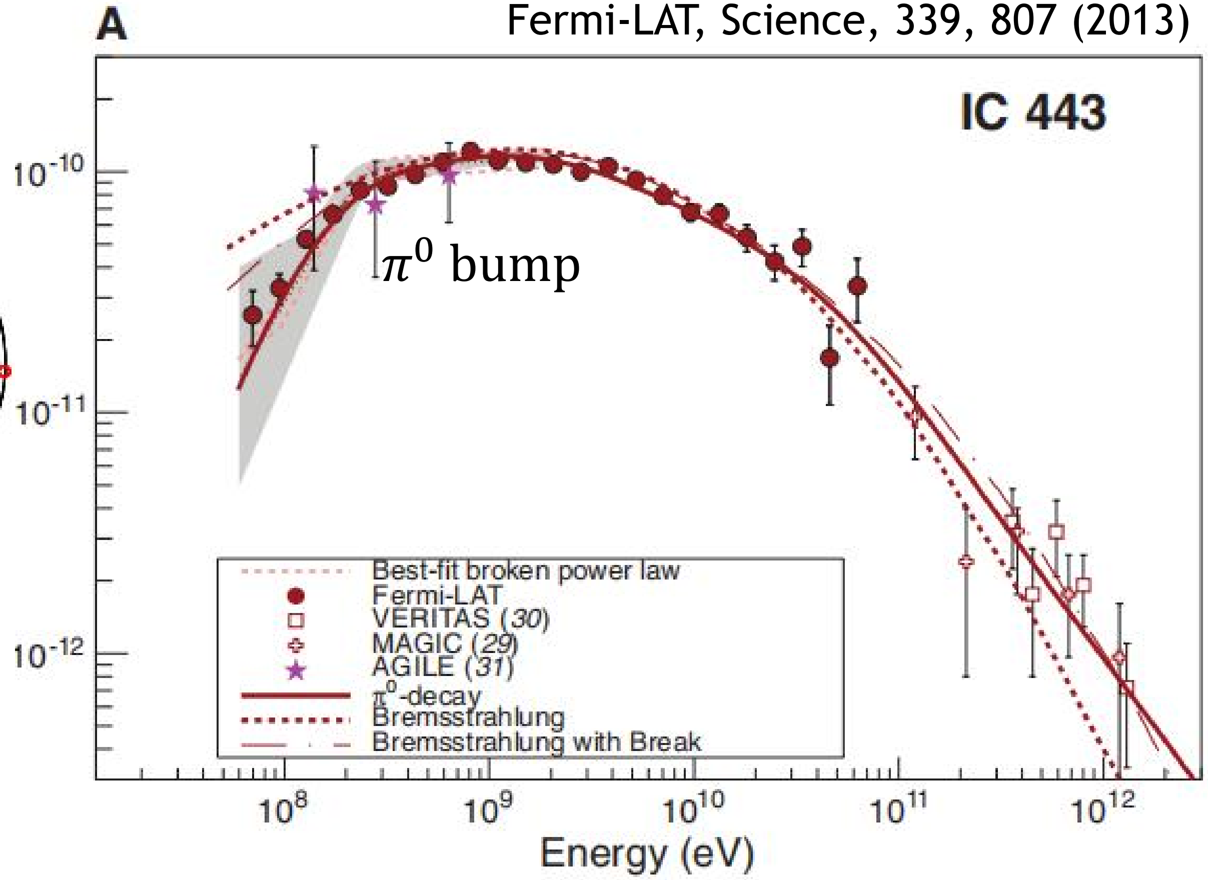
- CR particles lose their directions due to the random scatterings in interstellar magnetic field, resulting in very tiny anisotropies (10^{-4}~10^{-3})
- To measure the anisotropies require high statistics, and can only be achieved by groundbased experiments without measurements for individual species

Measurements of γ-ray sources

>5000 sources by Fermi-LAT

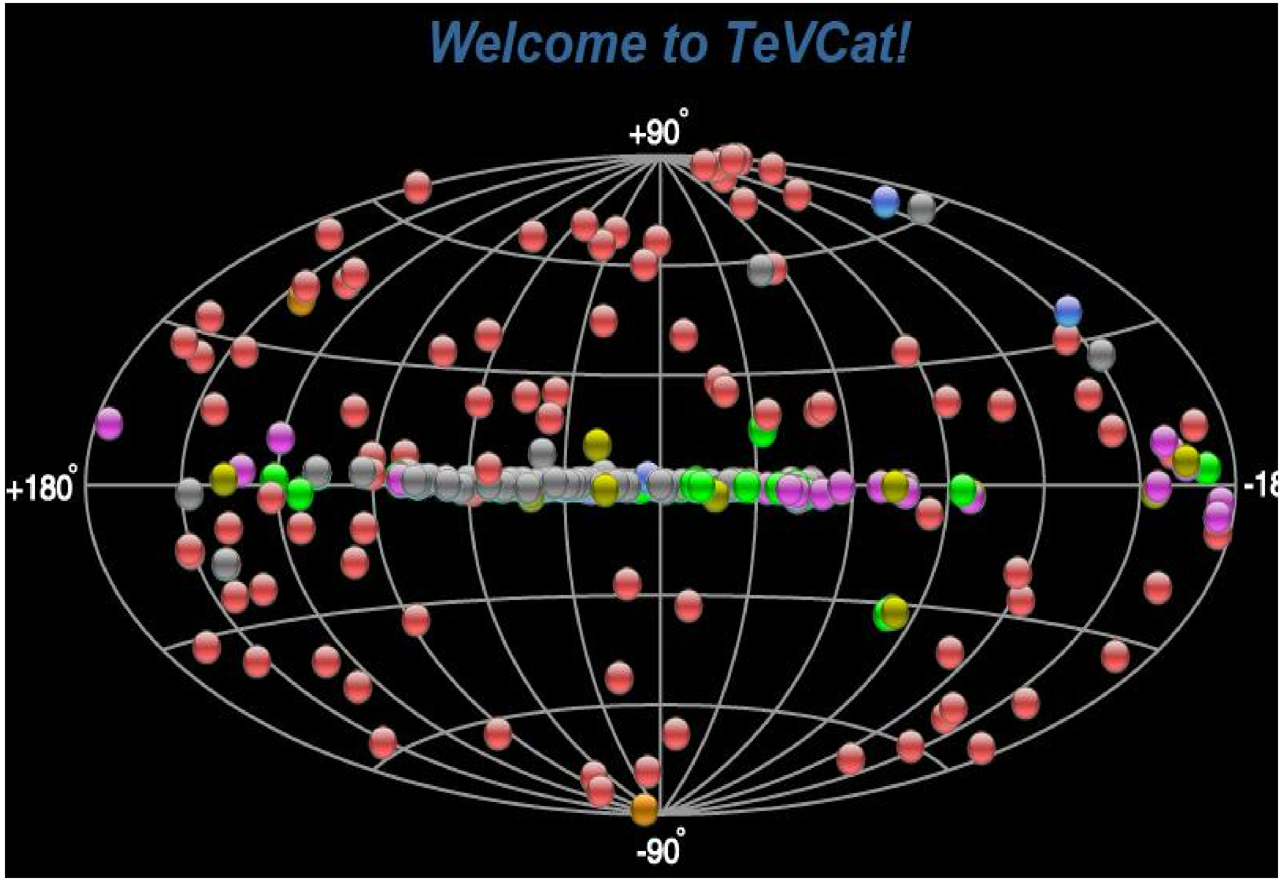


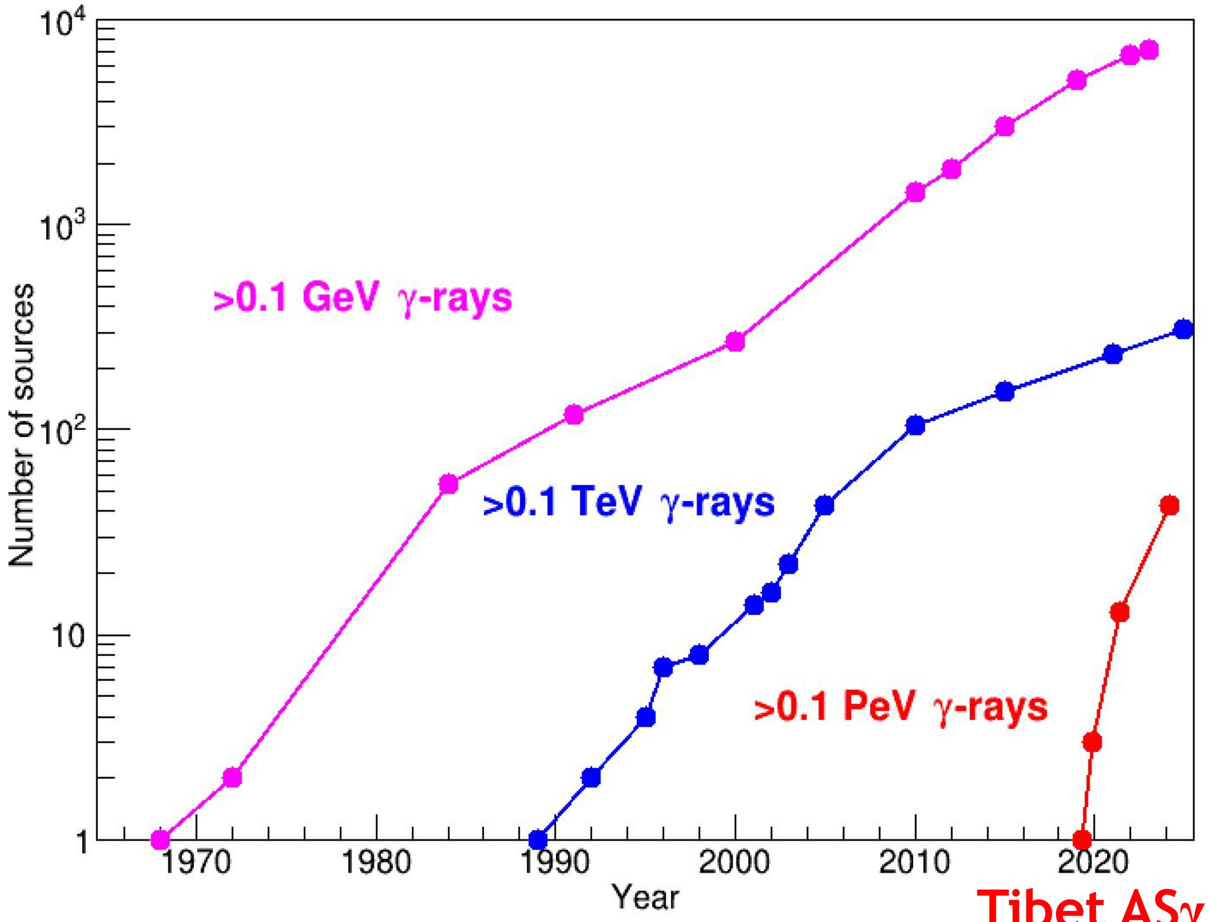
Fermi-LAT, Science, 339, 807 (2013)



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

Measurements of γ-ray sources





http://tevcat.uchicago.edu/

Tibet ASγ
HAWC
LHAASO

Selected progresses from Chinese cosmic ray studies

Yunnan cloud chamber

图1 上世纪60—70年代，“头顶青天脚踏云海”的中国科学院原子能研究所云南站

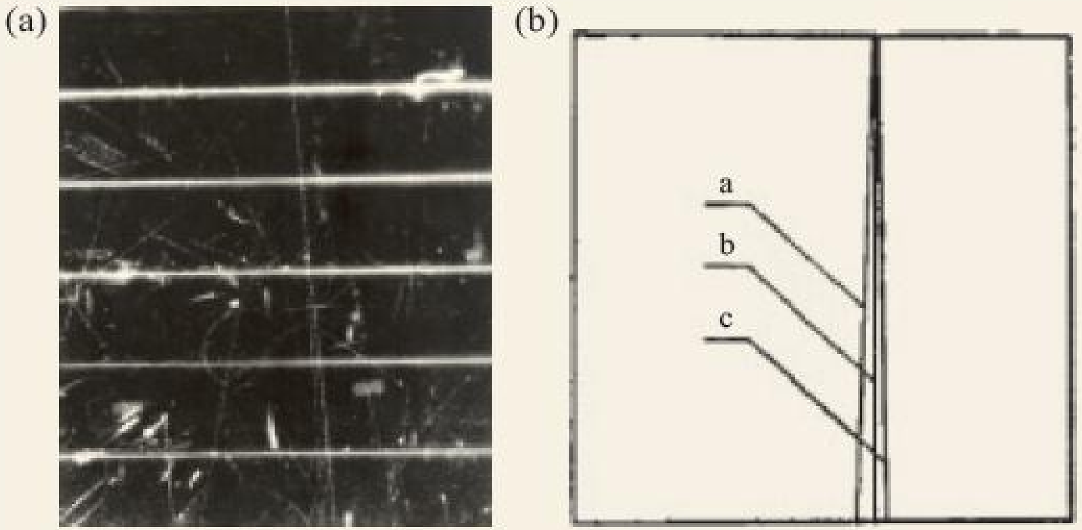


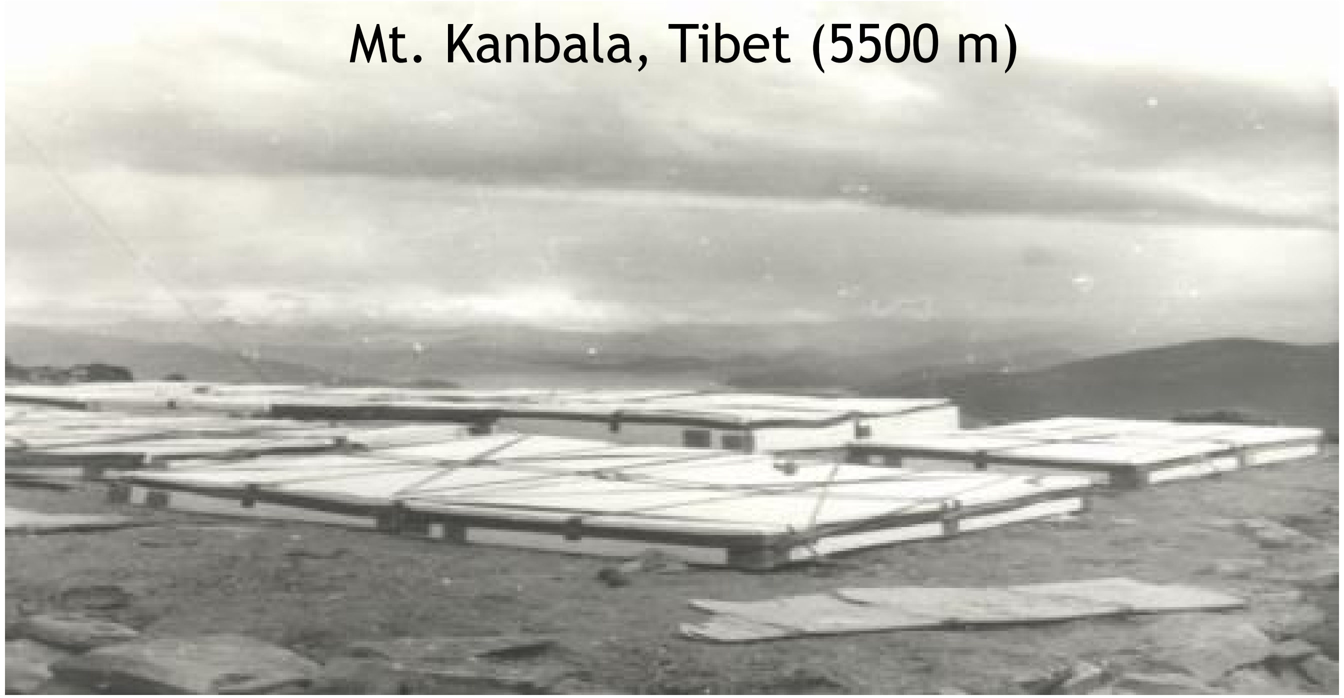
图6 (a)云南事例(16580号)正面全景照片；(b)16580号事例素描

A candidate heavy particle (m>12 GeV) recorded by the cloud chamber

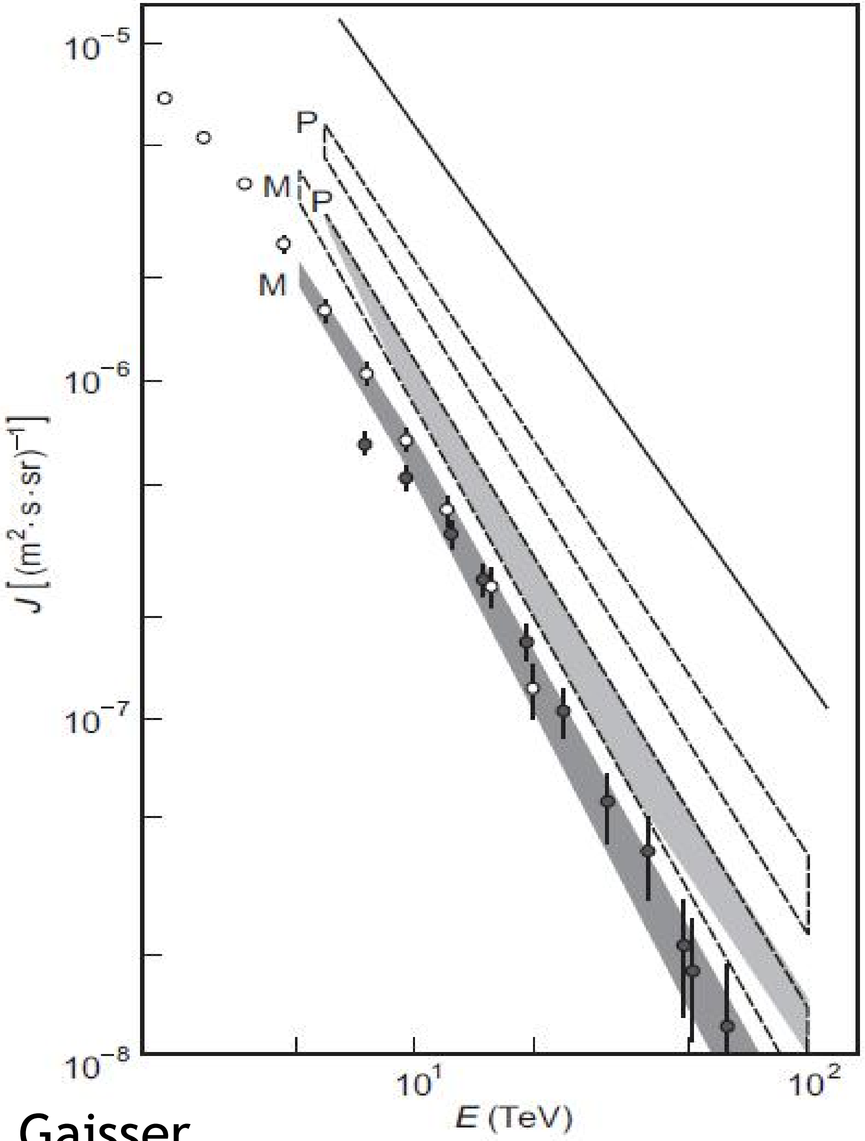
Chen et al. (1997, Phys. Rept., 282, 1)

Tibet emulsion chamber

Mt. Kanbala, Tibet (5500 m)



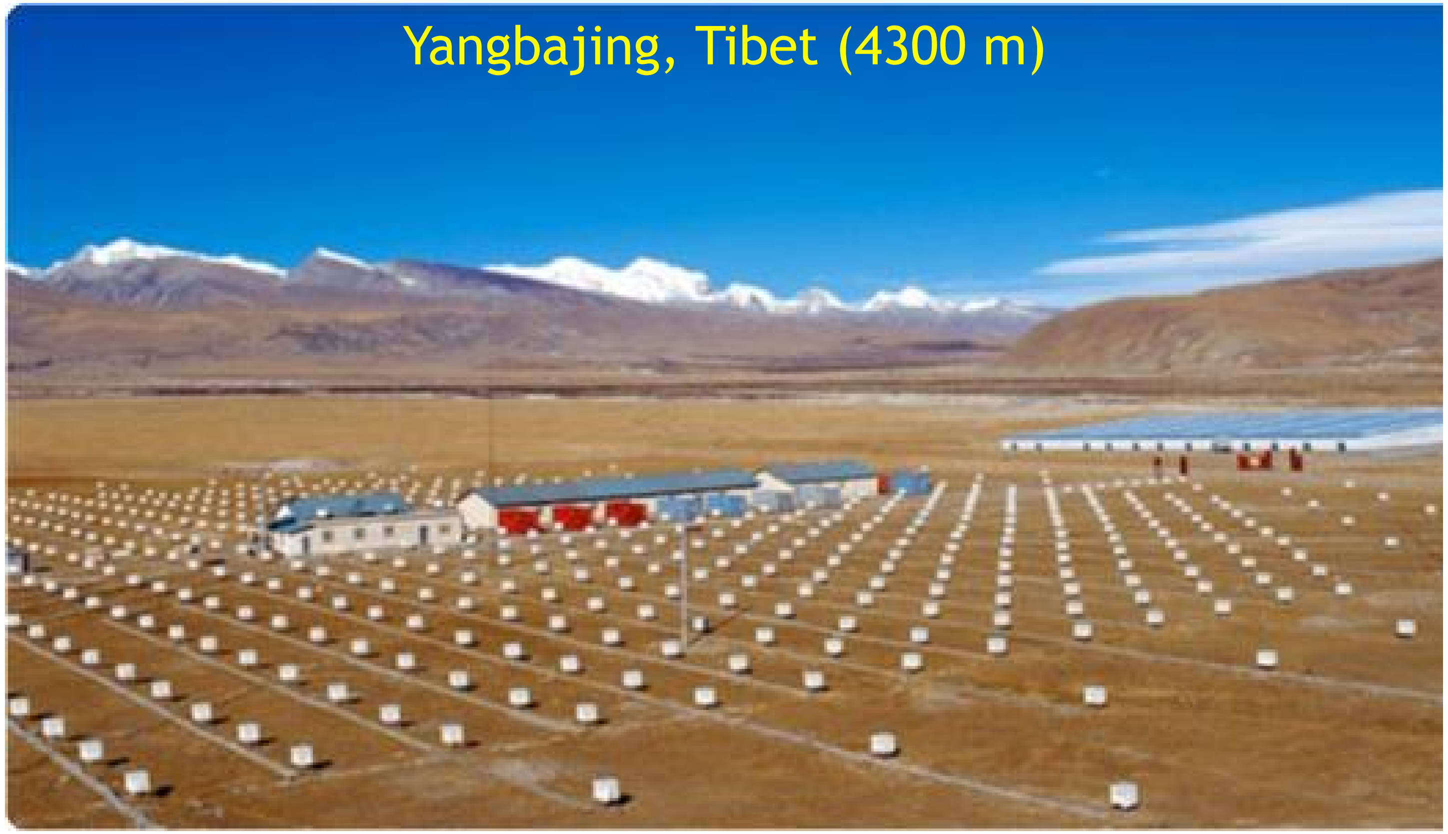
$$\sigma^{\text{inel}}_{p-\text{air}} \approx 290\ \text{mb} \times \left(\frac{E_p}{1\ \text{TeV}}\right)^{0.06}$$

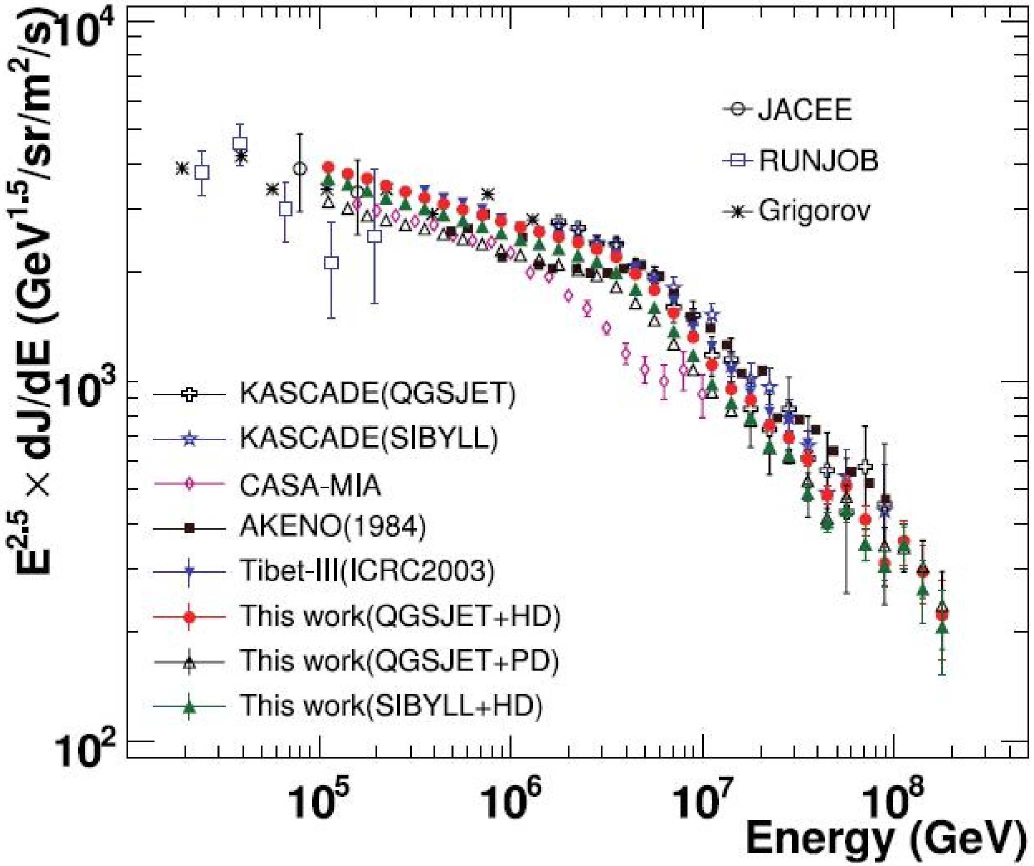


Ren et al. (1987, Nuovo Cim.C, 10, 43)

Recorded in textbook “Cosmic Rays and Particle physics” by T. Gaisser

Tibet Yangbajing: knee spectrum

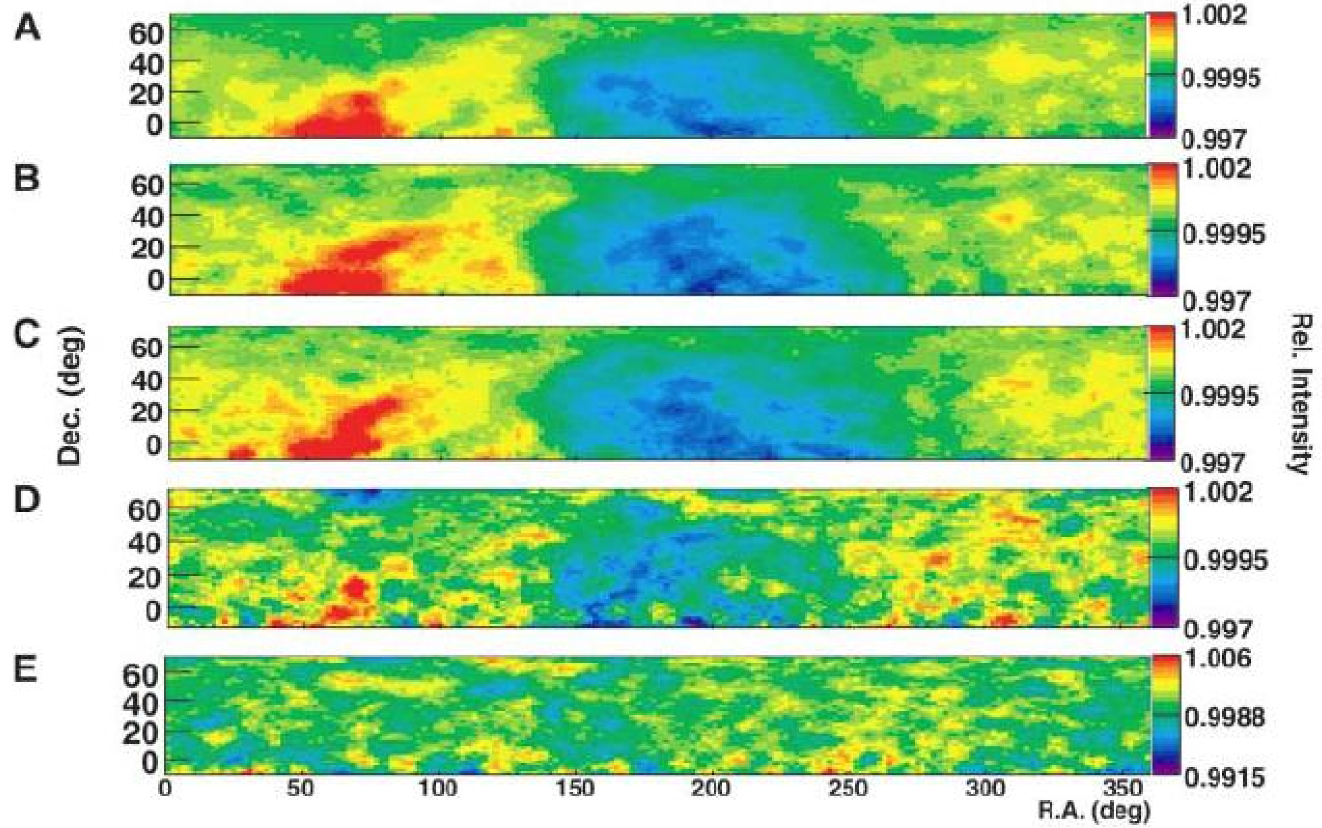


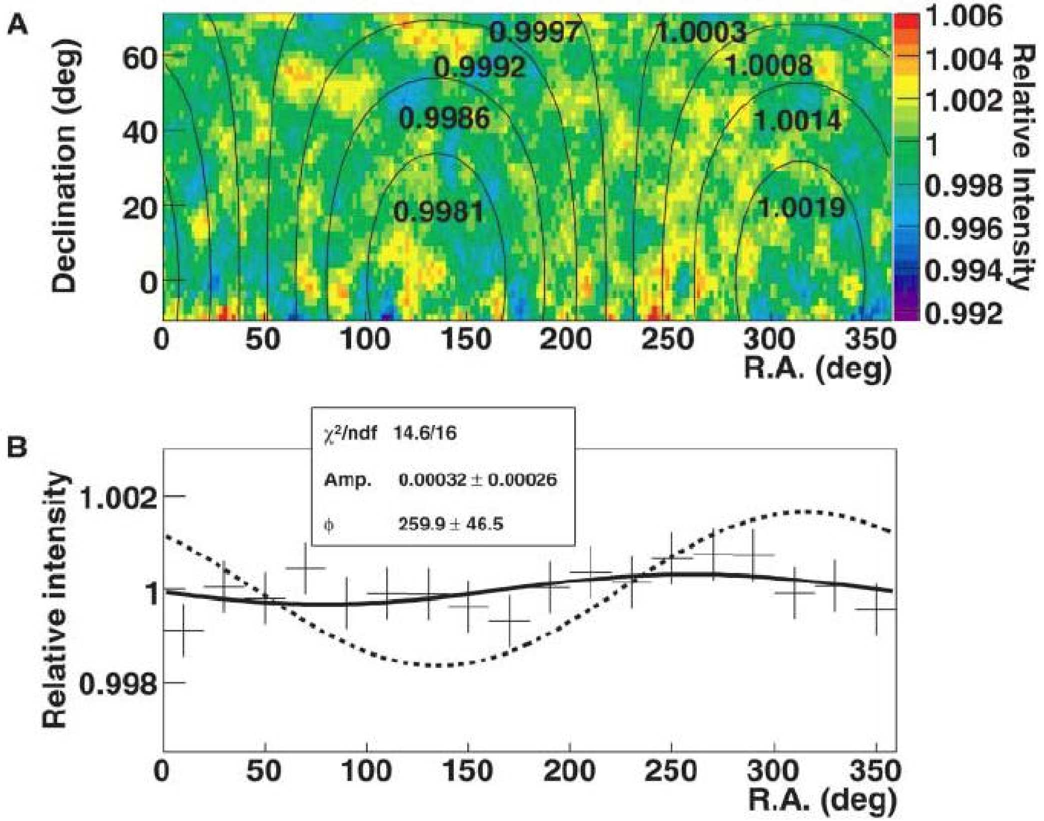


Amenomori et al. (2008, ApJ, 678, 1165)

Precise measurements of CR spectra around the "knee" region

Tibet Yangbajing: anisotropy





Amenomori et al. (2006, Science, 314, 439)

Two-dimensional anisotropies reveal co-rotation of CRs with the ISM (a milestone of CR studies)

Dark Matter Particle Explorer

(DAMPE)

DAMPE mission


NEWS IN FOCUS

POLITICS Canada's first science minister brings air of change p.445

STRING THEORY Philosophers join debate over scientific method p.446

2015 IN REVIEW Gene editing, climate change, Pluto and more p.449

PROFILES Ten people who mattered in science this year p.459

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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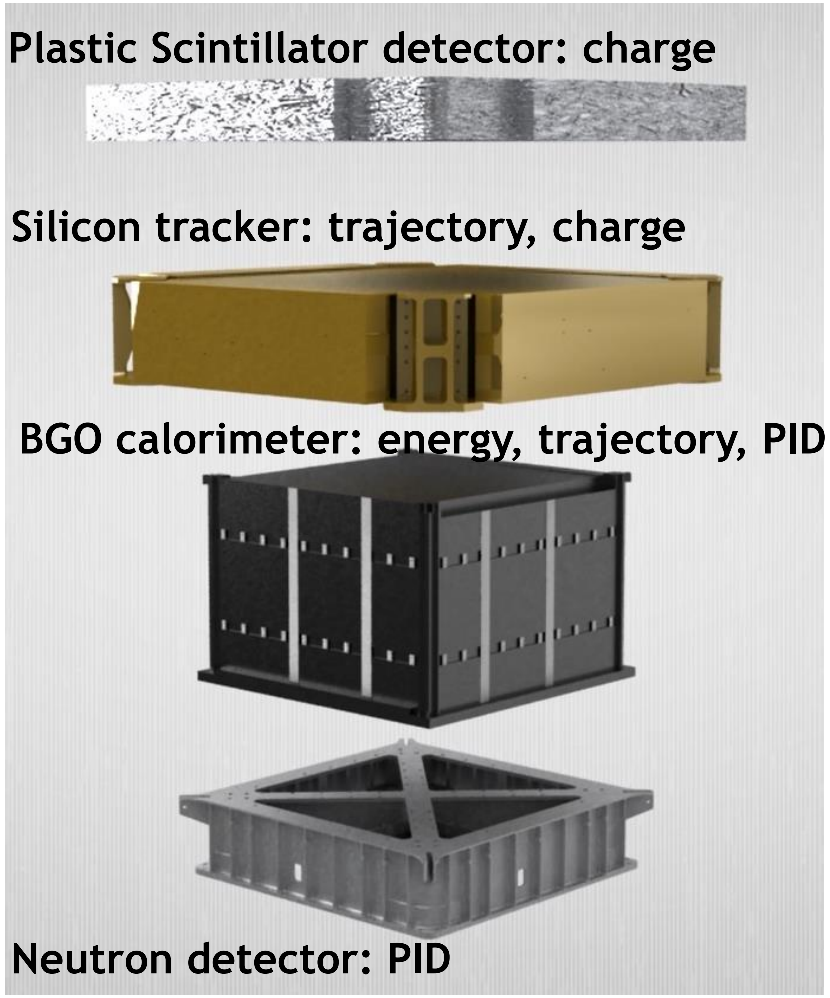
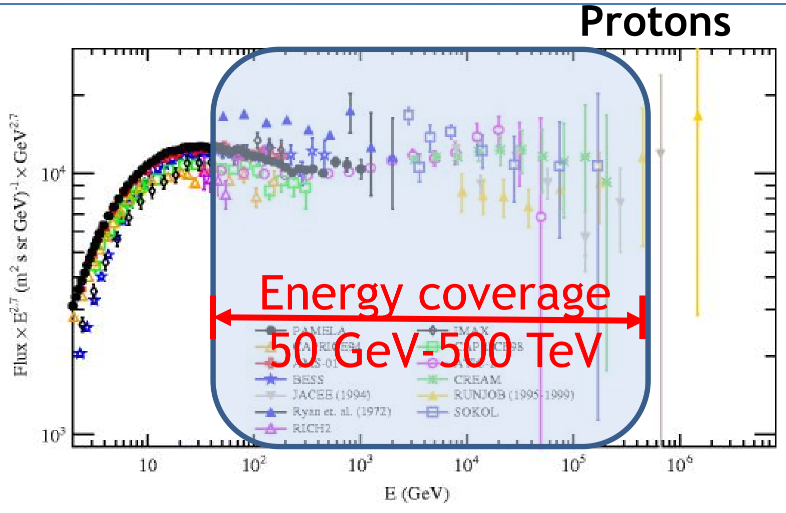
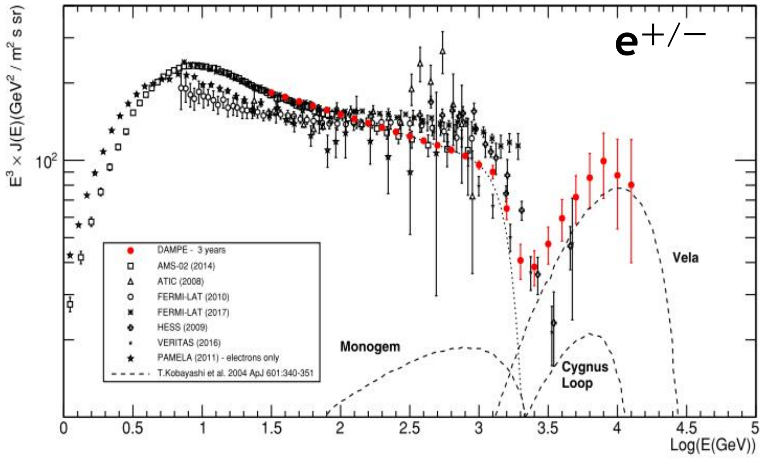
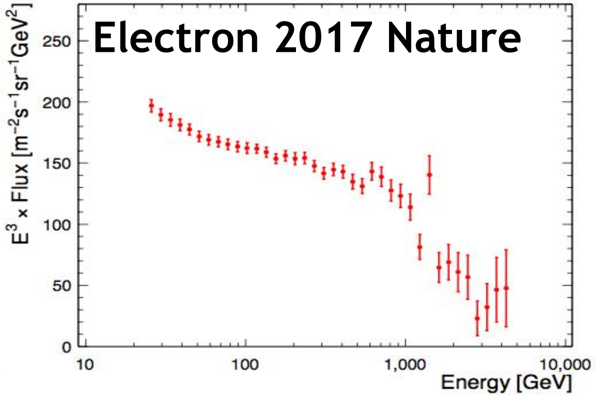


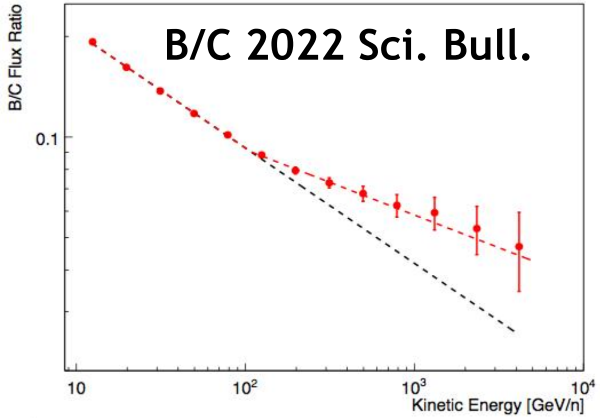


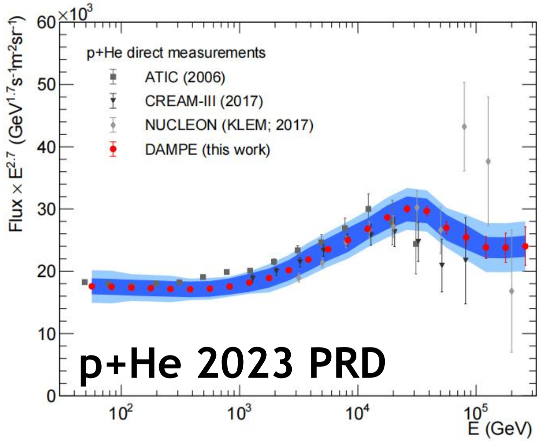


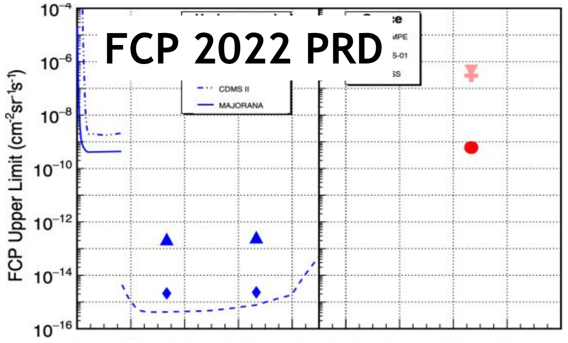
China launched DAMPE in the end of 2015, which provides a unique opportunitity to probe the fundamental questions of CRs

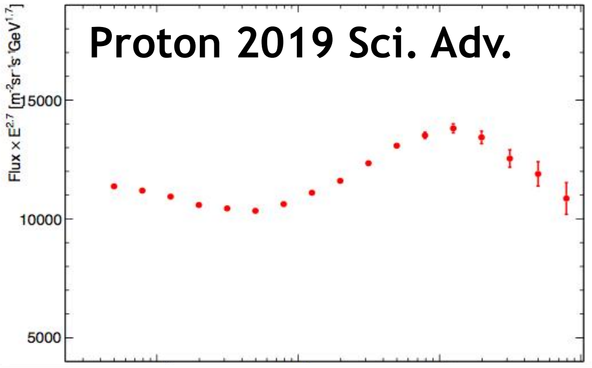
DAMPE science results

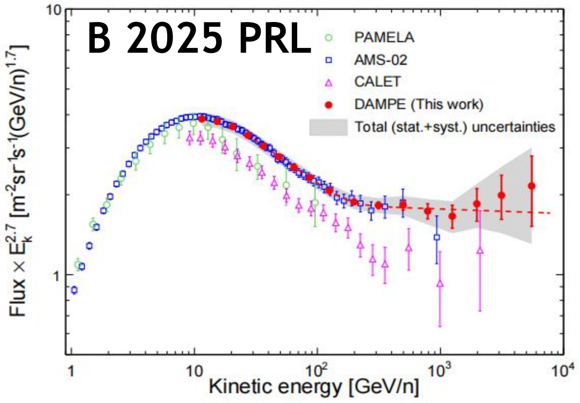


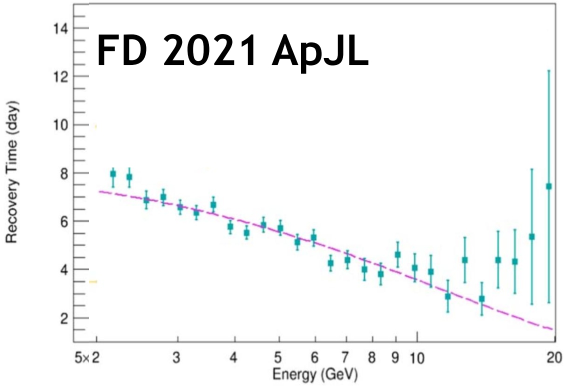


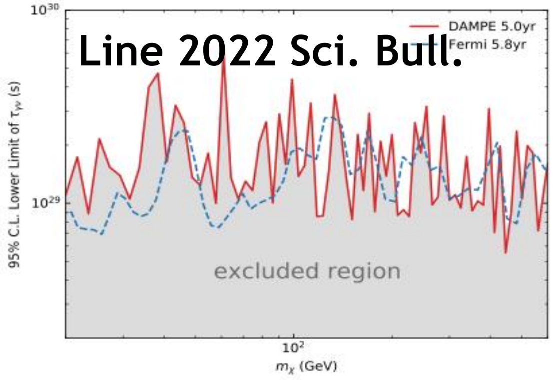


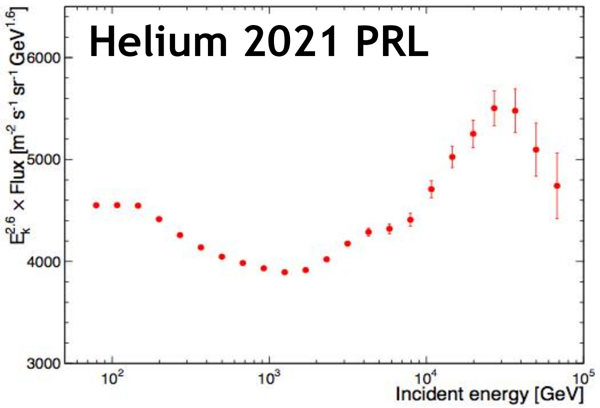




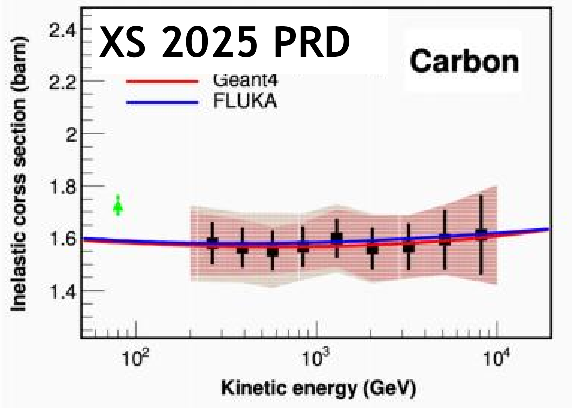






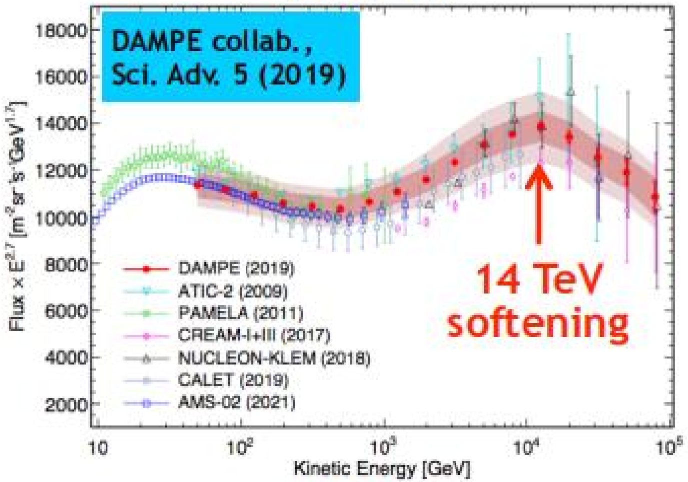


- ➢ Precise measurements of wide-band spectra of various species
- ➢ Search for new physics phenomena with highest sensitivity

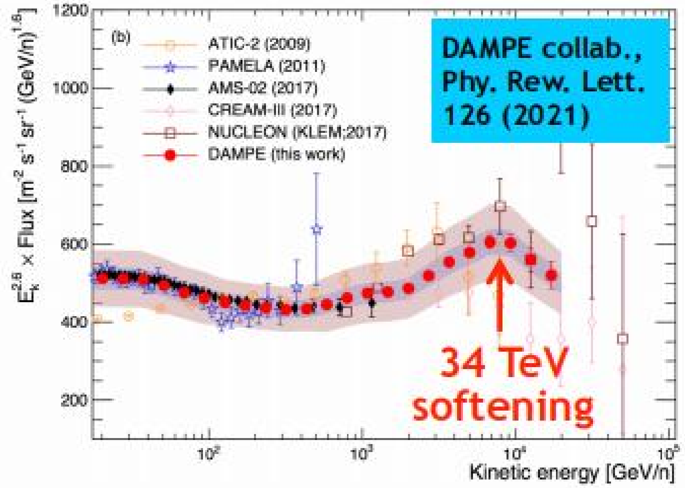


DAMPE proton and helium

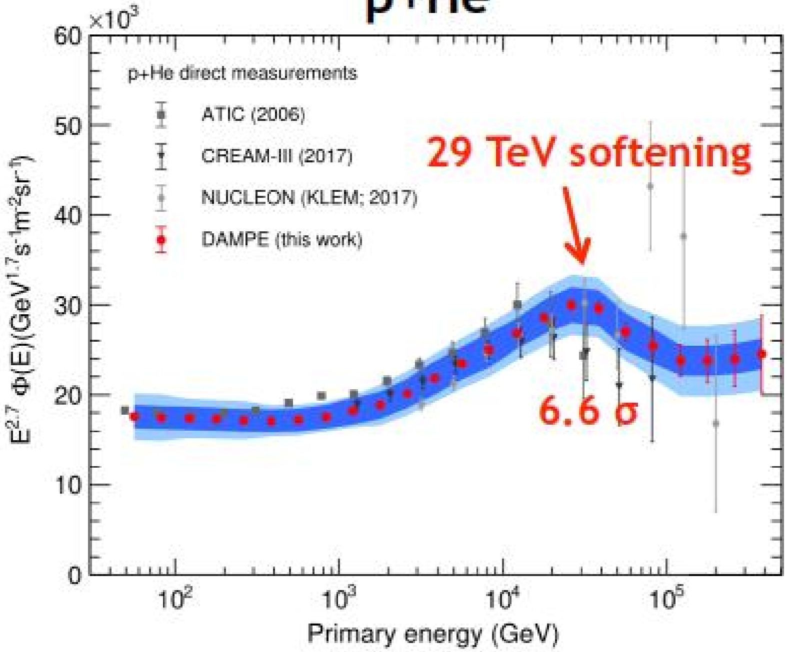
Proton



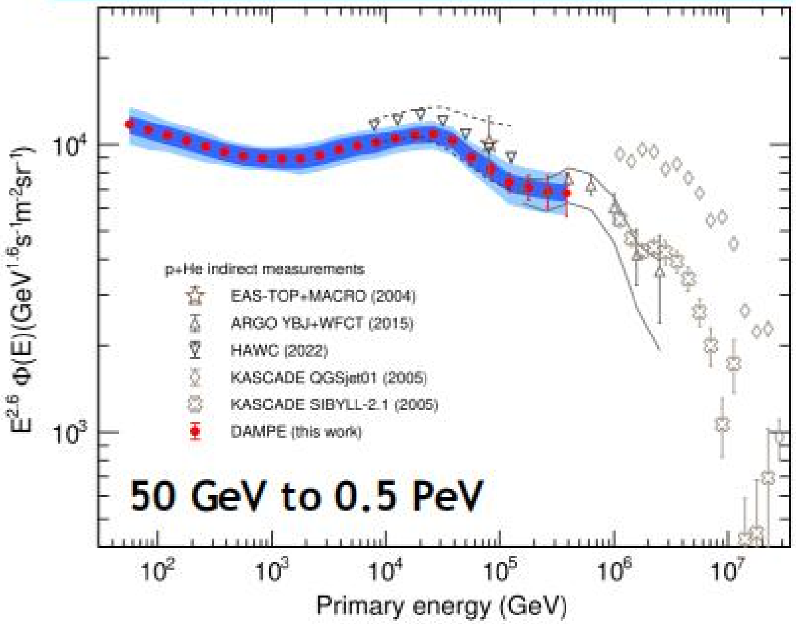
Helium



p+He



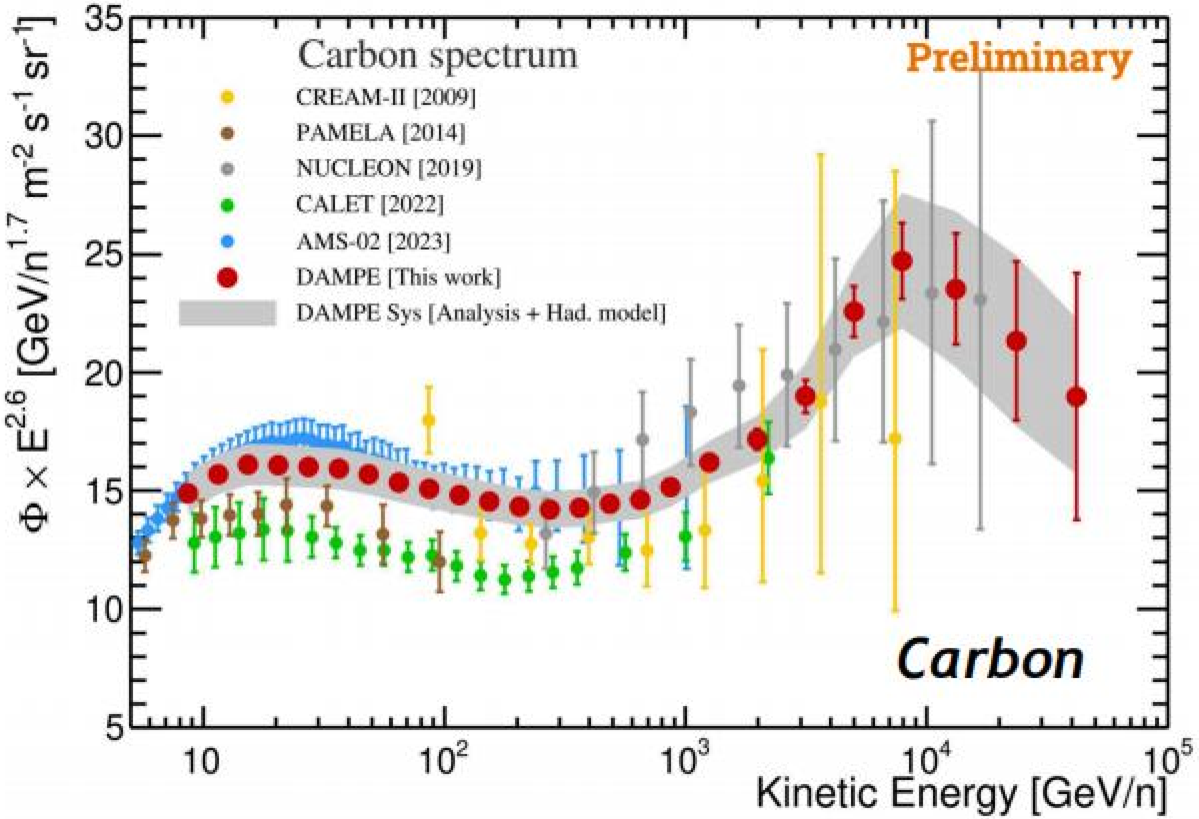
DAMPE collab., Phy. Rew.D 109, L121101 (2024)

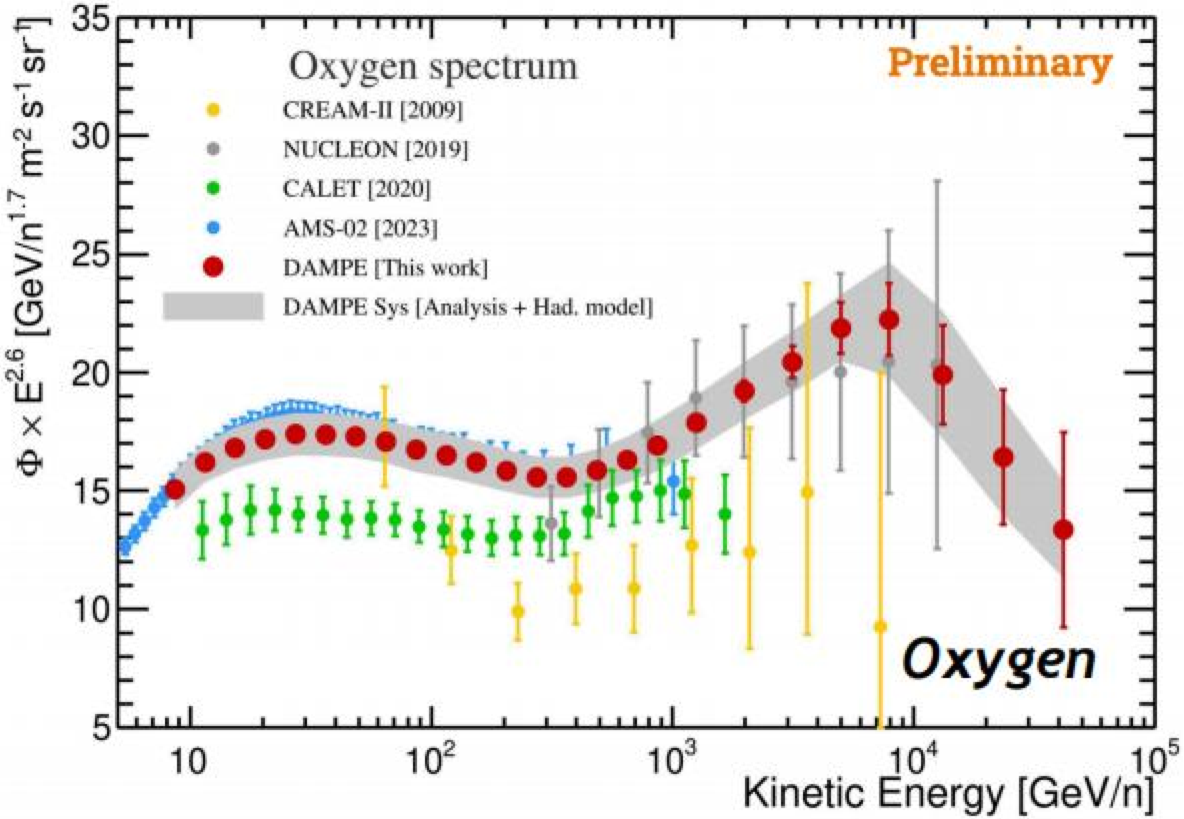


	Proton	Helium	Proton+Helium
E_b (TeV)	$13.6^{+4.1}_{-4.8}$	$34.4^{+6.7+11.6}_{-9.8-0.0}$	$28.8^{+6.2+2.9}_{-4.4-0.0}$
γ	2.60 ± 0.01	$2.41^{+0.02+0.02}_{-0.02-0.00}$	$2.51^{+0.021+0.01}_{-0.024-0.00}$
$\Delta\gamma$	-0.25 ± 0.07	$-0.51^{+0.18+0.01}_{-0.20-0.00}$	$0.43^{+0.066+0.066}_{-0.057-0.00}$

- **Link between space- and ground- based CR measurements**
- **Observation of the softening at 29 TeV and a hardening hit at ~150 TeV**

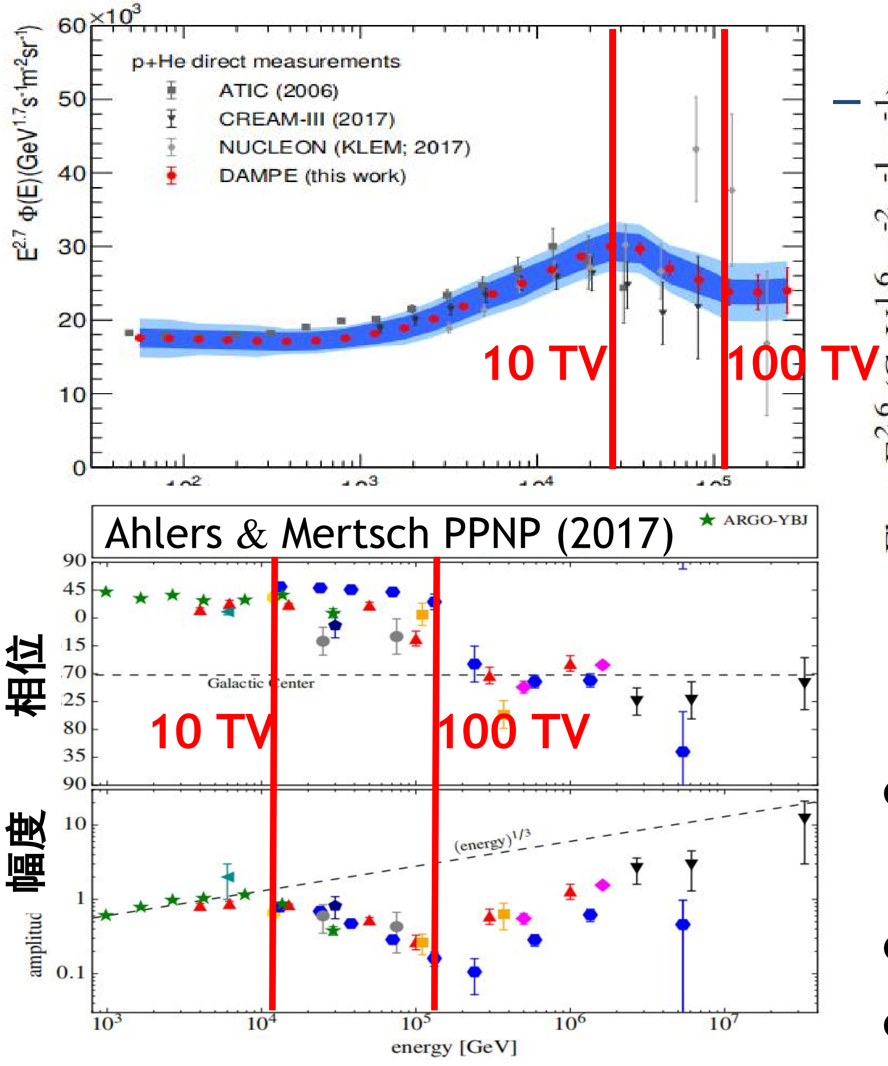
A universal softening

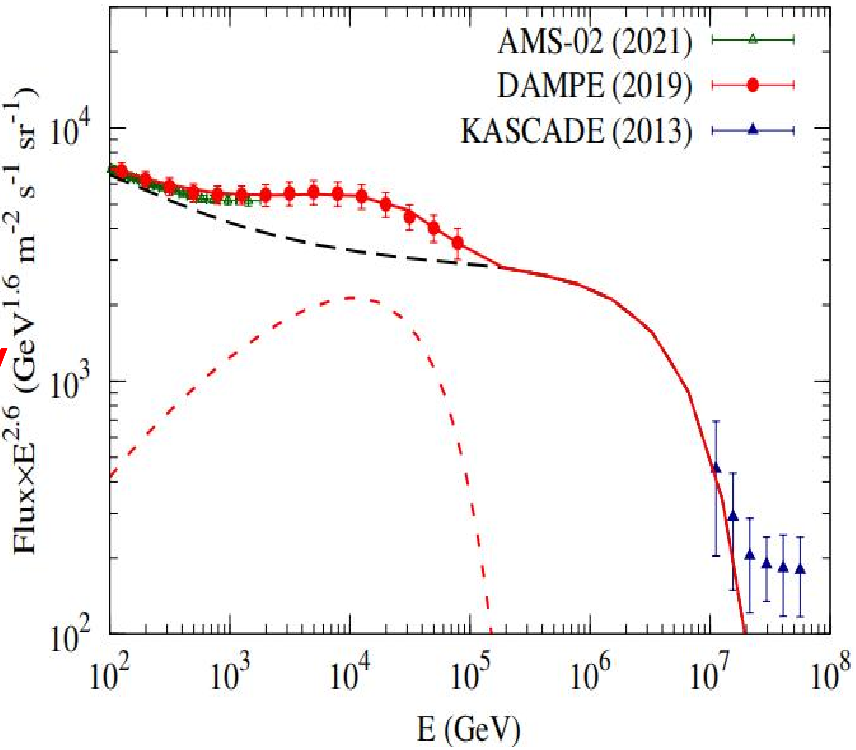


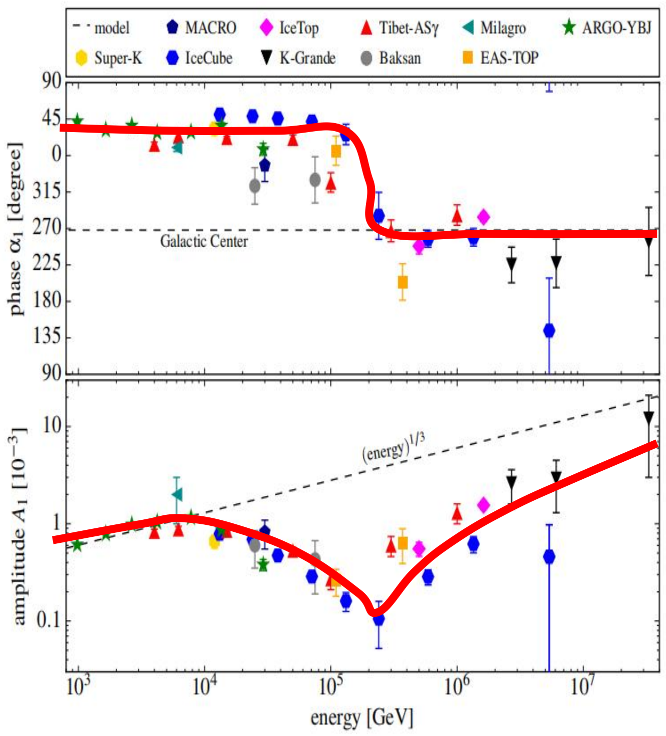


A universal spectral softening at ~13 TV of primary species has been observed

Correlation between spectra and anisotropy



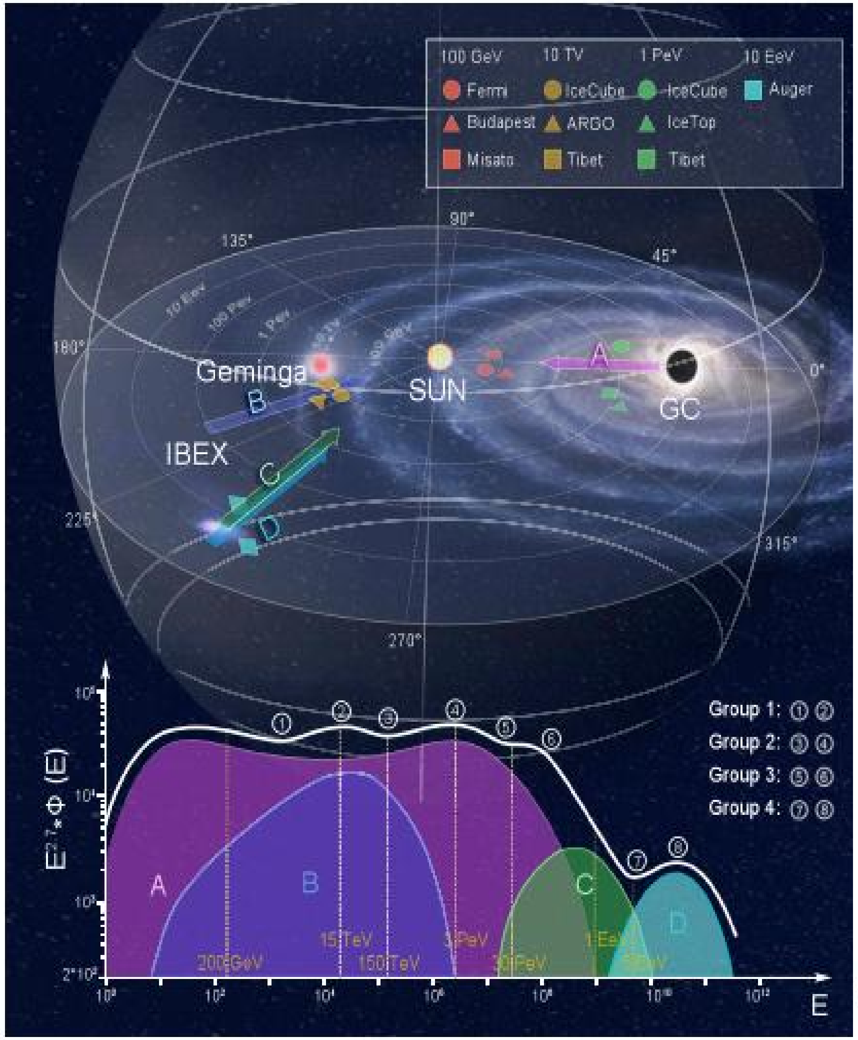


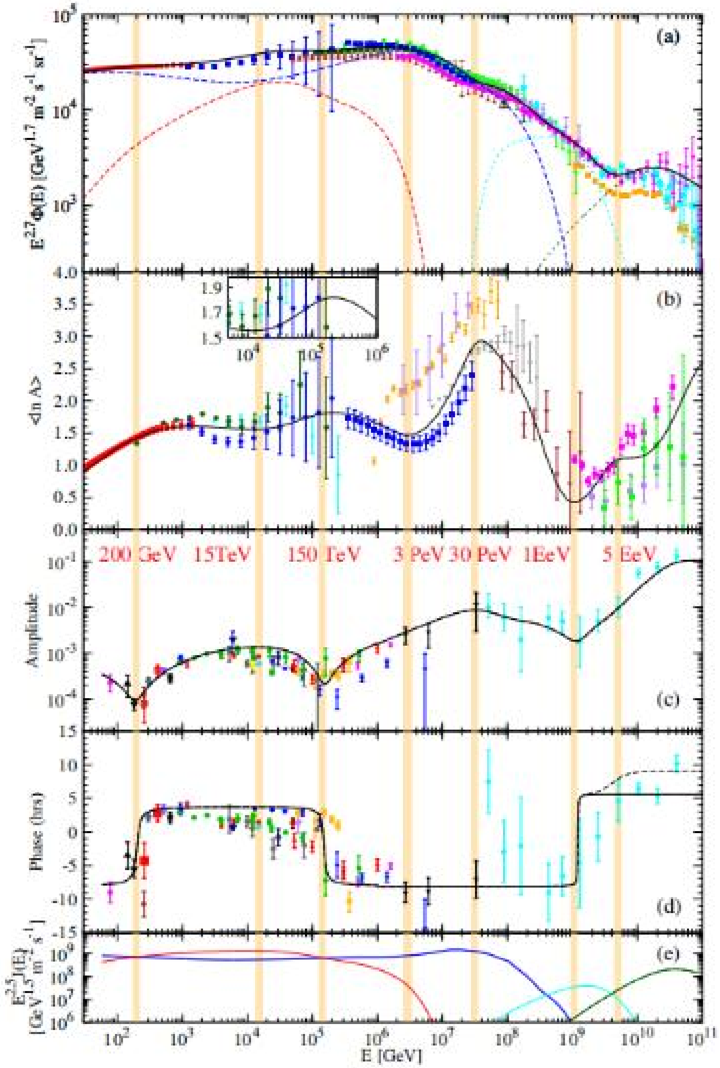


- Clear correlation between spectral and large-scale anisotropy structures exist
- Could be explained with a nearby source model
- Spectra：algebraic sum; anisotropy: vector sum

Liu + JCAP (2019); Yuan + FoP (2021); Qiao + ApJ (2023)

Correlations among spectra, <lnA>, anisotropy





Co-evolution of cosmic ray energy spectra, composition, and anisotropies

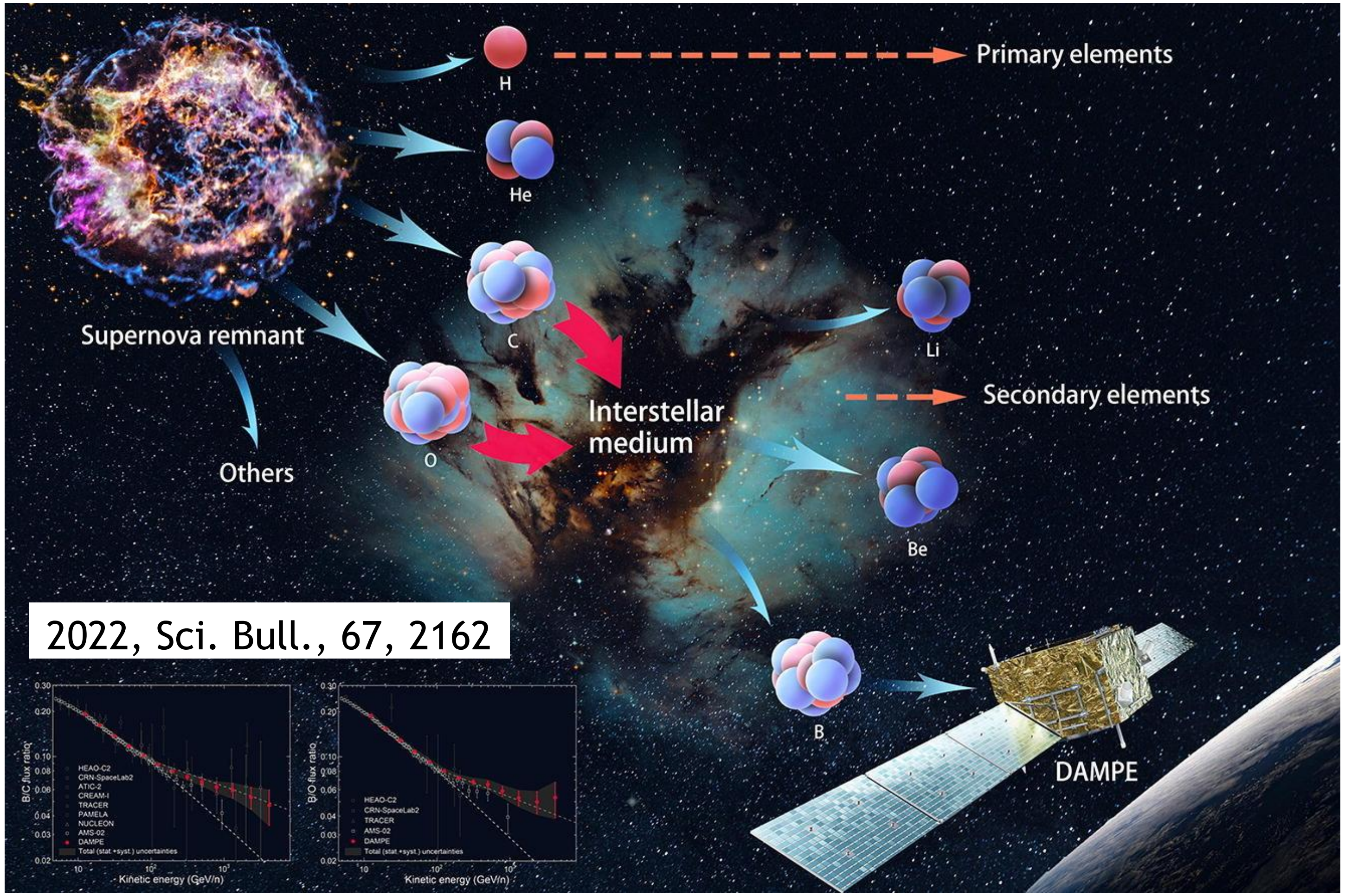
Bing-Qiang Qiao,[1,2] Qiang Yuan,[3,4,*] and Yi-Qing Guo[5,6,7,†]

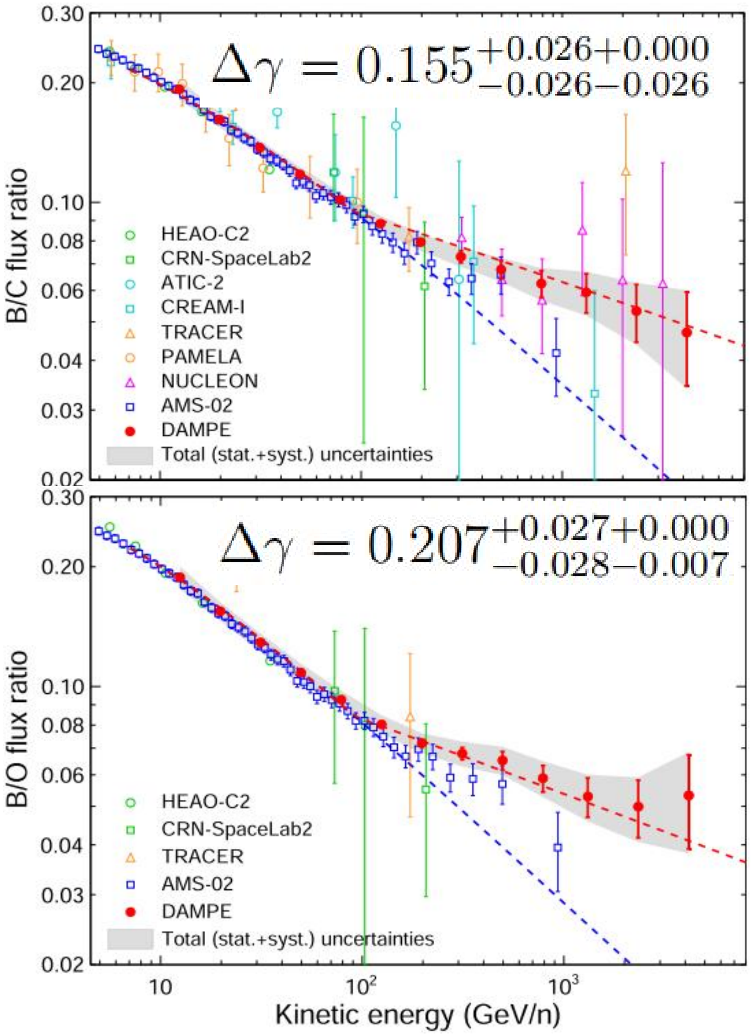
[1]*Deutsches Elektronen Synchrotron DESY, Platanenallee 6, D-15738, Zeuthen, Germany*
[2]*Institut für Physik und Astronomie, Universität Potsdam, D-14476, Potsdam, Germany*
[3]*Division of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, China*

The co-evolution of structures in spectra, composition, and anisotropy amplitudes and phases indicate a 4-component origin of cosmic rays in the whole energy range

Qiao et al. (arXiv:2506.18118)

Secondary-to-primary ratios

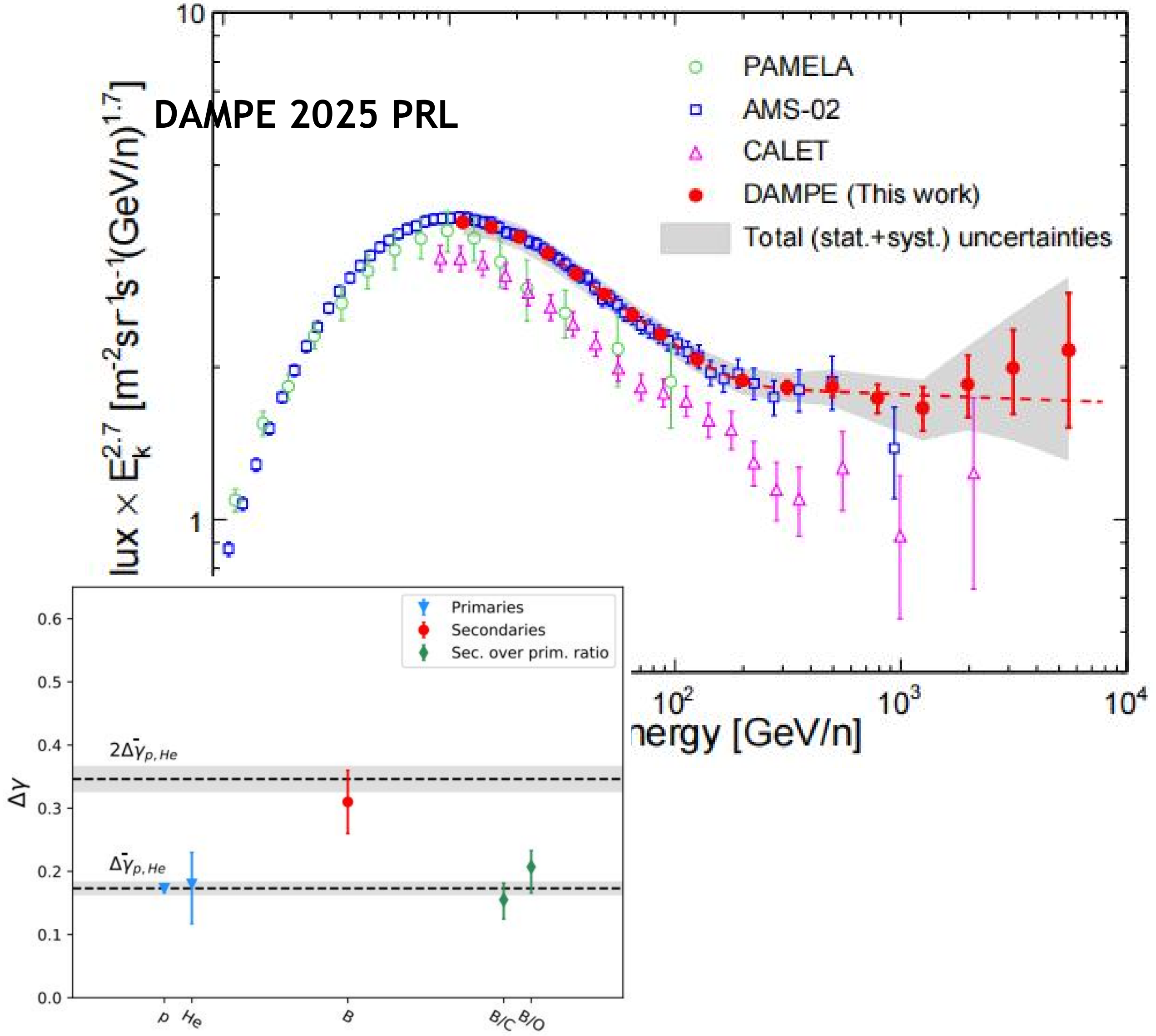




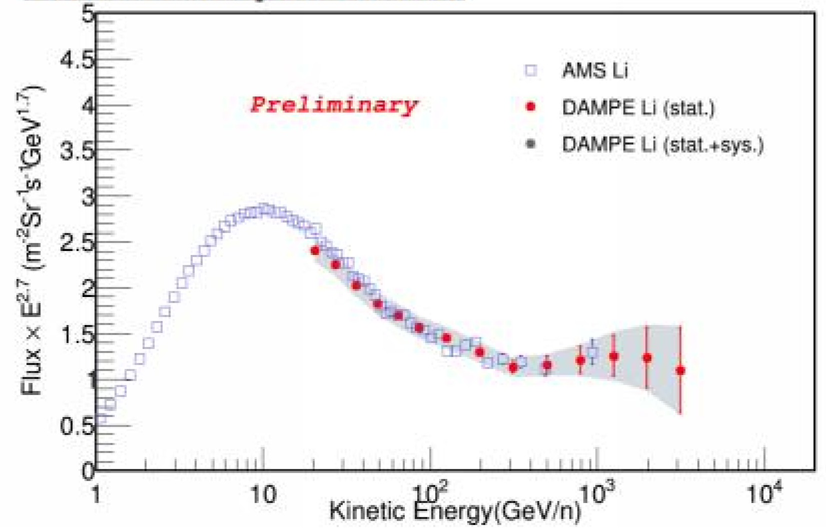
- DAMPE measured B/C, B/O with high precision, revealing breaks at ~100 GeV/n
- May reflect changes of energy-dependence of the diffusion coefficient (properties of the turbulence power spectrum of ISM)

Secondary spectra

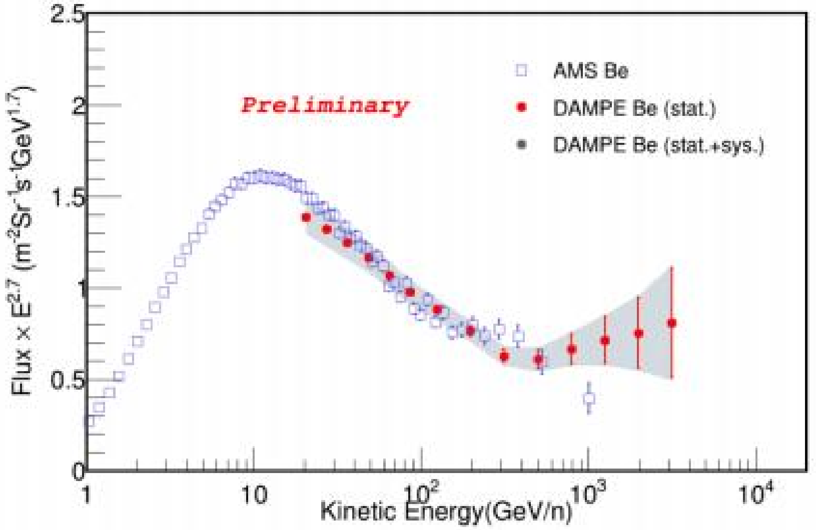
DAMPE 2025 PRL



Lithium spectrum

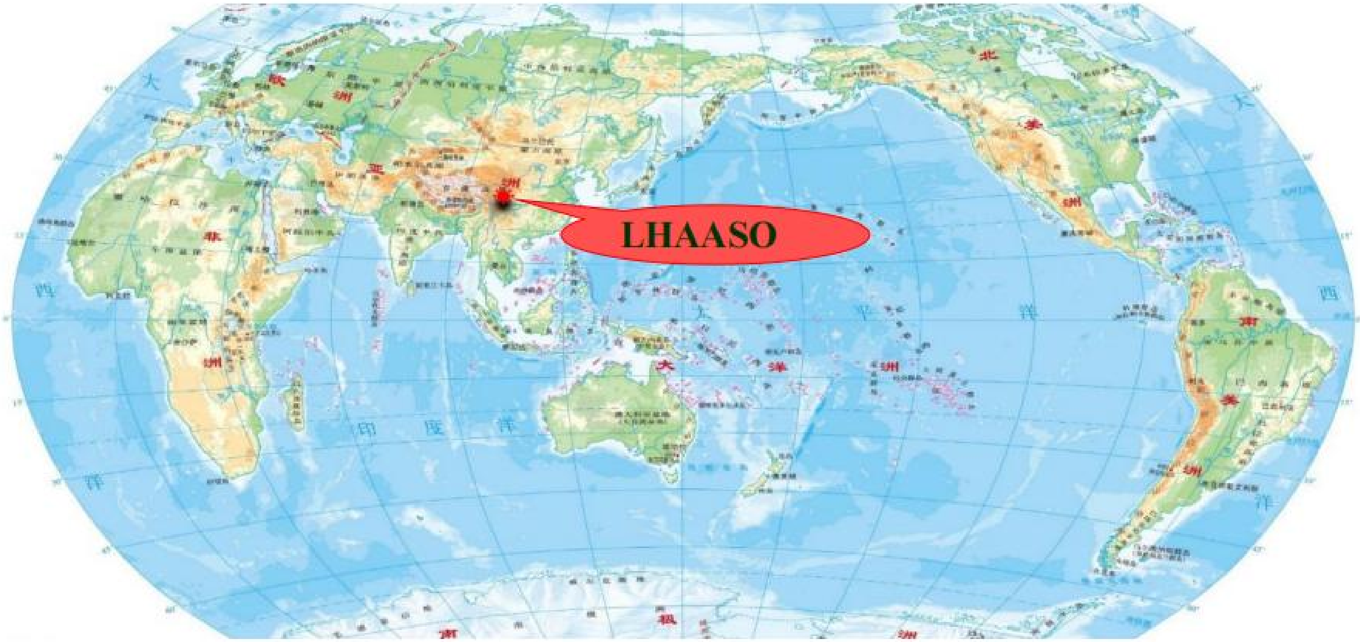


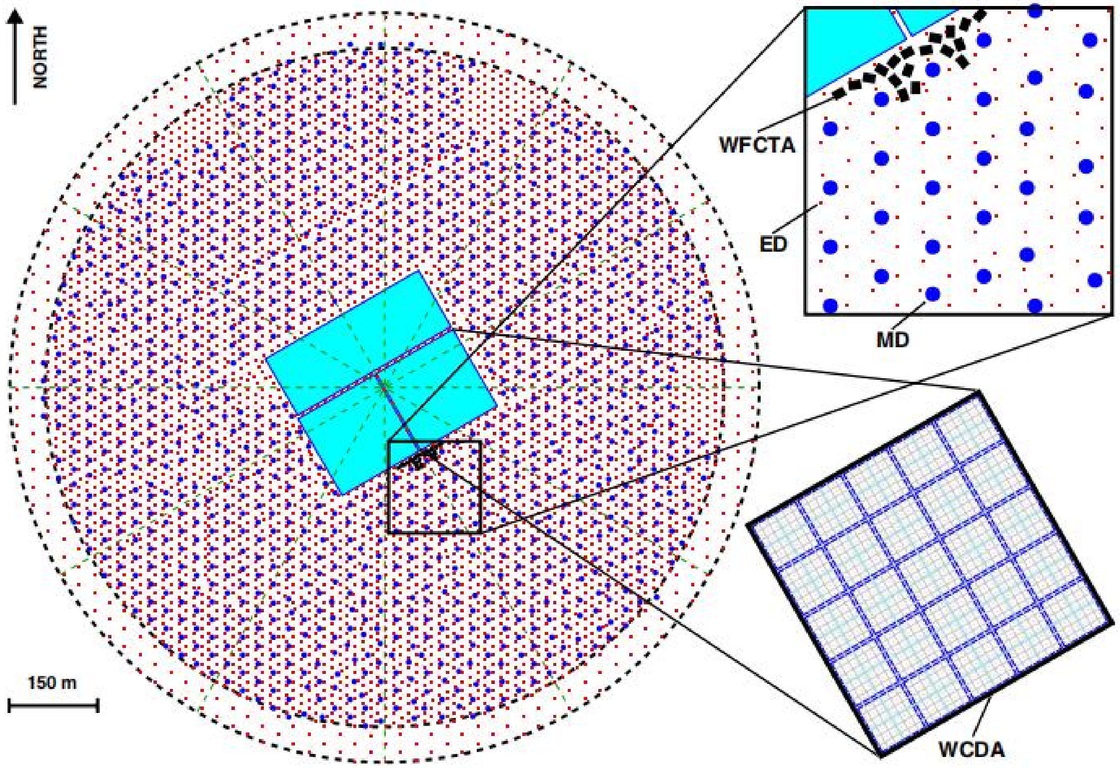
Beryllium spectrum



Large High Altitude Air Shower Observatory (LHAASO)

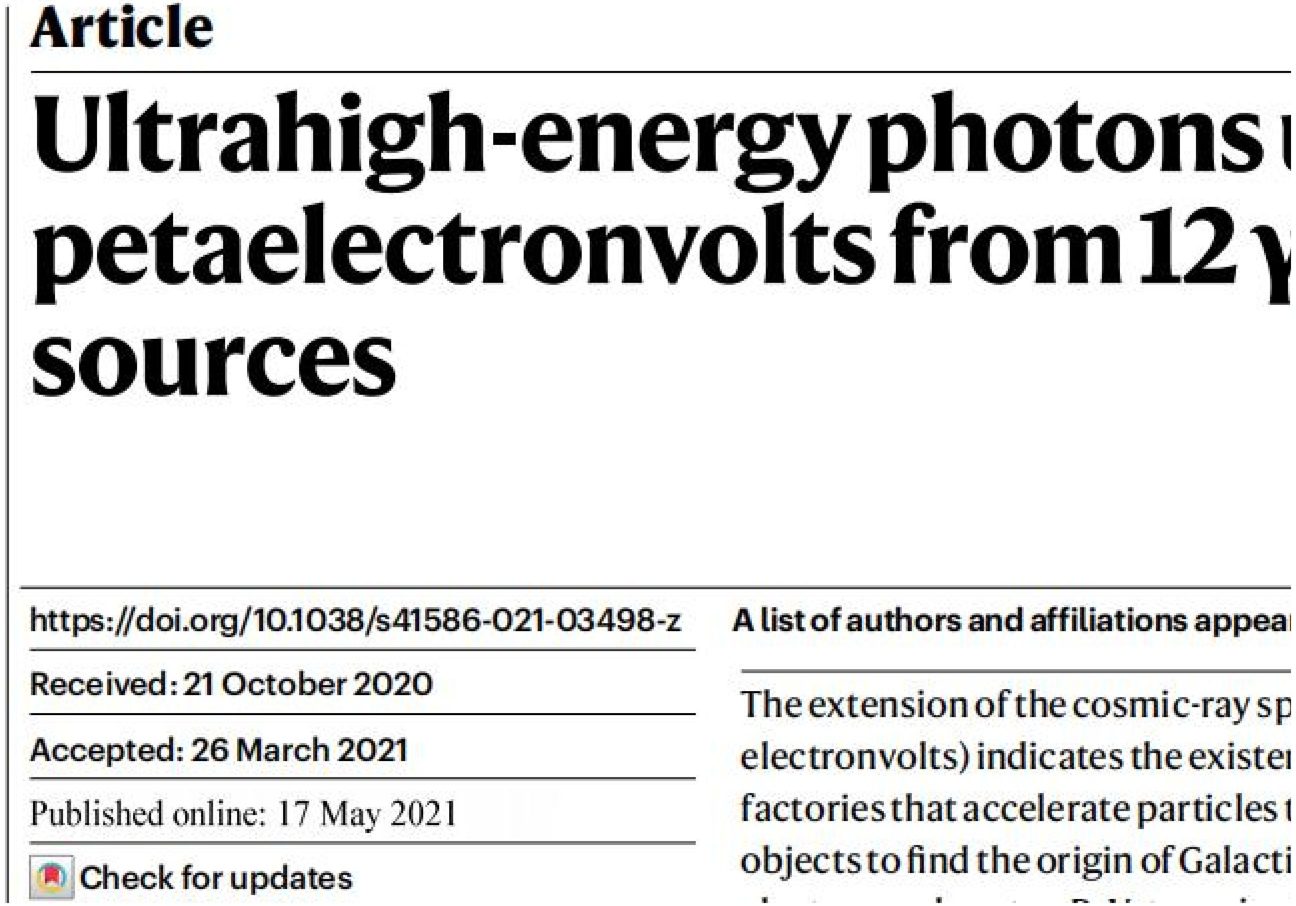
LHAASO experiment





- 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

Opening of the PeV window



Article

Ultrahigh-energy photons u
petaelectronvolts from 12 γ
sources

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

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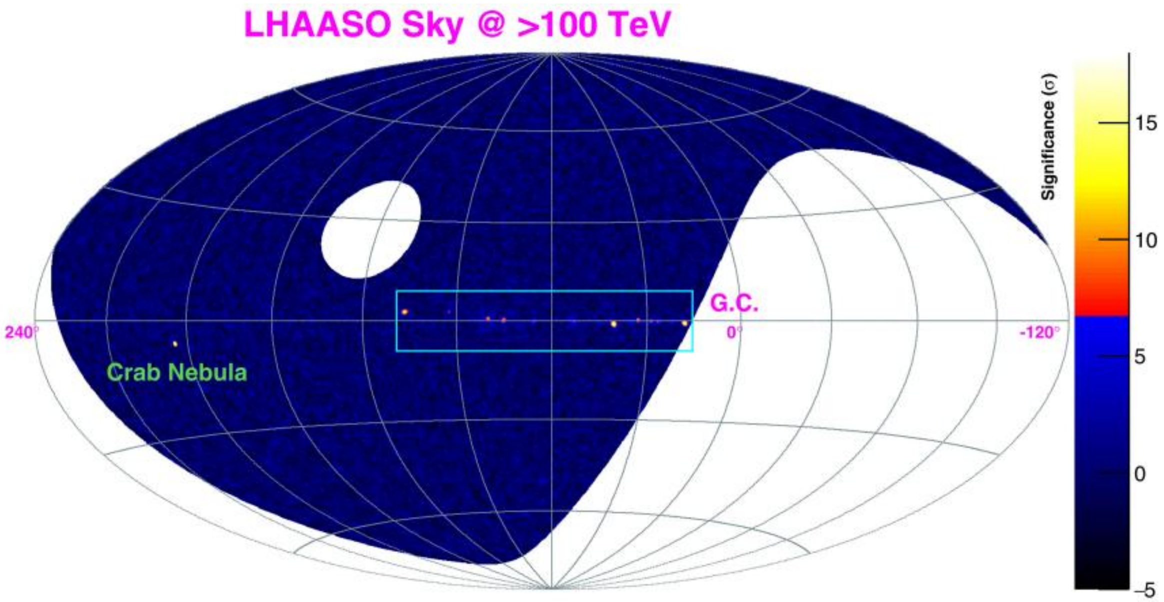
Accepted: 26 March 2021

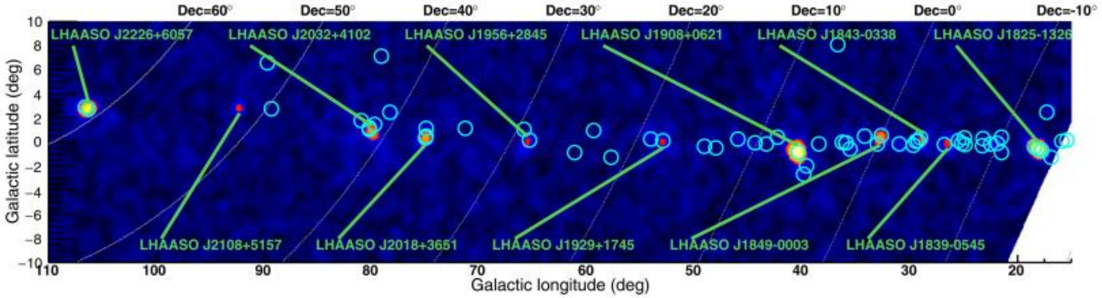
Published online: 17 May 2021

Check for updates

A list of authors and affiliations appear

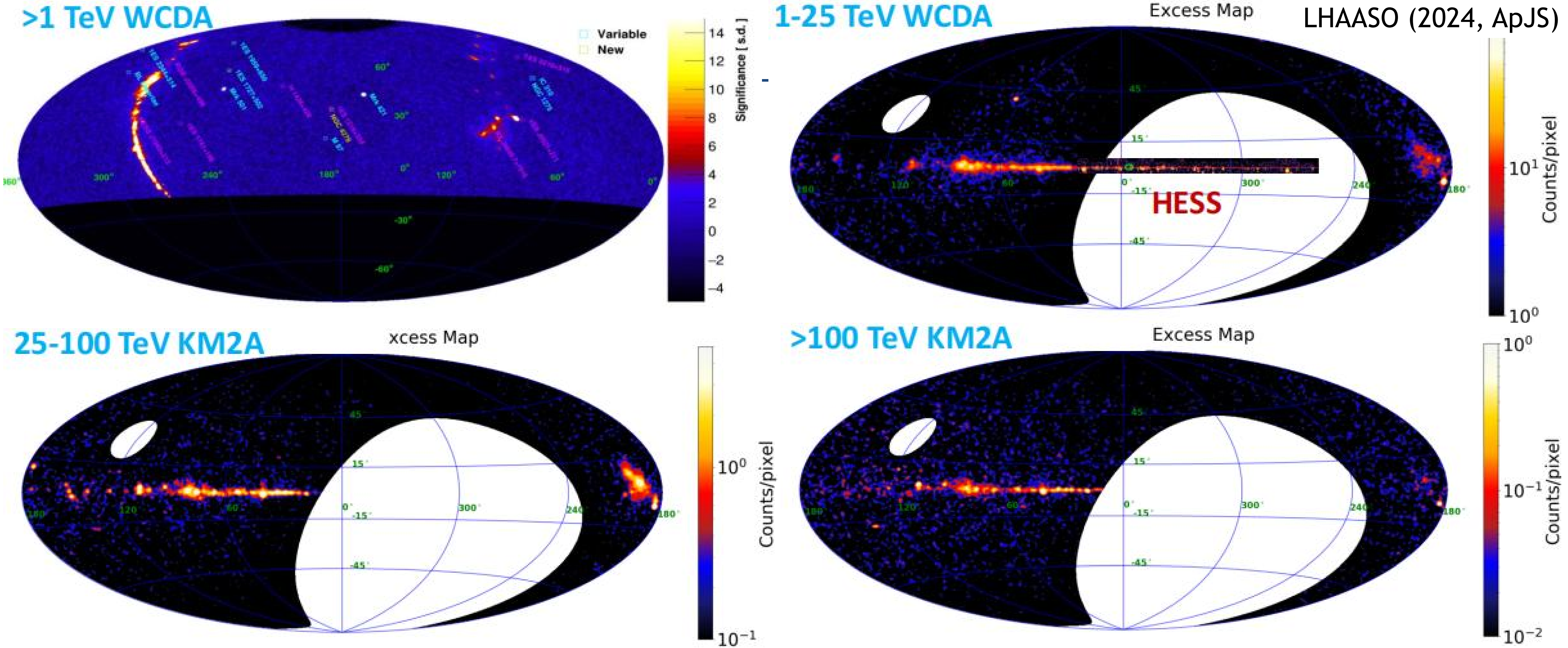
The extension of the cosmic-ray sp
electronvolts) indicates the existe
factories that accelerate particles t
objects to find the origin of Galacti





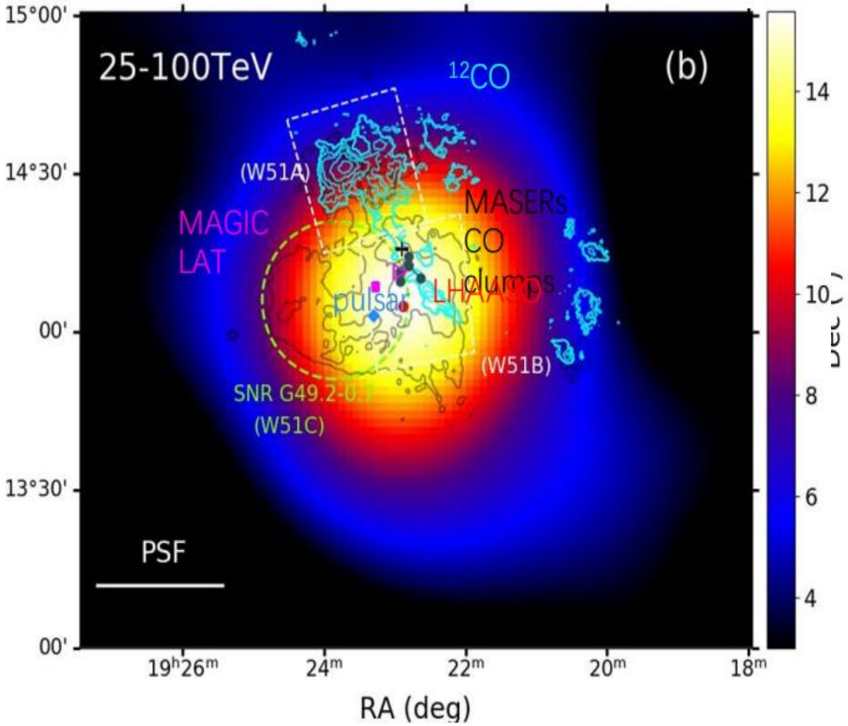
LHAASO successfully opens the PeV window, revealing that the Milky Way is rich of PeV accelerators (PeVatron)!

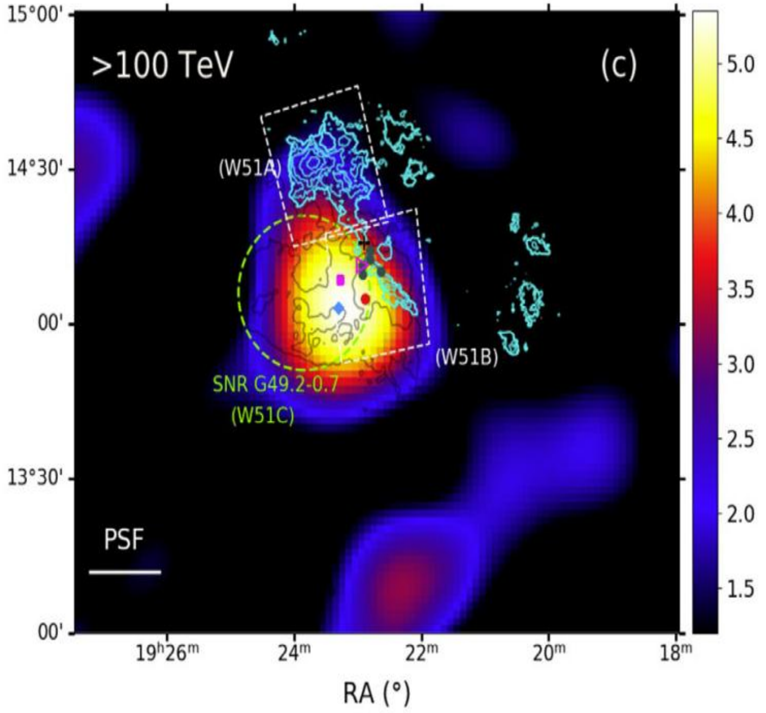
LHAASO VHE-UHE catalog

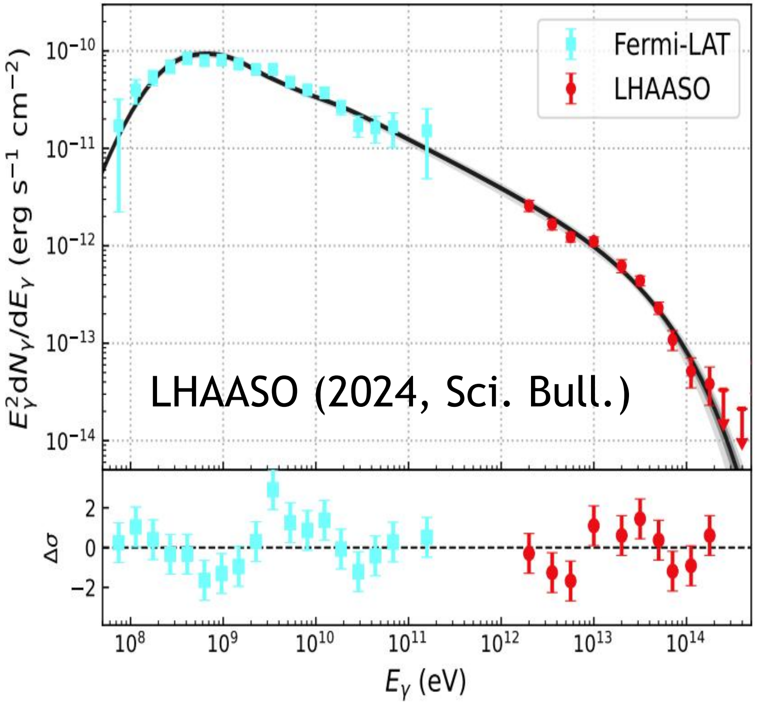


- ➢ 90 sources as of Sep. 2022, 32 newly reported, 43 with >100 TeV emission
- ➢ 77% by WCDA, 83% by KM2A, 61% by both

Touching acceleration limit of SNR





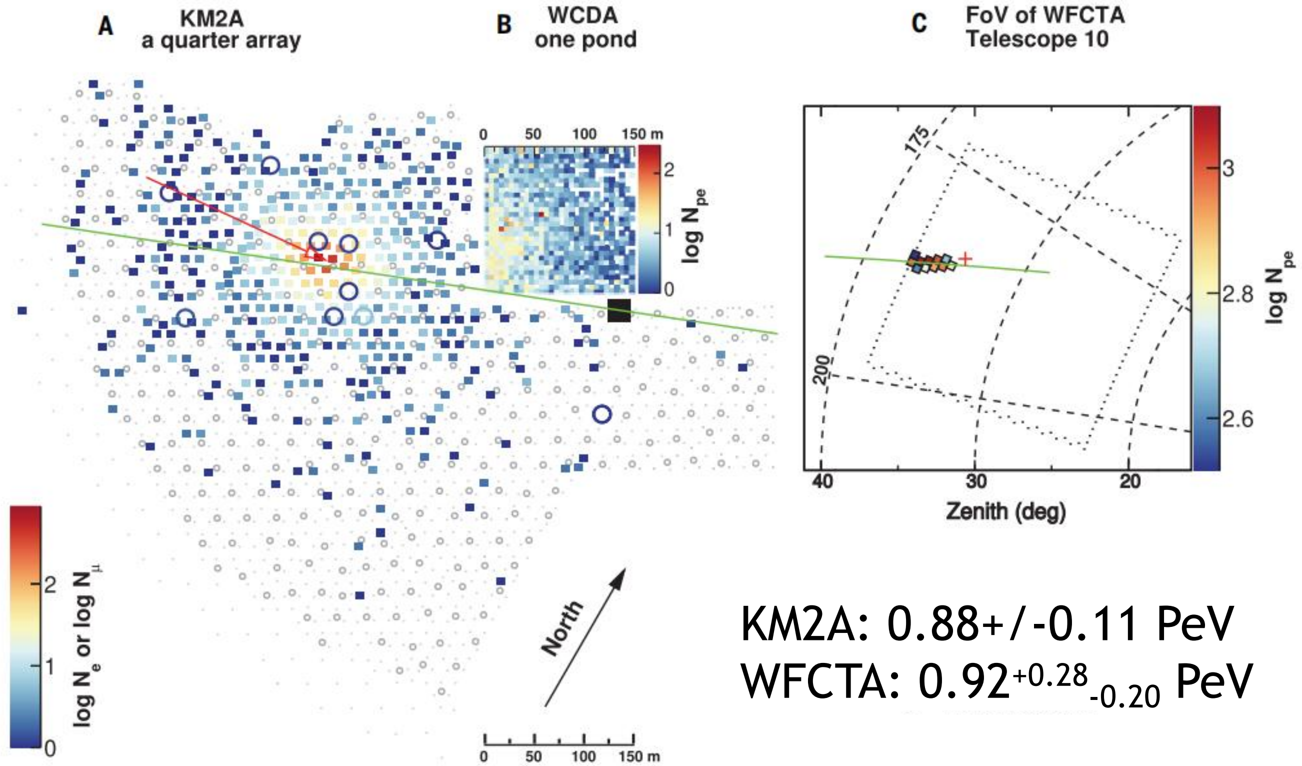


- T~18 kyr, d~4.3 kpc. Clear MC (molecular cloud) interaction, pion-bump feature by Fermi
- LHAASO detects extended emission coincident with Fermi and MAGIC
- Spectrum can be fitted with a cutoff power-law form, with Ecut~60 TeV, suggesting a cutoff energy of accelerated protons of ~300 TeV ➡ SNRs could be PeVatrons, but may not contribute significantly to CRs all the way to the knee

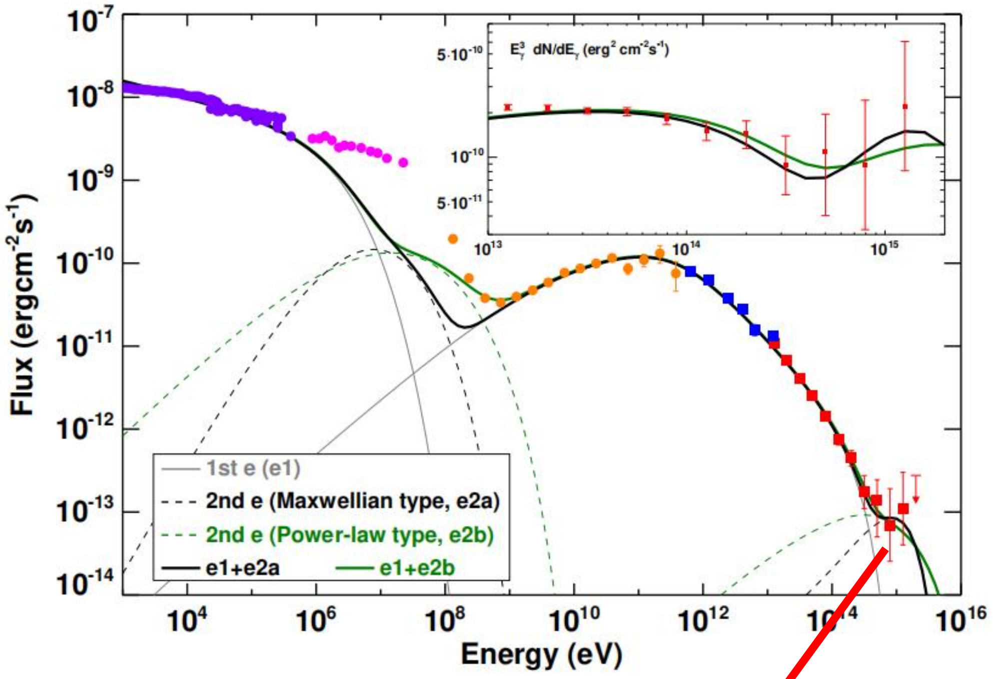
Crab nebula as extreme electron accelerator

Acceleration of PeV electrons by Crab nebula

LHAASO, Science, 373, 425 (2021)



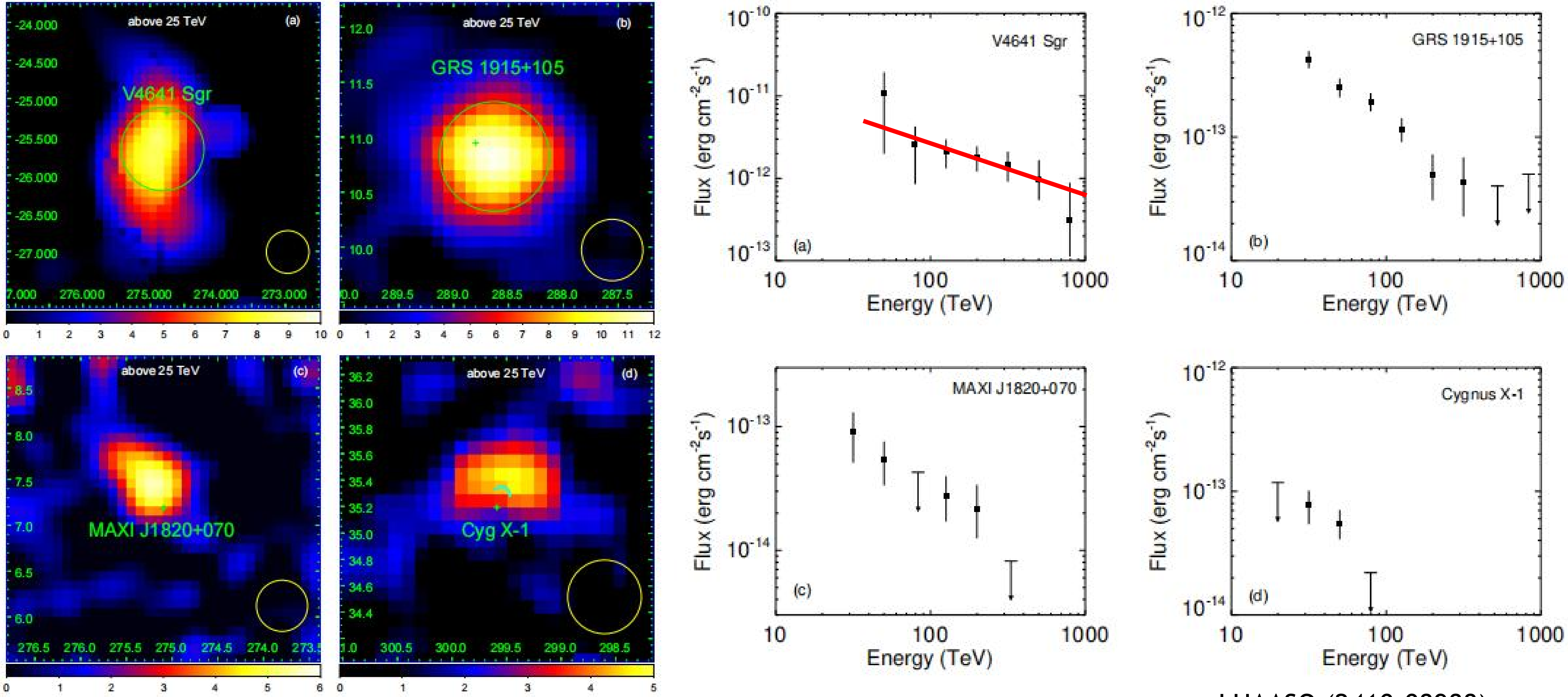
KM2A: 0.88+/-0.11 PeV
WFCTA: $0.92^{+0.28}_{-0.20}$ PeV



Possible new feature?

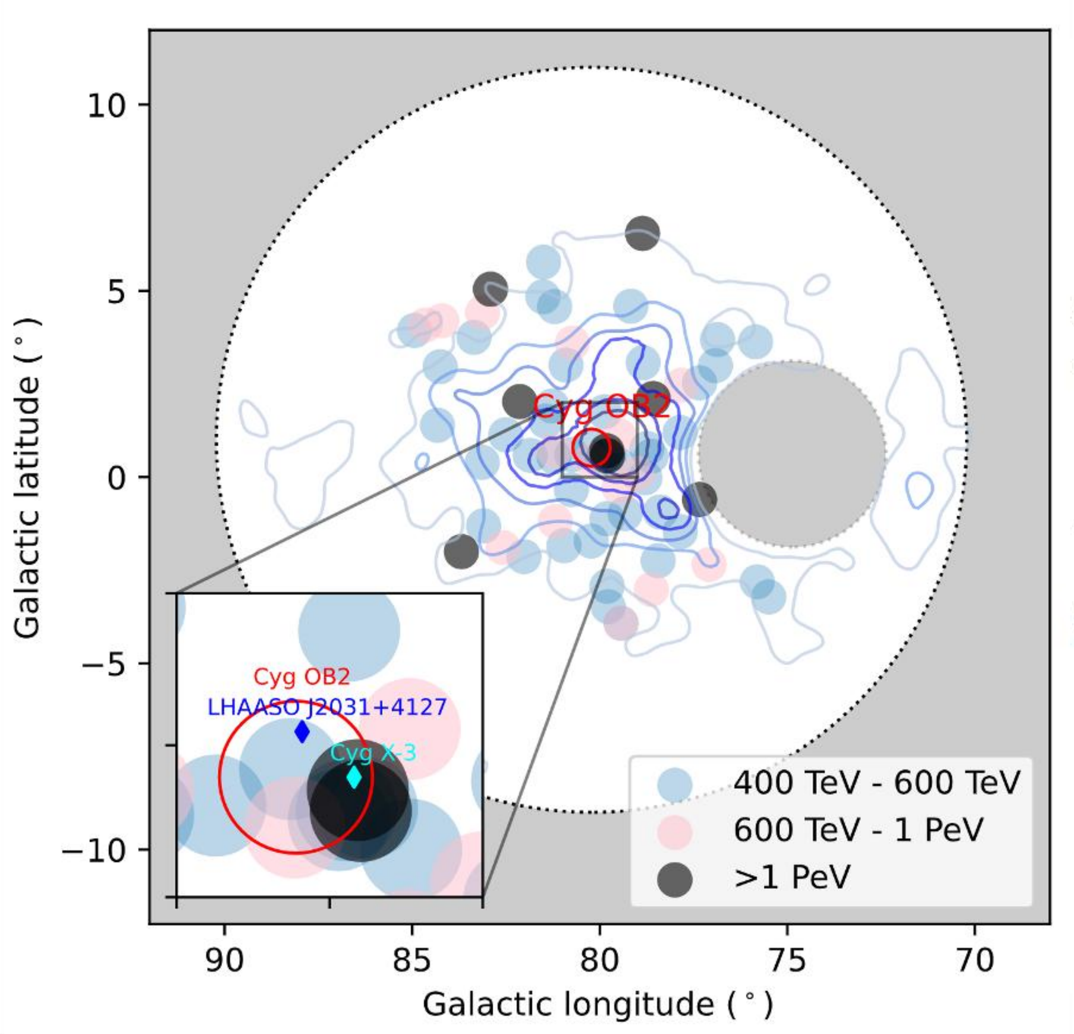
LHAASO measurement of the Crab nebula spectrum extends to PeV, revealing PWNe as PeV electron accelerator

Microquasars (BH jets) as a class of powerful PeVatrons

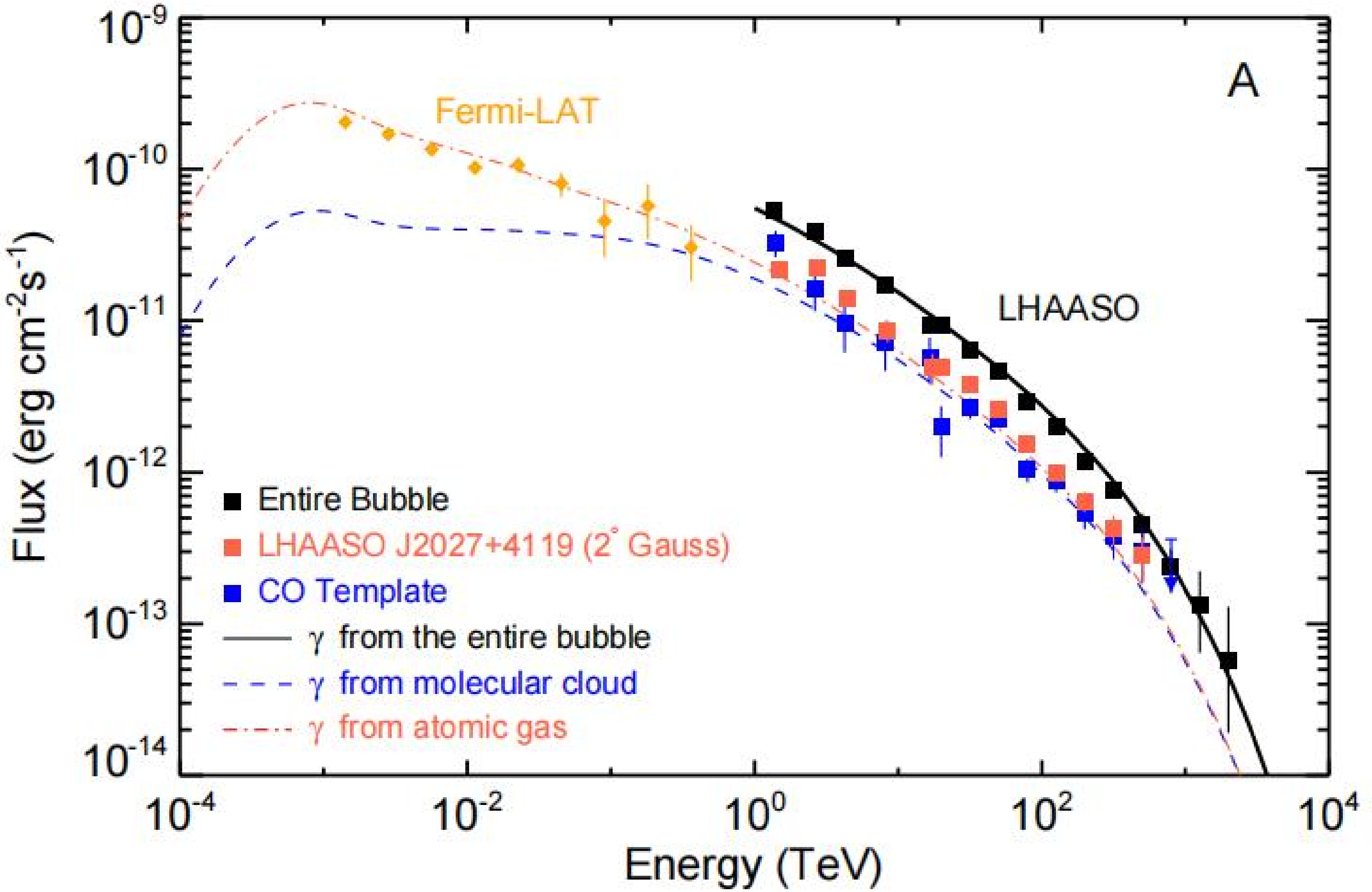


LHAASO (2410.08988)

Cygnus massive clusters: super PeVatron

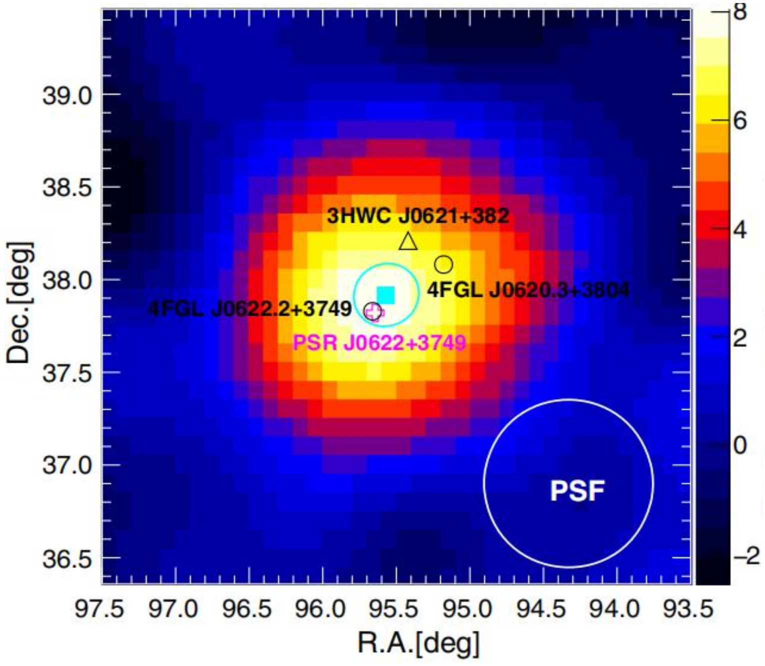


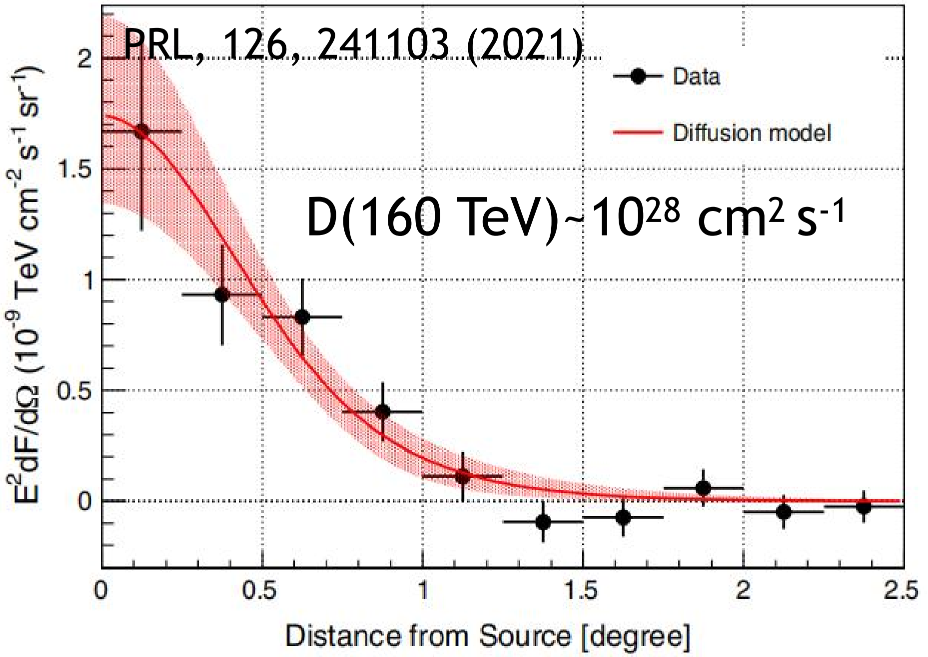
LHAASO (2024, Sci. Bull.)



Morphological and spectral decomposition: extended bubble w HI gas + hot spots w MCs

Pulsar halos to probe CR propagation





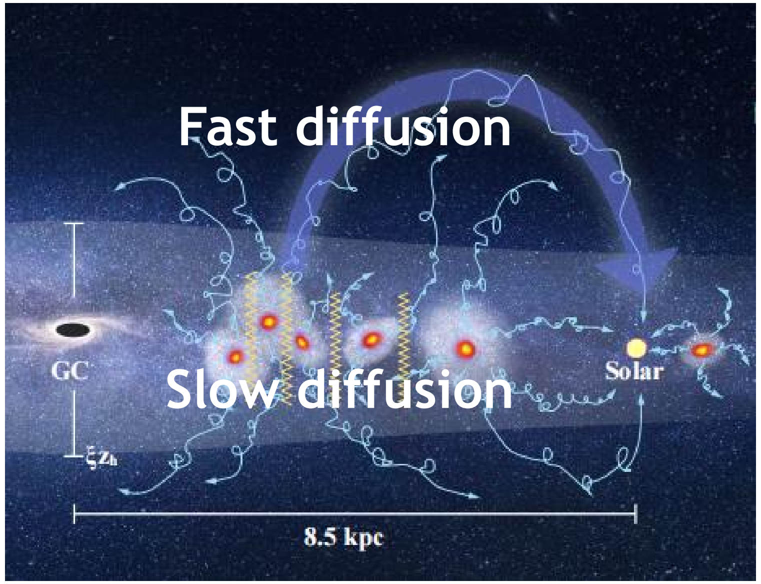
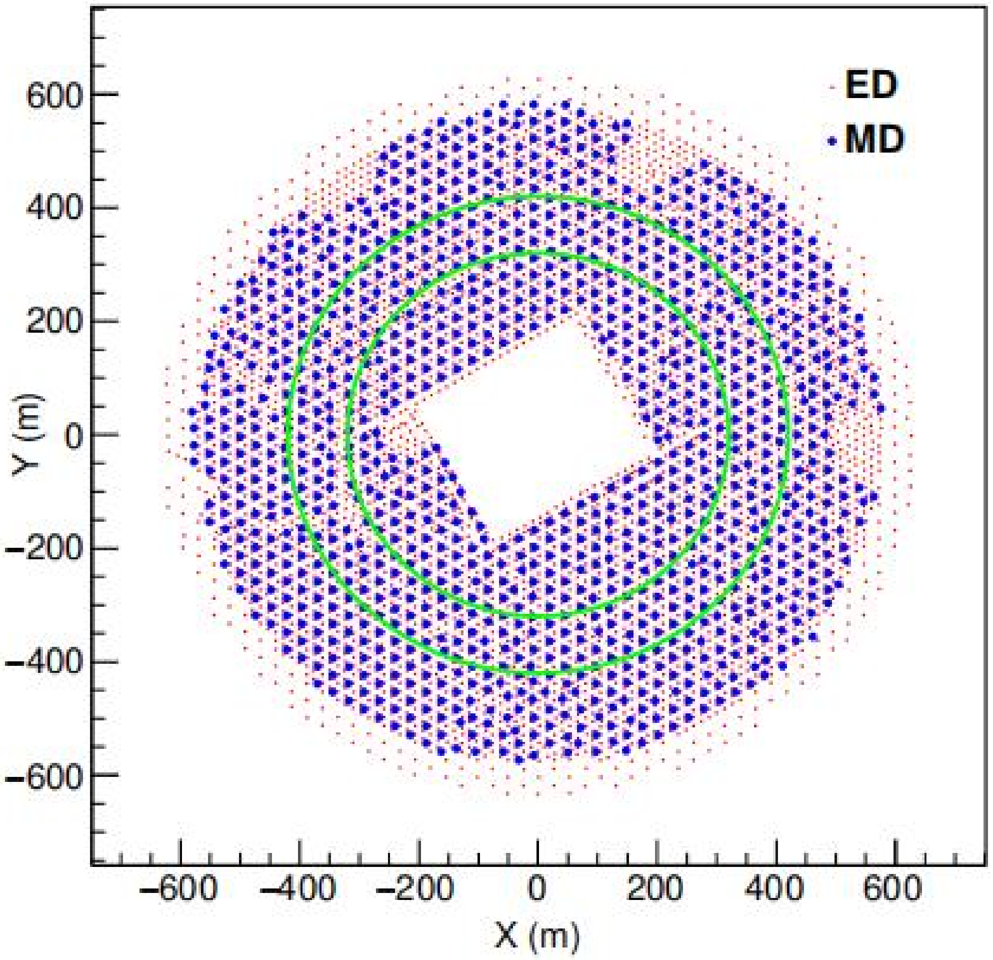


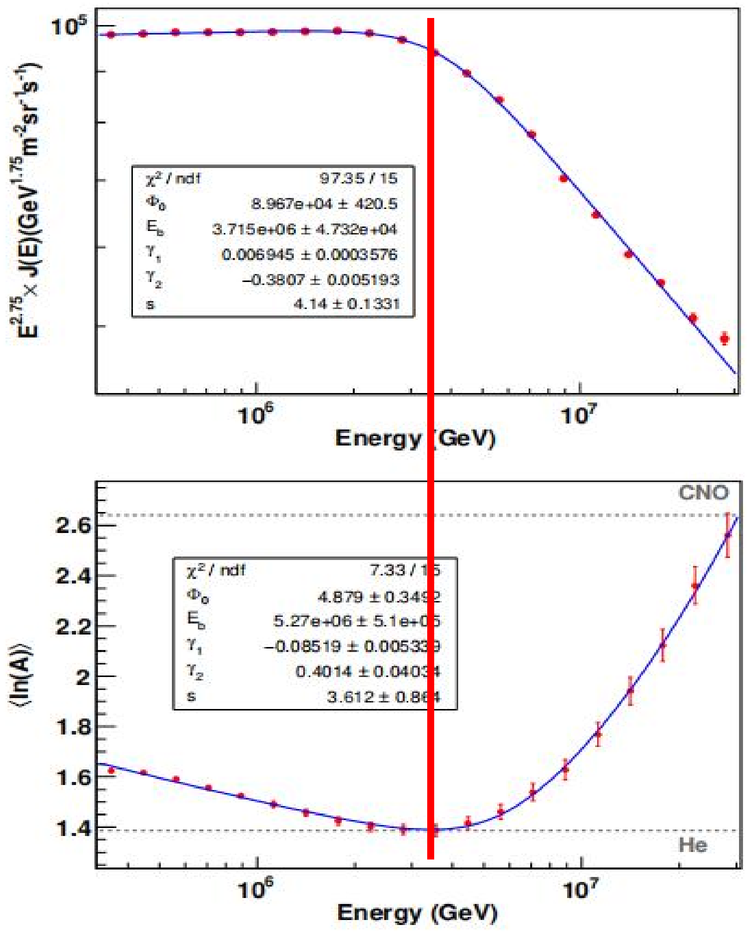
TABLE II. Comparison of the properties of pulsars J0622 + 3749, Geminga, and Monogem.

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

Cosmic ray spectra and <lnA> around the knee

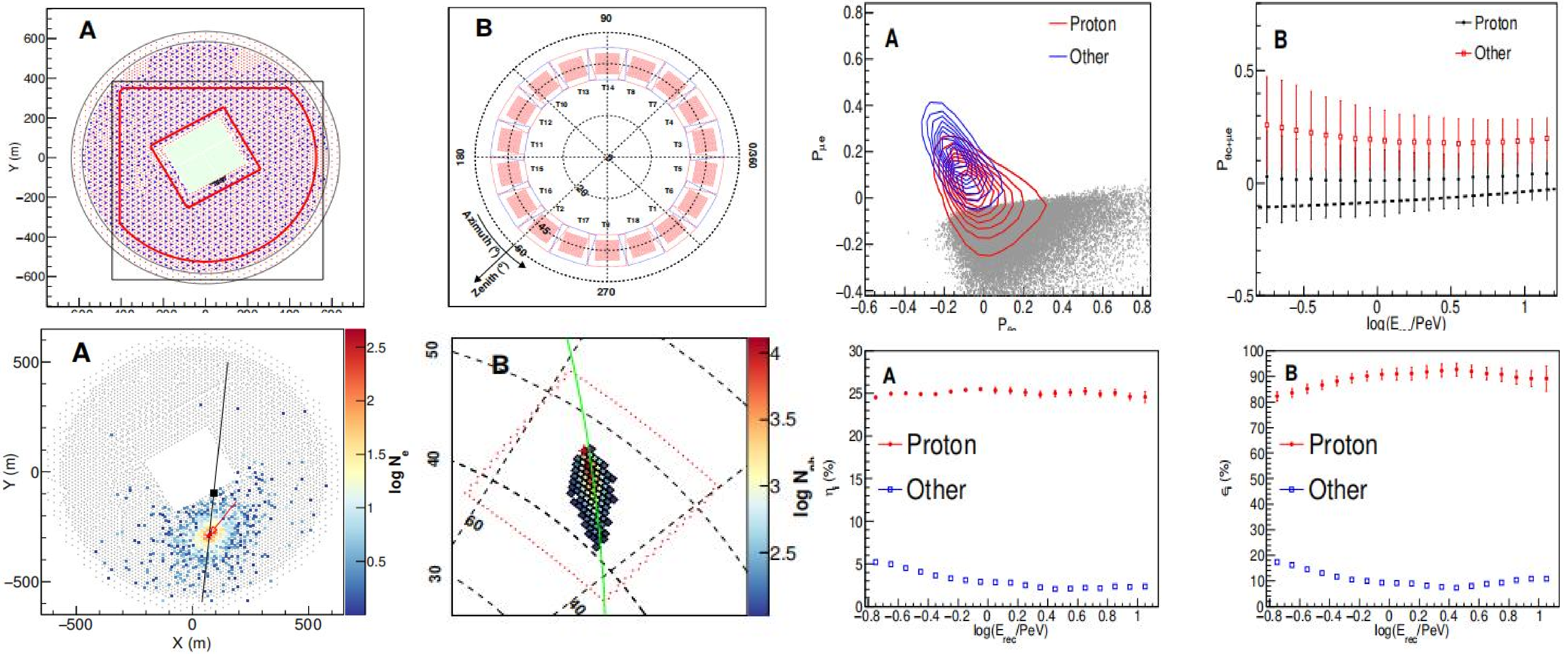




- Knee energy~3.7 PeV, index change~0.4
- Correlated spectra and <lnA> evolution
- All-particle knee is likely due to breaks of light composition

LHAASO (2024, PRL)

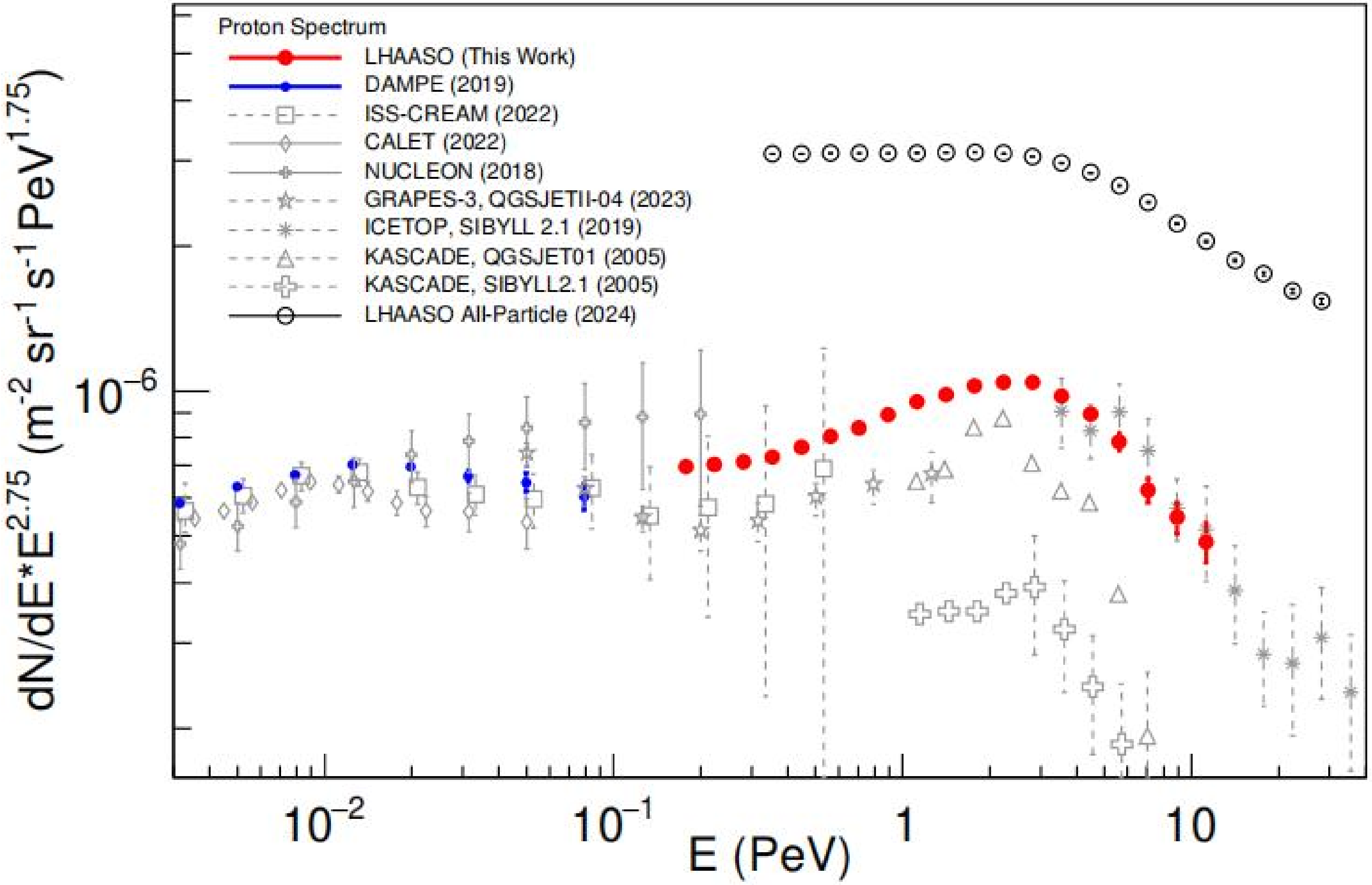
Observation of proton knee



LHAASO (2505.14447)

The combination of muon detectors and Cherenkov telescopes gives ~90% purity of proton sample with ~25% efficiency

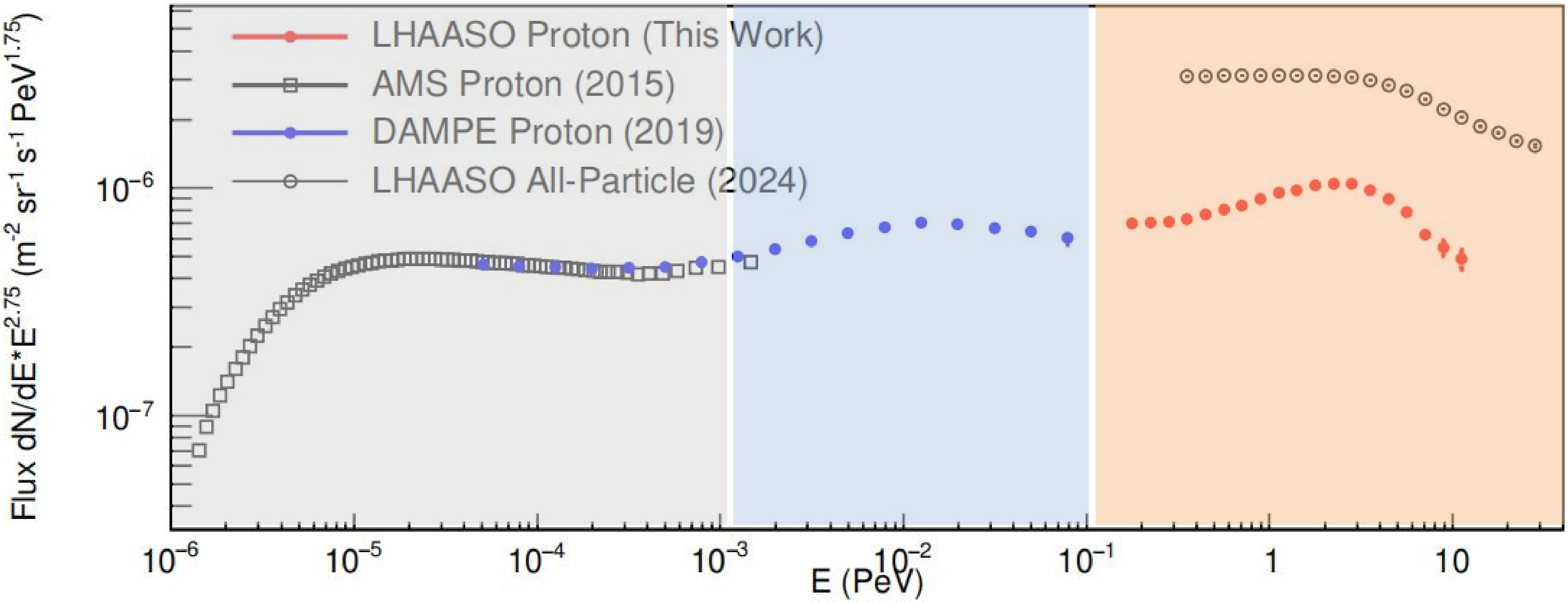
Observation of proton knee



- Hardening ~340 TeV, with index change ~ 0.2
- Softening (knee) ~3.3 PeV, with index change ~ -1.0
- Slightly earlier break and steeper spectrum above the break than the all-particle one

LHAASO (2505.14447)

Wideband spectrum of protons

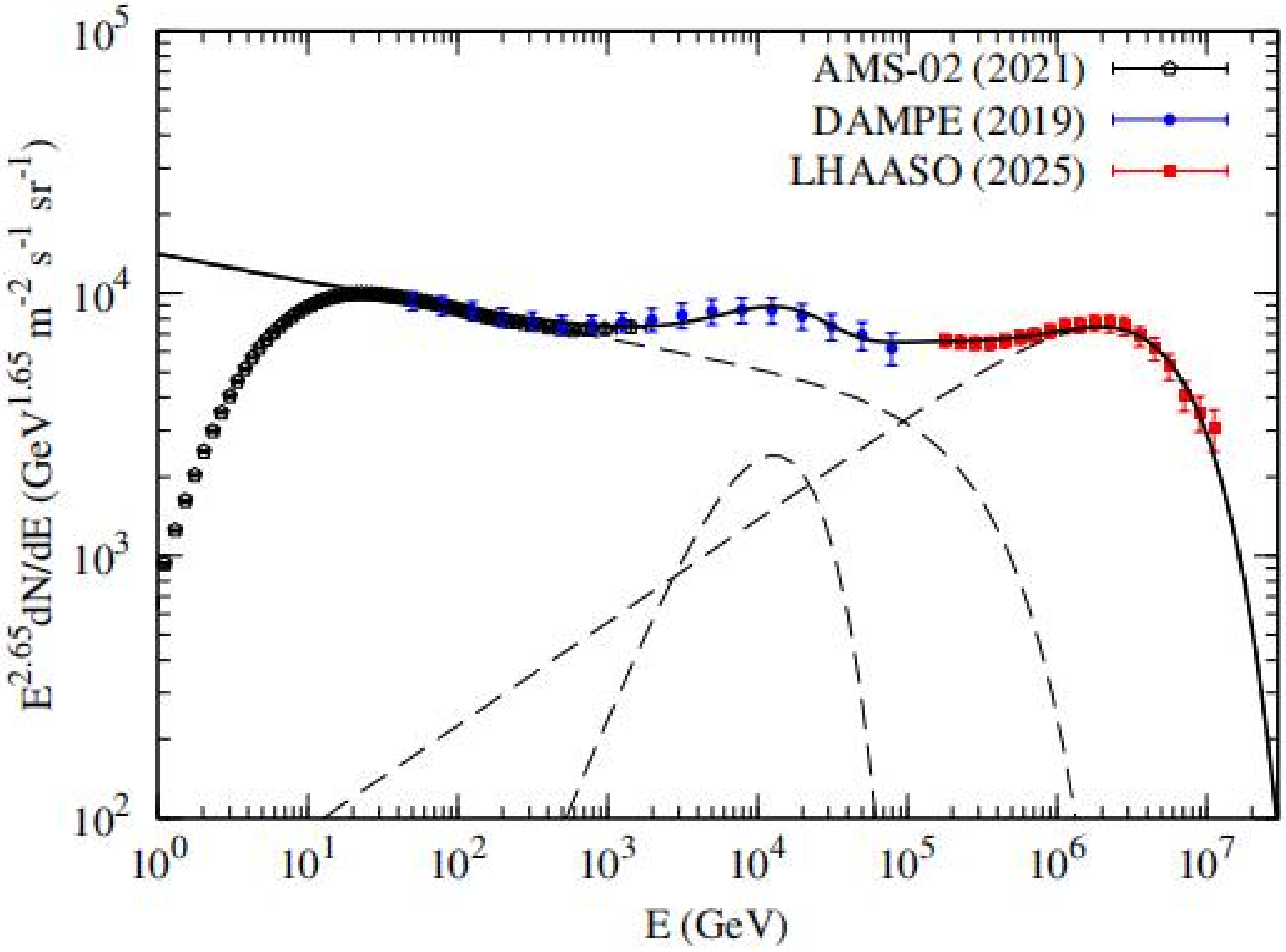


Different source populations as indicated by spectral structures? Probably related with gamma-ray source observations (SNRs, PWNe, μQs, ...)

LHAASO (2505.14447)

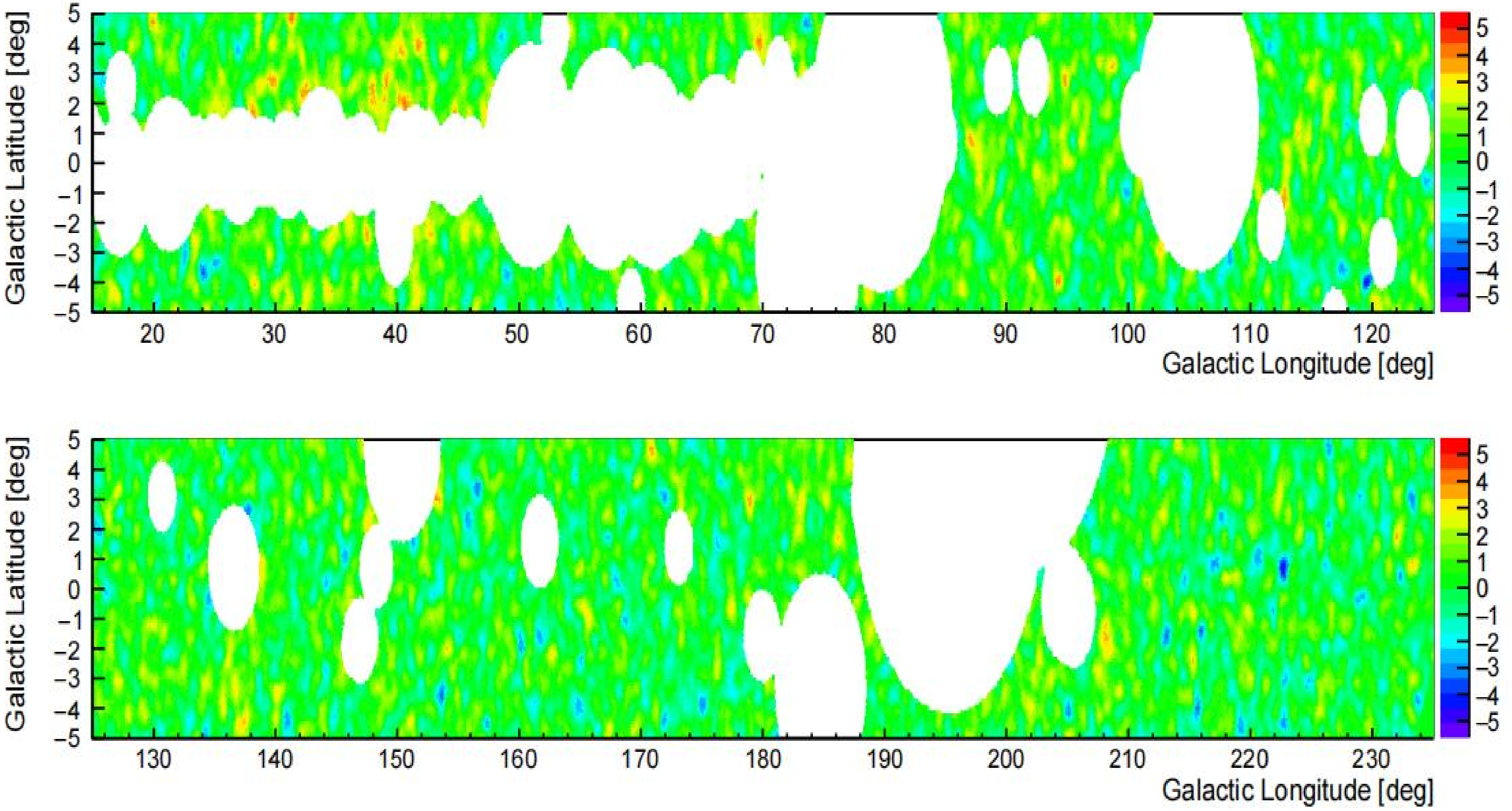
Joint DAMPE-LHAASO measurements are very much welcome!

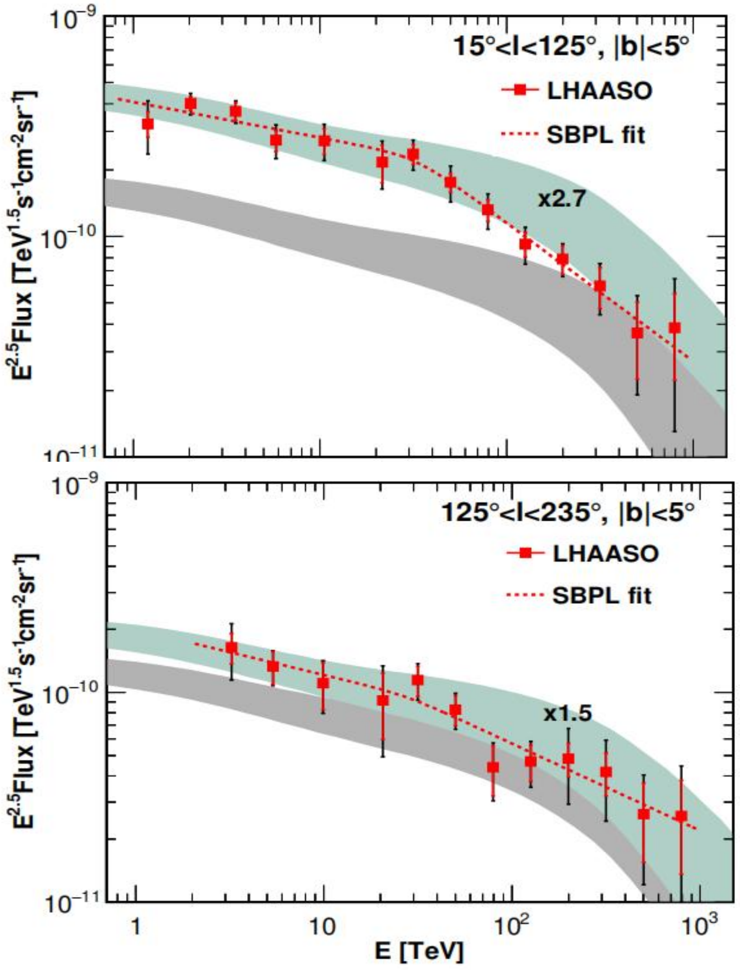
Wideband spectrum of protons



- Low-energy component (SNRs?)
- High-energy component (YMC? PWNe? Microquasars?)
- Nearby source component (Geminga SNR?)

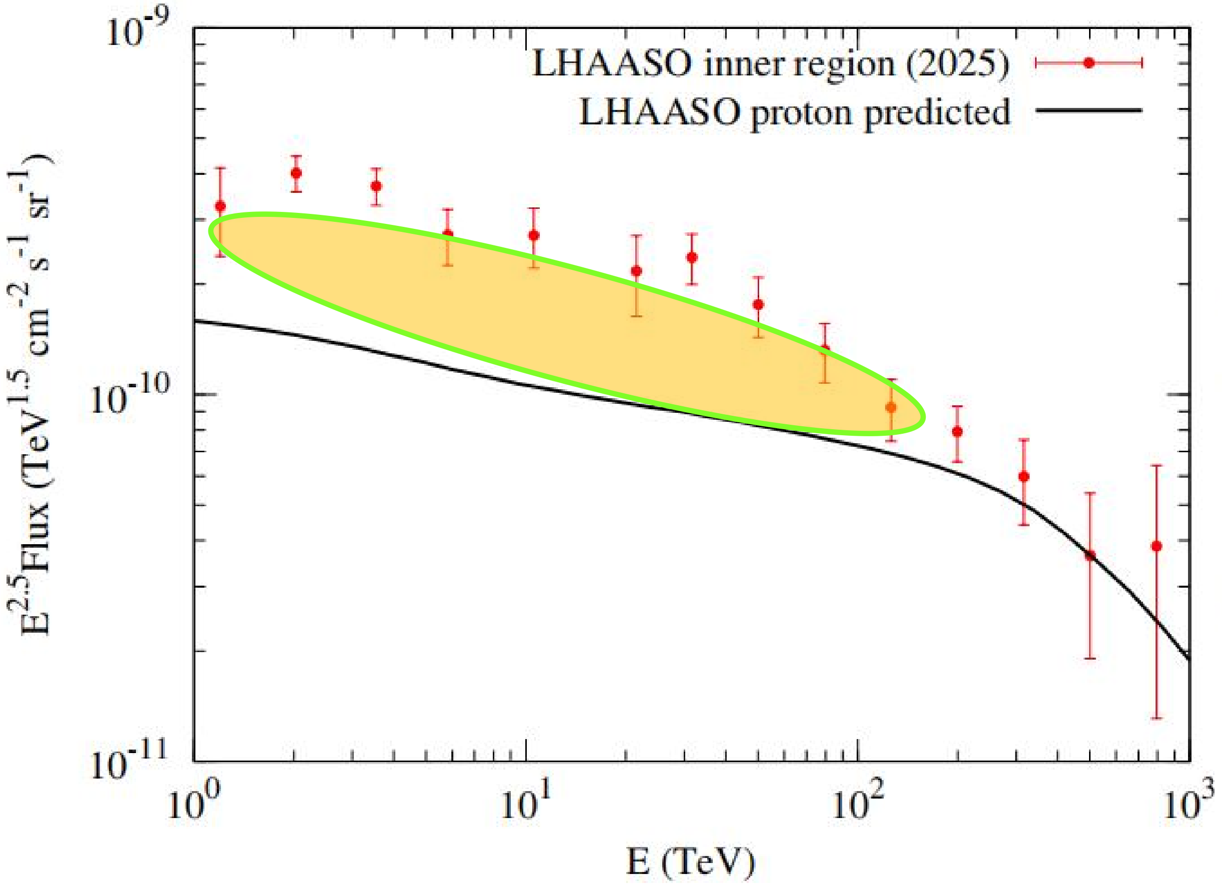
Diffuse γ-ray measurements

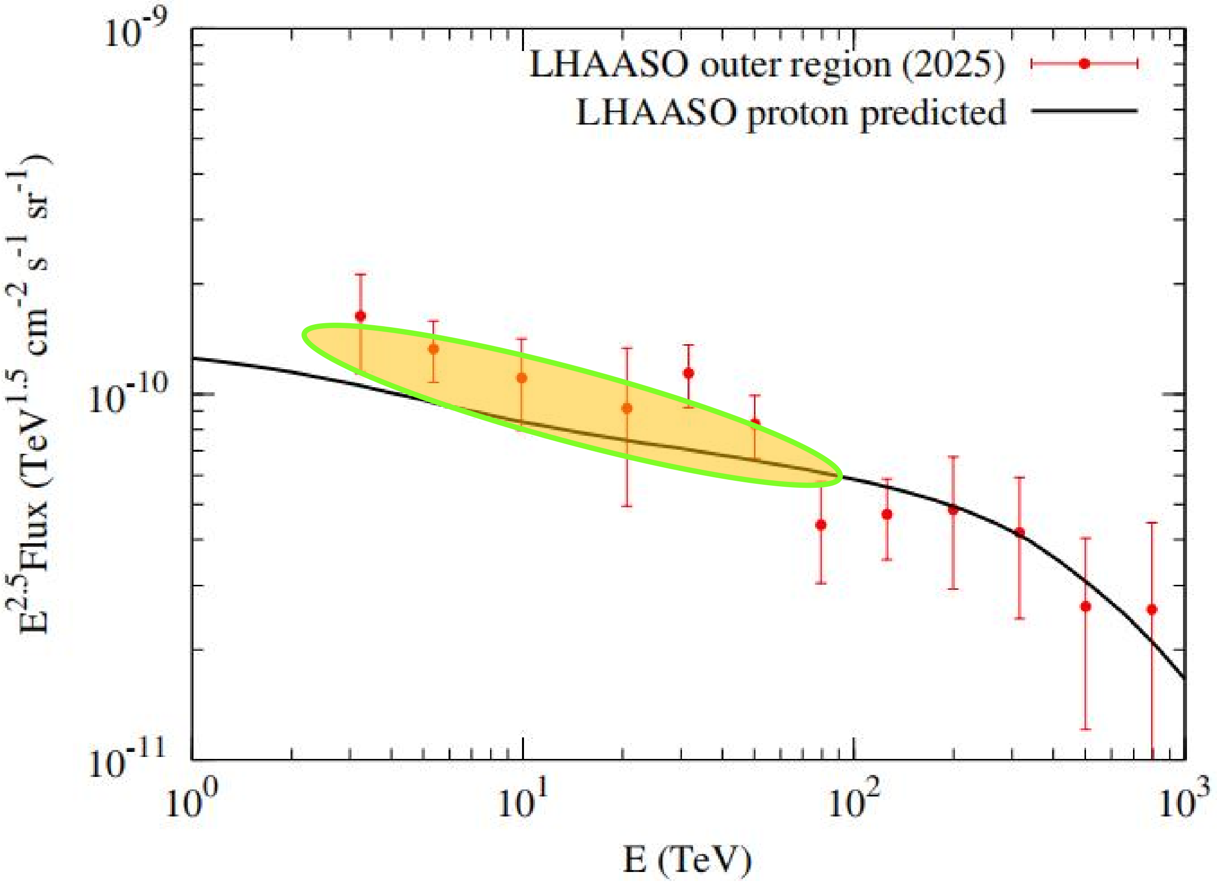




LHAASO (2023 PRL; 2025 PRL)

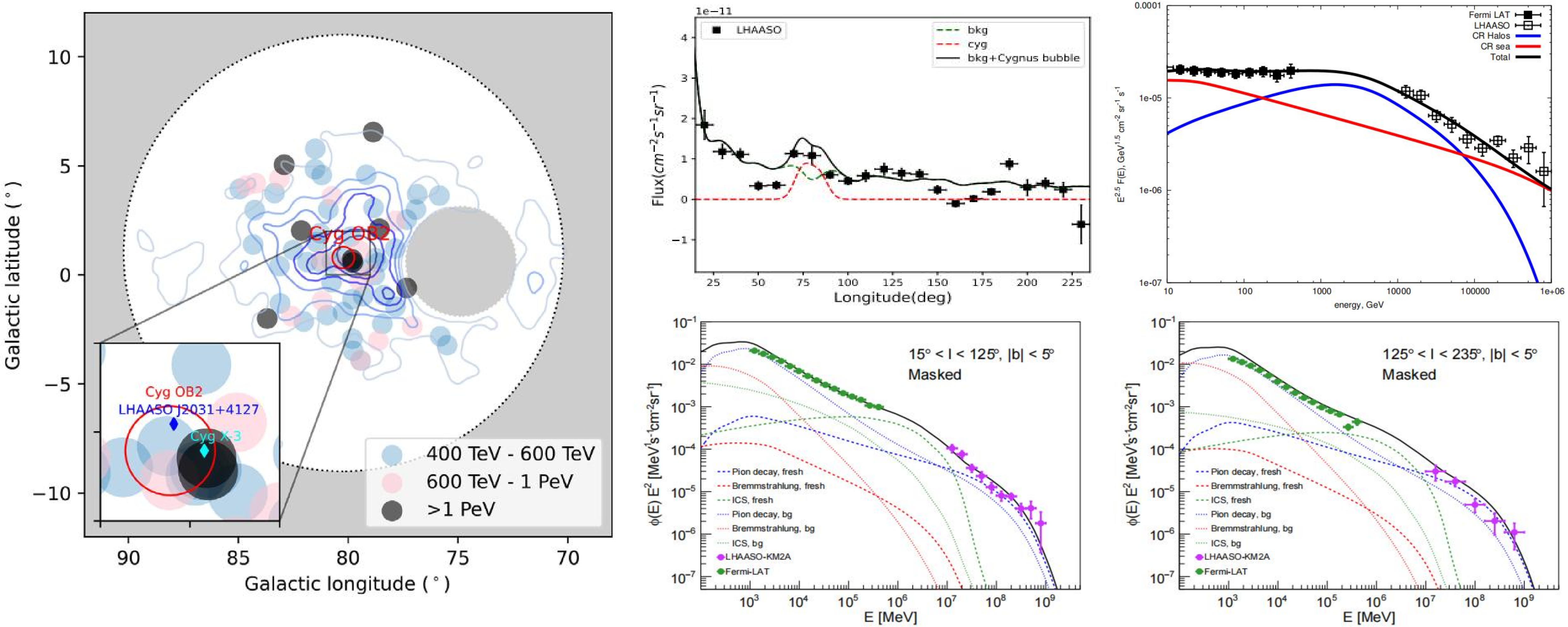
Diffuse γ-ray measurements





- Measured fluxes are higher than prediction below ~100 TeV
- Possible causes: unresolved sources; non-standard propagation scenario
- Caveats: uncertainties of CR and gas density distributions, and cross section

Confinement and interaction around sources



Cygnus bubble: super accelerator as extended as 10 degrees (LHAASO 2024, Sci. Bull.)

Nie + ApJ (2024); He + ApJ (2024); Yang & Aharonian (2024); Ambrosone + (2025)

New paradigm of GCR origin and propagation

传统图像：

- 宇宙线源连续分布
- 扩散系数空间均匀
- 宇宙线在星际介质中相互作用

新图像：

- 源离散分布，个别邻近源贡献显著
- 扩散系数空间依赖
- 在源附近和星际介质中均相互作用

Summary

- DAMPE and LHAASO are among the best experiments for CR/γ detection, offering important opportunity to understand the century-lasting question about CR origin and propagation
- Universal bump structures of primary CRs are revealed, which may be imprints of nearby CR source
- A number of super-PeVatrons are discovered, enriching the knowledge of source populations
- Excesses of secondary nuclei and diffuse gamma-rays indicates new propagation properties of CRs
- New observations of the spectra and anisotropies by joint efforts of DAMPE and LHAASO may eventually uncover the mystery of CRs

谢谢！